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A 31 cm Model Superconducting Cyclotron Magnet, I.

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Design study on a 31 cm model superconducting cyclotron magnet now under construction is described. The designed maximum operating magnetic field is 4T and protons can be accelerated up to 10 MeV (K_F value). Structures of coils, cryostat, yoke and iron pole tips are presented with expected field characteristics. Orbit properties estimated from the calculation with uniform magnetization approximation are discussed.

KEY WORDS: Superconducting AVF cyclotron/ Design study/ Main magnet structure/ Orbit analysis/

I. INTRODUCTION

Superconducting magnets have been progressively utilized for large-scale, high-power magnet applications; especially many big bubble chamber magnets have been already constructed and operated successfully for many years. Main aims to utilize superconducting magnet are not only to get higher magnetic field itself, but also to save energy and to make the magnet more compact.

Application of superconducting magnet to cyclotron main magnet[1] is thus very important from the point of view mentioned above. Superconducting main coils combined with conventional sectored iron pole tips seem to be a promising candidate for a new generation of compact, low-cost AVF cyclotrons. In order to see the feasibility of superconducting cyclotron magnet more in detail, we designed a 31 cm model superconductng cyclotron magnet, and along with this design, a magnet is now under construction. As the first of series of reports on the magnet, the design of the magnet is described in this note in detail, while the construction and performance of the magnet will be described in another forthcoming paper.

At present, large-scale superconducting cyclotrons are now under construction at East Lansing[2] and Chalk River.[3] Also 1/6 model superconducting cyclotron magnet has been constructed at Milano.[4]

II. GENERAL CONSIDERATION

As shown by Blosser and Johnson,[5] focusing properties of superconducting mag-

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net with sectored iron pole tips are strikingly different from the corresponding properties of conventional low field magnets; The flutter F defined with a relation,

$$F = \langle (B - \langle B \rangle)^2 \rangle / \langle B \rangle^2 ,$$

where

$$\langle B \rangle = (2\pi)^{-1} \int_0^{2\pi} B \, d\theta ,$$

varies inversely as the sqaure of $\langle B \rangle$, in marked contrast with the normal low field behavior where F is largely independent of magnet excitation. From this relation of F on $\langle B \rangle$, there is another operating limit K_F in superconducting cyclotrons in addition to the usual bending limit K_B;

$$E/A = K_F(Z/A)$$

We chose K_F value of 10.0 while K_B is 15.0. In a small diameter sectored pole tips such as ours, the effect of spiraling of pole tips is not strong[5] as expected from the multiplication factor $S(r)$ for effective flutter,

$$S(r) = 1 + 2 \tan^2 \alpha(r) ,$$

where $\alpha(r)$ is the angle between the radius vector and the tangent to the pole tip

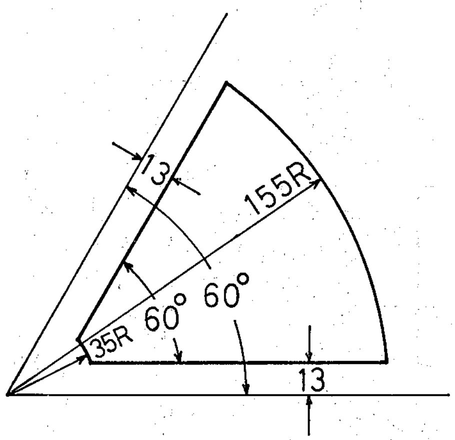

Fig. 1. Sector structure of a 31 cm model superconducting cyclotron magnet.

Table I. Main parameters of the 31 cm model magnet.

Pole radius	15.5 cm
No. of sectors	3, 44°～56° wide, straight
Minimum hill gap	3.1 cm
Maximum valley gap	58 cm
Yoke height	114 cm
Yoke inner and outer diameter	98 cm–110 cm
Total iron weight	～4 ton
Focusing limit (K_F)	10
Bending limit (K_B)	15

edge at radius r. Therefore we used the straight sector as shown in Fig. 1. General parameters of the present superconducting cyclotron magnet are listed in Table I.

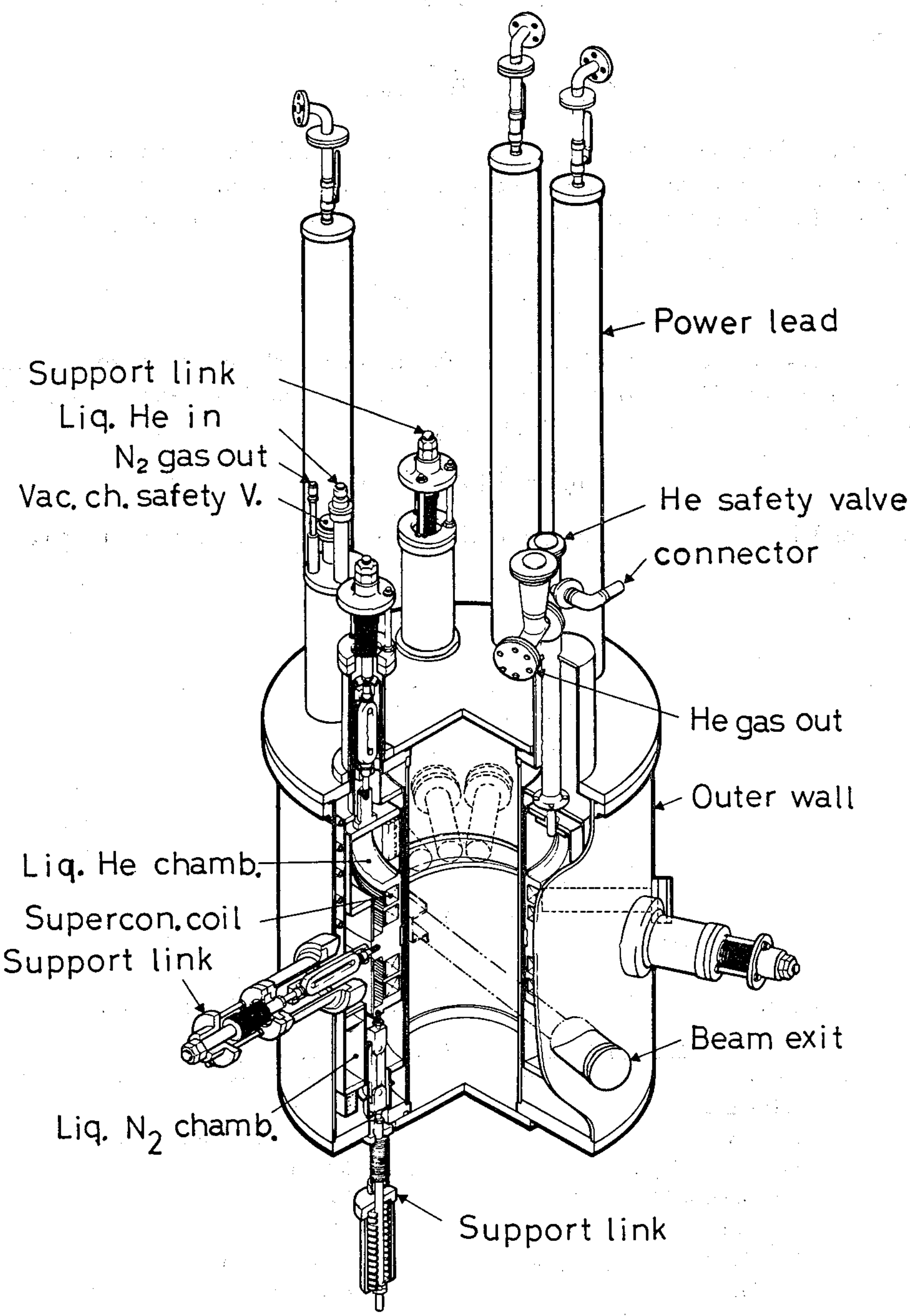

Fig. 2. Perspective view of the coil and cryostat.

III. COILS AND CRYOSTAT

Perspective view of coils and cryostat system is shown in Fig. 2. Coils above and below median plane are devided into two sections, lower and upper part with 405 turn each. The dimension of the coils and the cryostat are shown in Table II. Coil bobbin is held in position by a set of nine (three from upper and lower each, and three from horizontal side) epoxy and fiber-glass support links. The coils are cooled down by immersing into liquid He. Main parameters of superconducting

Table II. Main parameters of coil and cryostat

Inner coil radius	20 cm
Outer coil radius	23.5 cm
Coil height	3.4 cm
Coil splitting	2 sections
Lower coil distance from median plane	4 cm
Gap between two coil section	0.6 cm
Maximum current density	24700 A/cm^2
Ampere-turn at maximum current	1×10^6 AT
Conductor	NbTi
dimension	1×2 mm
superconducting wire diameter	40 μm
no. of wires	520
ratio of copper to superconducting wire	2
Cryostat inner diameter	32.6 cm
outer diameter	80 cm
height	80 cm

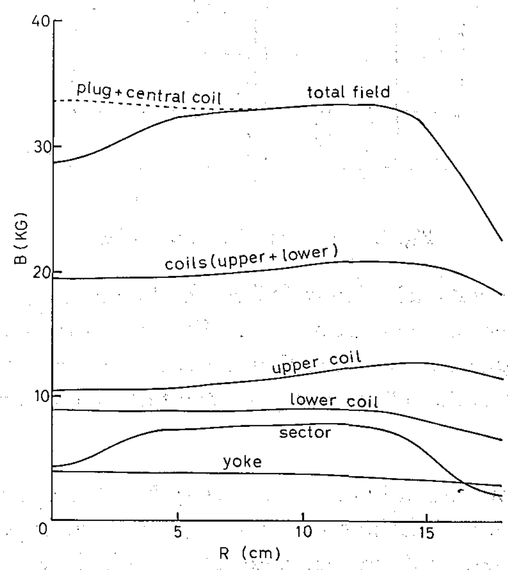

Fig. 3. Azimuthally averaged radial field. Contributions from two coils, yoke, sector and central plug-coil are separately shown. Coil excitation currents are 500 A.

wire are also shown in Table II.

Magnetic field due to the coils is shown in Fig. 3 at coil excitation current of 500 A each.

IV. IRON STRUCTURE OF THE MAGNET

4.1. Yoke

Yoke is of cylindrical type and can be separated into four parts; top and bottom disc-shape yokes, and upper and lower cylindrical side-yokes. Elevation view of the yoke is shown in Fig. 4. Main parameters of the yoke are listed in Table I. Magnetic field due to the coils and the yoke (without pole-tip) was calculated with the program TRIM[6] and the result is shown in Fig. 3. Magnetic flux density in the side-yoke is about 1.3T at the maximum coil excitation current of 700 A. Also shown in Fig. 3 is the magnetic field due to the yoke only which was obtained from the subtraction of coil field contribution from the total field.

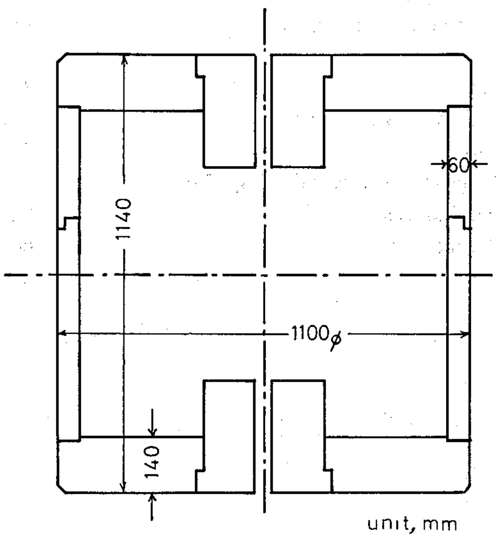

Fig. 4. Elevation view of the yoke.

At the maximum coil excitation of 700 A, the forces acting on the top and bottom yoke was estimated to be about 50 tons. With this force an elastic deformation of these yokes was estimated to be less than 60 μm at the center of the yokes. The backling and the contraction of the side-yoke due to this force are negligibly small.

4.2. Pole tips

Hill and valley gap profiles are shown in Fig. 5. These structures are adopted to fulfil the requirement of isochronous field shape as close as possible without trim coils. A 50 mm diameter hole in the center of the yoke is used for the insertion of ion source. A center plug will be put in along with the central hole. The effects of holes for rf coupler and dee stem have not yet been estimated. A bump of the

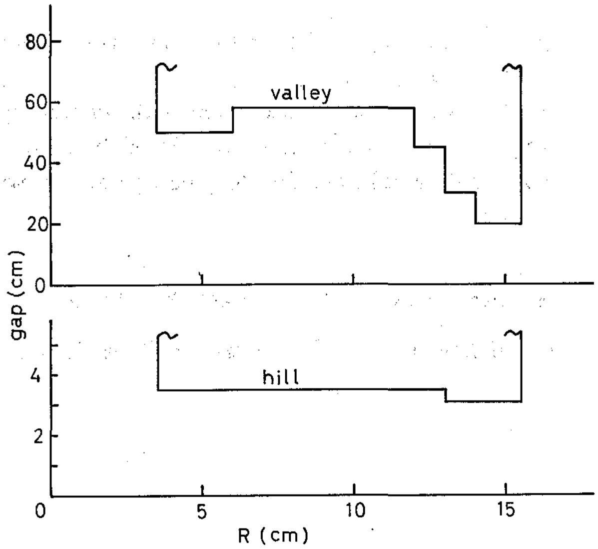

Fig. 5. Hill and valley gap profiles.

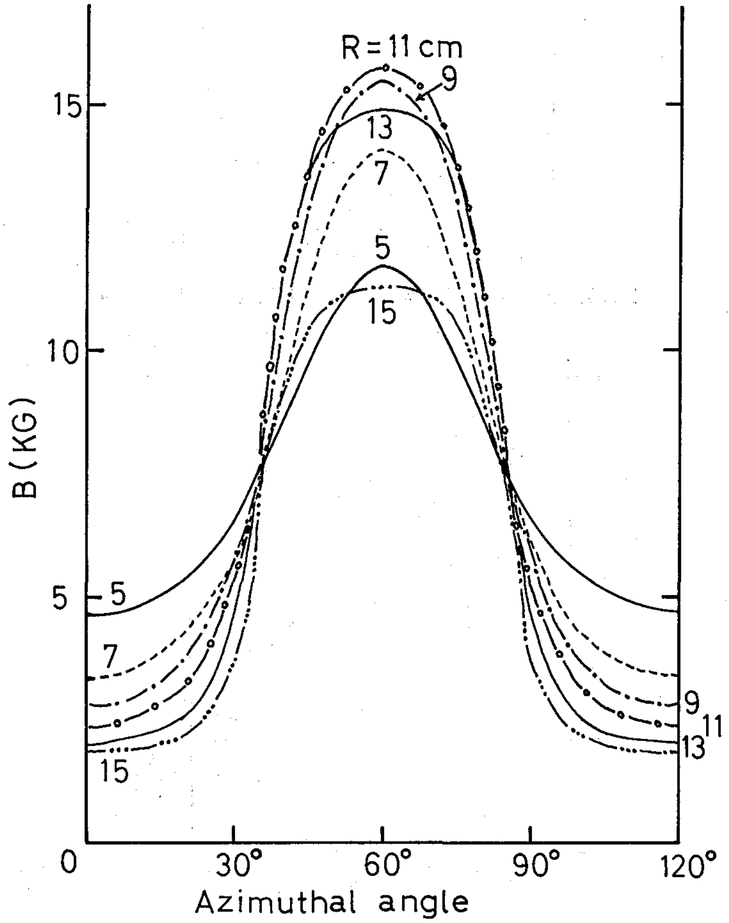

Fig. 6. Azimuthal variation of the sector field calculated with uniform magnetization approximation.

field in the central region for getting good initial focusing will be produced with the central plug and a central circular coil.

Magnetic field due to pole tips were calculated with an assumption of uniform saturation with the program SATDSK.[7] An example of the azimuthal field variation and azimuthaly averaged radial field due to ploe tips are shown in Figs. 6 and 3, respectively.

V. MAGNETIC FIELD CHARACTERISTICS

An example of radial field shape without trim coils is shown in Fig. 3. This

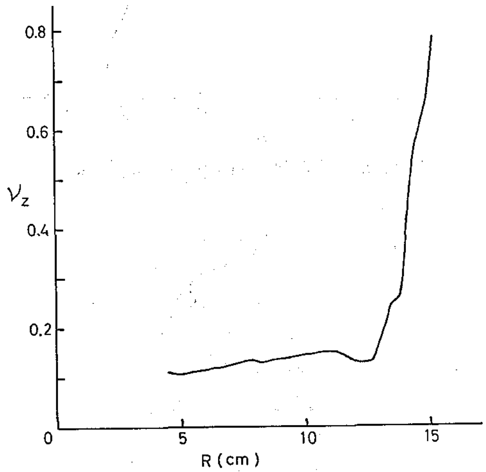

Fig. 7. Behavior of ν_z with radius R for 10 MeV protons.

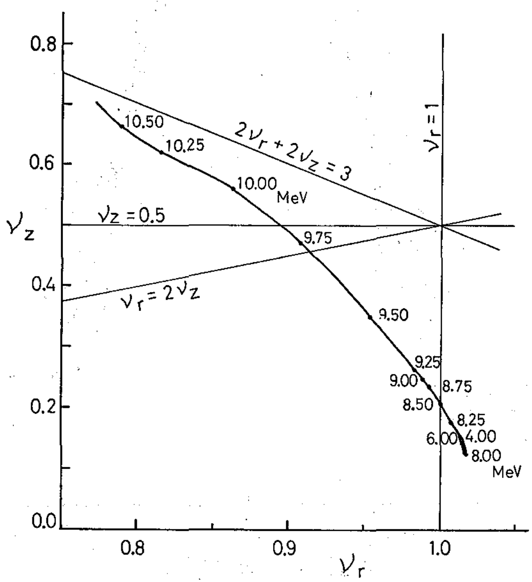

Fig. 8. (ν_z, ν_r) operating plot for 10 MeV protons.

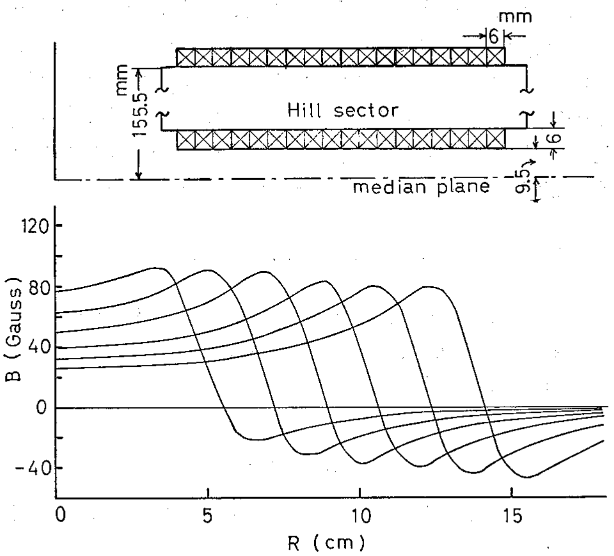

Fig. 9. An example of trim coil field. The dimension of the trim coils is shown in the inset of the figure.

field can be used for the acceleration of protons up to 10 MeV. In this figure the bump field was also added to the field from the coil and ion structure. Orbit characteristics were calculated with the assumption that the averaged radial field is given by the following curve which approximately gives an isochronous field for 10 MeV protons up to 14 cm radius;

$$B(r) = B_0/\sqrt{\left(1-\left(\frac{r}{r_0}\right)^2\right)}, \quad r_0 = 96.9\ \text{cm} \quad \text{and} \quad B_0 = 32.3\ \text{KG}.$$

The calculated result of the resonance parameter ν_z is shown in Fig. 7, and (ν_r, ν_z) operating diagram for protons is shown in Fig. 8.

Field trimming is acomplished with trim coils wound around the hill sector. Coils have rectangular cross section of 6 mm length, and 6 trim coils with 3 turns in one layer each, will be excited to adjust the field shape. An example of the trim coil field is shown in Fig. 9.

VI. DISCUSSION

As shown in the preceding sections, the design study of small-size superconducting cyclotron magnet indicated definite feasibility of constructing such a small-size superconducting cyclotron magnet.

In the present design, trim coils are used for field trimming. This method is more conventional compared with the trim rod method proposed by Bigham.[8] Although trim rod method needs more complex mechanical arrangement, it covers wider range of field trimming level in such a small cyclotron, because hill gap should be as narrow as possible to get enough flutter and trim rod does not require any more space between upper and lower hill sectors. More detailed study on the merit of using trim rod is in progress. In addition to serve the basic technical information for the construction of large-scale cyclotron magnet, the study of such a small-size cyclotrons has a possibility to open a new field of superconducting cyclotron application to medical apparatus.[9] The study of a possible rf structure of superconducting cyclotrons for therapy application has been in progress in our laboratory.[10]

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REFERENCES

(1) C. B. Bigham, J. S. Fraser, and H. R. Schneider, Chalk River Nuclear Laboratories Report AECL-4654 (1973).
(2) H. G. Blosser, *IEEE Trans. Nucl. Scie.*, **NS-26** 2040, (1978) and references there in.
(3) J. H. Ormrod, C. B. Bigham, K. C. Chan, E. A. Highway, C. R. Hoffmann, J. A. Hulbert, H. R. Schneider, and Q. A. Walker, *IEEE Trans. Nucl. Scie.*, **NS-26**, 2034, (1978) and references there in.
(4) E. Acerbi, G. Bellomo, M. Castiglioni, C. de Martinis, E. Fabrici, C. Pagani, and F. Resmini, *IEEE Trans. Nucl. Scie.*, **NS-26**, 2048, (1978) and references there in.
(5) H. G. Blosser and D. A. Johnson, *Nucl. Instr. Meth.*, **121**, 301 (1974).
(6) J. S. Colonias, "Particle Accelerator Design: Computer Programs", Accademic Press, New York, 1974. We used Argonne version of TRIM. The authors would like to acknowledge Dr. R. J. Lari for the use of the program.
(7) G. S. McNeilly, ORNL/CSD/TM-98 (1979).
(8) C. B. Bigham, *Nucl. Instr. Meth.*, **131**, 223 (1975).
(9) J. D. Hepburn, C. B. Bigham, and H. R. Schneider, *Int. J. Radiation Oncology Biol. Phys.*, **3**, 387 (1977).
(10) H. Takekoshi, S. Matsuki, K. Mashiko, and N. Shikazono, *Bull. Inst. Chem. Res. Kyoto Univ.*, **59**, 1 (1981).