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**Building Magnets at
Brookhaven National Laboratory An Account**

Erich Willen

February 2017

Superconducting Magnet Division

Brookhaven National Laboratory

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at
Brookhaven National Laboratory

An Account

*Erich Willen
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Drawing explained on page three

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Cover Illustration: The drawing shows the field in a RHIC dipole magnet when powered to operating current. The outer circle represents the 80 mm magnet coil diameter. The green central portion shows the “good” part of the 3.45 T field: where its strength is uniform to within $\pm$ two parts in 10^4 . The colored contours represent field changes of two parts in 10^4 of the central field. The white center circle shows an area encompassing 95% of the particles in a gold heavy ion beam traversing the magnet. Note that the beam is safely within the good field region of the magnet.

Introduction

The development of superconducting wire and cable in the late 20th century enabled high field magnets and thus much higher beam collision energies in accelerators. These higher collision energies have allowed experiments to probe further into the structure of matter at the most fundamental, subatomic level. The behavior of the early universe, where these high energies prevailed, and its evolution over time are what these experiments seek to investigate. The subject has aroused the curiosity of not only scientists but of the public as well and has facilitated the support needed to build and operate such expensive machines and experiments. The path forward has not been easy, however. Success in most projects has been mixed with failure, progress with ineptitude. The building of high energy accelerators is mostly a story of capable people doing their best to develop new and unusual technology toward some defined goal, with success and failure in uneven measure along the way. It is also a story of administrative imperatives that have had unpredictable effects on a project's success, depending mostly on the people in the administrative roles and the decisions that they have made.

This is a first-person account of some of the events in the development of high field superconducting magnets for the SSC and RHIC colliding beam machines in the 1980's and early 1990's at Brookhaven National Laboratory (BNL).¹ It is a history that is not well known and about which various people have expressed some curiosity. It is written in plain English (hopefully) instead of the jargon of the trade to make it more readable. In those years, after the demise of the BNL Isabelle/CBA program, the Magnet Division (MD) became heavily engaged in R&D for the SSC with a peak work force of some 175 physicists, engineers, designers, technicians, and support personnel. In addition to the SSC work, the Division in parallel developed the magnets for RHIC and transferred the drawings and technology for building those magnets to industry. It also undertook Work for Others that could be accomplished by the MD staff or facilities (please see the Topic, *MD: Projects Beyond SSC & RHIC* for a listing). Numerous innovative and significant magnet construction and design features were developed by the Division in those years (please see the section named *New Designs & Techniques* later in this account for a partial listing). Although the SSC dipole magnet was ready for industrial production well before 1993, the program was ended by Congress in that year and its magnets were never produced in quantity. The full complement (1740 plus spares) of RHIC magnets, however, was built: arc dipoles, quadrupoles, and sextupoles by industry, arc correctors and those fewer in number at BNL. The RHIC magnets have had a storied history---not a single dipole, quadrupole, or sextupole magnet has failed in the years that the machine has been operating beginning in 2000; one corrector coil has had to be replaced.

This has allowed unprecedented productivity and astonishing discoveries in the physics output of that machine during these years.²

After that intense R&D period and during the years of magnet production in volume for the RHIC machine, the Division continued its R&D work in accelerator magnets, not only for BNL but also for projects around the world (noted above). It developed and built the helical magnet system for RHIC and AGS, which allows the study of polarized proton collisions in RHIC. It built dipole magnets for the LHC at CERN, which are now used to bring the stored beams into collision in that machine. It is currently engaged in various development projects to use state-of-the-art high temperature superconductors for magnets. It is actively involved in the US project (named LARP) for upgrading the LHC. The Division has significant work to do but retains much untapped potential; reliable funding for its projects today remains problematic, even unattainable.

As noted above, this account is not meant to be comprehensive; rather it describes selected highlights of the Magnet Division's work over the years. Many valuable members of its staff are not mentioned but it must be understood that their contributions have been significant and important to the Division's success. The achievements of the Division were and are a group effort, a case where one-plus-one equals more than two. There was intense collaboration with LBNL and FNAL in the SSC years and those Labs also made many valuable contributions to that program. They are not covered here but have been noted or referenced in other accounts.³

My own role in building superconducting magnets began in 1980 with a Lab-wide appeal for help from leaders of the Isabelle project. Before that time, I was a physicist in the Physics, then the Accelerator, Departments, doing AGS experiments, working on the MPS detector, and helping university users of that facility. For the previous 17 years, my colleagues and I had carried out numerous experiments at the AGS, many of them innovative and difficult; the work included planning new experiments, designing secondary particle beams, building particle detection equipment, setting up logic circuits for triggering on particle interactions of interest, simulating experiments using Monte Carlo methods to understand acceptances, analyzing data, and publishing results. From that experience, I was well versed in building equipment and using facilities at BNL. At Isabelle, magnetic field measurements, then increasingly magnet performance issues occupied my time. After the demise of Isabelle/CBA and shortly after the start of the SSC project, I became head of the Magnet Division and continued in that role until the end of the SSC and the beginning of RHIC magnet industrial production in 1993. After that I headed the MD effort on helical magnets for RHIC and AGS, and on dipoles for LHC. Building magnets was in many ways a continuation of my earlier work of building equipment and conducting experiments, which I had always enjoyed.

Superconducting magnets for accelerators are challenging, unforgiving, and must be totally reliable. A single magnet failure means weeks of downtime for warmup, repair, and cooldown of the machine. Even a small failure rate would cause a serious loss of productivity in a machine with many thousands of magnets. The magnets must be built with great precision, the currents for generating magnetic fields are large, the stored energy is high, and the forces internal to the magnet are large. Among accelerator labs, few have an unblemished record: BNL's Isabelle (bad superconductor cable design and difficult mechanical design), LBNL's ESCAR project (catastrophic electrical failure of its magnet ring), FNAL's Tevatron (many initial magnet difficulties and ongoing magnet and interconnect failures through the life of the machine), CERN's LHC disaster shortly after startup (two-year shutdown to rebuild magnet interconnections after a destructive failure). DESY's HERA was the rare machine that escaped serious failure, though its startup was challenging as it suffered through a number of magnet coil failures. The project leader Bjorn Wiik had invited Bob Palmer to DESY as an advisor at the start of the project---this helped to get the project off to a good start.

In this account, many specialized subjects have been grouped in the section named Topics. This was done to allow the narrative to proceed without excessive interruption. References and certain specialized commentary has been placed in the section at the end named Endnotes. More complete technical descriptions including pictures and drawings of the magnet effort and many connected topics has been presented in several venues.

At the USPAS course on Superconducting Accelerator Magnets in January 2001 three experts intimately involved in the work at Brookhaven gave lectures.⁴ These three presentations, and others like them in other years and at various levels of complexity, encompass much of what we learned in the years of developing and building the SSC and RHIC magnets. They are recommended to anyone with an interest in this topic:

- Ramesh Gupta (shown in picture), Introduction, Magnetic Design and Analysis
- Animesh Jain, Magnet Theory and Magnetic Measurements
- Carl Goodzeit, Magnet Engineering

Millicent (Penny) Ball and her colleagues developed and marketed, with DOE funding, a CD-ROM tutorial describing the design, engineering and building of superconducting magnets after the SSCL, where she had been working, was closed.

A good description of the RHIC magnet system (and the other RHIC Collider systems) can be found in the comprehensive account published in the journal *Nuclear Instruments and Methods* in 2003.⁵

Both metric and English units for expressing physical parameters are used. This reflects the reality of technical work in the US, where each type of unit is in use. It is necessary to become familiar with both systems in order to survive.

This account is mostly about events that happened years ago. It is based on my recollections, my daily log of events, discussions with colleagues, notes of meetings, memos that were sent and received, schedules, travel reports, pictures, and various other documents from the period including the many technical notes that were written. For the SSC, the history by Wojcicki (Endnote 3) is helpful for learning of the machinations at the higher management levels of that project during its years in Texas. Our efforts on behalf of the SSC proceeded despite the turmoil there thanks to the dedication of the people with whom we interacted. Its tragic demise, a crippling blow to the heart of US science, continues to rankle those of us who worked on it.

I wish to extend my thanks to my colleagues Mike Anerella, George Ganetis, Ramesh Gupta, and Peter Wanderer for their careful reading of this manuscript and their helpful suggestions for corrections and improvements.

The aerial photograph below shows the various machines at Brookhaven that are mentioned in this account. The Magnet Division is housed in the large buildings and attached offices shown at the lower left in the picture.

Isabelle & CBA

Isabelle

In a memo dated July 11, 1983, Lab Director Nicholas Samios informed the Brookhaven community that a HEPAP meeting in Woods Hole, MA had voted 10-7 to reject the construction of CBA. The panel instead favored an “extremely high energy facility in the mid-to-late 1990s” (soon to be known as SSC, the Superconducting SuperCollider). It added that possible directions for Brookhaven included “R&D for a future large accelerator and a device for extremely high energy heavy-ion collisions using the CBA tunnel and superconducting magnets”. The Brookhaven Bulletin dated July 15, 1983 quoted Associate Director Paul Reardon on plans for the future: an R&D group to do SSC work, plans for the AGS, and work on a heavy ion device for the RHIC tunnel. Brookhaven’s Isabelle nightmare of several year’s duration was coming to an end and a new future, based mostly on hope, was in sight.⁶

The physics community had lost confidence that Brookhaven could build Isabelle and its superconducting magnets (by then CBA) in a timely manner; the physics goals were changing. Many Isabelle models had been built over several years but only one of them, the famous Mark V, ever worked in what was considered an acceptable manner. The basic problem was that the superconducting cable used for the magnet coils was unstable in a magnet. It was not based on cable design principles that had been shown by the Rutherford Lab in England to be necessary for magnet stability. When the current in a magnet changes, eddy currents are generated and persist in any loops within the cable that encompass magnetic flux. The superconductor wires need copper stabilizer and, to limit eddy currents, must be twisted and the wires transposed over short distances when cabled. When rolled into a flattened aspect the cable must be of limited width (8-10 mm). These fabrication principles effectively limit eddy currents and achieve stability against quenching from this source. The Isabelle cable instead was made up of large numbers of fine, untwisted wires woven into a flattened, rather wide braid (15 mm) by a machine (at first) that had been designed for making shoelace and that happened to be available at BNL (as told to me by its advocate, Al McInturff), then rolled to a specified thickness. This cable design had not been systematically tested for stability but it could be anticipated from the Rutherford work that the cable would not be very stable. When ramped, an Isabelle magnet’s eddy currents were large; this led to unstable quench performance not to mention terrible field quality during the ramping. In addition,

coils made with this cable typically suffered from turn-to-turn electrical shorts caused by broken wires, another source of instability during ramps. Breaks were inevitable in places with three wires that became heavily compacted when rolled.

There were further problems stemming from the mechanical design of the magnet itself. Coils were large: 120 mm in diameter, therefore challenging to build but needed because the magnet designers had insisted on a warm bore tube. Coils were placed under the required compression during assembly into the magnet yoke by shrinking them in a dewar of liquid nitrogen, then ramming them hydraulically into the heated, preassembled yoke. The process typically left the coils wet with condensation. Water in the coils was sure

to cause electrical problems in later operation of the magnet. This abominable approach had been adopted to address the mistaken belief that only a yoke made of single piece laminations (as opposed to the more common two half-piece laminations) could achieve the required field quality.

The two figures showing first, the Isabelle coil cross section, then its cold mass cross section, are included here for historic interest. Despite its several problems, there were some good features in the design---the use of coil wedges to control field quality and a cold iron yoke both originated in this magnet and were used in later magnet designs too.

As a relative newcomer to the project in 1980, it was both interesting and sad to observe the turmoil that the magnet difficulties caused. There were many talented people involved in the project but they were being led by people not qualified to deal with the technical difficulties that had arisen. The project head, Jim Sanford, a personable but bureaucratic physicist, had not previously built nor commissioned technical apparatus and lacked the ability to understand and judge the evidence regarding poor magnet performance and its causes, nor to understand the people who were reporting to him. The theoretically-minded accelerator physicist leading the magnet design team, Mark Barton, had insisted on the single piece yoke design (personal communication) and had little clue about the manufacturing difficulties that this and other "necessary" features caused. The superconductor cable (braid) choice was being vigorously defended by Al McInturff, a practical-minded, charismatic physicist whose largely one-man show in the Project failed to acknowledge and correct the poor conductor choice. Magnet field measurements were incomplete and frequently in error, thereby leading to further confusion about magnet performance. The top staff at Isabelle seemed to always be at loggerheads with one another in this period, with frequent clashes among the strong personalities on what to try next.

The Lab leadership had maintained its confidence in this cast of characters, doing what it could to give them support including the addition of various outside experts from time-to-time, and hoping that soon the project would right itself. There was always the fear on their part that if they admitted to difficulties, the DOE would end the project. Pressure came too from FNAL, which was building its Tevatron magnets in this period and was publicly critical of the work at BNL.

The main performance issue with these Isabelle magnets was that they typically reached only 80-90% of their design field, and only with a lot of training. At a 1977 meeting in Woods Hole, MA, the Lab had agreed to build a 400 GeV collider at the urging of the group of DOE, BNL, FNAL and other leaders assembled there. This was up from the original 200 GeV collider that had been planned and the increased energy was only partially compensated with a longer tunnel. With the stroke of a pen, the required magnetic field was changed from 4 T to 5 T at that meeting. The technical staff back at BNL was not consulted, although some of those people at that time had confidently written of building magnets with the higher field.⁷ This commitment then became a make-or-break goal at Brookhaven, unlike at FNAL, where the goal of 1 TeV for the Tevatron was considered flexible. In fact, that machine reached only about 90% of its goal for many years because of weaknesses in the magnets in their original incarnation.

Nevertheless, the severe, persistent current problems in the Isabelle magnets compromised field quality and would have made it a very difficult machine to operate. Also at Brookhaven, only a relatively few magnets were built and when they had difficulty, it immediately looked bad. At FNAL, by contrast, a different philosophy prevailed: scores of magnets were built and failed before reliable models appeared. Even then, the Tevatron has over the years had many magnet failures. Their design was less than robust but perhaps reflected only that the difficult art of building superconducting magnets had not yet been fully mastered at either laboratory.

CBA

Naturally, people at Brookhaven outside the Isabelle group were aware of the difficulties and were proposing alternate designs for the magnets. Among them was a small group in the Physics Department led by Bob Palmer (shown in 1st picture), who had noticed that the cable being used for coils in the Tevatron magnets was half the width of the Isabelle cable and could therefore be made into (two) coils fitting the Isabelle aperture by relative simple changes to the existing coil and assembly tooling. He was given permission and a very limited budget to proceed with building a magnet using this cable and a bolted two-piece yoke design. He assembled a talented group of physicists and engineers, including especially Ralph Shutt (shown in 2nd picture; please see the brief bio of this gifted, self-effacing physicist in Appendix C). Also included were Bob Louttit, Dave Rahm, Al Prodel, Carl Goodzeit, and Gene Kelly, a group that, in addition to innate capability, had actually built a lot of experimental equipment over the years. On a remarkably short time scale, by July 1981, they produced a short magnet that worked perfectly (5.3 T without training) and whose design could be used for Isabelle. It used the Tevatron superconducting cable in a two-coil $\cos \vartheta$ design where the coils included copper wedges to shape the field (Isabelle but not FNAL coils used wedges) and prestressed directly with yoke blocks tightened with bolts (allowing easy disassembly if needed, unlike the welded Tevatron collar design). Coil wedges are now routinely used in $\cos \vartheta$ coils. The bolted design proved impractical for larger, higher field magnets and was replaced in later designs with mechanically locking stainless steel collars. Mechanically locked collars were first used for HERA at DESY (made of aluminum) and then for the SSC magnets designed at BNL and the LHC magnets at CERN (made of stainless steel). In RHIC magnets the steel yoke was used as a collar. These magnets all used a cold-iron yoke, as in Isabelle (the Tevatron used warm iron).

This development of course dramatically changed the dynamic at Brookhaven. Director George Vineyard's resignation was announced in August 1981 and Physics Department Head Nick Samios was appointed Lab Director in May 1982 after a short search by the Trustees. By then, the Magnet Division had been reorganized to build and incorporate the new magnet design into Isabelle, later renamed Colliding Beam Accelerator (CBA). Palmer, with Ralph Shutt as Deputy

and Bob Louttit providing operational guidance and support, had replaced Ronnie Rau as Magnet Division Head in October, who had earlier (February) replaced Ed Bleser in this job. Bleser, a capable and experienced physicist, had been given the job under very difficult circumstances, almost as a sacrificial lamb. Within a few months of the successful Palmer magnet, remaining project staff opposition to a change in Isabelle had been swept away and the Magnet Division was working exclusively on the development of the Palmer design; a full-length version was tested in October, 1981. The professional staff by then included a mixture of Physics Department and Isabelle personnel, as did the technician staff which actually did the physical work of building the magnets. Confidence and a new sense of competence now prevailed as the old guard including many of its weak performers disappeared into other jobs or retired.

The years 1982 and early 1983 were busy and fruitful at Brookhaven. Magnet work shifted completely to the new "Palmer" design later in 1982 and into 1983. Tooling was designed and built to make the Palmer magnet, Isabelle tooling was modified wherever possible, material including superconducting cable was acquired. By April, additional dipole magnets (CM4,5; LM5,6,7,8) and a quadrupole magnet had been built and tested with good results. Plans were made for a full cell test in the Isabelle/CBA tunnel. In October, 1982, the first dipole, labeled LM8, was installed there. The test was conducted in May 1983 with great success, thereby proving the capability of the magnets, the refrigeration system, and the infrastructure to assemble the machine, by now called CBA. New magnet measuring techniques had been developed that allowed routine and unambiguous magnetic field quality measurements including eddy current effects in the field to be measured for the first time.

These developments were noted by DOE in the quarterly review of October 1982, where Ed Temple, the rigorous but fair-minded DOE official in charge of conducting technical project reviews, was especially positive.

Unfortunately, the larger high energy physics community was not pacified. Newly appointed Lab Director Samios was spending most of his time dealing with a barrage of pessimism coming from all directions. A HEPAP committee under S. Drell had concluded that the construction project could not continue with the available budget. In April 1982, a Science article entitled "A Requiem for Isabelle" written by W.J. Broad was filled with gloom and negative spin, beginning with the title. A New York Times Magazine story on CBA in December 1982 emphasized how completely Brookhaven had "messed up".

Paul Reardon, appointed Associate Director for High Energy Facilities in October 1982, continued to assist in the Lab's defense. Palmer was assigned to head a Task Force (replaced by Ralph Shutt as Magnet Division Head) to rebut the argument that the promised high luminosity of the CBA was not useful; that higher energy, not higher luminosity, was needed as the next step for progress in the field. This argument, pushed especially by Leon Lederman at FNAL, was

convincing to increasing numbers of the community's members. A 20 TeV collider had been discussed at Snowmass in the summer of 1982. Lederman, director of FNAL, spoke enthusiastically of a machine in this energy range, which he dubbed the "Desertron". That name was meant to describe an energy region still containing significant physics based on the Standard Model but beyond which lay a barren region of little interest. The issue culminated in the ill-fated 10-7 vote of the Woods Hole HEPAP committee in July 1983 to abandon CBA in favor of a higher energy machine. The transformation of the Laboratory from a bumbling and incompetent enterprise into a competent and productive one had come too late, and the field of high energy physics lost a machine that could have produced exciting and leading-edge physics for years to come.

The demise of CBA was a traumatic event for BNL. The future for accelerators at the laboratory seemed dark even as the Lab was discussing what could be done with the completed CBA tunnel. The construction of the tunnel in the sandy soil of Long Island (please see the photos below), overseen by E. Parke Rohrer, was largely complete (he left the Lab for other endeavors but returned in 1986 as Associate Director for Management and Physical Plant). The SSC program was not yet under underway and it was not known what role BNL would play in that program. It turned out that the skilled manpower and impressive resources at BNL for designing and building superconducting magnets were considered by the nascent leadership of the SSC to be important for the success of that proposed program. And of course the Lab needed those same resources for whatever machine might be decided upon in the future. What had been learned in the Isabelle/CBA programs at BNL, both the good and the bad, would not be lost but instead would become the foundation for the excellent magnets gradually developed for SSC and RHIC. With support from DOE, in particular Bill Wallenmeyer, Director of High Energy Physics, work continued with a focus on the new projects but also on an orderly termination of the old.

SSC

Introduction

The July 1983 recommendation to end CBA was accepted by DOE later in 1983. In parallel, planning to build SSC magnets at BNL with the approval of DOE had begun already in 1983 when possible designs for magnets for the machine were actively discussed, spurred by Bob Palmer, who was never short of new ideas and who had a good tolerance for those of others.⁸ Costs would be a major consideration so ways were sought in the earliest planning to minimize them. In order to avoid very long tunnels and to continue with a known technology, BNL was led naturally to cos Θ -style magnets, in which the product of magnet length and tunnel length was believed to result in a cost minimum. A coil diameter was picked, 32 mm, which seemed adequate based on computed beam stability requirements and expected magnet field errors. A 2-in-1 configuration, in which the required two beam tubes would be contained in a common iron yoke, was chosen. Upgraded, high homogeneity (HiHo) NbTi conductor capable of carrying higher currents than in the Tevatron and CBA was believed possible and was being actively pursued by industrial firms and university groups with strong support from DOE.⁹ The new conductor Nb₃Sn, capable of much higher currents at high fields, was available in the required cable configuration so consideration of magnets with such conductor was included in the deliberations.

Magnets made with Nb₃Sn superconductor would need enlarged ends to avoid stressing and breaking the brittle conductor filaments that result from the high temperature cure required for that material to form the superconductor; the magnets envisioned were too long to perform this cure after building the coils so pre-reacted conductor was used. Thus enlarged “dogbone” ends were included in the design of the coils.¹⁰ The picture shows an early SSC magnet, here using NiTi conductor, being assembled with such ends.

Models of this design¹¹ were built already in late 1983. They were 4.5 m long so that tooling and fixtures from the CBA program, whose magnets were this length, could be used. Superconductor cable from the CBA program was used, keystoned to the larger 2.8° needed for the smaller coil diameter. The coil design was necessarily ad hoc given that cable parameters could not be fully controlled. Tooling required to build the coils and assemble a cold mass was modified from the CBA program or built as needed. The iron yokes were made of blocks of glued

laminations. Stress on the coils was applied by means of bolted stainless shells designed for easy assembly/disassembly on these R&D magnets. The first of these SSC 2-in-1 cold masses was tested in liquid helium in BNL's vertical dewar in July, 1984. It reached its short sample limit of nearly 6 T with no training, an encouraging success.¹² It reached a maximum field of 7.3 T after a few quenches at 2.5 K in the liquid helium bath.

In all, four magnets in this style were built; all had similar good quench performance, with magnetic fields close to that predicted for the coil/iron design. The third of these magnets used the new high homogeneity NbTi conductor albeit with large 21 micron filament diameter. It reached a stable plateau field of 6.5T after a few training quenches and reached a maximum field of 7.8T at 2.5K. Numerous tests were done with these magnets: cross talk between two apertures as a function of field magnitude, effect of assembly shim variations on field harmonics, quench propagation studies designed to understand the needed quench protection parameters, etc. They provided a sound data set showing how such small diameter coils would perform but also pointed to the need for additional magnet instrumentation in the R&D plan going forward. Overall, we learned that there were too many questions about the magnets' performance that could not be answered---quench origins, quench development with time, coil temperatures reached, and more. These issues engendered much opinion and speculation and too many suggestions for changes that could not be evaluated very well. More instrumentation would be needed to correctly plot the best course forward. The last of these four magnets was tested in March of 1985.

The effort to build these magnets had a positive effect on the members of the Magnet Division; not immediately but gradually as the work progressed. These magnets were a complete break from the designs of the immediate past, a new challenge that seemed to have a bright future. There was interest from outside the Lab, with regular visits by Maury Tigner (shown) from the newly formed Central Design Group (CDG), Clyde Taylor from LBNL, and personnel from DOE. In addition to the totally new magnet designs, which required extensive new tooling, there was new magnet instrumentation for monitoring and measurements that had to be built, installed and used. With that and the stepped-up construction goals came more intense interaction between the engineers and physicists of the professional staff, and with the technicians on the floor doing the hands-on work of building the magnets. Magnet changes were required to improve performance, overcome construction obstacles or to modify some ill-fitting part. Measurements both during assembly and in the cryogenic testing pointed to changes that needed to be explored. Gene

Kelly (shown) was heading the mechanical effort: knowledgeable and hardworking, Kelly brought production engineering experience to BNL, a thorough knowledge of design room and machine shop capability, and took schedules seriously. George Ganetis oversaw the electrical and dewar testing effort and Peter Wanderer the analysis effort. The Division gained valuable experience in meeting schedules and responding to changing requirements. Work habits were formed that would be needed in the R&D effort to come, which not only required enhanced interaction within the Division at BNL but also ongoing interaction with the external customers of the Division's efforts.

Enhanced instrumentation included the installation of voltage taps on the coils to locate quench origins and to measure quench propagation velocities, strain gauges in the coils to measure coil stress levels, and of course the new tangential coil multipole measuring system for accurate, unambiguous analysis of magnet fields. As the use of these systems expanded, the understanding of magnet performance and the reasons for weaknesses grew to be far more disciplined than had been the case in the past. Perhaps the behavior of high field superconducting accelerator magnets will never be fully understood in all their myriad facets but many of their peculiarities came to be appreciated and respected. More will be said about this topic in a later section.

A number of coils were built with pre-reacted Nb_3Sn . Initially, there was some filament breakage in the conductor at the transition from a straight path to a curved path entering the ends. The curvature makes that a difficult section to wind without stressing the brittle filaments. This eventually was overcome and good coils were built, but the opportunity to build magnets was lost as the SSC program adopted the successful magnets with NbTi coils as the preferred design for the machine.

Division Oversight

At the start of the SSC magnet work at BNL, Associate Director Paul Reardon was in charge of HE Physics and his responsibilities included Director's Office oversight of the MD. Reardon was an enthusiastic supporter of SSC magnet work at BNL and he made every effort to encourage such work at the Lab. BNL had substantial capabilities for doing the R&D that would be required for SSC, capabilities that became available after the demise of Isabelle/CBA. The leadership at DOE supported funding for magnet work at BNL and the new CDG saw a good fit to its requirements. FNAL was busy with the completion and commissioning of the Tevatron and the magnet group at LBNL was too small to do all the work that would be required. Reardon initially lobbied for the new CDG to be located at BNL but the decision was made to locate it at LBNL. Reardon ensured good support for the MD's work in the years he was in charge, both with funding and from the machine shops and other BNL service departments.

He was also an avid booster of a new machine at BNL, which would later become RHIC. To make progress towards such a machine, he arranged for magnets built elsewhere to be sent to BNL for testing and possible incorporation into a magnet design for RHIC---in this program we received some FNAL magnets as well as some modified HERA magnets from BBC, one of the European companies that had built those magnets. He enjoyed interacting with others and in that vein, inaugurated various manufacturing studies with industry to estimate costs for SSC or RHIC magnets. These initiatives paid off later with the involvement of industry in the building of RHIC magnets. He definitely did not like the FNAL model where everything was built in-house. He also organized a work exchange program with DESY. We would provide them with magnet measuring apparatus, temperature sensors, and help with the acquisition and testing of superconductor; in return they would supply us with stands for testing magnets at the conclusion of their HERA magnet program. He typically returned from trips full of ideas about new magnet designs and construction approaches and a fair amount of effort was required by the professional staff to evaluate his steady stream of suggestions.

An unfortunate legacy of Reardon was the underestimate for the cost of RHIC. He always had in mind a cost that he felt would be supported by DOE, in particular by David Hendrie, then Head of Nuclear Physics, for a new machine. That figure was not derived from any realistic estimates for the amount that would be required. When Division engineers began to provide realistic estimates, they proved to be much higher than the low figures he had been using. Sadly, despite

his confidence that the numbers could later be changed, they never were adjusted. The project suffered greatly as a result and it had serious other consequences for Brookhaven as well. The eventual cost for the RHIC magnets was \$168M in as-spent dollars¹³, close to the figure we had estimated in 1993 (\$156M in \$1993 dollars) and about twice the initial figure used by Reardon. Even this (low) final cost was achieved only because of cost-effective designs for the magnets, the beneficial industrial participation in SSC work, and a helpful low in the economic cycle when RHIC contracts were awarded.

When Reardon left BNL for other endeavors (he began work at SSCL when the SSC Project moved to Texas), Eric Forsyth was appointed Head of the Accelerator Development Department (of which we were a part) in April 1986. He was an engineer who had been the leader of the successful Superconducting Transmission Line project some years earlier. Forsyth was not a good match for the Magnet Division. He had little if any interest in SSC work. Over time the funding for the SSC effort was about ten times larger than that for RHIC R&D and the SSC support of BNL staff and infrastructure was absolutely critical to the future success of RHIC. Nevertheless, he was unable to understand why we were all working so hard for SSC since “it’s not even a BNL machine”. In due course (mid-1987), Director Samios appointed Parke Rohrer to provide Director’s Office oversight of MD work. From his first day, Rohrer established a sincere interest and a deep and abiding faith in the Division’s work and supported it accordingly. Under his stewardship the Division’s work proceeded smoothly on both the SSC and RHIC efforts. A few years later the RHIC Project Head, Satoshi Ozaki was appointed, the SSC work diminished at BNL as the new SSCL in Texas flourished, and Rohrer faded from the scene, later retiring from his years of service on behalf of the country’s high energy physics programs. In January 1993 he had been recognized with the DOE Secretary’s Outstanding Contractor Program Manager Award, which pleased him greatly. He lived his last years in Lancaster County, PA among the Amish community from whence he came, passing away at his home in 2013.

Central Design Group and Magnets

In parallel to the work on the 32 mm magnets, BNL had been holding profitable discussions and exchanging technical ideas with LBNL, in particular their magnet group head Clyde Taylor, on building magnets for the SSC. LBNL had a program of building short models to test various design features, an outgrowth of their earlier ESCAR work. Based on their experiences, they offered a variety of ideas for joint consideration. They were particularly interested in pursuing improved NbTi superconductor; this led over the next few years, in collaboration with the University of Wisconsin and industry, to major improvement in the current capacity of that material, becoming known as “high homogeneity” (HiHo) NbTi (Endnote 9). This collaboration led to the proposal for the “A” magnet option in the upcoming Reference Design Study.

In December, 1983 the DOE and the heads of the high energy physics laboratories chartered a Reference Designs Study (RDS) to develop more detailed guidelines for a new machine. They set 20 Tev as the proposed energy as well as certain other basic parameters including luminosity. A range of dipole field options was to be explored to enable a search for the most cost-effective choice between magnet cost and tunnel length. Maury Tigner from Cornell was chosen to head this study, which was held at LBNL starting in February of 1984. The assembled scientists¹⁴ and engineers selected three superconducting dipole designs for further study: A) a high field (6.5 T) option using 2-in-1 magnets with $\cos \vartheta$ coils; B) a mid-field option (5 T) without an iron yoke using $\cos \vartheta$ coils; and C) a low field (3 T), superferric option in which the field would be controlled by an iron yoke driven into saturation by superconducting coils. BNL/LBNL were to continue to collaborate on design A, FNAL would work on design B, and TAC (Texas Accelerator Center) would work on design C. A subpanel of HEPAP headed by Wolfgang (Pief) Panofsky in the Fall of 1983 had reviewed requests to pursue needed R&D and in addition to superferric magnets, high field (8-10T) magnets based on Nb₃Sn had been recommended for further work; this would be used in design A if it worked satisfactorily.

The major difference between the model magnets BNL had been building and design A in the RDS was the 40 mm inner coil diameter, up from 32 mm. The accelerator physicists in the CDG who were calculating machine parameters and establishing its requirements were uneasy with 32 mm; this was perhaps too small considering the unknown field quality of the proposed magnet system and uncertain aperture requirements for such a large machine.¹⁵ The central field of the dipole magnets would be 6.5 T, a somewhat aggressive goal but one that seemed possible with improved superconductor, which would be specified as needing a critical current density for the NbTi alloy of 2400 A/mm² at 5 T (the FNAL Tevatron specification was 1800 A/mm²). This 6.5 T field would require a tunnel length of 90 km.

The atmosphere at the CDG in those early months of 1984 was stimulating, even exciting. There was an openness and friendliness among people newly met, an air

of adventure, anticipation, and great possibilities. Everyone recognized that we were embarked on an exploration, were guided by competent people; we were all eager to start the journey. The physical setting was ideal: a building high on a hill at the Berkeley Laboratory and on a high floor of the building, with views of the University and the city of Berkeley below, and San Francisco, the Bay, and the great bridges beyond to the West.

From this point forward, the CDG guided the magnet development. TAC worked independently (we measured the field in some of their early magnets at BNL) to develop its superferric Type C magnets (please see Topics, *Magnet Type* for the eventual outcome of the TAC program). The collaboration between BNL and LBNL expanded late in 1984 to include FNAL. This collaboration specified a new 6.5 T design, "D", which would keep the 40 mm coil aperture but have straight, not flared, ends. BNL was focused on building cold masses, LBNL was building short model magnets and working for improved superconductor, and FNAL was designing the cryostat and cold mass support and restraint system, and would be testing the planned long magnets. Long magnet cold masses, 16.6m long, after fabrication at BNL, would be trucked to FNAL, where they would be put into cryostats and tested. This design D would later be chosen to become the main ring dipole for the machine. Regularly scheduled meetings between the collaborators (called MSIM), numerous visits from CDG personnel, and frequent reviews kept everyone well informed and working from the same script. As models were built and measured, improvements were made to the design until in 1989, shortly after the establishment of the SSC project in Texas, the 40 mm dipole design was largely complete although additional magnets were built aimed at finding answers to lingering technical questions. The superconducting cable improvements and the

higher current specification of 2750 A/mm² had been adopted. The cold mass design had gone through several iterations of collars and yoke and the mechanical interactions of the coil/collar/yoke system were well understood. Numerous short and long models had been built and tested with good results.

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Work began on design D later in 1984. The magnets had a coil cross section labeled C5, designed by Gerry Morgan at Brookhaven, and were 4.5 m long. The coils used graded, partially keystone conductor for the inner and outer coils and used wedges to both maintain the conductor angles within the coils and to control the field quality of the magnet. They retained their dogbone ends (revised tooling was not yet available) and were prestressed with stainless steel collars¹⁶ that were keyed in a press and that could be removed to access the coils if necessary. A parallel effort at BNL had succeeded in building sextupole trim coils¹⁷ as required for the SSC magnets. A beam tube with such trim coils was included in the assembly of the magnet. Yoke laminations surrounded the collared coil assembly. A clamped stainless shell surrounded the yoke and served to hold the cold mass and allowed it to be hung vertically for testing in a dewar filled with liquid helium. Beyond a simple stainless steel restraining plate, no particular effort was made to contain the outward forces that develop in the ends when the magnet was powered. The end forces from either end in coils of this length (4.5 m) still act to restrain one another. Restraining these forces in longer (16.6 m) magnets would become a major issue later in the program.

Eight magnets were built in this series, labeled SLN008-SLN015. Some construction details varied from magnet to magnet. The 3rd and 4th magnets used cable made at LBNL. The 5th magnet contained many voltage taps and spot heaters but no trim coil. The 6th magnet used welded rather than clamped stainless steel shells. At 4.5 K these six magnets reached 6.6 T with little training, the short sample limit of the conductor. In subcooled liquid (2.6-2.8 K), 8 T was achieved. The allowed harmonics were close to the predicted values, and the unallowed harmonics were small. The sextupole trim coil operated well above the required current with little training. Magnets seven and eight had coils with straight ends and also worked well. The magnets were tested between June 1985 and January 1986.

The building of these eight magnets, requiring many purchased parts and lots of work in the machine shops, stressed the support systems at BNL well beyond normal. When a purchase order or a shop requisition is written at BNL, generally by an engineer in charge of a particular area, it follows a well-defined path through various groups that monitor the available budget, that place the order with an outside vendor, that assign a priority and schedule shop time, among many similar tasks. Each step takes time and depends on various individuals to handle

each order promptly and correctly. Delays that wreak havoc with the schedule could and did occur in many ways. This and the sheer volume of activity from the SSC program regularly caused confrontations between impatient engineers and harried support people. The amount of SSC work at BNL far exceeded the normal workload at the Lab and required unusually rigorous scheduling and follow-through. Generally, the leaders of the service divisions stepped up their efforts and were able to meet the demands of the program. The Magnet Division added several people to its staff who could help track and monitor the work flow. As discussed elsewhere, the biggest boost came several years later in September 1987 when Parke Rohrer was appointed the MD's supervisor. With his other supervisory functions (Central Shops, Contracts & Procurement, Plant Engineering) he could oversee the activity of building magnets from a unique perspective. His involvement made the Lab a more dependable and productive resource for the SSC program.

The next logical step after the success of these magnets would be to build the 16.6 m length magnets required in the machine. Many realized that long magnets could have issues that would only be discovered by actually building them but a few physicists in the CDG argued that such magnets would not reveal anything new, given the good performance of the earlier magnets. Budgets were tight before 1985 so funding for the needed tooling and parts was not available until later in 1985, when a start became possible. Because of the large amount of tooling needed for a 17 m magnet, particularly the longer coil winder and the complex coil curing press machines, it would take over a year to build and commission this tooling and begin the building of a long magnet. Some parts, in particular long shells, proved difficult to obtain, and the early examples lacked precision and straightness. Companies need special, costly tooling to make good shells and were reluctant to set up a facility for limited orders. The building of short magnets continued in parallel so that technical questions could be more quickly resolved. By the end of 1987, seven additional short magnets had been built and most of them tested.

The first two long cold masses, labeled LLN001 and LLN002, or alternatively D1 and D2, used coil design D (shown), included stainless steel collars and flared ends, and included trim coils on the bore tubes of the magnets.¹⁸ They were shipped to FNAL for cryostating and testing, the first in February 1987. This would become the normal *modus operandi* for these cold masses and the arrangement worked well. Initial results were encouraging but not a total success---both these magnets required training, did not reach their short

sample limit, and never reached a stable plateau. These results indicated that the coils or parts thereof were moving when powered to high currents and would require better stabilization. In time it became clear that the weakness in these and later long magnets lay in the magnets' end restraints, a weakness that only manifested itself in long magnets where the opposite ends no longer restrain each other as they do in shorter magnets. Additionally, the ramp splice supports, where the leads transition from inner to outer coils, were found to be inadequate, already in the short magnets. Field quality, including integrated field harmonics and dipole field angle, measured with the Mole newly built by BNL and furnished to FNAL, was good.

Next came the two magnets DD000X and DD000Z, also called DX and DZ, this time built with straight ends but otherwise the same basic construction. DX contained microphones as an experiment in locating quench origins. It also contained various quench initiation heaters to study quench propagation times as measured by voltage taps in the magnet. These helped to establish that natural quenches originated in the lead end as suspected. The magnet reached a stable plateau above the short sample limit after about ten quenches. Magnet DZ initially had about the same quench performance, but did not have the same array of instrumentation. With some further quenching this magnet failed catastrophically on November 3, 1987; an electrical short developed in the return end of the lower inner coil and on a subsequent quench, an electrical arc in the coil destroyed the magnet.

While technically not too serious, the failure of DZ was a major setback for the program.¹⁹ The visibility of the program was so high that a single failure of this type was one too many; various observers prophesized doom for the whole SSC program. The short resulted from a missing strip of Kapton insulation at the end of the coil. Design drawings had not been completed and the preformed Kapton shapes required for complete coverage of the coil were not yet all available; technicians were applying Kapton on a somewhat ad hoc basis when the magnet was built. Additionally, there was some mismatch in size of the wedge tips and in the pole spacer/shim, both at the ends of the coil. Modifications were made in the assembly procedures and parts, and failures of this type did not recur. The comprehensive report of the review committee²⁰ was helpful in pointing to

other deficiencies in the magnet's construction gleaned from its examination of the interior components of the magnet during its autopsy; in fact, the committee suggested that autopsies be done on future magnets, even if they had not failed, as another method of gaining insights into the mechanical behavior of components. This was a recommendation that could have been useful but that was not followed because of the resources it would have required.

The year 1987 proved to be a tumultuous time in the magnet program, even well before the failure of DZ late in the year. The CDG was coming under increasing pressure to demonstrate that long magnets meeting machine requirements could be built. Funding to build the necessary tooling had not been available early in the program but critics nevertheless wanted long magnets. The steady results and valuable lessons-learned from the BNL and LBNL short magnets superficially seemed insufficient for all the money being spent. At a number of DOE reviews in 1987, particularly from several critics who should have known better, we heard that BNL was "unproductive". At BNL, the RHIC partisans were increasingly restless that so much effort was being poured into SSC and so little into RHIC---this despite the lack of substantial funding for RHIC. The MD's immediate supervisor, E. Forsyth, was particularly voluble in this regard and spread his dissent widely. Luckily, our support from the CDG, particularly Tigner, remained steadfast, even though he was under more community and DOE pressure than anyone. He had asked me at one point, "who in the BNL hierarchy supports SSC?" Of course Lab director Samios lent solid support at the top laboratory level but that at times got lost in the day-to-day scrum of activity. Tigner during this period asked FNAL to begin making magnets, and a parallel program was started there, after hearing from Forsyth, incorrectly, that BNL would "soon stop doing SSC work", focusing instead, he said, on RHIC work. Rohrer's appointment as the MD's supervisor, Director Samios' best move, changed this paradigm. Here was a hands-on engineer of vast experience who immediately understood the importance of the SSC and took a deep interest in all our day-to-day work. His presence and wide authority soon unlocked the Lab's impressive resources for getting work done in an efficient and expedited manner. Henceforth, bureaucratic roadblocks disappeared, priorities were established and maintained, aggressive schedules could be met, and the irrational demands from RHIC partisans became background noise. His credentials throughout the wider high energy physics community helped to mollify critics and provided Tigner with a meaningful voice of support.

By the end of 1987, design improvements had been made and many variables had been tested and either adopted or rejected for the short magnet design. Six short magnets (now 1.8 m long) were built in 1987. The superconductor cable being made at LBNL had become more stable against collapse (tubing) and was dimensionally more consistent. The filament diameter in the wires was down to a very welcome 5 microns. The revised coil cross section was labeled C358A. It

incorporated new cable dimensions, revisions in wedge design, and an iteration for harmonics. Coil ends were filled with alumina-filled epoxy to remove voids. Collar stiffness was much improved by spot-welding them together in pairs. The field in the end regions was lowered by using partial iron and no iron yoke blocks, wherein stainless steel laminations replaced magnetic iron. In the evaluation program in the vertical dewars, all these changes were tested, documented and evaluated through the thoughtful analysis of G. Ganetis of electrical performance and P. Wanderer of measurements; Wanderer (shown) managed the flood of data in a timely and understandable way, was astute and knowledgeable about its meaning, and made certain that we all saw the data. These magnets had little training and good field quality. Thermal cycles on the magnets verified that they could safely withstand repeated stress changes and dimensional excursions. Strain gauge and voltage tap measurements enabled parts redesign to remove remaining weaknesses, including that of the ramp splice conductor support structure.

The performance of the first four long magnets also led to a series of changes in the mechanics of the design and in the instrumentation installed into the magnets. It was not understood if the somewhat erratic quench performance (aside from the electrical short in DZ) had originated from inconsistent prestress throughout the coil, poor prestress just in the ends, a lack of axial stress on the ends, erratic interaction between the collars and the yoke or between the yoke and the shell; perhaps some other flaw was responsible. A major issue was whether the collared coil should be axially restrained in the yoke, or be allowed to slide freely. The short magnets had tested some of the proposed new features, but clearly the long magnet tests pointed to some additional changes needed in the design that had not been learned with the short magnets. Tigner was invaluable in keeping changes reasonable and focused during this trying period.

A series of six long magnets, DD0010 through DD0015, was built in 1988. They used the new coil cross section, C358A, and the spot-welded collar pairs that had been introduced for the short magnets in 1987 (please see New Methods & Techniques, Mechanical: *Pinned & spot-welded high strength stainless steel collars*, for a description of these collars). Magnet DD0010 had 133 voltage taps on its coils and the shell had shell strain gauges added at FNAL. Magnet DD0012 had full axial restraint of its coils. Magnet DD0014 used tapered keys instead of the previously square keys to close the collars. This magnet's collared coil was free to move axially in the yoke by virtue of a slip plane between the collared coil and the yoke. Magnet DD0015 again had an axially free coil but was anchored at the magnet's center. It too had numerous voltage taps and spot heaters.

Magnets DD0016 through DD0018 came along in late 1988 and early 1989. These three magnets were built with the slightly revised C358D coil cross section,

improved tooling, and identical coils in order to study the reproducibility of the field quality in a series of magnets. They all contained numerous voltage taps.²¹

Magnets DD0019 and DD0020, and DD0026 through DD0028 (numbers 21-25 were omitted) now included the lessons learned from the previous magnets. They still had voltage taps and strain gauges to allow various studies of interest. They were built later in 1989 and into 1990: they used the C358D cross section, spot-welded collars, tapered keys to close the collars, preloaded ends to restrain axial forces, positive contact between collars and yoke and between yoke and shell. The yokes were compressed to a predetermined density before the welding of the shell to the yoke, giving a rigid structure to aid the support of the collared coil. Some of these magnets used collars made of Nitronic 40 stainless steel, the type used in previous R&D magnets, and others used Kawasaki high manganese stainless steel, which had a lower thermal expansion coefficient. This series of magnets showed that coils compressed with stiff collars and fully contained by the yoke, then axially restrained with a strong end structure, resulted in magnets largely free of training. By the end of 1989, given the good performance of these magnets, a solid design was in hand. The magnets tested later confirmed the design's effectiveness.

Also included in these magnets was a feature called cross-flow cooling, developed at BNL by Ralph Shutt with calculations by M. Rehak. This feature ensured that the forced-flow helium would circulate past the coils so as to prevent hot spots there rather than just bypass the coils via holes present in the yoke. Magnets DD0020 and DD0027 were tested in a new test station at BNL.

As can be imagined, large amounts of valuable data continued to be collected from this program. Obvious features were monitored and critical results used immediately but a careful, systematic, and valuable analysis of magnet behavior came later in the comprehensive work done by Arnaud Devred. He was a physicist and colleague from

France who excelled in this work. He made many valuable contributions to the SSC program with his analyses (referenced below) during his years in the US stationed at FNAL and at the SSCL. The plot shows his summary of the average inner coil stress for several of the later magnets. It shows the expected reduction with the square of the magnet current.

The final 40 mm aperture magnets, labeled DC0201 through DC0206, were built in 1990 and into 1991. Three of these magnets were tested at FNAL, the other three

were assembled with FNAL-supplied cryostats and tested at BNL. The copper to superconductor ratio on the inner coil was changed (increased) for some of these magnets to check a then current theory that more copper was needed to reduce premature quenching. The data were searched for any evidence of harmonic changes with repeated cooldowns from room temperature; none of consequence were found.

As noted earlier, in parallel to the long magnet program, numerous short magnets were built to evaluate various additional features. From 1988 through 1991, an additional 17 short magnets were built and tested. Collar ovality, high-manganese collars, tapered collar keys, epoxy content of the fiberglass cable insulation, all-Kapton cable insulation, and improvements in coil ground insulation were all features that were evaluated.

The 40 mm magnets, at the end of this program, were meeting all the performance specifications for the machine. Their design could have been readily transferred to industry for mass production with only minor changes to aid production efficiency.

The performance of the last 12 long magnets built, including two by FNAL, which had made tooling to build magnets in parallel with those being built at BNL, is summarized in the papers by Kuzminsky et al.²² and Wanderer et. al.²³ The design features of these later stage

Length Aperture	<5m ≤40 mm	>15m 40 mm	<5m 50 mm	>15m 50 mm
1984	3	0	0	0
1985	8	0	0	0
1986	1	0	0	0
1987	6	4	0	0
1988	3	7	0	0
1989	7	5	0	0
1990	6	6	1	0
1991	4	2	3	1
1992	0	0	0	6
Total	38	24	4	7

magnets and the results of analysis of their instrumentation are given in the paper by Devred.²⁴ The table lists the magnets built by BNL in the SSC R&D program, including also the 50 mm aperture magnets made at BNL beginning in 1990.

The plot (prepared by Joe Muratore) shows the quench currents (kA) of most of the BNL-built 17 m, 40 mm aperture magnets, beginning with DD0012. These

were still R&D magnets with varying mechanical construction and differing superconductor so variation in quench performance is to be expected; overall, the results are good and generally exceeded the machine requirement (dashed line).

Summary of SSC Work Through 1990

This list summarizes the Magnet Division activities for SSC before the work on 50 mm aperture magnets became the major focus of the program:

- Under the auspices of DOE, BNL began work on SSC magnets in 1983, shortly after the demise of the CBA Project. An experienced staff of physicists, engineers and technicians was available that could design and build models to investigate various possible magnet alternatives for the proposed SSC.
- To minimize costs, the early design was for a 2-in-1 magnet with a 32 mm coil aperture, designed to be built with either NbTi or Nb₃Sn superconductor. Four NbTi models were built and successfully tested, and successful Nb₃Sn coils were built. These latter were not tested in a complete magnet when it was realized that the brittle properties of that material might be unsuitable for a large machine such as the SSC. A 40 mm aperture version of this 2-in-1 magnet was described as "Design A" in the Reference Design Study of 1984.
- The Reference Design Study of 1984 involved numerous BNL scientists and engineers as well as staff from other laboratories. BNL played a leading role in preparing the technical magnet descriptions, cryogenic systems design, and cost and schedule estimates for the Collider magnet system.
- In 1984, design work on a 1-in-1 magnet with a 40 mm aperture began. The 40 mm aperture magnet work (both 2-in-1 and 1-in-1) was a collaborative effort with LBNL. The 1-in-1 magnet was known as "Design D". It was chosen as the magnet of choice for the SSC by the Sciulli Panel in 1985 and was featured in the Conceptual Design Report of 1986. Eight 4.5 m magnets of this style were successfully built and tested at BNL and several 1 m models with various design variations were built at LBNL.
- With the formation of the Central Design Group in 1984, the SSC magnet effort became more organized and focused. The 1986 Conceptual Design Report represented a major accomplishment of the CDG. BNL contributed extensively in preparing this report, primarily on the magnet technical sections and the magnet cost analysis. The magnet effort focused on "Design D" and was by now a joint collaboration with FNAL, LBNL and CDG. LBNL would provide superconducting cable, BNL would design and build cold masses, and FNAL would design and build long cryostats and test long magnets.
- Under the direction of the CDG, BNL began building the tooling and then cold masses for full length, 17 m models. Five models were built and tested in the period late 1985 through early 1987 in a collaborative effort with FNAL, LBNL and the CDG. These models pointed the way to design improvements that were incorporated in succeeding magnets, all of which demonstrated good magnet performance, with one or two exceptions. In parallel, numerous 1.8 m magnets were built at BNL to test design variations.
- In general, BNL's main role was to design and build dipole cold masses. To carry out this role, BNL undertook coil cross section design, coil end design,

magnet yoke design, mechanical design and finite element analysis of the cold mass, and tooling design and construction. Work was often on a best-effort basis in earlier years, particularly with regard to tooling, because of a chronic shortage of funds.

- In addition to the main effort on the dipole cold mass design and construction, BNL staff undertook numerous studies and component developments, at first based on internal assessment of requirements and later in consultation with CDG. Examples include:

- 1) Development of beam tube correctors
- 2) Copper-plating of beam tubes
- 3) Analysis of quench pressures and temperatures, quench propagation, bellows properties, magnet cooling
- 4) Instrumentation development, e.g. strain gauges, voltage taps, spot heaters
- 5) Development of field measuring probes and techniques; providing field measuring equipment to FNAL
- 6) Experiments on radiation resistance of materials using protons from the BNL Linac (the BLIP facility)
- 7) Measurement of material properties, e.g. iron permeability and susceptibility, stainless steel permeability, Kapton punch-through resistance, material creep
- 8) Cost estimates

Other BNL activities in support of SSC:

- Measurement of superconducting wire and cable characteristics, e.g. short sample currents, magnetization, resistivity ratios, cabling degradation, effect of Cu/SC ratio
- Development of industrial sources for materials and material fabrication such as yoke steel, collars, beam tubes, shells
- Magnet measurements on short models and later, long magnets, including:
 - 1) Quench origins, quench propagation, coil temperatures during quench
 - 2) Field measurements in magnet straight sections and in magnet ends, both warm and cold
 - 3) Time dependence of magnetization
 - 4) Magnet cooling with simulation of synchrotron radiation heating
 - 5) Trim coil measurements
- Development of improved cable insulation in collaboration with DuPont
- Development and identification of improved materials for coil ends
- Initial studies (with CDG) at National Synchrotron Light Source of beam tube outgassing rates and constituents under conditions simulating SSC synchrotron radiation

- Participation in the SSC industrialization program, including hosting of potential magnet vendors and supplying of drawings, specifications, and fabrication documentation
- Organization and supervision of several contracts with industrial firms to study magnet production and to make cost estimates for industrial manufacture
- Participation in numerous studies examining technical questions and in ongoing reviews of the SSC program. An extensive series of technical papers has been written covering most aspects of the dipole cold mass design and performance
- BNL was involved with several independent audits of the SSC cost estimates and projections, and hosted such reviews at BNL extending over periods of several days

Organization, Operations of the MD

The Magnet Division was fortunate to have large, sound buildings with overhead cranes, excellent power and water services, and a working cryogenic facility for its work. The Lab provided excellent support services in the way of various shops, riggers, electricians, carpenters, photographers, and other trades people, all experienced and competent. Over time, with new DOE rules, these all became very expensive; in an effort to cut costs, in-house groups were gradually replaced with contracted services where possible, or the services were simply discontinued. Even building space itself became subject to rental fees paid by the budget of the project using the space.

Once a particular SSC magnet series began, the initial models were usually a consensus effort based on a specification, study and discussion of the goals to be met. The professional staff, listed in Appendix C, would contribute their know-how in their area of expertise. As the program continued, revisions to the design would be required. A particular revision or a new series began with a list of Design Features prepared by me, usually from a previous list but also incorporating whatever new features were to be included in the magnet. The design evolved over time based generally on previous magnet performance and on changes suggested and agreed to by the (SSC) consortium or on engineering modifications generated by the BNL staff. A production schedule for the new series would be prepared by E. Kelly including also the new tooling that would be needed. For this schedule he would have to take into account the time required in our design room to prepare the needed shop drawings, the availability of shop time for making parts, the time for acquiring parts and material through the BNL procurement process, and the available manpower for building the magnets. His schedules became the guiding documents for all the people working on the project, including not only at BNL but at the CDG and the other labs in the consortium. For instance, the required superconducting cable was supplied by LBNL and so Kelly had to include realistic time frames for its acquisition. Division staff provided needed liaison; for superconductor A. Greene (shown) was invaluable for interacting with the staff at LBNL and the conductor manufacturers. Kelly would have regular meetings with his engineering staff and the design room staff so that he and they knew what was needed and expected. The schedule provided firm guidance also to the technician staff and its supervisors so that they too knew what to do each day.

The work load on the Division from the SSC program grew quickly and by the mid-1980's, we had over 150 staff members. This work required many purchases of materials and supplies, as well as numerous intralab requisitions specifying work from other Lab divisions and departments, mainly Central Shops.

The Division continued to operate with a Section as well as with a matrix (Task Force) structure, established by R. Shutt when he and R. Palmer first organized the Division after the Isabelle debacle. In that structure, the scientific and professional staff members were assigned to a particular Section: Analysis, Electrical Systems, Magnet Testing & Measurements, Superconductor Materials R&D, Production Engineering. Depending on their expertise and interests, staff was also assigned to Task Forces that had been established, each with a responsibility to analyze and solve particular problems. For instance, there was an Alternate Prestress Task Force to focus on the coil containment, a Magnet Assembly Task Force, a Superconductor Specification Task Force, a RHIC Steel Task Force, etc., some 30 in all. This approach worked well for it kept everyone focused on the work at hand, yet allowed those with particular interests to contribute also to areas outside their direct specialty. Communication was enhanced, any question could be asked, and a person would often pursue a particular concern or problem he might have heard about in passing and where he could help, to the great benefit of the program. Good rapport could also develop within the staff: people soon learned where expertise lay, who could help in a particular area, who might need help in their understanding or in their work. The listed membership of a Task Force would receive a written invitation for each meeting from the Task Force Head, but any staff member could freely attend, and frequently did attend, any Task Force meeting. There was no formality attached to these interactions.

The meetings provided a forum for hearing about and discussing results of magnet tests as well as bench tests and ad hoc experiments that would take place in the course of the daily work. Particular problems would surface in the building of the magnets and their subassemblies, problems that might have an obvious solution or that might be a puzzle---further investigation would suggest a design change or an alternate approach that might be better. For instance, during collaring of coils, there would be turn-to-turn shorts on occasion. Were these due to metallic chips in the coils? Were the coils not uniform in size so that overpressure in some sections caused shorts? Many issues of this type surfaced over the years and they often benefited from a collective wisdom that suggested reasonable solutions; their resolution usually improved the magnet.

The effort to eliminate turn-to-turn shorts in coils led to experiments that confirmed that the higher pressures needed to collar SSC coils caused the fiberglass wrap of the cable insulation to puncture the Kapton insulating barrier at the inner edge of the keystoneed cable, where the cable had been maximally compressed during manufacture. This was a basic deficiency in the structure of the coils and was not completely solved until a new all-Kapton insulating scheme was adopted (please see the Topic, *Kapton*).

Another realization that arose from the discussions was the need for a system of voltage taps and strain gauges to really understand the origins of quenching in a magnet. Deploying such a system, which took time and much effort to develop,

was like gaining sight where previously we had been blind. It also thankfully eliminated much speculation about the position and the cause of premature quenching in a magnet.

The development of the necessary instrumentation required the talents and initiative of individuals who understood the problem and had the interest and the knowledge to devise solutions. George Ganetis, a skilled and perceptive electrical engineer of unusually good common sense, was relentless in developing the instrumentation for strain gauges, voltage taps, and data collection (in addition to his normal duties of tending to the routine demands of the program). Carl Goodzeit, an erudite mechanical engineer with long experience in the former bubble chamber operations at BNL, was familiar with stress/strain questions in mechanical structures and took the lead in developing specialized strain gauges for the magnets. Their devices for the first time revealed precisely what happened to the stresses in a magnet as it was collared, cooled and powered. Coupled with the reliable field measurements routinely available from the new measuring systems developed several years earlier, we began to have believable, quantitative information about nearly every critical parameter in a magnet's performance.

A side effect of this type of organization was that staff would spend a sometimes inordinate, but necessary, amount of time in meetings. Shutt was relentless in his attention to detail on technical issues; meetings with him in attendance could go on for hours until every point was discussed and understood from every angle. His thoroughness set a good example; the members of the Division learned to be extra diligent in all aspects of their work. With him, there was no tolerance for the notion, attributed to Robert Wilson's approach at FNAL, "If it works the first time, it was over designed".²⁵ In the engineering world, one has to think: where is the failure point, what are the consequences, what have we not thought of? On many days there would be several meetings, depending on the projects underway, so that the entire day was spent in attending meetings. That routinely necessitated after-hours and evening work for much of the staff.

In order to better coordinate the many tasks underway in the Division, we instituted "Morning Meetings" at 9:30 AM each morning in my office. These meetings were attended by a handful of section heads and a few others guiding the daily work to hear about problems that had arisen and to plan a response: work conflicts and priorities, missing items, problems in construction or in measurements. Anything was fair game. Issues that would slow the work or delay the schedule or any problem needing immediate attention were considered.

Because Rohrer came to these meetings, and because he took a lively interest in our work, we could seek immediate support if needed from Shops, Purchasing, Plant Engineering and other Lab services, all of which were within his purview. These meetings proved enormously beneficial to the progress of our work and once started, continued without fail each day.

The increasingly reliable information we were gaining about magnet performance gave us the confidence to properly evaluate proposals for new designs, or changes to our own designs, or to indicate fruitful areas for further development. This could lead to an appearance of arrogance on our part when we interacted with outside individuals at meetings, or in reviews, or on their visits to our operations. Many interested persons visited over the years and sometimes offered well-meaning suggestions. We generally tried to base our plans on measurement and calculation, but visitors, sometimes not even familiar with

magnets, could still hold long-favored views or generate ideas that they wished to implement. In rejecting suggestions that we could see to be in error, or that were unlikely to be productive, or that could badly affect the schedule, we would sometimes hear indirectly of criticism about “those know-it-all SOBs” who were “stubborn and unresponsive”, or worse. However, without convincing evidence or argument, we were not going to risk failures in our magnets or delays in our schedules, if that could be avoided.

The pressure at times to make changes was enormous. Our supervisor Paul Reardon (until early 1986) would come around frequently with ideas that to him seemed promising or about which he was enthusiastic, meriting immediate consideration and even implementation. If not me, then a staff member would be cajoled to consider the idea and (usually) prove the idea unworkable. One of his great desires was that the RHIC dipole, a design with a single layer coil that provided a maximum field of 4.6 T, safely above the requirement for 3.5 T, be “upgraded” to run at 5 T. He would come back frequently to this topic with yet another argument, always pleasant and in good cheer, for how this could or should be done, and it was always disruptive (after all, he was the boss!). That field could not be achieved without more conductor in the design.

An ongoing problem at BNL came from the cadre of RHIC enthusiasts and managers in other Lab departments who believed that we should focus more on RHIC magnet work and not so much on SSC work. This problem has been mentioned earlier. The MD in any case had an active and productive program underway for RHIC magnet R&D and good progress was being made despite the paucity of funding. A frequent SSC collaboration visitor at the time, Clyde Taylor

of LBNL, commented to me more than once, “you guys are working on RHIC all the time”. The RHIC-only advocates of course ignored the fact that our budgets determined where we would work, not some causal preference that we had for this or that task. Our immediate supervisor through 1986 and part of 1987, the department chairman Eric Forsyth, never liked the SSC project and abided it only grudgingly, and with frequent administrative roadblocks placed in our way. But he was not alone. Once a specific request came from a leader in the Physics Department. He came around one day to ask that we forthwith organize a “Tiger Team” to focus only on building RHIC magnets. This was a hopelessly naïve suggestion, considering how the MD was organized, and it would have been like putting sand into the gears of a well-functioning machine. Fortunately, that proposal died without further disruption. Forsyth was eventually removed from the line of command and replaced by Rohrer. From that point forward, until S. Ozaki became head of the RHIC project in late 1989, we were mercifully spared from intra-lab politics. The symbiosis between the SSC and RHIC projects made RHIC magnets possible; they could not have been developed within the available RHIC budgets without the SSC infrastructure and staff in place to also do any funded RHIC work.

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The work of the MD was generally done in a safe and effective manner, as could be seen by our exemplary safety record. How could it have been otherwise considering the great multiplicity of machines, tools, heavy objects, high currents and high voltages, magnets with megajoules of stored energy, and numerous other devices in daily use, and by scores of technicians, engineers, and physicists. Inspections by an experienced and trusted person from outside the Division were a regular and useful occurrence, for he might point to some overlooked issue and help devise a solution. Newly built tooling and machines, and their designs, needed to pass a review board before they could proceed or go into use. Supervisors were encouraged to change old, unsafe habits: stepping on powered cables, for instance, because for superconducting magnets, they “don’t have any voltage”. Several times, sections of our operation were relocated in order to change bad practices. We wanted each person to make safety a personal responsibility, not dependent only on oversight by someone else.

Over the years this approach was changed by Lab management to a far more intrusive implementation of mandated, often inflexible requirements, many simply bureaucratic. It is unlikely that some of those making the rules ever worked with their hands or in an actual shop; the rules that came along at times seemed discordant and out of touch with the actual workplace. Technicians would be chastised for using a tool for other than its designated use: using a screwdriver rather than a pry bar to loosen a tight piece for trim, for instance. Gradually it was

required that every piece of machinery have a written operations manual, that every technician have regular training in his/her work assignment (though he/she was the cognizant worker) with a record kept of the training history, that all employees regularly go for routine instruction, that hard hats and protective glasses be worn by one and all in the plant, and on and on. This approach was instituted lab-wide over the years. No one has had the courage to say “enough”, because salary raises can be withheld if questions are voiced.

No one objects to a safe work place, but one must remember that only a workplace where no work is done can be guaranteed to be 100% safe (this self-evident statement is anathema to a safety officer). Indeed, we were once locked out for a few days from finishing a coil on a much-used winder, and missed an important milestone, because the operating manual for the winder had not been completed. The cost of implementing all the increasing requirements is not revealed in an understandable way, but the Lab overhead rates keep increasing, to over 100% now from about 40% some years ago. This means that the research that can be accomplished is reduced by a similar amount. Will taxpayers continue to fund R&D as the returns become increasingly meager? Several years ago, Will Happer, outgoing Director of Energy Research at the DOE, called attention to the trend. He said that he had hoped to make some more progress on cutting costs at the labs before he left the agency. “We go overboard on oversight” he said, citing as an example “a \$25 million annual cost of operating a research reactor at Brookhaven National Laboratory. A comparable reactor at the National Institute of Standards and Technology”, he noted, “costs just \$5 million a year. Contributing to the steep cost of the BNL reactor”, he continued, “is a payroll that includes a 16-person training staff to train three to four reactor operators.”

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Coordination of the many groups working on the SSC required numerous meetings and frequent travel. Video conferencing was not yet routinely available and email via personnel computers was in its infancy. PCs became widely available only in the mid-1980s.²⁶ For the magnet builders, the CDG organized Magnet Systems Integration Meetings (MSIM) that convened monthly on a rotating basis at FNAL, LBNL, and BNL. For Brookhaven, Bill Schneider would typically give a report on our status with similar reports from the other labs. Schneider, as deputy to Kelly, had a thorough grasp of the program details and excelled at explaining the issues. His departure in 1988 to work at CEBAF was a big blow to our program. Other cognizant persons would report as well, depending on the topics being considered. These all-day meetings were useful, highly technical, and served to keep the program on track. There were also Magnet Program Advisory Panel (MPAP) meetings involving fewer people where more administrative and planning issues would be discussed every few months. The

CDG sent one of its senior leaders on a weekly basis to discuss relevant issues (a group known as the “gang of four”). We participated in many of the SSC reviews held at the CDG and always had papers to present about our work at the various conferences being held. Numerous groups and individuals visited our facilities to interview the staff and see the work on this big national project “first hand”. Articles written about the work were generally fair but occasionally some negative commentary would appear. Tigner or a deputy were good at explaining and defending the program when such articles came out. The work was usually making good progress but also with occasional setbacks; technically, none of the setbacks was too serious. Early in the program, an online newsletter of sorts was posted describing events realistically but it had to be abandoned when it served as fodder for misleading interpretations by the project’s opponents.

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A fact of life in any DOE-sponsored project is that there will be plentiful reviews. There could be yearly reviews, design reviews, cost reviews, institutional reviews, industrialization reviews, readiness reviews, and more, both for SSC and separately for RHIC. Most of the reviews were sponsored by DOE. Every one of them focused the mind, which was good, but also took effort and time from already overworked staff to prepare and make the presentations and then for the follow-up work answering the issues raised by the reviewers. Surely the DOE could do its oversight job with fewer reviews. In 1989, to give an example, we had over ten of these reviews.

After the RHIC project had been approved for construction, we had a visit from a DOE procurement official and his staff of 4-5 individuals. This group, we were told, would be in charge of “purchasing” the RHIC collider and that we at BNL were one of several vendors from whom the machine might be purchased! They would be the ones to acquire the machine and make it available for scientists to do their work; we would be consulted by them as needed. It was an odd understanding of the situation and a stance perhaps meant to boost morale in that section of the DOE.

There were also monthly progress reports to prepare. Schneider would submit these and would at times be assisted by Per Dahl. In 1987, Dahl transferred to CDG where he did similar work writing for the SSC program, a task he enjoyed and at which he excelled.

Our CERN colleagues were always puzzled by all the reviews---they would tell us that they prepared once a year for a major review and not be otherwise evaluated by an outside agency. It must be said that, aside from the effort to prepare and follow-up, a review could be stimulating and rewarding, often depending on the reviewers. Once Herman Grunder, a respected accelerator physicist, came around as a reviewer and got curious about magnet

measurements. He came to my office and questioned me extensively on how we measured the fields in a magnet, what the measurements meant, how we knew from them what magnet feature needed adjustment and by how much. It was a lengthy and rewarding discussion, but I was never quite sure why it occurred---I hoped it was because he was curious and not just testing me; in the years after, he was friendly and collegial whenever we met. In another episode, a reviewing committee member at a review of SSC at the CDG in Berkeley got hostile and said regarding our work that we were “unproductive” and added, “you’ve spent \$10M and don’t have a thing to show for it”; we had not yet tested a long SSC magnet for perfectly valid reasons. This mean-spirited comment so upset the normally placid Parke Rohrer that it was about the only thing he spoke of for the next few days.

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The Magnet Division technicians were generally excellent---hard working, resourceful, competent, and skillful in unexpected ways. They were able to get nearly any job done, no matter how difficult and with little complaining, even when a sudden change might negate days of work. It was more like a partnership in which we all had a stake. They made good things happen and only expected sensible, thoughtful goals. Without meaning to offend many worthy individuals, among the leaders were Ray Ceruti, John Cintorino, Joe D’Ambra, Tom Dilgen, Sonny Dimaiuta, Chris Harbach, Dean Ince, Glenn Jochen, Bob Kehl, Dom Milidantri, Paul Ribaud, Ken Robbins, Andy Sauerwald, Ed Sperry, Dan Sullivan, Tom Van Winckel, Ed Weigand, Larry Welcome. Support staff people were excellent as well--- our Division Secretary Vera Mott, her successor Diana Votruba, Audrey Blake, Ron Prwivo, and others who eased the daily work load for everyone and who were frequently called upon to host and help our many visitors and to organize the occasional Division celebrations.

Changes in SSC Management

In 1988, we (the BNL Magnet Division and our colleagues elsewhere) were busily building magnets under the guidance of Maury Tigner and the Central Design Group. The SSC program had been making good progress towards the goal of a dipole design that met machine requirements. Mid-way through the year, this productive and cost-effective state of affairs began to change when a new paradigm was considered, then adopted, by DOE for building the machine. This paradigm excluded Tigner from further involvement in the project, the exact antithesis of what should have been done. That exclusion was, in my view, the single most important reason that the project failed.²⁷ Since the sequence of events that led to this sorry development is somewhat convoluted, it is of interest to outline how it came about. This account is not based on my personal knowledge, except in a few instances, but rather comes from published or well-circulated accounts, for instance that by Wojcicki (End Note 3).

The CDG's official start was in October 1984 when DOE Secretary D. Hodel released \$20M for SSC R&D. Tigner was the Head, and the activity was centered at LBNL in Berkeley.

- On January 30, 1987, President R. Reagan gave his approval to the SSC Project following the recommendation of DOE Secretary Harrington, a trusted advisor, who had received and approved the 1986 Comprehensive Design Report prepared by the CDG with extensive help from the national labs.
- Two committed champions of the project left the administration in this time period: Science Advisor G. Keyworth, who favored bold and meaningful steps in the US science program, left in late 1985; DOE Office of Energy Research Director A. Trivelpiece left in April 1987. His forceful presence would be sorely missed in the months ahead.
- In early 1988, the URA submitted a well thought out plan prepared under the direction of Ned Goldwasser for managing the SSC project. The DOE failed to act on this plan and thereby missed a golden chance to have a successful project.
- In August 1988, the DOE released a solicitation for management proposals. This solicitation incorporated the priorities of DOE planners who had their own vision of how the project should be managed. The technical nature of the project was given a lesser importance. Industrial partners would be brought in and the DOE itself who have a major, direct management role in the project. Only URA responded to the solicitation and it then became the chosen management contractor. Their proposed top leadership for the new SSC Laboratory included four people with Roy Schwitters as the Project Head of the SSCL. This leadership team would remain subservient to DOE managers. Tigner was offered a secondary role that he found unacceptable and he subsequently left the project. Two industrial firms:

EGG, which was a contractor for other DOE facilities, and Sverdrup, experienced in the construction of large technology facilities, for instance a launch complex at the Vandenberg AFB in CA, were proposed as industrial partners. Maury Tigner's departure from the project was a significant and unnecessary loss from which it could not recover (please see Topics, *SSC Project Failure & Costs* for additional discussion of this subject).

- In November 1988, the site selection Task Force announced the proposed site in Wachahaxie, Ellis County, Texas, as the preferred location for the new machine. It was an area of gently rolling hills with a pleasant

landscape that bloomed with wild bluebonnet flowers in the Spring (please see the nearby picture). Driving the local roads gave stunning vistas for miles in all directions when these flowers were in bloom. The people there were friendly and welcoming, excited to have this new project in their midst.

- In 1989, Schwitters recruited staff for the new laboratory. The new Head of DOE, retired Adm. James Watkins, had strong views on personnel based on his work with Navy contractors. For SSCL Deputy Director and Head of the Magnet Division Schwitters picked Tom Bush, a retired Navy captain with experience in missile procurement. Bush was friendly, astute, and talented but not at all knowledgeable about magnets.
- For Project Manager, Schwitters picked Paul Reardon, a very capable manager we knew well from his years as Associate Director at BNL overseeing our work as described earlier, among other responsibilities.
- Watkins, however, insisted that his colleague E. Siskin manage the project. In a compromise, Siskin was made General Manager, Reardon Project Manager reporting to Siskin, and Helen Edwards Technical Director reporting to Reardon, as would Accelerator Systems Division Head T. Kozman and the Heads of various other Divisions.

- These people were all competent and accomplished in their chosen careers. However, by most accounts and from personnel observation, this arrangement worked poorly: Project Head Schwitters was too far removed from the technical people, who would be called upon to make decisions on a daily basis that could significantly impact the project.

Most of the former employees of the CDG moved to the new SSCL in Texas. We continued to work with these colleagues as before to carry out the planned program, in particular with Roger Coombes, who had become Bush's deputy. As the new SSCL magnet division was built up under Bush, the interactions with the new staff naturally grew and generally worked smoothly. Soon enough, the SSCL would develop its own priorities so change could be expected in the months ahead.

One major change was not long in coming: Technical Director Helen Edwards, based on her very recent experiences in commissioning the Tevatron at FNAL, was uneasy with the 40 mm aperture of the magnets. She feared that such a "small" aperture could make the machine difficult to commission and later operate; a coil aperture of 50 mm seemed more sensible to her. Her unquestioned competence and experience made her voice respected and influential. At the Tevatron, she had dealt with magnets of lower field quality than was being achieved in the SSC magnets, but she was not yet willing to trust that the builders of the magnets could reliably achieve the claimed better field quality, which would reduce the need for a larger aperture.

The newly-formed SSCL decided in early 1989 to conduct a site-specific design review to evaluate the SSC magnet design as it had developed since the Conceptual Design Report prepared by the CDG in 1986. Schwitters appointed a Collider Dipole Review Panel in March 1989 as part of this Review. It met at the CDG in Berkeley for the period April 17-21, 1989 to "provide an in-depth review of the Collider dipole R&D program" and to "evaluate its readiness for release to industry for development of a production version". The panel was co-chaired by G. Voss of DESY and T. Kirk of the SSC CDG. The panel included 22 worthies from various segments of the accelerator world and included Helen Edwards as an Observer. We and our colleagues from FNAL and LBNL made presentations to this panel during the week (Goodzeit, Kelly, Wanderer, and Willen from BNL). The panel's report in June gave a generally favorable summary of the magnet status. However, it did list several areas of concern:

- operating margin at the design field and operating temperature;
- uncertain performance at the nominal injection energy of 1 TeV;
- unpredictability of operating field characteristics of production magnets derived from room-temperature measurements, and
- need for early systems tests of strings of production magnets.

At the SSCL, discussions and calculations of beam performance in the Collider proceeded at an intense pace through 1989. Edwards leaned toward increasing the

aperture. Others were reluctant: a call from Bush and Coombes in November 1989 complained that they “did not know what Edwards was up to” and feared she was “railroading” the 50 mm aperture. In August she visited BNL for a tour of our magnet work and for extended discussions about magnet performance. She organized a meeting of the SSCL Machine Advisory Committee (MAC) in Texas on December 4, 1989 and called to asked me to make presentations on magnet field quality, measurements, and on issues we felt were germane to the 50 mm aperture issue. This committee included many well-known and respected accelerator physicists from both the US and Europe. She was clearly struggling and working hard to reach the right decision on this critical topic.

A decision was not long in coming. Coombes called on December 6 to say that the MAC had recommended a 50 mm aperture and asked us to quickly estimate a program for short and long model magnets. A few days later our Lab Director Samios approved the MD’s involvement in this revised program, an involvement that would absorb a lot of Lab resources and MD effort at a time when RHIC advocates were getting ever more antsy about what they perceived as our minimal effort on magnets for “their” machine. Bush and his colleagues clearly appreciated this quick and positive BNL response; in comments over the next year, he said that “BNL had saved the SSC”, that the “project’s survival had been at stake”.

The Switch to a 50 mm Coil Aperture

The 50 mm aperture decision was made definite by SSCL in early January 1990. We were requested to settle on a magnet design (this work had started at the first hints of a revised aperture months earlier), to build a number of 1.8 m long models, and to call this the SSCL design. Bush at BNL in late January asked that we try to complete the first 50 mm model by the end of December 1990. He told us that a decision on where to build 15 m magnets was pending: at BNL, at FNAL, or in industry? He was also searching for a knowledgeable person to become the Chief SSC Magnet Scientist, a role that shortly afterwards wisely went to Bob Palmer. Palmer soon established the SSC 50 mm Task Force, a group from the four labs that would meet every two weeks to discuss issues regarding specifically the new 50 mm dipole design. The long-time MSIM group, which coordinated work between the labs, continued as before.

An early issue in the 50 mm design was the width of the cable to be used in the coils. A slightly wider cable could be used in the bigger aperture of the 50 mm magnets and would have the added benefit of increasing the field margin above that needed for 20 TeV in the machine. Bush OK'ed the wider cable by the end of February 1990. With that, the coil designs (W6733) could be completed as could the rest of the critical parameters for the new magnet.²⁸ The new designs were approved at a review at SSCL

on March 22. Final parameters for the needed tooling, the longest lead time item in the schedule, could proceed apace. The field lines at full field in the version with a vertically-split yoke, to be built at FNAL, are shown in the figure (from Gupta).

Over the rest of the year and into 1991, BNL put forth a herculean effort to build the new SSC magnets. Thanks to the efforts of Rohrer, in charge of Central Shops, Procurement, and Plant Engineering, among other duties, and with the support of Lab Director Samios, rapid progress was made and the first short model of the new design was tested with outstanding results on December 4, 1990. Its margin was 13.5%, safely above the level needed for 20 TeV operation in the Collider. By May 1991, three additional models had been built and tested, all with good performance.²⁹ The last two were built with the new Kapton CI cable insulation that had been developed in the joint multi-year program between BNL and DuPont. This insulation scheme gave improved coil electrical protection and better coil dimensional stability; it would become the new standard for accelerator magnets throughout the world.

During the year, a decision was reached by the SSCL to have BNL, as well as FNAL, build long magnets, albeit with the BNL start delayed by several months. Our first 15 m magnet, labeled DCA207, was tested on November 11, 1991, again

with very good results. FNAL's near-identical magnet was tested two days later, also with good results, but giving BNL a win in this friendly competition. The BNL version of the 50 mm SSC magnet cold mass cross section is shown in the figure below. The cryostats for these magnets continued to be supplied by FNAL.

SSC Magnet Production Plan

During this period, the Magnet Division of SSCL was preoccupied with the many issues that a new lab could be expected to face: the buildup of staff, establishing in-house fabrication and test facilities, signing off on the buildings and facilities that would have to be built and equipped to become a functioning laboratory. They soon took over the task, in close collaboration with LBNL, of specifying and ordering superconductor for the project, and began to supply the labs with needed conductor. They also wrote the specifications for eventual industrial production of the magnets. They set up a search committee to select a “leader” company that would make a dipole design to meet the specifications and build the majority of the dipole magnets, and a “follower” company that would provide backup and build a lesser number of the dipoles meeting the same specification. In competitive bidding, General Dynamics Corporation (GD) was selected as the leader and Westinghouse Electric Company (WEC) as the follower. In a wise move, SSCL decided that the companies would send core personnel, both engineers and technicians, to FNAL and BNL to work side-by-side with the experienced staff at these labs. FNAL was selected as the lead Lab in this process and would train GD staff; BNL would train WEC staff. The WEC people arrived at BNL in 1991 and remained for over a year. Thus, they had a direct hand in building the first long 50 mm magnets and in the process lent valuable assistance to the hard-pressed BNL staff, which was becoming increasingly busy with RHIC work. The first magnet they built at BNL, DCA209, was tested in February 1992 and worked well.

As time went on, it became clear that Bush was painfully uninformed about even basic technical facts, much less any of the subtleties, regarding the magnets he was charged with getting made. He showed little desire to learn about magnets: he never came for a tour of the extensive Brookhaven facilities, he rarely had a question or comment at meetings, he seldom made suggestions regarding the work that was underway. It seemed odd, even disturbing, that he was so little involved in technical details: how could this man, however astute he might be, keep control of magnet production and the cost of the contracts. When his approach for getting the job done became clear, we understood his intent: he would secure a contract with a vendor wherein the responsibility for magnet performance lay with the vendor, not with the SSCL. Thus he did not personally need to know about magnets but would rely on knowledgeable staff who could monitor that magnets performed as specified in the contract.

Beyond a doubt, Bush did the right thing by his standard, based as it was on Navy procurement practice. But it was the wrong approach for the SSC, and nothing in the SSC organizational structure was going to change this approach. From DOE Secretary Watkins on down through his SSC management ranks, drawn from Defense Department and military backgrounds, it was the way that contracts were structured in the world of defense projects. Those folks did not

have the intellectual reach to consider that there might be a better or more correct way to procure items in the high tech world of accelerators, and no one from that world seemed able or willing to make the argument with success.

As noted elsewhere (please see the Topic, *SSC Project Failure & Costs*), we had been cautioned in the industrialization program that this approach could lead to high costs, particularly by Andy Jarabek of Westinghouse. For obvious business reasons, a contractor would add large contingency factors for unknown risks, and ultimate magnet performance was at the top of that list of unknown factors. After all, building magnets was a highly technical proposition with which US industry had no experience. Industry managers who studied the project and its predecessors realized that magnets of the required type could be difficult to build and had had a history of false starts and unpleasant surprises. In addition to the cost risk, no large company would tolerate the approbation that would come from failure in such a high-visibility program, so no expense would be spared to avoid such a fate. The cost of covering every exigency would be included in the budget proposal. They no doubt had heard of the industrial experience in Germany with HERA magnets: costs were higher than had been projected and companies building magnets there were asked to, and did, subsidize their losses as a national priority.

We had been encouraged to have the laboratory assume this risk if possible. Based on our R&D work, we had become confident that this could be done; if magnets were built according to blueprints supplied by the lab, the performance of the magnets could be predicted and assured. This was the model used for the RHIC magnets, and it worked splendidly. Technically there was little difference in the magnets to be built in the two programs, the biggest difference being in the number of magnets required in each case.

Neither my colleagues nor I were ever consulted on the SSCL approach, and we were never asked to give our opinion on the subject. The SSCL seemed to function somewhat as would a hiker finding his way through unfamiliar terrain, without a guide to help avoid the pitfalls ahead. Not surprisingly, the SSCL approach resulted in a program with large costs and lacking critical expertise. This was something that could perhaps be tolerated in a defense program but it spelled doom for the SSC. In a separate section (Topics, *SSC Project Failure & Costs*: this theme is elaborated upon in that section), I estimate the cost of the SSC magnets if they had been built under a RHIC-style contract, using the actual costs for the RHIC production dipole magnets scaled to the structure and dimensions of SSC magnets.

It must be recognized that for the inexperienced manager or leader of a project, it may be difficult to know whether his or her own staff would have the judgement and expertise to take the responsibility for ultimate performance of the most critical component for the project's success. How would the leader really know that the staff will deliver? Would he not be better off to pay a contractor for that

assurance? This decision will be a judgement call, leading either to good results at minimum cost, or perhaps good results at a much higher cost, or failure. It may be an easy call or a difficult call and each circumstance will be different, depending on not only proven performance but on personalities as well. Only an experienced and knowledgeable leader would be likely to make the correct call.

As noted, GD had been chosen as the lead contractor. The company had talented managers as well as competent engineers and physicists on staff who were assigned to the job. They came around to the labs to gather up our designs and to study our tooling and factory layouts. They then redid everything for themselves, from A to Z. It became difficult to predict the performance to be expected from their magnets---superficially their magnet designs were similar to ours, but they differed in detail, being more oriented to mass production and with features that would aid the production process. Unsurprisingly, early magnets built by GD did not work correctly and the program ended before their problems could be understood. GD had secured a large building in Hammond, LA where they set up a factory to make the magnets. In a visit to that facility, some of us got to inspect a prototype that had been opened for inspection. Its premature and erratic quenching problems were believed to originate in the ends but a lack of instrumentation prevented a proper diagnosis; as visitors, we were not allowed access to some “proprietary” information on details of the magnet’s construction and performance.

In Hammond, GD had built tooling that seemed excessive, even grandiose, for the job at hand. For example, they built: complex machines that could spool superconducting cable into cassettes, then load these cassettes onto coil winding machines like film into a camera; fixtures to automatically move parts and subassemblies from station to station as in an automobile factory where hundreds of cars per day could be built; large presses that could accept a collared coil assembly and a prefabricated yoke, slide them together, then compress and weld the final shell, all with extensive automation. Meanwhile the follower company WEC based its own more modest tooling for its factory in Round Rock, TX on BNL designs and suggestions from our experienced production engineer Gene Kelly, who was responsible for much of the BNL tooling and factory layout. They were chagrined at what they also perceived as the excesses of the GD approach. Neither factory ever went into production but as expected the GD factory proved time consuming and costly to commission and modify; the WEC factory was easy and inexpensive by comparison. The modest factory set up by Grumman for the production of RHIC dipole magnets, also based on the Kelly infrastructure at BNL and on consultation with BNL engineers, proved to be reliable and efficient for the production of those magnets.

Completing SSC Work at BNL

With the approval from SSCL to build 50 mm aperture models in early 1990, the work to quickly produce short cold masses took precedence. The completion of the magnets in the 40 mm design proceeded as well, geared toward finishing the many valuable investigations of magnet design issues that had been planned for those model magnets. Included in those design issues were the following:

- Additional testing of the collars: tapered keys, antiovalized, Armco Nitronic 90 kpsi (N90) stainless steel
- Firm support of the collared coil: line-to-line fit to yoke, bonded yoke modules at ends, one-piece end plates 1.5" thickness, preloaded ends
- Inner cable Cu/SC ratio variation: 1.3/1 and 1.5/1
- Less epoxy in fiberglass cable wrap on one magnet
- Test of new Kapton CI cable wrap if possible

After the start of the 50 mm program, a total of four short models and seven long models were completed and tested in the BNL 50 mm program.

As noted above, the first of the short (1.8 m long) 50 mm aperture magnets was tested in December of 1990 and three more by May of 1991. Two additional magnets that had been planned were cancelled given the good performance of these four models. The first long (15 m) 50 mm aperture dipole was tested in November 1991, again with good results. Six more magnets followed in rapid order, with the seventh completed in mid-1992. The first two of these long magnets, DCA207 & DCA208, were built by BNL personnel with participation by WEC staff. The final five long magnets were built at BNL solely by Westinghouse engineers and technicians, with oversight by BNL staff. Tested magnets were shipped to SSCL for use in their planned string test. The photo shows some of

Parameter	Value
Operating field, T	6.65
Current, A	6550
Magnetic length, m	15.8
Strand dia, inner, outer, mm	0.808, 0.648
Num of strands, inner, outer	30, 36
Cu/SC	1.5, 1.8
Cable bare width, inner, outer, mm	12.19, 11.68
Num of coil turns, inner, outer	19, 26
Num of coil wedges, inner, outer	3, 1
Inner dia, inner coil, mm	49.6
Shell outer diameter, mm	340
Field margin, inner, outer, %	8.6, 11.1
Stored energy, MJ	1.58
Inductance, mH	74.6

these magnets arrayed at BNL before shipment to Texas.

These magnets all featured the new W6733 coil design and the best features from the earlier R&D efforts:³⁰

- A few basic parameters of the 50 mm magnet design are given in the table. Because of a decrease in the effective length of the dipole, the design field for 20 TeV operation was increased to nearly 6.7 T. The field margin was computed for superconductor strand with a critical current density of 2750 A/mm² at 5 T and 4.35 K, with 5% degradation due to cabling. The final two long magnets built, DCA212 & DCA213, had cable wrapped with the new DuPont Kapton CI insulating system.
- The collared coil to yoke interface was designed to be a line-to-line (zero clearance) fit upon assembly. The ends of the coils were preloaded and supported by rigid end plates. The yoke was split horizontally.
- A by-now standard collar pack with strain gauge transducers for monitoring coil stresses was included in the assembly, as were strain gauge transducers for monitoring end forces.

Holes in the yoke were sized and positioned to minimize saturation effects.²⁸ The transfer function of the magnet fell by only 2.6% at full field. The yoke design for the FNAL-built magnets was modified to account for that design's vertical split, though the coil design was the same as that used at BNL.

The quench performance and the field quality of these magnets were excellent.

The plot shows the quench currents (kA) of the seven magnets in kA; the dotted line on the plot marks the current required for 20 TeV. The quench levels were uniformly at or near the short sample limit and the field quality throughout the length of the magnets followed the calculated design. The improved superconducting cable stability had already been noted in short sample testing of the cable and now was seen as an unexpected and pleasant surprise in the magnet performance, compared to what had been achieved in the 40 mm program. The final magnet, DCA213, was subjected to repeated thermal and power cycles to simulate the conditions expected for the machine lifetime; no problem of consequence was found.³¹ These magnets, even more so than the final 40 mm

aperture magnets completed in 1991, could make a Collider with good margin and reliable, robust magnet performance.

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Shortly after the SSCL decision to specify 50 mm as the aperture for the Collider dipoles, Bush established a Task Force headed by Bob Palmer to discuss and advise on technical issues regarding magnets. This SSC 50 mm Task Force (also known as the Palmer Task Force) began regular meetings in February 1990 at the SSCL, continuing through the end of the year, and frequently meeting at one of the involved laboratories. Early on, this TF provided timely and important guidance to the project and highlighted important issues that needed resolution by project management. SSCL personnel were included, of course, as were several technical people from each of the laboratories. Recommendations of the TF were transmitted in writing by Palmer addressed to Bush with copies to TF members. Jim Strait from FNAL prepared and circulated comprehensive minutes that summarized the ongoing discussions in detail and that provided an excellent record of the issues considered including facts known and unknown, work accomplished and still needed, and speculative opining by the members. Much of the later discussion, after the initial meetings where pressing issues had been discussed and resolved, could be described as Subjects of Interest (SOIs). SOIs were topics interesting to magnet aficionados but which would be unlikely to have any immediate effect on the SSCL magnet program, which was busy building magnets to a real schedule.

The 40 mm baseline design for the Collider dipole had reached a level of maturity in the ongoing multi-lab R&D program that made it suitable for use in the machine. The proposed 50 mm design was therefore naturally a close analog of the 40 mm design but with a few modifications to meet the recommended new field margins of at least 10%. The cable would be wider to carry more current, and the larger aperture required stronger collars, leading in turn to a larger yoke. Using the LBNL-recommended new cable dimensions, BNL had designed a new coil cross section and had revised collar and yoke dimensions. While not all parameters had been finalized, this design became the new baseline for development as the Collider dipole and provided a concrete target for consideration by the Task Force.

Topics for immediate discussion and recommendation:

- Cable width
- Collar width
- Yoke outer diameter

The cable width would have to be based on the strand thickness, the number of strands to be used, and the mechanical stability of the resulting cable. The lab consortium and the LBNL cable fabrication experiments established

recommended parameters. Based on these, BNL (Morgan, Gupta & Kahn) designed the W6733 coil cross section, and the required collar width and yoke diameter followed based on mechanical and magnetic optimization calculations at BNL. The TF soon reviewed and approved the resulting design of the cold mass cross section.

Topics for further near-term consideration included:

- Increase the Cu/SC ratio in the strand? There was evidence that this would lead to more stable quench performance.
- Did the coil design need 2 or 3 wedges in the inner layer? Should the wedges be symmetric? How should the collar/yoke interface be designed?
- Switch to Kapton CI cable insulation? This would be a major change from the Kapton/FG/Epoxy insulation used for the Tevatron and all previous SSC R&D magnets. Experience at BNL had indicated weaknesses in that insulation scheme and in collaboration with DuPont had devised a new all-Kapton (Kapton CI) scheme that appeared superior.
- Should the collars be made of aluminum (Al)? There was a faction, mostly from LBNL, that continued to advocate for such collars. Because of the larger thermal coefficient of Al, these might give magnets with improved coil prestress. Experiments at LBNL had indicated this, and the HERA magnets were made with Al collars.
- Should the yoke be split vertically rather than horizontally? There was evidence that a vertical split would lead to better support of the coil and improved prestress, giving better quench performance. FNAL adopted this feature for the magnets it would build.
- Less pressing issues: Design of the conductor cross-over between inner and outer coils? Continue the steel yoke over the magnet ends? Support for the coil ends?

Topics important to the Collider:

- Aperture of the Collider quadrupoles: This coil aperture specification had remained at 40 mm even after the dipole coil aperture specification had been increased to 50 mm. The 50 mm aperture had been driven largely by the fear of insufficient quality in the dipole integral field, a reason that would not apply to the integral field of the much shorter quadrupole magnets. What problems would be caused by a discontinuity in the beam tube diameter? Was space needed inside the beam tube for a liner---a radiation shield to absorb synchrotron radiation, which might spoil the needed machine vacuum by heating the surface of the beam tube? Was a liner needed in the dipoles as well?
- Insertion quads: Designs were needed for the insertion quads (these quads are those near the beam collision points).

Subjects of Interest (SOIs):

- Alternate dipole designs:

- S. Caspi, LBNL: Narrow SS collars---yoke provides needed support, thereby gaining a little field margin.
- G Spigo, SSCL: Al collars, vertically-split yoke, Al bar in yoke split to control yoke closure---gain coil prestress when cold, reduce prestress when warm.
- D. Orrell, SSCL: Al collar design, build at FNAL, also have contractor build and evaluate a model---better control of coil prestress.

The program was too far along to abandon the existing design, which was performing well. One can imagine Tom Bush getting annoyed upon hearing of yet more suggestions from the physicists for major revisions. What was the point of these exercises? Interesting as they were, it was not our obligation to find all the various ways in which magnets could be built!

- Quadrupole magnet designs: R. Gupta presented various interesting and innovative ideas for the Collider quadrupoles and the insertion quads. These ideas were welcome because the Collider quadrupole aperture was not yet specified and there were unresolved issues with insertion quads regarding aperture, required gradients, operational temperature, and beam heating.
- Abandon the cross-flow magnet cooling scheme that was designed into the magnets? This scheme had been proposed several years earlier by R. Shutt and extensively modeled by M. Rehak at BNL to ensure that the long dipole magnets cooled uniformly and reliably. M. McAshan at SSCL wanted this idea abandoned. He insisted that during a quench, high helium pressure would damage a magnet, even though Shutt and Rehak had calculated that this would not be the case.
- R. Palmer championed a “long-range Mole”, a field measuring device that would crawl through a string of magnets and detect flaws that might affect the beam. This would be a take-off from the existing stationary BNL-developed Moles being used to measure the field in a long magnet. This idea was not pursued because it was not clear that it might be needed.
- Magnet prestress. This was a topic of frequent discussion: how important is it to magnet performance, how to reconcile the contradictory evidence on how it affected performance. Please see Topics, *Prestress* for further discussion.
- Cu/SC ratio. This was another topic of frequent discussion---again see the Topics section.
- Strain in the cold mass shell. This topic was of interest because it could affect the coil prestress. Its variation during thermal cycles and magnet excitation could give insights into the mechanics of the complete cold mass structure. FNAL committed to measuring this parameter.

TAP

In November 1990, Tom Bush organized a new committee named TAP (Technical Advisory Panel) chaired by Bob Schermer to “advise the SSCL Magnet Division”. Schermer had become Chief Magnet Scientist for the SSCL. Its instructions were to: “provide guidance to the MD on matters of both short term and long-term interest, e.g. HEB magnets, quads for the IRs, etc.; to identify important technical issues and recommend an R&D program to highlight them; to coordinate with the MSIM meetings and to either substitute for or coordinate with the meetings of the 50 mm Task Force under Palmer.” The membership of this new group was much the same as it had been for the Palmer TF. The issues discussed had a somewhat different focus; for instance, in the first meeting on November 14, 1990, the group discussed HEB dipole issues: coil diameter (then 50 mm), sagitta of the magnets, a rectangular beam tube to ease resonant extraction from the machine, small superconductor filament size (2.5 microns) to allow fast ramping, cooling issues. The insertion quads became a frequent and extensive topic for discussion: these were clearly a concern in the design of the machine and they required a long range development program. We began to get reports on the “baseline” Collider dipole design being developed by General Dynamics, the leader contractor. They were proposing, for instance: to “swage” collar packs instead of spot-welding collar pairs; to “fine-blank” the yoke laminations for better precision and more predictable mechanics; to “semi-perf” the yoke laminations to give better shear resistance; to “co-cure” the inner and outer coils; to incorporate a “fiducial bar” into the yoke to better control magnet roll. Ideas of this type continued to come from GD but some of them were hard to evaluate because we saw no data on their efficacy in a magnet. We had various reports to study: nicely done calculations by J. Jayakumar on Cu/SC ratio effects in conductor, comprehensive analyses by A. Devred of the effects of specific design features in our magnets as revealed by strain gauge and quench measurements, reports of magnet failures and eddy current problems in the HERA magnets.

Toward the end of 1991, we got reports of “craziness” at the SSCL: Paul Reardon was to be “fired” as the Program Manager, there was “no direction” in the program, there had been “nothing like it ever”, it was “crazy not to have BNL build more magnets”, “many of the staff were looking for new jobs”, etc.

Our work for the SSC continued to fade after the end of 1991. The upheavals in the SSC management did not have a direct effect on the SSC work we were doing; we were seen as a place of stability and were asked to undertake additional tasks through 1992 and 1993, until the SSCL was in a position to do them itself. As it happens, BNL could have done further work for the SSCL program because our staff was being reduced in parallel with the SSC program reductions at BNL.

RHIC

Early RHIC Magnets

At first, the proposed new machine for the existing tunnel was not well defined beyond that it should be a collider for ion beams and that its top energy for protons should not be too high. Some in the community were suspicious that it was a resurrected CBA “in disguise” and that it would perhaps compete with the new Tevatron at FNAL. Planning at BNL led by Director N. Samios plus BNL staff including H. Hahn as Technical Director of a Design Task Force³², and with input from the nuclear physics community, established the basic parameters for the new machine: a collider for heavy ion beams with beam energy 100 GeV/nucleon for gold, equivalent to 250 GeV for protons. For such ion beams the required aperture was 80 mm. The lattice would need many quadrupoles for focusing the ions beams to keep them small. The details of the machine lattice took some years to settle; an antisymmetric lattice was eventually chosen. The cost of this new machine was a major consideration as it was to be a facility for nuclear physics where budgets were traditionally more modest than they were for high energy physics. The initial and all subsequent magnet designs reflected this reality.

Various styles of magnet were proposed: window frame magnets with flat coils favored by Gordon Danby and colleagues, dual magnets (two $\cos \vartheta$ cold masses in a single cryostat), collared coil designs as for SSC, a “Unicell” design suggested by Danby where magnets would essentially be built in place to avoid costs such as interconnections, and several others. Two-in-one magnets could not be considered because of the need for a 2.5 to 1 current difference in the magnets for the case of heavy ions colliding with protons. That would be hard to achieve in a 2-in-1 magnet where the fields of the two apertures are closely coupled. Discussions dragged on for some time including frequent calls for cost estimates, a time-consuming business. Finally, in March 1985 Reardon reached the decision, after consultation with BNL accelerator and department experts, that the magnet style should be 1-in-1 $\cos \vartheta$ rather than dual $\cos \vartheta$, the two options left on the table at that time. The recent adoption of the antisymmetric lattice implied that a beam separation in the arcs greater than the 600 mm previously specified would be acceptable. This decision opened the way for more intense development of the 1-in-1 design, in particular to save costs, since they were at the time believed to cost more. Significant proposed savings in the design were soon made firm: for instance, avoiding stainless steel collars by using the yoke as a collar, using SSC cable in a single coil design, etc. Even the magnet paint color was held to a single choice to reduce cost; simple blue and yellow tape was applied to distinguish the two rings in the collider.

A “construction start” was optimistically believed to be a few years in the future. This goal was maintained for some years despite regular postponement. We prepared detailed scenarios for a DOE Review in April 1986 to build the magnet system starting in 1988 with the option for a 1989 start. The actual construction start came in late 1990 with funding allocated in the FY1991 nuclear physics budget passed by Congress. The determined advocacy of Samios had finally paid off. In the picture, he is shown with a section cut from a RHIC R&D dipole magnet and holding a piece of superconductor cable as used in the magnets.

The first RHIC magnets were ad hoc affairs, built with available resources because designs were not settled and in any case, there was little R&D funding available, especially to build the (expensive) tooling required for proper magnets. In 1984, Reardon and the MD negotiated with FNAL to build magnet coils for some model magnets that would be configured into a RHIC-like magnet. The Tevatron inner coil was 75 mm in diameter, nearly as big as the proposed 80 mm RHIC coil, so their tooling could be used to make coils, albeit without the wedges needed to shape a good field in a single layer design. The conductor was CBA/Tevatron cable. Soon FNAL shipped well-made coils to BNL that could be used to build a working magnet.

In order to determine the behavior of a curved magnet bent to the curvature required for RHIC a model named “Quick RHIC”, or RHIC-X1, was constructed at BNL beginning later in 1984 using the coils made at FNAL.³³ Whether a curved magnet would work correctly was a major issue at the time. The magnet that was built used modified CBA parts wherever possible. These included glued CBA yoke module blocks assembled into a stressed, bolted yoke. Pinned steel insert modules and fiberglass insulating shoes were used to fill the space between the coil and the inner yoke diameter. The assembly of the magnet was done in a manner similar to that used for the SSC yokes: the yoke module blocks were laid out on a strongback with spacers added to provide the required sagitta, 9.1 mm in this 4.2 m long yoke. The CBA assembly rails that tied together the coil blocks were adapted for the curvature simply by drilling oversized holes. With the bolts compressing the yoke blocks, and after some trial-and-error coil shimming to reach the needed coil prestress, the cold mass was closed. Friction was sufficient to maintain the curvature, even when this cold mass was hung vertically into a dewar for testing.

In early 1985, the magnet reached a field of 4.9 T with little training.³⁴ This showed that adding curvature to the yoke of the required amount would not have a deleterious effect on performance.

Four additional coil sets from FNAL were then shipped to Germany where they were collared at DESY in Hamburg and inserted into 4.5 m long yokes at Brown, Boveri & Cie. (BBC) in Mannheim, where HERA magnets were being manufactured. Two of these were assembled with aluminum collars and two with iron collars. The magnets were returned to BNL for testing, which took place through 1985. All four met their expected conductor short sample quench current with little training. The magnets built with aluminum collars reached a field of only 3.6 T, the ones with iron collars a somewhat higher field.³⁵ The field shape was horrific, as expected from coils without spacers, but the good quench performance was reassuring.

Then, a final 4.5 m long magnet labeled DRS001 was built at BNL, this time with coils made at BNL. Sufficient R&D funding for the MD had been made available to pay for the labor and materials to build the winding mandrels, curing formblocks and associated coil handling equipment needed to make actual RHIC-design coils. These first coils were designed by Pat Thompson. A keyed iron yoke was used to compress the coils. Tested in late 1985³⁶, the magnet had little training in 4.5 K liquid helium. In 2.6 K helium, it reached a field of 4.6 T, near its short sample limit at that temperature. Field quality was reasonable and the design could be iterated for required adjustments based on the field measurements. Six magnet cold masses of length ~4.5 m had now been built and tested.

Next came a group of four, full-length (9.7m) dipoles, designated DRA001 through DRA004.³⁷ The single layer coil included four spacers to shape the field. The cold mass of the first of these tested, DRA004, was constructed entirely at BNL again utilizing a keyed yoke and installed into a HERA cryostat supplied by BBC. Coils for the remaining three magnets were made at BNL, then sent to BBC for cold mass assembly (with welded yokes) and insertion into cryostats. Cryostated magnets were returned to BNL for testing. Two of these dipoles utilized conductor with 5 micron filaments, one spool supplied by Furukawa (DRA004) and one spool by Supercon (DRA003).

The quench performance of these magnets was respectable. The magnets were cooled with supercritical helium at 12 atmospheres pressure in the Magnet Division's Magcool test facility. The quench fields were all well above the operating field, and training was minimal. The quench plateaus for the magnets were 4.4 - 4.6 T. Examining the data more closely, the maximum field reached in the first dipole (DRA004, tested in February 1987) was 4.6 T compared to 5.0 T expected on the basis of short sample tests of the conductor. The maximum quench field in the second dipole (DRA003) was slightly lower. However, as the cable short sample current was lower, the magnet performed up to its expected limit.

The plateaus of the third and fourth magnets were in good agreement with their expected limits.

The performance of these magnets, and evidence from short sample measurements of various conductors, suggested that somewhat more stabilizing copper was needed in the new high-homogeneity superconducting wire for magnets to reach the higher quench plateaus made possible by higher current densities. This change was incorporated by increasing the copper-to-superconductor ratio from 1.8:1 to 2.25:1 for the conductor of future RHIC magnets.

Field quality measurements were made with an SSC-sized measuring coil, too small in diameter to be ideal for these larger aperture magnets. Nevertheless, the measurements were sufficiently reliable to suggest modest changes to the design for future magnets. Together with a number of ideas concerning how to simplify the design and to reduce production costs, these magnets provided a good basis for designing future R&D magnets. Despite the logistical challenge of shipping coils to BBC, having that company assemble magnets in its factory, and sending completed magnets back to BNL by sea and by air, we were able to keep production costs low, and we gained valuable experience in this cooperative arrangement between BNL and an industrial vendor. That experience would be invaluable in the future when the building of RHIC magnets would be entrusted to an industrial vendor in a competitive bidding process.

Approval of the RHIC Project

By early 1987, the Nuclear Science Advisory Committee (NSAC) had reviewed the proposed RHIC Collider and confirmed it as having the highest priority for new projects in nuclear science. The DOE accepted this priority and accordingly scheduled a Temple Review³⁸ for May 20-22, 1987. In the report on its findings, the review committee found the project “ready to proceed with construction funding”. Regarding the magnets, the review committee stated that the “superconducting magnet design, fabrication, and test capability at BNL is considered to be exceptional by the DOE Review Committee”. Noting the benefit to BNL from our work on SSC, the committee wrote that “the RHIC magnet geometry allows use of actual tooling, conductor, and other hardware developed at considerable cost and effort for these other projects”. This was a welcome comment in light of the continuing criticisms we were getting from some at BNL for “working too much on SSC”.

Data from the testing of two arc dipole magnets (DRA004 and DRA003) was presented. The committee wrote that magnets appeared to be at a level of development that was “enviable for a superconductor accelerator”, but recalled several items that we had already suggested required further investigation: the use of the phenolic RX630 as a coil/yoke spacer and its thickness, the somewhat large saturation of the yoke steel, and the conductor Cu/SC ratio, which it was believed was coupled with slightly erratic quench behavior.

All these items (and more) were sorted out over the next few years. The RX630 spacer was made thicker, which, in addition to the yoke saturation control holes, reduced the field saturation. It was subjected to creep tests---no significant creep in the pole, the region of highest pressure, was observed.³⁹ The 2 mil maximum thickness variation of the spacers allowed in the specification was achieved in production. The conductor Cu/SC ratio was increased from 1.8 to 2.25, based on stability measurements made in the lab. The source of the observed quenching instability, however, probably lay elsewhere. In any case, increasing the amount of copper in the cable allowed a more comfortable margin for the planned single diode quench protection scheme.

Because of the proposed construction start in 1989, some in the MD felt that it would be unwise to add many voltage taps and strain gauges to the RHIC R&D magnets as was being routinely done in the parallel SSC program. They might cause other problems in the next few “final” R&D magnets before start of production. Thus too few were added; we did not discover that the fit-up of parts in the magnet ends was not quite right, in particular in the conductor ramp from the pole to outside the coil. The sizing of coil support parts in the ends of a magnet, needed because the forces at high field move and cause quenching of any unsupported conductor, is a notoriously difficult problem; it cannot be accurately modeled because the coil compression, final size, and precise location as the coils are compressed cannot be specified. That ramp was gradually improved in

succeeding models and the instability disappeared (it had persisted even with higher Cu/SC conductor).

The switch to Kapton CI insulation was not even on the table in this review. This significant improvement was not yet fully developed and could not be part of the design. The danger of shorting from overstressed insulation was not abated until that change was adopted.

For the support of the cold mass in the cryostat, the SSC-style folded post being developed by FNAL for the SSC was shown. Later, the Engineering Division developed the two-piece straight post made of Ultem 2100 polyetherimide, a great simplification over the folded post. The low heat-leak folded post was not needed in RHIC because of a more generous allowable heat leak budget.

Designs for arc quadrupole, sextupole and corrector magnets were shown as well as a proposed assembly method for these magnets, which we named a "CQS unit". Plans for building these magnets as well as those needed in the insertion regions were presented. A five-year schedule for construction was developed by Kelly and Elisman including a proposed mix of industrial/in-house fabrication. In the end, based on full-cycle cost analysis, arc dipole, quadrupole and sextupole magnets would be built by industry, all others by BNL.

The procurement of superconductor was going to be a BNL responsibility, given the organizing skills of Greene, who had recently spent a year at DESY helping them organize their conductor procurement for HERA. The plan was presented at the review and carried out for production---please see Topics, *Superconductor for RHIC*, for additional details.

Industrial production studies had been underway for several years. These had been championed in particular by Reardon and they proved helpful in understanding the ways that industrial companies would interact with us later when Requests for Proposals (RFPs) were issued by us for RHIC magnet production. Three different companies were given contracts to do production studies and cost estimates for magnet production: Brown Boveri (BBC) in Germany, Ansaldo in Italy, and General Dynamics (GD) in the US. The first two were already building magnets for DESY and GD was interested in building SSC magnets. BNL had also made a cost estimate under the guidance of Reardon (with the assistance of Goodzeit) who at the time was anxious to minimize the RHIC magnet cost in order to enhance chances for project approval. He therefore omitted some items that he felt could be budgeted in other ways, within the context of the Lab's overall program in high energy and nuclear physics for which he was the Associate Director. He was overly optimistic in this endeavor and later, as costs became better understood, the true cost of the magnets grew increasingly out of step with the original estimate. The reported magnet cost was never properly increased by the Project Head, who controlled that aspect of the project, until well after production began.

The three commercial estimates were higher than the BNL estimate but differed one to the other. The BNL estimated cost per dipole magnet in \$FY1988 was \$58,872. The commercial costs were higher by factors of 1.38, 1.76, and 2.27. These comparisons were performed somewhat uncertain but represented a best effort attempt to resolve all the differences in the assumptions used in the various estimates. The actual cost per magnet for the production run at Northrop Grumman Corporation (NGC) in \$FY1991 was \$112K, a factor of 1.75 over the original BNL estimate, including a 6% increase for conversion to \$FY1991. Surprisingly one of the vendors had come close to estimating the actual cost of production.

In the review, the reviewers stated that the magnets “might require a net increase of only 5-7 percent”, and a later ICE review largely agreed with this assessment. Perhaps too little was known about the cost of magnets in this first-of-its-kind industrial production effort. In our later internal estimates, we came within a few percent of the actual cost of building the magnet system for the machine.

Magnet R&D Completion

Over the next few years, we continued to improve the arc dipole design and by 1993, when production at NGC was soon to start, we had built eight additional long dipoles, labeled DRB005 through DRB008 and DRC009 through DRC012. We had instituted a program of short 1.8 m dipoles that could be easily tested in a vertical dewar without the need for a cryostat. Their primary purpose was to thoroughly test the new all-Kapton cable wrap before adopting it for machine magnets; it passed all its tests with flying colors and has become the new standard for cable accelerator magnets. In addition, we built arc quadrupole and arc sextupole magnets, both of which were slated for industrial production.

Other parts of a machine-ready design were finalized. This included such items as the quench protection diode assembly, the magnet warmup heaters for accelerating the occasional warmup of the magnet to room temperature, the Ω -style expansion loops for the main busses, the magnet electrical interconnect assemblies, bellows expansion joints, a system of fiducial monuments on the magnets to allow accurate surveying and positioning in the machine, and a myriad of other items needed for a functional system.

The new Multiwire-derived technology (please refer to the Topic, *Printed Circuit Coils*) was used to build the various species of corrector magnets, and a number of QCS assemblies were built to proof the concept. Models of 100 mm insertion dipoles and 130 mm insertion quadrupoles were designed and built, as were 130 mm insertion corrector magnets, though further development was needed. By 1993, only the 180 mm insertion dipoles had not been built although a design was in hand; funding was not available. Twelve of these large and challenging magnets were required in the machine but because of their cost, no models could be afforded. An iteration of the design would have been prudent and could have avoided the retraining that is now required for some of these magnets after each warmup cycle.

Industrial Production

Lab Director Nick Samios announced the appointment of Satoshi Ozaki as RHIC Project Head on October 6, 1989. His appointment provided the needed leadership to begin the transfer to industrial production as had been planned. In November 1990, we held a meeting at BNL to introduce interested companies to the magnets that would be ordered. A picture of MD staff who helped to host the visitors is shown in *Appendix B Group Pictures* for this date. Interest was widespread, probably because of the impending program to build SSC magnets, for which we had held a similar session 22 months earlier in January, 1989. Attending the 3-day meeting were 30 companies and 80 company employees. A Request for Proposal (RFP), BNL No. 534000, was issued by BNL on May 29, 1991 to build the arc dipole magnets, 373 in total.

Preparing this RFP was the work of many people. The MD wrote or provided all the technical information for the company; the cryostat design had largely been prepared by the Engineering Division. I made certain that the responsibilities were clear: BNL would provide the prints, the company would build to those prints, and a process for assigning fault for errors was spelled out. The Procurement Division included all the DOE-required formatting and “boiler-plate”, as they called it. Mary Faith Healy, Head of the Division, Larry Smith, in charge of the contract, and Andy Feldman, an energetic and sharp-eyed procurement specialist in the Division, were particularly effective in putting together the document and following all the required procedures. The DOE offices at BNL and Chicago were heavily involved to ensure that no detail was missed. Most importantly, DOE allowed BNL’s industrialization plan to go forward in contrast to the serious missteps made regarding the SSC industrialization program.

The contract, BNL’s largest ever, was divided into three phases:

- 1) Tooling, development magnets (30): Cost plus fixed fee
- 2) Production magnets (282): Fixed price incentive fee
- 3) Insertion magnets and spares (61): Fixed price incentive fee

The RFP specified the design of the cold mass, the cryostats, and the many measurements that would be required including warm field measurements using measuring equipment supplied by BNL. A procedure for engineering changes in the design or processes was included. Tooling was to be designed and built by the vendor subject to review by BNL staff. BNL would supply the drawing package and detailed specifications for technical parameters. Material to be furnished by BNL included superconductor cable, stainless steel beam tubes (manufactured in Germany), yoke steel (manufactured in Japan), the quench protection diode assemblies, Kapton insulation, and welding wire for use at cryogenic temperatures.

Evaluation of the responses from would-be Suppliers (Vendors) would be by a Source Evaluation Board considering technical merit, overall cost, and business capability of the Supplier with points awarded in various prescribed ways. There

were four responses; a Supplier, NGC, was selected by early 1992 following evaluation of their Best and Final Offer (BAFO). The initial contract value was \$43M, the final cost upon completion was \$56M. The cost increase resulted primarily from increasing overhead rates as the Grumman facility phased out of defense work, and increased Phase I tooling and training costs. From that point forward, there could be only the most necessary changes in the design of the magnet, because any further changes would pass through a careful evaluation at the company and at BNL that would also assign a cost to the change. Changes would be time-consuming and costly. Changes, submitted as Engineering Change Requests (ECNs) in the end did not cause net cost increases in the contract.

This company had long built airplanes for the Navy on Long Island but that business was in decline, so they had buildings and infrastructure available for the work plus a skilled work force. Their bid required a dispensation from the Navy to allow a competitive overhead rate on this non-defense project. The building they proposed using was a large structure that had once been used for major construction projects but now appeared dark, dirty, oil-stained, and abandoned. Their rehabilitation of the building turned it into a clean, well-lighted, and inviting facility, an amazing improvement, and that is where all the magnets were built. With Mike Anerella, an insightful engineer with a very good memory who had long been building magnets in the R&D program at BNL, overseeing the work at NGC, and BNL design engineer C. Breining permanently stationed at the factory, the production was accomplished largely as planned, albeit with some serious technical and cost challenges along the way.⁴⁰ The picture shows a coil being made in the Grumman factory in Bethpage, NY.

Extensive testing during production was built into the contract, including warm field measurements using measuring coils and electronics supplied by BNL. No bad ring magnet was delivered to BNL, although two of the production magnets had errors with the placement of the RX630 spacers that were discovered at the factory; those two magnets were delivered to BNL and set aside for use if needed. Both the dipole magnets' quench performance (shown in the plot below) and their field quality were consistently good so that only 20% of the dipole magnets were cryogenically tested at BNL. An average of 1.5 quenches were required to reach plateau.

This was a successful, and first, involvement of industry in building accelerator magnets in the US.⁴¹ Their predicted labor requirements, including the learning curve built into the estimates, came remarkably close to actual labor, as seen in the plot. With complete control of costs, this is a model that could have been advantageously followed by the SSC project.

Below is a picture of the first magnet built at NGC being delivered to Brookhaven on a special air-ride trailer.

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In parallel to the work on dipole magnets, designs for ring quadrupole, sextupole, corrector and insertion magnets were being developed based on the requirements of the lattice being settled by the accelerator physicists. The design of the quadrupole magnets could be conceptually similar to that of the dipoles but with four individual coils rather than two providing the field and powered in a series connection with the dipoles. The RFP for the arc quadrupole magnets followed in short order, structured in similar fashion. Again NGC won the contract, now for the quadrupoles, which after all had many similarities in design and parts to the dipole magnets they were already primed to build. That construction effort proceeded smoothly.

The sextupole requirements led to a design where six individual coils wound with superconducting wire onto bobbins and positioned on the steel poles of a laminated yoke provided the field. The RFP for arc sextupole magnets was again structured in similar fashion. The contract to build these magnets was won by Everson Electric Company of Nazareth, PA. This was a small company compared to Northrop Grumman, but it displayed ingenuity and resourcefulness in its proposal. For instance, the coils of the sextupoles were designed to be wound on G10 fiberglass coil forms and BNL had not found a good way to make these forms except by gluing together pieces of G10 fiberglass sheet cut to the right dimensions. The resulting forms frequently broke and proved generally unreliable. The company's engineers proposed machining each form (1728 were required) from a solid block of G10. This was an audacious approach because G10 is difficult and expensive to machine: most cutting tools dull quickly and the dust

produced is dangerous to the health of the machinist so extra precautions are needed. They would set up a special room with proper ventilation and an automated milling machine equipped with expensive but long-lasting diamond cutting tools. This machine and the proposed setup could make the pieces safely and inexpensively. That one innovation made their proposal very attractive and earned them points in the evaluation.

Magnet Production at BNL

Corrector magnets required four separate multipoles in each package. The large numbers of such magnets led to an innovative design where the multipole pattern consisted of superconducting wire ultrasonically bonded to a Kapton substrate by a computer-driven wiring machine. That substrate was then laminated to a cylinder of the appropriate dimensions; four such cylinders each with its own multipole pattern mounted concentrically inside a steel yoke completed the magnet.⁴²

A CQS assembly contained three cold masses: quadrupole, sextupole and corrector. These were aligned on a precision bench where a stainless steel shell could be welded around the units to form a CQS cold mass for mounting into a cryostat. This is shown in the picture where a sextupole is in the front followed by a quadrupole and a corrector. The

corrector magnets were all built at BNL as were the CQS assemblies using the industrially-built quadrupole and sextupole magnets. The machine required some 96 variations of the assembly, which demanded careful management and quality control to avoid errors. The innovative and unique designs and fabrication methods developed for these CQS magnets led to impressive magnet performance and large cost savings for the machine compared to earlier approaches where magnets are all treated as separate units.

In order to bring the beams into collision, the regular lattice that guides the beams in the arcs of the machine has to be broken and the beams bent and focused to the collision point. The special magnets required to do this are (oddly) labeled “insertion magnets” by accelerator physicists. Typically, the beam undergoes large excursions in the process and hence the insertion magnets must have large apertures. This makes them challenging to build because the magnetic forces that must be contained increase linearly with aperture. In RHIC, whereas the arc magnets have a standard coil aperture of 80 mm, in the insertions the dipole apertures vary up to 180 mm and the quadrupole apertures up to 130 mm. Again, because of their small numbers and many different dimensions, these magnets were all built at BNL using the same technology as that for the arc magnets where possible. Here too some serious technical challenges had to be overcome by the engineering staff. In the insertion regions, the magnet cold masses were assembled into cryostats in situ in order to relieve the need for very large, difficult-to-handle structures.

Particularly challenging were the large aperture (180 mm) DX magnets. This program became a major success in spite of no R&D due to the funding shortage. The most difficult magnet in the accelerator, with the highest forces, they were built immediately on the heels of a single prototype, which at first failed

mechanically, then succeeded after the installation of improvised engineering improvements. All 12 units have operated without failure since they were installed, though some retraining is required on occasion. These magnets, had a little R&D been possible, would have had a redesign of the initial, soft coil ends and perhaps been designed with two coils, not one of 71 turns.

Finally, the many other tasks involved in getting the magnets finalized for the machine: the measurements of their field, the organization and handing-off of that data to the machine physicists, the bus-work, the electrical joints, the mechanical restraints, feedthroughs, bellows, pipe joints, etc. all required time and effort. The overall complexity of the completed system, and the careful work required to do it all correctly, is truly impressive.

Summary of the RHIC Magnets

A good description of each of the RHIC magnets can be found in the published NIM article on the RHIC machine⁴³ (also End Note 5). The table below lists the magnet inventory, 1740 magnets, for the machine. Following that are drawings of the various magnet cold masses, and a picture of the rings of magnets installed in the tunnel. The total cost of the RHIC magnet system as listed in a final B&E cost report was \$168M in as-spent dollars.

Magnet	Num	Coil Dia, mm	Length, m
Dipoles			
Arc	264	80	9.45
D5I, D5O	12, 12	80	6.92, 8.71
D6, D8, D9	24, 24, 24	80	2.95, 9.45, 2.95
D0	24	100	3.6
DX	12	180	3.7
Quadrupoles			
Arc	276	80	1.13
Q4, Q5, Q6	24, 24, 24	80	1.83, 1.13, 1.13
Q7, Q8, Q9	24, 24, 24	80	0.95, 1.13, 1.13
Q1, Q2, Q3	24, 24, 24	130	1.44, 3.40, 2.10
Sextupoles			
Arc, Q9	276, 12	80	0.75
Trim Quadrupoles			
Q4, Q5, Q6	24, 24, 24	80	0.75
Correctors			
B, C, D, E, F	96, 132, 78, 78, 36	80	0.5
I, J, K, L, M	12, 12, 24, 12, 12	130	0.5
Total	1740

Division Head, Division Status

(abbreviated version)

In November 1993 I was replaced as Head of the MD in a dispute over the cost estimate to build the RHIC magnet system and my reluctance to continue presenting and defending the official estimate. Ozaki gave as his reason for this move that the project was entering the Production Phase and needed new leadership. After that, I worked on helical and LHC magnets, two new endeavors just getting under way.

In my place he appointed Horst Foelsche, a hard-working and capable physicist from the AGS who had held various accelerator department leadership positions. Foelsche recognized the great challenge he faced in taking on such an active and multi-faceted program as the magnets for RHIC. He also understood that the program continued to have good leadership under Kelly, Anerella, Ganetis, Wanderer, Greene and others; that there were competent physicists, engineers, and technicians throughout the organization; that major contracts were in place; and that it was generally ready for production in most systems. His message to the staff was a welcome one of support for their work but also a warning that there would be a “take no prisoners” approach towards “recalcitrants and slackers”. On that score, he needed to have no worries because there were no “recalcitrants and slackers” and the staff, professionals that they were, wanted nothing more than to get on with the work of building RHIC. In addition to the technical and administrative issues confronting him as Division Head, he was asked to do an independent estimate of the magnet costs, which he did and that came close to but somewhat higher than the one I had done. The job was not easy for him because he had started suffering from severe headaches that later proved to be caused by an aggressive brain tumor. Sadly, Foelsche’s health deteriorated steadily and this good and decent man died somewhat over a year later in May 1995.

Art Greene took over the reins after Foelsche’s illness became debilitating in July 1994 and was appointed Magnet Division Head in late 1994. This was not a pleasant experience for Greene because of the project budget woes. The program was essentially in Ozaki’s hands but Greene felt ongoing, often ugly budget pressures from the spending monitors in the Project and had no way to allay their concerns. A year later, in a wise career move, he accepted a management position at the wire and cable company NEEW in New Hampshire and, beginning in early 1996, found much more congenial working conditions there compared to the difficult environment at BNL.

After Greene left, the supervision of the MD became the responsibility of Mike Harrison (shown), who had been appointed in 1991 as Associate Project Head in charge of the Collider. Harrison brought a sensible and calming approach to getting the magnets built. He allowed the work to proceed as it had been planned and underway. He paid serious attention to problems that arose and empowered the engineers to work out solutions as had been done in the past. By virtue of also being in charge of overall machine construction including the many other subsystems that were needed, he had a broader mandate and could find ways to juggle work and funding across the project. His yeoman achievements in the construction of the machine under very difficult constraints are not well recognized; there are few others who could have accomplished so difficult a task yet retained their sanity.

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Harrison had become Head of the MD in 1996 and continued in that role for some years after the completion of RHIC in 1999. Beginning in 1994, the Division began the helical magnet system for polarized proton studies at RHIC using external funding. Later, as the ring magnets for RHIC were completed, the MD also began to build interaction region dipoles for the LHC. These as well as the Booster magnet project of the early 1990s are discussed in the next section.

In addition to the aforementioned projects, there were numerous smaller but important projects for other machines around the world or planned by experimentalists wishing to use MD facilities---they are briefly listed in Topics, *Magnet Division Projects Beyond SSC & RHIC*. Today the Division is in the capable hands of Peter Wanderer and continues to attract modest funding for special magnets (please see the Topic mentioned above) and for new magnet development, some via SBIR grants: led by Ramesh Gupta, these projects have included energy storage magnets, the use of HTS conductor to build magnets, and Common Coil magnets. The Division retains a dwindling number of the skilled physicists, engineers and technicians who have been so productive over the years, beginning in the early 1980s, and who gave and continue to give the Division its good reputation for competence and achievement.

Additional Magnet Projects

Over the course of the R&D program, and in the years after 1993 when the SSC work had ended and the RHIC Project was in production mode, a number of other endeavors were underway in the Division. Some of these were small ventures and are described in Topics: **MD: Projects Beyond SSC & RHIC**. Three bigger efforts are described below.

Booster Magnets

The Magnet Division was given the task of assembling and testing the magnets for the new rapid-cycling (7.5 Hz) AGS Booster, a machine that was needed for heavy ion physics research at BNL. Required were 36 dipole and 48 quadrupole magnets, all water-cooled. The dipoles were sector magnets, each curved 10 degrees and 2.38 m long, designed by Booster staff. The quadrupole magnets were 4.38 and 4.26 m long, also designed by Booster staff. Having a commercial vendor build these magnets was apparently too costly. E. Kelly, ably assisted by engineer W. Stokes, laid out an assembly and test area in a MD building. Over a period of several years beginning in 1988, the dipole and quadrupole magnets were built and tested in that facility. The dipoles were assembled from steel blocks made of laminations that had been glued into wedge-shaped modules at BNL and coils made by a vendor. The quadrupoles were also made of glued laminations and vendor-built coils. A big challenge in this program was to produce steel blocks that were at once strong and durable, and with eddy current effects minimized in this rapid-cycling machine. The finished magnets were all measured and their performance certified in the MD. Our efforts were much appreciated by the leaders of the Booster project, as the two memos below attest.

BROOKHAVEN NATIONAL LABORATORY**MEMORANDUM**

DATE: Tuesday, March 5, 1991
TO: S. Ozaki and E.P. Rohrer
FROM: W.T. Weng
SUBJECT: **BOOSTER MAGNET CONSTRUCTION AND MEASUREMENT**

Over the past three years, the Magnet Division has been responsible for Booster magnet construction and measurement. It is a great pleasure to witness the completion of both dipole and quadrupole magnet construction for the Booster. In about six weeks, the Booster ring can be completed with filled half-cells and quarter-cells ready for beam testing.

I would like to take this opportunity to thank the important contributions made by the Magnet Division. Under the leadership of E. Willen and the direct supervision of E. Kelly and W. Stokes, they designed and constructed the fixtures for the magnet assembly and built the Booster dipoles and quadrupoles to the precision and stability that has seldom been achieved in the past. The Magnet Measurement Group and Electrical Group under the supervision of P. Wanderer and G. Ganetis, designed and constructed the measurement coil, power supply, and data acquisition system, and measured all dipoles, quadrupoles, and sextupoles with great resolution and reproducibility. Their combined efforts have resulted in the high quality Booster magnets meeting all the integrated field requirements with end multipoles much better than the design tolerance. It is fair to say that the quality of our magnets is on a par with that of other well-built accelerators.

Even when difficult circumstances arose, be it budget shortage, component delay, conflicting obligations, or shifting schedules, they managed to find a solution calmly and professionally. The Booster Project has been lucky to have this team of experts managing its magnet production. Brookhaven's program will certainly benefit from their contributions for a long time to come.

BROOKHAVEN NATIONAL LABORATORY**MEMORANDUM**

DATE: Friday, July 27, 1990
TO: E. Willen
FROM: E. Bleser
SUBJECT: **BOOSTER MAGNETIC MEASUREMENTS**

At the recent Booster Review, I had an opportunity to present the measurement results for the Booster magnets. Afterwards, one of the reviewers commented on the very high quality (10^{-4}) of the data. He said that for the accelerator he is building, they decided to do their own magnetic measurements and have subsequently had nothing but grief. They have difficulty achieving an accuracy of 10^{-3} , they have difficulty achieving throughput and the measurements have become the principal bottleneck in the machine construction. For their senior technical staff, magnetic measurements is viewed as a major disaster area.

This seems like an appropriate time to acknowledge the skills and professionalism of your group, which has unfailingly produced high quality measurements on demand. From our point of view, it has been a remarkably smooth and trouble-free operation, and since there have been no problems, we have probably failed to fully appreciate and acknowledge the very great contributions you and your group have made to the Booster construction. Let this note stand as partial acknowledgment.

LHC Magnets

Following the demise of SSC, the US high energy physics program turned to the Large Hadron Collider being built at CERN as the best available option for the study of elementary particles. CERN welcomed the participation of the US community, both to help build the machine and to help with the detector systems planned for that machine. To assist with the machine construction, the US magnet builders were given the task of planning and making the dipole and quadrupole magnets needed in the LHC interaction regions and some collimators and connection boxes also needed there. The DOE organized a group headed by Jim Strait of FNAL to guide this effort. The dipole magnets, to be the responsibility of BNL, would bring the circulating LHC beams into collision, and the quadrupole magnets, to be FNAL's responsibility, would focus the beams into the tight spot required for high collision rates in the detectors. Connection boxes for connecting power and cryogenic lines to the magnets and the collimators would be the responsibility of LBNL.

The table below shows the dipole magnets built by BNL for the LHC. There were 20 in all plus four spares. All used RHIC coils 80 mm in diameter and 9.45 m long. The yokes, cryostats, and interfaces were all quite different, however. All cold masses were straight, not curved like those in RHIC. The D1 magnets were 1-in-1 style like those in RHIC, but with a maximized beam pipe to accommodate beam excursions in the LHC. D2 and D4 (shown in figure) were 2-in-1 magnets with aperture separations of 188 mm and 194 mm respectively. The field in the two apertures pointed in the same direction, a change from other 2-in-1 magnets where adjacent fields point in opposite directions. Finally, the D3 magnets were 1-in-1 but with two cold masses in one cryostat, the apertures separated by 414 mm. The 20 magnets required a total of 32 cold masses and 36 coils. Magnet test results are given in the paper by J. Muratore.⁴⁴ Steve Plate at BNL interfaced with CERN on technical matters.⁴⁵

Name	Cold Mass (CM) Type	CM in One Cryostat	Aperture Separation (mm)	Number (Spares)	Number Apertures
D1	1-in-1	1	---	4(1)	4
D2	2-in-1	1	188	8(1)	16
D3	1-in-1	2	414	4(1)	8
D4	2-in-1	1	194	4(1)	8

John Cozzolino and Mike Anerella standing in front of the cryogenic test facility with a D1 magnet for the LHC.

Tom Van Winckel (front) and Ray Ceruti assembling a D2 magnet for the LHC.

A D3 magnet under construction: two cold masses in one cryostat.

Electrical connections being installed on the end of a D2 magnet.

Building LHC magnets in the Brookhaven magnet factory.

Finished LHC magnets, some with the special QQS end piece required by CERN on selected magnets, awaiting shipment to CERN.

An LHC magnet shipped from Brookhaven arriving on a rainy day at CERN in Geneva, Switzerland. Shipping sensitive equipment by sea is challenging because of the high g-forces that can be encountered on a boat that is crossing the Atlantic Ocean. Special support cradles and restraints were built (Paul Kovach, BNL) and sensors attached to protect the magnet and monitor the forces encountered on the trip. All BNL magnets arrived safely at CERN.

This picture (February 2002) shows me recording a video at CERN's request commenting on the magnet and its place in the grand LHC scheme. My colleagues and I had travelled to CERN to confirm the magnet's safe arrival and to assist with its unpacking.

Lowering a Brookhaven-built dipole magnet through the LHC access shaft to the machine below.

The magnet lowered to the bottom of the LHC access shaft.

A Brookhaven-built dipole magnet being positioned in the tunnel for connection to the cryogenic header (to the right and slightly lower than the blue magnet).

Helical Magnets-RHIC

The AGS at Brookhaven had long supported experiments with polarized protons and the planning for RHIC included the goal of polarized protons there too. The Japanese laboratory RIKEN concluded a Memorandum with BNL in 1995 to provide support for such a capability. In 1993, there had been discussions and meetings on the topic; I had made some estimates, at the request of Thomas Roser (shown), for the cost of a series of short, rotated dipole magnets for RHIC assembled into snakes and rotators. Such schemes had been described earlier by S.Y. Lee⁴⁶, building on previous work by K. Steffen at DESY, and required considerable linear space and magnets with large apertures to accommodate beam excursions in RHIC. In late 1993, M. Harrison asked me to consider a real design for the needed magnets. A continuous magnet with a strong, rotating dipole field along its length and a sizable aperture was required, but no one knew how to build such a magnet.⁴⁷ The corrector magnets being built for RHIC at the time were far too weak to do the job and their design was not one that could be sufficiently scaled.

Upon reflection, and talks with Gerry Morgan and Ramesh Gupta, we decided that superconducting wire or a small cable fitted into helical slots milled into a thick-walled metal cylinder as I had proposed might do the job. The slots in metal would furnish the needed mechanical structure to hold the conductor firmly in place against the sizable Lorentz forces. Simple calculations showed that we could reach fields in the 3-4 T range with reasonable conductor current and turn layout.

Consultations with Gene Kelly indicated that aluminum would be the metal of choice because it would be easier than stainless steel to machine and would be less prone to distortion as the slots were cut. The ends would be a problem because milling slots around the ends of a cylinder with the required precision would be challenging, if even possible.

Our early designs (shown in the figure), circulated already in March 1994, presented the proposed structure including the field that could be achieved for RHIC 80 mm apertures.⁴⁸ This motivated planning by the accelerator

physicists for using such magnets and it was not long before we had designs for snakes and rotators in RHIC. Many combinations of helicity, length and orientation are possible, but the layout proposed by Ptitsin and Shatunov seemed particularly expedient. It required magnets of 100 mm aperture, fields of 4 T, both left-handed and right-handed helices, and it fit into the RHIC lattice. These would have a full 360° rotation of the field in a length of 2.4 m. A paper detailing our proposals for helical magnets was presented at the Spin Workshop in September at BNL by Ramesh Gupta as was a paper describing their proposal for snakes and rotators in RHIC.⁴⁹

The origin of helical magnets for RHIC is now commonly credited to Ptitsin and Shatunov in the many papers that have subsequently appeared describing the spin program at Brookhaven. A more accurate accreditation would be “the architects of the helical magnets were Gupta, Kelly, Morgan, and Willen and their magnets were configured into RHIC snakes and rotators by Ptitsin and Shatunov”.

Gene Kelly was able to obtain the required aluminum cylinders and have them machined in Central Shops (shown in the photo) following sketches I made and drawings by designer Keith Powers. Technician Brian Vogt, a person comfortable with working on learn-as-you-go projects,

made the first prototype helical magnets using the cylinders. He used a newly designed 6-around-1 cable made of seven wires 0.013" in diameter (RHIC corrector wire) and wrapped with Kapton. The cable, with its center conductor not part of the twisted cable pattern, violated superconductor design criteria meant to avoid eddy current effects in a cable. However, the seven strand configuration made a cable that was mechanically very stable and the magnet would not have to ramp, so perhaps eddy currents in the cable would not be a problem. The ends were a makeshift affair using small plastic pegs in the cylinder to guide the cable on a path to the opposite side of the cylinder (see the adjacent photo). Vogt had the skill and the patience to make this first prototype with its hundreds of turns of small, unruly cables. After the wiring was complete, we potted the ends in epoxy to hold it together. These early coils carried the

required current with a comfortable margin, and after a few additional prototypes of this sort, we were on our way to designing a proper coil form with machined ends.

By 1997, we had determined that two concentric tubes each with slots to hold multiple layers of cable would be a suitable design for the helical magnets. Gupta had laid out the turns so that a good quality 2-D field would be achieved. Morgan had designed ends to match the turns of the helix and smoothly bring them to the opposite side of the cylinder. The many engineering details needed for working magnets had been planned and designer Keith Powers had learned to make the CAD drawings that were needed by the Shops to manufacture the coil tubes. The following is a description of some of the topics in

the building of the magnets: a prototype was tested by 1997 and the performance of production magnets was reported by 1999. References to this work are given in the Endnotes.⁵⁰ That list does not include references to the significant other work related to the RHIC spin program that went on in parallel to the building of the magnets. Many such references are included in the listed papers.

During this period, a different design was proposed by AML, a small company in Florida.⁵¹ They were funded by the RHIC project and made several unsuccessful prototypes. After several years, support for their work was discontinued by the project.

The figure above shows the adopted magnet cross section: the coil inner diameter is 100 mm, the yoke outer diameter is 356 mm; the yoke has a symmetric circle of holes near the outer surface to allow helium passage and to provide space for leads without losing the symmetry of the field as the turns rotate through the length of the magnet. The slots rotate along the magnet length but the holes in the yoke do not. Azimuthal Lorentz forces are contained in the individual slots and, in contrast to the case of $\cos \vartheta$ dipoles made with keystoneed cable do not accumulate at the mid-plane. Along the length of the magnet, the outward Lorentz forces are contained by a Kevlar overwrap and ultimately by the single piece yoke. In the ends the difficult Lorentz force problem is again solved by containing the forces in the individual slots, as shown in the figure. This figure also shows the reliefs machined into the tubes for the leads.

The aluminum tubes were purchased as blanks ready for the machining of the slots. Steps in their manufacture included extrusion, annealing, gun-drilling, honing (ID), and machining (OD). The most critical dimension was the inner surface of the outer tube, where the diameter was specified ± 2 mils. Straightness over the full length was specified ± 10 mils. Slots were machined into the tubes at BNL using a CAD file generated by AutoCad design software. The machining operation was done on a milling machine using a 0.5" end mill to cut the 0.560" wide slot in successive passes, each pass removing a depth of 0.25" material. A finishing end mill was used to finish the sides and bottom of the slot. All dimensions were measured relative to a keyway or pin at the end of the tube. Errors in slot position were approximately ± 10 mils or less along the length of the slot. The slot length could be off by up to 20 mils, due primarily to temperature variations and compressive forces during the machining operation.

Before winding, the slots were lined with Kapton for additional electrical insulation of the conductor. Preformed three mil strips secured with two mil adhesive film were applied along the length of the slot. The drawing shows a slot with this insulation and several other features discussed here. In the ends, the slots were insulated with short 3/8" wide, one mil thick, 50% overlapped strips of Kapton backed with silicone adhesive. This was labor intensive but no less costly way was found to apply insulation free of wrinkles and voids in that region. The integrity of the insulation was checked to 4 kV by passing a conductive piece of foam along the full length of each slot. Thin Nomex barriers were used as necessary to prevent damage to the conductor or to the Kapton insulation.

The superconducting cable was placed by hand (see the photo), without tension, into the slots in an ordered array. A machine was built, shown in the photo, to place the cable automatically but could not be used because of error accumulation in the position of the slot.⁵² The width of the slot was such that 12 turns of the cable (each 0.045" diameter including 0.039" cable, 0.004" Kapton insulation and 0.002"

adhesive coating) had on average about one mil of space between turns. A layer of B-stage fiberglass/epoxy with adhesive film on each side was placed between each layer. This material contained ~40% by weight of epoxy.

After winding, press plates of 0.125" thick G10 fiberglass were applied to each slot (visible in picture below) and secured with ring clamps. These plates were preformed to a helical shape or to the end shape by heating and forcing into an appropriate shallow slot.

A wrap of Kevlar was applied to the tube in a prescribed pattern. The Kevlar stretches and applies pressure on the press plates. In the subsequent curing operation, the stretch in the Kevlar allows the press plates to move radially inward without losing all tension, thereby compressing the windings and removing voids in the slots as the epoxy softens and fills the remaining spaces. Thus, after curing, the cable was held in a strong matrix of fiberglass and resin that could later withstand the Lorentz forces that could cause motion and quenching. Helium was still able to penetrate this package and fill the ~10% free space inside the Kapton wrap and around the wires of the cable.

As the cable is pressed radially inward during curing, it expands axially because of the helix and, in the ends, because of the curvature of the cylinder. To accommodate this growth, additional axial space (0.030") was allowed in the slot ends. The windings were observed to sometimes fill this space but not to do so consistently. If they did not, the growth was absorbed along the length of the winding. In all cases, any spaces left in the ends after the curing operation were filled with epoxy while the structure was being gently vibrated to ensure that all voids were filled. Cut-outs in the press plates provided access to the windings for this filling operation.

After curing to the prescribed recipe, the Kevlar was removed to allow access for the aforementioned filling and the dressing and securing of leads, using the same epoxy. The tube was then wrapped with a layer of fiberglass cloth to cushion

sharp edges that might damage the final Kevlar wrap. A new wrap of Kevlar was applied with 10 lb. tension and a pitch of 0.036". A layer of Tedlar was wrapped over the Kevlar to prevent epoxy of the final wet-wrap of fiberglass and epoxy from penetrating into the Kevlar. This was done to prevent cracking of epoxy bonds due to stress from differential thermal coefficients upon cooldown to cryogenic temperature. Multiple layers of fiberglass cloth and epoxy were applied to build a radial thickness sufficient to avoid hollows when the tube was subsequently machined to its finished diameter. The tube was continuously rotated while this epoxy cured.

To assemble the magnets, called storage units, the two coils were first assembled together, then aligned and pinned in a fixture using machined features

on the tube ends. This assembly was then oriented vertically and bolted to a plate that also serves as the primary alignment reference in the magnet. Still in a vertical orientation, stacks of yoke laminations several inches high were lowered around the coils with tooling designed to hold the laminations level so as to avoid binding. Typical clearances between tubes and between tube and yoke were several mils. The straightness of the tubes was critical for this assembly, and the use of aluminum tubes ensured freedom from stresses that might distort the tubes when they were machined. After the pre-weighed number of laminations had been installed, stainless steel tie bars were inserted through four of the yoke holes and secured with bolts that held the lamination stack. The yoke length was thus controlled by the machined length of the tie bars. The tie bars and the coils were held on a plate at only the lead end of the coils. The coils, controlled by the aluminum tubes, were therefore free to contract axially inside the yoke upon cooldown. A photograph of a completed magnet (the first production unit) is shown on the left above.

Yoke warmup heaters were installed through four of the yoke slots, then circuit boards were fastened to the lead end of the magnet. Each of the individual windings was connected in a series connection on the circuit boards. A 50 m Ω resistor was connected across each of the windings to avoid damage that might

occur from energy dissipation in a winding when the magnet quenches. These resistors were made of five folded 12.6" lengths of 16-gauge nichrome wire brazed in parallel into a copper block. Warm field measurements were made before the resistors were installed. These resistors may be seen in the photo on the right above.

The room temperature resistance of a winding was typically $20\ \Omega$. The average inductance of a winding was 0.3 H. The large inductance of the windings and the $50\ \text{m}\Omega$ parallel resistance leads to an indeterminate field in the magnet when it is ramped. This was acceptable because the magnet is designed to be operated only in a DC mode or with very slow ($<1\ \text{A/s}$) ramp rates. Diodes could have been used in series with the resistors if faster ramp rates had been needed.

Storage units were aligned on a precision bench to build the four-unit snakes and rotators. There the necessary wiring harnesses were attached, the outer containment shells were installed and welded, alignment fiducials were attached, and the various electrical and cryogenic feed-throughs were installed. Each completed storage unit had been tested cryogenically and

measurements made to ensure the device was working properly. The first snake was completed in July 1999 and the final rotator in May 2002. Photos of these completed units are included in the group photos section.

The measurements verified that each unit worked as intended. Several typical measurements are included below. The figure on the left shows the quench performance of the early production magnets. Some training is evident but all magnets reached their required field level and improved in later magnets. The

figure on the right shows the residual integral field in a typical magnet. In these magnets, this parameter must be small; all magnets comfortably met this requirement. The extensive measurements were all made available to the accelerator physicists who would be responsible for commissioning these magnets in the machine.

Helical Magnets-AGS

In order to reduce the loss of proton polarization in the AGS during acceleration, a superconducting helical snake was built for that machine in 2003-2004. This 3 T snake complemented a lower field room temperature snake built in Japan a few years earlier. Together these two snakes significantly improved the polarization level of protons delivered to RHIC. Thomas Roser had worked out the details of how partial Siberian Snakes could overcome imperfection and intrinsic resonances in the AGS and provided the impetus to build and commission the successful system now installed in that machine.⁵³ Roser was the intellectual leader of the Spin physics program at BNL and his steadfast support and patience with the challenging helical magnet program over its ten-year construction period enabled its success.

In this account, only a few details of the AGS superconducting snake will be given. Reference is made to papers where more complete descriptions can be found.⁵⁴ The snake for the AGS was built after the RHIC snakes and rotators were mostly complete and it benefited significantly from that program. It can be said that the AGS snake is the most intricate device ever built by the Magnet Division. The complexity of the coil design, the large size (forces) of the coils, the additional solenoid and small correctors included in the design, the extremely low heat leak that was required, the use of cryocoolers including the needed cryogen fill and quench recovery features, the tight quarters in the AGS---all these factors and more combined to make this magnet a daunting challenge. Only the skill and knowledge of the MD staff, and the aforementioned leadership support, made the project possible. Particularly involved in this work were Ramesh Gupta, Steve Plate, Paul Kovach, Mike Anerella, Keith Power, Andy Marone, and John Escallier. This snake did not benefit from R&D on its components yet it worked correctly from the first moments. It was (and is) a remarkable achievement.

It is a 3 T, two coil magnet some 1940 mm in magnetic length in which the dipole field rotates with a pitch of 0.2053 degrees/mm for 1154 mm in the center

and a pitch of 0.3920 degrees/mm for 393 mm in each end.⁵⁵ The coil cross-section is made of two slotted cylinders containing superconductor. So as to minimize residual offsets and deflections of the beam on its orbit through the snake, a careful balancing of the coil parameters was necessary. The first photo above shows one of the coils with the winding complete and ready for the overwrap that allows the tube to be ground to a precise diameter. This is shown in the second photo, where the slots on the surface were cut to aid helium circulation. In addition to the main helical coils, a solenoid winding was built on the cold bore tube inside the main coils to compensate for the axial component of the field that is experienced by the beam when it is off-axis in this helical magnet. Also, two dipole corrector magnets were placed on the same tube with the solenoid. A low heat leak cryostat was built so that the magnet can operate in the AGS cooled by several cryocoolers and not require a constant supply of liquid helium. The adjacent two photos show the snake nearly complete in the MD shops and being readied for cryogenic testing. Mike Harrison and Wolfram Fischer are the two persons in the 2nd photo. The last photo shows the snake being installed in the AGS ring. A technician is working on the magnet and Accelerator Department Engineer Joe Tuozzolo, who guided the snake's deployment into the AGS machine, is observing from the aisle.

Topics

Bellows

Bellows, usually made of corrugated stainless steel sheet, are needed between magnets to accommodate the length changes that occur as magnets are cooled to cryogenic temperatures. Since bellows are inherently unstable, they must be properly chosen so that they will not collapse or squirm under the required length changes and the varying pressure changes that occur in the operation of a magnet or in possible failure modes during magnet and system operation. This complex problem has been extensively analyzed by Shutt and Rehak, with some of their methods and results available in their excellent paper.⁵⁶ They give specific recommendations for the case of SSC magnets in their paper.

Collars

No topic was studied and discussed more than the collars and the mechanics of the collar-yoke interface in SSC magnets. Their design usually began with the finite element program ANSYS, which could calculate stresses and strains in mechanical structures by subdividing the structure into small elements subject to applied forces. At BNL, we began with simple laminations punched of Nitronic 40 stainless steel. They were paired together with pins, later spot welds (shown as dark spots in the figure), then assembled as packs. The packs were assembled around coils, then pushed together vertically in a press to compress the coils. The top-bottom collars were held together with keys in the sides of the collars. The idea here was to sufficiently over-compress the somewhat soft coil so that after cooldown and powering of the magnet, some compression of the coil package would be retained. A loose coil is likely to undergo training when first powered, though the evidence for that is somewhat contradictory. Collars were first used at FNAL in the Tevatron, where they were welded together along the edges while under compression in a hydraulic press.

The design of collars used in the 50 mm magnets (shown in the photo) had evolved into much more sophisticated and capable collars that reliably and reproducibly held the coils securely in position. They were still made of Nitronic 40 stainless steel, a high strength and widely available alloy

of low magnetic permeability, important in a magnet where the field must be precisely controlled. They were punched with a slight vertical ovality in a fine-blanking press for precision and spot-welded in pairs for rigidity.

These pairs were assembled into packs (shown is a pack for 40 mm magnets) using alternately left-right pairs to prevent twisting of the coils in assembly. The packs were held together with loose-fitting brass tubes in two places and fitted with appropriate brass shims at the poles. These packs were placed around the coils and locked together in a press using two tapered phosphor/bronze keys pushed hydraulically into place on each side. The now-

round collared coils were assembled into yokes designed to provide a line-to-line fit around the collars. This resulted in a redundant system where the coils were fully supported by the collars and the collared coils were securely held in place by the yoke, which was closed by a stainless shell welded around the yoke. The mechanics of this design resulted in magnets reliably free of training either initially or after magnet powering and cryogenic cycles.⁵⁷

Others found different solutions for their magnets. FNAL favored a vertically split yoke, still using Nitronic 40 collars.⁵⁸ DESY built their HERA Collider with free-standing aluminum collars using a full-length through pin to lock the collars, a design that requires a full length press for assembly. LBNL too favored aluminum collars and built several short magnets to demonstrate their proposed design. The initial LHC magnets used aluminum collars and their first models worked reasonably well. The attractive feature of aluminum is that it shrinks upon cooldown about as much as the coil, thereby losing less coil prestress in the process, at least in principle.

At BNL, we avoided the use of aluminum collars because of its large dimensional changes, both when stressed (about three times that of stainless steel), and when cooled to liquid helium temperatures (again about three times that of stainless). These large changes must be accommodated in the magnet design and can lead to difficulties with parts tolerance buildup. That may result in a sometimes loose magnet structure, requiring unreasonably tight tolerances in the fabrication of the magnet parts, tolerances that are perhaps not even possible to maintain in the coil dimensions.

This issue became critical at CERN in the latter stages of the LHC magnet R&D program. They had built numerous magnets using aluminum collars in their magnet development program and they began to realize, upon careful analysis of

their experience with those models, that it could be difficult to achieve needed tolerances in production. With respect to component and assembly tolerances, they noted⁵⁹ that *“the series manufactures is likely to take place at three different sites at an expected rate of some 20 cold masses per month, in two-shift work”,* and that *“design simplicity and robustness are considered to be of highest importance in view of minimizing labour cost and maximizing the likelihood that each magnet be well within the specified requirements.”* Therefore, they converted to stainless collars late in the R&D program and found ways to cope with the needed design changes and the significantly higher costs that this would entail, stating⁶⁰ that *“AS [austenitic steel] was chosen as collar material because: a) it allows to achieve the required structural behaviour with realistic component tolerances; b) the yoke halves can be made to mate (no gap) after assembly at RT [room temperature], avoiding thus accidental coil over-stressing during assembly and simplifying the overall assembly procedure.”* The picture shows a cut-away view of an LHC dipole magnet, including the large stainless steel collars surrounding the two beam pipes and the coils in the middle of the magnet

Cross flow cooling

A modification to the original cooling scheme for the magnets was adopted that forced the specified 100 g/sec of supercritical helium (4 atm pressure) to circulate from the top passages in the iron yoke around the coil and beam tube to the bottom passages.⁶¹ This method, called cross-flow or transverse cooling, was accomplished by blocking the top and bottom passages at alternate ends of the magnet, thereby forcing the helium to pass through slotted, stainless steel laminations placed at regular intervals in the yoke, along the collar loading flats, then between collar packs to the annular space between the bore tube and the coil ID. The helium was forced to flow inward between collar packs by periodic blocks placed in the collar loading slots. The original cooling scheme depended on conduction of heat from the bore tube outward through the magnet components to the passages; only one gm/sec circulated in the annular space between beam tube and coil, serving primarily to transfer heat between the two but not in itself able to extract much heat. Heat is deposited inside the beam tube due to beam loss and to synchrotron radiation; at 20 Tev, the synchrotron radiation amounts to two watts at the design luminosity but would reach higher

levels for beam currents exceeding design. In addition, the warm finger required during testing to map the field deposited considerable heat in the bore tube. With the revised cooling scheme, ten watts of heat deposited along the length of the magnet would result in a temperature rise in the magnet coil of only 0.07 K; with the original cooling scheme, this temperature rise would be 0.6 K. The pressure drop across the magnet remained suitably low at 0.001 atm.

Data Base

For the R&D effort, no formal data bases for tracking material and orders was used. Several competent scientists with software expertise including David McChesney and Millicent (Penny) Ball were available to help with specific projects such as cost estimates, labor data, or later, tracking orders for superconductor. To keep track of the large orders for superconductor being purchased for the RHIC magnets, McChesney and Ball provided PC-based programs to track the orders. Their facility with the new PC environment that was developing in the 1980's proved valuable to MD staff who were transitioning from the use of Lab central computing and the tasks commonly done with typewriters in those years (reports, letters, memos, schedules, etc.). The Engineering Section kept its own lists that included Bills of Materials, Drawings, Change Control orders, Work Schedules, etc. That Section also oversaw the Travelers for each magnet, Operations Procedures for the work underway and the machines being used, Training Schedules, etc.

In order to provide a tracking system for the large amount of material to be bought and the many work orders that would be placed for RHIC production, software engineer Stuart Kern was added to the staff. He chose a commercial Manufacturing Resource Planning (MRP) system, named Minx, after an evaluation of the scope and needs of the MD work for that production. Minx was able to track orders for material and work in an organized way and it proved helpful to the engineering staff over the years of production. To prepare the Cost Performance Reports for our project as required by DOE, Doug Fisher used commercial software able to track progress in the required terms. This Earned Value management approach was new to all of us and took a considerable effort to fully understand. The ACWP (Actual Cost of Work Performed), BCWP (Budgeted Cost of Work Performed), BCWS (Budgeted Cost of Work Scheduled), and several other concepts together all track costs and progress against schedules and reports them in the DOE-required formats. Doug Fisher was hired for that specific purpose by the Project Head. He came from the SSCL where he was Leader of the Business Management Group in the Magnet Division. He was well known to us through our close interactions with that Lab. His chosen system, named Winsite, was commercial software able to take data from engineering progress

reports and the Lab accounting systems and, with some intervention, issue the required reports.

After the SSCL began work in Texas, Penny Ball (pictured) accepted a job there to set up, with several colleagues, a data base to track magnet parameters. Called MagCom, it would contain specifications and measured values of material properties, configuration information, and test results on completed magnets.⁶² MagCom was implemented in Sybase, a powerful, commercial relational database system, and would be widely available to all in need of the information therein. The system her group developed was a much more comprehensive and capable system than any system contemplated at BNL and would have proven invaluable to the success of the SSC project.

Electrical Insulation & Testing

The high dielectric strength, polyimide film Kapton is used to insulate the coils of the magnet against turn-to-turn and turn-to-ground voltage breakdown. Such electrical failures can occur because of puncture through the film or by flashover around the edge of the film. Puncture-type failure may occur if the film contains manufacturing defects (pinholes) or damage. Failure due to pinholes is avoided by using multiple layers of material, thereby giving a low probability that pinholes will align to allow breakdown. The Kapton used to construct magnets was inspected to ensure fewer than ten pinholes/m². Damage to Kapton is avoided by good construction practice although it can occur if local pressures are excessive. In high stress areas Kapton with some percent of mineral loading was used to reduce material creep/failure. As noted under Topics, *Kapton*, the newly developed Kapton CI system became the standard cable wrap in the magnet programs because it eliminated several classes of insulation failure.

Flashover was avoided by the design practice of maintaining creep paths of >5 mm from any conductor around film edges to ground. This allowed coil “hypotting” in air at the desired value of 5 kV while maintaining the specification of 1 kV/mm common in electrical design work. These rigorous criteria were used so that the electrical integrity of the magnet was retained even in an atmosphere of low pressure helium, where the dielectric strength is much lower than air at room temperature.

Voltages in the magnet coils during quench can reach 1500 V with respect to ground and turn-to-turn voltages can reach 70 V, based on calculation. Distributed inductances and unexpected conduction paths can lead to breakdown voltages in many places. As standard practice for SSC magnets, ground insulation integrity

was checked by “hypot” testing at twice the expected voltage plus 2000 V, or 5000 V total. This testing was done under normal room conditions. Turn-to-turn insulation was checked by applying a 2000 V voltage pulse to each coil after collaring and looking for deviations from the expected ringing pattern of the pulse (“impulse” test). This results in a per turn test of greater than 70 V but not quite the factor of two test that would be desirable; higher voltages were not used because of the desire to avoid excessive terminal voltage. These tests were carried out repeatedly throughout the construction process to ensure the electrical integrity of the magnet.

Several other tests were performed as well: a “resistance” test, an “inductance and Q” test, and a “ratiometer” test. They are described in the report by Sintchak et. al.⁶³

Field Measurements, Mole

In 1980, John Herrera and I collaborated to improve the magnetic field measurements of Isabelle magnets. The system in use at the time was a Morgan coil apparatus in which each field harmonic (alternately called multipole) of the magnet that was to be measured had its own special winding on a rotating coil (e.g. a sextupole winding to measure a sextupole field component, etc.) This approach automatically rejected the dominant field in the magnet (typically four orders of magnitude larger than the signal of interest) and was a good system for doing rapid measurements on a magnet where the field might be changing with time. However, it had several drawbacks that made its output problematic: only a limited number of the magnet’s harmonics could practicably be measured, and there were frequently missing or intermittent measurements because of the practical problems connected with all the required slip-rings and wiring. A missing measurement meant that the feed-down of higher harmonics to lower harmonics could not be calculated, leaving the measurement uncorrected and its true value in doubt.

Other labs were using coils with radial windings in which the rotating winding produced a voltage that was analyzed with home-brewed digitizers and recorders after being “bucked” with the voltage from a second winding that was sensitive to mainly the magnet’s main field (e.g. the dipole field in a dipole magnet.) Such systems were limited in accuracy for they depended on manual adjustments of the bucking voltage applied to the signal from the radial winding, which contained the harmonic voltage of interest. There was a flourishing cottage industry at the time where the experts would develop improvements as better digitizing circuits became available and would have frequent conferences and meetings to discuss the latest and the best of such systems.

Our new system⁶⁴ used tangential coils and Hewlett Packard 3456A digital voltmeters (DVM), newly available at reasonable cost. The field was measured by rotating the tangential loop in the field at a constant angular velocity and digitizing the voltage induced in the loop 128 times during each revolution (4 sec).

The trigger to digitize was derived from an optical encoder attached to the rotating coil. A marker pulse from the encoder defined the reference axis. The resulting time spectrum of the voltage was Fourier analyzed to give the harmonic content of the field. In practice, several wire loops were employed to differentiate between the large fundamental multipole and the much smaller higher multipoles.

Each signal was separately digitized and the bucking of the fundamental was performed digitally in the computer. Note that the voltages from the measuring coils passed directly to the DVMs without conditioning or modification. The high input impedance of the DVMs minimized problems from slip-ring and wire resistance. The voltmeters integrated the signal over one 60 Hz line cycle to reduce common mode noise, present in most environments. These various features together with the internal calibration capability of the voltmeters gave the measuring system good inherent accuracy (typically 1 PPM), stability, and reproducibility. Their six-digit accuracy made digital bucking possible. In addition, we had secured stable AGS beam line dipole and quadrupole magnets, which allowed good absolute calibration too. The overall approach initially met with much skepticism ("nobody does it that way", "signals are too small", etc.) in the community.

The new measuring system was first used to measure Isabelle and CBA magnets. It quickly proved its worth for we were able to give a much improved understanding of the field behavior in those (especially Isabelle) magnets; the measurements were no longer receiving "blame" for the magnet's observed behavior. New models⁶⁵ with various improvements were developed as appropriate, e.g. for the small apertures of SSC magnets, and a "Mole" that could

be pulled through a long magnet and measure its field incrementally along the way⁶⁶. A Mole (basic elements shown in the drawing) required a

gravity sensor to determine the device's orientation and gas-driven motors with non-metal parts to operate inside the magnetic field. The various models were widely used throughout the SSC program and for RHIC production measurements. A tangential coil was also sent to measure HERA magnets at DESY when those magnets were being built as part of the Joint Work Agreement. Tangential coils were used at BNL to measure Booster magnets, Spallation Neutron Source magnets, and even to comprehensively measure AGS magnets, allowing a better map of the fields in that long-running machine and the improved beam tracking needed for the polarized proton program.

An excellent and thorough discussion of magnetic fields and their measurement is available in the lectures given by the very knowledgeable Animesh Jain in 2006.⁶⁷

Field Quality

For most magnets, the field quality is considered good if the field multipoles (harmonics) are on the order of 10^{-4} of the central field or less, specified at $2/3$ of the magnet coil radius. Other factors matter too, for instance, the magnet's central field integral and its variation along the length, its saturation at high field, its harmonic variation with ramp rate, its residual harmonics at low field, etc. Most of these field quality factors are well controlled or at least acceptable in a magnet that is well designed and properly built. Having the magnet's field be stable and reproducible with power cycles or cryogenic cycles is of course also important. This topic is discussed and methods to improve field quality in production are well described in the paper by Gupta.⁶⁸

Kapton

The remarkable ability of thin Kapton polyimide films to prevent high voltage breakdown in experimental apparatus was well known to experimentalists in high energy physics. Developed by DuPont, it first appeared in the 1970s as "H-film" and immediately proved its worth in spark chamber detectors, among others, where high voltage, ~ 10 kV pulses were used to trigger voltage breakdown along particle tracks, enabling their measurement in various ways. Before Kapton, there were no good

insulators that could provide the needed insulation in the detectors and pulsing systems; component failure was a constant problem. Accelerators made of superconducting magnets could probably not be successful without polyimide films; when these magnets quench, because of distributed inductances and large stored energy, high voltages can appear in unexpected sections of a magnet so protective insulation is needed virtually everywhere.

Early in the SSC program, the Magnet Division joined with DuPont⁶⁹ in a cooperative effort to develop improved cable insulation for SSC superconducting dipole magnets.⁷⁰ The effort was supported by the SSC Central Design Group and later the SSC Laboratory. It was undertaken because turn-to-turn and midplane shorts were routinely experienced during the assembly of magnets with coils made of the existing Kapton/Fiberglass (K/FG) system of Kapton film overwrapped with epoxy-impregnated fiberglass tape. Dissection of failed magnets showed that insulation disruption and punch-through was occurring near the inner edges of turns close to the magnet midplane. Coil pressures greater than 17 kpsi were sufficient to disrupt the insulation at local high spots where wires in neighboring turns crossed one another and where the cable had been strongly compacted in the keystoning operation during cable manufacture.

In the joint development program, numerous combinations of polyimide films manufactured by DuPont with varying configurations and properties (including thickness) were subjected to tests at Brookhaven. Early tests were bench trials using wrapped cable samples. The most promising candidates were used in coils and many of these assembled and tested as magnets in both the SSC and RHIC magnet programs then underway. The Kapton CI system that was finally adopted represented a suitable compromise of numerous competing factors. It exhibited improved performance in the critical parameter of compressive punch-through resistance as well as other advantages over the K/FG system:

- Undamaged under compression by a fiberglass overwrap
- Superior manufacturability
 - Relaxation of product storage requirements
 - Reduced coil curing time
 - Improved accommodation of component size variation
 - Reduced mold cleanup after cure
 - Improved coil repair/rework capability
- Increased radiation resistance
- Retention of ductility at cryogenic temperature

- Improved conductor placement uniformity

This new Kapton CI cable insulation system was met with significant opposition in the accelerator community, generally along the lines that “it was too risky, why give up a proven system”, referring (ironically) to the Tevatron magnets. The new insulation had been shown through extensive testing to be robust and reliable. It did require higher coil molding temperatures but those could readily be accommodated through proper design of the coil tooling. Its characteristics were equal to or superior in all known respects to those of the Kapton/Fiberglass system that had been used to date. In particular, its improved punch-through resistance gave a significant reduction in the probability of electrical faults in the new generation of high field, high prestress accelerator magnets. This characteristic more than any other was responsible for the reliability of the SSC magnets and later the RHIC magnets, where no time is lost because of magnet failure.

MD: Projects Beyond SSC & RHIC

Booster magnets, helical magnets, and LHC magnets are discussed in the section named *Additional Magnet Projects*. Beyond those, some small ventures where the MD expertise or facilities proved helpful were also supported from time to time. Examples of these are: an axion search headed by Adrian Melissinos using a superconducting magnet for the conversion of possible axions to photons; a search for WIMPS, also headed by Melissinos; a monopole search using cryogenics and SQUID detectors led by S. Berman and carried out by an IBM group including future director P. Chaudhari and MD physicist Al Prodell; planning the new muon g-2 project headed by Vernon Hughes, utilizing some Division engineering help and the expertise of MD physicist R. Shutt for their large superconducting magnet; field measurements of magnets for the Spallation Neutron Source built at Oak Ridge; detailed field measurements of main ring AGS magnets, required for building better field maps to improve particle tracking in that erstwhile machine. Several others are described in the following paragraphs.

Direct Wind Magnets: These are an outgrowth of the Multiwire technology developed at BNL for building RHIC and SSC corrector magnets. Originally Pat Thompson, and then Brett Parker, advanced this technology so that today many different types of small, intricate multipole magnets can be built that would be very difficult to make in other ways. Both software and hardware play critical roles in making the technology useful: the Direct Wind machine is able to attach wires to cylindrical surfaces in specified patterns with software guiding the machine in the precise path to follow for a particular magnet wiring pattern. The picture shows an adhesive-coated, Kapton-insulated superconducting cable being played out onto a cylindrical surface covered with a prepreg wrap. A shaped, metal tip is delivering ultrasonic energy to the cable/tube contact point with sufficient amplitude to attach the cable to the tube. In this way many different magnets have been built for machines and experimental projects around the world, including the following:⁷¹

- HERA II IR magnets in Germany
- BEPC II IR magnets in China
- JPARC corrector magnets in Japan
- ALPHA antihydrogen trap experiment at CERN
- ILC prototype quadrupole magnets at Brookhaven
- ATF2 upgrade magnets at KEK (for ILC tests)
- Corrector IR magnets for the SuperKEKB project at KEK
- eRHIC final focus septum magnet at Brookhaven

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LARP: The U.S. LHC Accelerator Research Program (LARP) consists of four US laboratories, BNL, FNAL, LBNL, and SLAC, who collaborate with CERN in the context of the High Luminosity LHC program (HL-LHC) on the Large Hadron Collider. The MD's role is to build and react Nb₃Sn quadrupole coils and to test magnets assembled at FNAL. The tests require high currents (~20 kA) and super-cooled helium (1.9 K). Significant additions and modifications to the magnet production and test facilities have been necessary to enable this capability.

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NSLS II: The NSLS II project, recently completed at Brookhaven, leaned heavily on MD expertise to measure and align its magnet system. This effort was led by Animesh Jain. These magnets' positioning in the ring required unprecedented levels of precision. MD measuring systems were used, and totally new measuring techniques were developed, to achieve the machine's goals for precision of field location in its ring. With remarkable insight, inventiveness, and sophisticated analysis and organization, Jain was able accomplish this massive and difficult task, relying on MD and Light Source engineering and technician manpower as needed to carry out the work.⁷²

The corrector magnets for the machine were built by various manufacturers around the world: seven vendors in six countries located on four continents. All manufacturers were responsible for the field quality of their magnets and to carry out magnetic measurements. These proved to be of uneven quality and the magnets had to be mostly remeasured at BNL. That necessitated a thorough-going analysis of the BNL field measuring system, which uses all-digital data processing rather than the analog systems used by the vendors. The BNL system proved to be precise, reliable, and able to correctly note errors and overcome deficiencies in the vendor results. For future projects, changes to product specifications were suggested based on the deficiencies that were encountered in the delivered magnets.

Another measurement issue was the alignment of the machine magnets. There were 30 cells in the machine, each containing six girders with up to seven multipole magnets on each girder. These multipole magnets had to have a relative alignment of ± 30 microns and a girder-to-girder alignment of ± 100 microns. A vibrating wire technique, first developed at Cornell, was used for quadrupoles but had to be further developed to do sextupoles as well. Measured magnet center

accuracy of ± 5 microns was achieved with relative alignments of 10 microns after position adjustment, meeting the 30 micron requirement. The picture above shows a girder with its various magnets undergoing alignment.

This was a daunting task with many challenges overcome to achieve the results. One particularly vexing difficulty was that much of the required equipment in the MD was at the end of its useful life and funds were not available to replace the worn-out items. Jain believed that because the equipment had become so poor, it would not be possible to measure the new Argonne light source magnets at BNL.

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Solenoid for eRHIC: A recent, completely different measurement undertaken by Jain and the RHIC electron lenses team was the straightness of the field lines in two 2.5 m long, 200 mm aperture solenoids built with great care by the MD to act as electron lenses in RHIC. Ions passing through the solenoids in close proximity to the electrons are cooled; the two beams must remain aligned to ± 50 microns for effective cooling. With limited available time in the tunnel, adapting a “needle-and-mirror” method previously used by others to the particular (and difficult) geometry at RHIC, Jain was able to show that the straightness of the field lines was well within the 50 micron requirement.⁷³

Magnet Failure: DD000Z (DZ)

A review committee composed of seven magnet experts directly involved in the SSC magnet program and headed by Roger Coombes of the CDG was appointed to investigate the failure of this magnet in November 1987. This committee autopsied the magnet and reported that the cause of the magnet’s failure was a failure of the electrical insulation of the coil. This was in turn caused by material buildup at a wedge tip, mismatch of a pole spacer and shim, and an insulating cap that did not overlap a pole spacer. No fundamental flaws in the design of the magnet were found. A number of other useful suggestions regarding the fit-up of parts interior to the magnet were made in the committee’s report.⁷⁴

Outside commentary about the failure ranged from calm descriptions to overwrought speculation about the program’s doom. One such report said the program had a “tendency to quick fixes” and that the magnets “might require a new design”. A more measured report came in the magazine **Physics Today**.⁷⁵ The writers, having actually visited BNL and gathering the facts, gave an accurate account of the SSC magnet program, its achievements and remaining challenges, and the problems with DZ. Their description correctly described the program that was underway and that would be followed in the months ahead.

Magnet Type

Why did cos ϑ magnets (please see the nearby illustration for their essential elements) become popular and the coil design of choice for accelerator magnets vs the seemingly simpler design made of rectangular flat coils and blocks of iron? Perhaps the main reason was economy of conductor---for a field in the range of 3 to 8 T, less quantity of expensive NbTi conductor is required to achieve the specified field including its accuracy. Certainly cos ϑ coils need specialized tooling and are generally more difficult to build than simple flat pancake coils, but once mastered, they offer great flexibility in shaping the field for good quality, a critical factor for accelerator magnets. Computer programs are able to find conductor configurations that, in the hands of skilled experts, produce remarkably uniform fields free of unwanted harmonics. Field quality optimization is aided by the use of spacers (wedges) in the coil cross section and the pole angle of the coil (the figure shows the RHIC coil cross section used by Thompson and Gupta for field optimization⁷⁶). Yoke saturation-induced harmonics and harmonics in the end region can also be readily controlled. Some cos ϑ designs were proposed for the SSC (design B) that did not use an iron yoke at all. In that case, some iron is still needed to shield the external field of the coils and to support them in a cryostat.

There have been strong lobbyists for the flat coil style of magnet: Gordon Danby and his group at BNL in the days of Isabelle difficulties urged that an iron-dominated magnet design be considered and the group actually built some models. However, they would clearly have required substantially more R&D effort than they believed or that was forthcoming at the Lab. In the SSC program, TAC worked hard to establish the design C iron-dominated “superferric” magnet as the baseline for the machine. They built a number of short, quite successful initial models but their design gradually became more complex as they worked to achieve good field quality at their design field of 3.5 T; trim coils and shaped iron became necessary, making the design more complicated than had originally been envisioned. A review committee (Sciulli Committee) convened by the CDG recommended against that option for the SSC, based on unknowns in performance and cost: “that style has not displayed the simplicity and ease of construction and operation it originally promised”. Their report was released on September 9, 1985

after in-depth meetings and presentations in Berkeley. TAC continued its work and continued to press its case for a few more years and built some very long magnets as specified in their proposals for the machine (very long tunnels were required in that proposal, roughly twice the length of the 90 km SSC tunnel) until its funding became insufficient to continue.

A new magnet design known as the Common Coil magnet, first investigated by Ramesh Gupta,⁷⁷ shows promise for future colliders. It uses flat pancake coils in a configuration in which the dipole bending fields are supplied by the two long legs of flat coils placed on either side of the beam pipe, as shown in the figure. This design economizes

on the amount of conductor needed and allows the use of several types of conductor including the brittle Nb₃Sn in a magnet design that could reach fields well above 8 T.

Prestress

Despite years of R&D, there is no unanimous view on the issue of prestress in cos ϑ magnet coils. It is generally agreed that for the SSC magnets the prestress at collaring should be less than ~12 kpsi to avoid coil damage and that at full current, the prestress on the coil should still be something greater than zero. The compressive Lorentz force for the SSC 50 mm dipole at 6.6 kA is 6.3 kpsi. The prestress goal of 10 kpsi at room temperature allows for loss upon cooldown. Under these conditions, the coil is unlikely to undergo stick-slip motions that are the source of premature quenching (training) in a magnet. Even here, however, some results violate these limits---magnets without much prestress have worked well, and magnets with good initial prestress have worked poorly. There will always be some motion of the conductor in a magnet as it is powered because the magnet is an elastic structure that moves when forces are applied.

Voltage tap data indicate that for a magnet in which the coils are well secured, any premature quenching is most likely to originate in the lead end of a magnet in the pole area. In this high field region, the conductor is near its critical current limit. It is also the place where the conductor must transition from the inner coil and continue to the outside or, in a two coil design, continue to or be soldered to, the outer coil (in a two-coil design). The transition must be held in place by a snug fixture, called a "ramp splice". In practice the parts of the fixture and the mechanical structure around the fixture may be out of place unless all its pieces are perfectly designed, sized, and placed. This is probably not achieved initially because the end geometry, the ramp geometry, and the part's motions under

pressure are too complex. More over its final location may not be as intended: frictional effects and the fixture's deformation under pressure may conspire to leave voids. Thus there is likely to be stick-slip motion under the large Lorentz forces. Such behavior leads to confusing and contradictory observations in a magnet's quench behavior. It cannot be predicted nor understood when observed. Experience has shown that generally only repeated and astute small changes to the holding fixture and its surrounding environment can lead to a magnet free of premature quenching at its lead end.

Printed Circuit Coils

See also the Topic, *Trim Coils, Beam Tubes* for the development of the Multiwire printed coil capability at BNL for the SSC program. That technology was adapted for building various diameter RHIC corrector magnets.⁷⁸ For those magnets the required windings were not long as in the SSC correctors but did require a diverse mix of multipoles, wire layers, good wire positioning, and many individual units. The drawing shows details of a RHIC dipole corrector winding. The initial wiring machines, control systems, control computers, and software packages were completely revamped to allow for serious production. The design of a needed corrector winding would be prepared by a knowledgeable physicist, usually Thompson or Morgan, using coil design programs they had written. He would then give the design file to the machine operator, who could proceed to make the needed coil. This technique developed into a versatile and robust facility with a capability that over the years has proven able to provide magnets of many types that would be hard and costly to build with other methods. An extension of the method to allow the placement of patterns directly onto tubes of varying size was developed and has been widely used for projects

built by BNL for labs around the world (please see the Topic, *MD: Projects Beyond SSC & RHIC, Direct Wind Magnets*). The photograph shows a dipole winding being made.

Quality Assurance

Throughout the various magnet construction programs at BNL, quality assurance was a feature built into the work. Both E. Kelly and A. Greene were instrumental in having rigorous procedures in place that would avoid mistakes and poor records. Each magnet being built had a record of its construction history that went with the magnet, called a Traveler. The person doing work on the magnet would add a signed sheet that recorded the part used, the work done or the measurement made. Procedures to be followed were prepared for all steps. Parts used for the magnet had been inspected in advance, whether procured from the BNL shops or from an outside vendor. This approach proved invaluable for quickly understanding a problem with the magnet if it occurred. This BNL approach melded well with industry practice when firms later bid on building magnets or establishing details of their own QA systems if they had won the job.

Quench Protection

The SSC and RHIC magnets needed protection against damage to the magnet during a quench. Damage can result from overheating of the conductor at the point of the quench before the current in the system can be turned off or the magnet's energy can be dissipated. Also, as the quench proceeds, the resistance of the conductor increases, leading to high voltages that can arc and cause major damage to the system including large pressures and rupture of the helium containment.

For the SSC magnets, heaters were included in the form of resistive metal foils surrounding the coils. These heaters were triggered upon detection of a quench, thereby quickly spreading the quench throughout the magnet so that the quench point would not absorb all the energy. For RHIC, quench protection diodes at cryogenic temperature were used to bypass current around a quenching magnet, one such diode for each magnet. They were connected in the forward direction across the magnet leads and had a conduction threshold of 3 V at 4.35 K.

Cold quench protection diodes were first introduced at BNL and were used in HERA before their use in RHIC. Their use introduces risk into the magnet system so great care in their selection, incorporation, and testing must be exercised. For RHIC they were constructed using a 76.2 mm diameter doped silicon element manufactured by Powerex Corporation. The elements were from an existing compression style hockey puck product line, with the diffusion process modified to achieve the cryogenic requirements. For the RHIC application, a non-hermetic assembly was required. The assembly includes two large copper masses as heat sinks and as compression contacts to the element, and a stainless shell with a threaded top cap. The surface contact with the element is a 76.2 mm circle, loaded

to 53.4 kN contact force. The pressure loading is through two 19 mm diameter ceramic balls axially configured to assure an even, concentric loading of the diode element. The top cap is welded to the assembly body (an important step) to prevent thread disengagement during the application of 7000 A test pulses, done at cryogenic temperature. Since the diodes are not hermetic, the polyimide passivation of the junction edge is of paramount importance, and required both visual and electrical screening to verify passivation integrity.

Early in the R&D for a suitable diode, measurements were made of $\int I^2 dt$ ($10^6 A^2$ sec or MIITS) versus temperature for a preliminary version of a RHIC dipole. This enabled calibration of a model used for predicting the quench energy margins in the final version of the RHIC dipole. Estimates of worst case $\int I^2 dt$ values for conductor with the nominal parameters and a single quench protection diode for each magnet gave a value of about 12.4 MIITS compared with an estimated cable damage level of 13.8 MIITS. This converts to a temperature margin of about 250 K before the damage temperature of 835 K is reached. Thus, due to the extra copper in the superconducting strand, quench protection is achieved for the magnets with a single cold diode across the leads of each magnet, and no active quench protection circuitry.

Short Sample

Please see the Topic, *Superconductor Studies in the Lab*.

Splices

The joints between the high current busses in a magnet system must be well designed and correctly made. As CERN discovered in the LHC program, a failure here can have catastrophic consequences. Whenever a joint of the superconducting bus must be made, either within a magnet or in the interconnects between magnets, the normal procedure is to back the superconductor with copper able to carry the current, should the conductor quench, long enough to turn off the current, perhaps several seconds. Normally the copper for the busses to be joined is overlapped a number of centimeters and the whole length soldered together. Butt joints at this point are never acceptable. The joint must be made in a well-designed fixture that compresses the parts and heats them to the required solder melting temperature. Unless the joint is made in this reproducible way, failures can occur, because it is not possible to check the joint quality afterwards by measuring its (very low) resistance. A mechanical retaining fixture is applied to the joint afterwards and becomes a permanent part of the magnet.

Spot Heaters

These were small metal strips, usually placed between the turns of a coil in a chosen place, with wires to the outside. They could be pulsed with a short voltage to trigger a quench in the magnet. They were invaluable for a variety of tests to help understand magnet performance. With many spot heaters in some magnets,

and also voltage taps, strain gauges, temperature gauges, etc., there could be many small wires exiting a magnet. It took great skill and diligence on the part of the technicians to correctly connect all these wires into the data acquisition systems.

SSC Project Failure & Costs

Without a doubt, the project management model imposed by the DOE (the government) killed the SSC project. In retrospect it is clear that the high energy physics leadership of the US should not have allowed it to happen. The DOE model prevented Maury Tigner, an individual who as the project's leader could have successfully built the machine, from even being involved in the project after 1988. This opinion is based on the facts of the successful and technically similar RHIC project, where that machine's critical path items including the planning for its industrialization program were under the control of the knowledgeable Parke Rohrer, physicist Director Samios, and the experienced Magnet Division. It is a model that Tigner would have followed, in my opinion, because he had an indirect hand in implementing the model at BNL through discussions of this topic in his many visits and via the various industrialization programs we had organized with the CDG. The naysayers who wished to see the SSC project ended would not have prevailed if cost/management problems had not given them an opening.

The change in aperture in 1990 contributed to increasing costs, but those costs were reasonable and could be estimated with confidence, because they were primarily in the cost of material. Actually the larger aperture magnets were somewhat easier to build, performed better with improved quench behavior and better margins, and had less field variation. The main culprit was the adopted construction model, where an industrial contractor was to fill an order for magnets meeting performance specifications furnished by the SSC lab. This meant that the contractor, not the lab, would be responsible for the performance of the magnets. In the SSC Industrialization Program, we had been warned by interested firms that a "build to performance" contract of this type would force contractors to include large contingencies to cover the unknown cost of meeting the prescribed performance for objects with which they had no experience. The lab would bear none of the responsibility. A "build to print" contract, on the other hand, would be one in which the lab would provide the prints for building magnets and contractors would build to those prints. This kept the knowledgeable and experienced experts in the game. Provided the contractor built to these prints, he would be paid and bear no further liability. As we learned in the RHIC magnet procurement, contractors are very good at estimating material and labor costs for a production run in a factory setting and therefore are comfortable with only modest contingency for such contracts. Their expertise and ingenuity in that area is well beyond that of any lab or research organization.

Of course, under a “build to print” contract, the lab must be certain that its design for the magnet is correct. Because of the many years of magnet R&D that had been invested in the SSC magnets, and our valuable interaction with companies through the ongoing industrialization programs, we were quite comfortable that our magnets would meet all the performance requirements for the machine and would be straightforward for companies to build. Only minor changes to the designs might be needed, for instance, for production efficiencies. Quality control of the magnet construction process had been built in from the first step to the last, and every step had been practiced, described in writing, and had checkoff sheets to be signed by the cognizant technician. Thanks to the many prescribed tests at each step of the process as well as parts quality control and vetting, component size measurements, electrical tests, and warm field measurements of completed magnets, no magnet could unknowingly leave the factory that was not correctly built. Its performance would be as expected for that design. There would be no reason to add costs for more R&D, rebuilds, or rejects. At BNL we were very comfortable with this approach, but clearly the leadership of the SSC project was not. We applied this model to the procurement of the RHIC magnets in 1991 with excellent results, whereas the model used at the SSC led to out-of-control costs. That was failed leadership on a grand scale.

We had some advance warning that the SSC approach was flawed. When soliciting bids from contractors for building the RHIC magnets, one of the responders was Westinghouse Electric Company (WEC). We made a site visit to their factory in Round Rock, TX as part of the evaluation of the bids. There Westinghouse had set up a production facility for SSC magnets, for they were to be the “followers” to GD for SSC magnet production. They had come to recognize how unnecessarily cumbersome and expensive the SSC/GD approach would be and lamented the fact that the SSC procurement was not going to emulate the RHIC model. Their views could be trusted for they were competent production engineers, knew both magnet designs well (from having built SSC magnets at BNL), and were full of good, innovative ideas for production.

The cost of the RHIC production dipoles built by NGC was \$2,777 per tesla-meter in 1993 dollars.⁷⁹ This does not include the cost of tooling, R&D costs, or the cost of a series of preproduction prototypes. It does however provide a good figure for estimating magnet costs based on the industrial production of a large number of magnets. It is the only data point we have for tying estimates to industry and it is a solid point because the bidding for the RHIC contract was competitive with three other vendors also submitting bids. To get probable SSC costs, it is necessary to adjust RHIC labor and material for the SSC design and to add the extra magnets

needed to fill the SSC tunnel. These scaling factors had been extensively studied in the magnet development years and were well understood.

The RHIC magnets were shorter and had lower field but their aperture was larger, so magnetic forces were about the same and their construction equally challenging. Scaling labor and material for magnet field, length and aperture, and adjusting for the added tesla meters needed, the Collider dipole cost for the SSC would have been \$1.1 billion in 1993 dollars. This is a figure far lower than was being estimated for the SSC construction scenario when the project was cancelled. It is also a figure that can be regarded as an upper limit because costs drop with production volume and the SSC required many more magnets than RHIC. In the case of RHIC, the cost of all magnets was 28% of total project cost, by far the largest cost component of the machine.

Strain Gauges

It was recognized that magnet coils should be compressed and well clamped to minimize conductor motion under the action of the Lorentz forces during magnet excitation. This tended to minimize or eliminate training and achieve a quench performance consistent with the short sample characteristics of the superconductor. The reliable measurement of the azimuthal coil stress (and longitudinal coil end forces, as well) could be an important aid in evaluating and improving coil clamping systems to reduce training.

Although azimuthal pressure sensing gauges had been used for some time in accelerator magnet assemblies, there had not been much success in obtaining reliable readings of coil stress changes at operating conditions and under conditions of magnet excitation when it was important to know if the coils were still being held under compression. The problems with previously used gauges were attributed to two characteristics of their design and use: edge effects leading to non-uniform loading, and problematic readout of the data from the gauge.

An improved system was developed to measure the compressive stresses in coils and the end restraint forces on the coils. Transducers were designed to have improved sensitivity to purely mechanical strain by using bending mode deflections for sensing the applied loads. In addition, the strain gauge resistance measurements were made with a new system that eliminated sources of errors due to spurious resistance changes in interconnecting wiring and solder joints. The

design of the transducers and their measurement system is comprehensively

presented along with a discussion of the method of compensation for thermal and magnetic effects, methods of calibration with typical calibration data, and measured effects in actual magnets of the thermal stress changes from cooldown and the Lorentz forces during magnet excitation, in the paper by Goodzeit et. al.⁸⁰ This new system gave reliable and consistent results that removed much of the previous guesswork about the cause of training in magnets.

Superconductor Cu/SC Ratio

Stability against quenching in a cable magnet is needed for a functional machine. A major issue is the cable design, in particular the amount of copper between filaments and the amount surrounding the filament bundle. In the early SSC magnets, a Cu/SC ratio of 1.3 was used; calculations indicated that this would be a good compromise: less copper makes room for more SC so a wire can carry higher current, and more copper ensures protection against burnout of the wire if it quenches. However, while it appeared that many magnets with more copper led to less training when the magnet was powered, the evidence was not always consistent. Short sample measurements by Ghosh et al. at BNL seemed to support the idea the higher Cu/SC ratios would help.⁸¹ To quote from their paper: *Training is a common problem in superconducting magnets, particularly in accelerator type dipole magnets which are made with high J_c multifilamentary NbTi cables and which have a coil geometry that is difficult to constrain against motion. While measuring short sample critical currents of cables for various accelerator magnet development projects it has been frequently observed that conductors have to be trained by repeated quenching in order to obtain voltage-current data that can be analyzed for the 10^{-12} Ω -cm resistivity current. Under controlled conditions it is possible to generate training behavior reproducibly and to relate it to certain physical factors. These are the critical current density, J_c , the copper matrix resistivity and amount (in particular, the copper to superconductor ratio), and the constraining pressure. In the design of every device a compromise has to be made between overall current density and stability and these studies lead to certain conclusions about the appropriate copper to superconductor ratio.*

Their results show a clear dependence on the Cu/SC ratio, as seen in the plot. They conclude with the comment: *There seems to be no conventional theory that predicts a strong dependence of training or stability on Cu/SC ratio and we do not have an adequate quantitative explanation for the experimental observations at this time.*

Superconductor for RHIC

If the production magnet building effort was to be successful, then the required superconductor would have to be of high quality and be available on time for the rigorous schedule of magnet production. The SSC program,

strongly supported by DOE and university groups, had succeeded in its goal of producing higher current wire with fine filaments and making good cable with this wire. This program was a major LBNL effort summarized in a LBNL report by R. Scanlan, a leader of that effort (End Note 9). The two photomicrographs, taken at BNL, show typical wires that were etched to reveal the NbTi filaments inside: the upper wire has $J_c = 1400 \text{ A/mm}^2$, the lower one has $J_c = 2200 \text{ A/mm}^2$. The smoother filament at the bottom is free of the hard nodules that are the source of detrimental diameter variations when the wire is drawn and is therefore called high homogeneity conductor. The RHIC program benefited significantly from those successes.

The procurement of conductor for RHIC, organized at Brookhaven by Art Greene with technical oversight provided by an experienced group of scientists including W. Sampson, A. Ghosh and M. Garber, extended over

two years and provided material in advance of its need in the construction program. With cooperative industrial partners, the complex task of specifying, ordering, monitoring and supplying cable to industry was accomplished with extraordinary success. In competitive bidding, the contracts to manufacture wire were awarded to Oxford Superconducting Technology of Carteret, NJ. Raw material came from ATI Metals Company in Wah Chang, OR and the contracts to manufacture cable were awarded to New England Wire Technologies (NEEW) of Lisbon, NH. These companies were able to fulfill their tasks well within contract requirements. The result was material available as needed and that allowed consistently high levels of magnet performance. It is rare for the requirements for an industrial product to be so demanding, the execution so smooth and the result so gratifying as in the procurement of the RHIC superconductor. Problems certainly appeared in the production process but it was always possible to resolve them quickly by the team of cooperating personalities engaged in the program.

For the RHIC dipole and quadrupole magnets, some twenty million meters of superconducting strand (wire) were manufactured.⁸² This strand had a diameter

of 0.65 mm and was made in two versions. One version had a copper/superconductor ratio of 2.25 to 1, contained 3510 filaments of 6 microns diameter NbTi high homogeneity alloy and had a (specified) minimum critical current of 264 A in a 5 T field at 4.2 K. The current density in this case was 2600 A/mm²---the strand typically achieved 2800 A/mm² in production. This was made into a 30 strand cable and used for the dipole magnets. The other version of strand had a Cu/SC ratio of 1.8 to 1, contained 4146 filaments of 6 microns NbTi alloy and had a (specified) minimum critical current of 286 A in a 5.6 T field at 4.2 K. This was made into a 36 strand cable and used for the quadrupole and certain other special magnets. The picture shows the disassembled parts of a superconducting cable including also the very fine NbTi filaments in an etched piece of the wire making up the cable.

The 30 strand cable was made with a keystone angle of 1.2° angle, a width of 9.73 mm, a mid-thickness of 1.17 mm and carried a minimum current of 7542 A in a 5 T field at 4.2K. Some 566 km of this cable were required. The 36 strand cable was made with a keystone angle of 1.0° angle, a width of 11.68 mm, a mid-thickness of 1.16 mm and carried a minimum current of 10,100 A in a 5 T field at 4.2K. Some 69 km of this cable were required. The cabling operation typically degraded the conductor by about 8% due to its compaction, an expected and quite reasonable amount. The drawing shows the conductors and their dimensions as used in RHIC.

Wire and cable dimensions were continuously monitored during production. These are important because they affect the uniformity of the coils and therefore the magnetic field in magnets such as these where the fields are dominated by the coil parameters. On-line laser micrometers confirmed that the variation of wire diameter was well within the specified 2.5 microns RMS specification for the drawing process. Cable thickness variations as measured with a specialized Cable Measuring Machine were well within the specified 1 micron tolerance. These small variances set a new standard for the industry.

The piece lengths of the produced strand (the length of wire produced continuously in the drawing operation) also set a new standard for the industry. These are important because it is desirable, and it was required, to avoid any cold welds in the magnet coils, necessary if the strand is too short for a complete coil. In addition, long piece lengths give flexibility in efficiently assigning the strand to coils. The average piece length for the dipole wire was 10.9 km where a minimum of 0.7 km was required. Even better, the piece length for over half the wire for the quadrupole magnets was over 35 km.

Finally, the short sample measurements of the wire and cable made throughout production showed that the current capacities specified for the strand and cable were consistently within the specified upper and lower limits. Both these limits are important for uniformity of magnet performance. Upper limits restrict the capacity to carry unnecessarily high currents; such capacity would change the persistent currents in a magnet with such conductor and thereby enable undesired harmonics in that magnet.

Superconductor Studies in the Lab

The Magnet Division supported a small group of physicists (W. Sampson (shown), A. Ghosh, and M. Garber) plus technical staff to not only carry out short-sample testing of superconducting wire and cable but also to study and provide measurements on various effects needed to guide the magnet-building program. This group had the expertise as well as the necessary dewars, liquid helium, power supplies, instrumentation, and technician support to quickly and effectively answer many technical questions as they arose. Short sample measurements were made by clamping a short cable sample into a strong insulating structure as shown in the figure and placing it into a magnet that generates a background field of five or six Teslas. The current through the test sample is increased until a resistivity of 10^{-12} ohm-cm develops the sample. This is taken to be the short sample value, or critical current value, for the cable and, done in this way, is reproducible for the sample as well as measurable in a consistent way for most superconducting cable of interest to magnet builders. Wire measurements were made in much the same way. The group made innumerable measurements over the years, not only for the SSC and RHIC programs, but also for the HERA project in Germany and for other groups that needed accurate evaluations. The details of the measurement can be found in a paper by Garber et al.⁸³

Below is a sample of reports of their many other studies over several years:

- Effect of Cu_4Ti Compound Formation on the Characteristics of NbTi Accelerator Magnet Wire, 1985, BNL-36632
- Critical Current Studies on Fine Filamentary NbTi Accelerator Wires, 1985, BNL-37019
- Magnetization and Critical Currents of NbTi Wires with Fine Filaments, 1985, BNL-37044
- Anomalous Low Field Magnetization in Fine Filament NbTi Conductors, 1986, BNL-38854
- Procedures for Measuring the Electrical Properties of Superconductors for Accelerator Magnets, 1986, BNL-38968
- Quench Propagation Across the Copper Wedges in SSC Dipoles, 1986, BNL-38853
- The Effect of Magnetic Impurities and Barriers on the Magnetization and Critical Current of Fine Filament NbTi Composites, 1987, BNL-40543
- Magnetization Studies of Multifilamentary Nb_3Sn Wires, 1988, BNL-41160
- Magnetoresistance of Superconducting Cables for Accelerator Magnets, 1988, BNL-41208
- Training in Short Samples of Superconducting Cables for Accelerator Magnets, 1988, BNL-41209
- The Effect of Self Field on the Critical Current Determination of Multifilamentary Superconductors, 1988, BNL-41210
- Normal State Resistance and Low Temperature Magnetoresistance of Superconducting Cables for Accelerator Magnets, 1988, BNL-41976

Support Posts

A significant contribution to the success of the RHIC magnet system was the cold mass support post developed by BNL engineer J. Sondericker and consultant L. J. Wolf for use in the cryostats. Early RHIC cryostats used a strap system to hang and stabilize a cold mass in the vacuum tank as had been used in CBA and HERA magnets but such systems, while effective, were costly and cumbersome. For the SSC magnets FNAL had developed a folded post design with two heat intercepts resulting in a very low heat leak as required for that large machine but not necessary in the smaller RHIC machine. The system developed for RHIC was a simple, two-piece cylindrical column with low enough thermal conductivity so as not to increase the heat load yet strong enough to support the cold mass under all load conditions without the need for additional thrust restraints. The two bolted piece design allowed an intermediate heat shield to be anchored to the post.

After testing many candidate materials, Ultem 2100 polyetherimide, a General Electric engineering thermoplastic, was selected for its excellent mechanical properties, low thermal conductivity, and good radiation resistance. Its strength is enhanced by the addition of glass fibers to the resin. Ultem is an inexpensive

material that can be injection molded into large shapes, making it an economical choice for the machine.

The paper⁸⁴ by Sondericker and Wolf gives many of the engineering considerations, design tradeoffs, and test results for this noteworthy magnet part. The figure shows a dipole magnet with the support post outlined with darker lines.

Trim Coils, Plated Tubes

The design of the SSC dipole magnets included trim coils on the outside surface of the beam tube as well as copper plating on its inside surface. Brookhaven undertook to develop both these technologies as part of its SSC program.⁸⁵ To produce the tubes, Trent Tube of Troy, MI was chosen because of its experience in producing long Nitronic 40 welded tubing. In collaboration with the BNL Material Sciences Group, a weld, draw, and anneal schedule was developed that yielded permeability variation throughout the tube that was unmeasurable with a ferrite scope at 20°C. The tube size was 17 m in length, OD 1.360", and wall thickness 0.044".

In order to make trim coil windings, located on the tube's surface with the required precision, a technique was adopted wherein the wires of the coils were attached to a flexible substrate based on a Kapton sheet and the substrate then fastened to the surface of the tube with a suitable adhesive. A system of precision cutouts in the sheet and accurately located pillars on the tube's surface was developed for locating the coil on the tube's surface. The many various materials used in this design all had to meet the severe mechanical, electrical, and environmental requirements of the magnet: cycling to and from cryogenic temperatures without failing in their function and the electrical parameters required for energizing the coil, for its quenching, and for inductive voltages from quenches in the main magnet coil. It took a lot of effort to identify acceptable materials. Some items were tested at the Brookhaven Linac Isotope Producer for stability in a radiation environment when their radiation hardness was not known. Improved materials were introduced as they were proven through the course of the program.

To position the superconducting wire on the substrate, an automated technique developed by the Multiwire Division of the Kolmorgan Corporation was adopted. In this technique, a wiring head plays out the wire through a stylus unto a substrate mounted on a moving platen underneath the head. The stylus vibrates at ~25 kHz with sufficient energy to melt a special coating on the substrate that

upon cooling, bonds the wire into position. This technique is capable of fractions of a mil accuracy in the position of the wire, well beyond that needed for this application. Initially capable of wiring substrates up to 24" x 24" in size, the machine was modified at BNL to allow substrates exceeding 10 m in length, and eventually up to 17 m in length. The superconductor used for the trim coils was typically a monofilament wire 8.2 mils in diameter, 9.2 mils including the insulation. It was required to carry 5 A of current in a 6.6 T field, with a safety factor margin of three.

Once the winding had been made, it was fastened to the beam tube with the requisite tooling and permanently fastened into position by passing through a radiant oven where heat sealed all components of the assembly together. The locating bumpers on the surface of the tube ensured that the winding was in proper position and also that the whole beam tube assembly could be accurately located in the magnet. A facility was developed in the empty CBA tunnel to carry out this work.

A variety of windings was produced for the SSC program including sextupole, octupole and decapole windings, some up to the full length of the magnet. The windings in a particular magnet varied according to the program requirements, including three windings in a magnet, and also no trim windings at all in some magnets. The performance of the trim coils made with this technique was generally quite good.⁸⁶

This approach to making trim coils was intensively developed at Brookhaven far beyond the needs of the SSC program and the initial wiring equipment and protocols provided by Kolmorgan and its experts. Please see the Topic, *Printed Circuit Coils*, for its application to RHIC and other projects.

Another SSC specification was that there be a copper coating of good conductivity on the inside of the beam tube. Working with the PCK Company, a plating method was developed that met the requirements. The company used a chemical process to clean, etch, plate, and vacuum dry the tubes as they hung vertically. Resistivity ratios of their tubes were measured at 4.2 K to be >900. Photodesorption outgassing rates were measured to be less than 5×10^{-9} Torr-liters/cm²/sec. Both measured rates met the SSC specification.

Tooling

Various machines were built at BNL to wind magnet coils, to cure and shape them, and to collar them. Additional tooling was built as well: a cable wrapping machine, a beam tube insulating machine, automated yoke-welding machines including hydraulic shell compression, lifting fixtures, automated machines to make printed corrector windings, cryogenic apparatus, measuring probes, and many smaller items.

For SSC coils, which would be 17 m long, a new “shuttle” winding machine was designed and built that was innovative and cost effective: the winding mechanism was kept fixed and the coils were moved and rotated under the fixed winding head. This allowed the precision parts of the machine to stay firmly anchored in position. Of course that required long tables and rollers on either side of the head for the long coil mandrel to shuttle back-and-forth under the head to pick up the cable. The mandrel was a precision part that could later be put into the curing press to “cure” the coil. Precision was needed because the dimensions of the mandrel affect the coil dimensions, and that accuracy was typically specified at 50 microns for the pole size and the diameter.

Before winding the coil, the proper length of cable had to be cut and the cable insulated. Lump detectors were built into the insulating machines to check for wires that may have been displaced in the cable. Such flaws could later cause turn-to-turn shorts in a magnet.

A curing press (shown) was used to mold the coils to a final, fixed size using pressure and heat. The press had a precision-made

cavity (formblock) that shaped the outer dimension of the coil and a “top hat” that could hydraulically compress the turns of the coil to their required position. For the older fiberglass/Kapton cable insulating system, temperatures of $\sim 150^{\circ}\text{C}$ for several hours were required to cure the epoxy. For the newer Kapton CI (all-Kapton) cable insulating system, the required temperature to set the polyimide adhesive was 225°C for several minutes. After curing, hydraulic pressure gauges were routinely used to check the coil’s dimensions on both sides along its full length. This press was a major piece of equipment that required time and a lot of machined pieces to fabricate.

The higher temperature needed for Kapton CI coils required a major upgrade of the oil heating and circulating facility that could efficiently provide the required temperatures in the tooling. Generally, the resulting coils were more uniform than those from the Kapton/FG insulated coils, another benefit, in addition to improved electrical protection, from the Kapton CI design.

A collaring press is used to compress coils so that collars can be installed and fastened around the coils, thereby keeping the collars locked in place. BNL collars for the SSC were stainless steel and were locked with tapered keys hydraulically forced into slots in the collars near the midplane. Vertical pressure upwards of 100

MPa was applied hydraulically with the press. Precision machined surfaces inside the press held the coil assembly in place and ensured that the required 50 microns tolerance in critical areas was maintained. The BNL press was only 2 m long so coils had to be collared incrementally, always leaving a discontinuity in the coil that had to be monitored. The BNL press was a versatile machine well-suited to an R&D program that needed occasional modification in the press geometry and capability. In production, a full length press would have been constructed and would have made the collaring operation less time consuming.

These machines were costly and time-consuming to build, due to their complexity and the precision required in some of their parts. Long lead times were required for major changes before a new magnet design could be built. The time required to build tooling was frequently not understood by observers without experience in magnets.

Weld Alloy

As written by Mike Anerella: Because impact testing of the RHIC cold mass shell welds cannot be carried out at cryogenic temperature, as required by the ASME Boiler and Pressure Vessel code, fracture toughness of the weld needed to be engineered to be well beyond required values. Directed by Steve Kane, experts at BNL and the National Institute of Standards & Technology developed a unique high-nickel, high-nitrogen superaustenitic weld alloy and a welding process that would enhance weldability of the alloy. Welding wire made according to the alloy's specification was purchased at the start of RHIC construction and used for all magnet pressure vessel welds completed at BNL and at Northrop Grumman Corporation. The welds in RHIC magnet helium vessels exceed the fracture toughness requirements imposed by the ASME B&PV code. There are 900 helium pressure vessels in the machine; none have failed in the years that the machine has been in operation.

Yoke

The field in a magnet is significantly affected by the permeability of the steel used in the yoke. This can vary from lot to lot in the steel production process. Of course the permeability decreases as the field in a magnet increases. Field variations can occur from steel placement errors during construction, or from position changes during excitation of the magnet. All these effects must be evaluated and controlled for their effect on field uniformity.

Shuffling of laminations was frequently used in earlier accelerators to randomize yoke-caused field errors in those machines. This was the case for the AGS laminations; the process was laborious and required that all steel laminations be available before the first magnet could be built. Shuffling has not been used for

high field superconducting magnets, where the contributions to the field and therefore the field errors from the yoke are smaller.

Magnet designers must still be mindful of errors in steel placement and from saturation effects. This was carried to an extreme in the Isabelle magnets, where a fear of field errors from variations in yoke closure in a split lamination design led to use of a one-piece yoke lamination. That requirement made yoke assembly impossible in an acceptable way and was one of the most serious deficiencies of that design. Superferric magnet designs, where the field is produced mostly from an iron yoke in an effort to save on the use of costly superconductor, lose their simplicity as the field reaches 3 T due to the need to compensate saturation effects with powered coils. For the higher fields of cos Θ magnets, where the steel becomes highly saturated, yokes can be shaped to minimize field non-uniformities. Gupta has described the techniques used in the RHIC magnets to minimize unwanted harmonics and variation in the allowed multipoles---please see the *Yoke optimization, harmonic corrections* paragraph under *Design* in the section labeled *New Designs & Techniques*, located several pages hence.

The steel yoke in RHIC was designed with an additional and somewhat unusual requirement: that it function as a collar to compress and contain the coils. This meant that the laminations needed a higher elastic modulus than is available in the normal low-carbon steel used in magnet yokes. A Task Force in the MD under G. Morgan studied this problem and developed a specification for steel that could be manufactured at acceptable cost, yet meet the dual magnetic and mechanical requirements.⁸⁷ It came as a surprise that the American steel manufacturers showed little interest in bidding on the order for this steel.

The yoke laminations were punched (fine blanked) from 6.35 mm thick ultra-low-carbon steel plate furnished by the Kawasaki Steel Corporation, Japan. The yield strength of the steel was specified to be no less than 221 MPa, a level achieved through cold-rolling thickness reduction. This allowed the laminations to be pressed onto the coils without significant yielding on the midplane where the forces during collaring are high. To achieve control of the important high-field saturation magnetization (M_s), the chemical composition (impurities) was strictly specified. This control of the chemistry also ensured that important low field parameters like the coercivity H_c remained under control. Measurements on ring samples⁸⁸ and chemical analysis of extracted pieces of the production steel were used to monitor the quality of the steel, but the tight quality control exercised by the company in producing the steel ensured that all the material delivered was of the required accelerator quality.

The laminations had an inner diameter of 119.4 mm and an outer diameter of 266.7 mm. They were pinned together in pairs to allow the yoke elements to act as

collars. To meet the rms tolerances for the magnetic field integrated over the length of the dipoles, it was required that the weight of steel in the yoke be controlled to within 0.07%. To achieve this tolerance, the lamination pairs that make up the yoke were weighed and their number adjusted to meet the weight specification. The selection of yoke pairs for the top and bottom halves was done in such a way that the total weight of the top half was slightly lower than that for the bottom half. This helped to reduce the skew quadrupole field at high fields resulting from the vertically off-centered cold mass in the cryostat. During magnet assembly, a press compressed the yoke around the coils. The yoke was subsequently held together with stainless steel keys hydraulically pushed into notches on the outer circumference. The design preload of 70 MPa acting on the coils was routinely achieved. The yoke laminations extended the full length of the magnet and were not terminated prior to the coil ends as is done in many designs to reduce the field in the mechanically difficult end region of the coils.

New Designs & Techniques

In the course of the magnet development work, numerous new designs and techniques were invented or introduced. They were needed to build and understand magnets, or to turn already existing ideas into viable designs, or to make them more robust or reliable. Many of these are now standard practice in accelerator magnets worldwide (e.g. Kapton CI cable insulation), others are unique to the magnets built at BNL (e.g. high strength steel for yoke laminations). Below is a summary of the most significant of these advances, many of which have been mentioned elsewhere in this account. They are gathered together here and described briefly so that these technological advances can be easily recalled. Based on their functionality, or uniqueness, or value to the project, a number of these items could have been sold for millions had they been commercial products in a consumer or industrial marketplace. Many of them could certainly have been patented had that been the Lab's practice at the time they occurred.

Design

- ***Correction coil, plated bore tubes:*** An early requirement for SSC dipoles was for bore tube windings to correct the magnet's sextupole field component and Cu-plated bore tubes to reduce their resistance to beam-induced image currents. The innovative solutions developed for both these items are discussed in Topics, *Trim Coils, Plated Tubes*.
- ***Cross flow cooling for long magnets:*** SSC magnets of 17 m length and relatively small cross section faced cooling challenges via the proposed forced flow of supercritical helium. The uniform cooldown of the magnets, the required safe cooldown time to avoid stresses from temperature differentials, the recovery from quenches, and the possible heating of the coil from beam radiation or beam spillage all indicated a requirement for directing the helium flow within the magnet. The cross flow cooling scheme designed by Ralph Shutt and Margarita Rehak provided this control. Their careful calculations, and measurements of heat dissipation within the magnet via temperature sensors and heaters, confirmed that the designed system would be effective in controlling magnet temperature excursions.
- ***Curved magnets:*** In order to reduce the required aperture for heavy ion beams in RHIC dipole magnets, the magnets were curved with a sagitta of 47 mm for a 10 m magnet so as to keep beams centered in the magnetic field. Initial studies of possible mechanical damage to a coil, relaxation effects, dimensional changes at cooldown, and other issues gave assurance that this curvature could be safely and consistently included in the magnet design.

- **Dual (2-in-1) magnets:** Advocated for the SSC by Bob Palmer as a way of reducing cost, BNL designed and built a number of such magnets with two side-by-side apertures in a single yoke. These models had two 32 mm apertures and fields of ~6 Teslas in each aperture. They proved to be stable and reliable magnets, and measurements detailed their magnetic behavior regarding cross talk between apertures, effect of unbalanced currents, quench protection issues, etc. The operational versatility of such a design is restricted so they were not chosen for the SSC when such magnets' space requirements and system costs were found to be insufficiently lower compared to those of a single aperture magnet system.
- **High homogeneity (HiHo) superconductor:** The current capacity of early NbTi superconductor was limited to ~1800 A/mm² in the wire strand (Tevatron) but work at several laboratories (e.g. Wisconsin and LBNL) indicated that higher current densities (and finer filaments) were possible if the alloy were more uniformly prepared. For the SSC, the specification became 2750 A/mm² with filament size of 6 microns, both routinely achieved as the program progressed. The higher current capacity allowed higher fields that required changes in magnet design: iron yoke saturation control at higher fields, improved quench protection against higher discharge energies (MIITS), protection against higher voltages at quench, etc. The improved conductor overall had less variability in its performance and offered cost savings by requiring fewer magnets in a machine to reach its specified integral bending and focusing fields.
- **Molded support posts:** Fiberglass straps had previously been used to provide low heat leak support of the cold mass within a cryostat. A set of several support posts would provide a superior method of support if the required strength, long-term stability, and low heat leak specifications could be met. FNAL developed a folded-post design for SSC magnets that could intercept heat at several stations along the post. A less complex post suitable for RHIC using Ultem resin was developed by the Engineering Division under J. Sondericker and consultant L. Wolf. (Please see the Topic, *Support Posts* for more details and references) Extensive testing confirmed its suitability for the job. A virtue of this post was its simplicity---a two-piece structure (allowing heat stationing at liquid nitrogen temperature) forming a simple column had sufficiently low heat leak that the need for a reentrant design to protect the cold mass from room temperature was avoided.
- **Yoke optimization, harmonic corrections:** Various innovative methods have been used by Ramesh Gupta to reduce the effect of yoke saturation

on the field harmonics in a magnet. In related work, Gupta has discussed a variety of schemes to correct the harmonics in magnets that may be found to be not fully optimized after the design is complete and magnets are under construction.⁸⁹

Mechanical

- ***Fine-blanked laminations:*** This is a process for punching laminations of greater precision as compared to those from a typical metal punching operation. The material is held firmly in place both top and bottom and a punch applies high pressure to the defined area so that it undergoes an extrusion rather than a shearing process. The resulting part has clean edges and can be repeatedly made with high accuracy. Though costlier than standard punching of laminations, the process has benefits for the assembled structure in terms of accuracy and parts fit up.
- ***Phenolic spacers for coil-yoke interface:*** In RHIC magnets, where the yoke acts as a collar to prestress the coil, a thick spacer is needed between the outer surface of the coil and the inner surface of the yoke for magnetic field reasons. This spacer is 10 mm thick. Initially a fiberglass composite was machined to act as the spacer, but a more suitable material was needed for production. In consultation with a materials expert from NGC, the recommended material, RX630, a phenolic material, had the required properties of strength, precision molding capability, lack of creep under stress, and good performance at cryogenic temperatures. This material was then also adopted for coil end spacers in the magnet system. Phenolics have superior radiation resistance compared to the epoxy used in fiberglass composites, so that was an added bonus for using this material.
- ***Pinned & spot-welded high strength stainless steel collars:*** Collars to prestress and contain SSC superconducting coils were a major challenge for the program. Their low permeability and high strength requirements, together with the dimensional precision needed, proved a daunting challenge that took years to resolve. Previous collars were unlike those required for SSC: the Tevatron used welded collars that could not be easily disassembled and that had lower operational constraints, and HERA was using aluminum collars for that machine's lower prestress conditions. The precision of the fine-blanking process for punching laminations, even on high strength stainless steel (Nitronic 40), the ability to pin or spot-weld pairs accurately and reproducibly, and the development of the tapered key assembly method all contributed to the success of this collar design. Spot-welding of collars was difficult to accomplish reliably and was mastered for BNL by the company H&J Tooling on Long Island. Tapered keys were

a feature developed by Craig Peters at LBNL. It reduced the over pressure required in the collaring operation

- ***Weld alloy:*** The special alloy developed to weld together the shells of RHIC cold masses solved a difficult problem in the design of the magnets. Normal weld alloy would not meet ASME requirements for fracture toughness at cryogenic temperature, which the code is not well designed to specify in any case. For the solution to this problem, please see the Topic, ***Weld Alloy***. Significant help was provided by Steve Kane, senior project engineer in the BNL Safety & Health Services Division.
- ***Yoke steel collars:*** RHIC magnets were designed to use the steel of the yoke as collars, made possible because of the magnets' single coil layer design, in contrast to the SSC two coil layer design. This proved to be a good and needed cost saving for the project. Using the normal low carbon magnet steel was not feasible because that product does not have sufficient strength to act as a collar. To develop the specifications for a suitable steel alloy that would have the requisite strength after work-hardening by rolling, while at the same time have the required high permeability required in the magnetic design, the MD assembled a Task Force under Gerry Morgan with experts in the mechanics and magnetic properties of steel. Working with industry experts, the specification that emerged was a model of clarity and effectiveness. In the bidding to provide the steel, only a Japanese company offered to produce this formulation; the American vendors had all lost their once-broad capabilities for such a specialty product. The delivered steel turned out to meet all its specifications and is sometimes called "super steel" because of its unusually wide-ranging and versatile combination of strength and magnetic performance.

Electrical

- ***Kapton CI (all-kapton) cable wrap:*** A major issue in superconducting magnets for accelerators is electrical shorts, especially turn-to-turn shorts in the coils of a magnet. Even the occasional short would be devastating for the reliability of a machine in which every magnet must work and the repair time for a shorted magnet is measured in weeks. The Tevatron and the earliest HERA magnets suffered from turn-to-turn shorts as did early SSC models built at BNL. Testing and analysis of those early models revealed serious weakness in the traditional Kapton and fiberglass cable wrap being used to insulate cable turns in the magnet. At the elevated prestress used for SSC coils, needed to cope with the higher magnetic forces, shorts could develop in the insulation along the narrow edge of a keystone cable where the hard fiberglass strands ruptured the underlying

Kapton insulation in an area of peak stress. A new insulation scheme was developed that eliminated fiberglass altogether, and this solved the problem. Working in a collaborative effort with DuPont, that company developed and supplied a modified line of Kapton that contained a mineral filler to reduce creep and a polyimide adhesive to aid in the building of the coils. This improved insulating scheme has proven to be a great advance and is now widely used in the field. Initially it was difficult to gain widespread acceptance for the use of this material, with many skeptics saying “why change what worked in the Tevatron”; the skepticism nearly led to the abandonment of this significant improvement in the reliability of magnets.

- **Quench protection diodes:** Please see the Topic, *Quench Protection* for a description of the RHIC diodes including the design considerations and tests performed to make them a reliable part of the magnet system.

Instrumentation

- **Digital field measurements:** Rotating a multi-turn wire loop in a magnetic field generates a voltage that can be analyzed for the harmonic content of the field. Digitizing this voltage directly with a commercial digital voltmeter 128 times per coil revolution gives unprecedented accuracy and reproducibility of the field harmonics. Previously, using home-built electronics, doubts about amplifier gain settings and digitizer calibrations often comprised the measurements and made them unreliable indicators of magnet field quality.
- **Mole:** The name given to a measuring coil that could be pulled through a long magnet to incrementally measure its field. Made up of a rotating measuring coil driven by air motors that could function in a high field, with sensors to indicate the vertical, and with voltages sent on a wire tether to outside the magnet for digitization, this device became reliable and was widely used in the SSC programs at BNL, FNAL, and SSCL, and by industry, after its development at BNL.
- **Strain gauges:** Developed primarily by Carl Goodzeit and George Ganetis, these devices evolved into a complete package including mounting in special bases and calibration for use in the magnet. For the first time they gave reliable measurements of stress in a compressed superconducting coil under all operating states of the coil, from collaring, to cold, to high field. These gauges provided measurements of coil dynamics that indicated needed changes in design for quench-free magnet behavior. Other strain gauge assemblies, called bullet gauges, were developed for measuring forces and deflections of end supports at the magnet ends (the end force in

the SSC 50 mm dipole at full current is 12 kpsi). These too proved of great value in understanding magnet mechanics under operational conditions.

- *Voltage taps & quench heaters:* A reliable system of instrumentation that could be installed onto the turns of a coil that allowed isolation of weak coil support places where quenches could originate. Up to 128 voltage taps could be installed on one coil, with attendant quench initiation heaters for calibration purposes, and an external array of data recording channels. This system was able to find weaknesses in a magnet design without the previous guesswork and the building of too many models.

Concluding Remarks

Probably no one was more impacted by the DOE's bad choices regarding SSC management than its early champion and first leader Maury Tigner. He had given his heart and soul to that machine and had worked unsparingly to bring it about. He considered it a "great enterprise" and used those words in a thank you note I received from him in December 1988. In that note he thanked me (us at BNL) for "your valuable contributions to this great enterprise". This was shortly after he had learned that he would no longer have a role in building the SSC. What a bitter experience for him, and ultimately for all of us working to build the machine! His kind note gave our work a very human face, which it badly needed in those awful years after Tigner left the project.

In summarizing all the various changes made to the original design of the SSC magnets, a few can be identified as particularly significant. These include much improved superconductor, the spot welding of collars, the full support of the collared coil by the yoke, the robust end restraints in long magnets, and the switch to Kapton CI cable insulation. Once these had been adopted, the magnet design, either the 40 mm version or the 50 mm version, could have been used for building the machine. Other changes were made, refined, and kept if they appeared to improve prestress, harmonics, quench performance, or some other parameter both initially and ongoing through tests, power cycles and thermal cycles. Subtle glitches may be found only after many models have been built, so R&D must continue for an extended period. But whether each change is required cannot be said. This uncertainty may be the case with any complex device, whether an airplane, a car, a stove, a vacuum cleaner. These devices are designed and built based on general principles informed by experience, and flaws are fixed, but it is unlikely that the builders go back and change a working design to find its limits, to see if every nut and bolt is needed in just that configuration. So it is with the magnets. A particular feature of the design is fixed if necessary, but most features are not changed if they appear to work. So no design is ever truly optimized to do its particular job properly, and no more than that. The stellar performance of the latter SSC magnets indicated that a good, reliable design had been achieved in the R&D program.

Regarding RHIC magnets, the same comments can be made. Considering the machine's success since it was commissioned in 2000, those who built it look back with a feeling of pride, relief, and accomplishment. To a new generation it is just a working machine. Not evident are the struggles to build it, nor how it came to be built. In a celebration to mark its 10th anniversary, the work of the builders was not even mentioned.

It is hard to acknowledge who built it, and how. The Internet pioneer Paul Barren said during interviews in 2001 and 1990, *"The Internet is really the work of a thousand people. The process of technological developments is like building a cathedral. Over the course of many years, new people come along and each lays down a block on top of the old foundations, each saying, 'I built a cathedral.' Peter added some stones here, and Paul added a few more there. If you are not careful you can con yourself into believing that you did the most important part. But the reality is that each contribution has to follow onto previous work. Everything is tied to everything else."* Building an accelerator is much like that.

Throughout there are many possible paths to take. Choices have to be made, and those choices result from analyzing the principal elements of each situation. The choices have to be based on certain principles: for magnets, above all electrical integrity, but also mechanical integrity, measurements, cost, time, outside expectations. There is always a question of who to trust, which results are valid, is another group pushing an agenda of its own. No matter the choice, people will be offended, so there will be those who find fault, especially if a choice shows some problem. That is the price of being effective.

Only years later, when the builders have retired, some having perhaps died, can a survivor observe and reflect, as was said in a famous old speech:

*Old men forget: yet all shall be forgot
But he'll remember with advantages,
What feats he did that day.*

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Appendices

Appendix A Definitions

AGS: Alternating Gradient Synchrotron, an accelerator (the first with strong focusing) built at Brookhaven in the early 1960s, still in operation as an injector for RHIC

ANSYS: Name of commercial software for calculating stress/strain and other parameters in mechanical structures

Axion: A hypothetical neutral elementary particle postulated to account for certain conservation laws (CP-conservation) in the Standard Model of strong interactions

B&E: Budget and Expense reports at BNL

BAFO: Best and Final Offer

BBC: Brown, Boveri & Company

BC: Bubble chamber, a detector consisting of a vessel of cold liquid, usually liquid hydrogen, operated so that when its pressure is quickly reduced, particle tracks through the chamber will become visible

BLIP: Brookhaven Linac Isotope Producer

BNL: Brookhaven National Laboratory, also called "Brookhaven", "the Lab" in this account

B-stage epoxy: a system where the reaction between the epoxy and the curing agent is not complete and the epoxy is therefore still a liquid. The epoxy becomes fully cured at a later time when heated to a specified temperature.

CBA - Colliding Beam Accelerator, renamed from ISAbelle when a new magnet design resolved the magnet problems, but cancelled after the delays caused by the previous magnet problems and the desire among physicists to move to the higher energies promised by the SSC

CDG: Central Design Group of the SSC, located in Berkeley, CA

CDR: Conceptual Design Report

CEBAF: Continuous Electron Beam Accelerator Facility located in Newport News, VA, now also called Jefferson Lab (JLAB)

CERN: European Organization for Nuclear Research, located in Geneva, Switzerland

Coil: Used interchangeably in this account for either the basic conductor structure in a $\cos \vartheta$ magnet---a length of superconductor cable wound on a mandrel and formed in a press to the required shape and size (sometimes called a half-coil); two such windings forming the full coil surrounding the beam pipe as in the RHIC magnet; or two full coils, called inner coil and outer coil, in a two-layer magnet, as in the SSC magnet

Cold mass: The central portion of a superconducting magnet that is at cryogenic temperature and that generates a magnetic field when current is passed through its conductor

Cos ϑ coil: A magnet coil in which conductor turns are placed around a magnet's aperture in an approximately $\cos \vartheta$ distribution, with most turns at the midplane and the fewest at the pole

CQS: In RHIC, a welded tube containing corrector, quadrupole, and sextupole magnets in sequence

Cu: Copper

DESY: Deutsches Elektronen-Synchrotron, located in Hamburg, Germany

Dipole: As used in this document, a magnet with a North and South pole, typically used to bend or steer a particle beam

DOE: Department of Energy of the US government

DuPont: A large American chemical company. In the 20th century, DuPont developed Kapton for electrical insulation uses as well as many other polymers such as Vespel, neoprene, nylon, Teflon, Mylar, Kevlar, Nomex. These materials are useful, even necessary, for building magnets and have few alternatives

ESCAR: Experimental Superconducting Accelerator Ring, a project at LBNL to provide experience with superconducting magnets in a small proton synchrotron and storage ring. It ended in 1978.

Final focusing system: see Insertion Magnets

FNAL: Fermi National Accelerator Laboratory, sometimes called simply "Fermi" or "Fermilab"

G10 fiberglass: a type of fiberglass/epoxy building material, available in a variety of geometric forms including sheets, rods, cylinders, etc., used for making strong, non-conducting objects

GAC: Grumman Aircraft Corporation; name changed to NGC, Northrop Grumman Corporation, during the RHIC project

GD: General Dynamics Corporation

Graded conductor: Conductor that has been adjusted for current capacity, for instance by altering the cable width or changing the fraction of superconductor in the cable, usually between inner and outer coils in a two coil magnet design

Harmonic: A term in the Fourier expansion of a magnet's field, other than the fundamental term. This word is used interchangeably with "multipole" in this account

HE(P): High Energy (Physics)

HEPAP: High Energy Physics Advisory Panel

HERA: Hadron-Electron Ring Accelerator, at DESY

High Homogeneity (HiHo): Description of the component mixture in the superconducting alloy NbTi

IISSC: International Industrial Symposium on the SuperCollider. Technical contributions to these (5) conferences were published in volumes labeled Supercollider 1 through Supercollider 5 (the final, 5th conference proceedings volume was not widely distributed)

Insertion Magnets: Magnets to take beams from a collider's regular lattice and bring them into collision, focused to a small spot size, as well as vice versa. Please see additional discussion in the section, **RHIC, Magnet Production at BNL**

Isabelle: Intersecting Storage-ring Accelerator, a proton-proton collider planned for construction at Brookhaven, which encountered serious magnet problems (see CBA)

Kapton: A polyimide film developed by DuPont, which has excellent electrical insulation properties and which remains flexible at cryogenic temperatures

LARP: LHC Accelerator Research Program, currently developing upgrades for the LHC

LBNL: Lawrence Berkeley National Laboratory (earlier, LBL), or simply "Berkeley"

LHC: Large Hadron Collider, located at CERN in Geneva, Switzerland

Lorentz force: The force on a current-carrying conductor in a magnetic field

MAC: Machine Advisory Committee at the SSCL

MD: Magnet Division at Brookhaven in this account

MDN: Magnet Division Note

MIITS: Units of energy, used to describe the energy deposited in a magnet during a quench; literally, millions of squared current multiplied by time ($I^2 \cdot t$) units

Mole: Field measuring device for long magnets, developed at Brookhaven, that could fit into small diameter SSC magnets and make incremental measurements

MPAP: Magnet Program Advisory Panel, appointed by SSC leadership to consider the direction of the early magnet program

MPS: MultiParticle Spectrometer, a large electronic detector facility built and used for particle experiments at the AGS in the 1970's and 1980's

MSIM: Magnet Systems Integration Meeting---organized to allow the different labs working on SSC cos θ magnets to coordinate their work

MT: Magnet Technology conference

Multipole: Please see "Harmonic"

Multiwire: A subsidiary of the Kolmorgan Corporation that made a machine that fabricated computer point-to-point wiring layouts. Their technique, also called Multiwire, was adapted by the company's expert John Schreiber and the MD to make RHIC corrector magnets

Nb₃Sn: Niobium Tin superconducting alloy

NbTi: Niobium Titanium superconducting alloy

NEEW: New England Electric Wire Company

NGC: Northrop Grumman Corporation, see also GAC

NIM: Nuclear Instrumentation & Methods, a journal

NSAC: Nuclear Science Advisory Committee

NSLS: National Synchrotron Light Source at Brookhaven, replaced in recent years by a new machine named NSLS II

PAC: Particle Accelerator Conference

PC: Personal computer

PPM: Parts per million

Prepreg: Fiberglass cloth impregnated with B-stage epoxy

Pre-reacted: A term applied to Nb₃Sn conductor that has undergone a heat treatment before being used to build magnet coils

Quadrupole: A four pole magnet used to focus beams. The strength of the field increases in proportion to the distance from the center. The focusing is in one plane

only. In the other plane, the field is defocusing. Quadrupoles can be wired to be horizontally focusing (vertically defocusing) or horizontally defocusing (vertically focusing). As discovered by Ernest Courant and colleagues at Brookhaven, several quadrupoles in succession can focus in both planes. This surprising result enabled accelerators to reach high energies without large (and costly) apertures, first demonstrated in the BNL AGS and the CERN PS

Quench: A sudden transition from the superconducting state to the normal, resistive state in a current-carrying conductor, marked by a rapid increase in resistance as the quench spreads from its point of origin to the rest of the conductor

R&D: Research & Development

RDS: Reference Design Study, the initial SSC plan, prepared and published in 1984

RFP: Request for Proposal

RHIC: Relativistic Heavy Ion Collider at Brookhaven, began construction in 1991, began operations in 2000

RIKEN: Japanese research laboratory, which generously supported and continues to support the Spin program at RHIC, and funded the helical magnet development and construction

Rotator: see Snake. A Rotator is a set of magnets designed to rotate the normally vertical spin of a polarized proton beam into the beam direction before colliding the beam with the opposing beam in a detector

RX630: phenolic material brand name, used for coil-yoke spacers in the RHIC magnets

SC: Superconductor

Snake: A term coined by Y.S. Derbenev and A. Kondralenko at the Institute of Nuclear Physics in Novosibirsk, the (Siberian) Snake is a device inserted into the lattice of a circular accelerator or collider to avoid depolarizing resonances by rotating the spin axis of a proton in a prescribed way, usually up-to-down or vv., thereby preserving the polarization of a proton beam during acceleration and storage. The name originates from the snake-like trajectory of a proton in the device; it was first described at the Russian accelerator institute in Novosibirsk, Siberia

SOI: Subject of Interest

SSC: Superconducting SuperCollider, cancelled by Congress in 1993; its physical infrastructure in Texas was about 20% complete

SSCL: SSC Lab in Texas

Standard Model: In particle physics, a theory combining the strong, weak, and electromagnetic forces into a single, inclusive description

Superferric: A magnet in which an iron yoke dominates the strength and shape of the magnetic field

TAC: Texas Accelerator Center, organized in 1984 to participate in the construction of the SSC

Tangential Coils: Magnetic field measuring coils in which the field detection windings are on the surface of a rotating cylinder

TAP: Technical Advisory Panel, a group formed by the Magnet Division of the SSCL to consider the technical aspects of magnets needed for that machine

Tevatron: A proton-antiproton collider at FNAL, the first to successfully use superconducting magnets on a large scale. Beam energies of 900 GeV and collisions of 1.8 TeV were first achieved in late 1986. This machine firmly established that a superconducting magnet machine could operate reliably and even be operationally more stable than a room temperature machine. After the Tevatron, three other machines using such magnets have been built; HERA at DESY, RHIC at BNL, and LHC at CERN. The latter two are currently in operation

TF: Task Force

Training: In superconducting magnets, the process by which a magnet reaches its current limit as determined by lab measurement of the conductor (short sample test). Please see the Topic, *Superconductor Studies in the Lab*

Ultem: polyetherimide plastic brand name

USPAS: US Particle Accelerator School

WEC: Westinghouse Electric Corporation

WIMPS: Weakly Interacting Massive Particles, hypothesized in the Standard Model but not found to date in nature

Appendix B Group Pictures

Magnet Division staff surrounding the first 17 m SSC cold mass before shipment to FNAL for cryogenic testing, April 23, 1986

SSC staff gathered at FNAL for a program meeting, shown with a 17 m magnet on test stand, May 6, 1988. Front row: Tom Nicol, Bob Wands, John Peoples, Carl Goodzeit, Ned Goldwasser, Bob Schermer, Erich Willen, Mike Chapman, Darryl Orris, Branko Berkes, NI. Between magnets: John Tompkins, Jack Peterson, Peter Mazur, Roger Coombes, Ken Mirk, Paul Mantsch, Jim Strait, Parke Rohrer, Clyde Taylor, NI, Maury Tigner, Peter Wanderer, NI, Juris Kaugerts, NI, Per Dahl, Max Zaslavsky, Craig Peters. Behind back magnet on left: Moyses Kushner.

Inaugural meeting at Brookhaven in August 1988 to introduce industry to the SSC project and to suggest ways for companies to become involved in building the machine. From left: Erich Willen, Robert Diebold, Ned Goldwasser, Nick Samios, Tom Kirk, Roger Coombes, Marty Blume, NI, Robert Hughes, Maury Tigner, John Peoples, Parke Rohrer, Ken Mirk.

Magnet Division staff who hosted the SSC magnet industrialization meeting at Brookhaven where companies received information and toured MD construction facilities for a week in January 1989. L to R, 1st row: Diana Votruba, Bob Hoade, Mike Anerella, George Sintchak, Chris Harbach, Cynthia Murphy. 2nd row: Audrey Blake, Vera Mott, John Skaritka. 3rd row: Carl Goodzeit, Tony Meade, Yuri Elisman, Steve Plate, Morris Shapiro, Gene Kelly. 4th & 5th rows: John Cozzolino, Charlie Briening, Alan Morgillo, NI, Bob Gottschalk, Art Greene, Dean Ince, Bob Kehl, Gary Cottingham, Bill Sandhoff, Erich Willen.

Magnet Division and RHIC staff who hosted the RHIC industrialization meeting in November 1990

Magnet Division and RHIC staff celebrating the delivery of the first RHIC dipole magnet built by Northrop Grumman Corporation, May 1994

Gathering of Magnet Division and Project staff in recognition of the first Snake assembly in the BNL/RIKEN spin project, July 1999

Magnet Division including some Project staff on the occasion of the completion of the final Rotator for RHIC, May 2002

Building magnets for the CERN LHC: the top picture (Aug 2002) shows Magnet Division and support staff in front of the shipping container for D1, the bottom picture (Feb 2003) shows MD and CERN staff at CERN confirming its safe delivery. L to R: Ranko Ostijic (CERN), Erich Willen (BNL), John Cozzolino (BNL), Jessie Schmalzle (BNL), Ed Killian (BNL), Andrzej Siemko (CERN).

Appendix C Staff

This partial listing of names identifies professional staff of the Magnet Division during the years 1980 through 1995, more or less, when the activities described in this account took place. A few other individuals are included as well, not in any systematic way, but who may have had a particular connection with those activities. The work ascribed to each individual is very abbreviated; most MD colleagues worked on a wider range of activities than those listed. All contributed to discussions, investigations, and understanding of magnet construction and performance issues.

Anerella, Mike: Mechanical Engineer; currently Chief Mechanical Engineer in the Magnet Division; oversight of magnet construction activities at BNL and at NGC. His daily observations of the work flow led to numerous improvements in the magnets over the years.

Bagley, Greg: Electrical Engineer; power supplies

Ball (previously Baggett), Millicent (Penny): Physicist; database development; software advisor to staff; moved to SSCL in 1990; with DOE funding, she and her colleagues developed and marketed a CD-ROM tutorial describing the design, engineering, and building of superconducting magnets

Chu, Paul: Mechanical Engineer; tooling design

Cornish, George: Software Engineer; instrumentation controls for curing press, winder, test facility, Hall probes

Cottingham, Gary: Electrical Engineer; veteran of earlier BNL accelerators; early Head of Electrical Section; power supply oversight; planning for quench protection

Cozzolino, John: Mechanical Engineer; yoke fabrication design; materials specifications; insertion magnets; LHC magnets

Dahl, Per: Physicist; veteran of earlier BNL accelerator work; magnet design questions; documentation; source for historic knowledge of BNL accelerators and their circumstances. Moved to the CDG in 1987.

Danby, Gordon: Physicist on AGS staff; experienced designer of AGS beam line magnets in the early days of that machine; favored iron-dominated magnets for Isabelle and RHIC; co-originator of MAGLEV train concept

Elisman, Yuri: Mechanical Engineer; design and fabrication of coil tooling; work planning

Escallier, John: Electrical Engineer; winding and testing of correction coils including the fabrication machinery for those windings; RHIC quench protection diodes

Foelsche, Horst: Physicist from Accelerator Department; briefly, Head of Magnet Division, late 1993 and 1994

Forsyth, Eric: Electrical Engineer; formerly Head of the Superconducting Transmission Line project, Head of Accelerator Development Department (ADD) May 1986 through June 1990; administrative supervisor of Magnet Division 1986 and part of 1987

Ganetis, George: Electrical Engineer; Head of Electrical Systems Section after Cottingham; a person of unusual zeal, thoughtfulness and insight, Ganetis was instrumental in the solution of numerous magnet performance issues and developed many new instrumentation, electronic, and electrical approaches; quench protection issues; diode quench protection for RHIC magnets

Garber, Meyer: Physicist; expert in superconductor performance issues; short sample measurements

Gardner, Don: Mechanical Engineer; construction of early magnet measuring coils; cold bore tubes

Ghosh, Arup: Physicist; expert in superconductor performance issues

Goodzeit, Carl: Mechanical Engineer, Deputy Division Head; analysis of mechanical structures, strain gauge development, initial RHIC cost estimates and WBS spreadsheets; moved to SSCL beginning late 1989

Grandinetti, Russ: Production Engineer; apparatus construction; magnet setup and removal

Greene, Art: Physicist; oversight of Isabelle quadrupole program; oversight of SSC and RHIC coil construction; BNL leader in procurement of improved superconductor; organizer of RHIC superconductor procurement, testing and data base; briefly MD head 1994

Gupta, Ramesh: Physicist; design of magnets for magnetic field quality, strength, physical characteristics; innovations to set and achieve new project goals

Hahn, Harald: Accelerator Physicist; active in Isabelle project; planning for RHIC lattice and machine parameters; RHIC RF system oversight

Harrison, Mike: Physicist; RHIC Associate Project Head, responsible for completion and commissioning of the RHIC Collider system; appointed effective 8/1/1991; later, MD Head in parallel

Herrera, John: Physicist; accelerator physicist; mathematical analysis; new measuring coil implementation, measurements analysis, accelerator physics issues

Hogue, Richard: Programmer; on line analysis of measurement coil data

Jain, Animesh: Physicist; field measurements and data analysis; database containing all RHIC and other magnet data; analytic analysis of errors, trends, measuring apparatus development and performance; numerous presentations of data and its meaning to machine scientists and engineers

Joshi, Piyush: Electrical Engineer; trim power supplies; warm up heaters; machine control and instrumentation

Kahn, Steve: Physicist; magnet coil and yoke design; analysis of collared coil cookies

Kane, Steve: Project Engineer, Safety & Health Sciences Division; assigned to RHIC as a systems safety engineer; provided significant help (unusual for a safety engineer but very welcome) to the Magnet Division in the development of a special weld alloy and welding protocol used to weld cold masses (please see Topic, ***Weld Alloy***); died in a tragic bicycle accident in 2012 caused by a motorist on the wrong side of the road

Kelly, Gene: Production Engineer; Head of Production Engineering Section; also supervisor of the Design Room; Central Shops liaison; work planning; floor layout and work flow planning

Kern, Stuart: Software Engineer; data base-related activities; MRP systems; record keeping and securing; off-line software

Killian, Ed: Mechanical Engineer; project engineering; expediting of shop work; review of design room drawings; LHC magnets

Kirk, Harold: Physicist; field measurement data analysis for Isabelle, CBA, early SSC

Kovach, Paul: Designer Engineer; transportation and support structures, cryostats, power leads and electrical interfaces, mechanical structures and tooling of numerous designs, shapes, and uses

Lambiase, Richard: Electrical Engineer; power supplies

Lee, S.Y.: Accelerator Physicist; frequent discussions and interaction with MD regarding preferable magnet configurations for RHIC; final RHIC lattice

LeRoy, Bob: Mechanical Engineer; analysis and design of collars for SSC

Lindner, Mel: Mechanical Engineer; engineering of sextupole, corrector magnets

Louie, Wing: Electrical Engineer; quench protection system; design and proofing of specialized controls for machinery and equipment; data collection for magnetic measurements

Louttit, Bob: Physicist; CBA magnet program; cryogenic systems oversight; supervision of MD program through start of SSC work

Marone, Andy: Mole, transporter design; warm beam tube design, helical magnet

McChesney, David: Programmer; developer of RHIC and MD data bases

Meade, Tony: Mechanical Engineer; oversight project engineering; Deputy Section Head

Morgan, Gerry: Physicist; magnet design including cross sections, end designs, yoke; steel specification for RHIC

Morgillo, Alan: Mechanical Engineer; oversight of coil construction

Mulhall, Steve: Mechanical Engineer; dipole yoke and containment design and assembly; leads; welding

Muratore, Joe: Physicist; cryogenic testing and measurements of magnets

Ozaki, Satoshi: Physicist; RHIC Project Head from late 1989; primarily involved with non-magnet machine issues, administrative matters and interactions with the DOE

Palmer, Robert: Physicist; instigator of the CBA magnet, MD Head with Shutt; imaginative proposals for magnet designs including: 2-in-1 magnets, required beam aperture, useful design improvements; Chief Magnet Scientist at the SSCL for several years

Plate, Steve: Mechanical Engineer; interconnect designs; bellows design; design of diode mechanical assembly, gas cooled leads; beam position monitors; oversight of BNL/CERN magnet interfaces; AGS helical magnet

Prodell, Al: Physicist; expertise in former BNL superconducting magnet programs including those for Bubble Chamber; material properties at cryogenic temperatures; oversight of cryogenic systems for magnet testing

Reardon, Paul: Physicist; Associate Director for High Energy Physics October 1982 through 1986; SSCL Project Manager 1989; had worked at FNAL on the Tevatron, in particular obtaining the superconductor and the cable needed for the machine; Associate Director at FNAL; Associate Director at Princeton Plasma Physics Laboratory

Rehak, Marguerita: Engineering Physicist; collaborator with Ralph Shutt on cross flow cooling for SSC; calculation of SSC magnet cooling and temperature distributions; bellows design

Rohrer, E. Parke: Associate Director for Management and Physical Plant; Magnet Division oversight and active participant in its work

Rufer, Charles: visiting engineer from CERN; studied the coordinate specifications of the RHIC lattice and found significant errors which, if not corrected, would have prevented closure of the rings, and which were causing errors in the computer simulations of beams in the machine

Sampson, Bill: Physicist; Head of the Superconductor Materials R&D Section; expertise in superconductor performance; numerous innovative measurement of SC behavior; short sample test facility

Schieber, Len: Mechanical Engineer; Multiwire coil fabrication; manufacturing engineering

Schmalzle, Jesse: Mechanical Engineer; engineering support for the overall magnet construction effort; document of the measurements made on magnets under construction; testing of cable insulation; collaring, sizing of coils; LHC magnets

Schneider, Bill: Mechanical Engineer; Deputy Head, Production Group; guidance of daily production activities; written reports; presentations at SSC meetings

Schultheiss, Carl: Electrical Engineer; instrumentation; power supplies

Shapiro, Morris: Mechanical Engineer; coil fabrication

Shutt, Ralph: Physicist; initially, with Palmer, Head of the MD; continuing interest and work in questions related to mechanics of the magnet at cooldown and at high fields, magnet cooling, bellows design; participant with Vernon Hughes in the design of the new BNL muon g-2 experiment. In his later years, Shutt was fond of coming around to talk of his life experiences, his take on events and on people and their ways, his likes and dislikes, even back to his days as a student in Berlin in the 1930's studying music and physics. Especially after the tragic death of his wife Reba in a car accident, and the later reconciliation and marriage to his prewar friend Ursula in Germany, he spoke freely and with thoughtful insight of people,

places, and events. Perhaps our common German heritage motivated him, or maybe my ability to speak German with Ursula---their tales as they told them could fill many pages. For instance, her successful efforts to keep Shutt's Jewish mother from certain death at the hands of the regime in WWII is an amazing account. Their stories are both comical and heartbreaking, some tragic, always interesting about their lives in the turbulent 20th century in Germany and America.

Sintchak, George: Electrical Engineer; calibrations; fabrication and testing of assemblies and magnets

Skaritka, John: Mechanical Engineer; fabrication of the Mole; bore tube correctors for long SSC magnets; copper-plating of beam tubes; printed circuit correction coils for RHIC using the Multiwire process

Stokes, Bill: Design Engineer; Tooling; Booster magnet engineering and construction

Sylvester, Cosmore: Mechanical Engineer; magnet measuring coils, worked with Don Gardner as a team in designing and building coils

Thomas, Richard: Physicist Programmer; code for magnet measurements control room computers, other data collection systems including those for control of Mole

Thompson, Pat: Physicist; initial designs of the RHIC magnets, software and designs for RHIC corrector coils; software to control machines that made such coils

Wanderer, Peter: Physicist: Head of Magnet Testing & Measuring Section; analysis and interpretation of magnet performance; correlation with design; circulation of results; frequent participant in Magnet Reviews to explain status of magnets and their performance; currently Head of the Magnet Division

Wild, Tom: Computer Software Engineer; Control Room computer system

Willen, Erich: Physicist; Magnet Division Head for SSC and RHIC programs; magnet measuring equipment; magnet performance; helical magnets, LHC magnets

Wu, K.C.: Cryogenic engineer; Magcool operations, upgrades and repairs; lead and feed-thru design; flow rate calculations

Zhao, G.: Electrical Engineer; veteran of HERA project; incoming magnet inspection; in-house magnet inspection

Appendix D MD Employees in April 1991

Administration

Sci & Prof
 * Willen, EH
 Admin
 Birkholz, WH
 Blake, AL
 Licari, JJ
 Mott, VM
 Murphy, CA
 Trojanowski, B
 Votruba, DM

Analysis

Sci & Prof
 * Shutt, RP
 Greene, AF
 Gupta, RC
 Kahn, SA
 Morgan, GH
 Rehak, ML
 Thompson, PA

Electrical Systems

Sci & Prof
 * Ganetis, GL
 Bagley, GP
 Cottingham, JG
 Joshi, PN
 Lambiase, RF
 Schultheiss, CM
 Sintchak, GF
 Zhao, G

Techs-Elec

* Harbach, CH
 Azzara, BJ
 Bell, SA
 Cattaneo, DR
 Conte, RA
 Dimaiuta, SA
 Ferdinand, RJ
 Fleming, TE
 Jiggetts, L
 Kurz, RF
 Mccaffrey, JW
 Meier, RE
 Nolan, TM
 Oldham, DJ
 Ribaud, PJ
 Weigand, EG
 Weih, N
 Wood, DD

Mag Test & Meas

Sci & Prof
 * Wanderer, PJ
 Cornish, GW
 Hogue, RW
 Kern, SH
 Mc Chesney, DD
 Muratore, JF
 Prodel, AG
 Thomas, RA
 Wild, TA

Techs-Meas

Biggs, JC
 Carapezza, WJ
 Casanas, E
 Cetero, FA
 Cintorino, JJ
 Gottschalk, RB
 Howard, RT
 Karpen, B
 Kuczewski, P
 Lehn, T
 Mc Neil, JP
 Saurwald, A
 Smith, BA
 Sullivan, DP
 Viotto, AL
 Williams, MD

SUPERCON MAT R&D

Sci & Prof
 * Sampson, WB
 Garber, M
 Ghosh, AK

Techs-Meas

Robins, KE
 Avent, CS
 Dambra, JA
 Kristiansen, WK
 Ostheimer, EA
 Sperry, ED

Production Engineering

Sci & Prof
 * Kelly, ER
 Anerella, MD
 Chu, P
 Cozzolino, JP
 Elisman, YL
 Grandinetti, RA
 Killian, E
 Lindner, M
 Marone, A

Meade, AP

Morgillo, AA
 Mulhall, S
 Plate, SR
 Shapiro, ML
 Stokes, WL
 Techs-Mech
 * Kehl, RC
 Boyle, G
 Bubka, SJ
 Ceruti, RB
 Dabrowski, CM
 Dilgen, TF
 Ince, DB
 Jackimowicz, RM
 Jochen, GH
 Kowalski, R
 La Bounty, JJ
 Mayman, CJ
 Mc Clusky, R
 Mc Keon, WF
 Milidantri, DJ
 Mottl, PJ
 Norden, DA
 Otten, RJ
 Sandhoff, WF
 Schiappa, DA
 Skidmore, FX
 Stone, ME
 Strelecki, HW
 Themann, WO
 Todd, RJ
 Tradeski, JW
 Ulrich, EJ
 Van Deroef, H
 Van Winckel, TR
 Vitkun, KW
 Vogt, BC
 Welcome, LM

Designers

* Briening, C
 Cuccia, JR
 Doyle, WH
 Mazzola, A
 Mcneill, HR
 Meier, RS
 Morton, KG
 Power, KA
 Rogers, EW
 Russo, LR
 Witbeck, GJ

Contract Employees

Designers

Andolfi, A
 Cooney, D
 Duffin, R
 Guarino, C
 Klein, J
 Massimo, J
 Miceli, J
 Montemagno, A
 Muller, C
 Schulze, V
 Sullivan, R
 Thomas, N
 Toner, J
 Unz, F
 Weiner, R
 Yonkers, A

Techs-Elec

Bolotine, M
 Gormley, J
 Goudikian, L
 Luneberg, J
 Mc Carty, R
 Meade, G
 Posha, D
 Sollowen, A

Techs-Mech

Carapezza, D
 De La Parra, C
 Foster, S
 Gonzoles, R
 Harris, P
 Hoade, R
 Jones, K
 Kuhnle, W
 Morrow, M
 Mott, D
 Sexton, K
 Swenson, W
 Vogel, K
 Weiner, J

* Head or Supervisor

End Notes

¹ This account is meant to be a description of the work done to build magnets at BNL and the results of that work. It is too limited to be considered comprehensive as a technical description of the magnets. Fortunately, many of the results of magnet tests, magnet performance, and the supporting effort for the described magnet program have been documented in internal reports and summarized in contributions to technical meetings and symposia, many published. For instance, magnets were usually tested at operating temperature and many files of data were collected and summarized in such reports, including quench performance, details of magnetic fields, strain gauge data, etc. The Magnet Division maintains a data base where most of this information can be found.

² A summary of all RHIC data runs, which began in the year 2000, can be found at <http://www.agsrhichome.bnl.gov/RHIC/Runs/>

³ S. Wojcicki, *The Supercollider: The Pre-Texas Days and The Supercollider: The Texas Days*, Reviews of Accelerator Science and Technology, Vol. 1 (2008) and Vol. 2 (2009). These excellent accounts give a comprehensive overview of the SSC project though they perforce miss much of the detailed effort and interactive endeavor that characterized the technical work. References to other accounts can be found in the Wojcicki volumes. Other accounts have appeared in the years since then.

⁴ <https://www.bnl.gov/magnets/Staff/Gupta/scmag-course/index.htm> This reference is to various US Particle Accelerator Schools, in particular the 2001 School held at Rice University in Houston.

⁵ M. Harrison, et al., Special Issue: The Relativistic Heavy Ion Collider Project: RHIC and its Detectors, *Nuclear Instruments and Methods in Physics Research A*, 499, 2003

⁶ The Isabelle/CBA saga is well described by R. Crease, *Phys. perspect.* 7 (2005) 404–452

⁷ A.D. McInturff, W.B. Sampson, K.E. Robins, P.F. Dahl, R. Damm, Prototypes and Proposed Isabelle Dipoles, *IEEE Trans. Nuc. Sci.*, NS-24, 3, June 1977

⁸ Dahl, P.F., The SSC Dipole: Its Conceptual Origin and Early Design History, *SSCL-320*, June 1990. Parts of this narrative on the SSC through the year 1990 are taken from, and additional detail is available in, this valuable account written by Per Dahl, a member of the magnet group at BNL through 1987 and then a physicist at the CDG in Berkeley

⁹ The eventual success of this superconductor improvement effort is recounted in a later paper: R. Scanlan, The Evolution of Tooling, Techniques, and Quality Control for Accelerator Dipole Magnet Cables, *Applied Superconductivity Conference*, Chicago, August 1992 and LBL-32635

¹⁰ E.H. Willen, *SSC Magnets with Niobium-Tin*, *SSC-TN-13*, April 1984

¹¹ P. Dahl, et. al., Performance of Four 4.5 m Two-in-One Superconducting R&D Dipoles for the SSC, *PAC85*, October 1985 and BNL-36627

¹² This result was reported by me at the Snowmass Summer Study in 1984---the first and only time I ever received applause while talking about magnets

¹³ Final BNL RHIC B&E report, dated September 1997

¹⁴ I was asked to help with the RDS and over a period of 3-4 weeks at the CDG in Berkeley wrote the sections of the report describing the proposed (high field) magnets.

This was the first of numerous trips by my colleagues and me to CDG for SSC work over the next few years. While in Berkeley, most of us stayed at the Hotel Durant on Durant Ave., not far from the lab. Bob Louttit preferred to stay at a motel on University Ave where he had stayed in the past for experiments on the LBNL Bubble Chamber. One night, there was some altercation at that motel and gun fire rang out. Louttit dived under his bed and was safe, but got little sleep that night. He moved the next day to a lodging on Shattuck Ave

¹⁵ A uniform field is important for beam stability in an accelerator. The first important non-linearity in a dipole magnet is a sextupole field, which increases in strength with the square of the coil radius. Therefore, a larger coil radius will naturally have a more uniform field at small radii, other things being equal

¹⁶ Please see *Collars* in the Topics section

¹⁷ Please see *Trim Coils, Plated Tubes* in the Topics section

¹⁸ The design and construction details of this initial series of long SSC magnets is described in P. Dahl et. al., Construction of Cold Mass Assembly for Full Length Dipoles for the SSC Accelerator, IEEE Trans. Mag., Mag-23, 2, March 1987 and BNL-38852

¹⁹ Please see Topics, *Magnet Failure: DD000Z* for some of the repercussions of this incident

²⁰ Again, please see Topics, *Magnet Failure: DD000Z*. The Review Committee's 60-page report gives a good snapshot of the methods and materials being used and the technical issues facing the engineers and technicians including the uncertainties and incomplete designs with which they coped in this leading edge work

²¹ The following papers give a good description of construction features of the magnets and the results of testing the magnets:

J. Tompkins et. al., Performance of Full-Length SSC Model Dipoles: Results from 1988 Tests, Supercollider 1, New Orleans, 1989, p. 33, and SSC-217

E. Willen et. al., Design Features of the SSC Dipole Magnet, 14th Intl. Conf. on HE Accel., Tsukuba, Japan, August 1989 and BNL-43285

²² J. Kuzminsky et. al., Test Results of 40 mm Aperture, 17-m long SSC Model Collider Dipole Magnets, MT12, Leningrad, June 1991 and SSCL-492

²³ P. Wanderer et. al., Results of Magnetic Field Measurements of 40 mm Aperture 17-m Long SSC Model Collider Dipole Magnets, MT12, Leningrad, June, 1991 and BNL-46738

²⁴ A. Devred et al., About the Mechanics of SSC Dipole Prototypes, AIP Conf. Proc. **249**, 1309 (1992) and SSCL-Preprint-006. This account includes pictures of the large tooling used at BNL to build the magnets

²⁵ Claus Rode in Cold Facts, 26, 2, Spring 2010, reviewing the book: L. Hoddeson, A. Kolb, C. Westfall, Fermilab---Physics, the Frontier & Megascience, Univ. of Chicago Press, Chicago, 2008

²⁶ Technology was changing rapidly in the 1980s with the advent of personal computers. At that time, central computers running Fortran were in heavy use for designing magnets, for analyzing data, or for storing data. Jobs were submitted with decks of cards, since those operating systems could not be engaged with remote terminals. Time sharing, now ubiquitous, was available on only a few computers. Physicists and engineers employing differential equations and using desk calculators solved numerical problems. Graph paper of all types was in plentiful supply. Small laboratory computers were widely used for

controlling equipment and for collecting data in the lab, in particular VAX machines made by DEC (Digital Equipment Corporation). Networks for sending data to another building were mostly home-made at BNL. Cell phones did not exist. Word processing was in its infancy; papers were typed by secretaries on typewriters. They often had to make carbon copies, even though Xerox copiers were widely available. Diagrams and figures for papers to be published were drawn according to strict professional standards by dedicated draftsmen/women, a service the Lab provided for a fee. In the MD, a room full of draftsmen/women working at drafting tables using pencil and paper was required to make all the engineering drawings required by Central Shops or outside vendors to fabricate parts. At meetings, talks were given using transparencies made by hand or Xeroxed pages. This all began to change as small but increasingly powerful computers and workstations became available; today few of the old methods remain.

²⁷ Please see the Topic, *SSC Project Failure* for more commentary on this subject

²⁸ R.C. Gupta, S.A. Kahn, G.H. Morgan, SSC 50mm Dipole Cross Section, Supercollider 3, Atlanta, March 1991, p. 587 and BNL-45290

²⁹ J. Muratore et. al., Construction and Test Results from 1.8 m-Long, 50 mm Aperture SSC Model Collider Dipoles, Supercollider 4, Atlanta, March 1991 and BNL-47852 and SSCL-Preprint-94

³⁰ Goodzeit et al. (SSCL), Anerella et al. (BNL), Cold Mass Mechanical Design, Quench and Mechanical Test Results for Full Length 50 mm Aperture SSC Model Dipoles Built at BNL, SSCL-Preprint-140, July 1992 and BNL-49401

³¹ P. Wanderer, Partial Lifetime Test of an SSC Collider Dipole, MT13, Victoria, BC, Canada, September 1993 and BNL-49325

³² H. Hahn, RHIC Magnet Design Study, RHIC-PG-9, November 1983. This paper first listed the basic machine parameters, labeled "tentative", as follows for beam energy 100 GeV: dipole field 3.3 T, 20:1 energy range, ring energy ratio 2.5:1, magnet aperture 3", magnet length 4.4 m. Several months earlier, there had been a Task Force at BNL that considered physics goals for the developing interest in heavy ion physics and general machine requirements to accomplish those goals: Report of Task Force for Relativistic Heavy Ion Physics, T. Ludlam & A. Schwarzschild, Editors, August 30, 1983, RHIC-PH-1 and BNL-101397. Additional discussions and work led to the parameters finally used for the machine design.

³³ P. Thompson, Calculated Performance RH-BNL-X1, MDN-119-16, January 10, 1985
S.R. Plate, Mechanical Construction of RHIC X1 (Quick RHIC), MDN-121-16, February 19, 1985

³⁴ Magnet Measurements, RHIC001 (RHIC BNL X1), TMG-333, June 1985

³⁵ P. Thompson, Predicted Performance RHX-BBC, MDN-100-16, October 5, 1984

Quench performance can be found in: P.A. Thompson et. al., Status of Magnet System for RHIC, 2nd Conf. on the Intersect. Between Part. & Nuc. Phys, Lake Louise, Canada, May 1986 and BNL-38459

³⁶ P. Wanderer, Comparison of Measurement and Prediction for RHIC Dipole DRS001, MDN-183-11, April 1986

³⁷ P. Wanderer et. al., Successful Test of SC Dipoles for RHIC at BNL, Part. Accel. 22(1987) and BNL-39922

P. Dahl et. al., Performance of Initial Full-Length RHIC Dipoles, 10th Int. Conf. on Mag. Tech., Boston, September 1987 and BNL-40545

P. Thompson et. al., SC Magnet Designs for the SSC and RHIC, 2nd Annual Conf. on Superconductivity and Applications, Buffalo, April 1988 and BNL-41349

³⁸ A "Temple Review" was a thorough review of a proposed new project by a committee of cognizant individuals appointed by DOE and chaired at that time by Dr. L. Edward Temple. This particular review was requested by Dr. David Hendrie, Director of DOE's Division of Nuclear Physics, Office of Energy Research. Temple was Director of Construction, Environment, and Safety at DOE. The committee was requested to "perform an assessment of RHIC's technical objectives and scope cost, schedule and management as well as to evaluate its readiness for inclusion in the FY 1989 Congressional Budget Request." Beyond these assessments, the committee was asked to "make recommendations regarding the project's scope, cost and schedule baselines." A review of this type was taken quite seriously at BNL, for Temple had a reputation as a stern taskmaster who demanded thorough, logical and technical presentations. He lived up to this reputation at BNL and was fair and knowledgeable; it was stressful but ultimately rewarding to go through one of his reviews. These reviews were in later years ably conducted by his deputy Dr. Daniel Lehman, beginning in 1991.

³⁹ M. Anerella, Creep Measurements on RX630 Insulators from 4.5 m RHIC Magnet DRS001, MDN-248-16, December 1987

⁴⁰ M.D. Anerella, D.H. Fisher (BNL); E. Sheedy, T. McGuire (NGC), Industrial Production of RHIC Magnets, IEEE Trans. on Magnetics, 37, 4, July 1996

⁴¹ D. Fisher, M. Anerella, P. Wanderer, Successful Partnership Between Brookhaven National Laboratory and Northrop Grumman Corp. for Construction of RHIC Superconducting Magnets, MT-16, Ponte Vedra Beach, Florida, September 26 - October 2, 1999 and BNL-72167

⁴² Please see the Topic, *Printed Circuit Coils*

⁴³ M. Anerella et. al., The RHIC Magnet System, Nuclear Instruments and Methods A, 499 (2003) p. 280-315

⁴⁴ J. Muratore, A. Jain, M. Anerella, J. Cozzolino, G. Ganetis, A. Ghosh, R. Gupta, M. Harrison, A. Marone, S. Plate, J. Schmalzle, R. Thomas, P. Wanderer, E. Willen, K.C. Wu, Test Results for LHC Insertion Region Dipole Magnets, PAC05, Knoxville, May 2005, p. 3106 and BNL-74831

⁴⁵ Needless to say, there was a need for thorough planning and good liaison between the MD and CERN to ensure that our magnets would fit their interfaces, that they would meet CERN's requirements and expectations, that they would be available when needed for their schedule. Our contacts at CERN were physicists Ranko Ostijic and Tom Taylor as well as cognizant CERN engineers. For BNL, mechanical engineer Steve Plate led the effort to interface with CERN. He was well organized and thorough, making sure that no detail was left unattended. On one trip, where we gave a talk filled with technical detail to the CERN staff, Tom Taylor told me of the good impression he made on them, hoping by his example that his own people become equally as well prepared and thorough.

⁴⁶ S.Y. Lee, Snakes and Spin Rotators for High Energy Accelerators, NIM A306, 1991, p.1-8

⁴⁷ E. D. Courant had investigated the use of a true helical field as compared to discrete horizontal and vertical deflectors in 1989: E.D. Courant, Helical Siberian Snakes, Proc. 8th Intl. Symp. on HE Spin Phys., 187, 1085, 1989. His calculations showed that such a magnet would give smaller excursions but recognized that this type of magnet had not been made

⁴⁸ The earliest pictorials were hand-drawn layouts made by me in December, 1993

⁴⁹ R. Gupta, G. Morgan, E. Willen, Design and Status of Helical Magnet at BNL; V.I. Ptitsin, Yu. M. Shatunov, Helical Spin Rotators and Snakes; Third Workshop on Siberian Snakes and Spin Rotators, A. Luccio and Th. Roser, Editors, Brookhaven National Laboratory, September 12-13, 1994, and BNL-52453

⁵⁰ References for the RHIC helical magnets:

E. Willen, R. Gupta, E. Kelly, G. Morgan, J. Muratore, R. Thomas, A Helical Magnet Design for RHIC, PAC97, Vancouver, May 1997

E. Willen, E. Kelly, M. Anerella, J. Escallier, G. Ganetis, A. Ghosh, R. Gupta, A. Jain, A. Marone, G. Morgan, J. Muratore, A. Prodell, P. Wanderer (BNL) and M. Okamura (RIKEN), Construction of Helical Magnets for RHIC, PAC99, New York, March 1999

E. Willen, et. al., Performance of Helical Magnets for RHIC, MT16, Ponte Vedra, FL, September 1999

E. Willen, et. al., Performance Summary of the Helical Magnets for RHIC, PAC03, Portland, May 2003

The helical magnet layout in the snakes and rotators, and drawings of protons traversing these devices, are given in: M. Syphers et. al., Helical Dipole Magnets for Polarized Protons in RHIC, PAC97, Vancouver, May 1997

⁵¹ AML was a company in Florida named Advanced Magnet Lab, Inc. making custom magnets. It had been started by Rainer Meinke, a physicist whom we knew from the HERA project at DESY. They had developed a machine to place conductor onto a cylindrical surface and believed that it could be adapted to making helical coils at less cost. With this promising technique, they were funded to make some prototypes. For their model coils, they cut shallow grooves into a metal tube in a helical pattern for the first layer of wires, then built up additional layers by placing wires in the grooves between wires of the layer below. Various types of adhesive and sticky material held the structure together during fabrication until completion, when the structure was permanently immobilized. They tested several prototypes and reached the required field but with lots of training, indicating a need for better support of the conductor. Their coils were well crafted and may have been successful with further R&D, but their window of opportunity passed them by when the BNL slotted coil design proved successful.

⁵² A machine was designed and built to place the insulated cable into the slots under computer control. The computer followed the same slot description used by the milling machine that cut the slots. The stylus of the machine guided the cable into its proper position and, using ultrasonic energy, melted the adhesive coating on the cable sufficiently to fasten it to the substrate. After each layer was wound, the machine paused while the operator placed the next layer of substrate. The machine was used to wind a number of slots but, because of unacceptable error accumulation in slot position, its development was ended and the slots were wound by hand. The machine lacked a feedback feature that would have allowed it to follow the actual slot. Winding by hand required a lot of labor at

first, but the labor dropped rapidly to acceptable levels as more adept technicians were found and the techniques used improved with experience.

⁵³ T. Roser, L. Ahrens, M. Bai, E. Courant, J.W. Glen, R.C. Gupta, H. Huang, A.U. Luccio, W.W. Mackay, N. Tsoupas, E. Willen (BNL), and M. Okamura, J. Takano (RIKEN), Acceleration of Polarized Beams Using Multiple Strong Partial Siberian Snakes, EPAC 2004, Lucerne, Switzerland, 2004 and BNL-73397

⁵⁴ A description of the AGS snake is given in: E. Willen, M. Anerella, J. Escallier, G. Ganetis, A. Ghosh, R. Gupta, M. Harrison, A. Jain, A. Luccio, W. MacKay, A. Marone, J. Muratore, S. Plate, T. Roser, N. Tsoupas, P. Wanderer, Superconducting Helical Snake Magnet for the AGS, PAC05, Knoxville, May 2005 and BNL-74868.

Papers detailing various design aspects include

R. Gupta et. al., Magnetic Design of a Superconducting AGS Snake, PAC03, Portland, May 2003 and BNL-71400

M. Okamura et. al., Design Study of a Partial Snake for the AGS, EPAC 2002, Paris, 2002

A.U. Luccio et. al., Cold AGS Snake Optimization by Modeling, Internal Report C_A/AP/128, December 2003

A paper detailing the technological effort to correctly make the slotted cylinders is:

M. Anerella, R. Gupta, P. Kovach, A. Marone, S. Plate, K. Power, J. Schmalzle, E. Willen, Engineering of the AGS Snake Coil Assembly, PAC03, Portland, May 2003 and BNL-71449

Detailed measurement results for the completed snake are given in two staff presentations (unpublished):

A. Jain, Magnetic Measurement Results in the AGS Cold Snake HSD601, August 2004

R. Gupta & A. Jain, Comparison Between Calculations and Measurements in Superconducting AGS Helical Dipole Magnet, November 2004

⁵⁵ Designing the exact physical length and pitch of the two helices was an iterative process. The coil design began with the required magnetic length and pitch from Tom Roser. Then R. Gupta used the field optimization program Opera3D to specify slot positions for the coil, including the ends. From Gupta's files, K. Power made CAD files that would specify for the shops where the slots should be cut. These CAD files were first entered into Opera3D to generate the field, in 2 mm increments, they would produce along the length of the magnet. From the field map thus produced, I used EXCEL to calculate the net deflection and slope of a particle traversing the magnet. Mostly due to end effects, these generally were not zero as required. Using the EXCEL "Solver" algorithm, EXCEL could minimize the residuals by varying the length of each helix, subject to maintaining the overall 2400 mm length, and the pitch of each helix. Since the starting points of these parameters were close to those required, the adjustments were small but significant. These final parameters were then used to make new CAD files to be used to cut the slots. This process ensured that no additional magnets would be needed to correct a misalignment of the AGS beam caused by the snake.

⁵⁶ R.P. Shutt and M.L. Rehak, Stability of Bellows Used as Expansion Joints Between Superconducting Magnets in Accelerators, Supercollider 3, Atlanta, March 1991, p. 1059 and BNL-45337

⁵⁷ An abbreviated description of the BNL 50 mm dipole design, which was based on the final design of a long series of preceding 40 mm aperture magnets, is available in M.

Anerella et. al., Construction and Test Results from 15 m-Long, 50 mm Aperture SSC Collider Dipole Magnets, Supercollider 4, Atlanta, 1992, p. 535 and BNL-48140

⁵⁸ Detailed analysis and considerations for this vertical yoke lamination split design are discussed in a paper by Jim Strait et. al.: J. Strait, K. Coulter, T. Jaffery, J. Kerby, W. Koska, M. J. Lamm, Experimental Evaluation of Vertically versus Horizontally Split Yokes for SSC Dipole Magnets, Supercollider 2, Miami, 1990

⁵⁹ C. Wyss, LHC Arc Dipole Status Report, Particle Accelerator Conference, New York, 1999. This paper details the impressive amount of data review and simulation studies that were carried out to reach the conclusions

⁶⁰ C. Wyss, The LHC Magnet Programme: From Accelerator Physics Requirements to Production in Industry, EPAC, Vienna, 2000

⁶¹ R.P. Shutt and M.L. Rehak, Transverse Cooling in SSC Magnets, Supercollider 2, Miami Beach, 1990, p. 209 and BNL-43414

⁶² M.J. Baggett (BNL) and R. Leedy, C. Saltmarsh, J.C. Tomkins (SSCL), The Magnet Components Database System, Supercollider 2, Miami Beach, 1990, p. 145

P. Baggett et al., The Magnet Database System, Supercollider 3, Atlanta, 1991, p. 3

⁶³ G.F. Sintchak, J.G. Cottingham, G.L. Ganetis, Electrical Insulation Requirements and Test Procedures for SSC Dipole Magnets, Supercollider 1 and BNL-43378.

⁶⁴ J. Herrera, H. Kirk, A. Prodell, E. Willen, Magnetic Field Measurements of Superconducting Magnets for the Colliding Beam Accelerator, 12th Int. Conf. on High Energy Accelerators, FNAL, August 11-16, 1983 and BNL-33487

⁶⁵ G. Ganetis, J. Herrera, R. Hogue, J. Skaritka, P. Wanderer, E. Willen, Field Measuring Probe for SSC Magnets, P, Washington, DC, March 16-19, 1987

⁶⁶ J. Skaritka was instrumental in proposing, finding, and incorporating the many specialized components needed in a Mole

⁶⁷ Jain lectures at the US Particle Accelerator School, Phoenix, January 2006:

<https://www.bnl.gov/magnets/staff/gupta/scmag-course/uspas06/AJ06/index.htm>

⁶⁸ R. Gupta et. al., Field Quality Improvements in Superconducting Magnets for RHIC, EPAC, London, 1994 and BNL-68135

⁶⁹ M. Anerella, A.K. Ghosh, E. Kelly, J. Schmalzle, E. Willen, BNL; J. Fraivillig, J. Ochsner, D.J. Parish, DuPont, Improved Cable Insulation for Superconducting Magnets, Particle Accelerator Conference, May 1993, Washington, DC and BNL-48532

⁷⁰ Early testing by J. Skaritka indicated the improved Kapton films coated with polyimide adhesive, when used to insulate SSC cable, could, remarkably, withstand greater than 50 kpsi applied coil stress before failing a 2 kV turn-to-turn electrical hypot test

⁷¹ B. Parker, BNL Direct Wind Magnets, MT-22, Marseille, September 2011; B. Parker et.al., Superconducting Corrector IR Magnet Production for SUPERKEKB, PAC 2013, Pasadena, CA, October 2013 BNL-102400

⁷² The work is described in several papers by Animesh Jain:

17th and 18th International Magnetic Measurements Workshops, Barcelona, September 2011 & Brookhaven, June 2013

48th ICFA Advanced Beam Dynamics Workshop on Future Light Sources, SLAC, March 2010

⁷³ Animesh Jain, Field Straightness Measurements in Electron Lens Solenoids for RHIC, 19th Int. Mag. Meas. Wkshp, NSRRC, Hsinchu, Taiwan, October 2015

⁷⁴ R. Coombes, Editor, SSC 17-Meter Magnet DD000Z Review Committee, SSC Central Design Group, January 1988 and SSC-N-437

⁷⁵ B. Goss Levi and B. Schwarzschild, Super Collider Magnet Program Pushes Toward Prototype, Phys. Today 41(4), 17, April 1988

⁷⁶ P. Thompson, R. Gupta, Design of Kapton CI Insulated DRE Series RHIC Dipole, MDN-456-16, July 1992

⁷⁷ R. Gupta, A Common Coil Design for High Field 2-in-1 Accelerator Magnets, Particle Accelerator Conference, Vancouver, Canada, May 1997

⁷⁸ A. Morgillo et al., Superconducting 8 cm Corrector Magnets for the Relativistic Heavy Ion Collider (RHIC), PAC95, Dallas, May 1995 and BNL-61264

⁷⁹ E. Willen, presentation at the INFN Eloisatron Project 34th Workshop, "Hadron Collider at the Highest Energy and Luminosity", Erice, Sicily, November 1996 and BNL-64183. The cost per Tesla meter quoted here, \$2777, is 3.2% higher than that given in the reference in order to adjust for two items previously omitted: the cost of Kapton CI cable wrap and the cost of welding wire

⁸⁰ C.L. Goodzeit, M.D. Anerella, G.L. Ganetis, Measurements of Internal Forces in Superconducting Accelerator Magnets with Strain Gauge Transducers, IEEE Trans. on Magnetism, 25(2), March 1989

⁸¹ A.K. Ghosh, M. Garber, K.E. Robbins, W.B. Sampson, Training in Test Samples of Superconducting Cables for Accelerator Magnets, IEEE Trans Mag, 25, 2, March 1989 and BNL-41978. This paper describes how the measurements were done and gives more details about the cables used in the tests, which were from various projects in addition to the SSC

⁸² A.F. Greene et al., Manufacture and Testing of the Superconducting Wire and Cable for the RHIC Dipoles and Quadrupoles, IEEE Transactions on Applied Superconductivity, June 1995 and BNL-60350

⁸³ M. Garber, W.B. Sampson, M.J. Tannenbaum, Critical Current Measurements on Superconducting Cables, IEEE Trans. Mag., Mag-19, 3, May 1983

⁸⁴ J.H. Sondericker, L.J. Wolf, Alternative Concepts for Structurally Supporting the Cold Mass of a Superconducting Accelerator Magnet, Supercollider 3, Atlanta, 1991, p. 175

⁸⁵ J. Skaritka et. al., Development of the SSC Trim Coil Beam Tube Assembly, PAC87, March 1987, Washington, DC and BNL-39615

⁸⁶ P. Wanderer, J. Herrera, P. Thompson, E. Willen, Performance of R&D Sextupole Trim Coils for SSC Dipoles, PAC87, March 1987, Washington, DC and BNL-39612

⁸⁷ G. Morgan, Final Report of the Task Force on the RHIC Iron Specification, MDN 420, February 26, 1992

⁸⁸ R. Thomas, G. Morgan, Measurements of Magnetic Permeability and H_c of Magnet Steels using Digital Techniques, Eleventh Annual Conference on Properties and Applications of Magnetic Materials, Chicago, May 12-14, 1992 and BNL-47851

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R.C. Gupta, Correcting Field Harmonics after Design in Superconducting Magnets, Supercollider 4, Atlanta, March 1992 and BNL-47601

R. Gupta et. al., Tuning Shims for High Field Quality in Superconducting Magnets, MT14, Tampere, Finland, June 1995 and BNL-61106

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