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ABSTRACT

As part of the program to investigate the properties of the clover-leaf cyclotron, a 20-inch-diameter proton cyclotron was constructed. In such a three-dee three-phase system it is possible to accelerate protons, deuterons, and tritons at the same setting of frequency and magnetic field but on different modes of the rf. For stable operation in the proper mode and with balanced voltages, it has been found necessary to provide both phase servos and amplifier efficiency servos. The dees could not be servoed individually until the interdee capacity was neutralized. Under such conditions it was possible to attain steadily 6.0 ma of protons at 1.0 Mev in the forward mode and 6.5 ma of deuterons at 0.5 Mev in the reverse mode.

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INTRODUCTION

As part of the program to investigate the properties of the clover-leaf cyclotron¹, a 20-inch-diameter proton cyclotron was constructed for the purpose of studying conditions for starting ions and problems of establishing and maintaining three-phase rf. The preceding paper² discusses briefly the entire cloverleaf cyclotron program and -- in considerable detail -- the problems common to all the three-phase rf systems that were constructed. The description of the rf system here will concern only those features which were unique in the 20-inch cyclotron. Further details of the rf system³ and the experimental program⁴ are available.

A three-dee three-phase cyclotron is a very versatile machine, so far as the multiplicity of ions is concerned, which can be accelerated at the same frequency and magnetic field. This is a consequence of the three modes available to the rf system. These properties have already been pointed out for a three-dee three-phase system⁵ as well as for a two-dee dual-mode system⁶. For example, in a system with two 120° dees, protons are accelerated on the out-of-phase mode, and deuterons on the inphase mode. In a system with three 60° dees, protons are accelerated on the forward mode, deuterons on the reverse mode, and tritons on the neutral mode. Further properties of the three-phase system are listed in Table I.

Table I

Properties of a three-phase system with 60° dees and $\omega = \Omega$ proton			
	Forward Mode	Reverse Mode	Neutral Mode
Ions Accelerated ω/Ω	$3n+1$	$3n+2$	$3n+3$ except $6n$
Energy gained per turn n even	$3 q V_o$	$3\sqrt{3} q V_o$	$6 q V_o$
n odd	$3\sqrt{3} q V_o$	$3 q V_o$	$6 q V_o$
Relative threshold voltage with $n = 0$	1	$2/\sqrt{3}$	$3/2$
ω = rf frequency Ω = ion frequency n = integer q = ion charge V_o = peak dee voltage			

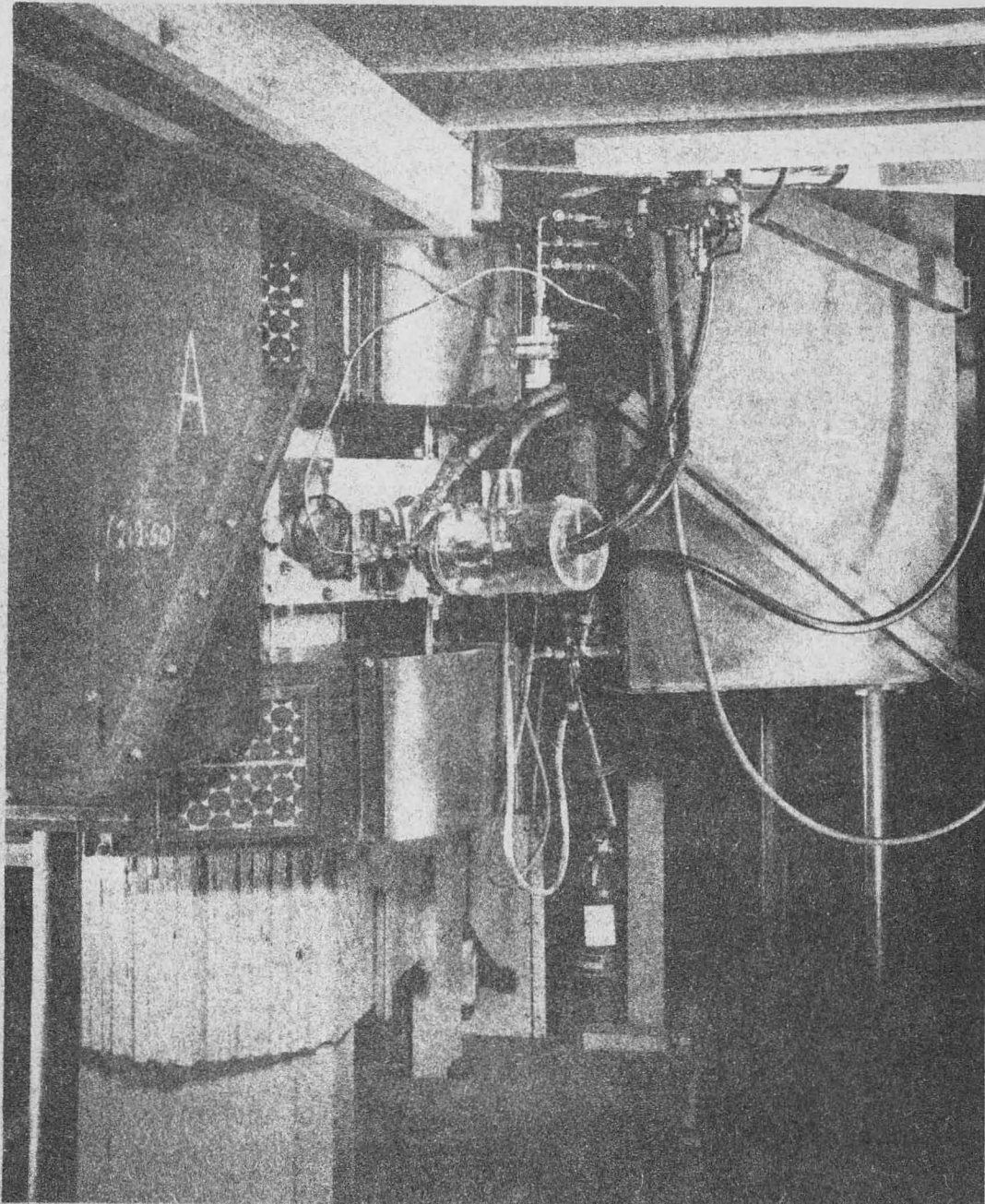
DESCRIPTION OF THE CYCLOTRON

The machine was designed around a magnet with 20-inch diameter pole pieces and a C-type yoke that was already available. A stainless steel vacuum tank was constructed incorporating the pole tips as part of the vacuum wall. Shims were used to provide usable magnetic field to a radius of 8.5 inches. In accord with the threefold symmetry of the system the vacuum tank was made hexagonal. Three of the sides were attached to the dee-stem tanks, one was connected to the manifold of a 14-inch oil diffusion pump, and the other two provided viewing ports and vacuum seals for the ion source and various probes. A view of the exterior, showing two of the dee-stem tanks and the source faceplate, is shown in Fig 1.

Each dee was a 60° sector attached to a foreshortened quarter-wave stem. The vertical clearance inside the dees was 2 inches and the dee-to-liner gap was 1 inch. The tips of the dees were demountable to allow varying the central geometry. The dee stems and the dee-stem tanks were L-shaped. Zircon insulators were mounted on the tops of the dee-stem tanks, and these provided the main mechanical support for the dee stems and, in addition, acted as vacuum seals. Course tuning was provided in the form of movable ground planes attached about 3 feet above where the dee stem emerged through the insulator. Fine tuning was accomplished by a 100- to 200- μ pf air capacitor attached to the dee stem about a foot below the ground plane near the point where power was coupled in from half-wave air-transmission lines leading to the amplifier cages. These elements together with the coupling loops from the neutralizing lines are shown in Fig 2.

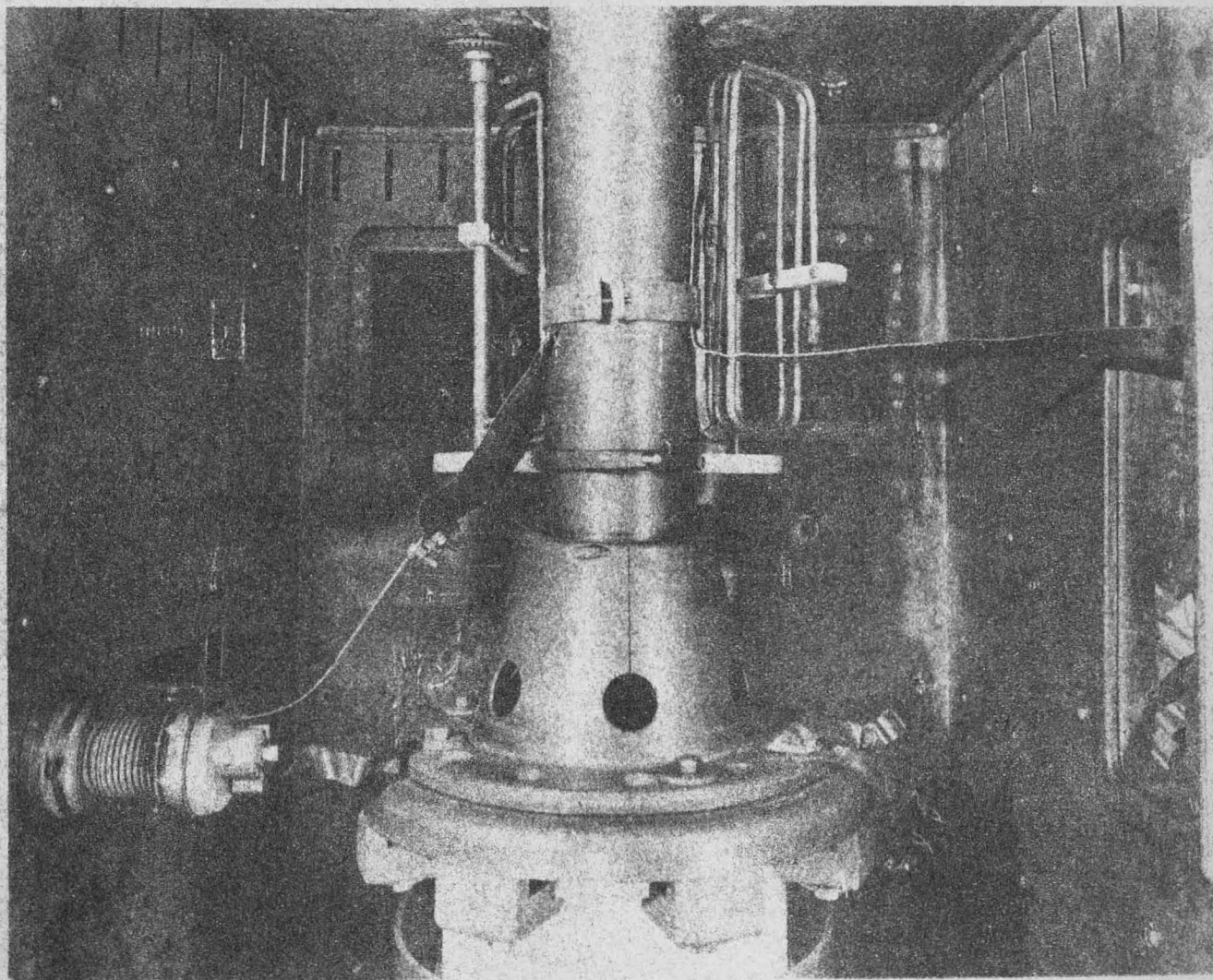
RADIOFREQUENCY DEVELOPMENT

The objective of the rf development was to provide balanced voltages on the dees with the proper 120° phase shift between them. The dees were identified, ABC, in the order in which a positive ion passed through them. A voltage phase sequence in the order ABC was termed the forward mode, in the order ACB the reverse mode, and with no phase shift the neutral mode. The phase shifts were initially obtained by using a driven system with $\lambda/3$ and $2\lambda/3$ delay lines between the master oscillator and two of the power amplifiers. In such a driven system some method is required to keep the power amplifiers at peak efficiency. Furthermore, some scheme



ZN369

Fig. 1



ZN367

Fig. 2

is necessary for preserving the proper phase shift between the dees. Originally there were three servo loops, one that controlled the efficiency of A amplifier, and two that controlled the phases of B and C dees with respect to A. The element corrected in each case was the dee-stem tuning capacitor. It was found, however, that the efficiency of the B and C power amplifiers decreased with time owing to detuning of the grid circuits. An attempt was made to make all three servo loops into efficiency servos across the amplifiers, but peak efficiency did not correspond to 120° phase difference between the dees. The problem was solved by replacing the delay lines by a phase generator, and by adding two more servo loops which controlled the B and C amplifier efficiencies by shifting the phase of the grid signal.

At the outset, a difficulty was encountered in obtaining balanced dee voltages, owing to capacitive coupling between the dees. Because of this coupling, it was possible, under some conditions of tuning, for one amplifier to induce more voltage on an adjacent dee than on the one it was driving. The coupling was further evidenced by hunting by the servos. Various steps were taken to overcome this instability, such as adding skirts to shield the dees from one another, and varying the time constants in the individual servo loops, but none of these proved satisfactory until the interdee capacitance was neutralized. This was accomplished by connecting transmission lines between the dee stems (see Ref. 2). Only with a well-neutralized system was it possible to control the dee voltages individually in both amplitude and phase.

Approximately 30 kw of rf power was available from the final amplifiers using RCA A2505 tetrodes. These tubes were protected by an interlocked air-cooling system, spark gaps at both ends of the half-wave transmission lines leading to the dee stems, and by an rf-dc fault circuit. This circuit compared the rf output with the dc voltage applied to the plate and removed the amplifier excitation if the rf failed to build up initially or dropped out during operation. At times there was considerable sparking and it was repeatedly necessary to restore the excitation, which was removed by the rf-dc fault circuit. Hence, a recycler was added to do this automatically, after a time delay which could be selected by the operator. Recycling would often be repeated continuously, requiring several attempts before

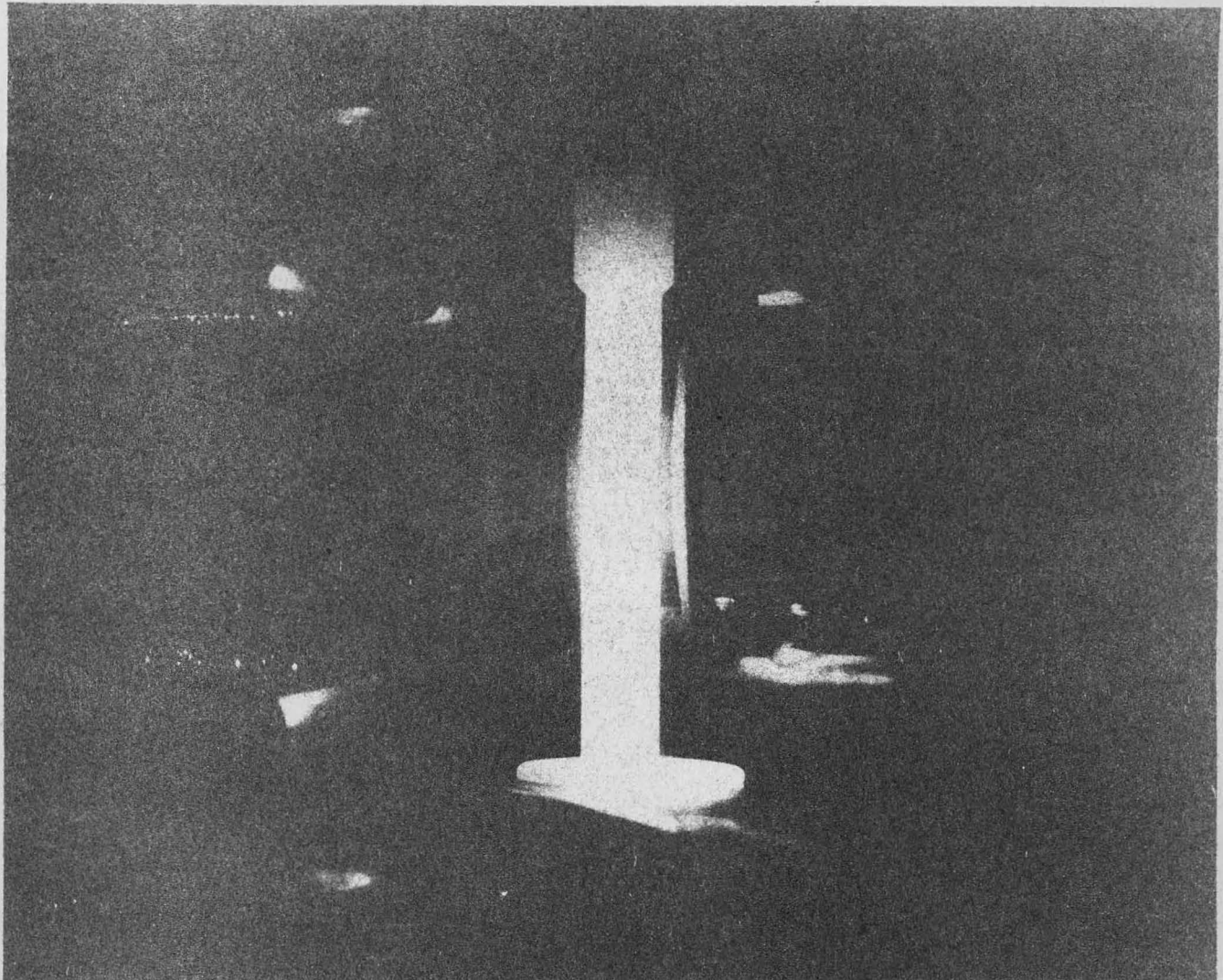
the rf came on, especially if the voltage was high, and it was found that during this time the servos received spurious signals and tended to creep away. Therefore, an additional time delay was added, also adjustable, which would deactivate the servos during the recycling.

If the cyclotron was shut down for several minutes or more after having run intense beams, thermal effects detuned the machine sufficiently so that ion lock prevented the rf from being restored. It was then necessary to retune the machine by exciting each of the dee-stem tanks with a grid dip oscillator and adjusting the tuning capacitances for resonance. A system to do this automatically was under development at the end of the program.

ION SOURCE DEVELOPMENT

Originally, the ion source was situated at the geometrical center of the machine. Conventional low-voltage hot-cathode discharges were employed with various arrangements of arc shields, e. g., a one-slot and a three-slot hood, an unshielded arc, and an open ring-shaped arc with a center post. In the most successful arrangement, which was a simple open arc with dee tips extending to within $3/4$ inch of center, the proton current was 3.2 ma measured at 8 inches (1.0 Mev). Considerable heating of the dee tips occurred under these conditions. A major improvement was effected when an off-center source was installed which injected azimuthally into one of the dees. The source design, of the hooded-arc type with an exit slot $1/8$ by $3/4$ inches, was patterned after sources that have been developed at Oak Ridge for use on the 22-inch and 86-inch cyclotrons.⁷ Various designs of dee feelers were tested and various parameters, such as the radial position of the source and the azimuthal orientation of the exit slot, were varied. Figure 3 shows the most successful source and feeler geometry. The radial position of the source was at about $1-3/4$ inches.

With the geometry of Fig. 3, it was customary to have between 6 and 7 ma of protons at 8 inches (1.0 Mev). The current was measured with an unshielded probe and at this radius was unaffected by 450-v positive bias on the probe. However, inside 6 inches the probe current rose steeply with decreasing radius and was decreased by positive bias voltage. The beam current was also measured calorimetrically. At beam levels of 1 to 2 ma



ZN374

Fig. 3

the calorimetric method gave 90% of the probe method, while in the 6-to 8-ma range this ratio dropped to 75%. The probe method was believed to be the more reliable. In Fig. 4, the beam current versus peak rf voltage is shown. In general, the dependence was linear, as was also the dependence of the beam on the total dc amplifier power. The beam load would cause a two- to threefold increase in the amplifier plate currents compared to the source-off condition.

Because of the fast-neutron background, only brief periods of operation with deuterons were attempted. In the reverse mode, it was possible to rapidly attain a deuteron current of 6.5 ma at 8.5 inches (0.5 Mev). In the forward mode, a current of 30 μ a was measured under the same conditions. This was presumably D_2^+ . Similarly, with helium gas an alpha-particle current of 1.5 ma was measured in the reverse mode.

It was possible by a system of slits to program the beam for two complete turns. Once determined, these slits ran cool only for a narrow range of rf voltages. The orbits are shown in Fig. 5. The orbit center was found to be displaced from the geometrical center by 3/4 inch. The variation in the dee voltages shown in the figure is indicative of a system not well neutralized.

ACKNOWLEDGMENT

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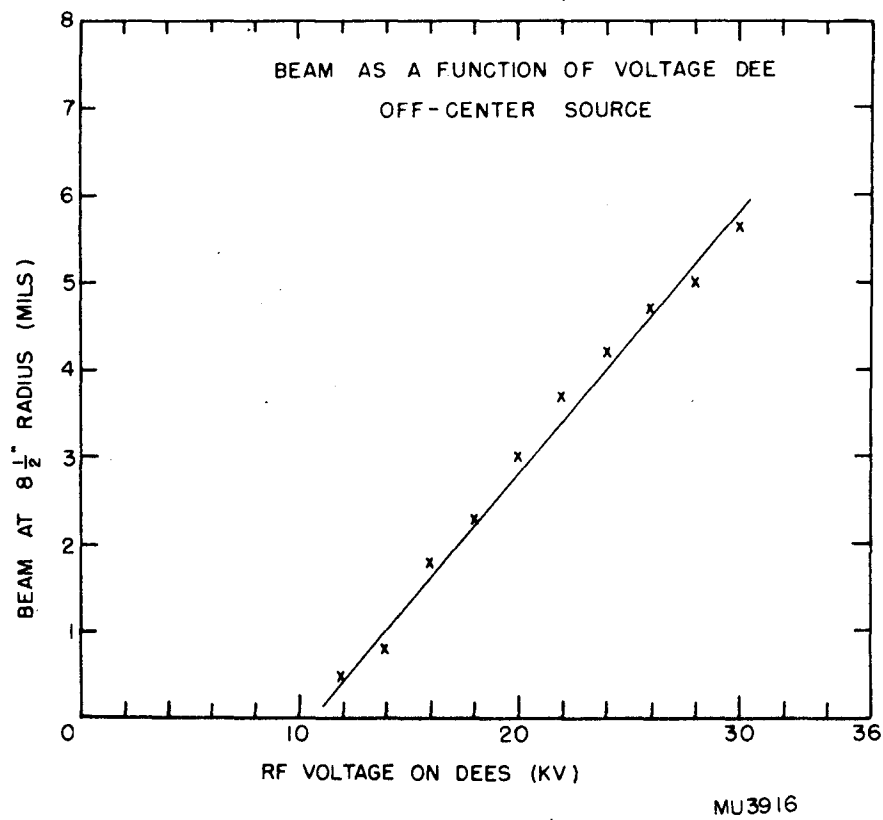


Fig. 4

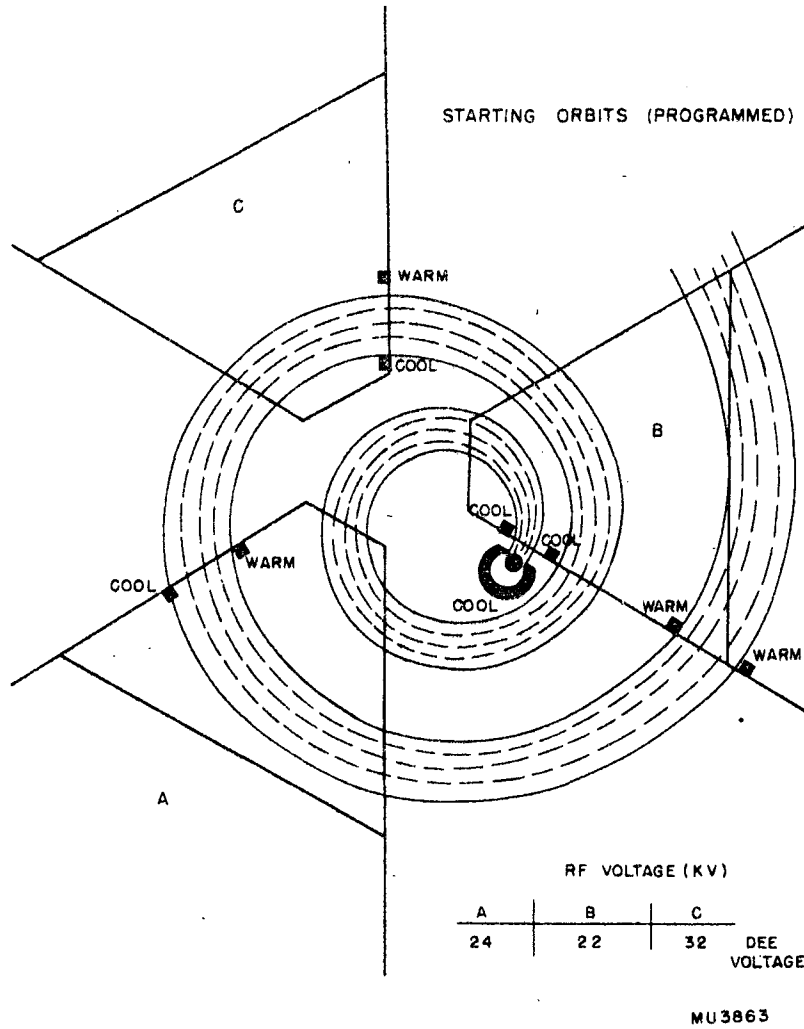


Fig. 5

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LEGENDS FOR FIGURES

- Fig. 1. Cyclotron exterior
- Fig. 2. Upper dee-stem assembly
- Fig. 3. Source operating
- Fig. 4. Proton current versus peak rf voltage
- Fig. 5. Starting orbits