DESIGN AND CONSTRUCTION OF SUPERCONDUCTING
QUADRUPOLE MAGNETS FOR ION BEAM FUSION

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by

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DESIGN AND CONSTRUCTION OF SUPERCONDUCTING QUADRUPOLE MAGNETS FOR ION BEAM FUSION

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ABSTRACT

A high gradient superconducting quadrupole has been designed and developed as the heavy ion beam focussing element in the low velocity portions of an rf linac for the Argonne Ion Beam Fusion Reactor. The quadrupole magnets will require an extremely short magnet coil length (~ 20 cm to 30 cm) and extremely high central gradients (~ 100 T/m to 200 T/m). The useful warm bore will be about 4 to 6 cm and the integral gradient homogeneity should be constant to $\pm 5\%$ over the useful warm bore. Special techniques have been developed which are especially suitable for multi-layer coil winding and coil assembly with high average current density over the coil cross section. A 5-layer quadrupole with 9 cm winding bore has been built and tested to the full performance of about 100 T/m with little training. The achieved average current density is 22,000 A/cm² at a peak field in conductor of about 5.0 T. An 8-layer quadrupole is under construction for a design gradient of 140 T/m over 9 cm winding bore. The peak field will be about 7.2 T.

I. INTRODUCTION

The $\pi/5\pi$ structure in the rf linac for the Argonne Ion Beam Fusion Reactor will require five superconducting quadrupoles with a gradient of ~ 75 T/m in a warm bore diameter of 6.0 cm and with an effective length ≥ 20 cm. For the linac of $\pi/3\pi$ structure, the required gradient will be about 140 T/m in a warm bore of 4 cm but with effective magnetic length ≥ 12 cm. A conceptual design of the cryostat and superconducting quadrupoles system is shown in Fig. 1. The superconducting quadrupoles will be shielded with either iron yokes or superconducting windings so that the fringing field at both ends of the cryostat will drop to less than 1% of the central gradient. Each of the five quadrupoles will have a separate cryostat. The cryostat vacuum wall will serve as part of the rf cavity. However, the superconducting quadrupole will have separate vacuum from the common vacuum in which the rf cavities are housed. The five quadrupoles will be connected in series and they will share a common liquid helium reservoir.

II. QUADRUPOLE COIL DESIGN

As shown in Fig. 2, the Fermi Laboratory Energy Doubler Conductor¹ is used because it is readily available. The load-lines for both the 5-layer quadrupole (100 T/m) and the 8-layer quadrupole (140 T/m) are shown in Fig. 2.

The winding configurations for a 5-layer quadrupole are shown in Fig. 3. The conductor distribution approaches $\cos 2\theta$, therefore, it will generate a uniform gradient across the winding bore. The coil forms subtends an angle of 34° which is determined by the considerations of allowable minimum winding radius and the acceptable peak field in the conductor.

The coil end configuration chosen is a circular saddle because it could be easily wound and conveniently assembled on a circular bore tube.

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For the useful bore size, it was necessary to achieve a high average current density if the ampere-turns are to be efficient. Therefore, the layer-to-layer banding thickness must be kept as small as possible. The layer structures for both the straight coil region and the coil end region are illustrated in Fig. 4. The small cooling channels between two adjacent bandings are considered adequate because spiral cooling channels exist in the superconducting cable.

Iron is provided to shield the fringing field. To avoid saturation of magnetization, the iron shield must be positioned far away from the winding. For the 5-layer quadrupole (100 T/m gradient), the thickness of the iron shield is 5 in. Despite the massive iron, it contributes less than 10% of the field gradients.

Figure 5 shows the details of the quadrupole interconnections. This coil interconnection scheme is designed to minimize the voltage differences within the coil.

The quadrupole magnet parameters are listed in Table I.

III. CONSTRUCTION DETAILS

The coil form is made from laminated phenolic sheet. It is fastened to a horizontal coil winding cylinder. The winding mechanism consists of a turntable on which the horizontal coil winding cylinder is supported. As the table rotates about its vertical axis, the winding drum is made to revolve about its horizontal axis. A quadrupole pancake winding together with its winding drum is shown in Fig. 6.

Each layer of coil consists of four coil quadrants. The gap between two adjacent quadrant coils is filled with Micarta strips as shown in Fig. 7. Slotted Micarta plates are cut to fit the space between the coil ends and the adjacent end flanges. An epoxy called A + B putty² is used to fill cracks or small gaps existing between Micarta coil end fillers and the winding.

Each layer of coil is assembled together by spiral banding. The banding is an aluminum alloy 0.76 mm thick by 7.62 mm wide, and is insulated with both Mylar type and fiberglass tape resulting in an overall banding 1.6 mm thick by 7.94 mm wide. The banding is mechanically terminated at the end flanges and electrically isolated from ground. The spacings between two adjacent turns of banding are smaller than 1.6 mm at the coil end region and less than 3.2 mm at the straight coil region. The direction of the spiral banding alternates from layer to layer so that the net torsion on the end flanges is small. Figure 7 illustrates the banding and the intercoil connections, and Fig. 8 shows a finished layer of coil assembly.

The outer banding consists of eight layers of bare aluminum alloy ribbon of 0.76 mm thickness. Between layers, a 0.05 mm thick Mylar sheet is placed to reduce eddy currents.

As shown in Fig. 9, to provide cooling channels for the outermost layer coil and also to allow quick dispersion of liquid/gas helium should the magnet quench, a layer of 0.35 mm thick G-10 spacer strips were placed on the surface of the banding for the

outermost coil layer. A layer of 0.09 mm thick Mylar tapes completely isolates the coil winding from the outer bandings.

IV. PERFORMANCE TESTS

The 5-layer quadrupole was tested in a vertical dewar as shown in Fig. 10. In the first test, it was energized to generate a central gradient of 94 T/m with only one training. The performance data are listed in Table I. The training characteristics are shown in Fig. 2.

TABLE I. MAGNET PARAMETERS

Warm Bore	6 cm
Winding Bore	9 cm
Winding O.D.	18.95 cm
No. of Layers	5
No. of Turns	392
Overall Winding Length	28 cm
Field Gradient Without Iron	94 T/m
Peak Field Conductor	5 T
Iron I.D.	25 cm
Iron O.D.	50 cm
Field Gradient With Iron	104 T/m
Operating Current	4050 A
Averaged Current Density	22,000 A/cm ²

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REFERENCES

1. "The Energy Doubler: A Progress Report for the Energy Doubler/Saver Collider Project," Fermi National Accelerator Laboratory Report (June 1976).
2. A + B Epoxy Putty, Made by the Biggs Company, 612 E. Franklin, El Segundo, California 90245.

Fig. 1 Five Superconducting Quadrupoles and their Cryostat.

Fig. 2 Energy Doubler Conductor and Load Lines.

Fig. 4 Layer Structure.

Fig. 3 Winding Configuration of 5-Layer Quadrupole.

Fig. 5 The 5-Layer Quadrupole Interconnection Scheme.

Fig. 6 A Quadrupole Pancake Coil with the Coil Winding Cylinder.

Fig. 9 Exploded View of Outerbanding.

Fig. 7 Banding and Intercoil Connections.

Fig. 8 Finished Coil Layer.

Fig. 10 Test Setup.