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SUPERCONDUCTING MAGNETS

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ABSTRACT

Superconducting dipole magnets for high energy colliders are discussed. As an example, the magnets recently built for the Relativistic Heavy Ion Collider at Brookhaven are reviewed. Their technical performance and the cost for the industry-built production dipoles are given. The cost data is generalized in order to extrapolate the cost of magnets for a new machine.

1. Introduction

1.1. Foreword

Superconducting dipole magnets for a machine as large as the Eloisatron have several important requirements: good performance, high reliability, low cost. To a large extent, these goals have been achieved in previous accelerator projects. Superconducting magnets built for existing colliders have proven reliable and provide very good field quality. Costs have been fairly well controlled (former SSC project excepted). These results, however, have not been achieved easily. The current cos θ magnet designs used in various accelerator projects, though they vary in detail, are the result of a very substantial development effort that has been carried out (in the US) primarily at three national laboratories over a period of many years.

It is unlikely that shortcuts will be found in the development of new types of superconducting magnets. The magnet system for the Eloisatron will have to be either an extension and evolution of existing magnet systems, or it will require a vigorous R&D program spread over many years. Time would be required to accomplish this work, not only the natural time that it takes to carry out such development work, but also the time required to overcome the prejudices that exist in the field because "it hasn't been done that way before".[1] In addition, it will be a challenge to find the commitment and resources for such long term R&D work.

1.2. Design Options

The major technical choice to be made is the field level of the superconducting magnets. Intermediate field (3 - 10 T) cos θ magnets have been chosen for accelerator projects to date (Tevatron, CBA, HERA, UNK, SSC, RHIC and LHC). For future machines, both low field (<3 T) and high field (>10 T) magnet options have strong advocates, who argue that fresh approaches are needed if the next step in collider energy is to be taken. Low field proponents maintain that new tunneling methods and developments in robotics open the possibility of low tunnel cost, which then favors inexpensive, low field magnets[2]. High field advocates reason that the synchrotron radiation produced in machines with such magnets stabilizes the beam and thereby eases the injection requirements and reduces the need both for costly precision in the field quality and some number of correction magnets[3]. The focus of this paper will be on the intermediate field magnet option---the properties of such magnets using RHIC 80 mm dipoles as an example, and how intermediate field magnets might be further developed for use in the Eloisatron. The industrial production of 373 RHIC dipoles has recently been completed so they offer a good data sample for performance and cost.

Another choice to be made is that of a traditional single aperture magnet vs. the 2-in-1 option[4] as planned for the LHC[5]. Fortunately, we will learn much more about such magnets in the near future as the LHC project proceeds. They save on costs and, more importantly for LHC, require less space in a tunnel than two rings of 1-in-1 magnets. However, they complicate magnet design and compromise machine flexibility. Such magnets were first built and tested for CBA but were not chosen because they limited the machine operation too much. Fig. 1 is a cross section of the CBA 2-in-1 magnet. A current imbalance in the two apertures of 2.5, necessary for heavy ion-proton collisions, produced unallowed harmonics of several tenths percent. Such big, unallowed harmonics are difficult to compensate. The SSC program in its early days also considered the use of 2-in-1 magnets and several such magnets, each 4.5 m long, were built and tested at Brookhaven.[6] Fig. 2 shows the design. The magnets performed well but the SSC Central Design Group, citing cost savings too small to warrant the extra performance risk, opted not to pursue this option.

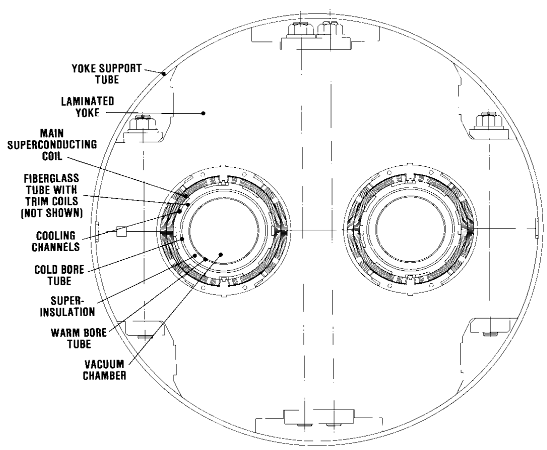

Fig. 1 The two-in-one magnet built for the CBA project. The coil ID was 130 mm and the field 5 T.

With progress in the development of high temperature superconductors, their potential use in accelerator magnets is gaining some credibility. Their availability would favorably change many difficult parameters in the magnet/accelerator business. Ribbon conductors are available in short lengths that could be used in prototype magnets and development work is underway or planned.[7]

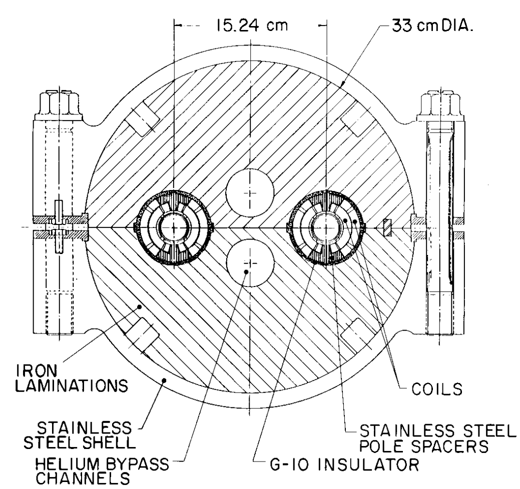

Fig. 2 Design of the four two-in-one magnets built for the SSC. The coil ID was 32 mm and the field 6.6 T.

However, their cost is much too high to be used for accelerator magnets at the present time or for the foreseeable future. They are also brittle so they must be handled with extreme care, and they require that the field in the magnet be parallel to their width in order to avoid degradation in the critical current level while ramped. This latter condition is difficult to achieve in a cos θ coil design, as seen from the field lines in a typical dipole (Fig. 3), so other, less efficient designs must probably be used. Another superconducting material that shows promise is Nb_3Sn. Dipoles made with this material could achieve fields in the range 12-15 T. It has been available for some years but its brittle nature has made it difficult to use in accelerator magnets. Most recently LBL is building a prototype magnet[8] that is designed to reach 12-14 T and a group at the University of Twente has built a magnet[9] for 11.5 T. A novel approach to Nb_3Sn coil construction using stainless steel foil as a cable insulator is being considered for magnets for the Muon Collider[10], under discussion in the US.

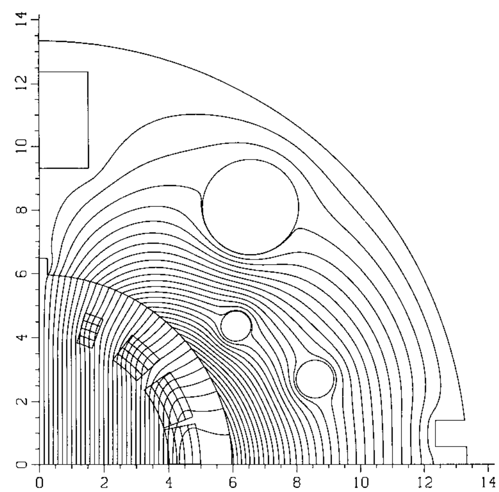

Fig. 3 Field lines in a cos θ magnet. Lines cross the coil at many angles.

Given the constraints and difficulties with other superconductors, NbTi will remain the choice in accelerator magnets for some years to come: it is relatively cheap and it is ductile. Ductility translates into toughness against filament breakage and thus high reliability.

2. RHIC Dipole

2.1. Design of the Magnet

A cross section drawing of the RHIC dipole is shown in Fig. 4 and some selected parameters in Table 1.[11] The field level required for this magnet, 3.45 T, was determined by the physics requirement of 100 Gev/nucleon beam energy in the collision of heavy ion beams and by the availability of the already-built CBA tunnel at Brookhaven. The coil aperture, 80 mm, was determined by the large beam size caused by intrabeam scattering after storage and by the field quality that could be expected as scaled from CBA and Tevatron magnets.[12] An affordable cost for the magnets was a consideration from the beginning and was made part of the design. Features such as phenolic coil-yoke spacers, yoke laminations serving as collars rather than costly, separate stainless steel collars, molded rather than machined coil end parts, and plastic support posts are among the cost savers, as compared for example to the contemporary SSC design.

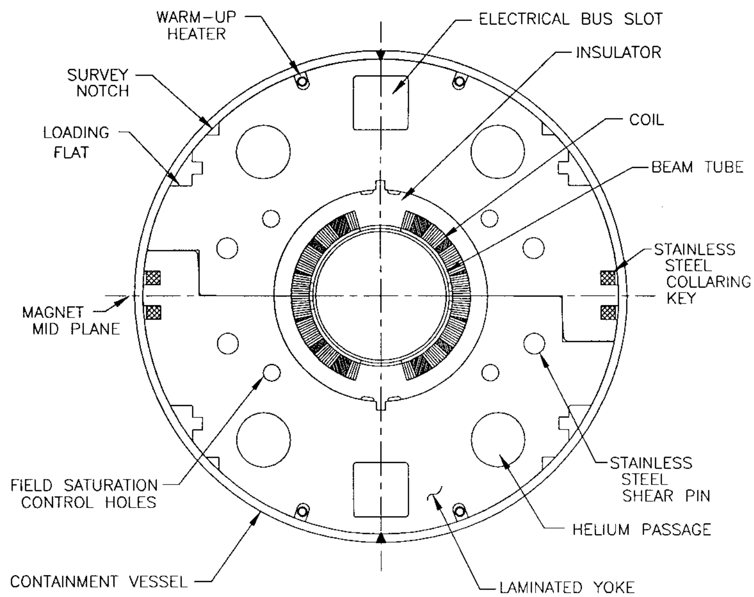

Fig. 4 A cross section of the central portion of the RHIC arc dipole magnet. For the RHIC machine, 373 of these magnets were built by the Northrop-Grumman Corporation in various lengths.

Table 1 Selected parameters for the RHIC arc dipole magnet.

Item	Value	Units
B_{op}	3.46	T
I_{op}	5.1	kA
Magnetic length	9.45	m
Coil ID	80	mm
Coil OD	100	mm
Number of turns	32	
Yoke ID	119.4	mm
Yoke OD	266.7	mm
Sagitta	48.5	mm
Inductance	28	mH
Stored energy	351	kJ
Ramp rate, nominal	0.042	T/s

Also built into the design from the beginning was industrial producibility, made possible by the availability of experienced and talented production engineering at Brookhaven during the R&D phase. This in-house capability was augmented by a number of industrial engineering studies[13] where the design was reviewed by interested industrial concerns under contract to Brookhaven and their suggestions incorporated as appropriate.

The goal was to have industry build magnets to Brookhaven prints and specifications, and this goal was achieved. Industry delivered finished magnets ready for tunnel installation. Most parts procurement was done by industry, though some critical and/or long lead time items such as superconductor cable, quench protection diodes, beam tubes and several other parts were supplied by Brookhaven. Yoke steel was purchased by industry following a detailed specification developed by Brookhaven. This specification was itself the result of ongoing testing at Brookhaven and extensive interaction with industry on the technical feasibility of various critical parameters, in particular the coercive force.

2.2. Production of the Magnets

A Request for Proposal (RFP) to build 373 dipole magnets for RHIC was released to industry in May, 1991. A contract was signed with Grumman Aerospace Corporation, later to become Northrop-Grumman Corporation (NGC), in June, 1992, at the end of the technical/price competition. The first magnet was delivered in April, 1994, and the final magnet in May, 1996. There was no preseries of throw-away magnets---because the design had been proven in a series of preproduction magnets (12) built at Brookhaven, it was anticipated that all magnets coming off the production line and satisfying the prescribed tests would be acceptable. Every magnet delivered by NGC was indeed suitable for machine use; there were no rejected magnets. The industrial production has been summarized at a recent conference[14].

The RFP contained a detailed technical description of the magnets and the Baseline Engineering Drawing Package & Parts List, and Ancillary Specifications, which defined the magnets that were to be built. Also included in the RFP was a Design Guide for Tooling and Procedures & Flow Charts that summarized the methods used at Brookhaven to build magnets. Industry was not allowed to change the design of the magnet without approval but was free (upon review) to build its own tooling and to adopt its own production methods. The RFP specified the electrical and mechanical testing that had to be performed on each magnet during the production process. This testing was carefully planned, based on experience, to reveal any fault at each stage of production. There were also performance specifications on the field quality as measured at room temperature with Brookhaven-supplied equipment and on the amount of training (quenching) allowed to reach short sample when the magnet was tested at Brookhaven.

With a Brookhaven design, and an industry-built magnet, who is responsible if the magnet fails or has a poor field after delivery? Brookhaven had confidence that such questions would not arise, but that if they did, then the testing specified would point unambiguously to a fault in construction (industry responsibility) or to a fault in design (Brookhaven responsibility). In fact, during construction, several construction errors were caught by the testing and corrected before a faulty magnet could be sent to Brookhaven.

NGC proved to be an outstanding company for building magnets, committed first and foremost to quality. Their pricing was aggressive, based on low unit labor man-hours, which they achieved. Relatively minor problems in the execution of the contract included an underestimate of the difficulty of building the required tooling, insufficient allowance for technology transfer, a host of changes initiated mostly by NGC to ease production but some also by Brookhaven, and troubles with some of the parts suppliers chosen by NGC. Overall, the company earned a very modest profit on the contract.

Of particular interest is the labor involved in building these magnets, for it indicates how efficiently industry can manage a production job. Fig. 5 shows the labor man-hours for each magnet from the beginning of production including a curve showing the company's labor estimate as prepared for the RFP. The company was able, in advance, to project labor man-hours quite accurately over the course of production. Averaged over the production, the cost per magnet, including the parts supplied by Brookhaven, was $109,366, or $2691/T-m for operation at 4.2 K and 15% below the short sample limit of the magnet at this temperature.

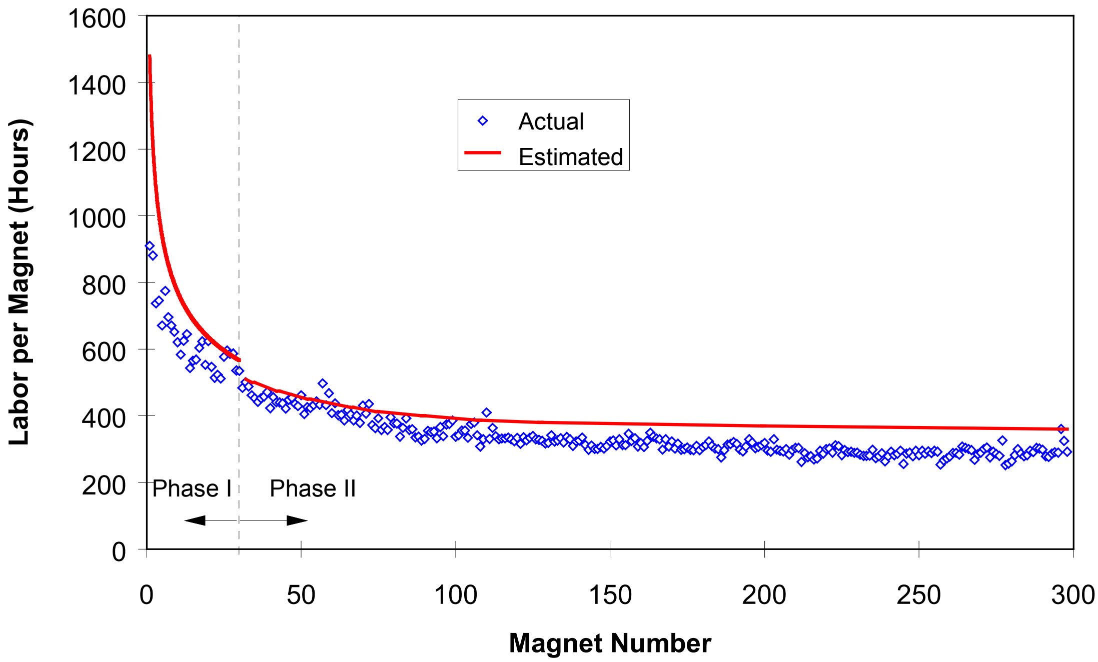

Fig. 5 Labor hours to build a magnet at NGC. The production magnets discussed here are those from Phase II.

2.3. Performance of the Magnets

With good performance, and as a cost-saving measure, it was decided not to cold-test each of the 373 dipole magnets built by industry. The first 30 were all tested to establish a performance baseline and after that, roughly 10% were cold tested. This partial cold-testing of magnets is only viable if the magnets are largely free of defects, as these magnets were. It has been established, as will be shown, that there is a good correlation between magnetic field measurements made on a magnet at room temperature and at cryogenic temperature. Thus, the field quality of magnets can be accurately determined without complete cold-testing.

2.3.1 Quenching

RHIC dipoles require little training to reach their plateau current, which is generally the short sample limit for the conductor used to build the magnet. A plot of their quench behavior is shown in Fig. 6. The average number of quenches to reach the plateau current was 1.47. Of the 51 magnets tested, none quenched below the operating current of 5000 A, thanks to the healthy margin built into the design. Two showed slightly erratic quench behavior and did not reach a plateau although they can still be used in the machine. Based on this level of performance, a general conclusion is that a 15% quench margin is adequate in dipole magnets to reach machine design goals.

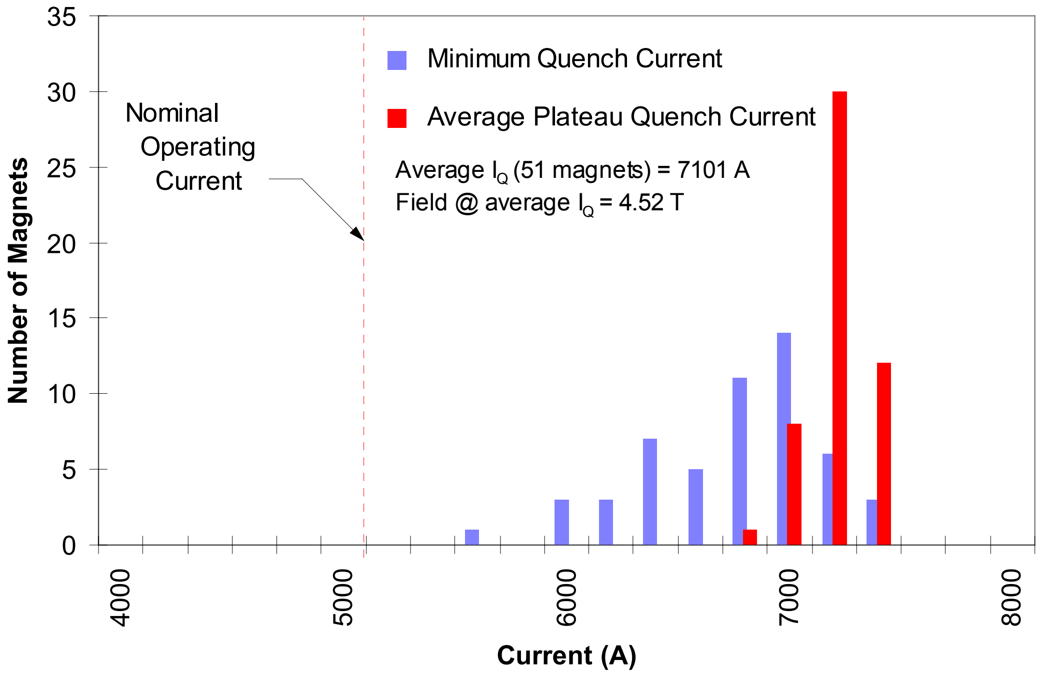

Fig. 6 Summary of the quench performance of the tested RHIC production dipole magnets. Typically one or two quenches were required to reach a plateau.

2.3.2. Field Quality

Field quality is excellent in the RHIC dipole magnets. The expected and measured warm integral harmonics (harmonics are given in "units"---parts in 10^4 of the dipole field---at 25 mm radius) are summarized in Table 2. The measured systematic values of the various harmonics (their values averaged over all the measurements) are not necessarily zero---allowed harmonics change when the magnet is cooled, and both the allowed and unallowed harmonics can change as a function of current and because of end effects. In addition, various component and construction variations that can not be accurately forecast, e.g. final coil dimensions, contribute to the systematic harmonics and also the random harmonics. In the table, the uncertainties (δb, δa) in the expected systematic harmonics reflect the uncertainty in predicting the average. From the table, it can be seen that the measured systematic harmonics fall well within the expected values. During the course of production, some minor changes were made to shift the allowed harmonics. Table 2 includes all the magnets---within each production subset, the systematic values are somewhat less than those given in the table.

Earlier estimates for the random errors[12], made by extrapolation from CBA and Tevatron data at the start of the project before RHIC magnets had been built, were considerably larger and in retrospect were too conservative. Improvements in magnet production technology account for the smaller random errors.

Table 2 Expected and measured warm integral harmonics in the RHIC production dipoles, at 25 mm radius.

	Expected		Measured	
	Systematic	Random	Systematic	Random
n	**b ± δb**	**σ(b)**	**b**	**σ(b)**
1	0.0 ± 0.4	0.8	0.25	0.37
2	4.0 ± 2.0	2.3	3.54	1.74
3	0 ± 0.2	0.3	-0.03	0.10
4	0.5 ± 0.5	0.6	0.22	0.44
5	0 ± 0.03	0.1	0	0.03
6	0.3 ± 0.1	0.1	0.12	0.12
7	0 ± 0.03	0.1	0	0.01
8	0.3 ± 0.1	0.1	0.09	0.11
9	0 ± 0.03	0.1	0	0.01
10	-0.5 ± 0.01	0.1	-0.53	0.02
n	**a ± δa**	**σ(a)**	**a**	**σ(a)**
1	0 ± 1	1.3	-0.20	1.62
2	-1.1 ± 0.1	0.5	-1.11	0.20
3	0 ± 0.3	1.0	-0.01	0.49
4	0.2 ± 0.06	0.2	0.18	0.07
5	0 ± 0.1	0.3	-0.01	0.17
6	-0.1 ± 0.03	0.1	-0.11	0.03
7	0 ± 0.03	0.1	0	0.05
8	0 ± 0.03	0.1	0.02	0.01
9	0 ± 0.03	0.1	0	0.01
10	0 ± 0.03	0.1	0	0

The RHIC magnet coil aperture (80 mm) is similar to that of the magnets built for the Tevatron (76.2 mm) and for HERA (75 mm). An interesting comparison between these magnets is to plot the measured field on the median plane as a function of coil radius. Such plots are shown in Fig. 7, at injection energy and at top energy. It is seen that the RHIC magnets have considerably less field variation at injection energy but that all the magnets have a good field at high energy. The reduced region of flat field in the HERA magnets at low energy is due to the low injection energy in that machine and the use of relatively large filaments in the superconductor, which cause persistent current harmonics at low field.

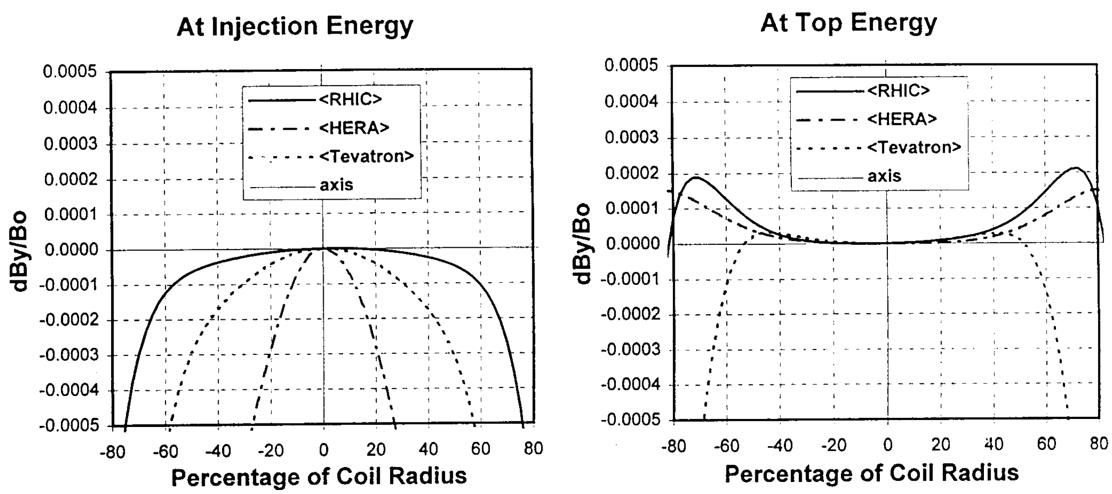

Fig. 7 The field on the magnet mid-plane in RHIC, HERA and Tevatron main ring dipole magnets calculated from the measured systematic harmonics. The first ten harmonics are included.

2.3.3. Warm - Cold Correlations

The RHIC dipole data show that field measurements made on a magnet at room temperature are well correlated with measurements made at cryogenic temperature. A typical plot of this correlation for the sextupole (b_2) harmonic is shown in Fig. 8. These measurements were made with a movable, rotating, 1 m long coil system[15] (MOLE) in the body of the magnet, both warm and cold. The sensitivity and accuracy of this system are sufficient to measure the very small field harmonics generated with only 10 A exciting the warm magnet. At that excitation, the dipole field is 7 G and one unit of a harmonic is only 0.7 mG. Table 3 lists the average cold-warm differences and their uncertainties for the various harmonics.

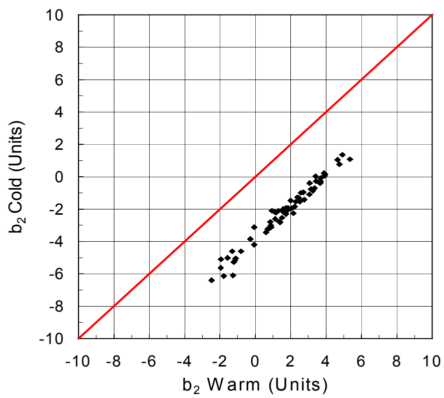

Fig. 8 Cold-warm correlation of the sextupole (b_2) harmonic measured in the RHIC production dipole magnets. The offset of the data points from the straight line is the result of dimensional changes when the magnet is cooled.

Table 3 Measured cold minus warm correlations and their uncertainties in the harmonics in the body of the production dipoles. Cold measurements were made at 5000 A.

	Correlation	Uncertainty
b_1	-0.07	0.01
b_2	-3.81	0.04
b_4	0.24	0.01
a_1	-1.37	0.09
a_2	-0.04	0.01
a_4	0	0

3. Magnet Field Quality

3.1. Field Quality Control and Improvement

Field quality in magnets has traditionally been a major concern of accelerator builders. In the past, this has led to magnet designs with apertures (and therefore costs) perhaps larger than necessary, in order "to be safe". While large apertures are the surest way to ensure that magnet field errors do not compromise machine performance, there are other ways to achieve the same end. Ramesh Gupta at Brookhaven has analyzed various types of field errors that occur and has summarized and suggested effective ways to correct them[16]. Many of his methods can be applied during series production and are thus powerful tools for improving field quality, if they have been planned for in advance.

For example, the allowed harmonics can be changed over a small range by adjusting coil midplane shims, pole shims, and wedge thickness while maintaining constant coil prestress. The integral transfer function can be adjusted by moving the boundary between iron and stainless steel yoke laminations at the ends of the magnet. The yoke packing fraction can be used to adjust the effect of iron saturation on integral transfer function. A systematic skew quadrupole component, caused by a top-bottom asymmetry, can be compensated by changing the top or bottom yoke length.

In the design of magnets, the astute use of cutouts in the yoke can virtually remove harmonic variations due to yoke saturation. After assembly, "tuning shims" can be used to remove unwanted harmonics. This latter method is especially effective at removing random errors in either the allowed or the non-allowed harmonics.

Gupta has estimated the expected field quality in 50 mm aperture SSC magnets if these methods are employed (excepting the tuning shim method). The estimates are based on the measurements made on approximately 13 full length model magnets built at Brookhaven and FNAL. The results are shown in Table 4, along with the nominal SSC specification used in tracking studies for the machine. It is seen that the expected errors are much improved over the specification, indicating perhaps that SSC tracking studies based on these specifications gave a too pessimistic picture of machine performance.

Table 4 Example of field quality improvements expected if adjustments are made during magnet construction. This example is for SSC dipole magnets, based on measurements of magnets that were built. The specification values listed were used in the SSC tracking studies.

	Expected		Specification	
	Sys (±)	σ	Sys (±)	σ
b_1	0.04	0.20	0.04	0.50
b_2	0.02	0.40	0.8	1.15
b_3	0	0.03	0.03	0.16
b_4	0.02	0.05	0.08	0.22
a_1	0.04	0.5	0.04	1.25
a_2	0.02	0.15	0.032	0.35
a_3	0.01	0.07	0.026	0.32
a_4	0	0.02	0.02	0.05

3.2. Field Quality Limitations

Field quality of course can not be improved indefinitely with the use of the preceding methods. The elastic nature of the components used to build magnets means that there is motion within the magnet structure of all magnets under the stress of cooldown and Lorentz forces. Because of friction, this motion is not completely elastic. Thus the conductor position and therefore the field harmonics can change with thermal and power cycles of the magnet. One observes changes in the field harmonics at some level upon repeated field measurements following power and thermal cycles.

This effect is particularly evident in the RHIC 100 mm aperture dipoles and 130 mm aperture quadrupoles near the final focus.[17] The large aperture of these magnets combined with the use of phenolic components in the cross section results in harmonic variations of nearly one unit (at 2/3 of the coil radius) in some of the low order harmonics of the magnets.

A review of SSC data shows that here, the variations are on the order of a few tenths of a unit in the low order harmonics.[17]

These observations show that there is a natural limit to the field quality that can be achieved in a particular magnet design. While the examples cited are cos θ magnets, this is undoubtedly true in all magnet designs. Each design will have its own natural limit. Metal components, with their greater stiffness compared to plastic or phenolic components, reduce elastic motion and, while more costly, are preferred in building the most accurate and reproducible magnets.

But electrical integrity, particularly in a large machine, is critical, even dominant, and phenolic components to separate the coil from the iron yoke as used in the RHIC magnets have made them extremely robust against electrical faults. Alternatively, polyimide film is routinely used in liberal quantities to insulate coil packages. There is a trade-off between cost, functionally, and ultimate field quality in accelerator magnets. For many reasons---technical, sociological, experience, competence---this trade-off is difficult to achieve in a rational way and hard to defend until acceptable working models have been built.

4. Cost of Magnets

The RHIC production dipole magnets were built in industry following a design provided by Brookhaven. The experience of building these magnets provides a good baseline for magnet cost and can be analyzed for extrapolation to future machines. The design of the magnets in a future machine would undoubtedly differ from that used for RHIC but if NbTi is used for the conductor and if a cos θ design is used, then the extrapolation can be expected to give reasonably accurate results. In this way, a cost for the magnets of a future machine can be established that is realistic and sensible.

4.1. Cost of RHIC Production Dipole Magnets

RHIC magnets were bought at a favorable price from the Northrop-Grumman Corporation (NGC). This was possible for the following reasons:

- Low cost design of the magnets, e.g. single layer coil, phenolic coil spacers, molded end parts, yoke serving also as collar, plastic support posts, simplified assembly.
- Competitive bidding for the production contract.
- Structure of the contract:
    - Build-to-print---no design risk to company.
    - Phase I: cost-plus, to cover the cost of tooling, training, production debugging, and the first 30 magnets.
    - Phase II: firm-fixed-price, for high rate production
    - Phase III: firm-fixed-price, for special lengths
- Favorable impact from the SSC Project, e.g. the cost of superconductor and yoke steel.
- Low point of the economic cycle (1991).
- Efficient tooling (guidance from Brookhaven).
- Experienced production team at NGC.

For these reasons, it is unlikely that the cost of intermediate field, cos θ NbTi magnets can be lowered very much.

4.2. Breakdown of Production Costs at NGC

NGC kept accurate records for each step of production as required by the contract. From these records, it is possible to determine the labor and material costs for various magnet components and subsystems built in Phase II of the contract (this excludes tooling, training and start-up costs). The touch labor, defined as the hands-on labor to build a magnet, is shown in Fig. 5. The plot shows a steady reduction in the labor required as the project proceeded such that near the end of the production run, less than 300 hours were required per magnet vs. 500 hours at the beginning of production. NGC was able to predict this labor cost rather accurately in advance, as shown by the solid line in Fig. 5, actually doing better than had been projected. Magnets built at NGC were delivered to Brookhaven complete and ready for ring installation. The company carried out numerous mechanical and electrical test as specified in the contract, including warm magnetic field measurements using equipment supplied by Brookhaven.

The distribution of this touch labor for the various magnet subsystems is shown in Fig. 9. The plot shows that the largest percentage of labor went into building the coils, a task that also included wrapping the superconducting cable with Kapton insulation.

Material costs for the various magnet subsystems are shown in Fig. 10. These are costs incurred by NGC and do not include the cost of materials supplied or paid separately by Brookhaven: superconducting cable, Kapton insulation, yoke steel, beam tubes, welding wire, and quench protection diodes.

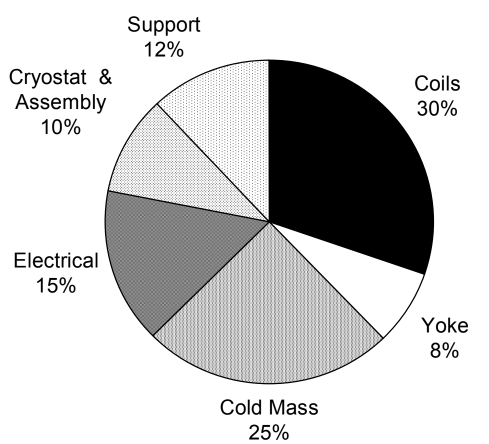

Fig. 9 Labor cost distribution for the production dipoles built by NGC.

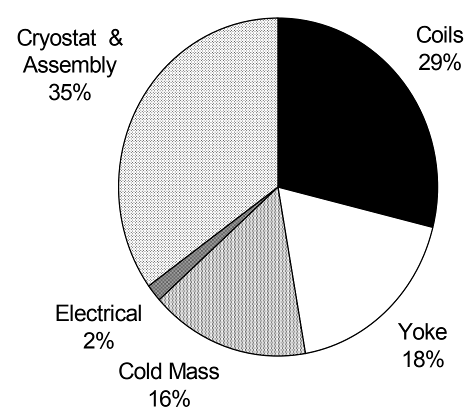

Fig. 10 Material cost distribution for the production dipoles built by NGC.

The distribution of total costs for a production dipole magnet is shown in Fig. 11. The same data, divided into either material or labor cost, is shown in Fig. 12. In this latter plot, NGC overhead, administrative, engineering and supervisory costs are grouped into the labor cost for the magnet. Included are all costs for a completed magnet ready for ring installation; not included are the cost of cryogenic testing at Brookhaven, nor the cost of magnet development nor supervision and administration at Brookhaven.

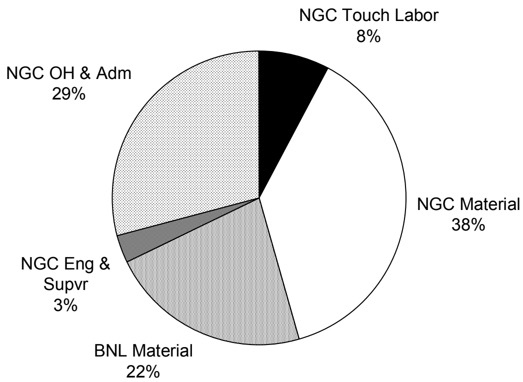

Fig. 11 Distribution of total costs for the production dipoles built by NGC.

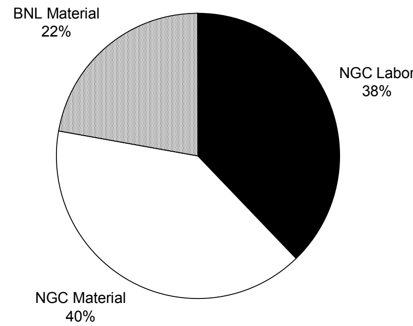

Fig. 12 Consolidated total costs for the production dipoles built by NGC.

The per magnet cost is converted into a cost per tesla-meter in Table 5. The operating current used for this conversion is 15% below the average quench current for the magnets in order to allow a realistic and necessary margin for the operation of magnets in an accelerator.

Table 5 Cost of RHIC production dipole magnets, including cost per tesla-meter, with 15% quench margin in the current. Cost is given in 1993 dollars.

Item	Units	Value
Operating current @ 4.5 K	A	6175
(15% below av. I_Q)		
Operating field @ 4.5 K	T	4.08
Operating field @ 4.2 K	T	4.30
Magnetic length	m	9.45
$\int$ Bdl	T-m	40.64
Cost per magnet	$	109,366
Cost per tesla-meter @ 4.2 K	$/T-m	2691

To place the magnets in context, the cost of magnets for RHIC as a percentage of the total RHIC project cost, including all magnets and not just the production dipole magnets detailed here, is shown in Fig. 13.

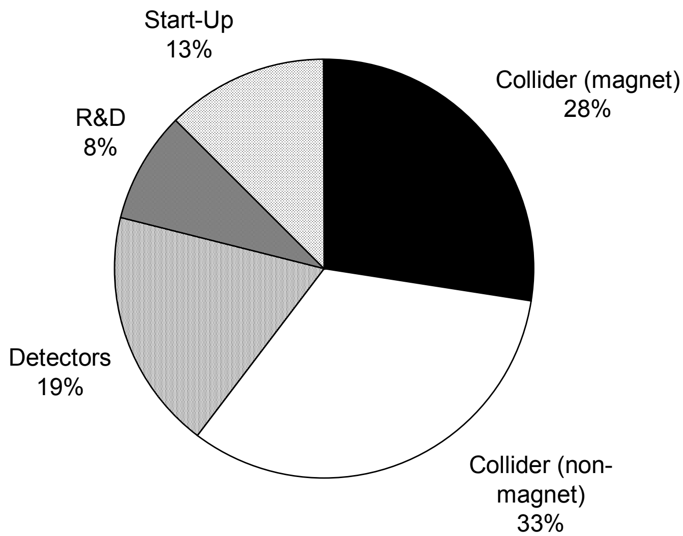

Fig. 13 Distribution of RHIC project costs. The magnet portion represents the cost for all collider magnets.

4.3 Scaling the Cost for Length, Aperture and Field

With the data that are available from the production run for the material and labor cost for each subsystem in the magnet, it is straightforward to scale the cost for changes in magnet length, aperture and field. The next few figures show this scaling. It must be understood that the scaling can only give approximate answers and must be done in a more detailed fashion when final sizes are established.

Fig. 14 shows the cost variation with length, for several different apertures. As expected, the cost per tesla-meter declines for longer magnets because of less relative contribution from end costs. Lengths beyond 18 m are difficult to handle and transport, and not much cost is saved with such longer magnets.

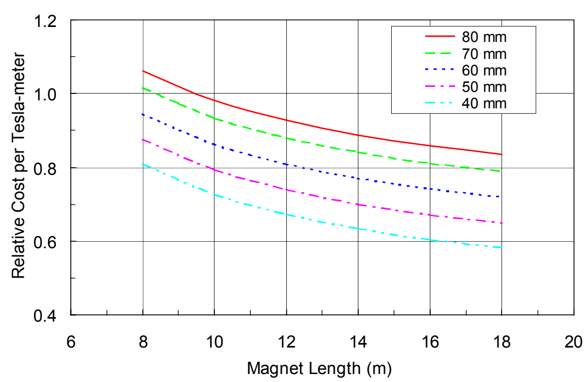

Fig. 14 Magnet cost vs. length for several coil apertures, based on the production cost of RHIC dipoles.

More field can be produced with wider cable and a second coil. The fields attainable relative to RHIC, using graded outer conductor and reasonable superconductor and copper current densities, are shown in Fig. 15 (these ratios are a function of coil radius and will be somewhat different for other starting sizes). Because the additional conductor

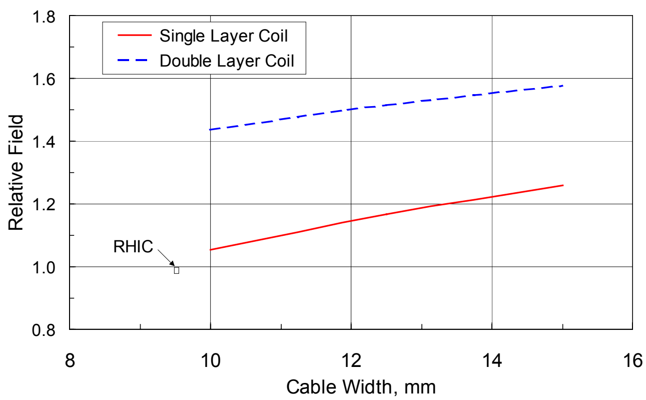

Fig. 15 Field relative to RHIC dipole as a function of cable width, for single layer and two layer coil designs.

of the second layer is at a larger radius, and because it reduces the current capacity of the first layer, it is less efficient at producing field. Therefore the gain is not one-to-one proportional to the amount of added conductor. The second coil adds less than 50% to the field that can be obtained with just one coil.

The cost of higher field magnets relative to RHIC is shown in Fig. 16. The RHIC magnet cost does not fall on the extrapolation of the line because it is not quite a fully optimized design. It is seen from the plot that a single layer coil using the widest cable is the most cost effective, and that a double layer coil is generally less cost effective.

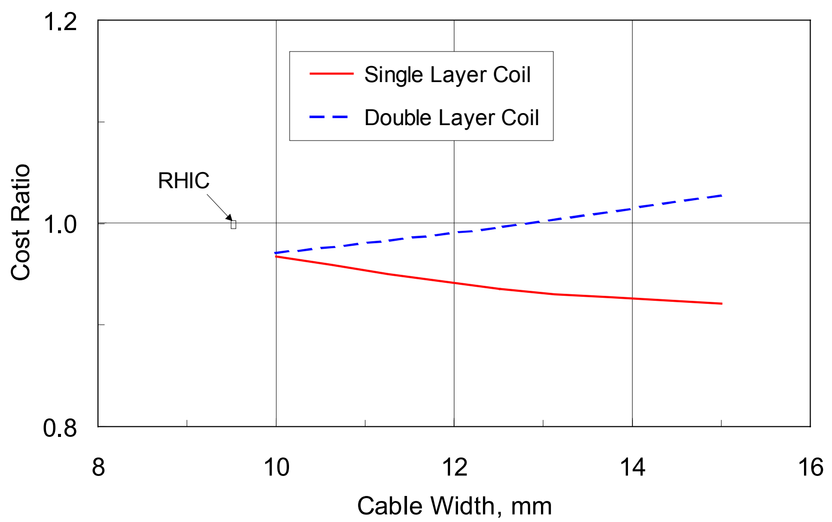

Fig. 16 Cost per tesla-meter, relative to RHIC production dipoles, for magnets with wider cable and one or two coils.

Using the scaling data, it is possible to look for a minimum cost magnet design. Such a design would have a small magnet aperture, long magnets, and a single layer coil made with a wide cable. Table 6 shows the costs for such a set of parameters. The lowest cost possible for the given data, based on the industrial production of RHIC magnets, is \$1436/T-m for a 40 mm aperture dipole.

Table 6 Scaling the RHIC production dipole cost to longer length and smaller aperture magnets.

	$/T-m
RHIC production dipole cost	2691
Cost scaled for 18 m length, 40 mm aperture (58 %)	1561
Cost scaled for cable width of 15 mm (92 %)	1436

4.4. Cost for 100 TeV

Using the RHIC production dipole magnets as a cost basis, it is possible to calculate the cost for a 100 TeV collider, if the cost for a tunnel can be estimated. For this purpose, the cost is taken to be $900/m, which is lower than for the SSC tunnel but that recent studies[18] have indicated may be possible in the future. With these assumptions, Table 7 shows the cost for the arc dipole magnets and the tunnel for a 100 TeV collider. The magnet cost is $6.0B and the tunnel cost is $0.42B. The tunnel cost is only 7.3% of the magnet cost. An obvious conclusion to draw from this analysis is that the way to minimize costs for a future machine is to minimize overall magnet cost rather than tunnel cost.

Table 7 Cost of dipoles and tunnel for some possible 100 TeV colliders.

Type	B_0 T	Cost $/T-m	Dipole Cost Two Rings $B	Tunnel (80% Fill) Length km	Tunnel (80% Fill) Cost @ $900/m $M
RHIC 9.45 m length 80 mm aperture	4.30	2691	11.3	610	549
Adjusted Size 18 m length 40 mm aperture	4.30	1561	6.6	610	549
Adjusted Field Single layer coil Cable 15 mm width	5.70	1436	6.0	460	414

4.4. Conclusion

Of course, in an actual machine, there are many other cost factors that must be considered. In a superconducting machine, the cost of the refrigerator and distribution system, as well as the operating cost of the overall system, are important factors. Future developments may lead to the use of high temperature superconductors, which would dramatically reduce the capital and operating cost of the refrigerator. It is unlikely, however, that the new materials will result in lower magnet costs, because the materials are likely to remain expensive, the Lorentz forces must still be contained, and they still remain cryogenic systems. A machine design using two-in-one magnets could reduce the magnet cost an estimated 10-20%, and operating at reduced temperature will increase the attainable field (also operating cost), but there is little else that can be done with present technology. The figures given here are likely to remain the lowest that are possible for realizable magnet costs.

5. Acknowledgment

The help of Ramesh Gupta in providing and understanding the measurement data is gratefully acknowledged.

6. References

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