A STRONG-FOCUSING CYCLOTRON WITH SEPARATED ORBITS

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(Presented by A.H. Snell)

The subject of this paper is a new concept in particle accelerator design with possible applications to machines of intermediate energy, say from 15 MeV to a few GeV[1,2]. The principle underlying this concept is that the equilibrium orbit is designed in three dimensions. It will be shown that many desirable features stem from this basic principle which permits the design, at least on paper, of an interesting new class of accelerators.

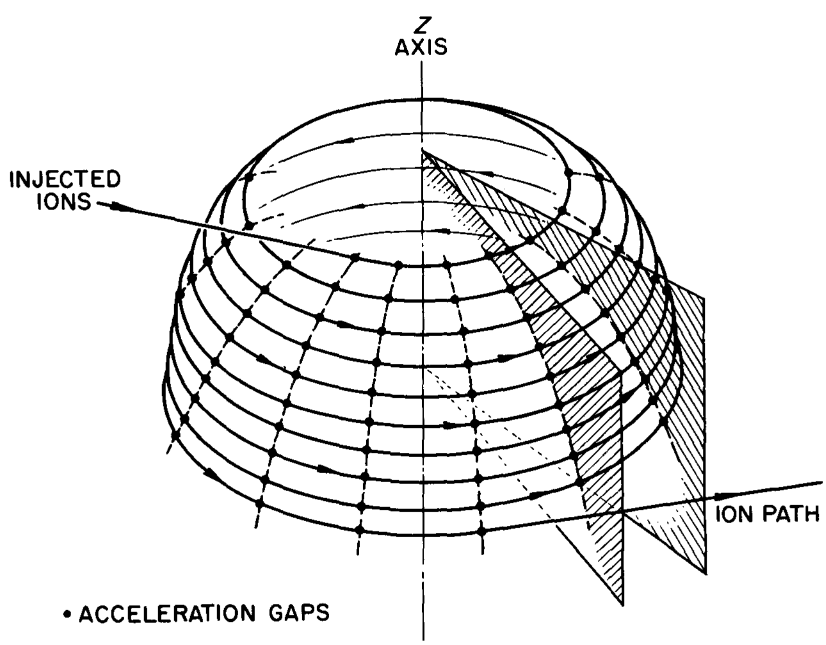

Fig. 1 Diagram of beam path with both radial and axial separation. Accelerating gaps are indicated by dots along the beam path. The RF voltages at the gaps joined by dashed line are in phase.

Assume that an equilibrium orbit exists and that an ion in this orbit describes a curve resembling a spiral-helix. Such a path is shown schematically in Fig. 1. Let this equilibrium orbit be intersected by a number of planes whose common line of intersection lies along the z axis and which are equally spaced in azimuth about the z axis, as indicated in Fig. 1. Now assume that at each point of intersection of these planes with the equilibrium orbit an RF accelerating voltage is applied across a gap and so directed as to accelerate ions along the equilibrium orbit. Let all the RF voltages at

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a given azimuth be in phase and let there be 2N such acceleration gaps per turn, corresponding to N planes. If the amplitudes of the RF voltages are maintained constant, then the rotational frequency of an ion on the equilibrium orbit can be made constant by suitable programing of that orbit path in space. The necessary condition for isochronism is that the mean magnetic field strength at the equilibrium orbit vary as γB_0, where B_0 is the field strength corresponding to zero energy. The actual magnetic field differs from the mean, however, because allowance must be made for the RF gaps and any straight sections introduced around the machine. To maintain synchronism with the RF the straight sections must occupy an integral number of half-periods at all radii and, so, might more accurately be termed wedge-sections.

In any accelerator it is necessary for there to be some restoring force to act on ions which deviate from the equilibrium orbit. Of the two basic types, 'weak' and 'strong' focusing, it is natural to favor the latter because of the smaller apertures that can be used. However, the potentially enormous saving in aperture which strong focusing should permit is not usually achieved. This is because of the many resonances that can occur between the ions and certain periodicities in the guiding field, causing a growth of betatron amplitudes and subsequent loss of ions from the beam.

If, however, the ions pass any given point in the machine only once during the entire process of acceleration, then many of the resonances associated with strong focusing machines are eliminated. It is apparent that the helical path of the equilibrium orbit in the proposed machine is of this single-pass type. Ideally, if there is no coupling between turns, then all integral, subintegral, and error resonances can be eliminated; even the coupling resonances could be avoided. This result follows because the 'working-point' on the stability diagram can move in a discontinuous manner, jumping over a resonance line if necessary; the magnetic field gradients can be changed in a discontinuous way at chosen points along the orbit. In the ideal case, therefore, only the basic instabilities common to all AG systems exist and these present no difficulty in design.

If a perfect guide field could be constructed, then the upper limit on the field gradients would be set solely by the condition for stability. In practice, the advantages accrued by using large n values are finally offset by the errors introduced in creating the fields. A reasonable compromise is achieved if the betatron frequency is made about an order of magnitude greater than the orbital frequency.

The question of how rapidly a beam, initially close to the equilibrium orbit, spreads as a result of random field errors is very important; this fixes the accuracy with which elements should be made. Preliminary estimates indicate that tolerances on mechanical adjustment could be about ± 1/100 in; centered on the ideal or equilibrium orbit. The corresponding field error is about 1 part in 1000, which is a moderately relaxed tolerance for a fixed-field machine. The effect on tolerances of imposing the condition that adjustments could be made where necessary to 'tune' the system are simply not known. Some conclusions might be drawn in this respect from the very successful hand tuning of several AVF cyclotrons.

In common with other orbital machines using AG focusing, this machine exhibits a large degree of momentum compaction. A direct result is that, provided the RF voltage exceeds a certain critical value, the ions show phase stability of motion with respect to the RF. The major advantage of phase-stable motion is that non-synchronous ions are successfully accelerated. The disadvantages are that ions on the average gain less than the maximum energy possible per gap crossing and that there is a spread in energy of the ions about that of the synchronous ion at all energies. As usual, the advantages far outweigh the disadvantages.

To generate the RF voltages, it is proposed that a cavity system be used, of the type illustrated in Fig. 2. Resonant cavities of this type have been carefully studied and appear to be eminently suited to this machine. Although it is possible to consider the entire RF system as part of one extremely large cavity, snaking its way alternately up and then down the radial spaces between the magnet sectors encompassing the entire ring, it is probably not the best solution. A reasonable solution is to make the system out of several identical parts, each cavity filling one or, at the most, two radial spaces. The several cavities could then be correctly phased by control of the amplifier stages feeding the cavities.

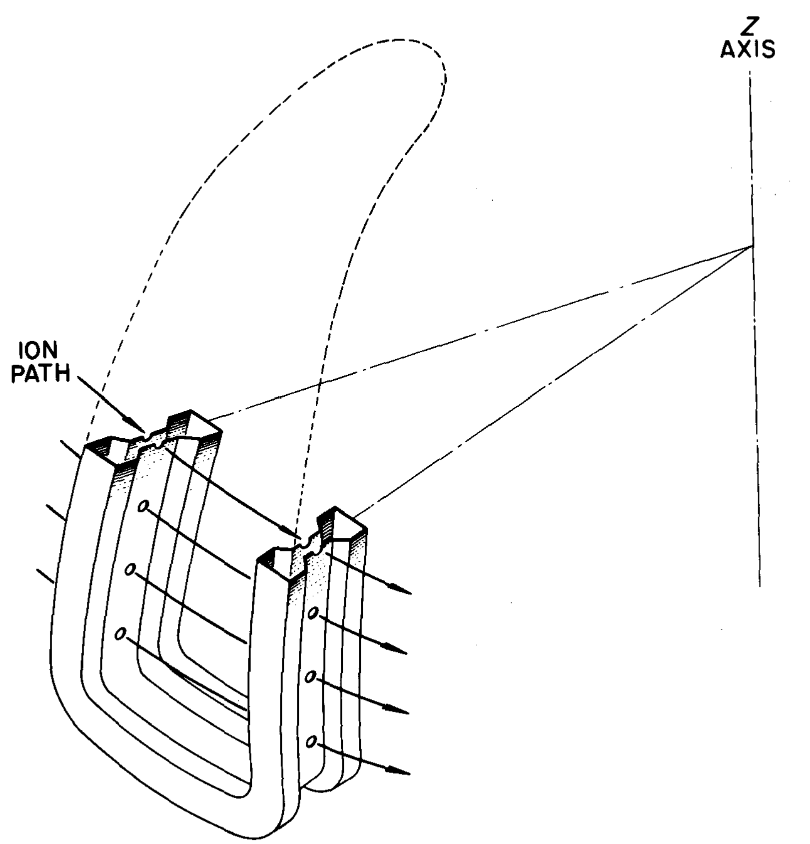

Fig. 2 Sketch of part of suggested radio-frequency cavity system. The electric field is a maximum at the centre of the cavity and is parallel to the path of the ions.

If it is assumed that a cavity system of the proposed type can be designed, then it is of interest to examine why the system is apparently more efficient in the transfer of power to the beam than is a linear accelerator. With a pill-box structure taken as representative of a linac, a comparison of the systems yields reasons which are two-fold. First, the amount of cavity per acceleration, that is, the total surface area of a cavity divided by the number of beam passes, is less in the proposed case. Secondly, the strengths of the electric fields are also less. It appears that these two factors are approximately equal in importance in causing an overall reduction in the power losses relative to an equivalent linac. In practice a ten-fold reduction in power level should easily be achieved.

To achieve dimensional stability each cavity would be enclosed within a vacuum chamber. Fortunately, the alternation of cavity and magnet stack around the machine makes it possible to balance out most of the atmospheric forces by tying each vacuum chamber to the adjacent magnet stacks.

The basic properties of the magnet have already been suggested. An important feature of the stacked arrangement of poles is the high magnetic efficiency which can be obtained. In addition, the several parts forming the magnet are not, individually, either large or intricate. It is possible that the magnet may be constructed from N sections of identical magnet blocks, the variations required in passing from cell to cell being absorbed in adjustable pole tips. Certainly, at the high energy end this would be true. At low energies, however, it might be necessary to make some coarse allowance for the rapidly changing orbit radius in the main magnet blocks.

The anticipated mean field strength on the equilibrium orbit is not high, a typical value being about 5 kG for a 1 GeV machine. In the main body of the magnet, therefore, saturation effects are unimportant. To achieve the field gradients necessary for the focusing of the beam, it is proposed that pole-tip inserts be used of the type shown in cross-section in Fig. 3. These inserts could be aligned accurately during manufacture and then simply slipped between the parallel faces of the magnet stacks. Final adjustment of the magnetic field would then consist of moving each insert to give the desired mean field at the equilibrium orbit. An attractive feature of this arrangement is the essentially complete decoupling between adjacent turns in a given sector. This is a result of the low mean field strength and the intermediate magnetic equipotential surfaces forming the magnet stacks.

To energize the magnets, coils could be wound around each pole face or stack forming one of the 2N sectors. A more detailed study for a proposed 1 GeV machine indicates, however, that a more efficient arrangement could be produced by winding the sectors collectively, so as to form quadrants, as suggested schematically in Fig. 4. This figure shows two additional features. First, since the direction of motion along the z axis in passing to successive turns is unimportant, the motion could, if necessary, be reversed at a suitable point along the flight path. Such a procedure results in a more efficient, more rigid, and smaller magnet. Secondly, four wedge-sections are indicated. In each of these sections it is suggested that small magnets be placed around the flight path so as to deflect the ions in the z direction. In this manner, the quadrants forming the magnet are all in the horizontal plane, which should greatly simplify the construction and alignment of the machine. Provision could also be made in these sections for the extraction of the beam at intermediate energies.

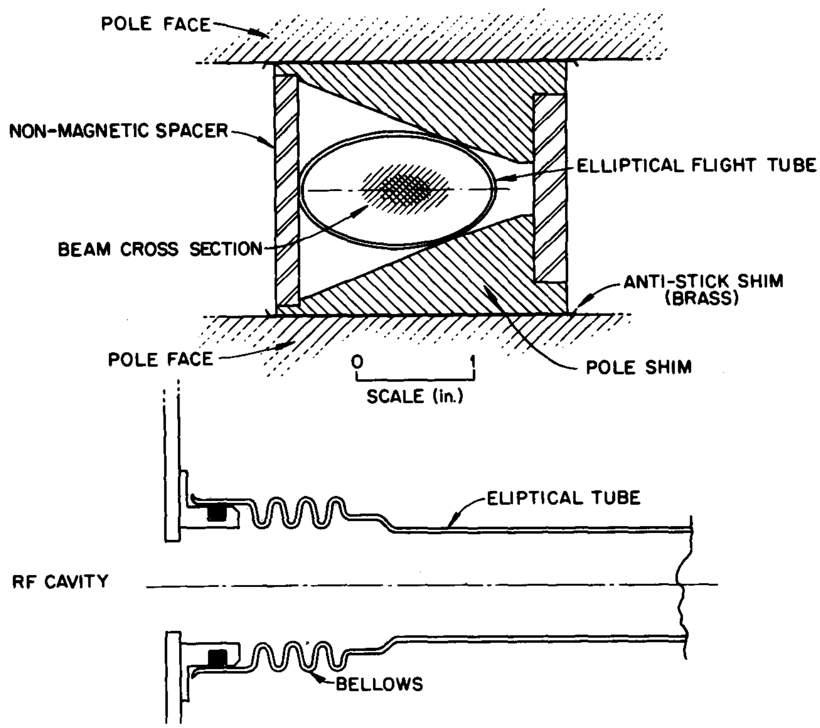

Fig. 3 Detail showing cross-section of the pole-face insert and the beam flight tube.

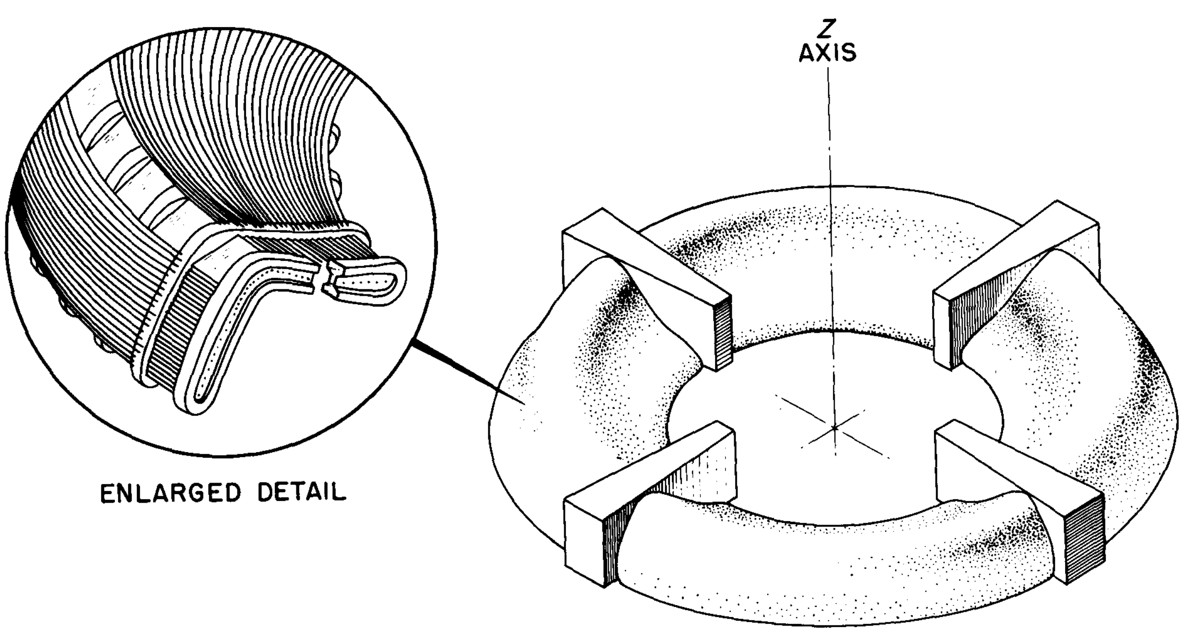

Fig. 4 Artists impression of a large SOC cyclotron, showing quadrants and wedge-sections.

ENERGY RANGE			TYPE OF MACHINE
0	TO	0.5 MeV	COCKCROFT - WALTON
0.5	TO	15 MeV	CONTINUOUS WORKING LINAC
15	TO	120 MeV	SEPARATED ORBIT CYCLOTRON
120	TO	1000 MeV	SEPARATED ORBIT CYCLOTRON

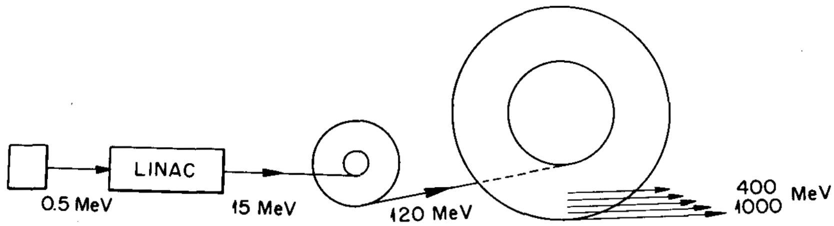

Fig. 5 An accelerator system for 1000 MeV protons.

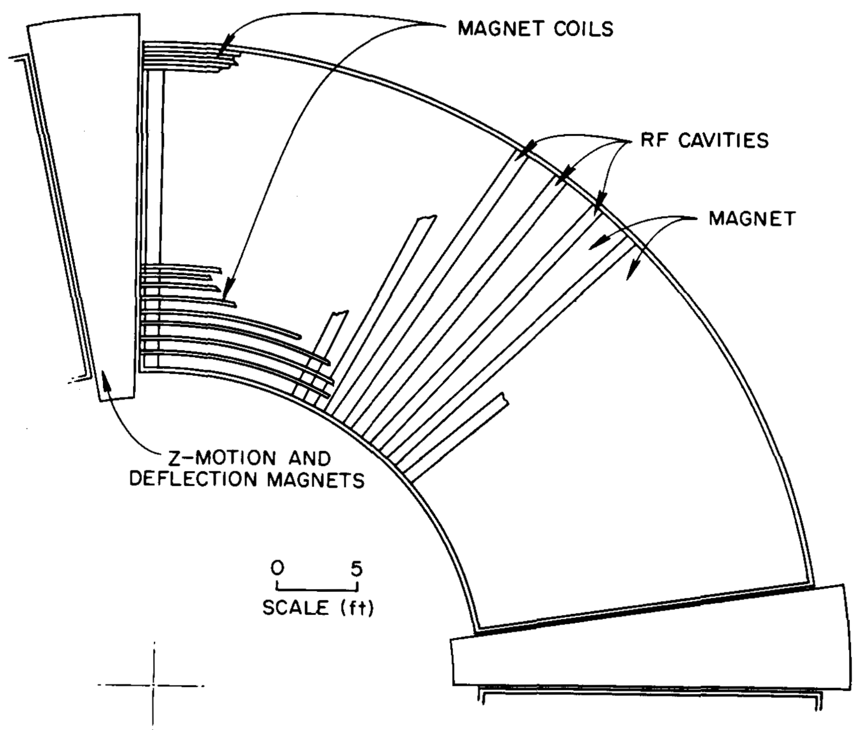

Fig. 6 Plan view of one quadrant of the second-stage SOC.

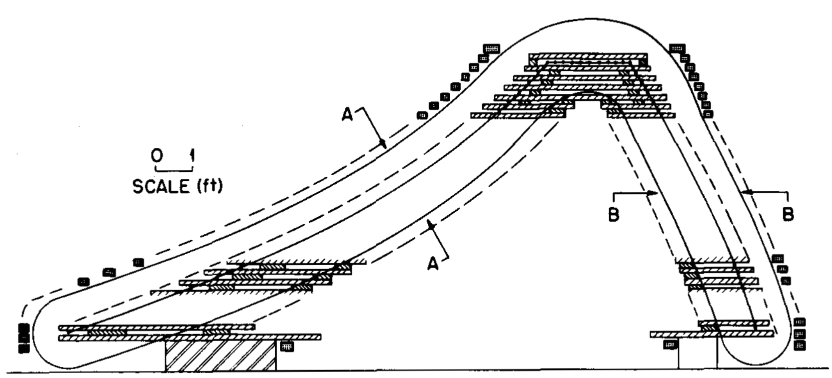

Fig. 7 Radial cross-section showing the arrangement of the magnet stacks, coils, and supports in relation to the RF cavity.

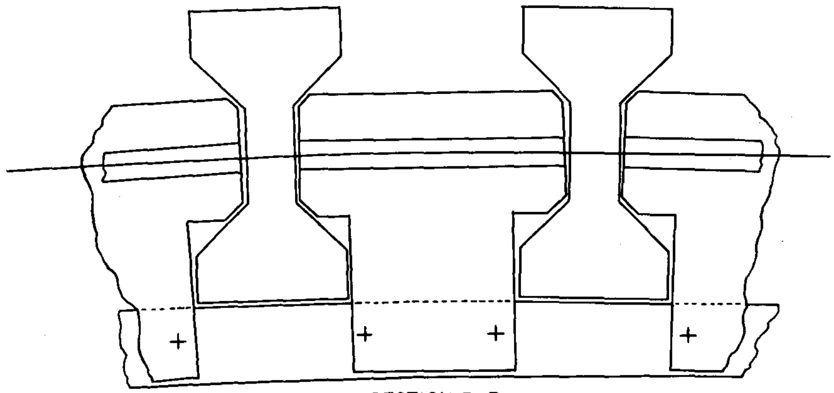

Fig. 8 Horizontal section through the second stage showing relative positions of the RF cavities, the magnet stacks, and the magnet support structure.

In applying these principles to a large machine it is convenient to split the overall system into several smaller accelerators, each part intended for a definite energy range within which it can be designed for optimum operation. Such a breakdown for a 1 GeV machine is shown in Fig. 5. Some relevant numbers are shown in Table I for the part covering the energy range from 15 MeV to 120 MeV. In Table II similar numbers are shown for the 120 MeV to 1 GeV part. A plan view of one quadrant of the last part is shown in Fig. 6, a radial cross-section in Fig. 7, and a horizontal section B-B in Fig. 8.

Table I

Separated Orbit Cyclotron, 15 to 120 MeV

Type	Simple Helix	
Number of sectors	44	
Number of turns	25	
Central magnetic field, B_0	2.5	kG
Cyclotron radius unit, R_∞	12.4	m
Radius at injection	2.18	m
Radius at extraction	5.7	m
Magnetic field, mean peak	4.0	kG
Magnet weight	120	tons
Magnet power	580	kW
Weight of copper	112	tons
RF frequency	170	Mc/s
Gap voltage	100	kV
RF power losses, at $\varphi = 20^0$	2.0	MW

Table II

Separated Oribt Cyclotron, 120 to 1000 MeV

Number of sectors 100; turns	60	
Central magnetic field, B_o	2.25	kG
Cyclotron radius unit, R_∞	14.1	m
Radius, at inject. 6.5 m; at extract.	12.2	m
Magnetic field, mean peak	4.9	kG
Magnet weight, coils 280 tons; total	530	tons
Magnet support structure	290	tons
Magnet power	2.3	MW
RF frequency	170	Mc/s
Gap voltage	150	kV
RF power losses and beam ($\varphi = 20^o$)	9.0	MW
z-motion magnets, total weight	64	tons
Extracted current, mean	1.0	mA
Extraction efficiency	100%	
Duty cycle, micro. 5%; macro.	100%	
Est. cost, per watt of beam	$16	

Est. total cost of machines for 0 to 1000 MeV
$\$16 \times 10^6$ or $£5.7 \times 10^6$ or $SF.64 \times 10^6$

At this point a summary of the basic properties of this machine is perhaps pertinent. In review, then, the Separated-Orbit Cyclotron exhibits the following properties:

1) Continuous beam output, as in an FF cyclotron
2) High transverse stability, as in an AG synchrotron
3) Phase stable in longitudinal motion, as in a synchrotron
4) Whole beam conveniently extracted, as in a linac
5) Output energy can be varied in steps, as in a linac
6) No serious instability resonances
7) Good quality extracted beam, as in a linac
8) Compact location, as in a cyclotron
9) No upper limit on energy, as in a linac

In the light of these considerations it is thought that such a machine is well suited to serve as either a meson factory or as an injector to a second accelerator, or both if the second machine is operated in a pulsed manner.

In conclusion, the author wishes to thank the staff of the Electronuclear Division at the Oak Ridge National Laboratory for their encouragement.

References

1. F.M. Russell, Nucl. Instr. and Meth., (submitted) 1963.
2. F.M. Russell, A Strong-Focusing Cyclotron with Separated Orbits, ORNL Report 3431 (1963).

DISCUSSION

LAPOSTOLLE : Regarding the variable energy by steps as in the linac, there is some difference in that with a linac the beam is in the same place at the different energies. You can even have a continuous adjustment of the energy. In the SOC the beam is in different places at the various energies. So you cannot get a continuous quick energy change on a fixed target as you can get in the linac.

SNELL : Yes, you have to do something to move the beam to the experiment.

KERST : The way people have been drawing cyclotron orbits leaves them separated because you want small phase acceptance; why not get rid of the yoke and put iron in between the separated orbits.

SNELL : You say, why not squash it all flat?

KERST : Right. Then you are back to a cyclotron. You could put the iron between the separated orbits but then you don't have space for ampere turns. If you could really use superconductivity, then couldn't you put it in the one plane?

SNELL : You would lose the advantage that you can extract at various energies if you squashed it flat.

LAWSON : If you squash the machine flat, the orbits will be too close at high energies. You see from the figure that the radial separation at high energy is small.

LIVINGOOD : I believe the squashed flat variety was proposed many years ago by Gallop in England. At that time strong focusing was not known, and he was contemplating a series of weak focusing magnets and a very loosely wound spiral so that the machine would cover a very large area. It was essentially a linac with weak focusing cyclotron magnets distributed along the path.

BRUCK : This device resembles the constant-radius Okhawa electron cyclotron that could perhaps be generalized for non-constant radius. The advantage of this could possibly be simpler magnet structure and easier precision requirements on alignment.

LAWSON : This machine differs from that of Okhawa in that the orbits are truly separated. Okhawa's machine, for example, will still suffer from integral resonances.

SYMON : I was not quite sure that I understood the point about eliminating the periodicity so as to avoid resonances. I had always thought that the advantage of a periodic machine was that it does have resonances, consequently the spectrum of imperfections is concentrated at narrow resonances and if you keep the oscillation frequencies away from these resonances they are stable. If you have a machine which is not periodic but has the same amount of imperfections, then the spectrum of these imperfections is continuous and, consequently, at any oscillation frequency the oscillations are driven and they grow, although, of course, they grow much more slowly than they would in a periodic machine if Q is on a resonance.

LAWSON : In a cyclotron, operating at fixed frequency, one cannot stay between resonances, one must pass through them.

KERST : This reminds me of a suggestion by Christofilos in 1953, to avoid resonances by modulating the Q-values. The problem was studied by Courant and Snyder. In that case, it did not work for the reason pointed out by Symon. However, you are presenting something different and you may get by in this particular situation.