PRELIMINARY STEPS FOR APPLYING SUPERCONDUCTORS TO FFAG ACCELERATORS*

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INTRODUCTION

In our effort to see the possibility of applying superconductors to accelerators, using magnetic guide fields, we came up with several questions. For some of them we have an answer, for others we see probable solutions, but there are still several for which we do not see a workable solution. Although this is our present situation, our answers and doubts are presented in this paper.

Some general considerations will be made on the problem of building a superconducting ring for an accelerator. These considerations will apply only to the guide field; problems related to injection and extraction or rf acceleration, although very important, are not discussed in this paper. Rather than presenting a detailed study of a cryogenic system with optimum performance, emphasis is placed on those problems where clear solutions are needed if one thinks seriously of building an accelerator.

Without talking specifically of a particular type of accelerator (pulsed or dc), we will discuss in general the problems of accuracy in field measurements, in positioning and alignment of a magnet set subject to thermal contraction and strong magnetic forces.

In what follows, three possible ways of building an accelerator magnet ring are presented.

(A). The whole accelerator is in a vacuum chamber which serves as a cryogenic enclosure. This scheme is shown in Fig. 1. This design will apply to small machines, perhaps not more than 4 m diam; beyond this size this design is not economical.

If the magnets, forming the ring, have no obstructions in the median plane (open midplane), field measuring and positioning can be made inside of the enclosure at 4.2°K. It is required to have a support for the field measuring instruments and a boom that can move radially and azimuthally. The field mapping will be in polar coordinates.

One can conceive ways of "zeroing" the measuring scales at 4.2°K before starting to take magnetic measurements. A proper design may allow the field measuring devices to remain inside of the enclosure for future checking of the fields. Notice that this can be accomplished easily as there is no vacuum chamber in the field region.

For closed mid-plane magnets, the previous procedure will not apply. Magnetic measurements need to be carried out on a separate cryogenic measuring chamber (see Fig. 12); once a magnet is "measured" it takes its place in the ring. One very important point in this operation is that positioning a magnet requires reference marks that are related to magnetic measurements; the operation

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of the magnets is at 4.2^{o}K; thus, to minimize errors, a correspondence between field values and coordinates should be established at such a temperature. We will come back to discuss this point further.

(B). The second alternative corresponds to the case of an accelerator having all the magnets in the ring sharing a common vacuum-cryogenic chamber as well as the same mechanical support. This case is illustrated in Fig. 2. This design will be suitable for large machines.

One can visualize at least two possible ways for field measuring and positioning of the magnets.

(i). Using a cryogenic measuring chamber as mentioned above, regardless of whether the mid-plane is open or closed.— After measuring each magnet it is transferred into the ring. The final alignment of all magnets should be made at 4.2^{o}K; thus, it is essential to have access to reference marks or targets through the cryogenic enclosure. Azimuthal positioning can be done by normal surveying techniques and radial positioning by laser interferometry.

(ii). Using a field measuring machine that can be part of the ring.— A magnet (and modular vacuum-cryogenic chamber) can be roughly positioned in the ring, the enclosure evacuated, cooled down, field measurements taken, and the reference marks established for future accurate positioning. In this case, as before, the reference marks should be accessible, through a window, from outside of the enclosure. Successive magnets will be accommodated in the ring until closed. Although this procedure may have some advantages, a detailed economic study will be needed to decide its applicability.

Versions A and B are also attractive from the point of view that, having the vacuum chamber at 4.2^{o}K, ideal conditions against gas scattering will be obtained.

(C). The field region of the magnet is at room temperature, each magnet being a separate unit (see Fig. 3). This design may be suitable for a very large machine, where each magnet is far away from its neighbor. In this last option, the minimum separation between two adjacent magnets is determined by the magnitude of the magnetic force that can be tolerated without producing misalignments.

The advantage of this design is that the magnetic fields can be measured, using well-known techniques, at room temperature; however, positioning reference marks should be located in the magnet, not in the shell of the cryogenic enclosure that, by definition, cannot be rigidly attached to the magnet.

This design may require a separate vacuum chamber, whereas in the two previous ones the cryogenic enclosure provides the vacuum needed for thermal insulation as well as for the beam. As mentioned before, the absence of a vacuum chamber may allow us to measure magnetic fields, at least in some spots, when the whole magnet ring is already assembled. This was a practice followed in the past for FFAG accelerators using iron magnets.

The previous examples illustrate the types of problems that will be encountered in this field. Neither of these designs presents a complete picture of the situation, as many details have been omitted for simplicity. Satisfactory solutions require the development of a new technology to meet tight tolerances in an environment at 4.2^{o}K. A possible way to find some solutions will be outlined in this paper.

THE FFAG ACCELERATOR

The application of superconductors to accelerators seems to be most probable in the case of machines using time independent magnetic fields. The FFAG accelerator is an attractive candidate. It has, however, a clear disadvantage, namely, the complexity of the magnetic field; it is, nevertheless, the type of machine that we will consider in what follows.

Among the two types of FFAG accelerators, we are interested in the spiral sector type[1] in which the field in the median plane is given by the well-known expression*

$$B_z = B_o\,(r/r_o)^k \left\{ 1 + f \cos \left[N\theta - K \ln (r/r_o) \right] \right\} .$$

In a very small accelerator, one can produce this field by a current distribution running along a spiral from the inner to the outer radius of the machine.[2**] Acceleration can be obtained by betatron action. However, if rf acceleration is used as in the case of a large machine, continuity within the spirals is no longer possible and the accelerator guide field needs to be interrupted by short straight sections. Furthermore, if each unit (between two straight sections) needs to be kept within a reasonable size, further division of the unit will be necessary. The spirals will then be broken into many pieces as illustrated in Fig. 4.[3] By assigning the required magnetic potential at the reference radius, the corresponding potentials (or ampere-turns) can be calculated along the different blocks forming the spiral. The change in potential per sector, i.e., between adjacent coils in any block, determines the ampere-turns required to excite each pole. Figure 4 shows these coils in an iron yoke. For simplicity in the calculations, the iron poles can be considered as magnetic equipotentials. For an air core magnet the required field may be obtained by some form of current distribution; our problem consists in selecting the distribution that satisfies both magnetic and mechanical requirements; the latter is related to deformations resulting from forces and thermal effects. The current distribution, from the geometrical point of view, should also conform with the shape of the superconductor, as mechanical stability in superconducting coils cannot be obtained through operations like vacuum impregnation or epoxying.

Taking these points into consideration together with the fact that the radial aperture in an FFAG machine is somewhat large, we believe that the block configuration of Fig. 4 may satisfy all requirements, at least in the first approximation.

A simple way to obtain a current distribution that may satisfy the field requirements was proposed by Blewett.[4] Given the scaling condition between sectors, the ampere-turns required for excitation are found for the successive poles located along a radius and for a given azimuth. This yields the field patterns already shown in Parzen's and Kruger's papers. The presence of negative fields is undesirable because

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* See G. Parzen's second article in these Proceedings, p. 1052.

**This is discussed by P.G. Kruger in these Proceedings, p. 1059, although not in connection with small accelerators.

1. K.R. Symon et al., Phys. Rev. 103, 1837 (1956).
2. D.W. Kerst et al., Rev. Sci. Instr. 31, 1076 (1960).
3. Proposal for a High Intensity Accelerator, MURA, September 1963.
4. J.P. Blewett, Brookhaven National Laboratory, Accelerator Dept., AADD Technical Note No. 30 (1967).

they cause an increase in the circumference factor of the accelerator. The problem then consisted in finding the currents that will satisfy the scaling condition plus the condition that $B = 0$ at the minima. This yielded five equations with five unknowns from which the currents were determined.

To see the practical difficulties that one may encounter in producing such a field when dealing with finite size coils and to study edge effects, which are difficult to calculate, a small copper model was built. The same three coil configurations used by Blewett were studied. A schematic view of the magnet appears in Fig. 5. The dimensions were determined experimentally to give the best fit to the calculated values, and the winding scheme was obtained from Blewett's note.

A comparison of our results to the calculated field can be seen in Fig. 6. The accuracy in the field measurement is about 0.5%. The results presented here were obtained after many trials where conditions were changed, and although there is still some discrepancy between the two curves, we believe that more work could yield better results. This, however, was not attempted as we are now interested in developing computer programs for calculating the fields in a realistic configuration involving finite size coils also satisfying the requirements needed in an accelerator.

THE SUPERCONDUCTING MAGNET

Before one can think about using superconductors for magnetic guides in FFAG accelerators, one should have clear answers to the following questions, all related to an environment at 4.2°K.

1) Can one measure magnetic fields with accuracies of the order of 0.01%?
2) Is it possible to establish reproducible correlations between currents and fields compatible with the above accuracy?
3) In an FFAG magnet, how can one solve the problem of "low field superconductivity"?

There are also questions of an engineering nature, namely, can reference marks, related to field measurements, be established and extrapolated outside of the cryogenic enclosure maintaining accuracies of a few parts in 10^5 (in 100 in. length)?

These and other questions related to rf acceleration, injection and extraction at low temperatures are important to the accelerator builder.

A simple magnet configuration as illustrated in Fig. 7, having rectangular coils, may be a step in the right direction. The geometry is simple enough to facilitate calculations and interpretation of results. If one wants to be realistic, the dimensions and fields must be consistent with the parameters that may be used in an accelerator.

A possible field value of about 50 kG may be obtained in such a magnet using coils having about a 4 in. × 4 in. cross section and 18 in. long with a 6 in. separation between the centers of the coils. The expected variation of the B_y component of the field is shown in Fig. 8. The results of the calculation indicated that field uniformity of one part in 10^4 should be expected in a cylinder of 1 in. diameter and about 2 in. long. Each of these coils can be made using a conductor having 15 strands of superconducting NbTi in a copper matrix of a rectangular cross section 0.055 in. × 0.115 in. with a copper-to-superconductor ratio of 3.5:1. This conductor should carry at least 500 A at 50 kG.

In the absence of diamagnetic effects, the equigauss plot in the cross section of the coil should be as shown in Fig. 9. This indicates the regions in the coil that one should protect against low field instabilities.[5]

Magnetic forces can be a serious problem in these coils as can easily be seen from Figs. 10 and 11. The expected total attractive force between the upper and lower coil is about 210 tons.

It would be naive to think that a coil subject to thermal contractions and large magnetic forces can maintain the dimensions as imposed by field tolerances, i.e., a displacement of the center of the coil bundle of 0.002 in. will produce a field change of about 0.01%. Thus, most likely correction coils need to be used; presumably these should be made of copper.

The first tests of this magnet can be carried out in a Dewar, the magnet standing in the vertical direction. Dimensional changes due to thermal contraction and magnetic forces may be observed and measured through a window in the Dewar. The field measurements can be made with an NMR probe (bore at room temperature) which will serve as a primary standard. Other magnetic measuring instruments, flip coil, rotating coil, and bismuth probe can then be calibrated both at 300°K and 4.2°K.

The final tests should be conducted in a cryogenic enclosure as shown in Fig. 12. This can be used for field mapping and establishing reference marks for future alignment. Provisions should be made for positioning the magnet with respect to the same coordinate system used for the magnetic field measuring instruments.

The enclosure essentially consists of two coaxial cylinders — the inner one at 77°K serves as a radiation shield between the magnet at 4.2°K, and the outer shell is at room temperature. Initially, liquid helium can be used in the reservoir designed for such a purpose; in the future a refrigerator may take the place of the helium reservoir. Many details have been omitted in this figure for clarity, but the final design contains the power connections, helium transfer and liquid level controller, plus instrumentation required for operating the enclosure and the magnet. The side windows will be used for alignment of the magnet.

Several mechanisms are now under study to select the most appropriate one for performing operations like rotations, displacements, etc., as required by the positioning devices and field measuring equipment.

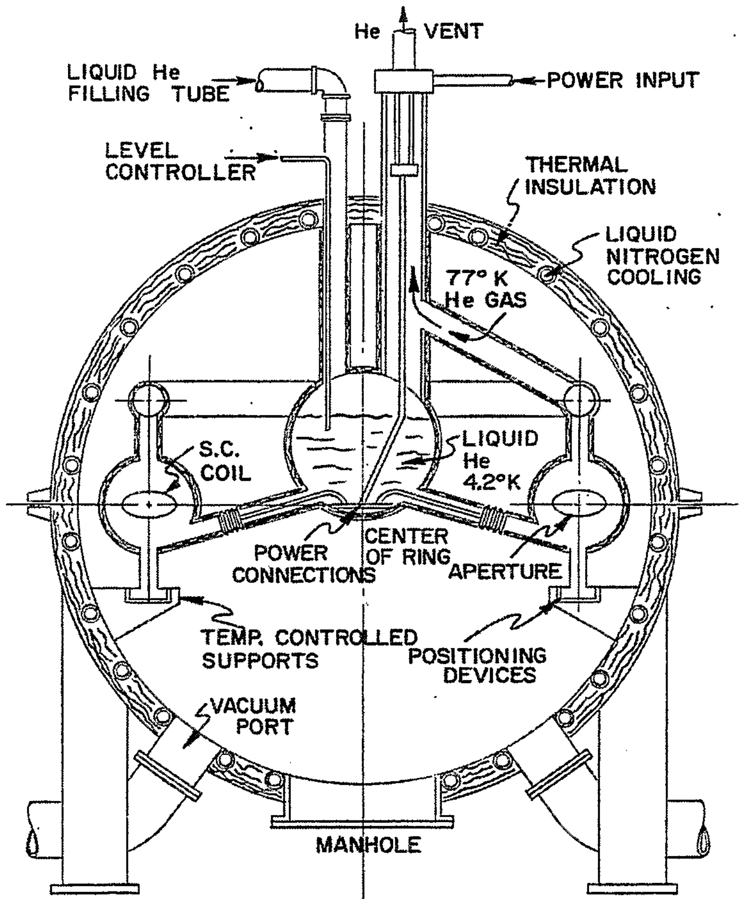
The chamber is of a modular type; thus, combinations of magnets can be studied by adding a module of the size required to accommodate as many magnets as needed.

It is our hope that these steps will help us to better understand the problems in this field and look for the appropriate solutions.

We are grateful to Dr. T. Khoe for many illuminating discussions on the general subject of magnetic fields, and to Dr. E. Crosbie for his interest and support of this project.

Thanks are also due to Mr. E. Berrill who is developing the technology for measuring fields at low temperature.

5. G. del Castillo and L.O. Oswald, these Proceedings, p. 601.



CROSS SECTION OF ACCELERATOR

Fig. 1. Simplified version of a "superconducting" accelerator inside of a common vacuum chamber and cryogenic enclosure. The elliptical areas represent the magnetic field region. The beam circulates in a plane normal to the paper. The center of the machine coincides with the center of the spherical enclosure. This version offers optimum cryogenic conditions. For simplicity the use of liquid helium is illustrated; however, in this as well as the following cases, a refrigerator should be used.

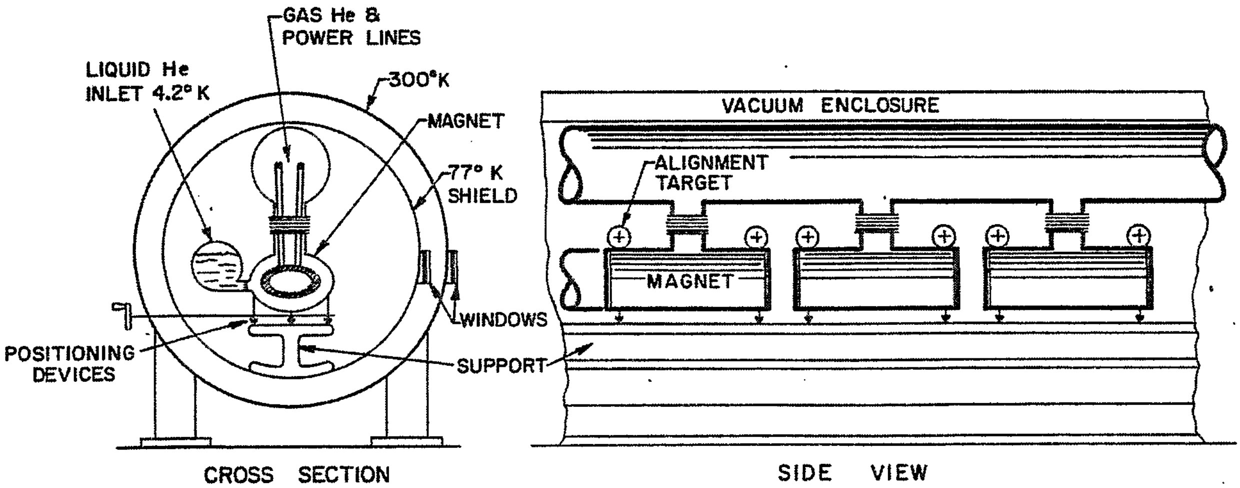


Fig. 2. Version of an accelerator using a common vacuum-cryogenic chamber and magnet support. Notice that windows for magnet alignment as well as manipulators for fine adjustment are required.

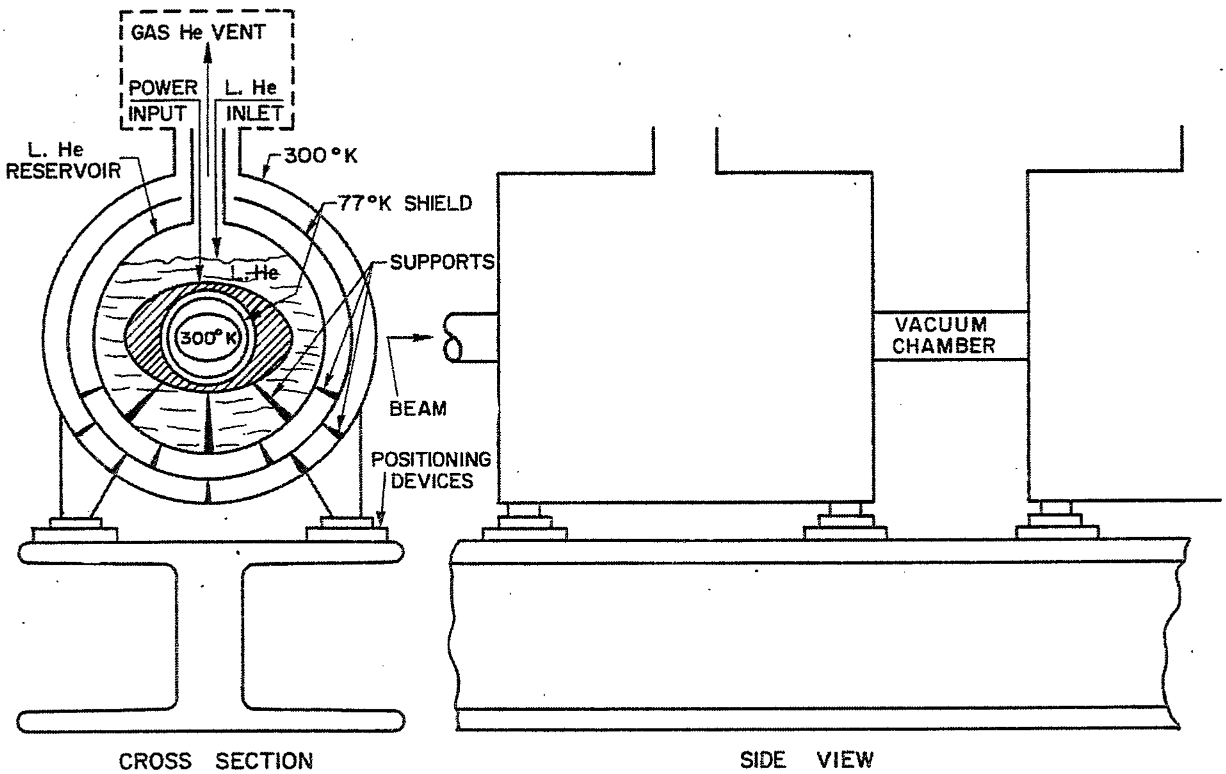


Fig. 3. Accelerator version using superconducting magnets with bore at room temperature. This design will be suitable for a large size machine or beam transport system. No alignment targets are included, as it is unlikely that after cool-down the targets located in the outer enclosure will remain unchanged relative to the magnet. Positioning of these magnets should follow other techniques different from triangulation.

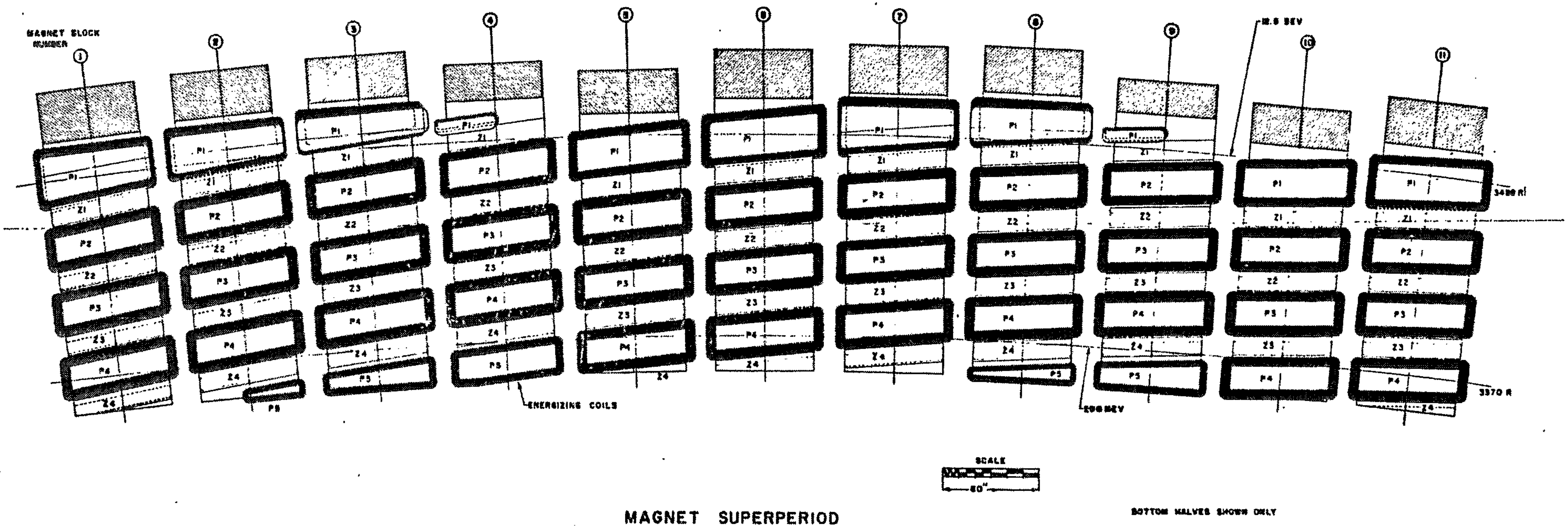
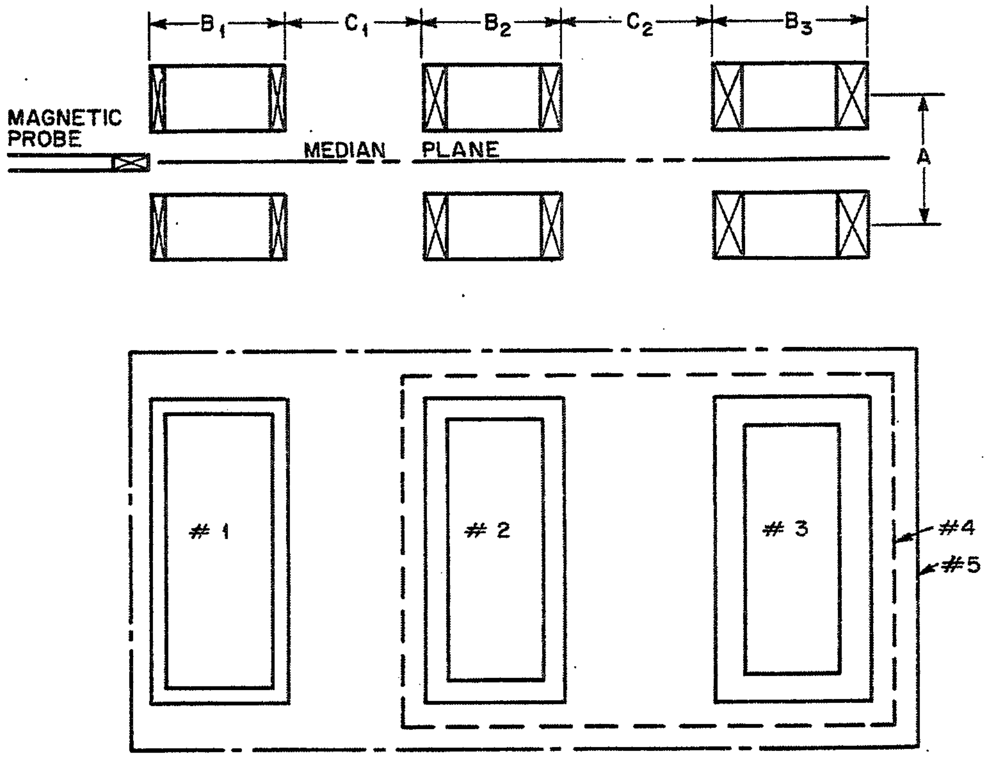


Fig. 4. Superperiod of a large FFAG accelerator using iron magnets (MURA Proposal, 1963).



DIMENSIONS

$A = 1.43''$

$B_1 = 1.59''$

$B_2 = 1.59''$

$B_3 = 1.75''$

$C_1 = 1.59''$

$C_2 = 1.75''$

WINDING SCHEME

COIL #	TURNS
1	10
2	132
3	299
4	44
5	137

Fig. 5. Practical realization of J. Blewett's scheme. The two-dimensional calculation was used to build this magnet. The A = B = C condition used by Blewett was corrected, as indicated, to take into account finite size coils and end effects.

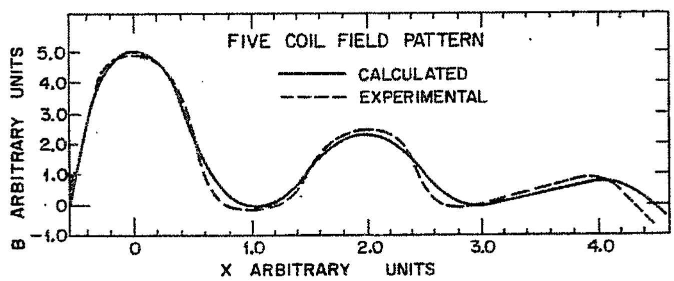
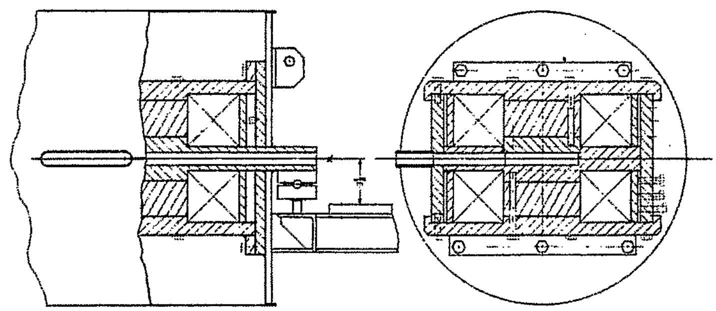


Fig. 6. Comparison between the results of magnetic measurements made in the model magnet and the two-dimensional calculation.



SIDE VIEW

FRONT VIEW

Fig. 7. 50 kG superconducting magnet. The stainless-steel structure surrounding the coils is needed to minimize dimensional changes due to magnetic forces. Two windows each 1 in. X 5 in. are provided along two perpendicular axes for magnetic measurements. The magnet is surrounded by an enclosure to be used in conjunction with the field measuring chamber (see Fig. 12).

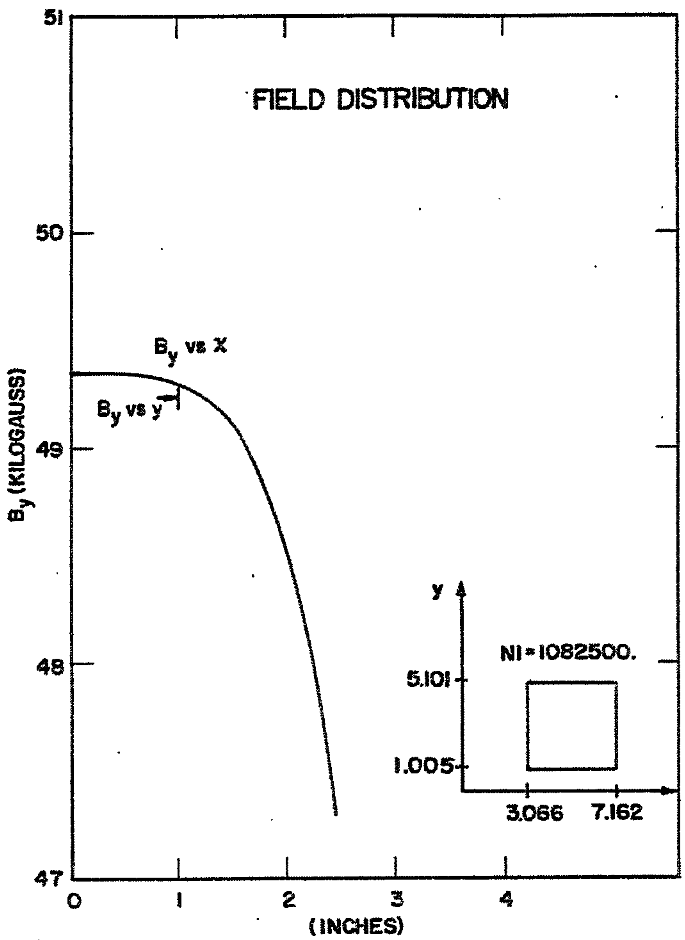


Fig. 8. Variation of B_y component of the field with respect to coordinates X and Y. The expected field uniformity is of one part in 10^4 in a cylinder 1 in. diam and 2 in. long.

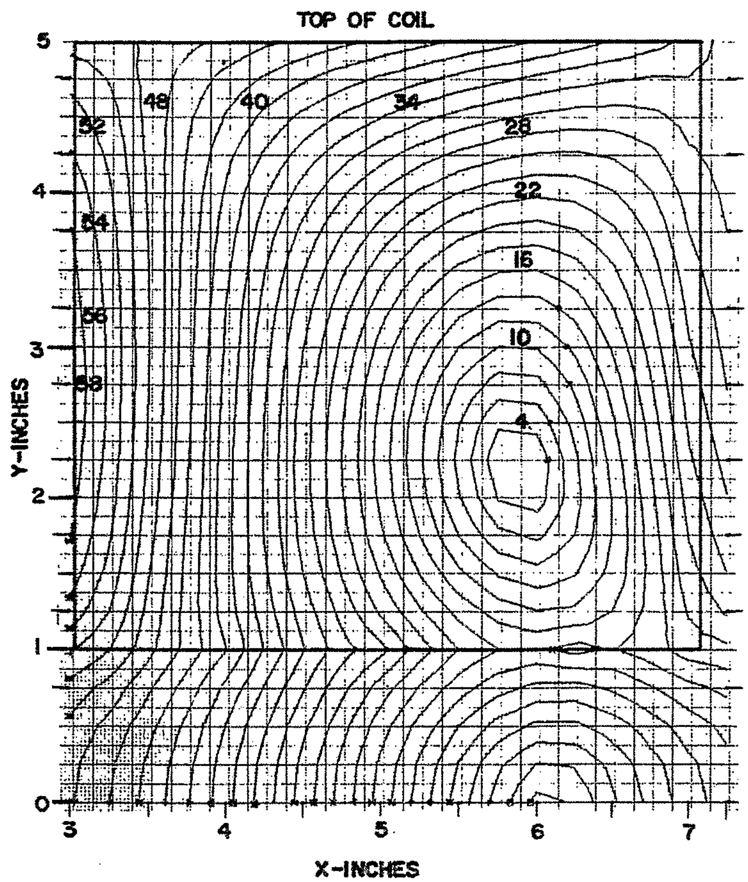


Fig. 9. Equigauss plot in the cross section of the coil shown in the insert of Fig. 8. No diamagnetic effects are considered in this calculation.

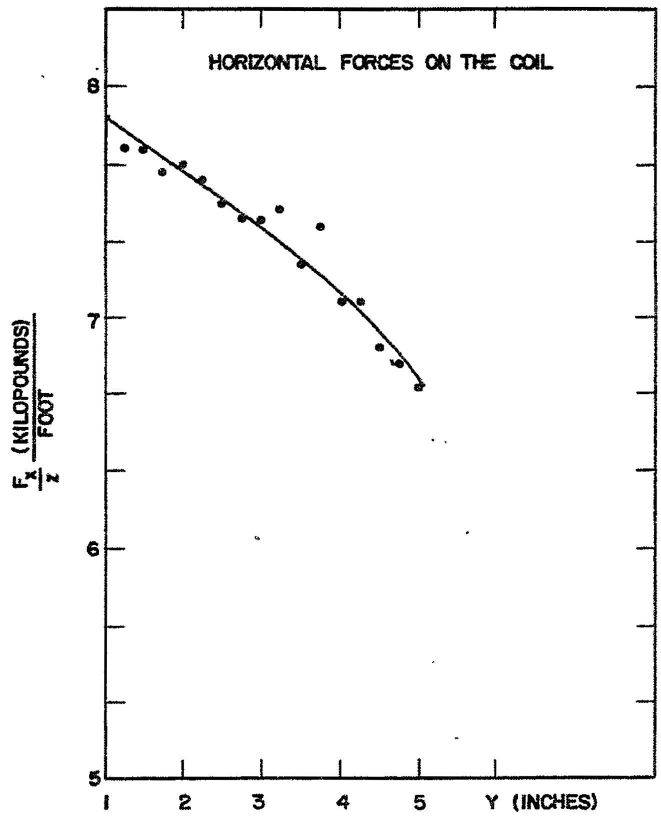


Fig. 10. Horizontal force distribution in the cross section of the coil.

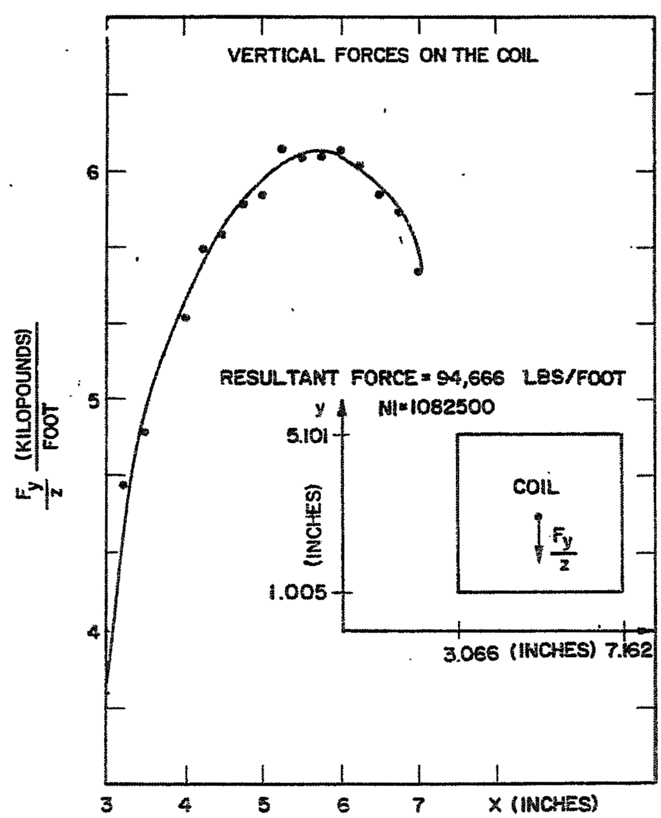


Fig. 11. Vertical force distribution in the cross section of the coil.

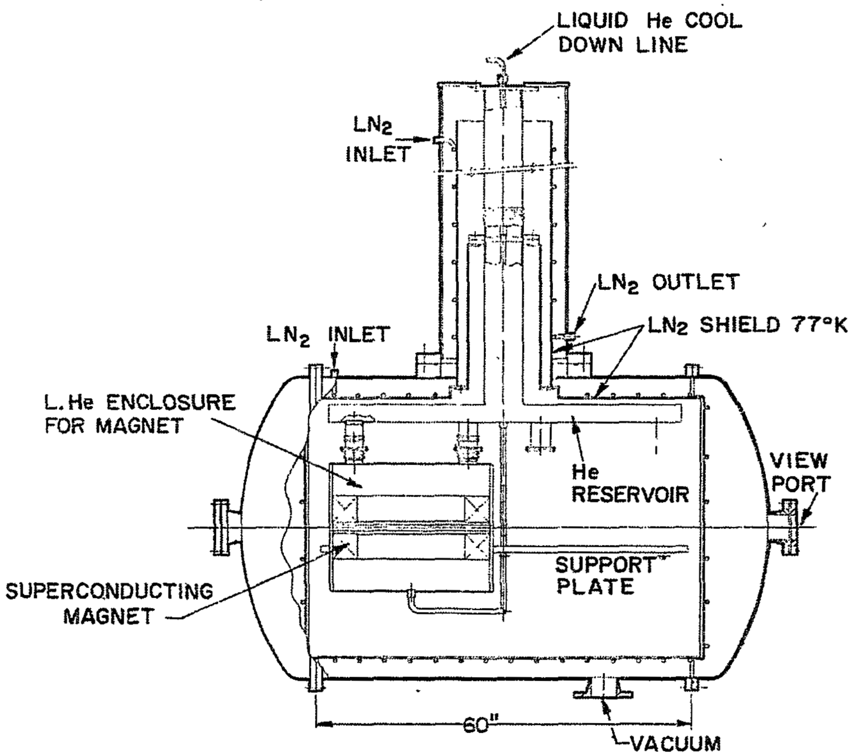


Fig. 12. Cryogenic field measuring chamber. The design is based on Fig. 1. The magnet, surrounded by its liquid helium enclosure, is shown near the end of the chamber. The other end is used for the field measuring instruments (not shown in the figure). For clarity many other details have been omitted. The diameter and length of the outer cylinder are 4 ft and 5 ft, respectively.