MAGNET FOR AN 800-MEV SEPARATED ORBIT CYCLOTRON*

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Summary

The Separated Orbit Cyclotron consists of individual sector magnets and rf cavities placed alternately in a circular arrangement. The beam is bent and focused by alternating gradient fields produced by pole tips with a minimum radial spacing of 4.5 inches. Magnet design and construction problems are minimized by using the same pole-surface contour and the same mean-field intensity throughout the entire machine. All pole tips in one sector are mounted on a common yoke and driven by a common pair of coils. Shimming gaps are provided between the yoke and the pole tips so that the same mean field intensity can be achieved for all orbits. Only the azimuthal length of the poles is changed to maintain the correct focusing and bending properties of the magnets.

The Separated Orbit Cyclotron, as characterized by F. M. Russell in his original proposal[1], was a "beehive" structure. That is, its orbit formed a spiral helix with individual focusing magnets periodically placed along the orbit path and with accelerating cavities between the magnets. In this paper, and in the others describing SOC in this conference,[2,3,4] the orbit path is in the form of a flat spiral as is normal in a cyclotron, but with much more radial separation between turns. This transition was made because of the economies achieved with the "flat SOC."

The beam makes only one traversal through any given strong-focusing magnet element. The necessary orbit spacing is obtained by using a very high energy gain per revolution and by using a relatively low average magnetic field, that is, the diameter of the machine is made large. Synchronism is maintained for a large machine by "harmonic operation." The time for a particle to make one revolution is an integral number of rf periods, in most practical designs between 10 and 20.

A number of criteria govern the choice of a magnet design for SOC. A minimum orbit spacing is desired so that the overall machine size will be minimized. This, in conjunction with the beam aperture requirement, limits the achievable gradients to a narrow band. The ease of fabrication to a tight dimensional tolerance and the ease of alignment of the pole tips in setting up the machine are important, along with magnet power. The overriding criterion, of course, is that the cost of the entire system be the minimum that is consistent with good quality beam.

Our recent studies have dealt chiefly with an SOC having a magnet configuration in which the alternating gradient pole tips of a given "sector" are all driven from a common yoke structure by a common coil pair. This arrangement yields certain pole-tip alignment advantages and uses less magnet power than some other designs. The configuration is best illustrated by Fig. 1, which shows a magnet sector and an adjacent cavity.

For simplicity of design and construction the average magnetic field between a pair of poles is maintained at a constant value of 7 kgauss throughout the machine and only the azimuthal length of the pole tips is altered to maintain the proper field strength as the particles gain energy. The magnitude of the field gradient, and thus the pole face contour, is also maintained constant at about 1 to 1.5 kgauss/cm throughout the machine. The length of the gradient region of a magnet can be varied to meet the criterion of optimum focusing force as a function of particle energy. Zero gradient, or flat, sections can then be added to each sector to achieve the proper average field for each orbit. Under these conditions, and when a beam aperture of 1.5 in. is provided, the minimum spacing between orbits can be as small as 4.5 in. (We have used 5 in. for most of our studies.)

A cross section of four pole pairs with their associated beam tubes and field shaping shims is shown in Fig. 2. This back-to-back arrangement of the poles is essential for minimum orbit spacing. It can be achieved only if there is an odd number of magnet sectors and a magnet configuration requiring an even number of sectors to complete the focusing period, for example, alternating triplets (FDF, DFD, . . .) or alternating singlets (F, D, . . .). The field-shaping shims extend the useful region of the magnetic field by shunting some of the fringe field away from the gap in the region where the field does not decrease rapidly enough. The fields obtained with and without these shims are shown for comparison in Fig. 3. The useful region is 1.8 in. wide with the shims but only 1.7 in. without, but perhaps of more significance is the reduction of the minimum orbit spacing from 5.5 in. to 4.5 inches.

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A gap has been provided between the pole and the yoke to take care of variations in yoke saturation with radius so that all poles in a sector can be driven to the same field level with a single coil pair. The variation of field with radius in a 1/8-scale model is shown in Fig. 4, along with the appropriate gap required to correct the variation and the results of a preliminary test on a crude 1/8-scale model of an SOC sector magnet. By careful adjustment of the magnetic material in the pole-base gap it should be possible to achieve the desired field in the beam aperture to the required tolerance. The 1/8-scale model from which the data were obtained is shown in Fig. 5. For economy of construction the yoke was "burned out" of an obsolete model of another machine. The pole tips are straight and do not have contoured surfaces. The contour of the pole tips has been modeled separately at 1/2 scale.

An SOC for accelerating protons to 800 MeV could be made in any one of many ways. One design which has been studied in considerable detail and at present seems to be rather attractive is composed of several stages. Stage 1 is a 0 to 0.75 MeV Cockcroft Walton and a 0.75-20 MeV linac, stage 2 is a 20-100 MeV SOC, stage 3 is a 100-350 MeV SOC, and stage 4 is a 350-800 MeV SOC. The choice of the energy division points is largely one of economics. The magnets for all stages are the same in principle. Some of the characteristics of each stage are shown in Table I.

References

1. F. M. Russell, Nucl. Inst. and Meth. 23, 229-230 (1963).

2. N. F. Ziegler, "Accelerating Cavities for an 800-MeV SOC," to be published in the proceedings of this conference.

3. E. D. Hudson, R. S. Lord, and R. E. Worsham, "A Low Energy Separated Orbit Cyclotron," to be published in the proceedings of this conference.

4. R. E. Worsham, "The Beam Dynamics of the SOC," to be published in the proceedings of this conference.

Table I: Design Characteristics of a Multi-Stage SOC

Stage	2	3	4
Energy span (MeV)	20-100	100-350	350-800
No. of sectors	15	15	24
No. of orbits	25	24	23
Harmonic no.	13	13	21
Weight of steel (tons)	770	2100	3800
Weight of copper (tons)	26	35	56
Magnet power (kw)	250	335	540
Orbit path length (ft)	1950	3400	7260
Orbit radius, inner (in.)	101	213	550
outer (in.)	213	340	675

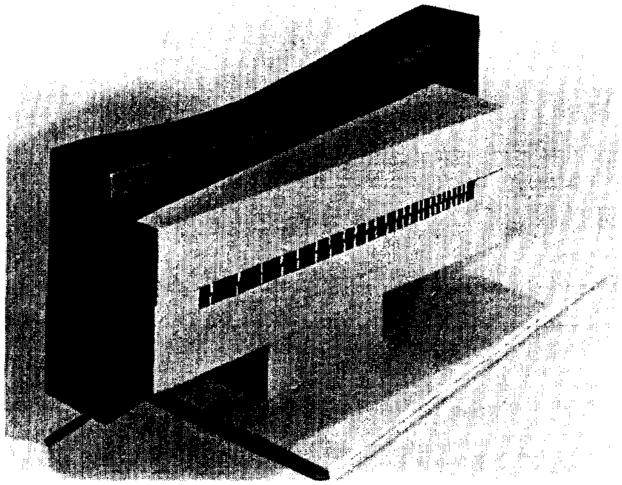

Fig. 1. Sector magnet and rf accelerating cavity for the 200-800 MeV stage of an SOC. The magnet coils, omitted here, are shown in Fig. 5.

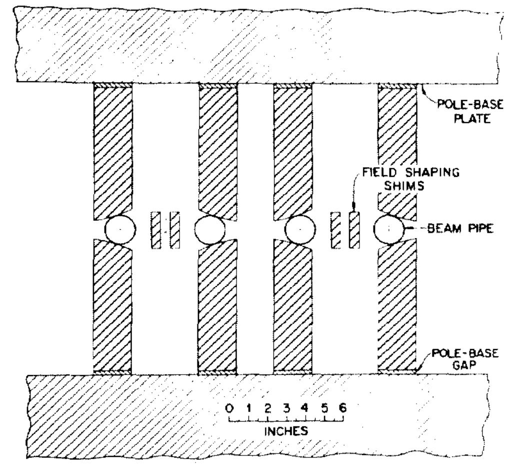

Fig. 2. Cross section of four pole pairs of an SOC magnet.

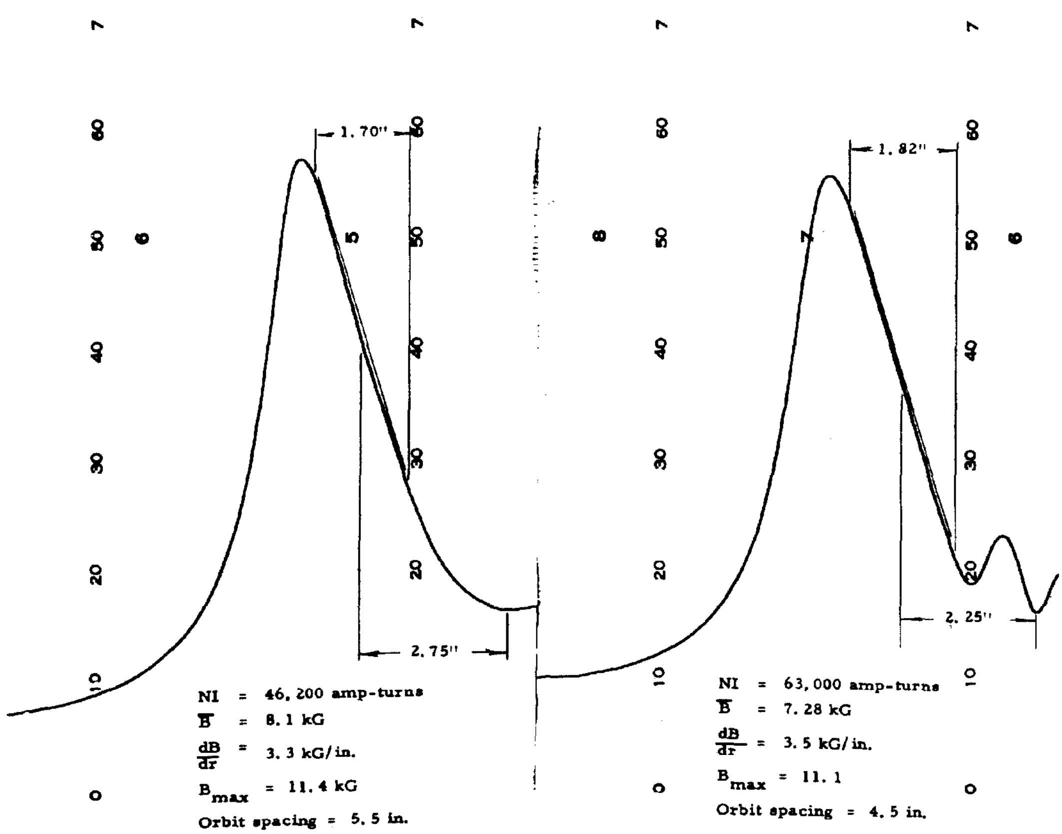

Fig. 3. Magnetic field from a pair of poles without (left) and with the field-shaping shims (right). The data are from a 1/2-scale model of the poles.

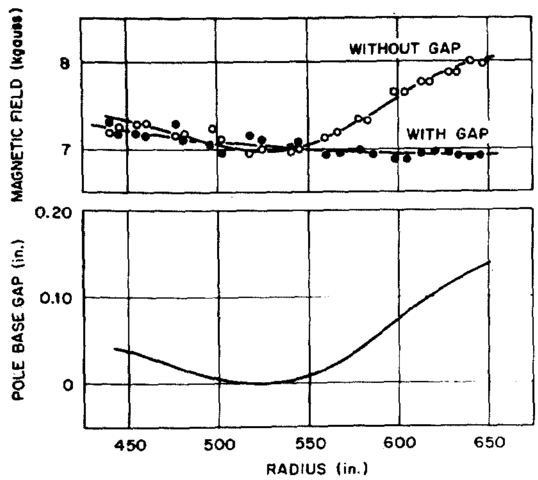

Fig. 4. Magnetic field in the beam aperture (1/8-scale model) with and without a corrective gap between the base of the poles and the yoke. The effect of varying reluctance in the magnetic circuit for orbits of different radii, due to saturation of the yoke, can be seen.

Fig. 5. An 1/8-scale model of a sector magnet. The pole gap is maintained by brass spacers that would be omitted from the final machine. This model is sufficiently accurate for obtaining only gross properties of the magnetic circuit.