A SIX TESLA ANALYZING MAGNET FOR HEAVY-ION BEAM TRANSPORT

MASTER

by

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Summary

A superconducting analyzer magnet for particle beam deflection has been designed and is being fabricated for use at the Argonne Tandem-Linac Accelerator System (ATLAS). This six tesla magnet will provide 45° of deflection for the heavy-ion beams from the ATLAS tandem electrostatic accelerator and together with its twin will replace the existing conventional 90° analyzer magnet which will become inadequate when ATLAS is completed.

Introduction

The Argonne Tandem-Linac Accelerator System (ATLAS) for heavy-ions requires a beam deflecting and analyzing magnet system with bending power $B\rho$ (magnetic field times bending radius) of 3.4 Tesla-meters for the existing 90° bend between the 9 MV tandem electrostatic accelerator and the superconducting heavy-ion linac. Existing space at the facility dictates that the overall radius of the bend must be about one meter. When two or three high field accelerator-type dipole magnets were considered for the task, it was apparent that each would require a curved bore tube bent through 30° or more to accommodate the large sagitta of the beam. Such a magnet would also be quite short and consequently the quality of its field would largely be determined by the shape of its end turns. A curved very short superconducting dipole magnet would present a formidable and costly design challenge. Thus a split-solenoid type of magnet was identified for the task. The cost of the less efficiently used field-volume of such a solenoid is apparently more than offset by the relative simplicity of the design.

Preliminary estimates indicated that the cost of a solenoid magnet would be dominated by the cost of the iron shield required, and that a system of two smaller solenoids each providing 45° of a beam deflection would be far less costly than a single large magnet generating 90° of deflection. In addition, the optical properties of a pair of such magnets are such that the analyzing requirements for the system are properly facilitated.

Magnet Design

In Fig. 1 is shown an elevation of the 45° analyzer magnet now under construction. Reentrant iron pole tips extend from the end yokes to within 2.54 cm of the median plane of the magnet. Although the pole tips are quite saturated at full magnet excitation they provide a significant enhancement to the median plane field over that generated by the coils alone. It was found that the coil winding thickness of 2.0 cm provides a sufficiently fast radial falloff of the field so that the multipole content of the analyzer field is correctible at peak magnet excitation.

With an overall current density in the winding space of 27.6 kA/cm² the half-coil length required

Fig. 1 45° Superconducting Analyzer

to generate the desired field in the gap is 18 cm. The external iron yoke provided reduces the fringe field to less than 25 gauss a distance of 18 cm radially beyond the yoke and a distance 10 cm axially beyond the end caps. Because the magnetization in the external iron yoke is well below saturation the fringe field in the entrance and exit beam apertures of the yoke will not exceed a few gauss.

Beam Optics Consideration

The present 90° iron analyzer magnet has a mass times energy product of 52 amu-MeV for protons. This magnet has grossly inadequate bending power for heavy ions and its optics causes large time spreads in pulsed beams. With the new superconducting analyzer pair, the ion beam will be focused to a small waist (full width ≈ 1.5 mm) between the two magnets. The optical system thus formed does not introduce significant time spreads because all possible path lengths are nearly equal. The 45° bend in the first magnet provides sufficient energy dispersion at the waist to allow defining slits to select the beam energy with a resolving power in the range 1000 to 2000 depending on the final choice of optic parameters. The primary function of the second 45° magnet is to complete the required 90° deflection.

Because of the existing space limitations there is insufficient distance available between defining slits and magnets to focus the beam using magnetic-field edge effects alone, as is common for conventional magnets. Consequently, two normal-conducting quadrupole doublets will provide the primary beam focusing function. Nevertheless, edge focusing in the superconducting magnets is used to advantage by requiring beam trajectories that are non-normal to the circular equi-field lines.

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The curvature of the equi-field lines of a circular bending magnet causes an astigmatism that would greatly reduce the resolving power of the system, unless corrected. The possibility of solving the problem by shaping the field within the superconducting magnet itself was rejected as being too difficult. The solution favored at present is to design the external room-temperature quadrupoles to provide the needed hexapole corrective term.

The bending magnets include iron poles in order to achieve the required bending power (mass x energy product ≈ 500). This has the drawback that the geometrical parameters of the magnet, and hence the beam focusing action, vary somewhat with field level. Calculations show that this is not a major effect, and it can be largely eliminated by adjusting the field strength of the quadrupoles.

Conductor Design

The choice of operating current of 1000 A and the corresponding overall conductor size was judged to provide suitable assurance of acceptable winding precision. To achieve a relatively thin coil, a monolithic NbTi conductor with copper to superconductor ratio of 1.3 to 1.0 was selected to enhance overall winding current density. Safety calculations made with a version of program QUENCH¹ indicated that quench voltages and temperatures were acceptable. The specifications of the conductor procured for the analyzer magnet are given in Table I. Measurements of the short sample performance of the material showed that it exceeds the critical current specifications by about 10%.

Table I
Conductor Parameters

Material	NbTi and Copper
Bare Dimensions	0.102 x 0.203 cm
Cu:NbTi	1.3:1.0
Number of Filaments	2046
Filament Diameter	21 Microns
J_c at 5 T, 4.2 K	1000 Amperes
Insulation	0.005 cm Formvar

Winding Design

A one-piece forged thick-walled stainless steel cylinder was machined to precise shape for the coil winding bobbin. The conductor is helically wound on its wide face with the beginning and ending turns at the outer ends of each coil-half (away from the median plane). An even number of layers (14) in each coil half ensures no net axial currents to perturb the field. Each layer of conductor is insulated from the next by a sheet of Mylar 0.025 cm thick. The conductor is supported against the radial magnetic load by a banding of stainless steel ribbon helically wound onto the coil to a total thickness of 2.0 cm. The pretension in the ribbon will generate about 14 MfA radial preload against the peak magnetic burst pressures anticipated when the coil is tested without the iron yoke. The leads from the upper coil to the lower coil are fastened parallel to each other but insulated from each other with 0.016 cm thick epoxy-glass laminate and Mylar. This lead pair passes the median plane of the magnet azimuthally remote from either beam window. The coil design parameters are presented in Table II.

Table II
Analyzer Magnet Parameters

Number of Coils	2
Coil I.D.	48 cm
Coil O.D.	52 cm
Coil Height	18 cm
Inter Coil Gap	5 cm
Coil Amp-Turns	9.72×10^5
Operating IJ	27.0×10^3 A/cm ²
Magnet Stored Energy	1.8 MJ
Median Plane Field	6.0 T
Peak Conductor Field	4.5 T

Cryostat Design

The analyzer coils will be cooled by pool-boiling liquid helium at a maximum pressure of 3.4×10^5 Pa (0.5 psig). The coil bobbin (Fig. 1) has heavy-sectioned rings at its upper and lower ends to provide rigid attachment points for the coil support links. The calculated axial decentering forces have a spring constant of 530 N/m. For simplicity all axial support is provided at the top of the bobbin, and the tubular members serve as conduits for cryogen supply, current leads, emergency venting, etc. for the coil. These members transmit any vertical forces on the coil to the top of the iron yoke where a system of spherical bearings provides sensitive adjustment so that the magnetic centers of the coil and the iron yoke can be precisely aligned.

The radial forces, decentering, with a spring constant estimated to be 2.3×10^6 N/m are supported by three tension links at the top, and three at the bottom, of the coil. Like the vertical support members these links transmit magnetic loads to the outside of the iron yoke to strain-instrumented spherical bearings. The system of load cells at the bearings will monitor all links and prevent magnet operation if excessive loads are indicated.

The axial compressive load between the coil halves is 1.53×10^5 lbs (6.8×10^5 N) with the iron yoke in position. For the preliminary coil tests in an open laboratory cryostat, blocks will be inserted in the beam windows of the bobbin to support the increased axial compressive load safely.

The coil bobbin together with a thin sheet of stainless steel welded to the outside after the coil is wound constitutes the helium vessel. A copper thermal radiation shield, conduction cooled by liquid nitrogen contained in a reservoir at the top of the shield, entirely surrounds the helium vessel. Both the helium vessel and the 80 K shield are covered with multilayer insulation. The outer vacuum vessel of welded stainless steel will be shimmed into the iron yoke when the system is assembled.

To supply cryogenics to the magnet coils, reservoirs above the top of the magnet yoke will be provided. The helium reservoir will be filled on demand from the ATLAS liquid helium distribution system. Gas-cooled current leads installed in this reservoir are cooled by boiloff gas from the magnet system. Safety interlocks will discharge the magnet if the liquid level in this reservoir is not maintained.

Iron Yoke Design

Thick iron plate has been procured for the top and the bottom pieces of the yoke and for the annular side pole tips. The magnet cryostat will be inset axially into the end plates of the yoke so that the radial support links are inside the parting line between these pieces and the sides of the yoke. The ring-like side of the yoke is split

axially so that each half can be slid radially into place when the iron is assembled around the cryostat.

Reference

1. M. N. Wilson, RREL/M/151, Rutherford Laboratory, Chilton, Didcot, UK, 1969.

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