iii. Standard Aperture Dipoles

The arc dipole magnets have a coil i.d. of 80 mm, are 9.7 m long and, with 264 of these magnets required, represent by far the largest single cost item for the collider. In addition, there are 24 insertion dipoles "D8" which are identical to the arc dipoles, and 72 insertion dipoles "D9, D6, D5I and D5O" which are shorter in length.

Dipole Cold Mass

Figure 1-3 shows a cross-section of the dipole cold mass. The dipole design is based on a single-layer "cosine theta" coil, wound from a partially keystoned, 30-strand NbTi superconducting cable and mechanically supported by a laminated "cold steel" yoke encased in a stainless steel helium containing cylinder. The helium vessel is also a load bearing part of the yoke assembly. This cold mass assembly is mounted within a cryostat consisting of a cylindrical vacuum vessel, an aluminum heat shield, blankets of multilayer thermal insulation, cryogenic headers, and the magnet support system. The nominal dipole operating field is 3.458 T at a current of 5.050 kA and an operating temperature between 4.3 and 4.6 K.

The RHIC dipole cold mass design incorporates a relatively large bore (80 mm), a modest operating field (3.45 T), a single-layer coil, a steel yoke assembled as collars, and no internal trim coils. The general design parameters are listed in Table 1-7.

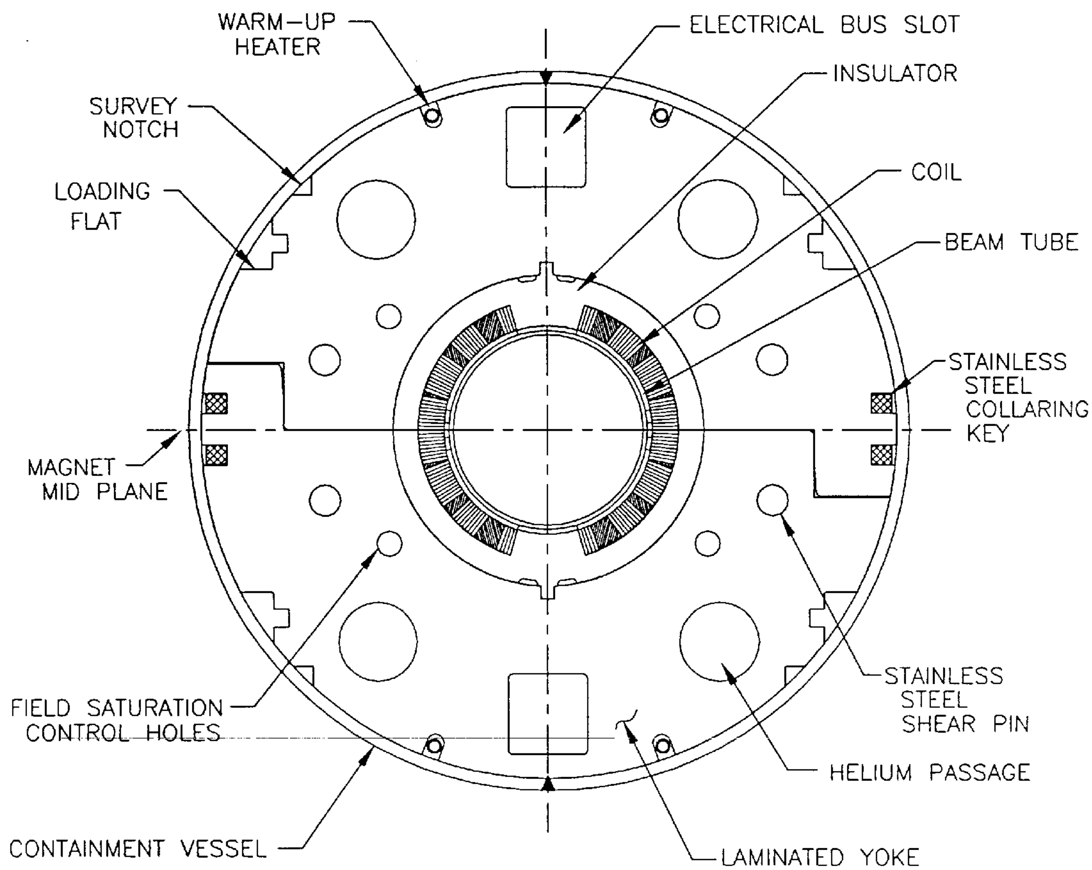

Fig. 1-3. Standard-aperture dipole cold mass cross-section (coil i.d. = 80 mm).

Table 1-7. Standard Aperture Dipole Parameters

Coil i.d.	(3.15 in.) 80	mm
"ARC" DIPOLES		
No. arc dipoles, two rings	264	
No. insertion dipoles, D8	24	
Magnetic length, arc and D8	9.45	m
Magnet rigidity - Injection	97.5	T·m
- Top energy	839.5	T·m
Integrated field strength, top energy	32.677	T·m
Dipole field - Injection	0.401	T
- Top energy	3.458	T
Quench field	~ 4.6	T
Operating temperature, max.	4.6	K
Ramp rate, nominal	0.042	T/s
Current - Injection	568	A
- Top Energy	5.093	kA
Lamination length	(379.4 in.) 9.64	m
Cold mass length	(383 in.) 9.73	m
Dipole bending radius, cold	243	m
Mechanical sagitta for 383 in. cold mass length	(1.91 in.) 48.5	mm
Cold mass, including interconnect cans and flange	(7952 lb) 3607	kg
Inductance	28	mH
Stored energy	351	kJ
INSERTION DIPOLES		
No. insertion dipoles, 6.92 m - D5I	12	
8.71 m - D5O	12	
2.95 m - D6 & D9	48	

Table 1-8. Dipole Beam Tube

Outside diameter	(2.875 in.) 73.0 mm
Outside diameter inc. Kapton wrap	(2.883 in.) 73.2 mm
Wall thickness (77 mil)	1.96 mm
Inner diameter, nominal	69 mm
Weight, nominal	(79 lb) 36 kg
Beam tube-coil radial gap	(133 mil) 3.4 mm

Dipole Beam Tube

The dipole utilizes a cold beam tube with dimensions given in Table 1-8. It is centered horizontally inside the coils with 2.7 mm thick by 76 mm long, G-10, longitudinal bumpers with 0.3 m axial spacing and vertically by the RX630 pole pieces, thus defining a helium buffer space. The tube is seamless, 316 LN stainless steel and is wrapped with 25 μm Kapton with 60% overlay, providing 76 μm of insulation which is hi-pot tested at 5 kV.

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 copper wedges; the size and positions of the wedges and the coil pole spacer have been designed to result in field harmonics meeting the rigid field quality specifications required for RHIC. The four current block design, which has 3 symmetric wedges, is identified as 9B84A in the DRE dipoles. The coil design parameters are given in Table 1-9.

The superconducting cable, 9.73 mm wide and 1.17 mm in average thickness, consists of 30 strands of 0.65 mm wire, cabled, compacted, keystoned (to 1.2°) and insulated with 2 double layers of Kapton CI film. The first double layer has polyimide adhesive on the outer side of the tape; the second has it on both sides.

Table 1-9. Arc Dipole Coil Design

Inner diameter	(3.146 in.) 79.9	mm
Outer diameter	(3.938 in.) 100.0	mm
Length, overall	(379.75 in.) 9.646	m
Length, coil straight section	(364.80 in.) 9.266	m
Cable length per magnet	(4002 ft) 1220	m
Cable mass per magnet, bare	(220 lb) 100	kg
Effective cable mid-thickness with insulation under compression	(0.05322 in.) 1.352	mm
Minimum creep path, conductor to ground	(0.2 in.) 5.1	mm
Dielectric strength:current to ground @ 5 kV	< 200	μA
Yoke-coil insulating spacer thickness	10	mm
Midplane Kapton thickness	(0.004 in.) 0.10	mm
Cable wrap material thickness, Kapton	(0.001 in.) 25	μm
Pole angle (coil center radius)	73.178	deg
Number of turns	32	
Number of turns, 1st block (closest to pole)	4	
Number of turns, 2nd block	8	
Number of turns, 3rd block	11	
Number of turns, 4th block	9	

WEDGE PARAMETERS

Wedge #	Angle	Inner Edge Thickness	Height
1	16.684°	(0.2802 in.) 7.12 mm	(0.382 in.) 9.70 mm
2	9.833°	(0.1217 in.) 3.09 mm	(0.382 in.) 9.70 mm
3	8.105°	(0.0155 in.) 0.39 mm	(0.380 in.) 9.65 mm

The coils are keyed to the yoke laminations through a precision-molded, glass-filled phenolic (RX630) insulator-spacer. The phenolic spacer separates the coil from the steel yoke and provides both electrical isolation of the coil from ground as well as reduced saturation effects at high field.

The coil ends have been revised to simplify construction and to reduce harmonic content. The number of parts in the ends, about 64 in each coil end, was reduced, by using thicker spacers between the turns, to about 23. The solid spacers, which will be molded of Ultem 6200 during production, replace spacers assembled from laminations and improve the fit as well.

Dipole Yoke

The steel yoke performs several functions: it serves as a ferromagnetic return path, thus enhancing the central field by 34%; it also acts as a "collar" that applies mechanical prestress to the coils through the precision-molded, glass-filled phenolic insulator-spacer which references the coils to the yoke laminations. Finally, the steel acts as a shield to eliminate interbeam magnetic interference in the adjacent ring of magnets.

The yoke laminations are punched from 6.35 mm thick low-carbon steel plate. To meet the rms tolerances for the magnetic field integrated over the length of the dipoles requires that the weight of steel in the yoke be controlled to within 0.07%; to achieve this, the laminations that make up the sections of a yoke are weighted and adjusted to this tolerance. During magnet assembly, a press compresses the yoke around the coils; the yoke is subsequently held together with steel keys on the outer steel surface to the design preload of nominally 69 MPa kpsi at room temperature acting on the coils.

After completion, the coil-in-yoke assembly is inserted snugly into a 4.9 mm thick, split stainless steel shell, which is then welded along the vertical midplane. Before the welding begins, the magnet is placed in a fixture that introduces the required 48.5 mm sagitta; this sagitta is locked in place when the stainless steel half-shells are welded together. The welding operation also forms the outer, high-pressure (2.1 MPa) helium containment vessel. The shrinkage of the weld causes increased compression of the steel collar blocks and, therefore, the coils. Further compression is provided at operating temperature due to the differential contraction of the stainless steel shell relative to the steel yoke. The yoke design parameters are listed in Table 1-10.

Table 1-10. Arc Dipole Yoke and Yoke Containment Design Parameters

YOKE		
Inner diameter	(4.700 in.) 119.4	mm
Outer diameter	(10.5 in.) 266.7	mm
Lamination length	(379.4 in.) 9.64	m
Length, including end plates	(383.0 in.) 9.73	m
Lamination thickness	(0.250 in.) 6.35	mm
Length, lamination packs	(0.500 in.) 12.70	mm
Weight of steel	(6079 lb) 2757	kg
Mechanical sagitta for 383 in. cold mass length	(1.91 in.) 48.5	mm
Bus cavity - width	(1.25 in.) 31.75	mm
- height	(1.25 in.) 31.75	mm
Number of cooling channels	4	
Diameter of cooling channels	(1.187 in.) 30.15	mm
YOKE CONTAINMENT SHELL		
Inner diameter, prior to assembly	(10.516 in.) 267.1	mm
Wall thickness (0.192 in.)	4.9	mm
Weight of shell	(674 lb) 306	kg
ASSEMBLY PRESTRESS		
Room temperature	> (10 kpsi) 68.9	MPa
Cold	> (4.8 kpsi) 33.1	MPa

Table 1-11. Dipole, Electrical Design Requirements

Dipole bus stabilization copper	58	mm^2
Quadrupole bus stabilization copper	58	mm^2
Bus expansion joint motion	46	mm
Warmup heater, resistance/heater @ 300 K	2.24	Ω
Warmup heater, power/heater	938	W
Quench protection diode, max. energy	140	kJ
Quench protection diode, max. reverse leakage current @ 1 kV	10	mA
Quench protection diode, 4.2 K forward voltage threshold @ 10 mA	3.0	V

Electrical Connections and Quench Protection

The design of the machine uses separate main electrical bus systems for the dipoles and the quadrupoles. The bus conductor for these and the various corrector magnets is placed inside an insulating "pultrusion" that is then installed as a completed package into the bus slots at the top and bottom of the yoke. The electrical connections between bus conductors and magnet leads are at the ends of the magnets, within the volume contained by the stainless steel helium containment vessel and end bellows. The end volume also contains the thermal expansion joints for the bus conductors and quench protection diodes. A heater consisting of a stainless steel pipe will accelerate the occasional warm-up of the cold mass.

Early in the R&D project, 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 present version of the RHIC dipole. Recent estimates of worst case $\int I^2 dt$ values for conductor with the planned copper-to-superconductor ratio (Cu:SC) of 2.25:1 and a single quench protection diode for each magnet give 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. The electrical design parameters for the dipole magnet are listed in Table 1-11.

Dipole Cryostat

The cryostat is the structure which must make the transition from the 4 K environment of the magnet cold mass to ambient temperature as shown in Fig. 1-4. The cryostat must accurately position the magnet cold mass to a given point in the accelerator lattice, while at the same time, minimizing the refrigeration load, by a method that can be implemented reliably in an industrial production setting. The major components comprising the cryostat are the 6 mm thick carbon steel (ASTM A53) vacuum vessel of 610 mm outer diameter, the aluminum heat shield (1100-H14) maintained at a nominal temperature of 55 K, blankets of multilayer aluminized Mylar thermal insulation, the various cryogenic headers, and the post-type supports which carry the loads generated by the magnet to the ground.

The superinsulation blankets use alternating layers of reflectors (6 µm non-crinkled Mylar, aluminized on two sides) and spacers (0.15 mm REEMAY 2006). In order to miminize the heat load, the thickness of the aluminum on the Mylar used at 4.5 K is thicker (600 Å) than that on the Mylar at 55 K (380 Å) because of the difference in wavelength of the shielded radiation. The cryostat design parameters are given in Table 1-12.

The support post is comprised of two identical molded plastic "hats" attached end to end. A standard arc dipole will have three such supports. Plans call for them to be precision molded as tubes with flanges from Ultem 2100, a glass-filled plastic material. The heat shield is captured between the top and bottom hats. The bottom of each post is bolted rigidly to the vacuum tank. The cold mass is attached to cradles atop each post. The cradles are machined from stainless steel castings. The center cradle is fixed to its post, while the end cradles can move in the axial direction, allowing the cold mass ends to shrink toward the center during cooldown.

The legs of the vacuum chamber are carbon steel castings. The surfaces of these legs are used to provide the exterior survey fiducial references; survey fixtures will translate the positional information provided by the reference features to a location outside the vacuum tank.

Table 1-12. Dipole Cryostat

Vacuum vessel, o.d.	(24 in.) 610	mm
Vacuum tank, wall thickness	(0.25 in.) 6.4	mm
Heat shield, o.d.	(21.0 in.) 533	mm
Heat shield, wall thickness, upper section	(0.09 in.) 2.3	mm
Heat shield, wall thickness, lower section	(0.125 in) 3.2	mm
Recooler supply header, i.d.	(2.71 in.) 68.8	mm
Helium return header, i.d.	(2.71 in.) 68.8	mm
Utility header, i.d.	(2.71 in.) 68.8	mm
Shield cooling pipe, i.d.	(2.157 in.) 54.8	mm
Number supports	3	
Support spacing	(141.5 in.) 3.59	m
Weight distribution		
Center post	40%	
	(3395 lb) 1540	kg
Outer post ea.	30%	
	(2532 lb) 1148	kg
Post, i.d.	(8.38 in.) 212.8	mm
Post, wall thickness	(0.189 in.) 4.8	mm
Heat leak per leg at 4.5 K	0.1	W
Heat leak per leg at 55 K	1.0	W
Superinsulation layers, cold mass only	17 Reflector, 32 Spacer	
Superinsulation layers, cold mass plus piping	38 Reflector, 53 Spacer	
Superinsulation layers, shield	62 Reflector, 62 Spacer	

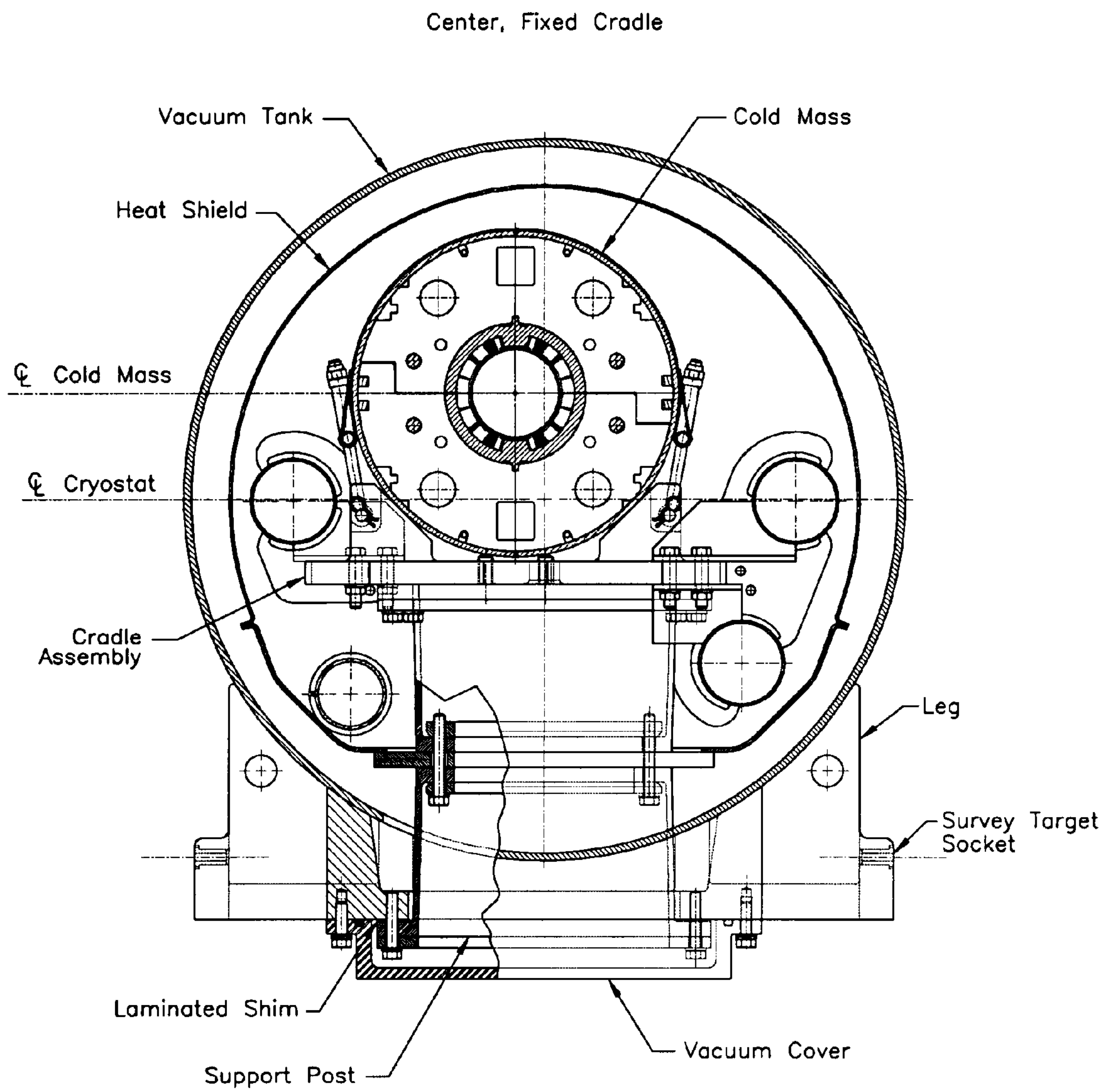

Fig. 1-4. Arc dipole cross-section (610 mm vacuum vessel o.d.).

Contractually Obligated Dipole Magnetic Field Quality Requirements

Warm magnetic measurements to measure field multipoles are required when magnet construction has been completed, including all welding and installation into the cryostat. 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. The data will be examined for conformance to field quality requirements specified in the contract with the magnet supplier. These include the dipole field angle orientation, the integral of the magnet's dipole field, the multipole content of the field, and the variations of the field parameters along the length of the magnet. The field specifications for the magnet include nominal values and allowable variations with respect to nominal. It is anticipated that all magnets properly built to print will easily pass the field quality test, and that only a magnet with serious construction deficiencies will fail to pass the test.

Table 1-13 gives the field variations specified for the arc dipoles for RHIC. The number given for each random variation is the maximum standard deviation σ about the mean allowed for any sample of 10 or more consecutively-made magnets. Any particular magnet of a sample may be up to 3σ outside the listed random variation and still be acceptable, provided the systematic multipoles of the sample remain within the specified value. The dipole field angle α is determined relative to the cryostat survey monuments.

Table 1-13. Contractual Dipole Field Quality Requirements

Tolerances of Integral Field and Field Angle		
Integral field, magnet to magnet variation, rms	5×10^{-4}	
Single magnet, mean dipole angle, α	±5 mrad	
Single magnet, variation (twist) of dipole angle $\Delta\alpha$ from mean, rms	3 mrad	
Specified Geometric Field Variations of Measured Multipoles*		
	Allowed Multipoles	
	Systematic (limit)	Random (σ)
Sextupole, b_2	±1.4	4.6
Decapole, b_4	±0.7	2.2
	Unallowed Multipoles	
	Systematic (limit)	Random (α)
Normal		
Quadrupole, b_1	±0.6	2.0
Octupole, b_3	±0.4	1.3
Skew		
Quadrupole, a_1	±1.3	4.0
Sextupole, a_2	---	1.3
Octupole, a_3	---	2.2
Decapole, a_4	---	0.6

*Quoted as 10^{-4} of dipole field at 25 mm radius