SUPERCONDUCTING BEAM HANDLING EQUIPMENT*

R.B. Britton and W.B. Sampson
Brookhaven National Laboratory
Upton, New York

Summary

The conventional quadrupole and dipole magnets, used to focus and bend the beams of charged particles produced by accelerators, consume very large amounts of power. Superconducting magnets are an attractive method of reducing this power requirement while offering the advantage of higher fields and field gradients. A number of model superconducting beam handling magnets have been built and tested and a full-size quadrupole doublet is under construction. The use of high current density Nb_3Sn conductors allows compact design, reducing the cryogenic requirements and capital cost of the magnets.

The Brookhaven AGS complex consumes about 40 MW of electric power. Most of this is resistive loss in the copper windings of magnets. It now appears that superconductors may be used to replace copper magnet windings and that the new magnets will probably consume less than one-tenth as much power. They are also expected to cost less to build, occupy less space, and produce more field. Because of the higher fields and gradients, they will also reduce the costs of radiation shielding.

The major power consumers which we are considering are the dc dipoles and quadrupoles which require approximately 2½ times the power of the pulsed dipole-quadrupole magnets in the AGS ring.

A general design for multipolar magnets wherein the poles are approximately parallel with the axis of a cylinder has been developed by Beth,[1] as follows:

Current sheets of small radial thickness are formed on a cylindric surface according to the function:

$$I_\theta = I_o \cos \frac{n\theta}{2}$$

where I_θ = current surface density (amp/cm),

n = the number of poles, and

θ = the angular position from an antipole.

The field within a dipole magnet is:

$$B = \frac{8 I_o}{10} \quad \text{gauss}$$

where I_o = current density at antipole (amp/cm),

r = radius of the current sheet (cm).

In a quadrupole, the gradient is

$$G = \frac{2\pi I_o}{10 r} \quad \text{gauss/cm} \quad .$$

In Fig. 1, these currents are illustrated as the cut ends of conductive ribbons. The technique is also applicable to multipole magnets of higher orders such as sextupoles and octupoles.

The lower order magnets, particularly the dipole, will produce large external fields. Therefore, a shielding system using mirror current sheets (Fig. 2) is desirable.[2] For an outer to inner coil diameter ratio of 2, the inner field would be reduced by 25% in a dipole or 6½% in a quadrupole. Alternatively, ferromagnetic shielding could be used, in which case the internal field may be similarly increased.[3]

Several methods have been used to approximate the cosine functions, including for quadrupoles a square uniform current array.[4] Cylindric arrays of equicurrent steps or equicurrent density changes have been used as shown in Fig. 3. In the latter, equiangle steps of current density are employed in each 90° change in $n\theta/2$. Further approximations are made in that the radial thickness of the current sheets is finite rather than zero, and the wedge-shaped current steps are reduced to rectangles separated by wedge-shaped shims. It has been shown by Kruger et al.[5] that the magnetic precision of a quadrupole with 10° steps and the other approximations above is ± 0.01% at 80% aperture. This means that the electrical design is far better than the mechanical tolerances will be.

The field levels and gradients obtained in prototype superconducting beam magnets are considerably higher than those obtained in conventional copper-iron magnets. The first quadrupoles with square current arrays and 3 cm bore produced 10 kG per centimeter gradient. The second type (Figs. 4 and 5) with circular current arrays and 7.6 cm bore produced 8.5 kG per centimeter with 32 kG at the walls.

A dipole, which has a 4 × 8 cm aperture, has been pulsed repetitively to 650 A (10 kG) at two second intervals. The dissipation is small during pulsing and it appears that it may be possible to construct superconducting synchrotron magnets in the near future.

All of the beam magnets have operated at or very close to the short sample B-I curve for the

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ribbon being used. Therefore, no improvement in field is to be expected by improved winding techniques. Calculations also show that adding a second layer of superconductor to the 7 cm quadrupole requires 150% more material but can only add 40% to the gradient. This and similar calculations show that high performance beam magnets can only be achieved with very high current density conductors. The test magnets were all built with Nb_3Sn ribbon. All except the square array used a ribbon 1.27 cm wide by 1/8 mm thick. Typically, this ribbon will carry 600 A at 40 kG for a current density of 40,000 A per square centimeter.

One way to compare the performance of superconductors is by their field times current density product. The above ribbon would be rated accordingly at 1.6×10^9 gauss-amperes per centimeter squared. Newer superconductors with the same physical size have been tested and have reached values as high as 5.2×10^9 gauss-amperes/cm^2. The field obtainable from a magnet should be a constant determined from the geometry times the square root of this product. Figure 6 illustrates this for several types of ribbon and shows the performance each should give with a typical quadrupole design.

The first superconductive beam magnet planned at Brookhaven is a quadrupole doublet of 10 cm bore by 60 cm length per element. The frame of one element is shown in Fig. 7. It will be separated into four parts for winding and each coil will be divided into five sections of different current density. Using the superconductor mentioned above, the quadrupole should operate at approximately 12 kG/cm gradient, with a peak field of 60 kG at the walls.

One of the worst problems concerning superconducting beam handling magnets is the cryogenics. This problem is in two parts. First, one must enclose every magnet in a dewar. In the case of the 10 x 60 cm element, the special dewar will cost as much as the complete magnet assembly. The second part of the cryogenics problem is refrigeration. The refrigerator to operate both elements of this doublet will cost approximately twice as much as the magnets. Therefore the cryogenics total is presently estimated at three-fourths of the total system cost.

For larger systems, the cryogenics cost becomes a smaller percentage of the total. The dewar cost falls from mass production and one large compressor may be used to operate many refrigerators.

Nearly 100% of the power requirements for superconducting beam magnets goes into refrigeration. The doublet is ultimately expected to absorb 5 W at 4.2°K through thermal leaks into the two dewars. This will require 5 kW of power to the compressors, or roughly one-tenth of the power loss in an equivalent size but lower gradient copper-iron magnet.

References

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5. P.G. Kruger, J.N. Snyder, and W.B. Sampson, "Digital Calculations of Magnetic Fields Owing to Currents in Nb_3Sn Ribbon in Superconducting Quadrupole Lens," BNL Accelerator Dept. Internal Report AADD-113-R, September 16, 1966.

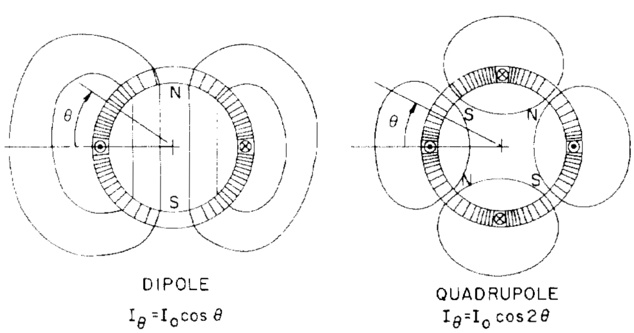


Fig. 1. Current sheets to produce dipole and quadrupole fields.

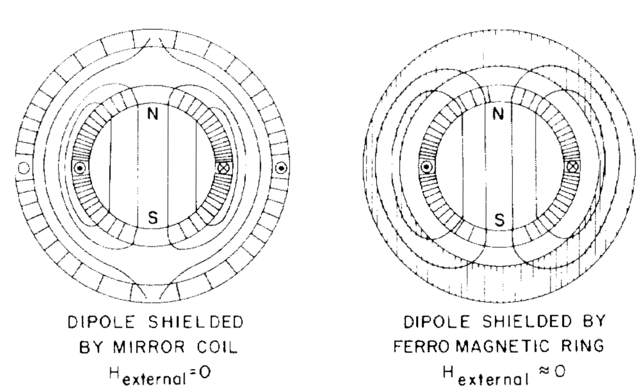


Fig. 2. Shielding techniques for superconducting beam handling magnets.

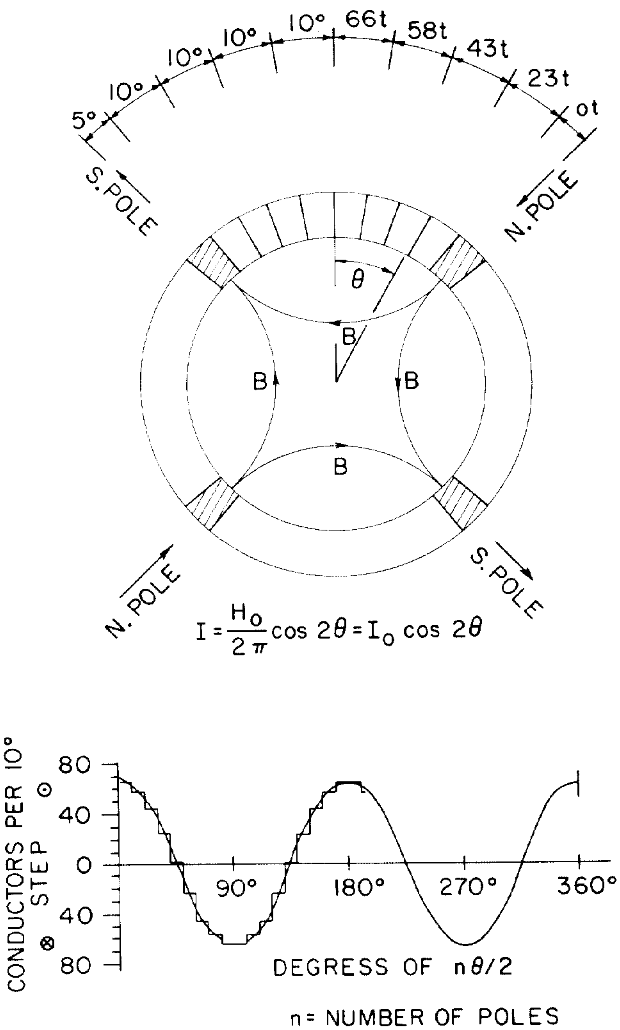


Fig. 3. Equiangle step method for approximating the cosine current variation in a quadrupole.

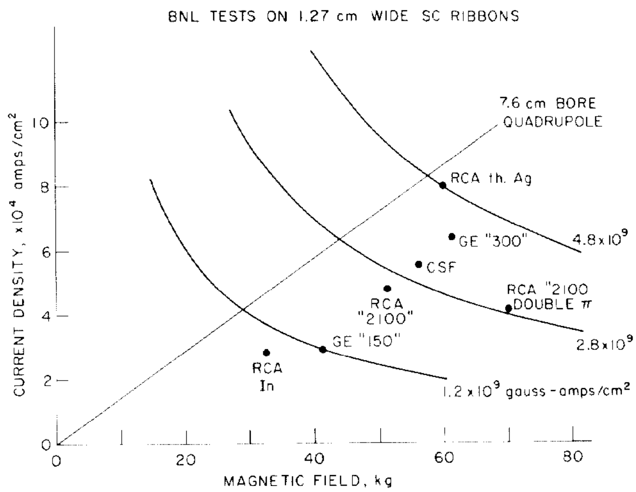


Fig. 4. Quadrupole frame design to accurately position current sheets.

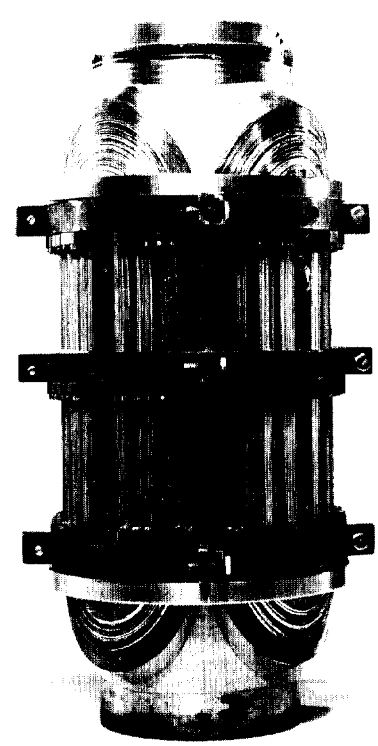
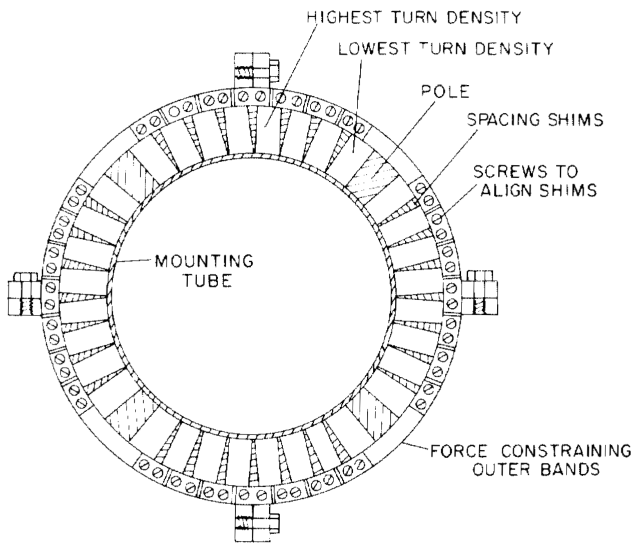


Fig. 5. Model quadruple, 7.6 cm bore × 20 cm effective length.



CROSS SECTIONAL VIEW OF SUPERCONDUCTING QUADRUPOLE

Fig. 6. Current density vs. field for various Nb_3Sn superconductors.

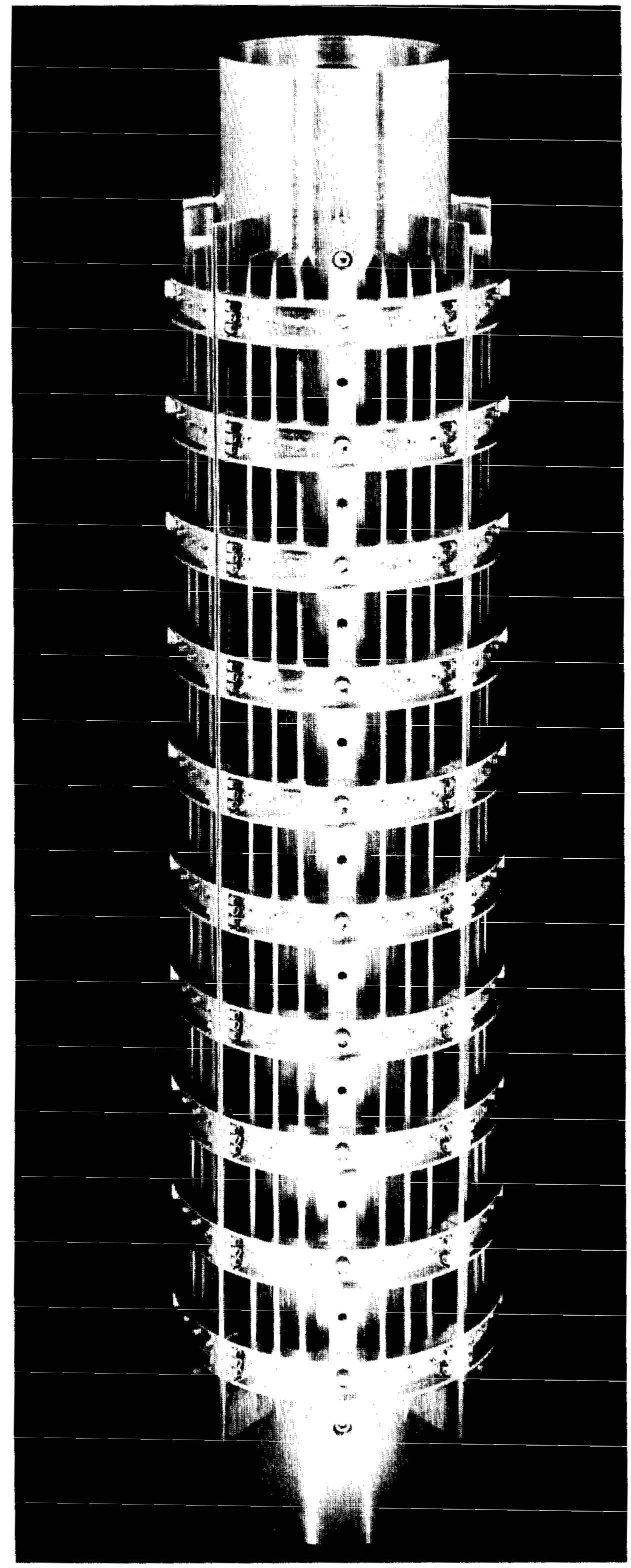


Fig. 7. Frame for 10 × 60 cm quadrupole element.