June, 2011

Accelerator Project for Upgrade of LHC (APUL)
Final Design Report

APUL document # 185

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(APUL)
Final Design Report (FDR)

M. Anerella, A. Ghosh, R. Gupta,
J. Muratore, S. Plate, J. Schmalzle, P. Wanderer, K.C. Wu

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Preface

The APUL Project received CD-0 approval from the DOE in October 2008 and had a successful CD-1 review in January, 2010. A week later, CERN announced that its plans for an upgrade of the LHC magnet systems near the two major experiments, ATLAS and CMS, would undergo significant revision. The original objective of APUL was to contribute to this upgrade. The scope of APUL has been revised in response to CERN's change of plans.

In the spring of 2010, CERN asked for assistance from the DOE in several areas, including an increase in the reliability of the magnets supplied by Brookhaven National Laboratory as part of the DOE-sponsored US-LHC Project at the time of the construction of the LHC [1]. The current scope of APUL responds to this request.

Chapter 1 gives an overview of the project. Most of the common elements of a Design Report recommended by DOE are covered in this chapter.
Chapter 2 describes the deliverables of the APUL project.

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1 Overview of the Project

1.1 Introduction

In this chapter of the APUL Final Design Report (FDR) we present an overview of the APUL project focusing on the description of the elements of the FDR which can be found in more detail in other documents which will be completed for the CD review process. For documents such as these only a short summary will be presented, together with the reference.

The following items of the common elements of the FDR recommended by DOE O 413.3-1 will not be included since they are not applicable to the APUL project:

- Dedicated Safeguard and Security Plan. None of the work performed for the proposed upgrades will be classified and no safeguard and security issues are foreseen during design, construction or operations phase. Access to the BNL site engaged in this activity will be controlled primarily to ensure worker and public safety and to protect property. Appropriate safeguards and security requirements are already in place, and verified by a site visit by the BNL Safeguards and Security staff.
- Decontamination and Decommissioning plan. No radioactive material will be involved in the fabrication process. The final product owner will be the European Laboratory for Nuclear and Particle Research (CERN); therefore no decommissioning plan is necessary.
- Site selection criteria and site survey/ evaluation. In this project there are no site related issues.
- Plan for demobilization and/or disposal of facilities being replaced. No facilities will be replaced.

1.2 HEP Mission and LHC Science

The mission of the DOE program in High Energy Physics (HEP) is to discover and explore the laws of nature that apply to basic constituents of matter and their interactions. The core of the mission centers on the investigations of the properties of elementary particles and how they reflect the symmetries and the development of space time in our universe. This is an area of research that is fundamental to the advancement of science and technology as well as mankind’s broader intellectual perspectives. The current frontier machine in particle physics is the Large Hadron Collider (LHC), which is operated by CERN and located outside of Geneva, Switzerland.

The LHC is a particle discovery machine constructed to respond to specific issues raised by the apparent failings of the otherwise very successful “Standard Model (SM)”, which is the current theory of particle interactions. The development of the SM is the most significant achievement of elementary-particle physics of the past 40 years. It has provided a framework for categorizing all observed phenomena within a formal gauge theory of electroweak and strong forces. Despite the fact that this model is remarkably consistent with observations, it is flawed in that it is has many free parameters, and even more telling is that it becomes internally inconsistent beyond Tera electron volt (TeV) energies.

The LHC is operating well in the energy range which is be 3.5 times higher in center of mass collision energy (7 TeV) than the Fermilab Tevatron, the collider next highest in energy. A further energy increase to 12-14 Tev is planned for 2014. In this new energy range we may find the missing building block of matter which is responsible for the mass of the particles, the Higgs particle. We also hope to encounter rich new physics. The absence of new physics would still leave us many areas of the SM to study.

The goals of APUL are in full accord with those articulated in the Strategic Plan of the DOE Office of Science to “explore the fundamental interaction of energy, matter, time and space,” as well as with its mission to “keep the U.S. at the forefront of intellectual leadership” [2].

APUL is a DOE project. Consequently, all of the relevant DOE project requirements described in DOE Order 413.3-1 have to be respected.

The APUL Project will be governed by the Experiments Protocol to the International Co-Operation Agreement Concerning Scientific and Technical Co-Operation on Large Hadron Collider Activities [19], with the scope and schedule specified in an Arrangement signed by BNL and CERN [20].

1.3 APUL Background and Summary of Deliverables

Readers familiar with the APUL project need to be aware that the APUL D1 magnet discussed in this document is not the same as the D1 magnet reviewed in January 2010. The magnets have the same name because they occupy the same relative positions (first magnets) in an Insertion Region (IR). However, they are located in different IRs (IR1 and IR5 for the original APUL D1, IR2 and IR8 for the current APUL D1) and their performance requirements and specifications differ. For example, the D1 reviewed in January had a length of 7.4 m and an aperture of 180 mm, while this FDR describes a D1 with a length of 9.7 m and an aperture of 80 mm.

For the initial construction of the LHC, superconducting magnets and other components were provided by Brookhaven, Fermi, and Lawrence Berkeley National Labs through the US-LHC Project [3]. Brookhaven National Lab (BNL) made dipoles for the D1, D2, D3, and D4 positions. The magnets were based on magnets used in the Relativistic Heavy Ion Collider (RHIC) at BNL [4]. The superconducting coils in all the magnets made at BNL for the LHC had the same specifications but other components (such as the iron yokes) differed, based on magnet type.

BNL made five D1 magnets. Four have been installed and are now operating in the LHC. The fifth is a spare. CERN's original request was for BNL to provide two spares of each type. However, the number of spares was reduced to one of each type due to budgetary constraints.

The spare D1 magnet has a defect (one of the two redundant coil heaters is shorted to the magnet coil). At the time of the US-LHC project, CERN accepted the magnet because it passed acceptance testing at BNL and because the defect would not affect magnet operation if the heater is not connected to the heater power supply. However, this solution does eliminate the use of one of the two coil heaters used for quench protection in the magnet. With the LHC now in operation, CERN has reviewed the complement of spares and requested that the spare D1 be repaired or replaced [1].

There are two options for repair or replacement of the D1 using BNL facilities. In evaluating these options, it is important to take account of the status of the magnet tooling. The tooling for making the 9.7 m D1 coils was recently consolidated and, in the process, an important portion of it excessed. Tooling to make 4 m coils is being set up as part of the RHIC program. This tooling can be extended to make coils needed for the D1 magnet. Tooling for the assembly of D1 coils to make a magnet is available, but needs some refurbishment.

The first option for repair or replacement is to return the magnet to BNL, completely disassemble it, and determine whether the coil can repaired or must be replaced. If the coil cannot be repaired, extension of the coil production tooling and construction of a suitable replacement coil would delay completion of the magnet repair by more than a year. During this time, there would be no spare D1 at CERN, a significant disadvantage for this option.

The second option is to construct and test a new spare D1 magnet. The spare would be available near the start of the LHC run in 2014, when the collision energy will be increased. Construction of the spare requires that the presently-available tooling for winding and curing coils be extended from 4 m to 10 m. This is a significant expense. However, extension of the coil tooling would make it possible to repair coils in the other three types of magnets (D2, D3, D4) supplied by BNL since they use coils made to the same specifications as D1. For most magnet failures, the non-coil components can be reused. Thus, if any of these magnets failed, the spare would be installed and the failed magnet returned to BNL for repair, providing an effective alternative to the two spares requested by CERN for the US-LHC Project and increasing the long-term reliability of the LHC.

The third option – construction of a new D1 – is presented in this FDR. The scope also includes construction of a cold mass, which will be installed in a cryostat at CERN, so that there will be two spare D1 magnets.

1.4 Schedule and Cost

The Level 1 Milestones are: CD-1 September, 2010, CD-2/3 August, 2011, and CD-April 2014.

The estimated cost of APUL $6.785 M (for the present scope) plus $2.939 M (for work on the previous scope) for a total of $9.724 M. Including contingency for the present scope, the Total Project Cost is $11.422 M.

1.5 Preliminary Project Execution Plan

A comprehensive Preliminary PEP has been developed by DOE personnel based on the input of the APUL project team [5]. The PEP contains all the relevant information which was requested in document DOE O 413.3-1: performance baseline, project description, acquisition strategy, life-cycle costs, work breakdown structure, organizational break down structure, cost and schedule, risk analysis and risk management, system engineering and value management planning, resource requirement, project control and project reporting system, integrated safety management, planned design reviews, change control and management, inspection, testing.

1.6 Work Breakdown Structure

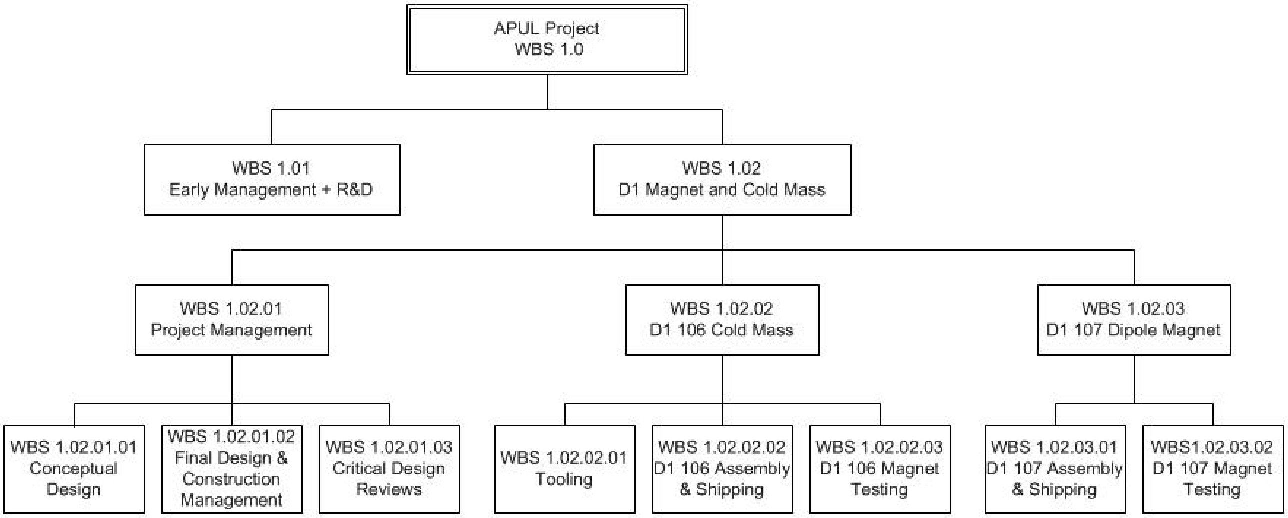


Figure 1.1: Overview of APUL Work Breakdown Structure, to Level 4

The Work Breakdown Structure (WBS) organization is shown in

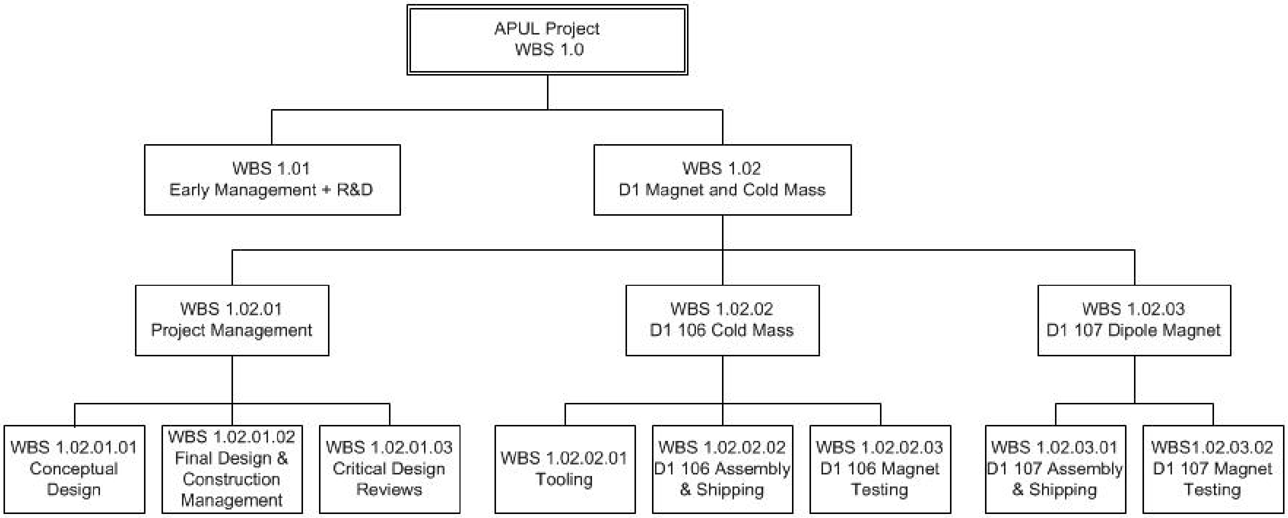


Figure 1.1. The detailed description of the WBS and its dictionary are accessible in a separate document.

1.7 Assessment of Strategy for NEPA and Safety

The National Environmental Policy Act (NEPA) and the Hazard Analysis strategies are in separate documents. The NEPA review was originally prepared for APUL as reviewed in January, 2010. Except for the change in scope (deletion of deliverables from Fermilab), it does not need modification for APUL's present scope. That is, there has been no change in NEPA-related matters since the same facilities will be used for the present magnet production as for the originally-proposed magnet production.

A summary of the NEPA document is as follows. There are no envisioned NEPA issues since existing facilities at Brookhaven National Laboratory and vendors will be used to provide all APUL equipment. No new facilities, utilities, or civil construction activities such as excavation, building demolition or erection, or building upgrades or maintenance are required for APUL. APUL was granted a NEPA Categorical Exclusion for work at BNL in May 2009 [6]. By Executive Order 12114, a NEPA review is not needed for magnet operation at CERN [18].

A Hazard Analysis has been performed and relevant hazard mitigation has been recommended for the present scope of APUL. It is important to point out that no activities have been envisioned which have not been performed previously (in a safe manner) [7].

1.8 Stakeholder Input

There are no significant stakeholder issues anticipated. Local and regional businesses and universities are in favor of the physics goals of the LHC. BNL has excellent relations with the local community. Through its existing outreach and community programs, BNL will keep stakeholders updated on the progress toward completion of APUL. CERN, including the ATLAS and CMS experiments, supports the increased reliability. The risk of stakeholder issues is, therefore, small.

1.9 Readiness Assessment and Review Concept

The APUL Project will undergo a series of reviews to monitor the progress of the cost, schedule, and technical aspects of the project.

1.9.1 Technical Reviews

The Project described here will have at least one full scale technical review annually. For all major procurements there will be a final design review before the purchase is initiated in order to ensure that the design and specifications meet the need of the project and that value engineering principles have been applied.

1.9.2 Director's Reviews, Laboratory Oversight Group (LOG)

The Brookhaven Associate Laboratory Director (ALD) for Nuclear and Particle Physics or his designee will appoint a committee to conduct periodic reviews of the APUL Project to monitor its progress. Director's Reviews are held at the ALD's discretion, typically on an annual basis and prior to any major DOE CD review. The reviews will be conducted by members of the Laboratory Oversight Group, Chaired by the ALD or his designee (e.g., Deputy ALD for Particle Physics).

1.9.3 DOE Reviews

DOE will review the APUL project according to its procedures. Consequently it is expected that the APUL project will be reviewed by the DOE before CD-1, CD-2 and CD-3 approvals. There will be also annual reviews by DOE.

1.10 Quality Assurance

At Brookhaven APUL will follow BNL Quality Assurance Policy, which is described in the Quality Management section of the Standards-Based Management

System (https://sbms.bnl.gov/sbmsearch/msd/QMS/QMS_msd.cfm). The Project Manager assigns the QA/QC function to the appropriate Level 2 manager for the APUL Project. Stop Work Authority related to quality of work has been delegated to all personnel within the Project.

The APUL Quality Assurance plan is presented in detail in a separate document [8].

2 Technical description of the Project

2.1 Introduction

The dipoles required in Intersection Regions (IRs) of the LHC have field and aperture requirements close to those of the RHIC [4] arc dipole magnets. Thus the superconducting coils developed for those magnets were used in cost-effective dipole designs that satisfied CERN's requirements [9]. Under the auspices of the US-LHC Project, the required magnets were built at BNL. Tooling constructed for the RHIC program was used, as far as possible. Some of the tooling has since been decommissioned. The remaining tooling will be used, with modifications as needed, for the construction of the APUL deliverables, which are one D1 magnet and one D1 cold mass. (A magnet is composed of a cold mass installed in a cryostat. Thus, APUL will build two cold masses and one cryostat.)

The RHIC arc dipole is a well understood magnet with good quench performance and field quality. The magnet is well matched to CERN requirements. The maximum operating field of the RHIC arc dipoles is 3.45 T, but with significant margin, so operation at the LHC's ultimate energy of 7.54 Tev, which requires a central field of 4.093 T (6290A), is well within the range of the magnet. The measured RHIC multipoles served as the basis for the US-LHC D1 specifications. For APUL, CERN has imposed the additional requirement [20] that the absolute value of the normal sextupole, evaluated at 17 mm radius, be less than 2 "units". To accomplish this, provision will be made to add iron shims on the outside of the helium vessel at the magnet midplane.

The D1 superconducting coils are mechanically the same as those built for the RHIC arc dipole magnets. The D1 magnets are designed with one RHIC-style cold mass in a cryostat.

Some changes are necessary, however. The cold masses will be straight, not curved with a 47 mm sagitta as in RHIC. The cold bore tube will be larger in diameter. Quench protection heaters will be required so that the magnets can be protected from absorbing excessive energy in case they quench. (This protection was provided by diodes in RHIC but these diodes are not suitable in the high radiation environment of the LHC.) Steel keys will be used when the coils are collared in the yoke. This document will describe the principal features of the RHIC arc dipole and the changes that are needed for the LHC D1.

The cold masses will be installed into an LHC-diameter (0.914 m) vacuum containment. CERN will supply temperature sensors, sockets for fiducials, and beam tubes. Brookhaven will build a heat shield that fits around the cold masses and will include the necessary cryogenic piping and its supports.

The cold masses are assembled into cryostats to make completed magnets. The cryostat consists of a cylindrical vacuum vessel, aluminum heat shield, blankets of multi-layer thermal insulation, cryogenic pipes, and the magnet support system. A variety of measurements, both mechanical and electrical, will be made on the magnets during the construction process. All subassemblies must satisfy the test requirements before incorporation into a magnet.

Completed magnets are tested at cryogenic temperatures.

2.2 Technical Description

2.2.1 Superconductor

A 30-strand (wire) superconducting cable will be used in the fabrication of the two cold masses. A similar cable was used for the RHIC arc dipole and quadrupole magnets [4]. This cable, in BNL inventory, was fabricated during the US-LHC project**.** Consequently, the cable fabrication methods are well developed. The superconductor wire to be used in the cable was purchased for the SSC program and has been kept in storage since the end of that project. Its properties are similar to those of the wire used for RHIC, but with a copper to superconductor ratio of 1.8 rather than 2.25. With active quench protection in the magnets, and a sizable margin between required operating current and predicted quench current, it is anticipated that this material will give satisfactory results.

The mechanical and electrical properties of the superconducting wire to be used are summarized in Table 2-1. Each wire consists of 4165 NbTi alloy superconducting filaments with a nominal diameter of 6 µm and a spacing of >1 µm. The exact number of filaments was chosen by the superconductor vendor based on the details of the billet design. Copper is used as the matrix between filaments. It occupies the central core of the wire, and it provides an outer covering for the wire. Copper represents about 64% of the wire cross section and is important for the cable and magnet operational stability as well as for protection against burn-out through overheating during a quench. The wire diameter of 0.648 mm was tightly controlled during final stages of manufacturing and was checked with a laser micrometer.

The wire minimum critical current is defined at a temperature of 4.22 K, an applied magnetic field of 5 T perpendicular to the wire axis and a resistivity of 1×10^{-14} Ω·m based on the total wire cross section. This current corresponds to a minimum current density in the NbTi superconductor of 2750 A/mm^2 at 5 T. The SSC wire meets or exceeds this minimum specification.

Table 2-1 Superconducting wire parameters.

Item	Units	Value
Mechanical		
Nominal filament diameter	µm	6
Nominal filament spacing	µm	> 1
Nominal copper to superconductor ratio		(1.8 ± 0.1):1
Number of filaments		4165 ± 20
Wire diameter	mm	0.648 ± 0.003
Wire twist direction		Right
Wire twist pitch	mm	13 ± 1.5
Electrical		
Wire min. critical current at 5 T, 4.2 K	A	325
Wire maximum critical current at 3 T	A	1.6 3 measured I_c @ 5 T

Wire maximum R(295 K)	Ω/m	0.082
Wire minimum RRR		38

Thirty wires are fabricated into a Rutherford-type cable by first twisting them around a mandrel, then rolling them into a flat, keystoned shape with dimensions given in Table 2-2 and Figure 2-1. The variations of the cable dimensions, especially the cable mid-thickness, were tightly controlled because the magnetic field quality of the magnets and the coil prestress are dependent on them. The cable lay is chosen to be opposite to the wire twist and requires a cabling machine operating in a planetary mode for fabrication. The cable minimum critical current (see Table 2-2) is defined in a similar way to that for the wire, but with the magnetic field perpendicular to the wide surface of the cable and with compensation for self-field. The cable minimum critical current can be obtained from the wire minimum critical current at 5 T times 30 (number of wires in cable) and multiplying by 0.95 (allowance for 5 % degradation in cabling). All cables that are used for coil winding are fabricated without any “koldwelds”.

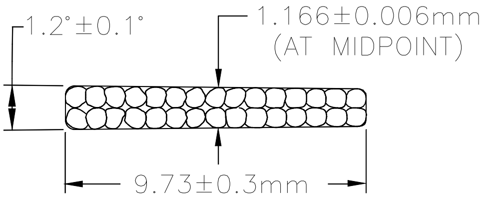


Figure 2-1 Cross section of the cable to be used to fabricate coils for LHC dipoles.

Table 2-2 Superconducting cable parameters.

Item	Units	Value
Mechanical		
Number of wires in cable		30
Cable mid-thickness	mm	1.166 ± 0.006
Cable width	mm	9.73 ± 0.03
Cable keystone angle	deg	1.2 ± 0.1
Cable lay direction		Left
Cable lay pitch	mm	74 ± 5
Electrical		
Cable minimum critical current at 5 T, 4.2 K	A	9260
Cable maximum R (295 K)	Ω/m	0.00287
Cable minimum RRR		38

Several differences with respect to RHIC magnets are noted. The cable interstrand resistance may differ from that in the Oxford-produced cable used in the RHIC production magnets. This will change the field distortions due to eddy currents while the magnets are ramped. In addition, the SSC wire to be used has at least some annealing vs. no annealing of the wire used in RHIC (indicated by cable RRR higher than ~ 40). Coils made with this wire are expected to have less post-cure shrinkage than experienced with the RHIC coils, so the coil lengths will be somewhat longer than in RHIC. These differences are not expected to compromise magnet performance in any significant way.

As mentioned, the wire to be used for these magnets was purchased in the SSC program and was available for the LHC program. Wire from four vendors was available and, in order to study its properties, cable was made from each type of wire, and the properties of the cable were measured [10]. Some results are listed in Table 2-3.

Table 2-3 Selected properties of the prototype cable made from wire available to the LHC program. The properties of the available wire are known to vary, however.

Vendor	Cu/SC Ratio	Interstrand Resistance, μΩ	I_c, kA (5T, 4.2K)	J_c, A/mm^2 (5T, 4.2K)	R, Ω/m (295K)	RRR	Shrinkage,%, 1 hr@225 C
Alsthom	1.87	127	9.651	2770	0.00276	44	0.41
Furukawa	1.76	12	9.949	2762	0.00283	39	0.40
Outokumpu	1.82	14.2	10.448	2983	0.00280	53	0.30
Oxford	1.79	542	10.349	2887	0.00280	45	0.36

2.2.2 Beam tube

Dimensions are given in Table 2-4. Two of the four D1 magnets in the LHC require a maximum aperture, so the beam tubes are larger than the RHIC beam tubes. A smaller gap between the beam tube and the coil can be allowed since the magnets will be cooled by superfluid helium (1.9 K).

The tubes are centered inside the coils: horizontally with G-10 bumpers spaced axially at regular intervals, vertically by the phenolic spacers. The gap between tube and coil defines a helium buffer space. The tube is seamless, 316 LN stainless steel and is wrapped with 25 μm Kapton with 66% overlay. This provides 75 μm of insulation, which is tested for integrity to ground at 5 kV.

Experimental requirements at the LHC require the maximum aperture in two of the D1 magnets, leaving no space for a full length liner. Thus, copper-plating of the beam tubes will be required to reduce the beam impedance.

Table 2-4 D1 Dipole beam tube parameters.

Item		
Outer diameter	mm	78.00 ± 0.38
Outer diameter inc. Kapton wrap	mm	78.1
Wall thickness	mm	1.96 ± 0.18
Inner diameter, nominal	mm	74
Weight, nominal	kg	38
Beam tube-coil radial gap, nominal	mm	1.0

2.2.3 Dipole Coil

The superconducting coil is assembled from two half-coils that are wound on automated machinery and then formed into a specified size in a precision molding operation. It consists of a single layer of 32 turns per half-coil arranged in four blocks with intervening, symmetric copper wedges; the sizes and positions of the wedges and pole spacers give field harmonics that are small. The four current blocks per half-coil design is identified as 9B84A. The cable is insulated with 2 double layers of the polyimide film Kapton CI. The first double layer has polyimide adhesive on the outer side of the film; the second has it on both sides. This all-polyimide insulating system requires a brief exposure to a temperature of 217 °C to set; an appropriate curing cycle was developed and extensively used in the RHIC program with excellent results. The coil ends have been designed to simplify construction and to reduce harmonic content. The number of spacer parts, machined from Ultem, in the two ends of each half-coil totals 27: 17 turn spacers, 2 end saddles, and 8 wedge tips. The coil design parameters are given in Tables 2-5 and 2-7.

The coil length given is that of RHIC production coils. As mentioned earlier, the superconductor wire in those coils was “full-hard”, whereas the SSC surplus wire to fabricate the cable to be used in these coils is “half hard”. This means that it was annealed towards the end of its production. Coils have a tendency to shrink and develop considerable tension during the curing process, so that they become shorter upon removal from the curing mandrel. This is due to tension in the superconducting filaments within the wire, which is developed during wire manufacturing in the draw-down steps, and which is released as the copper anneals during curing. Those that have been made with annealed wire demonstrate less shortening, so the length of these coils for the LHC magnets in expected to be somewhat longer (several millimeters) than given in Table 2-5.

Table 2-5 Dipole coil design parameters.

Item		
Inner diameter	mm	80
Outer diameter	mm	100
Length, overall	m	9.646
Length, coil straight section	m	9.266
Cable length per half-coil	m	610
Cable mass per half-coil, bare	kg	50
Cable mid-thickness with insulation, under compression	mm	1.352
Dielectric strength: current to ground @ 5 kV	μA	< 200
Coil-collar insulating Kapton thickness, inc. quench resistor	mm	0.64
Midplane Kapton thickness	mm	0.10
Cable wrap material thickness, Kapton CI	μm	25
Pole angle	deg	73.18
Number of turns per half-coil		
1st block (pole)		4
2nd block		8
3rd block		11
4th block (midplane)		9

Table 2-6 Coil wedge parameters.

Wedge	Angle, deg	Inner edge thickness, mm	Radial width, mm
1 (pole)	16.68	7.12	9.70
2	9.83	3.09	9.70
3 (midplane)	8.10	0.39	9.65

The coils were keyed to the yoke laminations through the precision-molded, glass-filled phenolic (RX630) insulator-spacers. The phenolic insulators separate the coil from the steel yoke and provide both electrical isolation of the coil from ground as well as reduced magnetic saturation effects at high field. To reduce problems with assembly of the beam tube and coils, the radial thickness of the RX630 spacers was decreased from the US-LHC value, 9.68 mm. to 9.47 mm.

2.2.4 Dipole Yoke

The steel yoke performs several functions: it serves as a magnetic return path and thereby enhances the central field, it acts as a “collar” that applies mechanical prestress to the coils through the phenolic insulator-spacer that references the coils to the yoke, and finally, it acts as a shield to reduce stray field in the adjacent ring of magnets. The yoke laminations contain holes for the necessary busses and for the flow of helium. The sizes and positions of these holes, and of the locating notch for the RX630 spacers, were carefully determined to minimize saturation effects. For RHIC, special strain gauge instrumentation and test methods were developed to ensure that the stresses in the magnet met the design goals. Using the yoke laminations as collars dictated the lamination thickness. The magnetic uniformity of the steel was a concern because randomizing of the steel properties through shuffling of laminations was not practicable in a job this large. Table 2-7 lists the design parameters for the yoke, shell, and end plate.

Table 2-7 Dipole yoke and yoke containment design parameters.

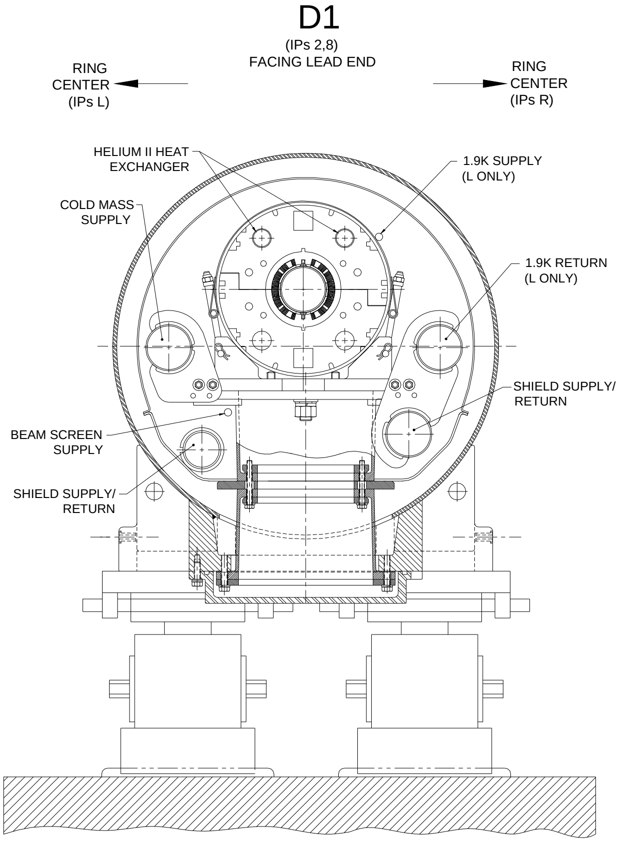
Item	Units	Value
Aperture for collared coil	mm	119.4
Yoke horizontal size	mm	266.7
Yoke vertical size	mm	266.7
Lamination length	m	9.64
Length inc. end plates	m	9.72
Overall length	m	10.23
Weight of steel	kg	2,757
Shell, wall thickness	mm	4.8
Shell, weight	kg	306
End plate, thickness	mm	31.8
End plate, weight	kg	18
Cold mass weight	kg	3,607

2.2.5 Electrical Connections and Quench Protection

The electrical connections to the magnets will be made with the usual convention in which current into the positive or “A” lead produces a normal dipole field with the south pole at the top. Definitions and conventions used at Brookhaven in the building and measuring of magnets are given in [11]. Results will be reported using the European convention (e.g., normal sextupole is b3, rather than b2 as for RHIC.)

The bus conductor for each magnet and its immediate neighbors is placed inside an insulating conduit that is then installed as a completed package into the bus slots of the yoke, typically at the bottom. The electrical connections between bus conductors and magnet leads are at the ends of the magnets, within the end volume contained between the stainless steel magnet end plate and the end of the magnet cold mass. This end volume also contains the thermal expansion joints for the bus conductors. These will follow BNL designs as developed for RHIC. No magnet warm-up heaters to accelerate the occasional warm-up of the cold mass are planned; warm gas only is used for warm-up in the LHC.

Quench protection heaters are used to protect the coils from excessive local energy deposition during a quench. The basic heater design was developed and extensively tested by BNL in the SSC program. The heaters run the full length of the magnet, one per quadrant, and are installed between the collars and coils at the time of coil assembly for collaring. Two independent circuits per magnet are included. In operation, these magnets will be connected in series and the quench protection system will, when triggered, fire one of these independent heater circuits in all the magnets.



The active quench protection system being planned for these dipoles will be the same as the first D1 magnets already delivered to CERN. The system will result in much lower peak quench temperatures than is the case in the similar RHIC dipoles, which are protected with diodes only, even though the conductor in these magnets will contain less copper. In the RHIC program, 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 margins in the final version of the RHIC dipole. Final estimates of worst case $\int I^2 dt$ values in RHIC magnets for conductor with a copper-to-superconductor ratio (Cu:SC) of 2.25:1 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. This damage temperature was measured in earlier experiments on full sized magnets at Brookhaven. Quench heater tests will be performed on the new completed D1 magnets to confirm the MIITS value for worst case operating conditions. Also quench heater performance will be tested and documented for use by CERN.

2.2.6 Cryostat

A cross section of the D1 cold mass housed in a cryostat is shown above. Each magnet that is delivered by BNL to CERN must fit correctly into a predetermined slot and must be so configured that connection to the LHC cryogenic and electrical system is facilitated. The Interface Specification developed for the US-LHC Project [16] will be used for APUL.

The D1 dipoles operate in a static bath of superfluid helium at 1.9 K. The operating temperature is determined by the logistics of position in the lattice of the LHC.

2.2.7 Transfer Function and Field Angle

Plots of the field angle and transfer function versus current are shown in Fig. 2-2 for one of the D1 magnets made for the US-LHC Project.

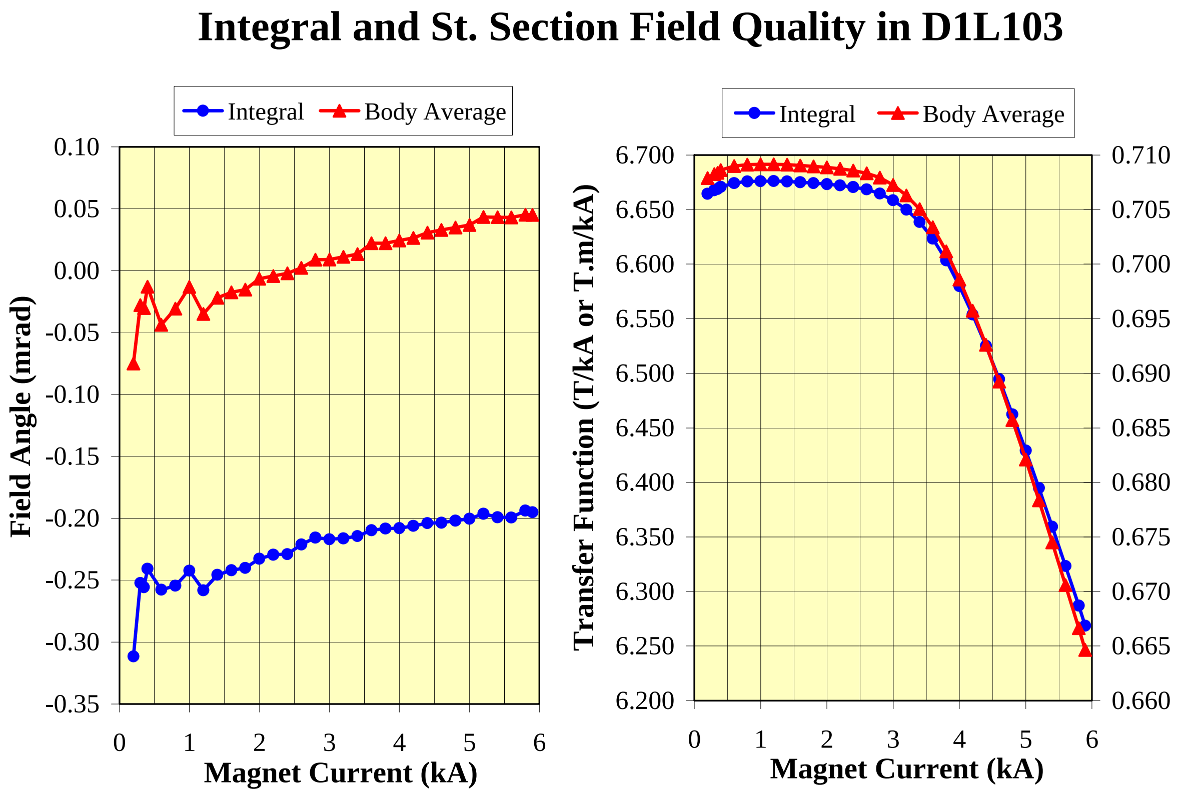


Fig. 2-2. Field angle and transfer function for D1L103.

2.2.8 Magnetic Field Quality

2.2.8.1 Measurements

Magnetic field measurements at room temperature ("warm") will be made after the coils are installed in the yoke in order to check that the measured values of the multipoles are within the expected range. Except for small systematic offsets in the lower allowed multipoles, warm field measurements have been shown to be closely related to the field multipoles measured when the magnet is cold. This will allow detection of errors in magnet construction that may not have been detected in the earlier construction testing. If needed, the low-order multipoles can be adjusted at this stage by uncollaring the coils and making small adjustments to the shims at the coil pole or midplane.

Warm magnetic measurements will be made again when be made when magnet construction has been completed, including all welding and installation into the cryostat. This measurement will check the dipole field angle orientation, the integral of the magnet's dipole field, and the variations of the field parameters along the length of the magnet. Following the warm tests, cold testing in 4.5 K liquid helium will be done on each magnet to check quench performance and to verify field quality. (Brookhaven does not have facilities to test at 1.9 K.)

The MOLE measuring system [12] developed at BNL and used for RHIC field measurements will be used for the LHC magnets. Integral fields will be measured with the stationary integral coil system [13] used for RHIC magnets.

2.2.8.2 Measurement Errors

The extensive measuring program carried out for RHIC magnets has given data that can be analyzed for systematic and random measurement errors. Such an analysis has been carried out, including also an analysis of errors in the calibration of the measuring coils. The analysis has been summarized in a series of tables and plots [14]. Table 2-7 is excerpted from the report. For clarity, the reference radius is 25 mm as in the report. These errors apply to the measurement system used for the RHIC arc dipole measurements, which will be used for these magnets, and will be different for other measuring systems. They are, however, a good benchmark for the accuracy that can be achieved in a carefully built and calibrated system.

Table 2-7 Estimated measurement errors. δ is the maximum error due to measuring coil construction/calibration, given as a percent of the value of the harmonic. $\sigma(b_n)$ and $\sigma(a_n)$ are the random errors in the measurements. $\Delta(b_n)$ and $\Delta(a_n)$ are the suggested values for the total measurement errors for magnets with small harmonics as in the RHIC dipoles. These include also some variations due to magnet changes after quench and/or thermal cycles as seen in the RHIC magnets. They are obtained by rounding the sum of the effects of all expected error sources upward and by specifying minimum values for several of the harmonics. Note: sextupole is n=3, σ and Δ in units (parts $* 10^{-4}$ of the central field), reference radius=25 mm.

n	δ, %	$\sigma(b_n)$, units	$\Delta(b_n)$, units	$\sigma(a_n)$, units	$\Delta(a_n)$, units
2	0.48	0.061	0.10	0.043	0.50

3	0.78	0.033	0.50	0.015	0.05
4	1.08	0.012	0.05	0.010	0.10
5	1.38	0.004	0.10	0.005	0.02
6	1.68	0.003	0.02	0.004	0.05
7	1.98	0.002	0.02	0.002	0.02
8	2.28	0.001	0.02	0.002	0.02
9	2.59	0.001	0.02	0.001	0.02
10	2.89	0.001	0.02	0.001	0.02
11	3.19	0.001	0.05	0.001	0.02

2.2.8.3 Expected Values

The magnets are designed to have harmonics that are small. Thus, the geometric multipoles (harmonics) are expected to be near zero. At low fields, persistent currents in the superconductor will generate normal sextupole (b3) and decapole (b5) components. The Functional Specification (Table 3.3) contains lists Reference Harmonics at low and high field [15]. For this magnet, CERN staff has requested that the normal sextupole be less than 2 x 10^{-4} units at high field, due to limitations in the corrector system. The production plan contains steps that will allow adjustment of this harmonic, if needed.

2.2.8.4 Measured values

Only one of the five US-LHC D1 magnets was measured at high field. The results for the normal and skew quadrupole and sextupole are given in Figs. 2-3 and 2-4. The variation of the normal sextupole with current is within the ± 2 unit limit requested by CERN. The absolute value can be adjusted by a small change in the assembly shims.

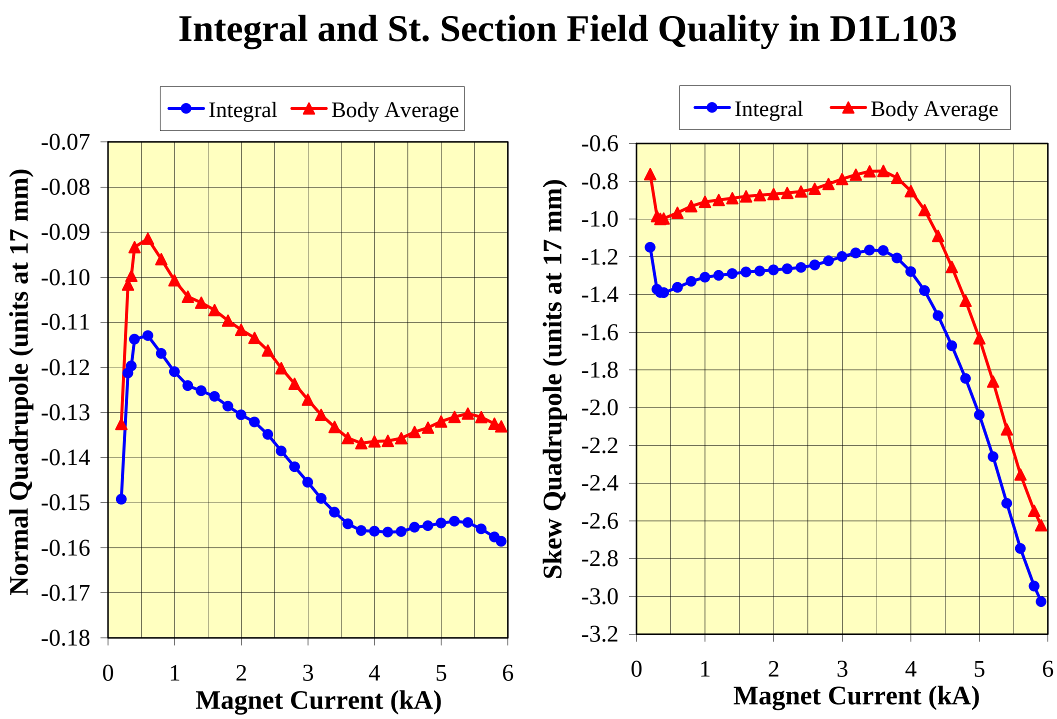


Fig. 2-3. Normal and skew quadrupole as a function of current in D1L103

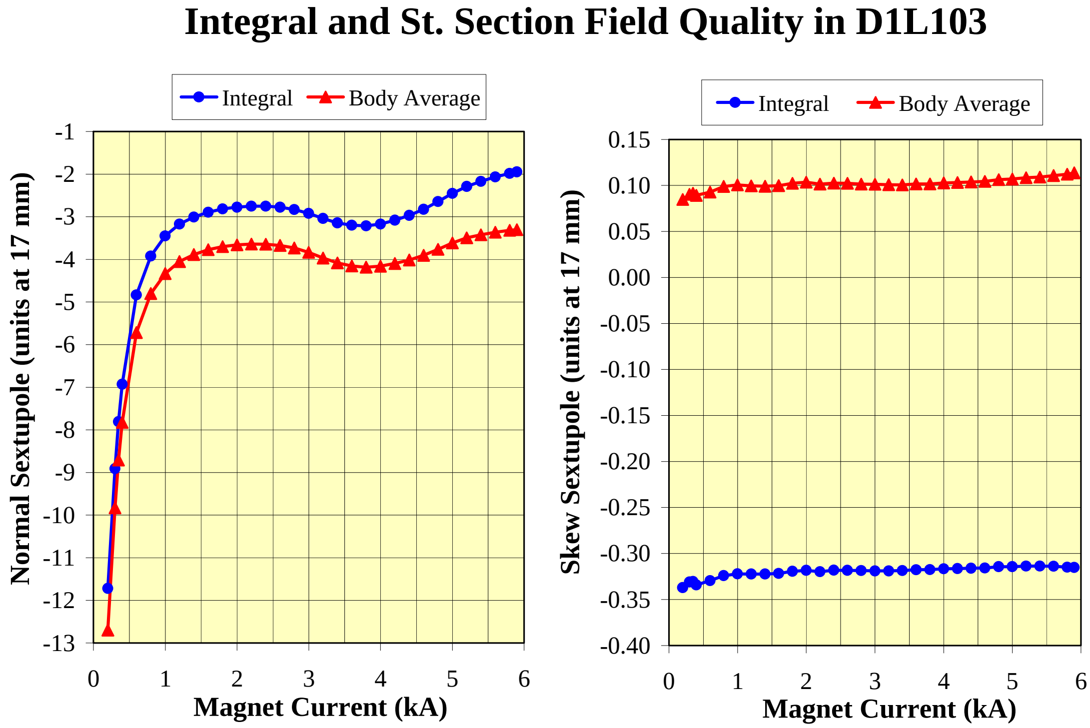
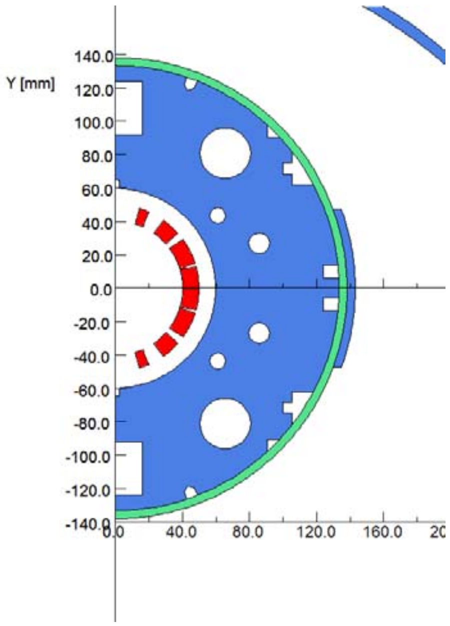


Fig. 2-4. Normal and skew sextupole as a function of current in D1L103

2.2.8.5 Shim for High-Field Sextupole for APUL

Fig. 2-5 (below) shows the placement of a shim at the midplane of the cold mass, just outside the helium vessel. Calculations indicate that, by the fraction of iron in this shim, he normal sextupole can be adjusted to fall within the specification (that it be less than 2 x 10-4 units). Placement of the shim outside the helium vessel makes it possible to make this adjustment without opening the helium vessel, saving time and schedule.



2.2.9 Shipping

Once construction and testing of the magnet and cold mass are complete, they will be shipped to CERN, using the same method that was successfully used for the US-LHC Project. To prepare the magnet for transit, steel support posts and end restraining frames will be installed to protect the cold mass support posts from damage. (The cold mass will be easier to prepare for shipping.) The magnet and cold mass will be sealed and filled with dry nitrogen so that moisture cannot penetrate the cryostat or cold mass. The magnet will be mounted on a shock-absorbing frame and then placed into a standard 40-foot-long shipping container. This container will be transported by truck to a shipping terminal, then by ocean freight to a terminal in Europe, then by truck to CERN.

2.3 Infrastructure Modifications

The reliability of the RHIC magnets has been excellent and none of the spare arc dipoles has been used in RHIC. Because of this, it was decided to decommission the tooling used to make 10 m coils and utilize the space for other purposes. Tooling to make the 3.7 m DX coils was also moved, but is being set up again. The DX magnets operate at the quench limit and maintaining a production facility for DX coils was judged to be a prudent course of action. As insurance against needing 10 m coils, the DX winding and coil cure tooling were set up in locations that allow it to be extended to 10 m. For APUL, the tooling will be extended to 10 m.

The cryo test facility used to test the US-LHC magnets, MAGCOOL, has not been maintained and will not be used for APUL. The helium liquefier has been upgraded with new controls and is now configured for doing only vertical dewar testing. APUL will modify the liquid helium distribution piping and an existing lead box assembly to test the D1 magnets in their cryostats. These modifications will enable the APUL D1 magnets to be tested at in liquid helium at 4.5 K. In the LHC, the D1 magnets will operate in 1.9 K superfluid helium, where their operating current will be higher than at 4.5 K.

3 Interface with CERN

As noted earlier, general arrangements for the construction of components for the LHC by DOE-sponsored projects such as APUL is covered by the agreement covering upgrades to the ATLAS and CMS detectors.

Three documents prepared for the US-LHC Project (the Functional Specification [15], the Interface Specification [16], and the Acceptance Plan [17]), contain nearly all the information specific to D1. An Arrangement signed by BNL and CERN lists the scope and schedule, as well as the tighter sextupole specification, for APUL [20]

4 References

Documents with titles in **bold** font are posted on the APUL June 20, 2011 DOE Review Website in the BNL Indico system (https://indico.bnl.gov/conferenceDisplay.py?confId=389), password apulcd2/3

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