SYNCHROTRON MAGNETS WITH CRYOGENIC EXCITING COILS*

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I. INTRODUCTION

By suitable choice of magnet parameters it is practical to excite iron magnets of the window frame type to fields exceeding 40 kG while retaining useful field properties.

High field performance is obtained by employing excitation current density values intermediate between normal 300°K practice and the very high current densities required for moderately thin shell air core magnets of small cross section.

Cryogenic aluminum exciting coils are competitive with superconducting coils from an ac loss point of view and appear to have many practical advantages.

In this paper a brief description of high current density iron magnet performance is given together with a summary of some parameters as applied to a 2 TeV (2000 GeV) machine lattice.

II. STUDIES ON EXCITATION OF HIGH CURRENT DENSITY WINDOW FRAME DIPOLES

Various papers have been written by the authors on the subject of a separated function magnet lattice for large synchrotrons.[1-3] In addition to the advantages in flexible operation and control of an operating accelerator, and in flexibility and economy in constructing an expandable machine, it was recognized that efficient operation at high fields is limited by the low current densities practical at 300°K. It was stated that with superconducting or cryogenic exciting coils of about five times smaller cross section than are typical at 300°K, useful fields would be obtained to about 30 kG. This work has been pursued further.

For very large machines, various factors lead one to the conclusion that the vertical aperture can usefully be at least as large as the horizontal, i.e., a circular vacuum pipe would be quite satisfactory. Typically the vertical aperture has been one-half to one-third of the horizontal. Scaling up the aspect ratio of the vertical to horizontal aperture dimensions leads to equivalent levels of saturation and of harmful aberrations setting in at significantly higher values of the field.

A modeling program has been carried out. A flexible "kit" magnet was constructed in which the side yokes and pole plates are separate structures so that the basic

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*Work performed under the auspices of the U.S. Atomic Energy Commission.

1. G.T. Danby, J.E. Allinger, and J.W. Jackson, Brookhaven National Laboratory, Accelerator Dept. Report AADD-115 (1966).

2. G.T. Danby, J.E. Allinger, and J.W. Jackson, IEEE Trans. Nucl. Sci. NS-14, No. 3, 431 (1967).

3. G.T. Danby, J.E. Allinger, and J.W. Jackson, in Proc. 2nd Intern. Conf. Magnet Technology, Oxford, 1967, p. 87.

aperture parameters can be easily changed. The steel is M-36 silicon steel sheet left over from the AGS construction.

Figure 1 shows an assembly containing a matrix of search coils inserted in the aperture. The entire structure is simply immersed in liquid nitrogen.

Figure 2 illustrates schematically the type of construction. The top and bottom yokes (12 in. × 12 in. × 4 in.) are always used, and various side yokes, pole pieces, and coils are employed.

Figure 3 shows the effect on saturation of increasing the vertical gap dimension for a constant coil thickness of 1 in. and a constant aperture width of 1.8 in.

The slope of the saturation curve is inversely proportional to the vertical aperture; the aberrations similarly diminish with increasing vertical aperture. One is approaching more closely the uniform field between two parallel current sheets of infinite extent. For a synchrotron (or general beam transport) one can expand the field in multipolarities about its center and ask what terms are present over the necessary high field aperture.

For the present geometry, the field aberrations are predominantly sextupole. On the horizontal and vertical mid-planes the 10-pole term is quite small even at full aperture in the case of an approximately square aperture. At maximum extent on the 45° axes, i.e., in the corners, the 10-pole term is four times larger. However, experimentally at $\sim$ 90% of the way to the corner the fit is still good to sextupole and 10-pole terms, and in agreement with the horizontal mid-plane data. Practically speaking, an inserted vacuum pipe would be roughly circular, and the 10-pole field aberration at the vacuum pipe at all angles would have the same magnitude as on the mid-plane at full aperture. Figure 4 shows aberrations on the horizontal mid-plane for a 2.4 in. version.

It can be seen from Figs. 3 and 4 that the 2.4 in. gap model has about 20% saturation of the B vs I curve at 41 kG, and about 3.7% sextupole. This aberration can be corrected with properly distributed exciting coils in the magnet. Figure 5 illustrates a partial correction with a three-turn pole face winding. However, passive improvement with crenolations or pole shaping is very attractive. It should be borne in mind that a synchrotron should have sextupole control in each half cell in any case for beam manipulation and high intensity operation, even for "perfect" magnets with zero aberrations. As a result, reducing the above aberrations by about a factor of two is sufficient to keep combined control and aberration correction sextupole elements to modest proportions.

Tests to further improve magnet performance are in progress. This interacts with broader considerations of economically and operationally optimum current densities for a given application.

In summary, practical iron dipole magnets of $>$ 40 kG peak excitation have been demonstrated. The flux density in the yoke is of normal magnitude, and saturation occurs only in the pole regions adjacent to the aperture. In principle, small cross section insertions in this region of either high field magnet steel ($\sim$ 3 kG improvement) or of low temperature ferromagnetic rare earths could further enhance performance.

These magnets are very compact because of the high current density. This leads to a structure of small over-all cross section. The ratio of useful aperture stored energy to total stored energy is very large.

III. CHOICE OF IRON CORE MAGNETS

Since this is not primarily an accelerator meeting no attempt is made to justify in detail the use of window frame iron dipoles in preference to air core cylindrical current distributions.

In the present design to a very good approximation the field is everywhere parallel to the plane of the current sheets both inside and outside the conductor. Pressures on the turns are almost uniformly outward, and modest in magnitude (the coil pressure is ~ 1200 psi at 40 kG). Window frame dipole magnet coils are not "pole face windings" except in a quite weak sense. With good but common tolerances on the inner turns (which are wound first in a coil) aberrations due to coil locational errors are very small.

High current density air core magnets of small bore can have, in principle, negligible two-dimensional aberrations. However, they require high mechanical and electromagnetic stability of the current elements in the presence of complex forces of large magnitude.

In practice, for air core current distributions, an iron sheath may be attractive as a shield and to enhance somewhat the field, unless workable magnets can be made with much higher field-current density (B_j product) material than is presently contemplated. However, the multipolarities generated by the current distribution still largely determine the field properties, so the basic advantages and disadvantages of such thin shell cylindrical air core magnets are not greatly affected by concentric shields.

In this paper we concentrate on dipole magnets. Figure 6 shows reasonable lattice parameters for a 2 TeV synchrotron of 40 kG peak field, with ν values of ~ 20. With a half cell length of ~ 185 ft, only an ~ 8 ft length of room temperature quadrupoles would be required. Quadrupoles are a minor consideration at this stage. However, one could also use cryogenically excited quadrupoles for compactness. As with the dipoles, higher current density coils will lead to considerably higher gradients being practical.

TABLE I

Coefficients of Nonlinear Terms in a Typical Brookhaven 3-in. Quadrupole

Ratio of Coefficients	B_{tip} = 7.1 kG	B_{tip} = 13.5 kG	B_{tip} = 16.3 kG
4θ/2θ	0.025%	0.048%	0.068%
6θ/2θ	+0.052 -16°39'	+0.057 -16°40'	+0.160 -16°30'
10θ/2θ	-0.415 - 8°19'	-0.372 - 7°47'	-0.286 - 6°22'
14θ/2θ	+1.096 - 8°09'	+1.059 - 8°15'	+0.925 - 8°26'
3θ/2θ	0.03	0.05	0.07
5θ/2θ	0.01	0.03	0.05
7θ/2θ	0.02	0.02	0.02

Table I lists the amplitudes of aberrations measured almost touching the iron poles in a 3-in. diam Brookhaven quadrupole. The aberration multipolarities are given as a percentage of the quadrupole field at the measurement radius, which is ~ 0.025 in.

from the iron. The true quadrupole aberration terms are 6θ, 10θ, and 14θ; these depend on the details of the particular design. For the magnet concerned, 6θ can be made arbitrarily small, and all vary slowly with excitation. However these terms vary in amplitude with very rapidly increasing powers of radius, so that over a useful aperture of 80-90% of the pole aperture these effects can be made completely negligible. The 3θ, 4θ, 5θ, and 7θ terms represent "noise" either due to structural asymmetry or to errors in the measurements. These results are typical and illustrate the high stability of such iron magnets.

IV. PROPERTIES OF LOW TEMPERATURE PURE ALUMINUM COILS

Magnet coils of pure metals operating at cryogenic temperatures have been considered for a long time.[4] Large stored energy magnets have been built, but, in general, have been overshadowed by the advantages of superconductors for such devices. Air core cryogenic synchrotron magnets have also been considered by several groups, but, unless a quite low duty factor was assumed, the high current density required for efficient small bore magnets has led to formidable refrigerator requirements. Considerable interest exists in the USA and other countries in various power frequency systems using either cryogenic or superconducting conductors.

The great promise of superconductivity has perhaps overshadowed too greatly considerations of pure metals. In the paper by Arp in these Proceedings,[5] it appears that very high resistivity ratio aluminum could be made available by large-scale commercial processes. As a result, even at the very low temperatures associated with superconductivity, aluminum may be very attractive for many applications.

For the present application it appears that the refrigerator requirements for the resistive losses in aluminum coils of existing material may be about the same as for optimistic superconductor ac losses. The aluminum coil system seems fairly straightforward. It is our judgment that, in addition, there are great practical operational and over-all cost advantages for Dewars, transfer lines, etc., by operating at higher temperatures (18-27°K). As a result, we arbitrarily concentrate the discussion in this range, although very low resistance appears practical at the helium temperatures associated with superconductors.

We now very briefly summarize some resistance properties, for which we are principally indebted to Arp.[5]

The resistivity, for no magnetic field present, is given by

$$\rho = \rho_o + \rho_i(T) \quad .$$

The term $\rho_i(T)$ represents the lattice resistivity and varies approximately as the cube of the temperature below 20°K. Above 20°K it approaches the fifth power law with temperature. The term ρ_o is due to impurities and lattice defects. In practice the resistivity ratio $\rho(300°K)/\rho(4°K)$ gives ρ_o, since $\rho_i(4°K)$ is extremely small.

For aluminum in a magnetic field ρ_H saturates at $\sim 2.8\rho$. The saturation occurs at lower fields as ρ decreases. In the present case, saturation occurs at a few kilogauss.

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4. R.F. Post and C.E. Taylor, in Advances in Cryogenic Engineering (Plenum Press, 1959), Vol. 5, p. 13.

5. V. Arp, these Proceedings, p. 1095.

Anomalous resistive behavior occurs for thin material when the electron mean free path becomes appreciable compared to the thickness. However, in a magnetic field, the cyclotron radius reduces this effect.

For our case where we consider 0.015 in. tape coils and an effective resistivity of $2.75 \times 10^{-9}\ \Omega\cdot$cm, anomalous effects are very small.

Strain also increases ρ. The effect commences to be noticeable at 3000 psi and becomes quite appreciable about 10 000 psi. For the present coils, the pressures at 40 kG are only 1200 psi, so strain is not a problem.

In summary, for the coils considered herein, which are $\sim$ 0.015 in. $\times$ 1.000 in. tape, operating in the 18-27°K range, the resistivity is effectively the bulk resistivity.

We define a constant resistivity for the magnet coil $\langle\rho$ eff.$\rangle$ which gives the correct dissipation for the assumed magnet cycle. Actually, the field in the coil varies with time and with location, so the effect of magnetic field should be somewhat below saturation. We assume $\langle\rho \text{ eff.}\rangle = 2.75 \times 10^{-9}\ \Omega\cdot$cm at an operating temperature T.

Assuming effectively pure aluminum, $\rho_i(T)$ at $T \sim 25^{\circ}$K is $\sim$ 2000 times less than at 300°K. As a result, the resistivity ratio of the material should be a number large compared with 2000 to give this almost ideal aluminum behavior (i.e., perhaps 10 000).

Assume a power duty factor of 40% to 40 kG. This corresponds, for example, to a 1 sec dwell time, 1 sec rise time, 1 sec flat-top, and a 1 sec invert. (These equal time intervals can be changed from 1 sec without affecting the heat load.) This corresponds to a 25% flat-top duty factor. For a 2.25 in. magnet gap and a coil cross section of 5.33 in.^{2} of aluminum the dissipation is 60 W/ft.

Additional Losses (all for 1 sec rise time):

(1) Vacuum chamber eddy currents. Assume a 0.020 in. cylinder of 2 in. diam and of $\rho = 10 \times 10^{-6}$. This gives 0.8 W/ft.

(2) 0.015 in. aluminum tape coil eddy currents: 2 W/ft.

(3) Iron eddy currents (0.025 in. steel): 2 W/ft.

(4) Hysteresis in iron: 6 W/ft.

(5) Dewar and transfer line losses: 1 or 2 W/ft.

V. REFRIGERATION REQUIREMENTS

The over-all dissipative load is about 70 W/ft. This is approximately independent of rise rate, the dominant loss being resistive. For a given magnet design the dissipation is invariant with absolute scaling of aperture, if the same relative cross-sectional dimensions are maintained.

There are, however, several mechanisms by which this load can be varied by large amounts.

1. Refrigerant

For 27°K (neon), the dissipation should be increased by about 50% (this is a lumped correction which includes both the higher $\langle\rho$ eff.$\rangle$ at 27°K and the higher refrigerator temperature, since refrigerator efficiency is considered at 20°K).

For $20^{\circ}K$ (hydrogen), the dissipation would be reduced to two-thirds of the 70 W/ft.

At $18^{\circ}K$, the dissipative loads would be reduced to one-half of the 70 W/ft. (At $10^{\circ}K$, and with very pure Al, i.e., $\sim$ 50 000 resistance ratio, the resistive dissipation goes down an order of magnitude; the other factors become more significant.)

2. Coil Area and Saturation

The dissipation was computed for a comparatively large coil of 5.33 in.^{2} of actual conductor. It now seems more probable that one would use a coil of $\sim$ 4 in.^{2} over-all cross section, which could be made with a very high packing factor. This would increase the dissipation by about 35%. Magnet saturation also was not included, and prolonged operation at peak field with long flat-tops would increase the power by about 50%.

3. Duty Factor

Sixty percent of the dissipation is in the flat-top, and only 40% in the rise and fall of field. With saturation included almost all the excess is in the flat-top. Present large synchrotrons do not have such long flat-tops (and it is not certain that one could use them effectively if they were available). Furthermore, the power supply and rf costs and problems of a 1 sec rise time are formidable and it is probable that for 2 TeV operation, at least 2 or 3 sec of rise time will be used. A 2 or 3 sec flat-top at top energy is luxurious.

4. Energy Storage

One great advantage to the flexibility of cryogenic (or superconducting) accelerators is that the major electrical dissipation is transferred from the power supplies to the refrigerant. The heat of vaporization is so large for neon or even hydrogen that it would take hours of running to vaporize most of the refrigerant, even with the refrigerator off. (For neon 100 kW evaporates 1 liter/sec.)

A $300^{\circ}K$ synchrotron has about a 1 sec time constant, so that unless a very large machine is pulsed formidably fast the power supply sees a very dissipative load. This greatly increases power supply cost and power consumption. A fast cycle requires a massive power supply (and rf system).

With a time constant of $\sim$ 1000 sec, one has complete freedom to trade off the power supply cost and complexity, assuming an adequate flywheel, and the rf and refrigerator capacity. In the cryogenic case, one could, for example, have alternate pulses to 2 TeV and to 1 TeV and thereby cut the dissipation almost in half. (The 1 TeV load goes down by more than the $\frac{1}{2}$ factor due to B^2.)

In summary, the figure of 70 W/ft refrigeration capacity is a conservative one, and a machine of high performance could be constructed with refrigerator capacities two or three times lower than this.

As an illustration of a large refrigerator plant, a 33 000 hp hydrogen plant at Sacramento, California, manufactured by Linde, would produce 530 kW at $20^{\circ}K$, operating as a refrigerator. This is a conversion ratio of 50 for input power to $20^{\circ}K$ power. Responsible designs at $20^{\circ}K$ for large systems give a range of conversion ratios from 35 to 50. By comparison, at $4^{\circ}K$ the range of conversion ratios is 300 to 500. For comparison to superconductors a dissipation of 50 W/ft at $20^{\circ}K$ is about equivalent to 5 W/ft at $4^{\circ}K$.

Figure 7 shows a magnet and Dewar cross section. Neither the magnet nor the Dewar design or refrigerant capacity are meant to be taken as more than an illustration.

Figure 8 illustrates a type of assembly of the ends of magnets and Dewars.

CONCLUSION

It appears that cryogenically powered magnets of the type described can be constructed with existing purity commercial aluminum and be competitive with projected superconductor coil ac losses. The compactness and high efficiency of stored energy actually in the useful region, plus the inherent flexibility of a system with a very long time constant will be very beneficial to over-all accelerator design.

ACKNOWLEDGEMENTS

We wish to thank the Senior Staff of the Accelerator Department at Brookhaven for their support of this activity.

We wish also to thank the Senior Staff of the Bubble Chamber Group and the Accelerator Department's Cryogenics Group for their assistance and the offering of their experience in large cryogenic systems.

We are also indebted to V. Arp of NBS for his knowledge and assistance in the properties of pure aluminum.

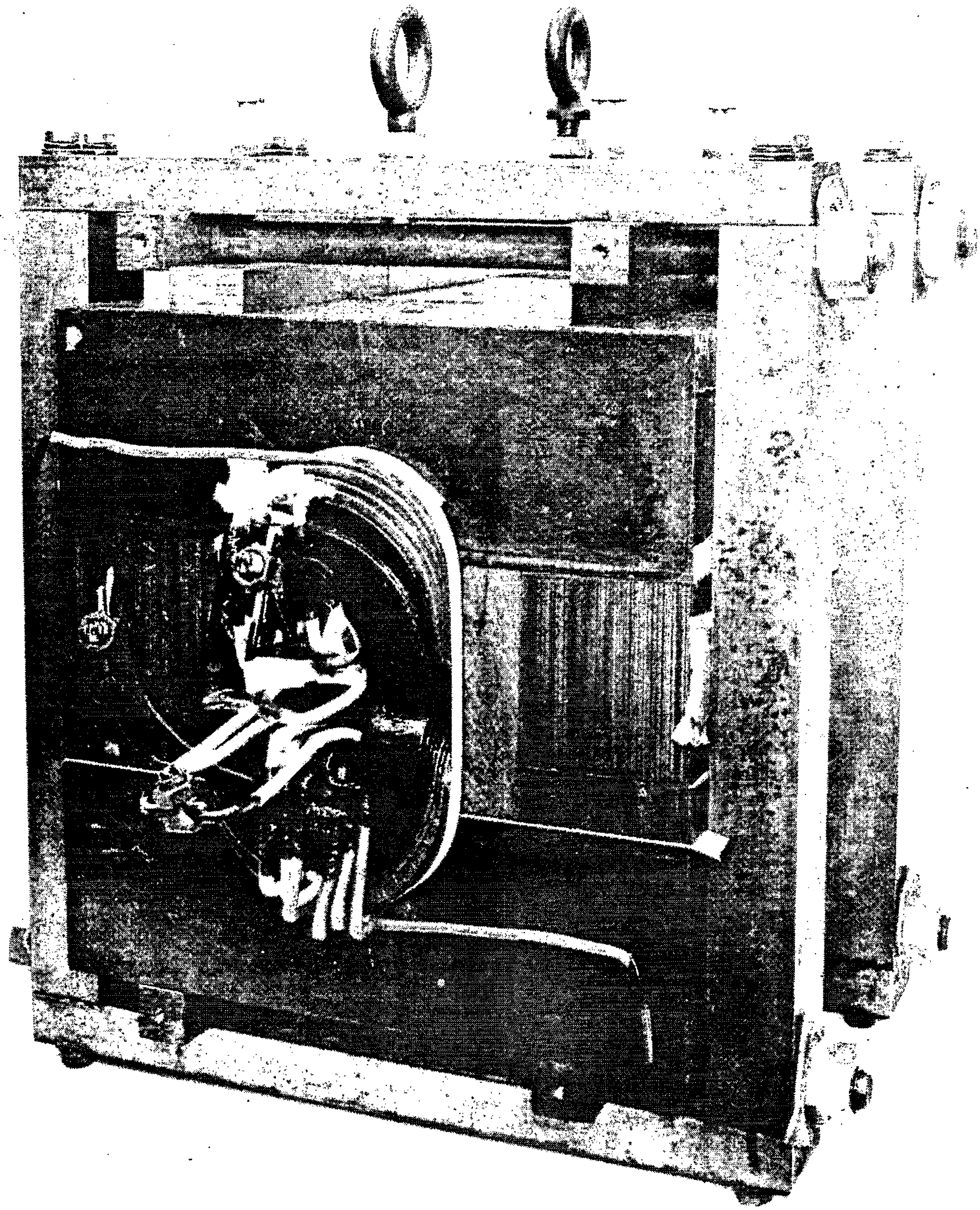

Fig. 1. Magnet model.

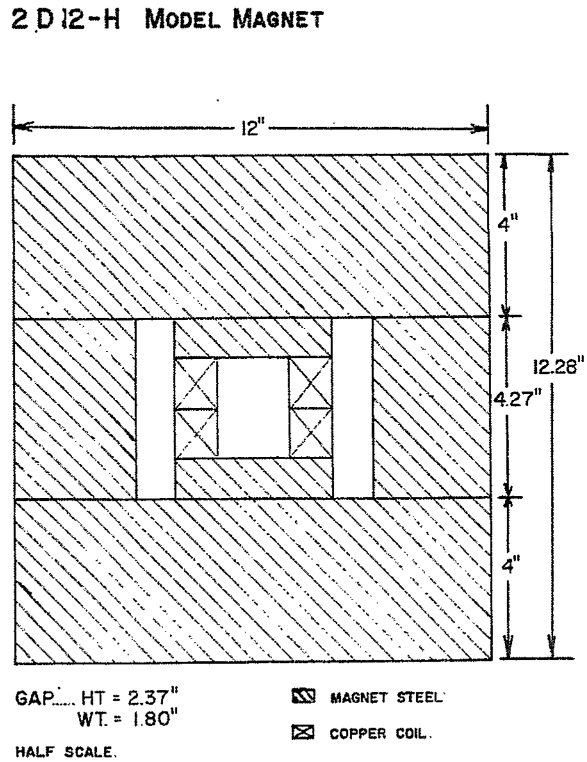

Fig. 2. Schematic assembly drawing of "kit" magnet.

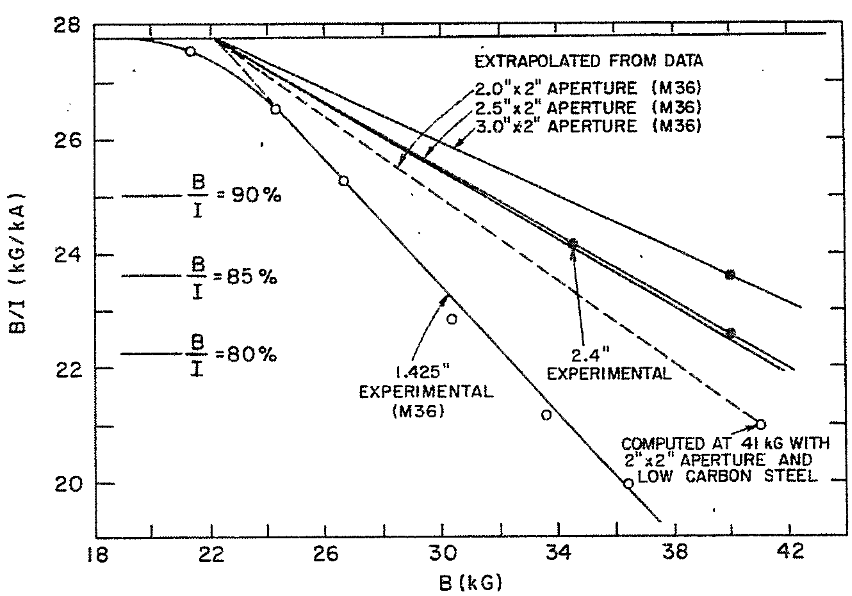

Fig. 3. Saturation effects for various magnet geometries.

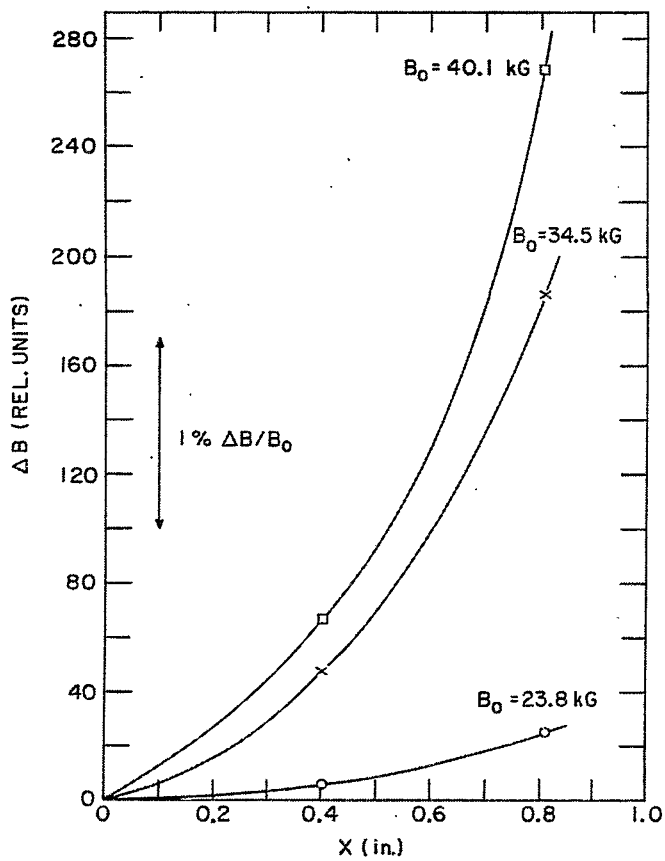

Fig. 4. Aberrations in 2.4 in. model.

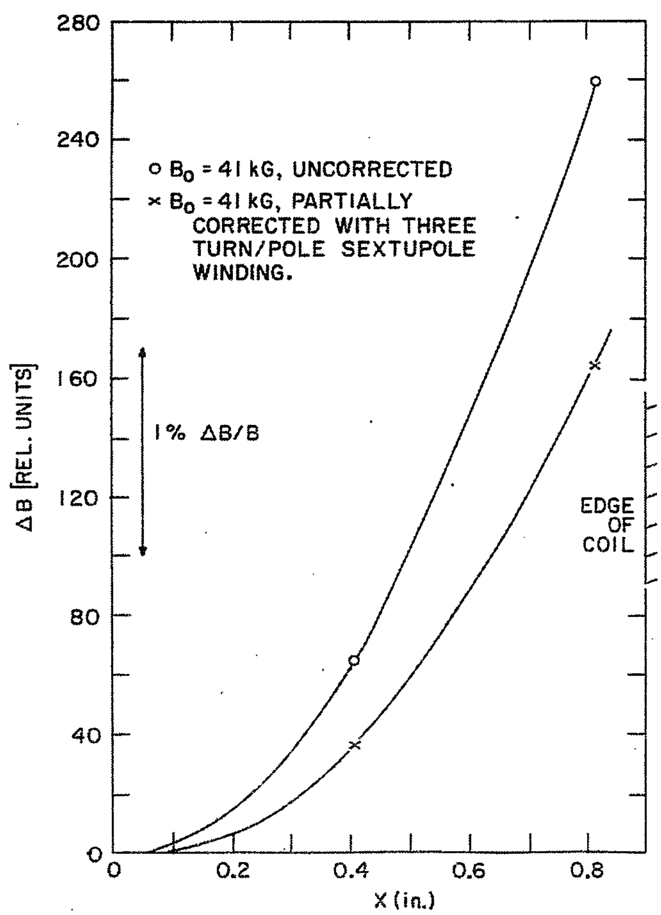

Fig. 5. Sextupole aberration partially corrected by pole face windings.

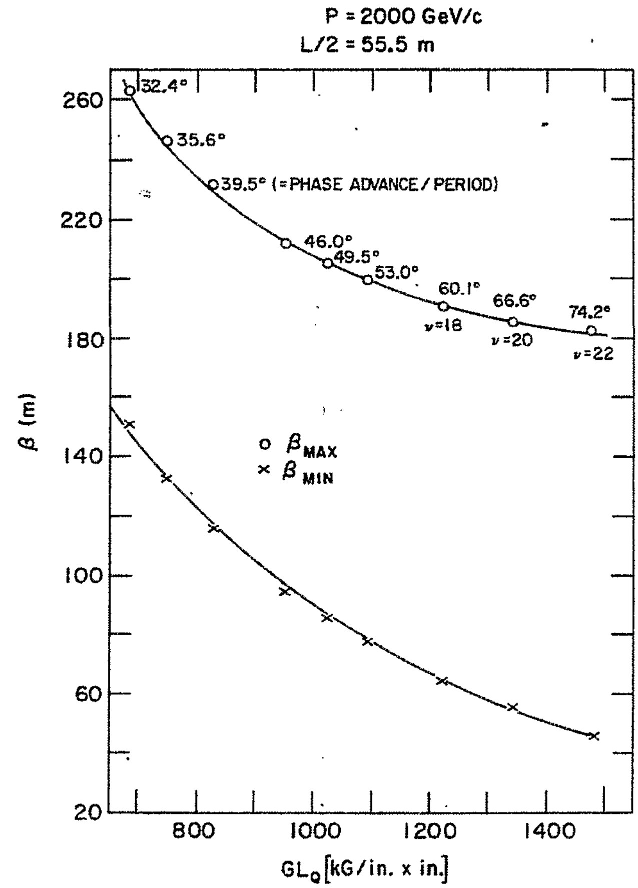

Fig. 6. Typical lattice parameters for 2 TeV synchrotron.

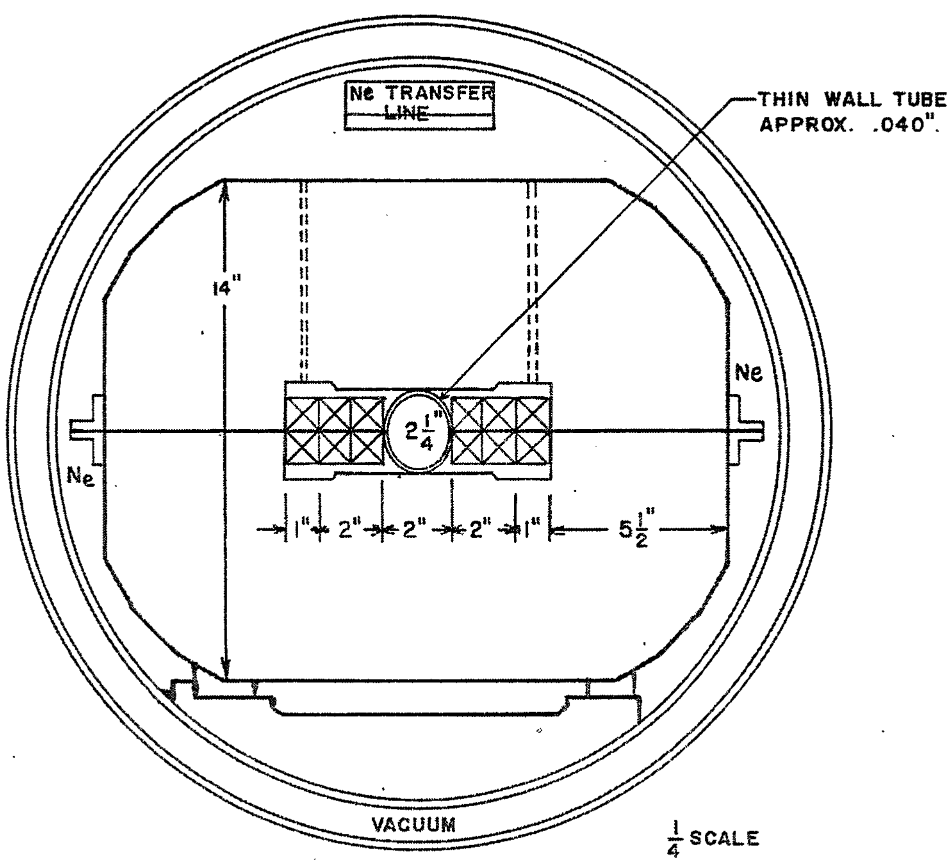

Fig. 7. Cross section of cryogenic magnet and Dewar (representative only).

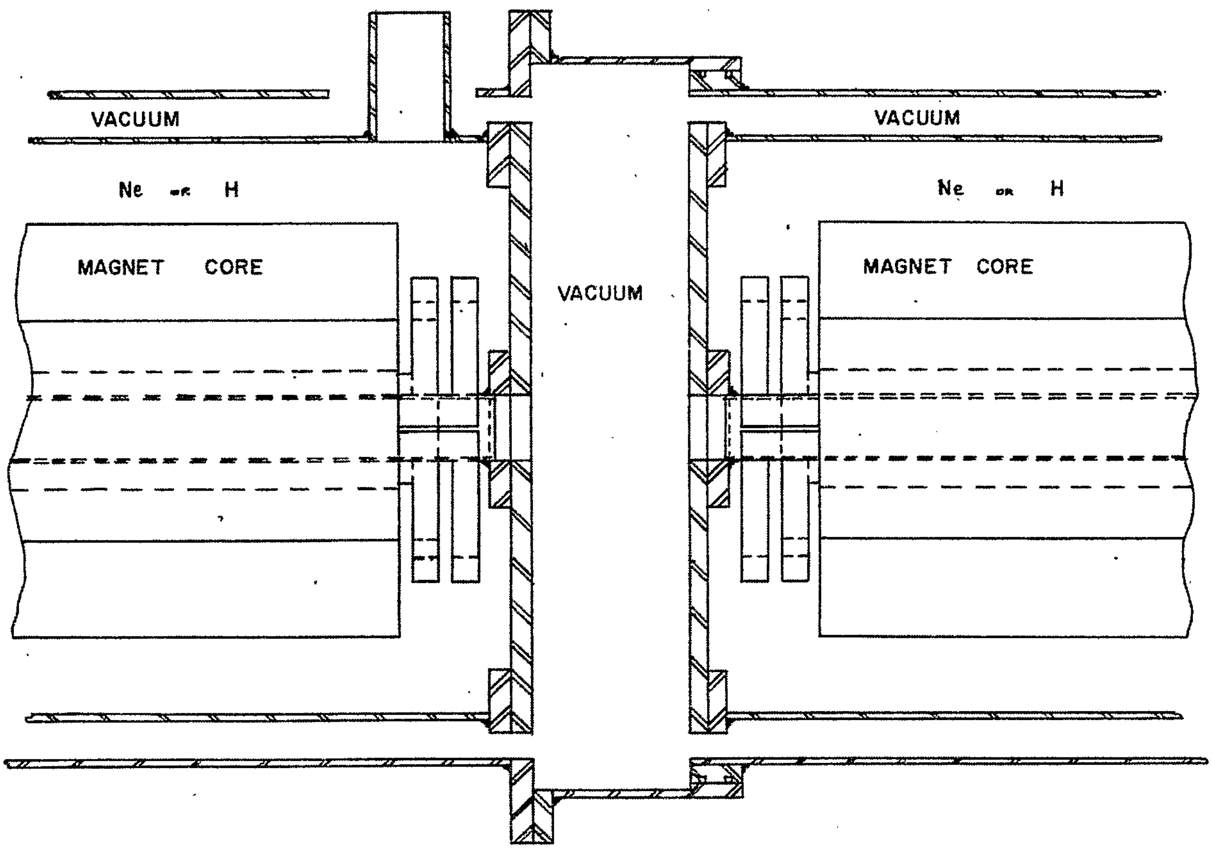

Fig. 8. Possible end section of magnets and Dewars.