© 1967 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

MAGNET SYSTEM FOR A 4-MeV EXPERIMENTAL SEPARATED ORBIT CYCLOTRON*

E. D. Hudson and F. E. McDaniel

Oak Ridge National Laboratory
Oak Ridge, Tennessee

Summary

One of six sector-magnets for the 4-MeV Separated Orbit Cyclotron Experiment (SOCE) has been assembled and tested. The magnets for the SOCE are quite different and much simplified from previous SOC magnet concepts; all pole tips are of the same radius of curvature and each set is excited by a separate coil-pair. The pole-tip fields vary smoothly from 3.5 kilogauss at injection (1 MeV) to 6.6 kilogauss at full energy. The field index, n, varies from 0.58 to 0.52. A unique pole-tip design with an integral vacuum chamber has been developed. The ampere-turn requirements for the main pole-tip coils and trimming coils have been determined. A simple but highly precise magnetic field scanning device has been developed for use with the SOCE magnets.

Introduction

The 4-MeV Separated Orbit Cyclotron Experiment (SOCE) is being built to study experimentally a variety of problems that are theoretically complex, such as space-charge and beam loading phenomena, and to gain practical experience and insight into the operation of the SOC as a system. The SOCE will be a multiparticle variable energy, accelerator providing protons in the energy range 1.7 to 4.0 MeV, deuterons from 1.7 to 4.0 MeV, and ^{3}He ions from 2.7 to 8 MeV. Fig. 1 shows the plan of the accelerator. The principal specifications of the machine are listed in Table I. Variable energy

Table I - Specifications for the SOCE

Energy range, MeV	
Protons	1.7-4.0
Deuterons	1.7-4.0
Alpha particles	3.4-8.0
^{3}He ions	2.7-8.0
Sectors	6
Turns	4
Turn separation, min, in.	11.8
Turn separation, max, in.	17.8
Beam radius, min, in.	62.0
Beam radius, max, in.	115.2
Aperture, in.	1.5 by 3.0
Pole-tip magnetic field (4-MeV p), G	3300-6600
Field index, n	0.58-0.52
Magnet copper, tons	1.5
Magnet steel, tons	44
Magnet power (4-MeV p), kW	40
Harmonic number (4-MeV p)	32
Frequency, MHz	50
Peak cavity voltage (4-MeV p), kV	83.4
Cavity power loss, kW	18

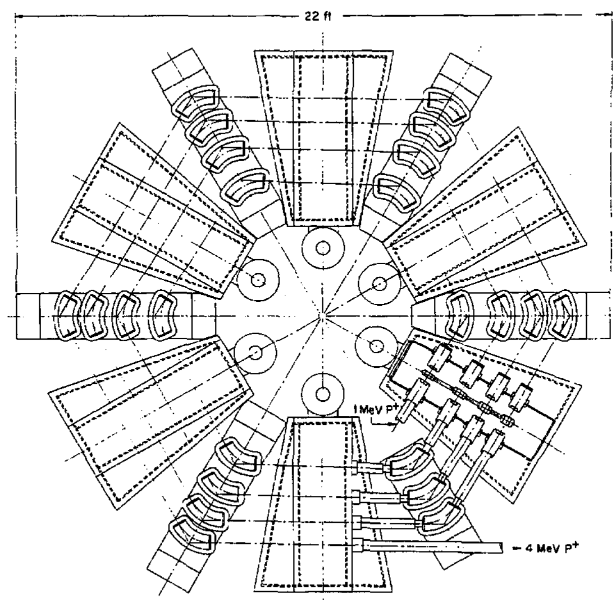

Fig. 1. Plan view of 4-MeV Experimental SOC.

is accomplished by varying the magnetic field to provide resonance at some chosen harmonic (32-50 for protons). Additional details of this accelerator experiment will be found in companion papers in these Proceedings.[1, 2, 3]

The magnet system for the 4-MeV SOC departs radically from previous concepts. The details of one sector magnet are shown in Figs. 2 and 3. Magnetic focusing is "constant gradient," as in a weak focusing synchrotron but, as a result of the large circumference factor, the focusing is actually quite strong. All pole tips are of constant radius, a characteristic permitting the use of a simplified fabrication method. The pole tip field strength varies linearly with momentum, from 3.5 kG at injection to 6.6 kG at extraction for 4.0-MeV protons. The field index, n, ranges from 0.58 to 0.52 in steps through the machine; all magnets on the first turn are n = 0.58, on the second n = 0.56, etc.

Pole Tip Contours

The pole tips are 6.5 in. in width and have a constant slope, except for a 0.375-in. flat

*Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

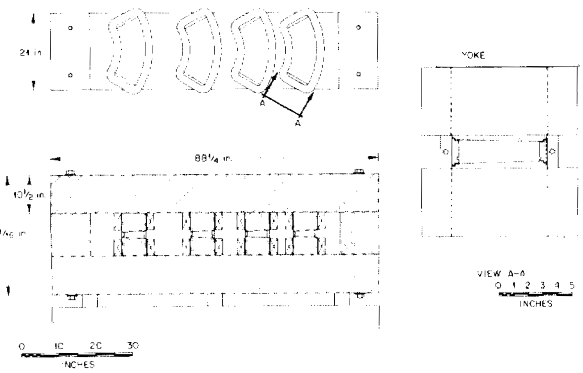

Fig. 2. Drawing of SOCE sector magnet.

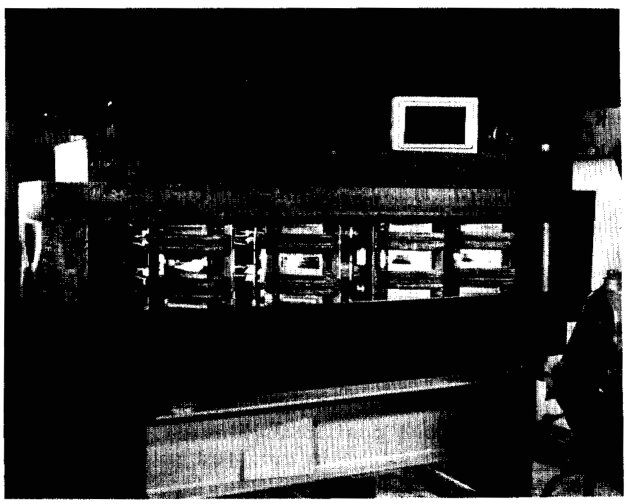

Fig. 3. The completed sector magnet.

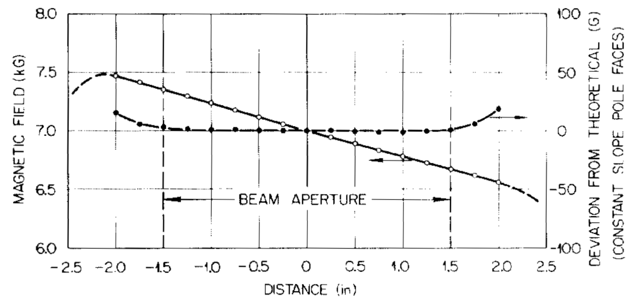

Fig. 4. Pole-tip magnetic field and gradient.

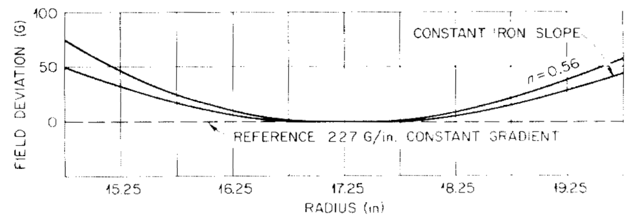

Fig. 5. Deviation of magnetic fields for n=0.56 and for constant iron slope on pole faces.

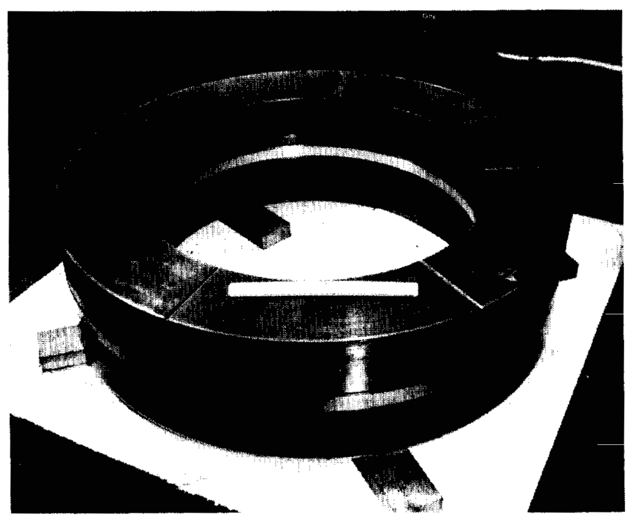

Fig. 6. Pole-tip ring assembled prior to being cut into six 60° sector magnets.

region provided at the inner and outer edges to facilitate the welding of the integral stainless steel vacuum chamber walls. Constant-slope pole faces were used for simplicity of fabrication and because they give a magnetic field which closely approximates constant-n shape. Measurements of magnetic field variation with radius across the beam aperture for an n = 0.56 magnet are shown in Fig. 4. The deviation of the magnetic field from a constant-n variation is approximately 0.1%, see Fig. 5. Beam dynamics studies show this deviation to be unimportant; neither the beam emittance or phase acceptance are significantly affected.

Pole Tip Fabrication

The magnet design readily lends itself to mass production techniques. A 360° ring of tips is machined as a single operation with a vertical turret lathe, Fig. 6. The upper and lower pole tip rings are assembled by welding stainless steel rings at the inner and outer radii. A very shallow weld is used to minimize warpage. The pole-tip assembly also serves as the vacuum chamber; suitable fittings will be provided at the ends to couple to the beam pipe.

Pole Tip Coils and Power Supply Considerations

The magnetization curves for the four gaps of the sector magnet are shown in Fig. 7. The coils of the four pole-tip sets have the same current and number of turns in each coil has been chosen to give approximately the correct magnetic fields in the four gaps. The trimming coil adjustments needed to compensate saturation effects are quite small; the gap fields are maintained in a constant ratio to within 1/2% over the 75-250 ampere operating range of the magnet. Over this range the mean magnetic field of the maximum-energy pole tip varies from 3000 to 9200 gauss. Coarse adjustment of

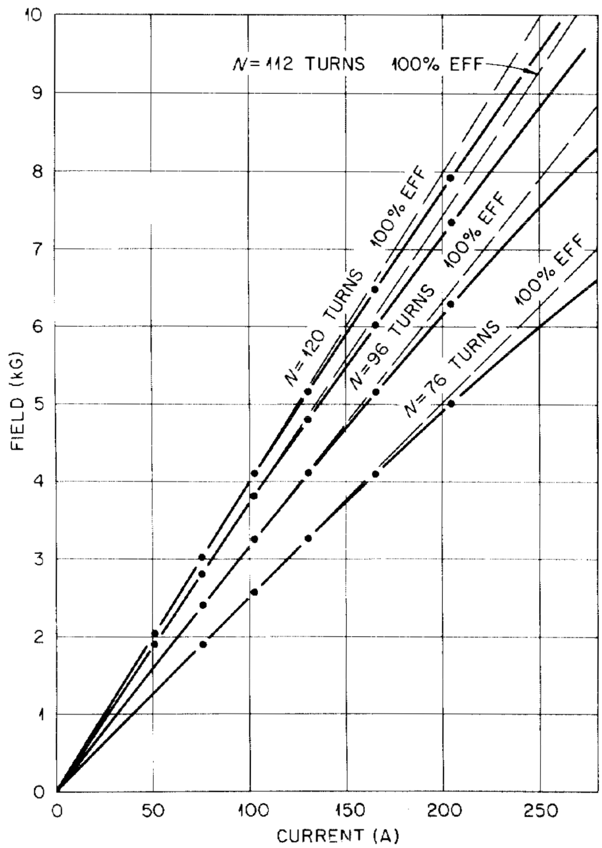

Fig. 7. Magnetization curves for the four gaps in the prototype magnet.

the magnetic field of each pole tip to within 7% of the correct value is made by choosing the appropriate number of turns of the pole-tip coils. Trimming windings on each pole tip provide fine adjustment of the magnetic field; the maximum trimming coil power required is approximately 50 watts (20 amperes, 2.5 volts).

The coils are wound with 1/4 in. square copper conductor with a 1/8 in. diameter water passage. The coils for each pole-pair consist of 8 two-layer sections. These are connected in four parallel circuits (with due attention to symmetry) to match an existing power supply. The power requirement at the highest field is 1000 amperes at 150 volts. The trimming coils consist of 24-turn double layer pancakes of 1/8 in. square copper bonded to the main coil sections to provide cooling. Although their maximum current will be only 20 amperes they are actually capable of 100-ampere operation.

Interaction Effects

The four pole-tip sets of a sector magnet are weakly coupled by the yoke. The effect is small, as illustrated by Table II. For example, a 100 ampere-turn increase in the excitation of pole tip 1 (lowest field) produces an increase in magnetic field in that gap of 34.5 gauss and decreases the magnetic field in gaps 2, 3, and

Table II - SOCE Magnet Gap Interactions

Coil No.	Change in Magnetic Field (gauss/100 ampere-turns) Gap 1	Gap 2	Gap 3	Gal 4
1	34.5	-1.12	-0.94	-0.75
2	-1.15	33.2	-1.26	-1.14
3	-0.94	-1.31	33.1	-1.31
4	-0.79	-1.02	-1.23	33.4

4 by 1.13, 0.94, and 0.75 gauss respectively. These interactions are small enough to be ignored in calculating the number of turns required for each main coil but must be taken into account in final adjustment of the magnetic fields with the trimming coils. The magnitude of the interactions depends markedly on the size of the yoke. For these data the yoke area is equal to the pole tip area (100% yoke). The gap interactions are about a factor of 10 larger for a 50% yoke as measured on a 1/4-scale model.

Magnet Measurement System

Comprehensive mapping of the magnetic field of the pole tips is necessary to determine the effective magnetic length and the contribution of the end effects to the focusing properties. The limited access to the 1.5 in. x 5.5 wide magnet gap, a result of integral vacuum chamber design, has necessitated the development of a special Hall probe positioning device, Figs. 8 and 9. The Hall probe is mounted on a nonmagnetic plate that is restrained radially and vertically by small grooves in the vacuum tank side walls. The azimuthal position is determined by a precision azimuthal indexing device (Ultradex) located near the magnet and coupled to the plate by a long nonmagnetic bar. The indexing device is mounted on a milling machine table. The table horizontal motions are used to locate rapidly the center position of the indexing device when transferring the field measuring equipment to a new pair of poles. The system is capable of positioning the Hall probe in one-degree steps within ±0.001 in. It advances

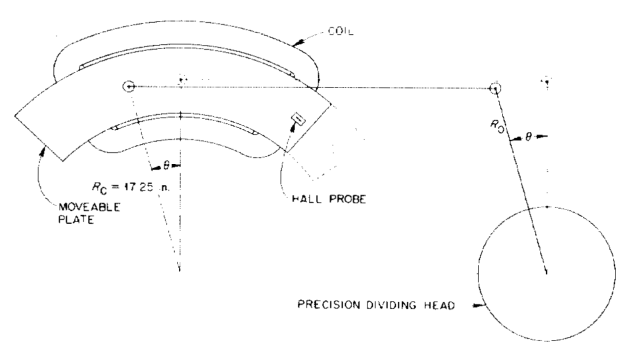

Fig. 8. Schematic of Hall probe positioning device.

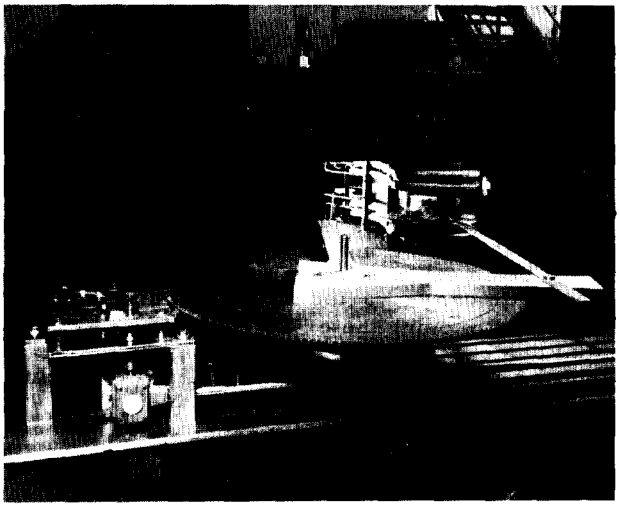

Fig. 9. Field measuring device in prototype magnet.

automatically after the field at each position has been measured and recorded. The radial position for each azimuthal scan may be changed in 0.250-in. increments by inserting the Hall probe block dowels into the proper holes on the positioning plate.

References

[1]R. E. Worsham, et al, these Proceedings.
[2]N. F. Ziegler, these Proceedings.
[3]S. W. Mosko, these Proceedings.