# A 4-MeV EXPERIMENTAL SEPARATED-ORBIT CYCLOTRON*

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## Summary

A small experimental Separated-Orbit Cyclotron is being built to provide experience in the design and operation of this new type of accelerator. It will permit examination of the sensitivity of the SOC design to methods of construction and to errors in alignment. Some features are variable so that the flexibility of this class of machines for the acceleration of various particles and the applicability to high beam intensities can be evaluated.

## Introduction

The decision was made last spring (1966) to build a small operating Separated-Orbit Cyclotron which would supplement the model studies being made for a 10-50 MeV SOC and the design studies for other larger cyclotrons.[1] The machine was designed specifically to aid in the improvement of design and construction techniques and to minimize cost without any sacrifice in performance. In setting up and operating the cyclotron, several critical requirements will be tested, such as: the optical alignment method which can give correct positioning of the pole tips to ±0.002-in., the method of adjusting rf gaps to vary accelerating voltage on a cell-by-cell basis, and the effectiveness of turn-by-turn corrections in the beam path to compensate for random misalignment errors. Experimental work will be possible in the regions where the theory is least certain. In particular, the quality of beam transmission and the amount of beam losses can be evaluated under the effects of rf voltage errors, rf noise, and increased space charge and beam loading. Further, multiparticle variable energy operation can be demonstrated.

The experimental SOC is designed primarily for protons of 4.0 MeV, but the provision for varying the energy also makes it possible to accelerate other ions, as tabulated below:

| Particle | Output Energy (MeV) | |
|---|---|---|
| | Min | Max |
| Protons | 1.8 | 4.0 |
| Deuterons | 1.8 | 4.0 |
| $H_2^+$ ions | 1.8 | 4.0 |
| Alpha particles | 3.6 | 8.0 |
| $^3He^{++}$ ions | 3.6 | 8.0 |

## Description of the Machine

The general layout for this six-sector, 24-cell machine may be seen in plan view in Fig. 1. Each cell consists of the portion of a cavity for one beam passage, one set of pole tips, and the two drift sections connecting the pole tip and adjacent cavities. Thus, four beam orbits through six sectors represent 24 cells. The use of an injector system leaves the central region free for the optical alignment apparatus--a permanent part of this experiment. A 625-kV Cockcroft-Walton set and the short linac injector will be placed at the side. The beam axis of the linac will be parallel to but four feet above the path of the beam where it enters the first cell of the SOC. To maintain axial beam alignment in the SOC, beam position detectors and two pairs of coils will be mounted in each orbital turn. The set of two pairs of alignment coils are spaced at a distance equal to one-quarter beta-

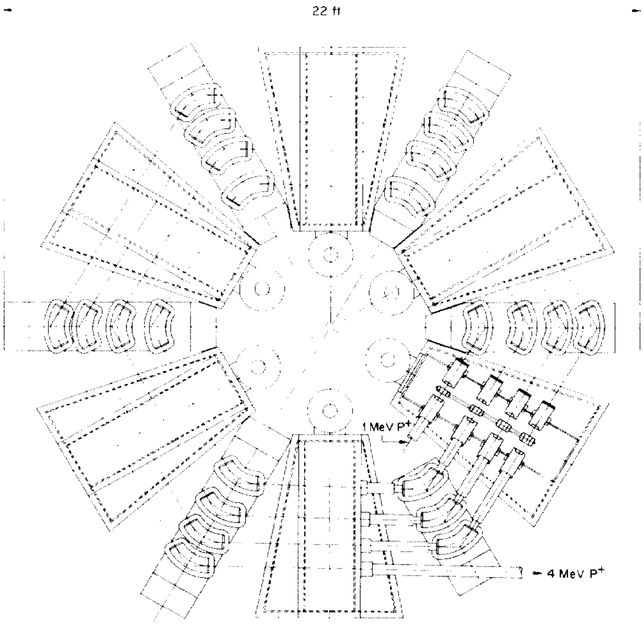

Fig. 1 Plan view of 4-MeV SOC.

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tron oscillation and require a field-length product of ±600 gauss-inch to provide a ±0.5 in. realignment. For radial alignment, the trim coils on the pole tips will be used. The principal machine specifications are listed in Table I.

## Beam Stability

A characteristic of any SOC is that for efficient cavity operation, the circumference factor must be large. This requirement leads to an optimum average central magnetic field of about one kilogauss. With the large drift-to-magnet-lens-length ratio available even the simpler focusing systems, such as constant-n or edge focusing, can be strong and the momentum compaction factor large. Here, for n near 0.5, $\nu$ values of ~1.4-2.5 can be obtained in the 6-sector machine. Thus each cell, near injection, can operate with ~90° betatron oscillation phase shift in the region of maximum acceptance. Although phase focusing is not very strong here, the momentum compaction factor of 1.2-2.6 shows that operation will be below the transition energy. Along the 24-cell path the phase oscillation will total 1.5 cycles.

The curves of Fig. 2 show that n = 0.4 to 0.6 should give satisfactory operation of the machine in any of the cells. The value of n will be placed near 0.5 in the last few cells, however, to strike a compromise between the stability limit at $\nu = 3$ and the coupling resonance between axial and radial motion at n = 0.5. The n value was increased to 0.58 for the first few cells so that the phase focusing would be stronger at low energy.

In Fig. 3, the number of cells per cycle of phase and betatron oscillation throughout the machine is shown for n = 0.5. The 2:1 coupling resonance between phase and radial motion is completely avoided.

## Variable Energy Operation

The energy output from an SOC may be decreased by tuning the machine to operate on a higher harmonic number. For example, proton operation on the 33rd harmonic here means the protons should have 32/33 of the maximum design velocity in each cell. The magnetic field, which must be adjusted to a lower value for the correct BR-product in each cell, will change shape as a function of cell number only slightly because of the small change in momentum-to-velocity ratio as a function of energy. The decreased energy output requires less cavity voltage. The reduction of the cavity voltage is partly offset, however, by the smaller transit

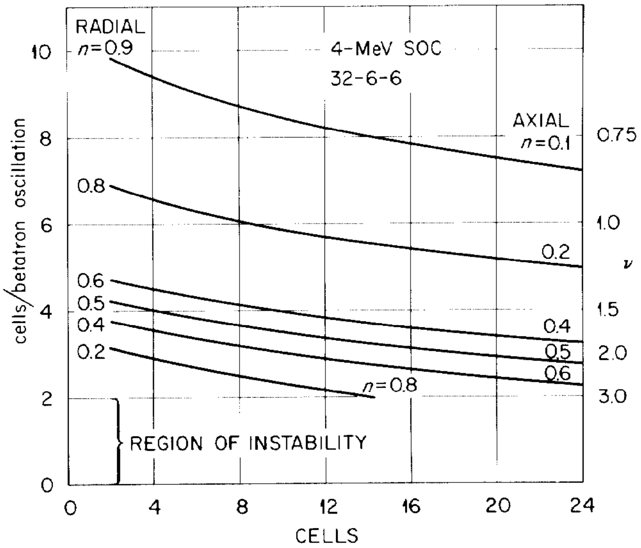

Fig. 2 Stability of betatron oscillation in the 4-MeV SOC.

Table I. Features of 1-4 MeV Experimental Separated-Orbit Cyclotron
(Values refer to 4.0-MeV proton case, except as noted)

| | | | |
|---|---|---|---|
| Frequency of accel. voltage | 50 MHz | $\nu_r$ | 1.4 - 2.1 |
| Harmonic no. | 32 | $\nu_z$ | 1.6 - 2.5 |
| Sectors | 6 | Momentum compaction, $\alpha$ | 1.2 - 2.6 |
| Cells | 24 | Minimum turn spacing | 11.8 in. |
| Inj. radius | 138 cm; 54.2 in. | Cavities | 6 |
| Ext. radius | 262 cm; 103.1 in. | Type | coaxial |
| Pole tip radius | 43.8 cm; 17.25 in. | Drift length, $\beta\lambda$ | 0.18 |
| Mag field, min | 3.50 kG | Gap lengths, $\beta\lambda$ | 0.20 |
| Mag field, max | 6.50 kG | Peak voltage, kV | 83.4 kV |
| Mag field, max* | 9.19 kG | RF power, no beam | 53.2 kW |
| Aperture | 1.5 x 3.0 in. | RF power, 10-mA beam | 83.2 kW |
| Field index, n | 0.58 - 0.52 | | |

*For 4.0-MeV deuterons, highest value of field required.

time factor and by increased angular spacing of the two gaps in each cavity, as seen by the slower particles. The curves of Fig. 4 show the input and output energies for protons and deuterons and the corresponding cavity voltages for the design values of gap and drift tube lengths. The lowest energy output as well as the highest may be limited by the cavity voltage available. Here, where the relativistic effect is small, the cavity voltage need change only by 2.5% with machine radius to maintain exact synchronism in the worse case, as shown in Fig. 5. To fill in the energy gaps between those values obtained by just changing harmonic number, a change in frequency may be made. The range required is equal to the design frequency divided by the design harmonic number. Here, a frequency range of 50 ±0.78 MHz should be sufficient.

## Injector

The injector for a variable energy SOC of this type must be as versatile in energy output as is the SOC. Also the energy of the particles injected into the first cell of any linac injector at 50 MHz should be at least 200 keV for sufficiently weak rf defocusing forces to get a phase acceptance greater than 90° and a high value of radial transit time factor. A 625-kV, 25-mA Cockcroft-Walton power supply to be used as the dc injector solves this latter problem.

The linac injector consists of three separately-excited rf cavities. Each cavity has a single drift tube and two accelerations with a spacing of $\beta\lambda/2$ at the highest design value of $\beta$. By controlling each cavity independently in voltage and in phase any output energy in the range from the dc injector energy, 250 to 500 keV, up to 1000 keV can be obtained. The 4-in. dia center conductor and the 28-in. dia outer conductor of each cavity is tapered at the high voltage end to provide, in the case of the output cavity, gaps of 1.96-in. and a drift tube length of 1.78-in. One of the cavities is now being constructed. Each drift tube will have a peak voltage of 90 kV and require up to 6 kW at a beam loading of 10 mA. The spacing between the center planes of adjacent cavities will be 15 in. to leave adequate space for a single quadrupole lens per cell.

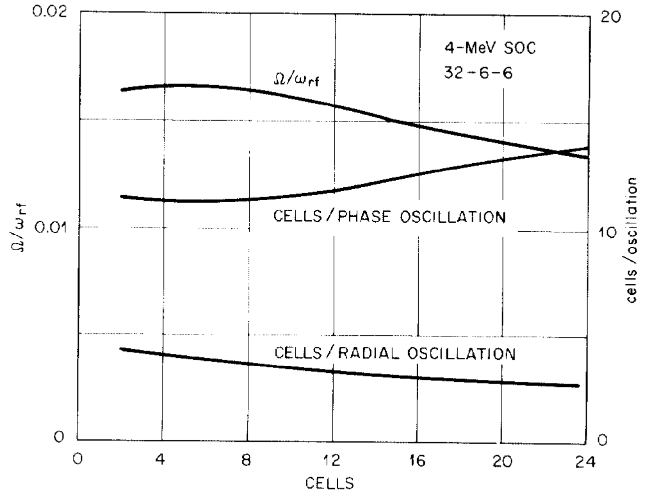

Fig. 3 Wavelengths of radial betatron and of phase oscillation for N=0.5.

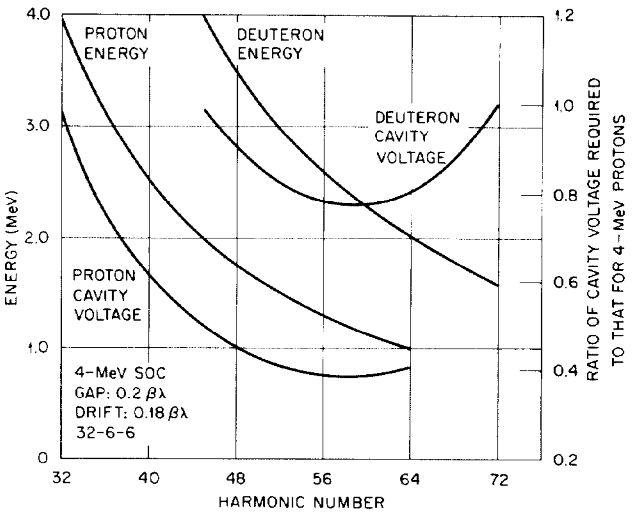

Fig. 4 Output energy and operating cavity voltage vs harmonic number for protons and deuterons.

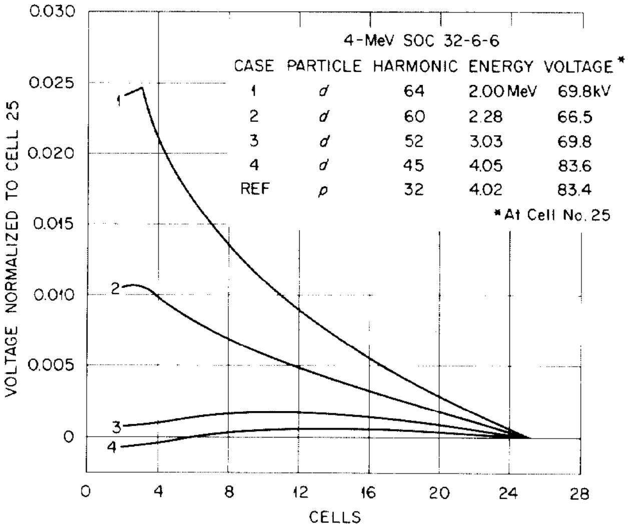

Fig. 5 Cavity voltage required in each cell for exact synchronous operation with harmonic operation.

A single buncher cavity of similar construction will be placed one meter in front of the first linac tank. An operating voltage of ~15 kV will increase the acceptance from 90° to 220°.

## Injector Beam Matching and Transport

The major portion of the beam leaving the last injector linac cell will extend over a 10 to

20° spread in phase and have a large energy spread, about 5%. This thin, finger-like shape is quite unsuited to the shape acceptable by the SOC. After the beam drifts two meters the large energy spread causes the overall phase spread to be about 120°. The beam shape at this point is, however, such that it can be reshaped by a sinusoidal rf voltage of ~75 kV peak. A further drift of two meters folds the beam into a spiral shape which fits into the acceptance "fish" diagram of the SOC. The four-meter path length from the injector to the SOC input cavity is sufficient to permit the linac to be mounted above the SOC at a convenient working distance. Two 90°, nondispersive, bending magnet-quadrupole systems have been found which will transport the beam from the plane of the linac down to the plane of the SOC; the system is being designed.

## Error Analysis and Tolerances[2]

Since this is an experimental machine in which the effects of alignment errors are to be studied in particular, the tolerances are being made smaller than necessary for an operating machine. For example, the edges of the pole tips will be cut much tighter than the ±1° tolerance required to make the effect of edge focusing negligible. To prevent the beam path center from wandering more than 0.1 in. radially in each turn the tolerances for random errors in pole tip location, length, and field need be:

| | |
|---|---|
| Radial displacement | ±0.025 in. |
| Azimuthal displacement | ±0.025 in. |
| Skew | ±1.2° |
| Length | ±0.080 in. |
| Field | ±7 parts in $10^4$, |

where each error type is given equal weight. The displacements are measured with respect to the center point of the path through the pole. The tolerance specified will be about 0.1 of these values in all cases. For axial motion, the types of error are axial displacement (error in median plane location) and skew, both of which should be negligible because of the tight alignment tolerances of this machine.

To minimize the phase oscillation amplitude caused by errors, the phase of each cavity voltage is to be held to within ±1° of its prescribed value while each cavity voltage will be regulated to ±0.5%, or better. Errors of either of these magnitudes would produce similar amplitudes of phase oscillation.

This precise construction will permit the experimental introduction of particular types of errors in the machine and measurement of the effect on the beam, with nearly no interaction from other errors.

## Present Status

At this time, the design of the major components is completed to the point that full-scale sections or models have been constructed. One complete sector of the magnet[3] has been built to prove the techniques which have been developed for SOC. Field measurements, partially completed, show that field shaping is quite straightforward and that the fields at adjacent tips may be independently adjusted to a ±10 gauss level. Tests have been completed on a full-scale wood-and-foil rf cavity.[4] The rf fields expected in the gaps and the rf losses were measured, and a computer program has been completed to set up the machine from the measured rf fields. The rf amplifier design[5] is completed to the point that a prototype of the ten identical amplifiers required has been built. Details concerning these components are presented in other papers to be published in the Conference Proceedings.[3, 4, 5]

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