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A HIGH FIELD SUPERCONDUCTING BEAM TRANSPORT IN A BNL PRIMARY PROTON BEAM*

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Abstract

Construction of a slow external beam switchyard at the BNL AGS requires a rapid 20.4° bend in the upstream end of the beam line. Two curved superconducting window dipole magnets, operating at 6.0 T and about 80% of "short sample" magnetic field, will be utilized with two small superconducting sextupoles to provide the necessary deflection for a 28.5 GeV/c primary proton beam. Because the magnets will operate in a primary proton beam environment, they are designed to absorb large amounts of radiation heating from the beam without quenching. The field quality of the superconducting magnets is extremely good. Computer field calculations indicate a field error, $\Delta B/B_0$, equivalent to $\pm 1 \times 10^{-4}$ up to 75% of the 8.26 cm full aperture diameter in the magnet.

Introduction

The improvement program for the slow extracted beam switchyard at the Brookhaven National Laboratory AGS includes a fourth independent "D" target station. To utilize an existing experimental hall made available by the shutdown of an internal target, the 28.5 GeV/c primary proton beam must be bent through an angle of 20.4° with respect to the "A" beam line as shown in Fig. 1.

In order to locate target station "D" more centrally in the experimental hall so as to provide space for the secondary beams from the primary target and facilitate shielding of the primary proton beam to the target, two high field superconducting magnets designed to operate at 6.0 T will be used to produce the 20.4° bend. The design of these magnets will be based on that of the 8° superconducting window frame magnets which have been operating for over 5 years in another primary proton beam line at the AGS.[1]

Electrostatic beam splitters upstream of the superconducting magnets require that the primary proton beam be of very low divergence (∼0.15 mrad). This divergence leads to a beam size at the magnets of up to 5 cm which would include 99.9% of the intensity distribution of the beam. A 0.1% loss of a 10^{13} protons/pulse beam in the magnets every 2.5 sec. will generate an additional 20 watt heat load. The structure of the magnets will be curved to follow exactly the trajectory of the proton beam. This unique construction will minimize the overall size of the magnets by avoiding the dimensional increases which are necessary in straight magnets from sagitta considerations.

Magnet Parameters and Construction

The parameters for the two superconducting dipoles and sextupoles in the 20.4° magnet bending system are given in Table I.

The dipoles will each be 3.05 m long with a 7.303 cm diameter cold bore and will be curved with a radius of 14.603 m to match the particle beam trajectory. Each magnet will be constructed around a 7.620 cm OD stainless steel bore tube which will be rolled on the 14.603 m radius. This tube will be placed in a mold and encapsulated in fiber glass epoxy which, when assembled with pole plates and coil end blocks, will become the coil form on which the dipole is wound as shown in Fig. 2. A small radial clearance will be established between the tube and the epoxy so that no mechanical stresses will result from differential expansion and contraction.

The main dipole coil will consist of 9 layers of 42 turns each wound with a 1.68 mm x 3.36 mm formvar insulated Cu-NbTi composite conductor, and a single outside layer of 102 turns wound with a similar 1.30 mm x 2.59 mm conductor. The conductor for the outside layer will be wound so that its larger dimension is at 90° to that of the inner layers' conductor. This orientation will enable more turns of this smaller conductor to be placed in the low field region of the coil. Each conductor will have 2718 filaments of NbTi twisted in a copper matrix with a Cu to NbTi ratio of 1.25 to 1.

Additional windings consisting of two 26 turn Helmholtz pair coils will be located approximately 60° from the horizontal centerline of each magnet as shown in Fig. 2. These coils will be connected electrically in series with the main coil and will not only add to the dipole field but also provide some sextupole bias correction.

Sheets of anodized high purity aluminum 1.27 mm thick and extending the full height of each coil will be inserted between each coil layer. The aluminum sheets will be coined with vertical grooves that allow liquid He to make direct contact with the coil conductors. The vertical grooves will terminate in horizontal coolant channels at the top and bottom of each coil package which are, in turn, in contact with the magnet iron. Excellent thermal and dynamic stability will be provided by the heat capacity of the helium and the high thermal conductivity and diffusivity of the aluminum.

Each total coil package will be confined mechanically after winding by bolting side retainer plates to the pole plates as shown in Fig. 2. The side retainer plates will make an integral unit of the central tube and coil assembly and provide the correct curved geometry for a close fit in the laminated core. They will also provide a modest compressive preload on the coil package before assembly in the core.

The iron magnet cores will be split on the horizontal midplane. They will be laminated with an adhesive applied to one face of each lamination to bond them together and insulate them from each other. The split cores will be held together by the interlaminar bonding and stacking studs with an expected packing factor of 96%. The magnet design will permit pulsed operation. A thermal fit of the split cores around the coil assemblies with appropriate shims will result in a metal to metal fit.

To provide additional correction, two small superconducting sextupoles will will be included as part of the magnet system, one in the upstream end of the first magnet cryostat, and the second in the downstream end of the second magnet cryostat. The conductor for these sextupole magnets is a 0.81 mm x 1.62 mm Cu-NbTi composite with 627 NbTi filaments and a Cu to NbTi ratio of 5 to 1. The parameters for the sextupole magnets are given in Table I.

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Magnet Cryostats

In concept, the design of the two magnet cryostats is typical of low heat-leak systems with a thermally shielded inner vessel supported within an outer vacuum vessel by a high impedance suspension system. For this magnet system, each inner vessel housing a magnet will be supported from the top plate of the outer vessel as shown in Fig. 3 and top loaded into the outer vessel. With this arrangement, the magnet-inner vessel assemblies will be easily accessible for servicing and may be quickly lifted out and removed from the area as units, thus minimizing exposure of service personnel to the high radiation environment in which the magnets will be located.

The vacuum vessels will be welded box-like structures fabricated from aluminum plate. The removable top plates from which the magnets will be supported will complete the enclosures. The vacuum vessels will be approximately square in cross-section and curved along their lengths to conform to the curved magnet assemblies. Each inner vessel will be supported at two points along its longitudinal axis by a length of heavy-duty roller chain positioned so as to compensate for rotational moments resulting from the curved geometry of the magnets. Lateral and longitudinal motions of each inner vessel will be constrained by orienting the support chains off-plumb. The ends of the chains may be adjusted vertically and laterally to position the magnets precisely.

The inner vessels will be fabricated from stainless steel pipe curved to form a close-fitting envelope about the magnets. Multi-layer insulation will be used to provide a thermal barrier.

The outer vessels of the two bending magnets will be coupled in tandem to form a common insulating vacuum envelope. Flexible bellows assemblies will be used between the adjacent ends of the inner vessels to interconnect the helium gas and liquid volumes in the two vessels. The two dipole magnets will be connected electrically in series as will the two sextupole magnets so that only two pairs of helium gas-cooled current leads will be required. Figure 4 shows a side elevation view of the magnet-cryostat assembly.

Magnetic Field Calculations

Magnetic field computations using the cross-section of the superconducting dipole coils shown in Fig. 2 indicate that the "D" line bending magnets will have extremely small aberrations at all field levels except for the sextupole component $(r^2, 3\theta)$. For the "D" line magnets, the sextupole component will be biased so that it varies from $-0.18\%/\mathrm{cm}^2$ at low field values to $+0.18\%/\mathrm{cm}^2$ at high field values. This biasing will be accomplished by connecting the two Helmholtz coil pairs shown in Fig. 2 in series with the main magnet coil.

Figure 5 shows the sextupole corrected field quality computed for the magnets at 6.0 T in terms of the absolute value of the magnetic field deviation $|\Delta B_y|/B_o$, and the quantity R, where $R = r/r_{sc}$, r being the radial distance to the point at which the field quality is computed, and r_{sc}, the distance to the superconducting coil. The figure indicates that the magnetic field deviation is about $\pm\ 1 \times 10^{-4}$ for all points in the aperture within 75% of the distance to the superconducting coil at 6.0 T. The field quality is equal to or better than this value at all magnetic field levels below 6.0 T.

Discussion

The superconducting magnets for the "D" line are designed so that operation at 6.0 T will be at 80% of the thermal runaway short sample field of the magnet coil.[2] At 4.2 K, therefore, the magnets should ideally operate to 7.5 T. The iron flux return path thickness, however, was designed for 6.0 T so that severe saturation would reduce performance from the 7.5 T ideal.

In design, the performance reserve was provided because the magnets will be operated in a primary proton beam extraction channel where it must be assumed that beam radiation heating may occur. Magnets of this generic type have demonstrated unusually high heat absorbing capability and stability.[3] However, when operation is at 100% of short sample, there is by definition no thermal reserve or no capacity to absorb heat.

A 1.0 m long model magnet of similar design has been operated to 6.2 T or about 100% of short sample for that magnet.[4] This field intensity was achieved after a few quenches, the first of which occurred above 5.0 T. This experience plus the long operating history of the superconducting 8° bending magnets in the primary proton beam to the North Area of the AGS[1] gives confidence in the design.

References

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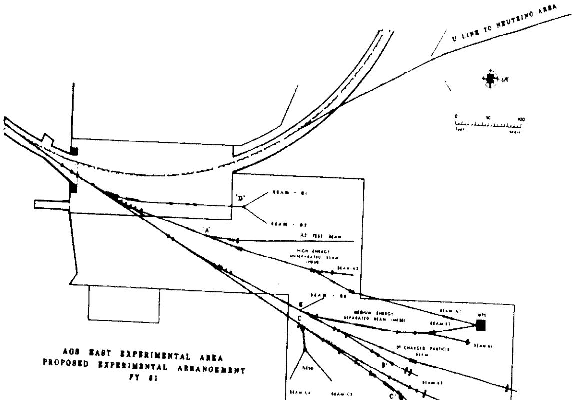

Fig. 1 Exp. Area Arrangement-FY 81

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D BEND SUPERCONDUCTING MAGNET PARAMETERS

I.	DIPOLE MAGNETS - 2 EACH	
	BEND ANGLE	10.20^0 PER MAGNET
	MAGNET IRON O.D.	19.25" (48.895 CM)
	MAGNET IRON LENGTH	120" (3.048 M)
	CORE PACKING FACTOR	96%
	COLD BORE DIAMETER	2.875" (7.303 CM)
	MAGNET GAP HEIGHT	5.850" (14.859 CM)
	MAGNET COIL HEIGHT	5.725" (14.542 CM)
	MAGNET COIL I.D.	3.250" (8.255 CM)
	L_B ASSUMED	121.06"(3.075 M)
	B AT 30.9 GeV/c	6.0 T
	B AT 28.5 GeV/c	5.5 T
	I AT 6.0 T	1654 AMPS
	NI AT 6.0 T	883,236 A.T.
	STORED ENERGY @ 6.0 T	~ 700 KJ
	INDUCTANCE @ 6.0 T	~ 0.5 H
II.	CORRECTING SEXTUPOLE MAGNETS - 2 EACH	
	POLE TIP I.D.	3.125" (7.938 CM)
	B POLE TIP AT 6.0 T	1.66 T
	EFFECTIVE LENGTH	12.00" (30.48 CM)

Table 1 S.C. Dipole & Sextupole Parameters

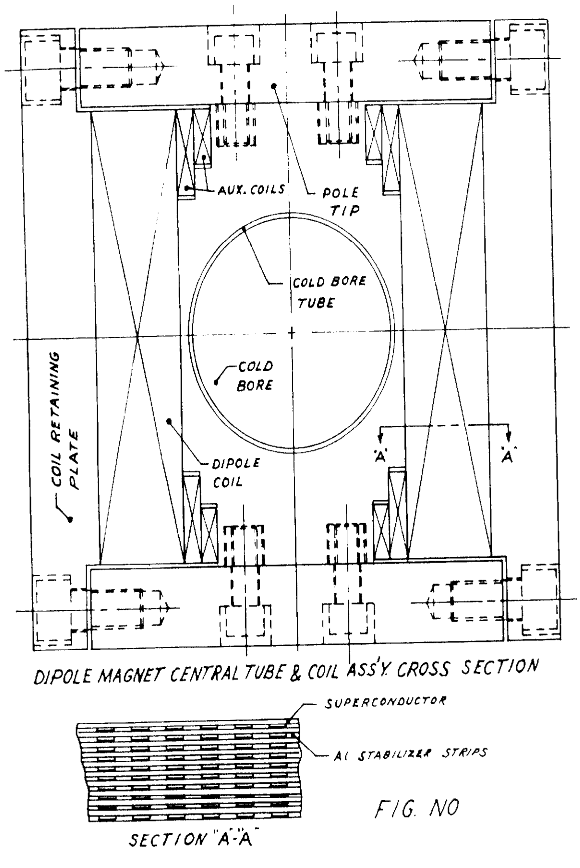

Fig. 2. Dipole Magnet Central Tube & Coil Assy. Cross Section

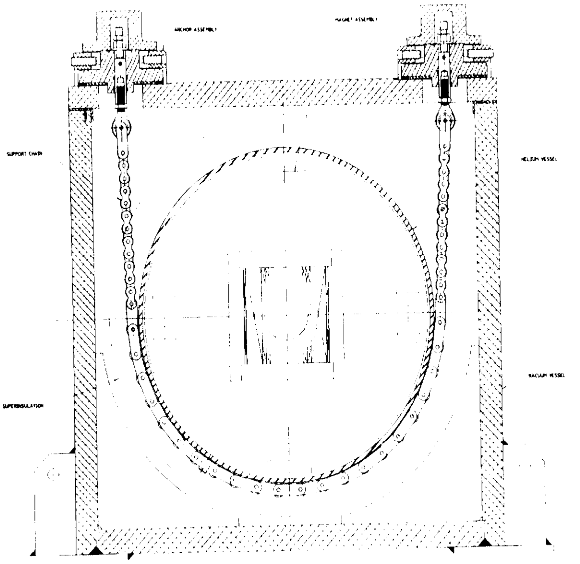

Fig. 3 Dewar & Magnet Cross Section

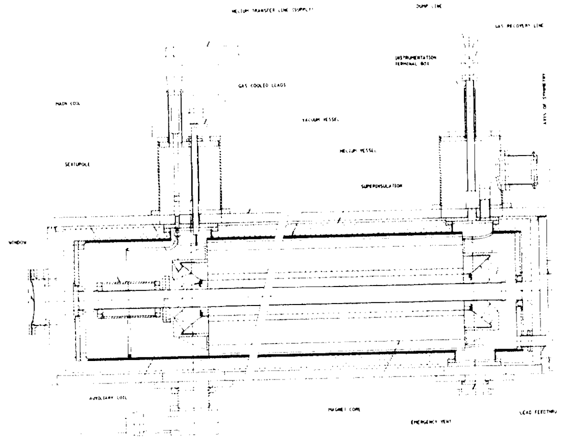

Fig. 4 Dewar & Magnet Side Elevation

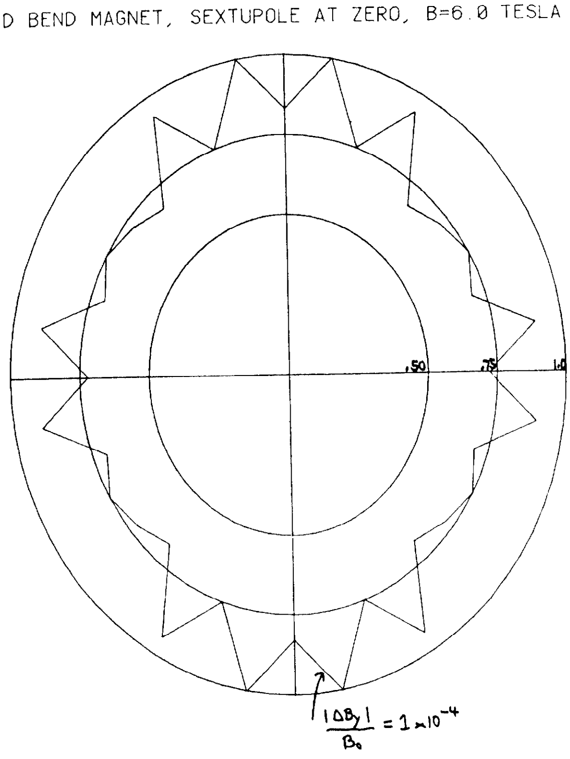

Fig. 5 Dipole Field Purity Plot