A SECTOR MAGNET FOR A 10-50 MeV SOC*

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Summary

A full-scale prototype magnet sector of a 12-sector, 10-50 MeV separated orbit cyclotron has been built and tested. Eleven pairs of alternating-gradient pole tips are mounted on a yoke structure which provides a common magnetic return path. The pole tips are all excited by a single pair of coils which surround the pole tip mounting bases at the upper and lower yoke faces. The pole tips combine both the negative- and positive-gradient sections in a single unit; the magnetic field gradients are about 800 gauss/in. The pole tips are 4.5 in. wide and have a mean gap of 1.75 in. They were machined by the numeric controlled milling process. Special edge contours were developed to achieve a useful radial aperture of 3 inches. Experience with the prototype magnet demonstrates that magnets for separated orbit cyclotrons present no special difficulty in design, construction, or alignment.

Introduction

The separated orbit cyclotron accelerates ions along a spiral-like path with a pitch (turn-to-turn spacing) of several inches. The guiding magnetic field provides beam bending and focusing forces along each turn independently. In the usual arrangement of the accelerator a number of sector-shaped magnets are arranged radially at equal angular intervals about a circle and radio frequency cavities for beam acceleration are placed in the intervening spaces. A sector magnet consists of a long yoke structure in which are mounted several pole tip pairs, one pair for each of the separate turns.

The purpose of this work was to evaluate the fabrication, alignment, and magnetic field adjustment required for this unusual type of magnet structure. This report reviews in particular the construction and testing of one sector magnet of an 11-turn, 12-sector separated orbit cyclotron which would accelerate protons from an injection energy of 10 MeV to a final energy of 50 MeV.

A model of the 10-50 MeV SOC was constructed to illustrate the design of the accelerator, see Fig. 1. There are 12 magnet sectors and 11 radio frequency cavities. One space between sectors is left vacant to provide room for the injection and extraction magnets, and for beam diagnostic equipment. The energy of the beam can be varied in steps of about 3.6 MeV by moving the extraction magnet in a radial direction to intercept the beam at the desired turn. The accelerator will also provide deuterons in the energy range 5-25 MeV and alpha particles from 10 to 50 MeV. The main features and dimensions of the accelerator are listed in Table I.

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Table 1 - Specifications for a 10-50 MeV SOC*

Energy range, MeV	
Protons	10-50
Deuterons	5-25
Alpha particles	10-50
Turns	11
Sectors	12
Turn separation, min, in.	10
Turn separation, max, in.	20
Beam radius, min, in.	132
Beam radius, max, in.	282
Beam aperture, in.	1.5 x 3.0
Magnetic field, G	7000
Gradient, G/in.	800
Magnet copper, tons	15
Magnet steel, tons	550
Magnet power, kW	240
Harmonic number (protons)	24
Cavity frequency, MHz	50
Cavity power losses, kW	~900

*This is the design on which the prototype magnet is based. The specification of an improved design with 14 turns and an rf power requirement of 600 kW are given in reference 1.

The Magnet Assembly

The structural features of the prototype magnet are shown in Figs. 2 and 3. The 11 sets of pole tips are mounted from the precision faces of the upper and lower yoke pieces. The magnet excitation coils surround upper and lower yoke faces. Trimming coils are provided on each pole-tip pair adjusting the magnetic field levels for the acceleration of alpha particles and deuterons. The required adjustment varies smoothly from injection to final radius. The maximum change from the nominal 7000-gauss level is about 5% (350 gauss); the maximum trimming coil power is only 15 watts per pole tip. The pair of hexagonal headed

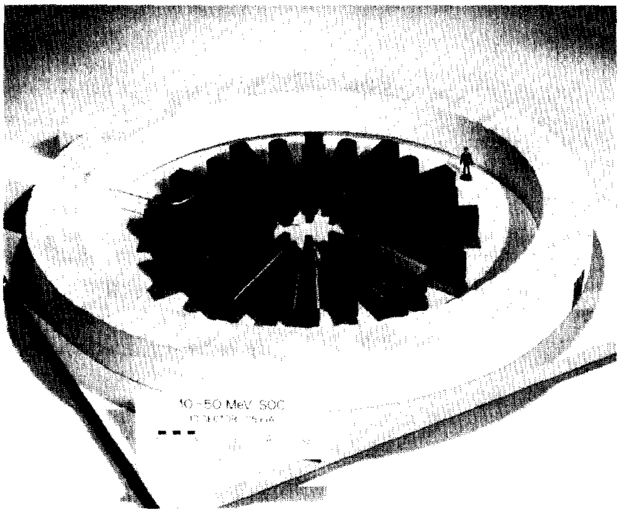

Fig. 1. Model of the 10-50-MeV SOC Showing Magnet Sectors Alternating with Accelerating Cavities. The beam is extracted at various energies with a moveable 90° magnet.

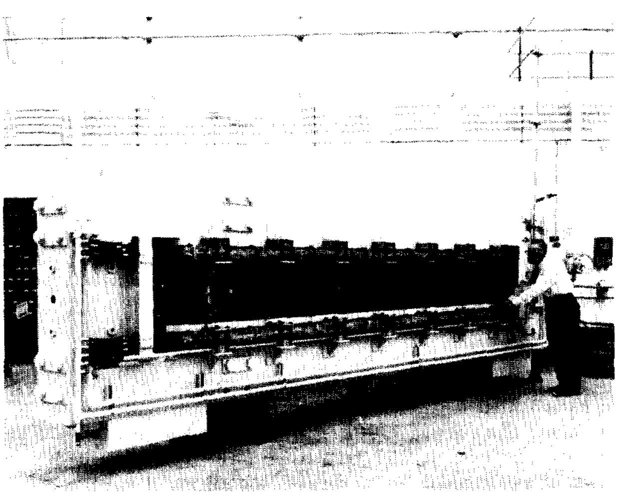

Fig. 2. Sector Magnet with Eleven Pairs of Pole Tips.

adjustment screws shown in Fig. 3 protruding from the base of each pole tip control the coupling shims which are used to adjust precisely the field under each pole tip to the 7000 gauss specified at the ion path. The coupling shims act as variable air gaps to compensate for the magnetic potential drop in the long slender yoke.

Yoke

The yoke is of hot-forged low carbon steel. A maximum carbon content of 0.15% was specified; the actual carbon analysis was 0.06%. The pole-tip mounting surfaces of the upper and lower yoke are slightly raised planes which run the full length of the pole mounting area, see Fig. 4. At the center of each ridge a "T" slot was machined to capture the bolt clamp assemblies (4 for each pole tip). This method of mounting gives maximum flexibility for adjustment of the radial and azimuthal position of the pole tip. The pole tips are precisely positioned by optical alignment methods.

In procuring the yoke, separate bids were requested for flatness and parallelism tolerances of ±0.002, ±0.003, and ±0.005 in. Over this range of precision the price varied by only 7%. The 46-ton yoke assembly was procured

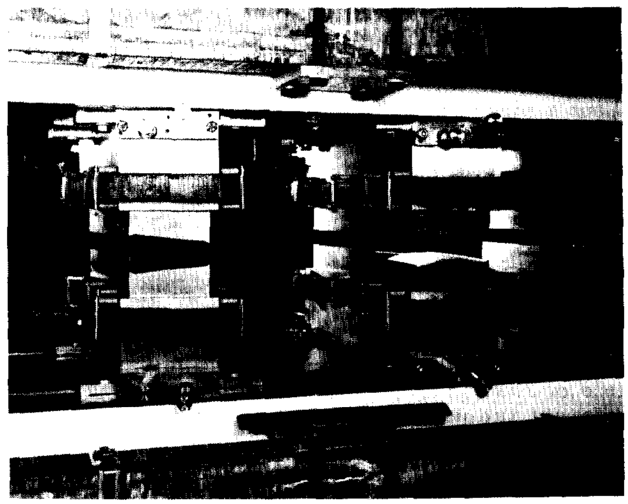

Fig. 3. Details of Pole Tip Pairs 3 and 4.

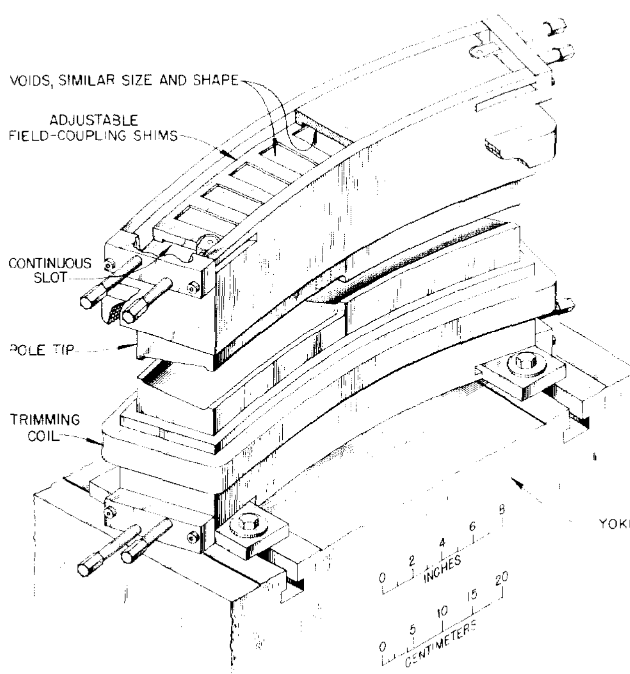

Fig. 4. A Pole-Tip Assembly Mounted on the Yoke.

with tolerances of ±0.002 in. at a price of \$31,250 (~\$0.34/lb). The additional cost of the more precise yoke was more than offset by subsequent simplification of the pole-tip mounting and alignment systems.

The lower yoke was leveled at ORNL to within ±.001 in. of absolute flatness by optical methods. The yoke is supported by six jacks, two at each end and two at the center of the span. The 23-in. deep lower yoke is flexible enough to be adjusted a few thousandths of an inch at each support point with negligible changes at other support points.

After the upper yoke was installed (supported by a stanchion between pole tips near center span), the upper pole mounting surface was also flat within ±0.001. Subsequent gap measurements gave a variation of ±0.0005 in. about a mean value of 16.0025 in. for the 12 points measured.

These results illustrate that sufficiently accurate median plane alignment can be achieved by using the precision surfaces of the yoke itself as the primary alignment surface.

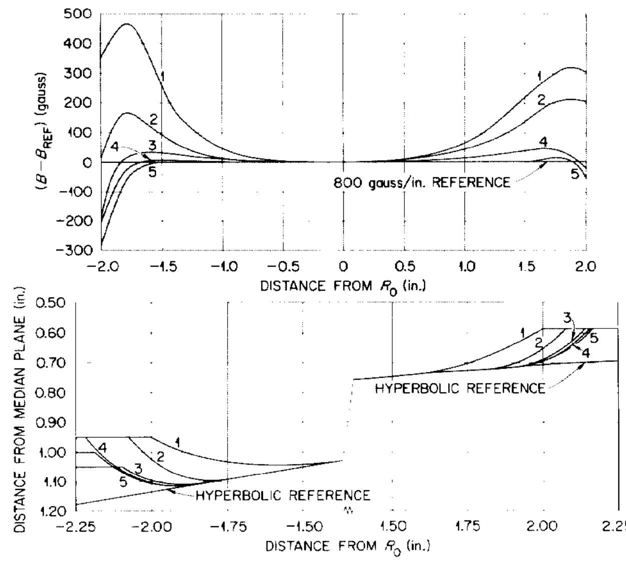

Fig. 5. Field Changes Produced by Changes in Pole Edge Geometry.

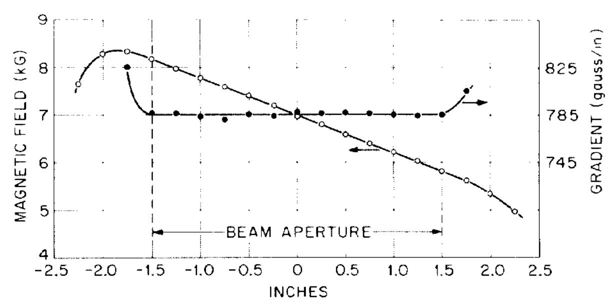

Fig. 6. Magnetic Field and Gradient vs Radius.

Pole Tips

The eleven sets of pole tips for the separate turns are designed to operate at a central orbit field of 7000 gauss, hence each unit has a different radius of curvature according to the particle momentum. The pole-tip radii vary from 25.8 in. for the first pole tip (injection energy) to 57.8 in. for pole tip eleven (final energy). For constant axial and radial focusing frequencies the pole tips would all have different gradients; it has been shown, however, that the machine is less sensitive to magnet errors if constant gradients are used. The optimum gradient is that which gives maximum acceptance at final energy, in this case 800 gauss/in.

The pole tip faces are basically hyperbolic with edge shims to minimize field falloff near the inner and outer radii, and thus shaped to give the largest possible useful aperture. The several stages in shaping the pole-tip section are illustrated in Fig. 5. The initial shape, curve 1, purposely over-compensated the edge effect. The remaining curves show the results of subsequent refinements. The pole-tip surfaces were cut with a numerically controlled milling machine. Thus, it was practical to make very small contour change between measurements. The magnetic field and gradient for the final pole-tip contour are plotted in Fig. 6. The useful aperture (±1% $\Delta G/G$) is about 3 in. wide; without edge corrections it would be less than 2 inches.

Most of the details of production of the tapes were handled by the machine tool programmers. Except for the first few sets of pole tips which were replete with programming errors and machine operator mistakes, a dimensional accuracy of ±0.001 was achieved.

The fabrication of the pole tips including programming and tape preparation required about 4000 man-hours, of which about 1000 man-hours should be allocated to development. The unit cost (based on 3000 man-hours) was \$750 per linear foot or \$5/lb. It is believed that these costs could be reduced by about a factor of two by simplifications in design and fabrication methods.

Magnet Tests

The first measurements of the magnetic field at the center of the several pole-tip gaps is as shown in Fig. 7(a); the variation is a result of magnetic potential drop in the long yoke. The pole tips nearest the yoke ends have shorter return flux paths, hence higher fields. In this design all gap fields are made identical by reducing the higher fields to the value of the lowest. This is accomplished by providing an appropriate magnetic potential drop at the base of each pole tip by means of variable "coupling shims."[2] These consist of a pair of plates with alternate recessed and solid areas, see Fig. 4. In addition continuous slots of appropriate depth were machined in the several coupler plates to approximately equalize the magnetic fields; the results obtained are shown in curve (b) of Fig. 7. Fine adjustment of the couplers resulted in the field shown in curve (c); all fields are within ±1 gauss of the desired 7000 gauss level. The coupling shims have a field adjustment resolution of 50 gauss/in. or 2.5 gauss per turn of the positioning screws. The magnet power for a field of 7000 gauss is 18 kW; the magnet efficiency at that field is about 80%.

A radial scan of the magnet along the center of the positive gradient section of the pole tips, Fig. 8, shows that the field between pole tip sets

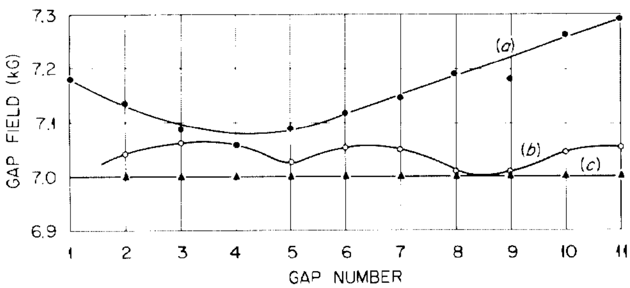

Fig. 7. Magnetic Field Measured at R_o for Each Gap (for reference only).

(a) Solid Coupling Shims

(b) Continuous Gap on One Side of a Coupling Shim

(c) After Final Adjustment of Completed Shims

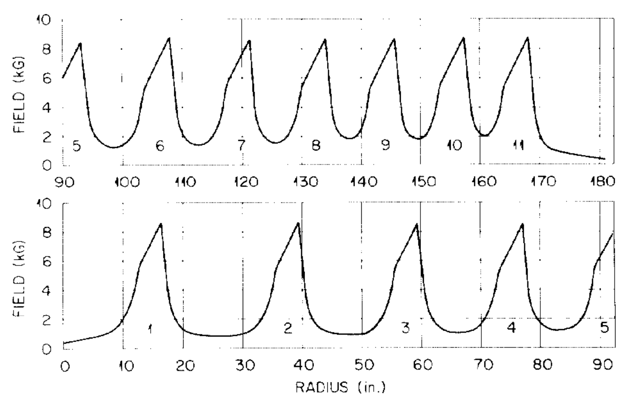

Fig. 8. Magnetic Field of the Prototype Sector with 11 Pairs of Pole Tips.

varies from about 1 kilogauss at the low energy end to 2 kilogauss at the high energy end. This suggests that somewhat smaller turn spacings (more turns) could be used which would reduce the rf power requirements.[3]

Detailed measurements of the magnetic field distribution under the pole tips will be made in 1° steps azimuthally and 1/4 in. radially with a precision Hall probe system to elucidate the details of the fringing field in the region of beam entrance and exit and the magnetic field distribution in the transition region between the positive and negative sections of the pole tip.

Conclusion

The design, construction, alignment, and preliminary testing of the prototype sector magnet for a 50-MeV SOC have demonstrated that this type of magnet presents no special difficulty. Further work will include detailed measurements of the pole-tip fields to establish the effective magnetic length of the elements, the effects on focusing of the fringing fields at the magnet ends, and the magnetic field transition region between the positive and negative gradient sections of the pole tip. The knowledge gained in the construction, alignment tests of the prototype will be directly applicable to magnet designs for separated orbit cyclotrons of much higher energies.

References

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3. J. A. Martin, IEEE Transactions on Nuclear Science, NS-13, No. 4, 288-299 (1966).