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ENERGY MULTIPLICATION BY BEAM RECYCLING IN AN ISOCHRONOUS CYCLOTRON*

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Summary

We have made an initial computer study of a recycling method for increasing the final energy of heavy-ion beams from ORIC. The system involves simultaneous acceleration of two beams. A first beam originating either in an ion source or external injector is accelerated, extracted, and reinjected in a higher charge state obtained by means of a foil located between the turns of the first-pass beam. For example, with a 20 MV tandem injecting into ORIC the energy for ^{208}Pb after the first pass would be 1.9 or 2.3 MeV/u and after the second pass 5.2 or 6.3 MeV/u depending on the injection charge. The requirements of this scheme are 1) sufficient dee voltage to override the differing mass increase factors of the 2 beams; 2) good beam quality and accelerator stability to insure spatial separation of orbits; 3) an all-magnetic extraction system to assure identical paths for the 2 beams; and 4) relatively standard external beam separation and reinjection equipment.

Introduction

If a suitable number of electrons are stripped from heavy-ions after acceleration to full energy, the ions can be reaccelerated in the same cyclotron on a different harmonic, $h = \omega_{rf}/\omega_{orbit}$.

The energy gain in the second acceleration is given by the square of the harmonic ratio,

$$E_2/E_1 = (h_1/h_2)^2 \quad .$$

In a scheme for double acceleration proposed by Dzhelepov[1] et al., the two beams emerging from the cyclotron were separated by an electrostatic deflector and the primary (first pass) beam was reinjected by stripping inside the cyclotron. This method of injection is currently used at Orsay[2] and at Dubna.[3] Bennett[4] has proposed a double acceleration scheme in which two strippings take place without extraction of the primary beam.

The studies reported in this paper assume the use of a narrow aperture all-magnetic septum[5] to extract both primary and recycled beams along the same path, with velocity selection performed outside the cyclotron. Some of the calculations presented will relate particularly to the Oak Ridge Isochronous Cyclotron (ORIC) as an example.

Conditions Required for A Recycling System

Several conditions must be met for a successful recycling cyclotron.

(1) The harmonics of the two accelerations and the ion charge states for the first and second accelerations (q_1, q_2) must meet the condition $h_1 q_1 = h_2 q_2$.

(2) For maximum beam intensity the equilibrium charge state after stripping must be within a few charges of the required charge, q_2.[6]

(3) The energy gain per revolution must be sufficiently large so that the phase excursions during the primary and recycle accelerations do not become excessive. This imposes a practical limit on the final energy.

(4) After stripping the beam must enter the first orbit of the second acceleration period at the proper phase.

(5) There must be adequate turn separation at the intermediate radius to provide turn separation at the intermediate radius to provide space for the hardware needed for the injection. In this study we have assumed a stripping foil as the injection device.

(6) Both the initial and recycled beams should arrive at the septum with the same $B\rho$, radius, and preferably radial momentum (p_r).

Practical Configuration

To illustrate the concept of a recycling accelerator a possible configuration is shown in Fig. 1, using ORIC as an example. The source of primary beam can be either an internal ion source or an external source such as a tandem Van de Graaff. If an external source is used the injected beam passes through a stripping foil located inside the cyclotron to achieve the required charge and orbit for acceleration. The primary beam is electrostatically separated from the secondary beam after passing through the magnetic extraction system. A 180° magnet is used to turn the primary beam for reinjection into the cyclotron. A stripping foil, located between turns of the primary beam, achieves the proper charge for reacceleration. The phase of the beam at the start of the second acceleration can be adjusted by changing the path length traveled outside the cyclotron, either by changing the position of the 180° magnet, or by dividing it into three sectors and changing the magnetic fields in the end sections and center section independently. The location of the stripping foil and other parameters can be adjusted so that the first pass and second pass beams both arrive at the entrance with the same $B\rho$, r and p_r.

General Characteristics

The energy to which a given mass can be accelerated with a recycling machine has been calculated for several magnet sizes (Fig. 2). The curves shown represent cyclotrons with E_0's from 50 to 300 where E_0 is a constant that characterizes the cyclotron magnet and is defined by the relationship

$$E/u = E_0 \frac{q^2}{A^2}$$

where E/u is the full energy of the machine, in MeV/u, q is the charge state, and A is the mass number. E_0

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for ORIC is 90. The curves of Fig. 2 are for third harmonic acceleration on the first pass and fundamental acceleration for the second pass ($h_1 = 3h_2$). The charge state for the primary beam was chosen so that the charge after stripping ($q_2 = 3q_1$) would be within one charge state of the equilibrium charge, as computed from the empirical formula of Nikolaev and Dmitriev.[7]

The dee voltage required to limit the phase slip to ± ~50° has also been plotted (Fig. 2).[4] A single 180° dee has been assumed for this computation. Existing cyclotrons use dee voltages from ~50-100 kV. The use of multiple dees reduces the dee voltage required, and cyclotrons are now being constructed with 1000 to 2000 keV/turn using cavity acceleration.

Staying on the equilibrium charge will yield highest intensity beams. If a higher ion source charge is chosen, resulting in a deviation of several charge states from equilibrium after stripping 3:1, the energy of the final beam will be substantially higher - but at a lower intensity. Also shown under the shaded area are the energies obtainable *without* recycle with an E_o = 100 cyclotron, assuming a charge state from the ion source corresponding to a total ionization potential of 1200 volts (approximately the limit of current ion source technology). It is expected that the intensity as well as the energy will be greater with recycle than without because a lower ion source charge state will be used. We estimate that the final beam intensity will be from 1 to 10% of the primary extracted beam intensity if the equilibrium charge after stripping is within ± 1 charge state of the required charge. The major losses are expected in the stripping foil, in the extraction system, and in charge exchange collisions with the residual gas.

The required ion source charge states for 3:1 stripping are shown in Fig. 3. At an E_o of 100 (approximately that of ORIC) the maximum required charge is only 5+ which will give >10 microamperes for reacceleration. The stripped charge in this case would be 15+, which is well beyond present ion source technology, and the final energy would be nine times greater than the energy of the 5+ beam without recycling.

Similar curves are shown for the harmonic ratio 7:3 (Figs. 4,5). For 7:3 the ion source charge states are higher than that needed for 3:1 stripping, resulting in higher final energy. However, the required dee voltage is also higher by about a factor of two at the same final energy. The E_o = 200 and E_o = 250 curves require ion source charges well beyond the present limits of technology. However, an external injector could be used to obtain the required charge state by stripping as the beam is injected into the cyclotron.

Turn spacing is an important parameter of a recycling system. The stripping foil for injecting the second pass beam must go between turns of the first pass beam. The first pass turn spacing is given by

$$\Delta r_1(r) = \sqrt{\frac{m_o c^2}{2 E_{f_1}}} \; \frac{r_f}{r} \; \frac{V_o \cos \phi_1(r)}{Bc}$$

$$= \frac{h_1}{h_2} \sqrt{\frac{m_o c^2}{2 E_{f_2}}} \; \frac{r_f}{r} \; \frac{V_o \cos \phi_1(r)}{Bc}$$

where h_i and E_{fi} are the harmonic number and final energy per nucleon on the ith pass, m_o is the nuclear mass, r_f the final radius, B the magnetic field (radial variation neglected), $V_o \cos \phi$ the energy gain per turn per charge for a particle with phase ϕ, and c the velocity of light.

Taking r to be the second pass injection radius we have

$$\frac{r_f}{r} = \frac{h_1}{h_2}$$

$$\Delta r_1(r_{inj_2}) = \left(\frac{h_1}{h_2}\right)^2 \sqrt{\frac{m_o c^2}{2 E_{f_2}}} \; \frac{V_o \cos \phi_1(r)}{Bc} .$$

This Δr is plotted in Fig. 6 vs E_{f_2} for various values of V_o.

Figure 7 shows results of a detailed computer study of a possible recycling system. The calculation used exact equations of motion and the measured magnetic field data from the MSU cyclotron. A backward tracking procedure was used so that identical extraction coordinates would be imposed as initial conditions. The magnetic field was set between the isochronous contours for the two beams in a way which produced approximately equal and opposite phase slips for the two beams as shown in Fig. 8. The calculation tracks an injection orbit for a 3:1 charge change and a reacceleration orbit for a 5:3 charge change. These are shown in Fig. 7. Optical properties along both these injection paths were checked by running displaced rays. Table I gives orbit coordinates at several interesting points.

Problems Unique to Recycling

The most significant difficulty of such a recycling system appears to be the control problem. The first beam must be injected, and its energy and direction adjusted to give centered orbits. The injection phase and the radio frequency must then be set to fit the design negative phase slip for the first pass (Fig. 8), and the rf voltage set to line up the final turn on the extractor. This beam must then be cycled through the recirculation transport system, reinjected, and aimed at the second stripping foil. If the energy is not an accurate match to the foil position (note the mismatch between "E" and "F_1" in Table I) the extractor radius must be changed and the dee voltage adjusted. It is important that the second pass beam be accurately centered. A partially transparent probe would be required since a normal stopping probe would see only the first pass beam. The second beam must be lined up on the extractor but any dee voltage adjustment shifts both beams and hence is unsuitable for this purpose. A frequency shift has the desired effect of moving one beam in and the other one out. With such a shift the two final turns could be lined up and the extractor moved to match the revised radius. This would, however, disturb the second pass injection orbit since the energy would change and iteration thru the alignment cycle would be necessary.

In addition to the control problem a recycling system also involves greatly enhanced sensitivity to field errors and hence reduced quality as compared with a single pass system. The condition for minimizing sensitivity to field errors[8] corresponds to maintaining the phase as close to 0° as possible. A recycling system, however, necessitates a large phase excursion, as seen in Fig. 8, and so the sensitivity integral will be large. An rf flat-top would likewise be of no help, since the phase slip would slide the beam off the flat-top and lead to increased rather than decreased energy spread. Particles which survived the whole process would in fact clearly be sharply grouped in time - a pulse length of 2 to 4 rf degrees is likely.

Conclusion

Recycle provides a number of opportunities to increase the heavy-ion energy of existing cyclotrons and for integrating them into systems with higher energy. These schemes include, but are not limited to, simple recycling in an existing cyclotron, injection into a cyclotron from an external source such as a Van de Graaff and then recycling, and injection from an existing cyclotron into a new recycling machine.

For example, the energy of a ^{58}Ni beam from ORIC could be raised approximately a factor of two to 6 MeV/u with simple recycling. If a 20 MV tandem Van de Graaff were used as an injector for ORIC, and the beam were then recycled, a ^{208}Pb beam of approximately 6 MeV/u could be obtained.

As a third example of recycle ORIC could be used as an injector for a recycling machine. A $^{238}U^{6+}$ beam from ORIC would strip to 12+ for injection into a recycling separated sector cyclotron. If the E_0 of the second cyclotron were 330 the final energy would be 7.5 MeV/u. If the initial charge state were 7+ the final energy would be 10.2 MeV/u. The beam intensity is estimated to be 10^{11} to 10^{12} particles/sec. Several other possibilities exist but have not been explored in detail.

References

1. V. P. Dzhelepov et al., Proceedings of Sixth International Conference on High Energy Accelerators 1967, p. 295, Cambridge Electron Accelerator.
2. E. Baron et al., AIP Conference Proceedings, No. 9, Cyclotrons-1972, p. 243, American Institute of Physics (1972).
3. I. A. Shelaev et al., AIP Conference Proceedings, No. 9, Cyclotrons-1972, p. 232, American Institute of Physics (1972).
4. J. R. J. Bennett, Particle Accelerator 3, 43 (1972).
5. E. D. Hudson and F. E. McDaniel, Fifth International Cyclotron Conference, p. 180, (Butterworths, London, 1971).
6. C. D. Moak, IEEE Trans. on Nucl. Sci. NS-19, 243 (1972).
7. V. S. Nikolaev and I. S. Dmitriev, Physics Letters 28A, No. 4, 277 (1968).
8. M. M. Gordon and D. A. Johnson, AIP Conference Proceedings, No. 9, Cyclotrons-1972, p. 298, American Institute of Physics (1972).

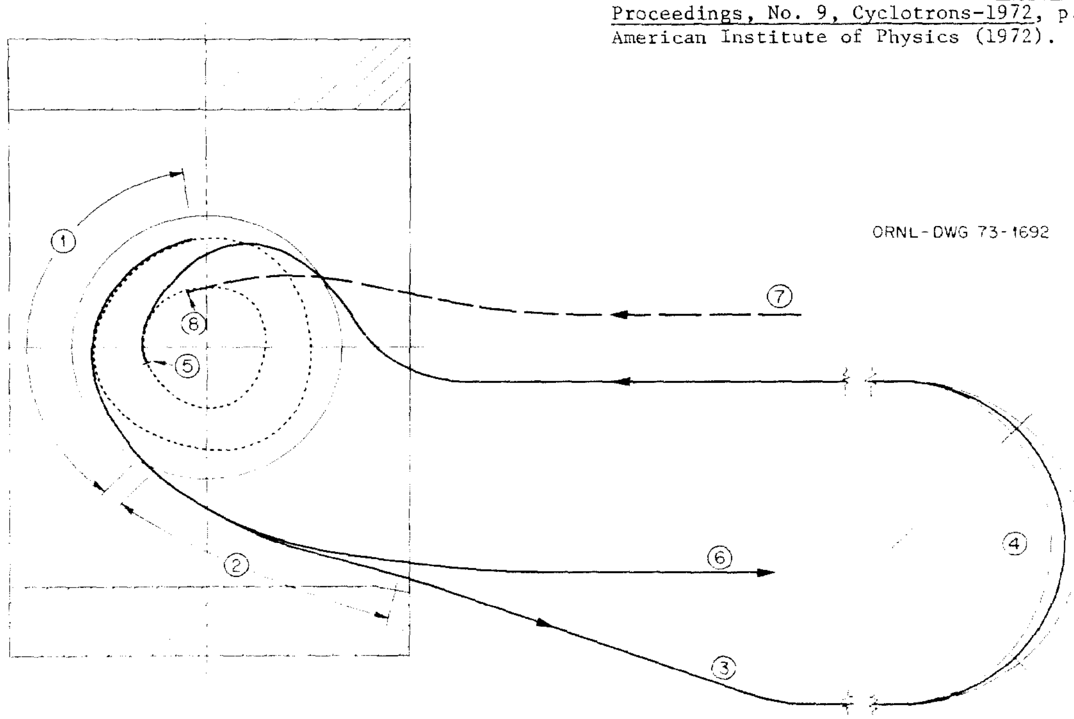

Fig. 1. Schematic of a recycling system for ORIC

(1) All-magnetic extraction system
(2) Electrostatic velocity selector
(3) First pass external beam
(4) 180° magnet
(5) Stripping foil for beginning of second acceleration
(6) Second pass external beam
(7) Beam from optional external injector
(8) Stripping foil for (7)

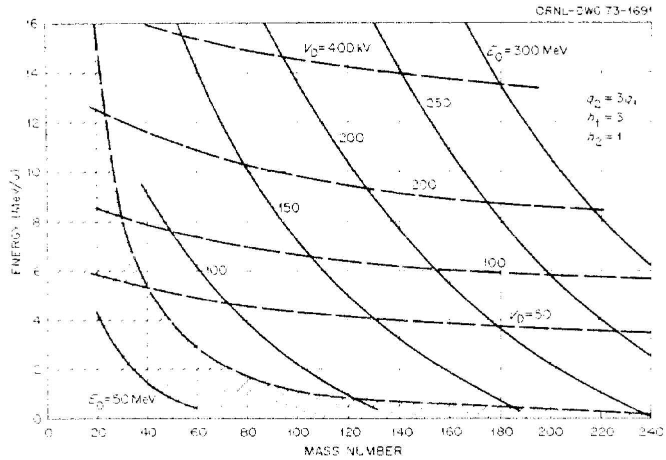

Fig. 2. Energy obtainable for various sizes of cyclotrons with recycling and 3:1 stripping. The shaded area represents the capabilities of an E_0 = 100 cyclotron without recycling.

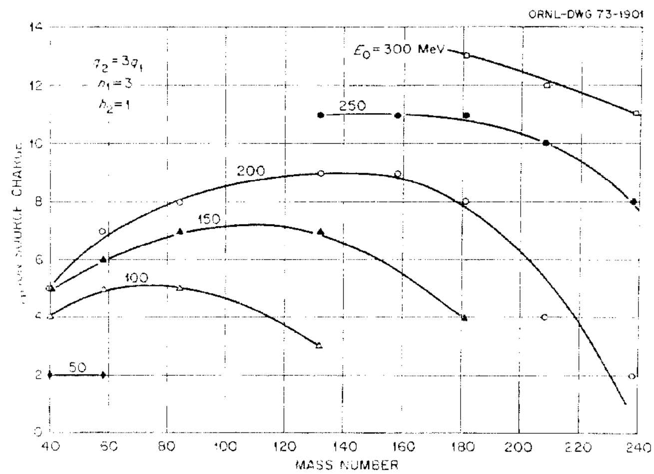

Fig. 3. Ion source charge states required for conditions of Fig. 2. The charge states must be integers. The curves indicate trends, only.

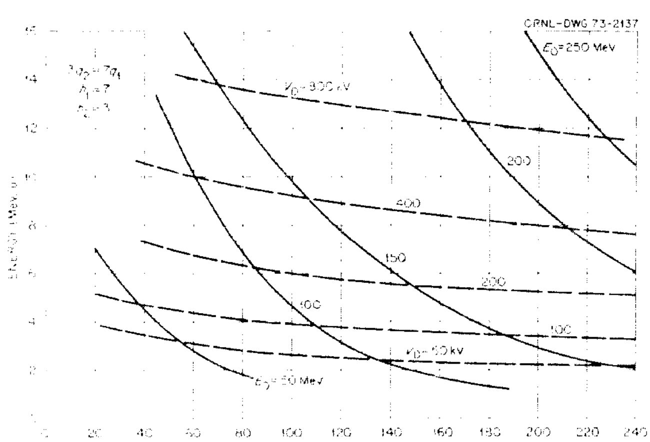

Fig. 4. Energy obtainable for various sizes of cyclotrons with recycling and 7:3 stripping.

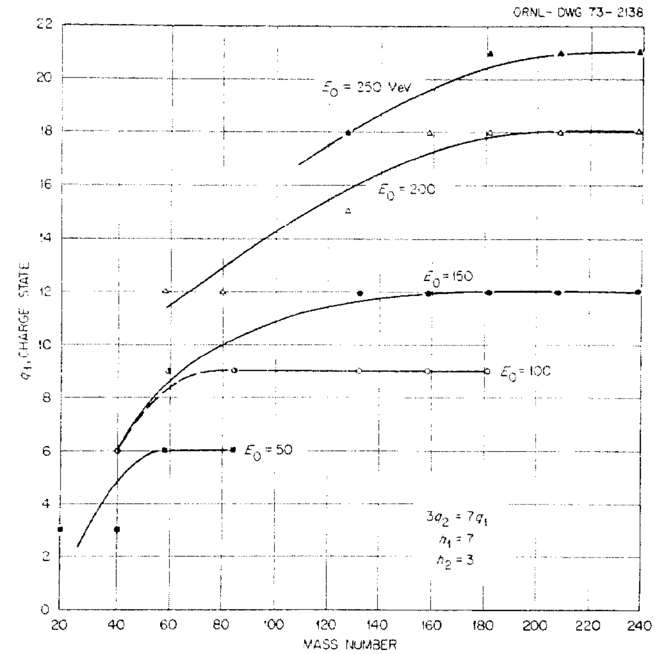

Fig. 5. Ion source charge states required for conditions of Fig. 4. The charge states must be integers. The curves indicate trends, only.

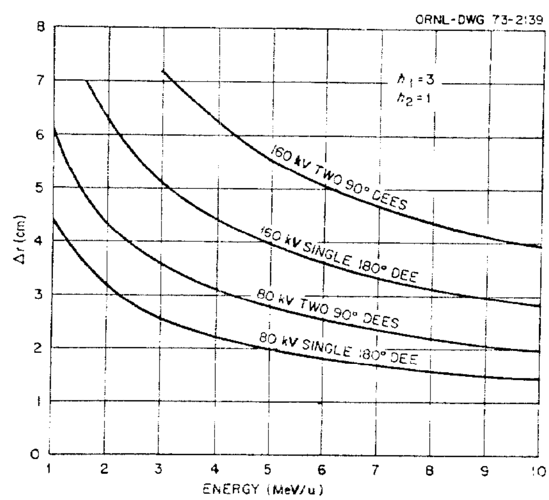

Fig. 6. Turn spacing available for the stripping foil assuming a beam phase of 40° at the foil radius.

Table I

Location	E/A (MeV/nucleon)	Radius (inches)	P_r * (inches)	Phase (rf deg)
"C"	0.601	13.901"	- .503	41.33°
"F_1"	2.500	27.739	-2.210	-32.00°
"E"	2.515	16.356	- .489	-34.10°
"F_2"	6.925	27.739	-2.210	+32.00°

* To transform P_r to standard relativistic units divide by the cyclotron length unit, c/ω_0.

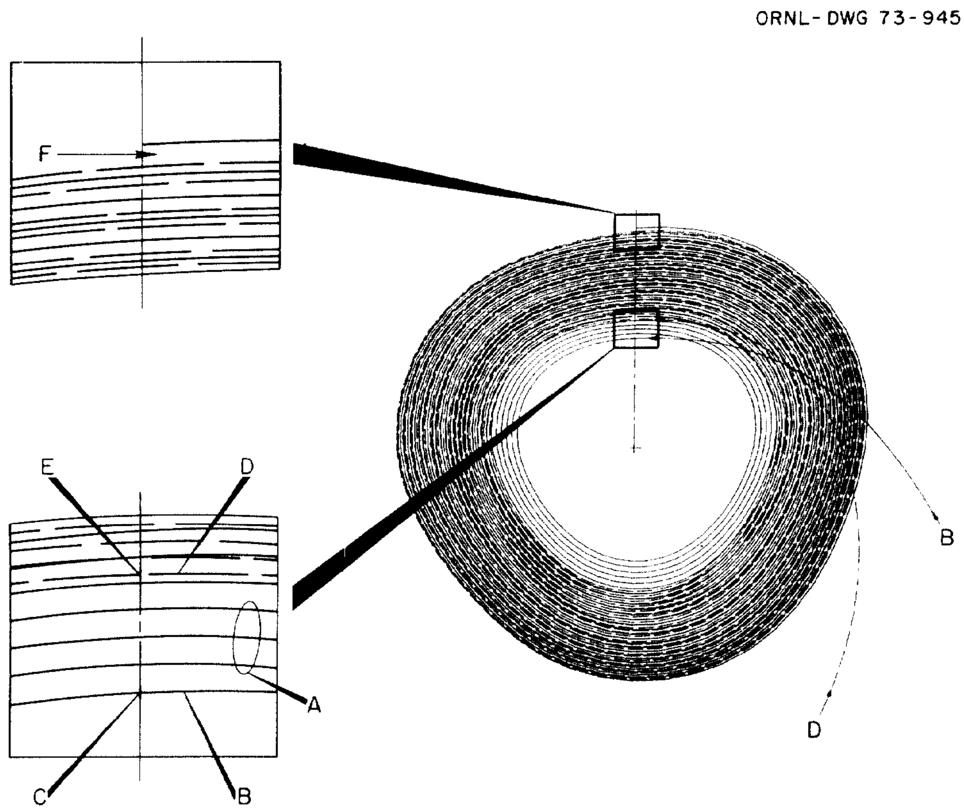

Fig. 7. Orbit patterns from exploratory computer study of recirculation system. Orbits "A" are a part of the first pass through the machine and could originate either from an internal ion source or from external injection along the path "B". The injection orbit "B" is assumed to hit a stripping foil at "C" which increases the Z/A of the ion by a factor of 3 after which the ion is accelerated as indicated by the solid line. After 28 turns the solid line orbit enters a magnetic extraction system at "F". Its position and magnetic rigidity are the same as on the first pass and it therefore goes out along the same extraction trajectory. Values of the energy, phase, and position coordinates of the orbit at labeled points are given in Table I. The assumed acceleration system in this calculation consisted of two 45° dees centered at ± 90° relative to the angular reference line of the figure and operation at 5 (3) times the orbital frequency of the first (second) pass beam. The results are valid for any Z/A if the spatial scale is changed to be consistent with the given magnetic field-energy relation and the dee to ground voltage is set at (20 kv) (A/Z) where Z is the charge state on the first pass.

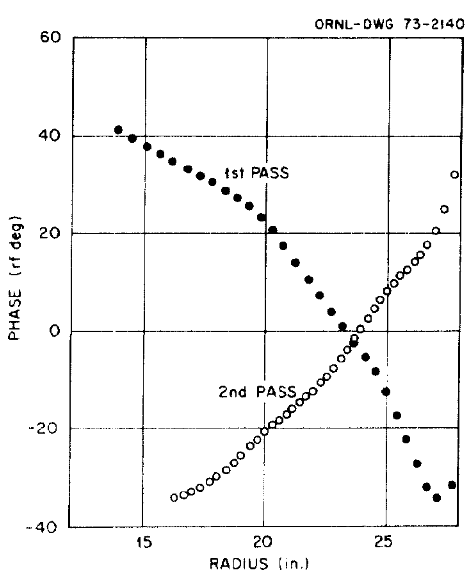

Fig. 8. (left) Phase vs radius for the two trajectories shown in Fig. 7. The opposite, approximately equal phase slips reflect a trim coil adjustment falling between the isochronous settings for the two beams.