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A LOW ENERGY SEPARATED ORBIT CYCLOTRON*

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Summary

Acceleration in the SOC is achieved by rf cavities placed at equal angular intervals about a ring of alternating gradient guide field magnets wrapped in a flat spiral. Coaxial cavities with two accelerating gaps and having voltage uniform with radius appear to be more economical than tapered rectangular cavities, for machines up to 100 MeV. Deuterons and alpha particles can also be accelerated in a proton machine by operating it on a harmonic number differing by a factor of two. About 5% adjustment in magnetic field is necessary to correct H_ρ when β_p is twice β_d.

The concepts of the separated orbit cyclotron were first proposed[1] in 1962 by F. M. Russell of Rutherford High Energy Laboratory, England, while spending a year at the Oak Ridge National Laboratory.

The separated orbit cyclotron (SOC)[2, 3, 4] being considered at ORNL features a strong focusing dc magnetic guide field wrapped into a flat spiral, so that an ion beam passes through discrete separated turns. The general appearance of an SOC may be seen in Fig. 1 which shows a model of a 350 to 800 MeV machine. A "cw" beam is accelerated by fixed-frequency rf cavities placed in a ring alternately with sector magnets.

Three requirements must be met for operation of the machine. First, it must be isochronous. The length of the orbit path for each revolution must be such that the particle "flight time" remains constant from revolution to revolution. Second, the operating frequency of the rf cavities must be such that there is a fixed integral number of rf periods during each revolution. This is commonly referred to as the harmonic number; it may be either even or odd. Third, the phase of each cavity must be adjusted so that the synchronous particle crosses the gap at the phase stable angle, about 30° before the rf voltage reaches a maximum.

The average field strength in the guide field magnets must be appropriate for the momentum of the particles at every point in the machine. Focusing, or stable motion, will occur only if the field gradients are within certain limits. These required gradients vary with β and with the e/m of the accelerated particle in the usual fashion, as in AG synchrotrons.

For the high energy stages of SOC (above 100 MeV) the tapered rectangular cavity appears to be the most economical. For the region below 100 MeV, however, the introduction of the "coaxial" cavity results in reduced rf power and cavity costs. Fig. 2 shows the general outline of a 10 to 50 MeV SOC with coaxial cavities. A single sector magnet and a coaxial cavity are shown in Fig. 3.

Each sector magnet has a "triplet" alternating gradient element for each turn. A typical stage usually has 15 to 30 turns and consequently 15 to 30 pairs of elements driven from a common yoke structure by a common coil pair. This arrangement requires less power than a design with individual coils for each of the elements. The average field between the pole tips is 7000 gauss, and the gradient is about 3500 gauss per inch.

Each cavity has two accelerating gaps separated by a distance $\beta\lambda/2$ so that the phase of the voltage is appropriate as the particles cross the gaps. As contrasted with the tapered rectangular cavity in which the voltage varies approximately sinusoidally with radius, the voltage in the coaxial cavity is uniform with radius. The maximum voltage in either case must be the same to achieve the same orbit separation at maximum radius. The orbit separation for the coaxial cavity, where the gap voltage is constant with radius, is shown in Fig. 4. At 10 MeV the separation between orbits is 10 in., decreasing to 5 in. at 50 MeV. An energy gain of 40 MeV is obtained in 14 turns, or orbits, with coaxial type cavities while 19 turns are required when tapered rectangular cavities are used. The additional power in the cavity resulting from the higher voltage at the small radii is more than compensated by the fact that nearly all of the coaxial cavity is useful in accelerating the beam. A large part of the rectangular cavity cannot be used because the voltage is too low, but it must be excited.

A further advantage is that the number of orbits is reduced in a machine having coaxial cavities, since the energy gain per revolution is larger at small radii. This results in a lower cost magnet and a possible relaxation in fabrication tolerances. The characteristics for the 10-50 MeV SOC are tabulated in Table I. When the rf gap is equal to $\beta\lambda/4$ the particles

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receive 90% of the energy they would have received if the rf gap had been very small. The synchronous particles cross the cavity gap where the voltage is 86.6% of maximum, or 30°, before the voltage peaks. These factors reduce the voltage gain per gap crossing to 78% of the peak voltage.

SOC machines with an injection energy of 50 kV have been considered. Although such a machine can be built, present studies indicate that it has a very small, if not negligible, acceptance mainly because the large voltage gain per gap crossing produces radial oscillations larger than the beam pipe aperture. The oscillations are caused by the particles having an incorrect energy. Since particles can be accelerated when the voltage is from -30° to +60° from the phase stable angle of -30°, the percent energy spread in the beam will be fairly large in the low energy stages when the rf voltage is large. For this reason it appears that an injection energy near 10 MeV may be more suitable for the low energy SOC.

The SOC described above was designed for the acceleration of protons. A brief study has shown that it is also possible to accelerate deuterons and alpha particles in the same machine. Since the magnetic rigidity (the ratio of momentum to charge) of a deuteron or alpha particle is approximately equal to that of a proton traveling at exactly twice the velocity, the SOC will accelerate particles of either type if the harmonic numbers differ by a factor of two. Magnet trimming coils would be required to correct for the slight difference in rigidity (caused by the non-integral mass ratios). The magnetic field correction would be only a few hundred gauss out of 7000, about 5%, see Fig. 5. The lower accelerating potential required for deuterons could probably be achieved simply by exciting the cavities with less rf power. It is also possible to vary the energy of the output end of the accelerator in steps by using different harmonic numbers. Some such possibilities are tabulated in Table II; the required field corrections are small, as shown in Fig. 6.

In general, the use of alternating gradient magnetic focusing introduces no special problems because a generous amount of space is available for the magnets and their coils. The SOC principle allows the use of low frequency (i. e., 50 Mc/s); this results in large transit time factors with wide cavity gaps, and permits very high voltage using only existing rf technology.

References

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Table I. Design Characteristics of a 10-50 MeV SOC.

Sectors	7	Harmonic number	16
Orbits	14	Frequency	50 Mc/s
Beam radius		Wavelength (λ)	236.2 in.
Min	84 in.	Cavity voltage	260 kV peak
Max	180 in.	RF gap	$\beta\lambda/4$
Magnetic field	7000 gauss	Min	8.5 in.
Gradient	3500 G/in.	Max	18.5 in.
Magnet copper	14 tons	Phase stable angle	-30°
Magnet steel	327 tons	Cavity power	525 kW
Magnet power	139 kW		

Table II. Operating Values for a 7-Sector, Multi-Particle SOC.

Particle	Injection Energy (MeV)	Final Energy (MeV)	Harmonic Number	B_o (kG)
p	10.00	60.31	9	7.000
d	4.94	27.75	18	6.939
α	9.81	55.14	18	6.893
p	8.08	47.36	10	6.287
p	6.66	38.63	11	5.706
p	5.59	32.14	12	5.225
p	4.75	27.17	13	4.818
p	4.09	23.29	14	4.471
p	3.56	20.19	15	4.171
p	3.13	17.68	16	3.908
p	2.77	15.61	17	3.677
p	2.47	13.88	18	3.471

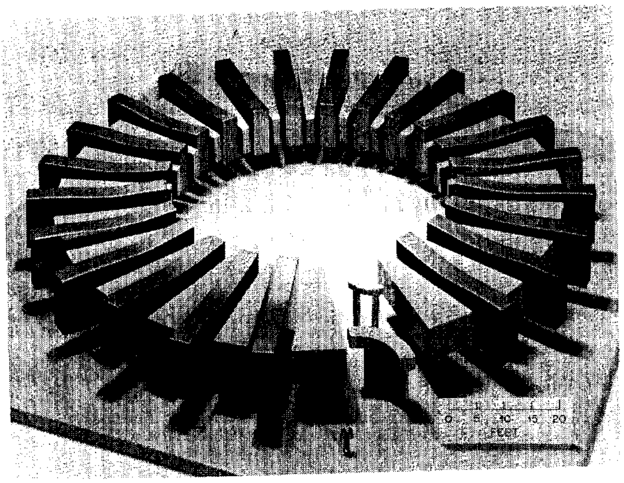


Fig. 1. Model of 350-800 MeV SOC showing magnet sectors alternating with accelerating cavities. The beam is injected and extracted through 90° magnets.

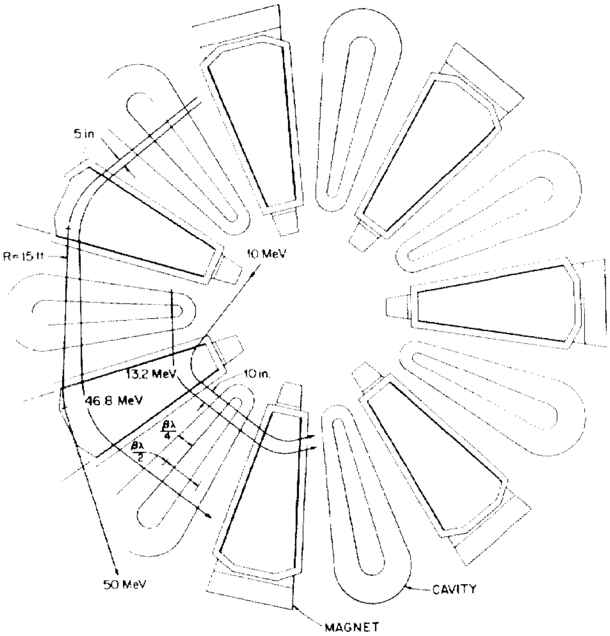
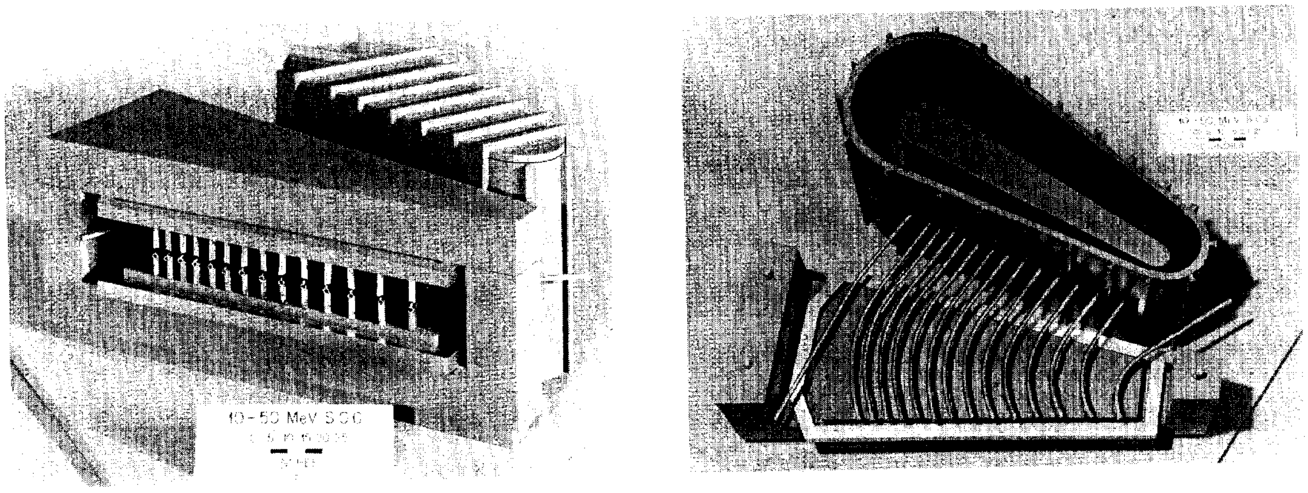


Fig. 2. Schematic of 10-50 MeV SOC with coaxial cavities. The beam is injected by having a higher field in the first pair of poles and extracted by reducing the length of the last pair.



(A) (B)

Fig. 3. Model of a single sector of the 10-50 MeV SOC. Only the beam tubes and the cavities are under vacuum.

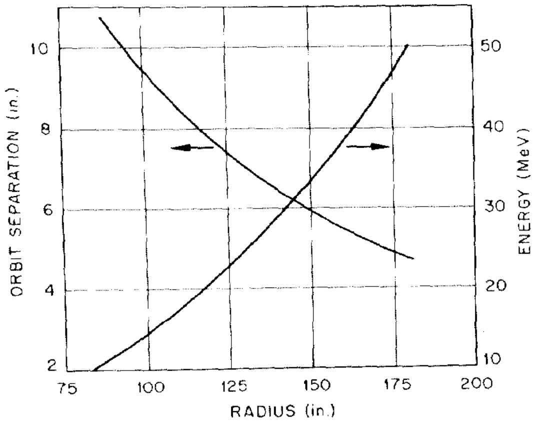


Fig. 4. Orbit separation and energy vs radius for a cavity design having constant voltage with radius, but with tapered gap and hence tapered electric field.

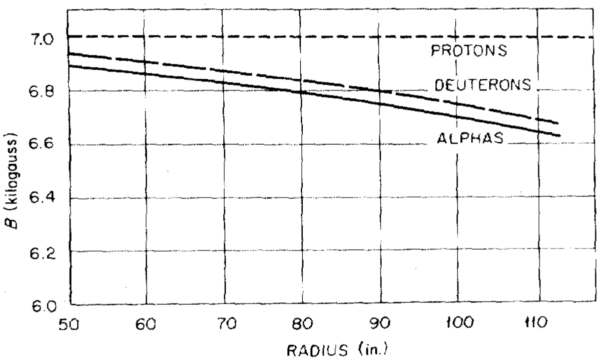


Fig. 5. Magnetic field vs radius for accelerating protons, deuterons, and alphas in the same machine.

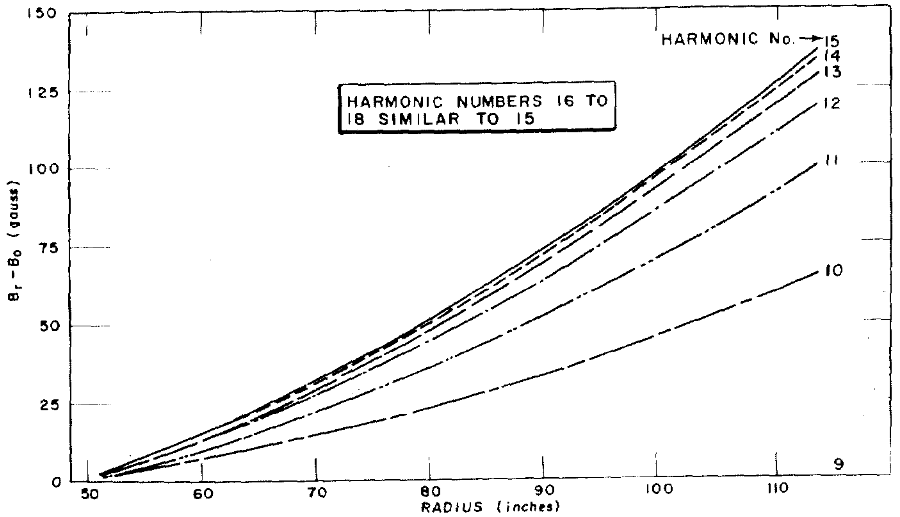


Fig. 6. Magnetic field correction required in each pole as a function of radius to operate a ninth harmonic SOC on higher harmonics at reduced input and output energies. The values of B_0 required are given in Table II.