BROOKHAVEN SUPERCONDUCTING DC BEAM MAGNETS*

R.B. Britton
Brookhaven National Laboratory
Upton, New York

Superconducting (SC) beam magnet development was started in the Accelerator Department at Brookhaven in the spring of 1965. Work has since progressed to the point where dc quadrupoles are considered (by the author at least) to be ready for application to experimental beam lines. Dipole development, however, is just beginning and is running about two years behind. For both types of magnets, the field strengths obtained to date (15 to 35 kG peak) have been limited by instabilities to about one-half of the potential for niobium-tin superconductors when used in a single layer of 1.27 cm wide ribbon. By potential is meant the field at which the current in the magnet would reach the level obtainable in a short sample of the same material. This level is attainable in small solenoids.

The beam magnet work was initiated by Sampson and Kruger with ideas for a Panofsky-type quadrupole,[1,2] as shown in cross section in Fig. 1. This magnet consisted of four slabs of uniform current density arranged to form a square parallelepiped. Gradients up to 10 kG/cm were produced in a 3 cm diam bore, but despite the good performance, this winding method was abandoned because of the following deficiencies: the windings are not convertible to any multipole magnets other than quadrupoles; the magnetic field is highest in a small region at the corners which causes the entire superconductive block to be limited by the corner turns; the end loops introduce field errors and are exceedingly bulky; and the windings are tedious to construct. Nevertheless, several of the quadrupoles were developed, as shown in Fig. 2.

A more desirable topology for a radial field magnet winding, shown by the cross sections in Fig. 3, was arrived at in November of 1965. With this method of laying coils first against an octagon and then flat against a circular or elliptical beam space, one can readily develop multipole fields having two, four, six, eight, or more poles. The first quadrupole using coils wound on a cylindrical form, shown in Fig. 4, was tested in January 1966, and developed 8.5 kG/cm in a 7.6 cm bore. The ideal current and winding distribution, shown in Fig. 5, for such magnets was not obvious, however, and it remained for Beth to solve this and all other problems[3] related to optimizing the position of current blocks for minimum field errors within multipole magnets of various cross sections. The electrical theory which is required for the design of these radial field magnets has thus been available and has remained unchanged since the summer of 1966.

A solution to the field purity at the center of a long magnet does not, of course, guarantee a workable field at the ends of the coils. To determine these errors in our quadrupoles, Sampson, Robins, and Kruger have made measurements both by a short

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1. L.N. Hand and W.K.H. Panofsky, Rev. Sci. Instr. 30, 927 (1959).

2. P.G. Kruger, W.B. Sampson, and R.B. Britton, Brookhaven National Laboratory, Accelerator Dept. Report AADD-104-R (1966).

3. R.A. Beth, Brookhaven National Laboratory, Accelerator Dept. Reports AADD-102 (1966), AADD-112 (1966), AADD-135 (1967), AADD-103 (1966).

filamentary bismuth probe[2] which could be revolved at various radii in planes perpendicular to the axis, and by a long (78 cm) integrating coil which summed the field completely at a radius of 3.5 cm through a 60 cm length element. The conclusions from the two methods of measurement are that the fields fall off smoothly as one leaves the end of this type of magnet (see Fig. 6). The experimental measurements appear to be in good agreement with calculations made by Kruger et al.[4] It is therefore assumed that the present shape of the winding end loops is close to optimum and that any changes found necessary to produce perfect field fall-off at the ends will be small and topologically possible with brittle ribbon conductors.

Mechanical design of frames to contain the windings was the next problem. The first design for this was an externally supported, bolted, composite structure of high efficiency but also high cost because of the requirement for excessive machining time. This structure is used in our 10 cm bore x 60 cm length quadrupole element, shown in Fig. 7.

To reduce fabrication time for the magnet frame, an internally supported, monolithic frame was designed. The machining time for this solid frame was only about one-tenth of the time required for the composite. However, it can only hold 70-80% of the theoretical maximum number of turns per coil section, and the turns must work at a 5-20% greater diameter than the theoretical minimum. This penalty is small for large metal frame dipoles with few sections, but can be severe for small bore, nonmetal frame quadrupoles or higher order magnets which require many coil sections. A solid frame for an elliptical bore dipole is shown in Fig. 8.

The insulation for ribbon superconductors as used in all beam magnets at Brookhaven has been either a thin ribbon of stainless steel or a varnish coating put on the ribbon by the manufacturer. For small magnets (less than 25 mH), at currents up to 700 A, the varnish insulation has been satisfactory. When the stored energy exceeds about 10 000 J, however, it becomes advisable from a protection point of view to use metal interleaving. The function of the metal is to provide uniform electrical shorting between turns throughout the winding. It also has better heat transfer properties than organic insulation. The shorting is highly resistive compared with the superconductor and does not affect the normal, slow energizing of the device. If the magnet quenches, however, the relaxation time constant for the shorted winding in the normal state is long enough to allow the magnetic energy to dissipate uniformly through the winding in the form of heat. When large coils of Nb_3Sn ribbon are operated without shorting, a quench at high current will frequently precipitate an arc that then destroys a portion of the winding.

Insulation has also been found necessary for the frames of beam magnets, though less than one might expect. The problem is not one of avoiding long time constants due to shorting through the frame, but rather that of avoiding any great asymmetry in time constants between, say, the four coils of a quadrupole. The insulation which is presently being used for stainless-steel frames is a spray paint applied by a technique developed by F. Abbatiello of our laboratory. The same method works for aluminum. Two other methods used to insulate aluminum are to have it anodized, or to treat it in Alrok solution after all machining is done.

The development of a superconductor for beam magnets is a long story — one which the author believes will continue for many decades. The part which has made the Brookhaven beam magnets practical, however, has been the competitive development of Nb_3Sn in a ribbon of appropriate width, length, uniformity of thickness, strength,

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4. P.G. Kruger, J.N. Snyder, and W.B. Sampson, Brookhaven National Laboratory, Accelerator Dept. Report AADD-113-R (1966).

and stable current density, J_s. The J_s referred to here is that obtainable in the magnet winding. An appropriate width for a beam magnet conductor is about one-eighth of the bore diameter (with greater widths, the wedges consume too much winding space), and for strength a thickness of at least 75 μ assuming the material to be primarily copper on a niobium or nickel alloy substrate. The minimum length is about 100 m if one wishes to avoid having joints in the high current density sections. Ideally, each coil or section would contain a single length. At the moment, ribbon is most readily available in either 0.23 or 1.27 cm width, but some companies offer any width up to 5.0 cm. Lengths of 300 to 950 m are available without a joint. Yield strengths are typically 7 lb or more for ribbon 1.27 × 100 μ thick.

The requirement of uniform thickness has been difficult for the manufacturer to meet. We presently are trying to get ± 2.5% thickness tolerance on ribbon of 75 to 200 μ total thickness. Thickness variations affect winding density which directly determines current density, and the latter, of course, affects the shape and precision of the magnetic field. The thickness variations existing in much of the ribbon obtained to date have made it difficult to produce a quadrupole of 10 cm bore precise to better than ± ½% at 80% aperture.

The most difficult conductor requirement to obtain is a high J_s. If one fixes the conductor width and for the sake of minimizing complexity uses only a single layer of winding, then the maximum field obtainable in a dipole, or at the wall of a quadrupole is as follows:

$$B = \frac{2\pi}{10} J \times 1.27 \approx 0.798 J \quad ,$$

where B is in gauss, J is in A/cm^2, and 1.27 is the width of the current sheet in cm. Similarly, the field gradient, G, in gauss/cm is given by

$$G = \frac{2\pi}{10} \frac{J}{r} \times 1.27 \approx 0.798 \frac{J}{r} \quad ,$$

where r is the mean radius of the current sheet in cm.

In windings which contain a large volume of Nb_3Sn ribbon, the limiting factor in their performance is stability.[5] In other words, they are not limited by critical field and critical current but by a statistical probability of a sudden quench at a $J_c \times B$ product far below the straight sample performance of the material. This limit appears to be on current density alone, and for single layer windings which are exposed to helium on one or both sides, the limit is always above 25 000 A/cm^2 and usually below 55 000 A/cm^2 for a winding containing between 200 and 800 m of ribbon.

The only fact which is known about the current density problem is that some pieces of supposedly identical ribbon are over twice as good as others. For this reason, our present technique is to test every piece of ribbon in a simple pie winding prior to putting it into a device. In addition to yielding data on J_s, this test also gives winding thickness and provides an opportunity to search for flaws.

5. W.B. Sampson, Brookhaven National Laboratory, Accelerator Dept. Report AADD-111 (1966).

There are at present two SC beam magnets under construction at Brookhaven. One is a quadrupole[6] designed by Sampson and the author. The frame of this magnet is shown in Fig. 7, and a finished winding for it in Fig. 9. The winding distribution is essentially the same as that shown in Fig. 5. Two of these elements have been wound and tested to gradients of about 3.5 kG/cm. A horizontal Dewar has been obtained for one element and is being tested without a magnet at present.

The other magnet is a dipole designed by D. Jacobus and the author. The bore is an ellipse, 17 cm × 7 cm, and the effective length is 60 cm. Four current sections are used per coil, as shown in the lower part of Fig. 10, with different current densities in each so that the current blocks essentially cover the circumference. Various views of the aluminum frame containing a single dummy winding are shown in Figs. 8, 11, and 12. A field of 25 to 30 kG is expected in this magnet with a uniformity of ± ½% over the full cross section at the center. Diamagnetic effects similar to those seen in solenoids are expected to affect the field uniformity more than winding errors. A Dewar for this dipole is being fabricated at Brookhaven.

An estimate of the cost for duplicating these magnets is given in the following table. The cost of refrigerators, which can easily exceed the cost of a single magnet, has not been included.

TABLE I

Estimated Duplication Costs for Brookhaven Beam Magnets

	Quadrupole Doublet 10 × 60 cm each 3.5 to 7 kG/cm Gradient		Elliptical Bore Dipole 7 × 17 × 60 cm 25 to 50 kG Field	
Frames	2 Composite 1100 shop hours	$11 000	1 Monolithic 100 shop hours	$1 000
Superconductor 1.27 cm wide × 125 μ thick	1600 m @ $6/m	$9 600	1200 m	$7 200
Dewars	Outside shop	$8 000	Brookhaven shop	$16 000
		$28 600		$24 200
Winding and assembly time for magnets		12 man-days		6 man-days

6. R.B. Britton and W.B. Sampson, IEEE Trans. Nucl. Sci. NS-14, No. 3, 389 (1967).

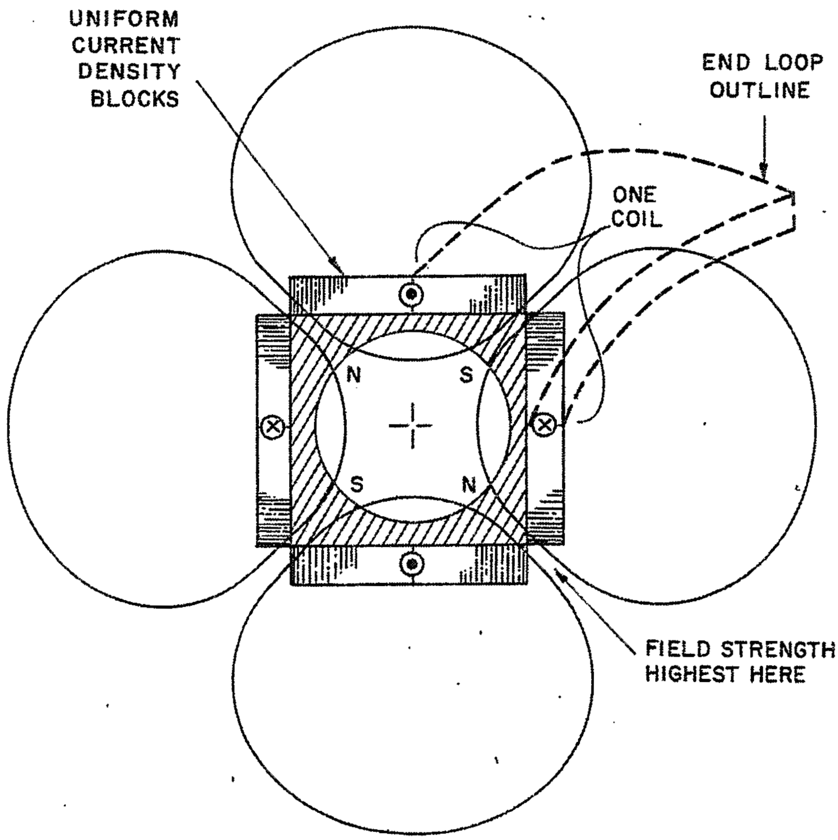

Fig. 1. Panofsky-type quadrupole — cross section.

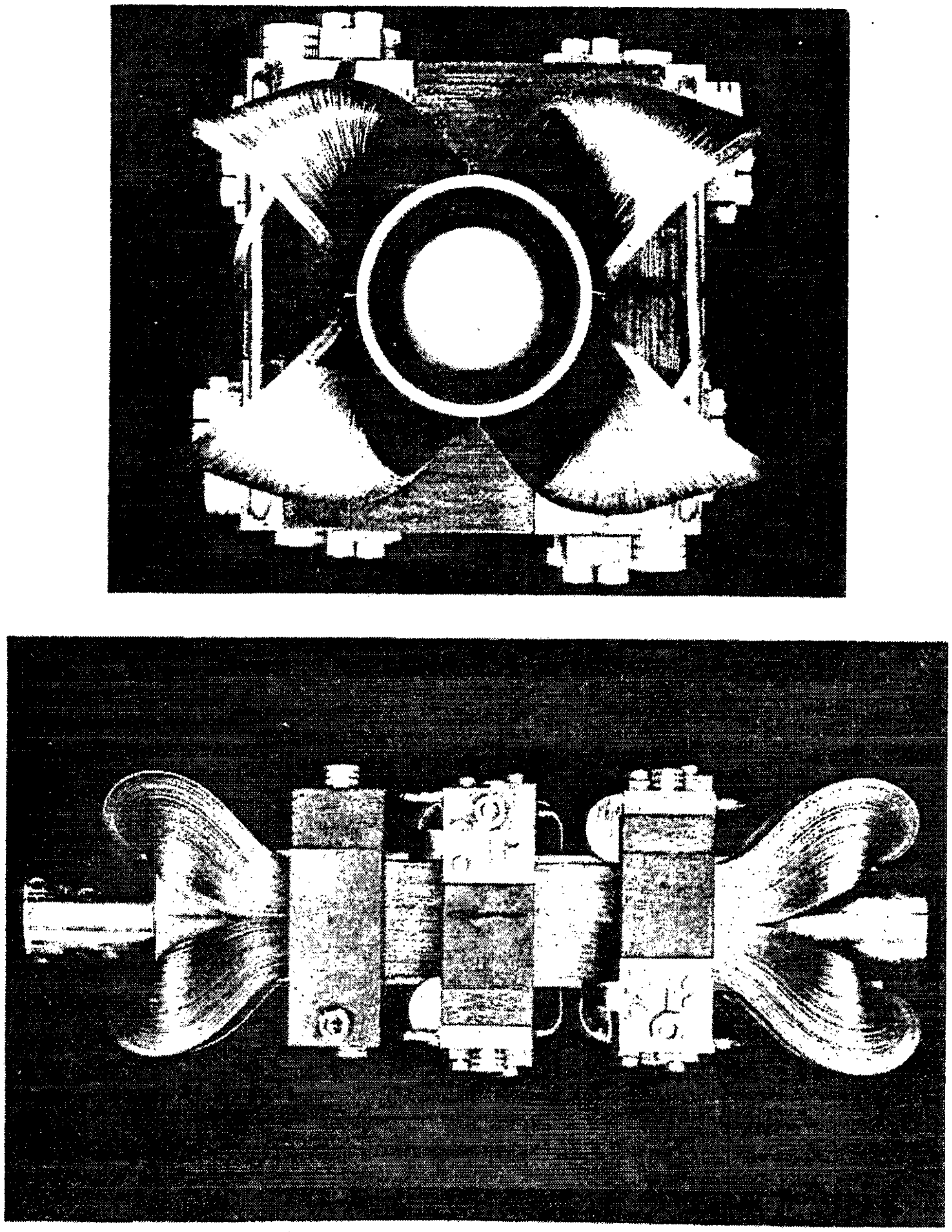

Fig. 2. Superconductive Panofsky quadrupole.

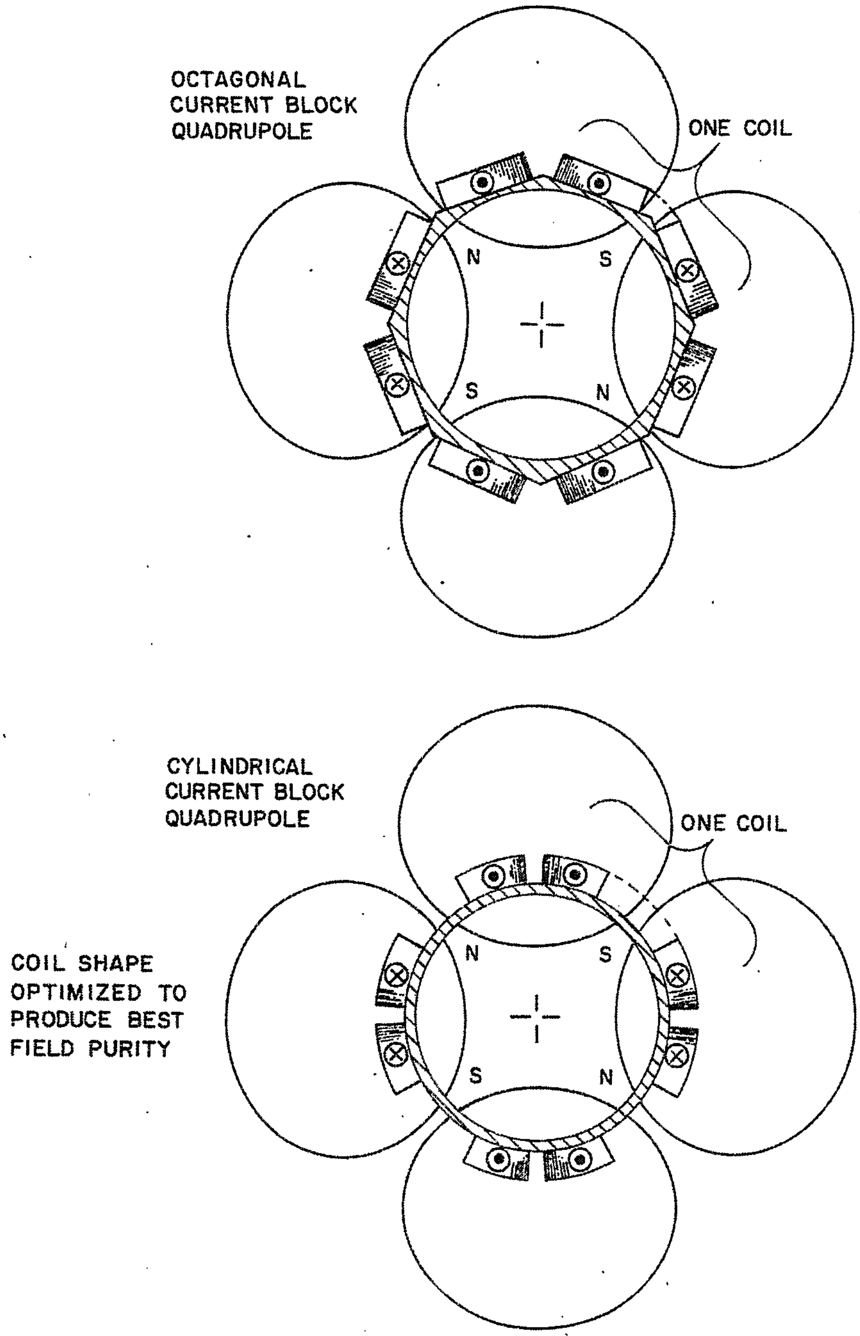

Fig. 3. Octagonal and cylindrical current block quadrupole cross sections.

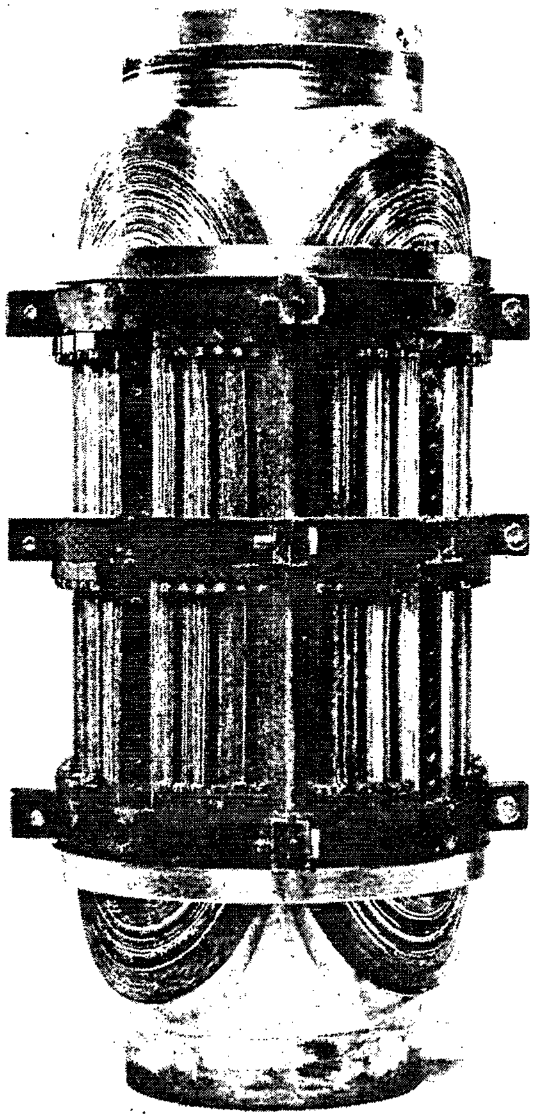

Fig. 4. Cylindrical current block superconducting quadrupole.

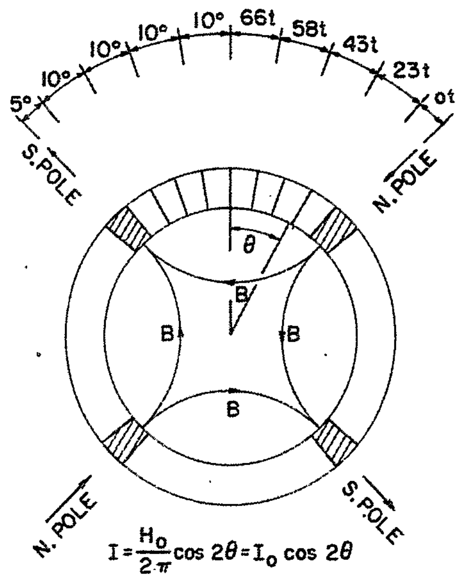

Fig. 5. Turns distribution for cylindrical quadrupole.

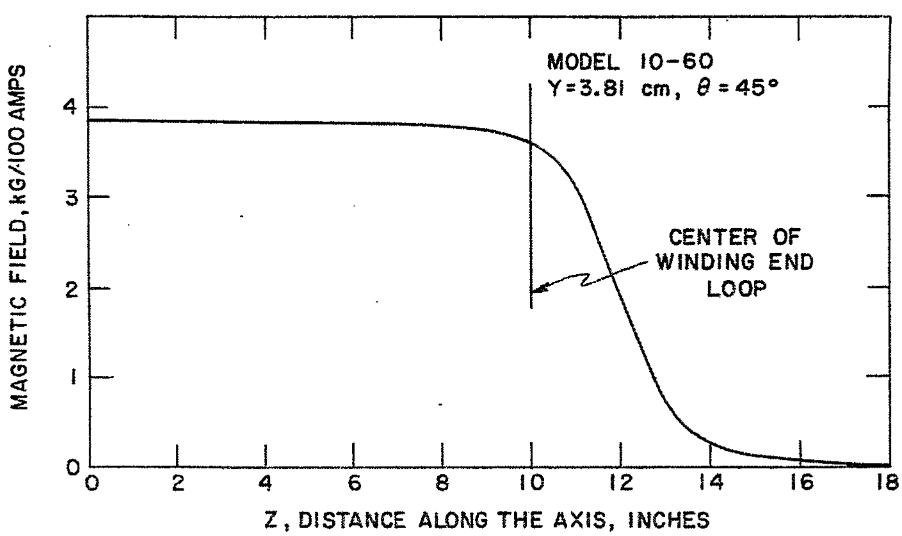

Fig. 6. Field strength vs axial position in quadrupole.

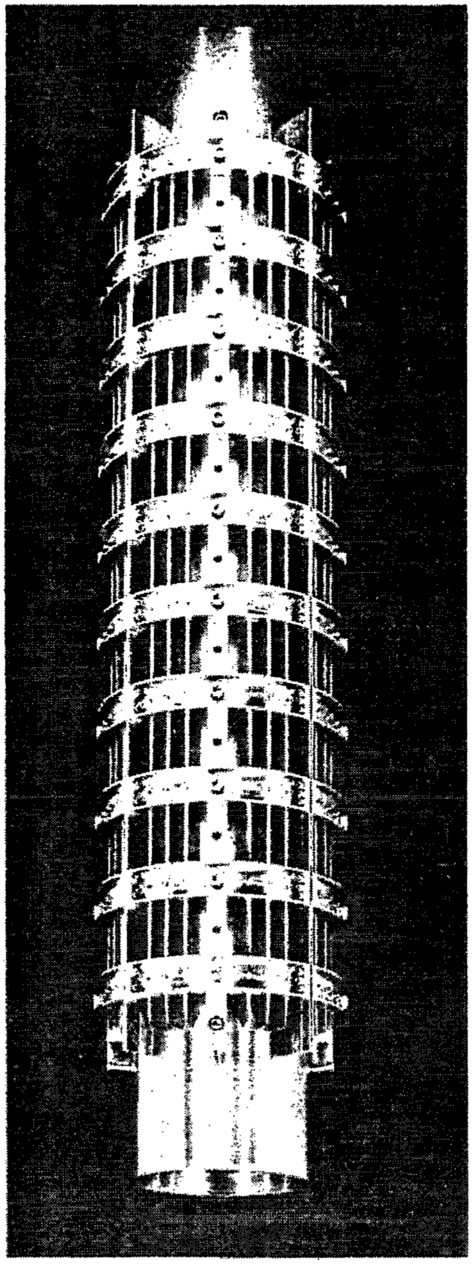

Fig. 7. Externally supported frame construction for quadrupole.

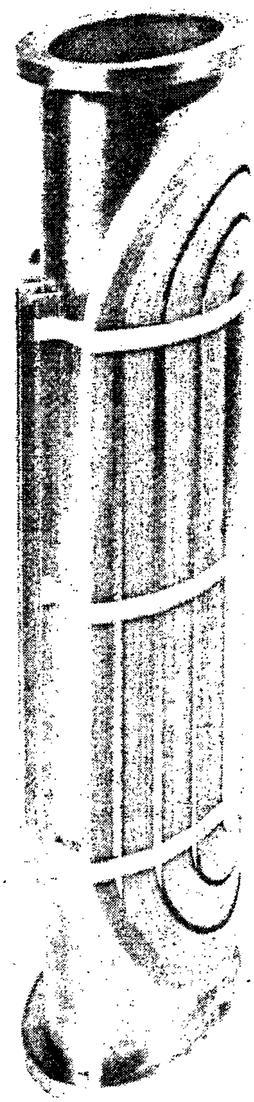

Fig. 8. Internally supported frame construction for dipole.

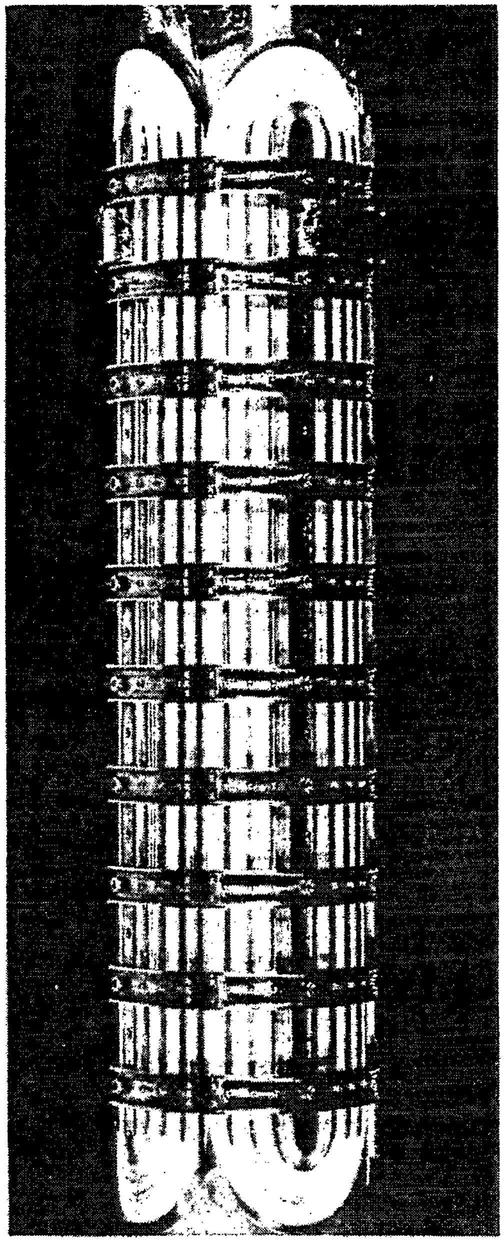

Fig. 9. Quadrupole element — 10 cm bore × 60 cm length.

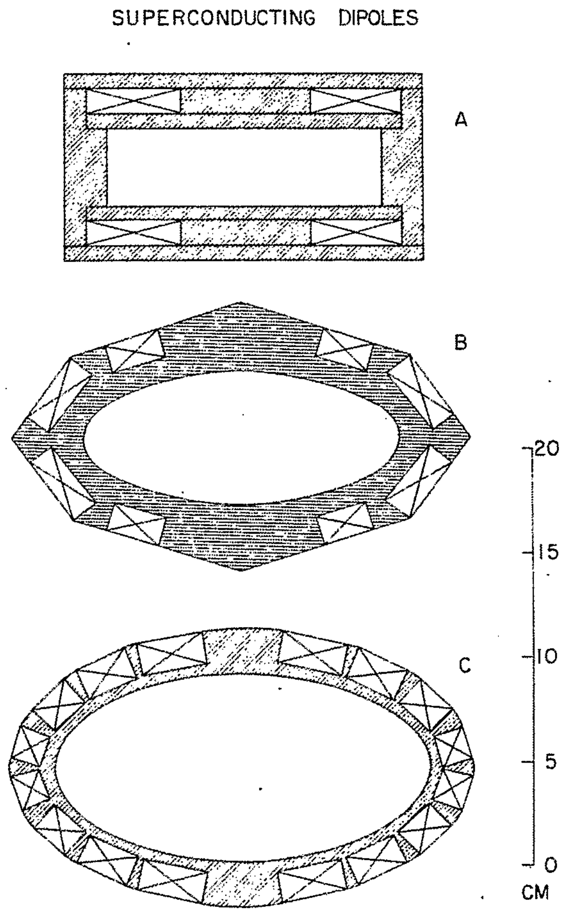

Fig. 10. Winding cross sections of superconducting dipoles.

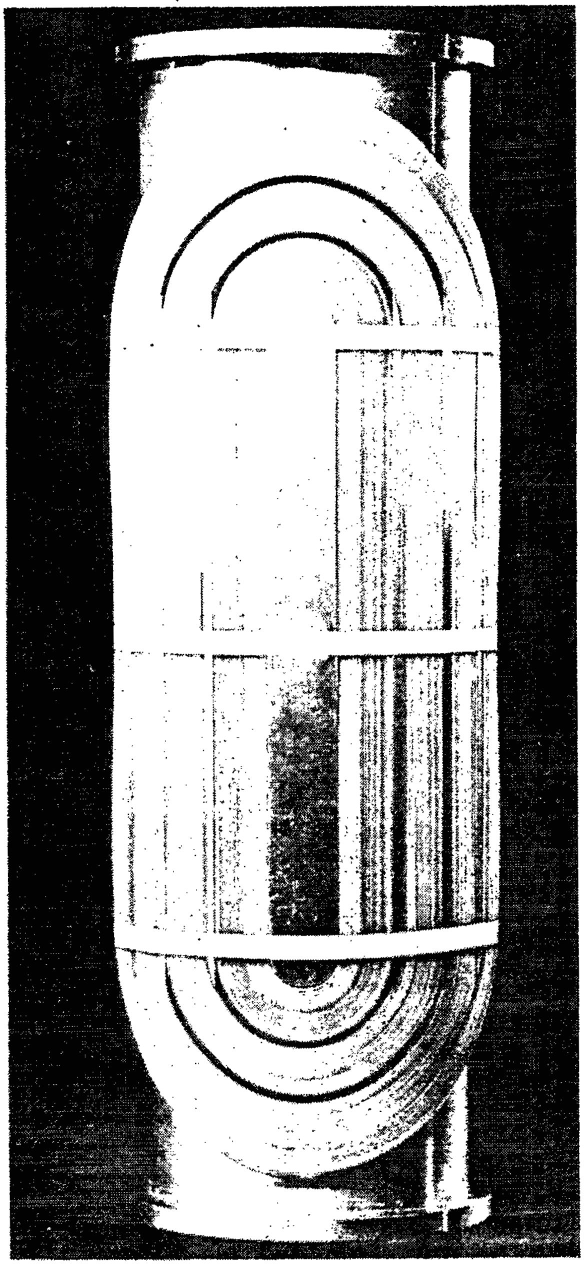

Fig. 11. Top view of elliptical dipole with dummy winding.

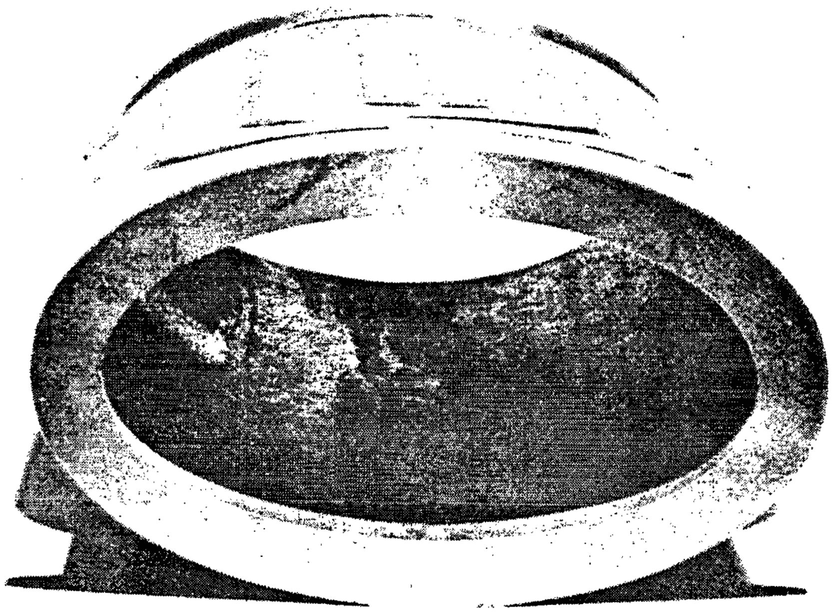

Fig. 12. End view of elliptical dipole.