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D. J. Clark, Hogil Kim, K. R. MacKenzie, and J. T. Vale

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Modification Studies for the Berkeley 184-in. Cyclotron

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Summary

Studies are in progress on possible improvements to the center region and extraction system of the 184-in. cyclotron. The center region is being studied with a 28-in. model proton cyclotron. It has been operated without frequency modulation at 16 kG and 23 kG at 1% duty cycle. Frequency modulation has now been added to study space charge and capture problems. Computer studies are also being done with an orbit code including electric field (Ref. 1), to study median plane motion. The extraction system is being examined to reduce losses in the regenerator region.

Center Region Studies with a Model Cyclotron

A 28-in. model cyclotron has been used to study injection problems. It operates at 1% duty cycle with dee voltages up to 20 kv. The first operation was without frequency modulation, to study the first 30 revolutions in the cyclotron. To increase the vertical focusing, grid wires were inserted in the downstream side of each accelerating gap, as used at Birmingham (Ref. 2).

The first geometry used is shown in Fig. 1. Frames were inserted in the dee and dummy dee to reduce the gap width and support the .003 in.

grid wires. The beam space is about 1.5 in. The diameter of the ion source is 3/16 in. Fig. 2 shows the proton beam current with this configuration with 16 kG magnetic field and 20 kv on the dee. The curves show that to obtain maximum beam at 3 in. one needs a large enough ion source slit, grids with frames, and an optimum arc current in the source. If too much beam is started at the source, large vertical losses occur. The calculated space charge limit for this case is 3 mA at 3 in. radius.

In order to simulate 184-in. conditions more closely, the magnetic field was increased to 23 kG. As shown in Fig. 3, the grids were now supported without frames, the pole gap was reduced, and beam space reduced to 1-1/4 in. The curves of Fig. 4 show that at a dee voltage of 17.5 kv, grids help the vertical focusing considerably. Source clearance is adequate, but attenuation is larger than in the 16 kG case because the larger number of turns causes faster approach to the space charge limit of about 1 mA.

Preliminary tests have been made with frequency modulation on the model. These were done at a 16 kG field to ease the radiofrequency problems. The geometry is the same as Fig. 3. We have thus far obtained average currents of 2 μA at 3-in. radius and .1 μA at 6 in. radius (extrapolated to the 184-in. repetition rate) after space charge and acceptance losses have occurred. We hope to increase the beam current by removing some of the outer grids, which intercept beam on the first inward phase oscillation swing. We plan to use a combination of center cones and sector focusing to get more vertical focusing in the region of 2 to 6 in. radius. The radial stability in this region where $\nu_r \simeq 1$ needs careful study, to assure that beam can be accelerated without radial losses.

Computer Studies

The motion of accelerated particles in the median plane is being studied with the Pinwheel orbit code of Michigan State University (Ref. 1). This code integrates the equations of motion with any input magnetic and electric fields, to give the particle position and instantaneous center of rotation in rectangular coordinates. It is being used to study acceptance time with various magnetic and electric field shapes, and several frequency modulation rates. It will be used also to look at radial stability in a sector magnetic field.

Cyclotron center regions can be divided into two categories--"wide gap" and "narrow gap" geometries. The wide gap case is the one found in most synchrocyclotrons, where the gap from dee to dummy dee is several inches. Hundreds of particle revolutions will occur in this central region of nearly uniform electric field. The acceptance time calculated for the 184-in. magnetic field, assuming a perfectly uniform electric field at the center, is shown in Fig. 5. For the present dee voltage and initial rate of frequency modulation the calculated acceptance time is about 100 μsec, in reasonable agreement with machine operation. This contrasts with the prediction of Bohm and Foldy (Ref. 3) of several μsec for the narrow gap case. The rate of frequency modulation is about a factor of ten less than their prediction. The injection is thus near the maximum frequency swing of the FM cycle, rather than part of the way down at a higher df/dt. These discrepancies are explained by the nearly uniform electric field which exists for hundreds of revolutions, rather than the full dee voltage energy gain assumed by Bohm and Foldy. This electric field produces a slow rate of energy gain requiring a slow initial df/dt. There is also very strong phase focusing, which tends to keep the particles in phase with the dee voltage, improving the capture efficiency.

Another computer result for the wide gap geometry of the present 184-in. cyclotron is shown in Fig. 6. This shows the spread in orbit centers induced by the present dee bias, which is 25% of the dee voltage. The effect of dee bias is to give more acceleration at one dee gap than the other, pushing the orbit off center. The scalloping effect of Fig. 6a is due to the phase oscillations, which periodically bring the orbit back near the machine center. Fig. 6abc shows the history of particle center motion for three starting times. The radial amplitude induced is about one inch, a good fraction of the observed amplitudes of 2-3 inches.

The narrow gap case was studied next. There the particle is given an impulse acceleration at each gap. This is the geometry suggested by MacKenzie (Ref. 4) and now being tested in the 28-in. model shown in Fig. 3. The acceptance time is shown in Fig. 7 for two magnetic field shapes. It is the order of 5-10 μsec--much shorter than the wide gap case.

The optimum df/dt is now about 10 MHz/msec compared to 1 MHz/msec for the wide gap case. These values are typical of the Bohm and Foldy predictions, although there is some quantitative disagreement with their curves (Ref. 3, pg. 653). The reason for the short acceptance time and high optimum df/dt is the much higher energy gain per turn for the narrow gap case. The center region is filled with beam in a few μsec, requiring a rapid df/dt to capture this beam. This fast df/dt and lack of phase bunching prevent beam from being captured if it is a few μsec too early or late. The big advantage of this type of center region is improved b beam quality, which would allow a considerable increase in extraction efficiency, as at ORSAY (Ref. 5).

The problem is to get at least as much average beam current as with the present wide gap 184-in. geometry. The requirements for this are, first, that enough current must be injected by the ion source and early accelerating gaps, during the short acceptance time, to give sufficient charge captured for acceleration. Second, the space charge limit on the total charge in one cycle (Ref. 6) must be high enough to contain the necessary charge. The first condition requires efficient ion source design, high injection dee voltage, and good vertical focusing, but not too large a center cone. The second condition requires good vertical focusing and large beam space in the dee.

Extraction Improvement Studies

The present extraction system for the 184-in. cyclotron is a non-linear regeneration system. The regenerator is located at 82.5 in. radius, which is just before the $\nu_r = 2\nu_z$ resonance. The main magnetic field is about 22.4 kG. The magnetic perturbation at the full amplitude of the regenerator is about 6 kG. The amount of deflection is about 100 kG-degrees. The final orbit separation is about 8-1/2 inches (7). There is essentially no septum magnet, but there is a magnetic channel to focus and transport the beam. The entrance of the channel is located after the regenerator. The current at 78 in. radius is about 2 μA and at the entrance of the regenerator 0.5 μA survives. At the entrance of the magnetic channel we have 0.2 μA, and at the cave about 0.1 μA. Therefore the extraction efficiency may be 5%. Through a 1/2" × 1/2" collimator at the cave the beam current is about 0.02 μA.

This poor extraction efficiency is mainly due to poor quality of the internal beam. The beam loss at the beginning of the regenerator is vertical loss, because there are no obstacles in the median plane. The measured amplitude of the radial oscillation of the internal beam is about 3 in. This low energy beam which has a big radial amplitude, can enter the regenerator without regeneration. During this time the vertical amplitude increases rapidly causing loss of beam. The efficiency may be increased by improvement of the internal beam right at the center of the machine. In the machine there is a considerable first harmonic error in the magnetic field (about 10 gauss), but it does not disturb the internal beam quality, because the changes are adiabatic.

For a given internal beam quality we can reduce the vertical losses if we can keep the low energy particles away from the regenerator. Now a study is being made using a time varying first harmonic coil of which the peak amplitude is about 40 gauss. This will move the center of precession by about 3 in. and therefore the beam cannot enter the regenerator until the equilibrium orbit is the same as the regenerator radius. When the beam reaches the final energy, we turn off the main oscillator and slowly decrease the first harmonic for slow extraction or decrease fast for fast extraction. Then the particles will be regenerated as soon as they enter the regenerator. For adiabatic changes the radial gradient of the first harmonic should be around 10 gauss/in. For a slow extraction the frequency of the time varying first harmonic can be about the same as the frequency of rf modulation. This will reduce the beam losses at the beginning of the regenerator, and also improve the external beam quality.

Acknowledgements

The authors wish to acknowledge informative discussions with Dr. Ken Crowe, and the encouragement and advice of Drs. Robert Thornton and David Judd. Mechanical engineering was under the direction of Lee Glasgow and electrical engineering was directed by Bob Sorensen. Pete Watson's group made magnetic field measurements on the model. The 184-inch crew helped with operation and experiments. Computer runs and program modifications were carried out by Victor Brady.

184-in. Figures

Fig. 1. Center geometry in the 28-in. model cyclotron used at 16 kG field. Frames in dee and dummy dee give a narrow gap and support grid wires for vertical focusing.

Fig. 2. Beam current vs. radius for several center geometries in the 28-in. model cyclotron. The dee voltage is pulsed at constant frequency with a 1% duty cycle.

Fig. 3. Center geometry in the 28-in. model cyclotron. Grid wires are now supported on fingers extending from the dee and dummy dee. This configuration was used at 23 kG, and with preliminary FM operation at 16 kG.

Fig. 4. Beam current vs. radius comparing operation with and without grids and frames. Dee voltage pulsed at constant frequency with a 1% duty cycle.

Fig. 5. Acceptance time calculation for "wide gap" geometry of 184-in. cyclotron vs. rate of frequency modulation. Spatially uniform electric field of 1 kv/in. Magnetic field of 184 in. cyclotron.

Fig. 6. Calculated motion of orbit centers for a particle acceler ated in an rf electric field (1 kv/in) uniform in space ("wide gap"), with a dee bias (.25 kv/in). Magnetic field of 184-in. cyclotron.

Fig. 7. Acceptance time calculation for "narrow gap" geometry vs. rate of frequency modulation. Dee voltage = 20 kv. Magnetic field = 23 kG.

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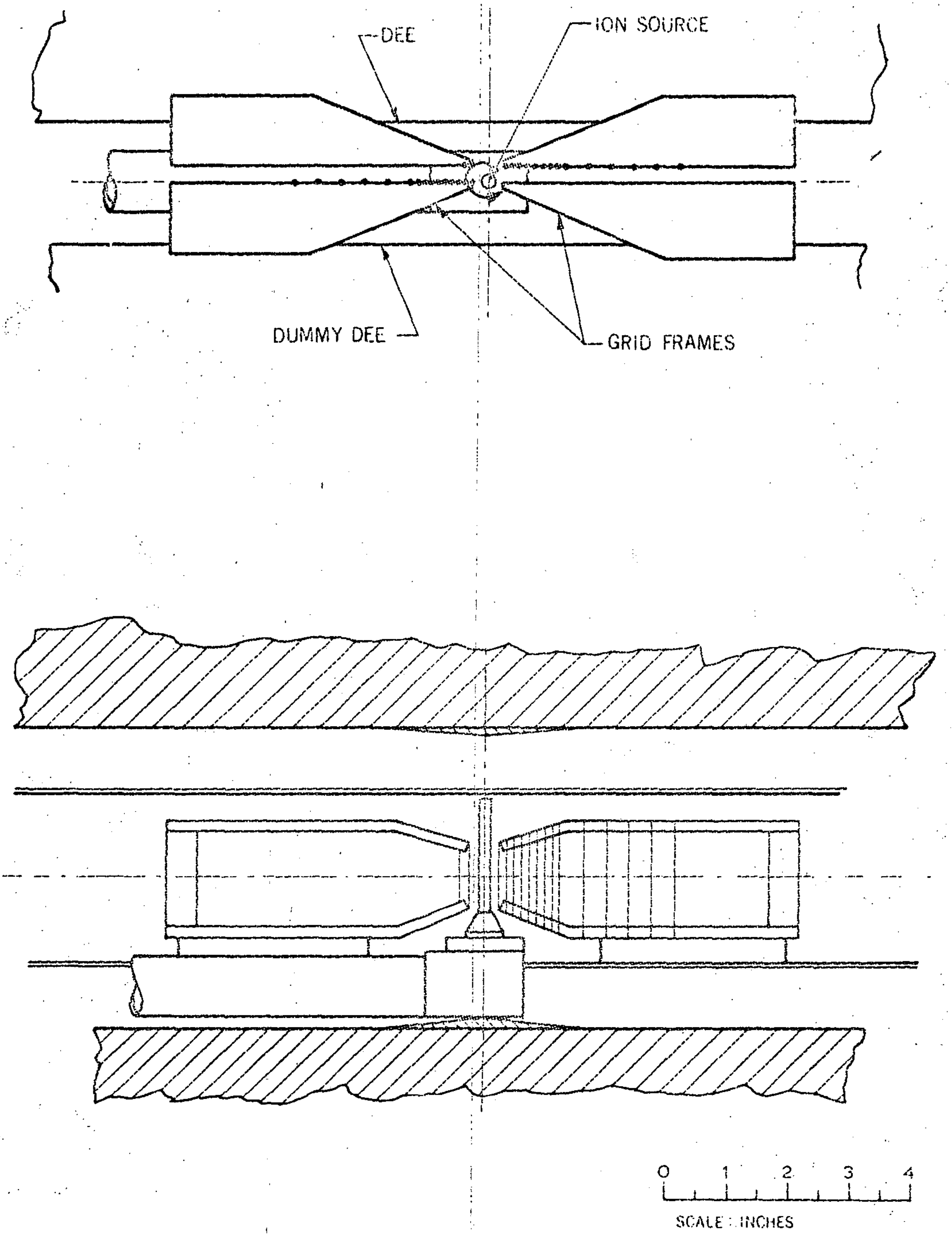

Fig. 1

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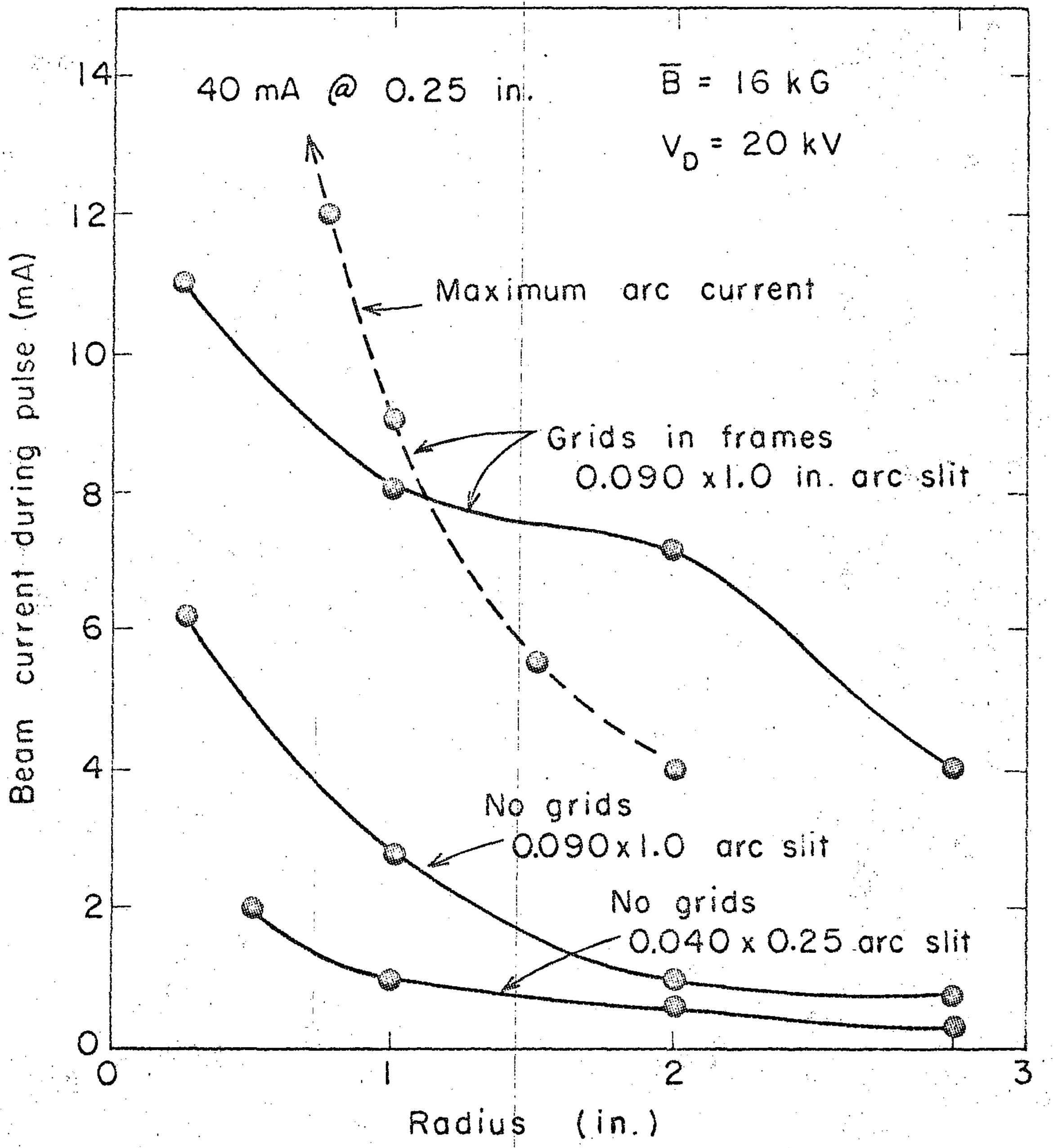

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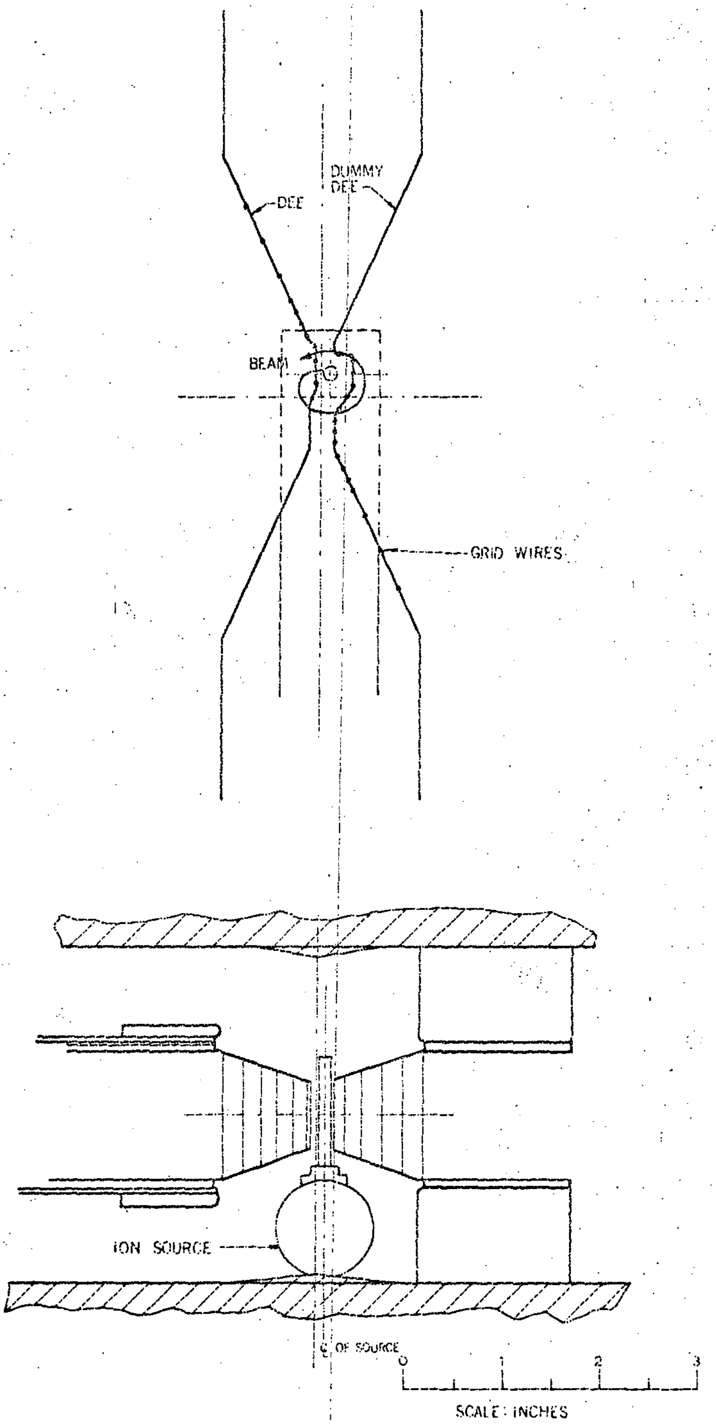
Fig. 2


DUMMY DEE
DEE
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GRID WIRES
ION SOURCE
℄ OF SOURCE
0
1
2
3
SCALE: INCHES

Fig. 3

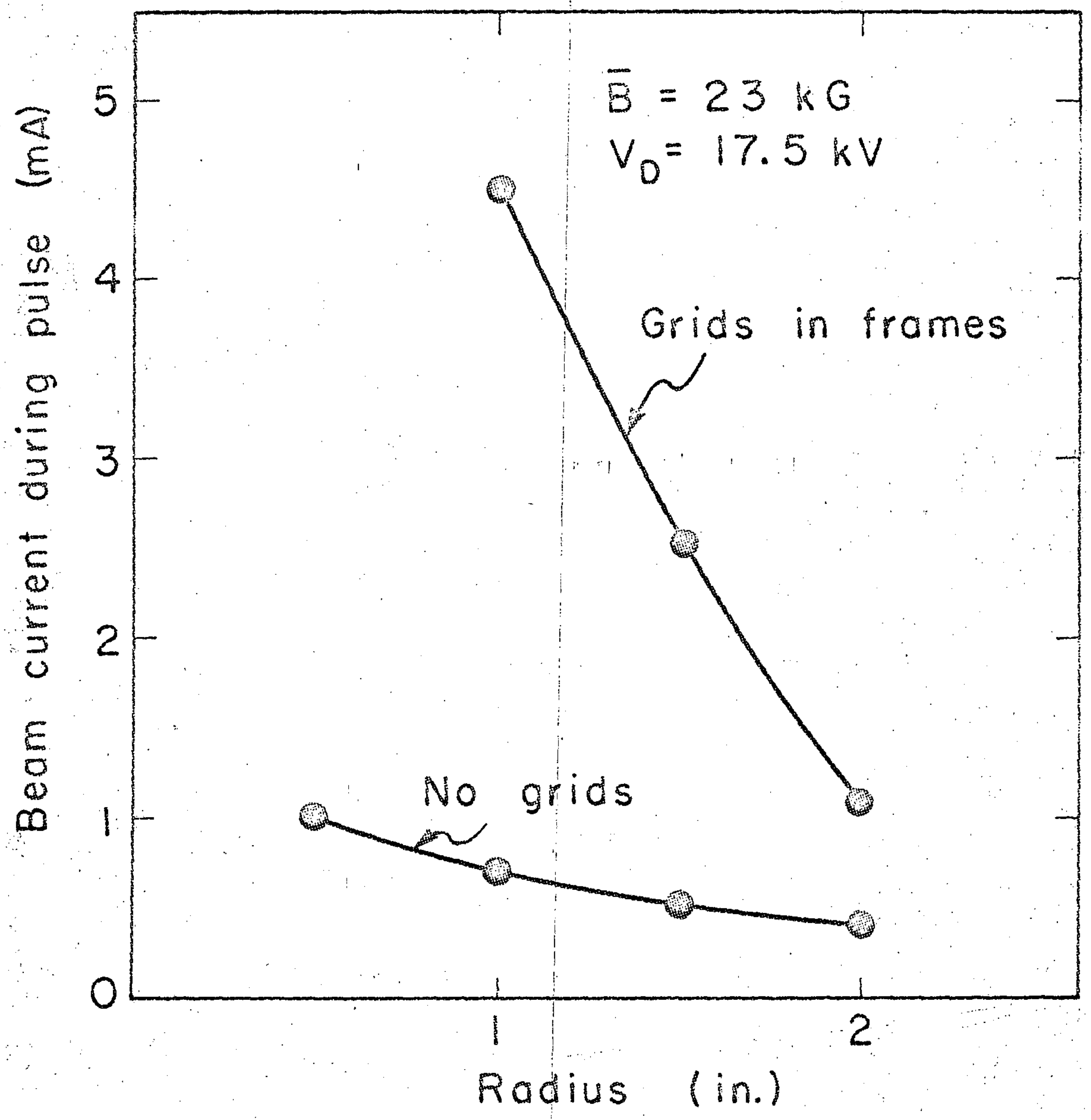

Fig. 4

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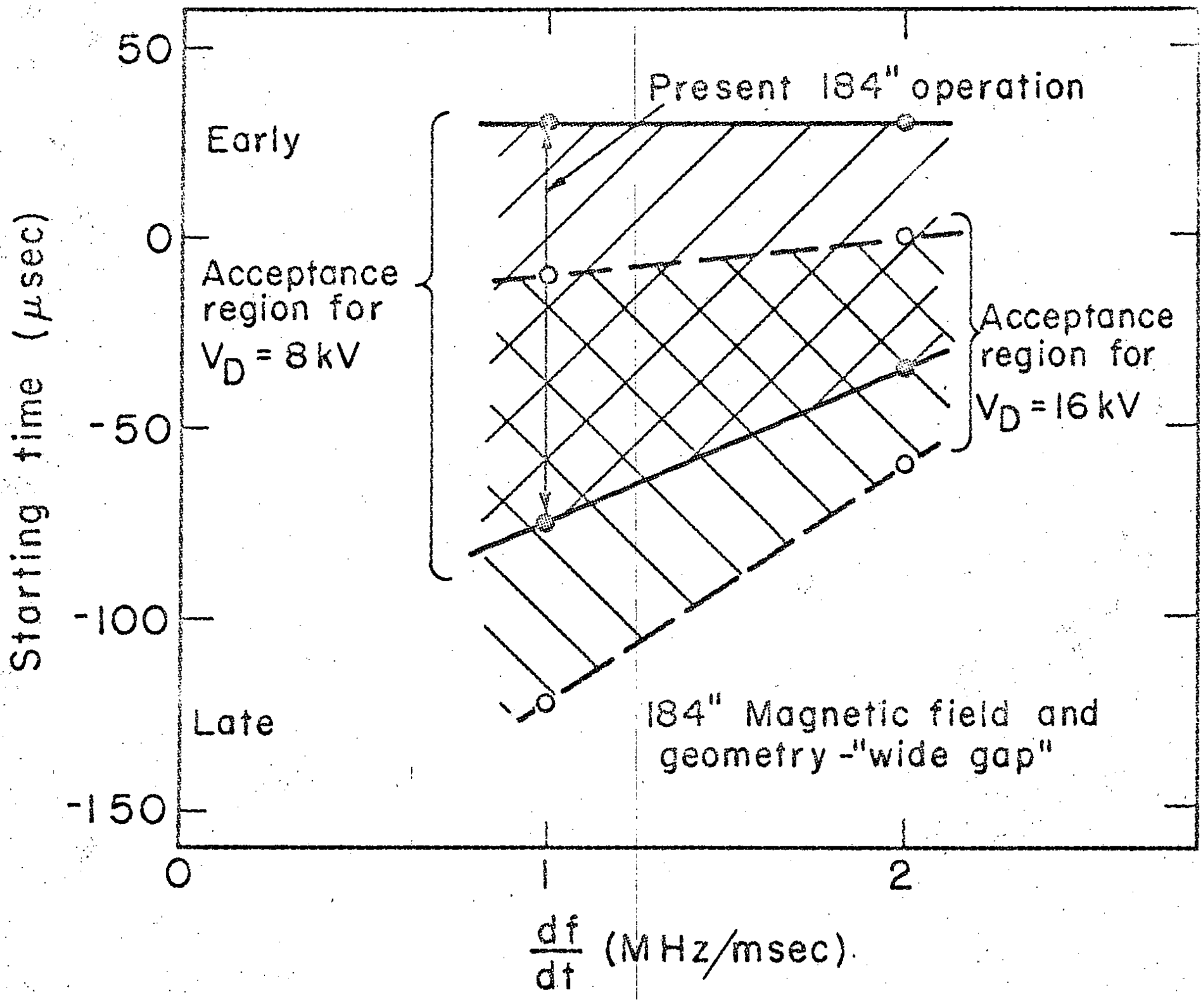

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Fig. 5

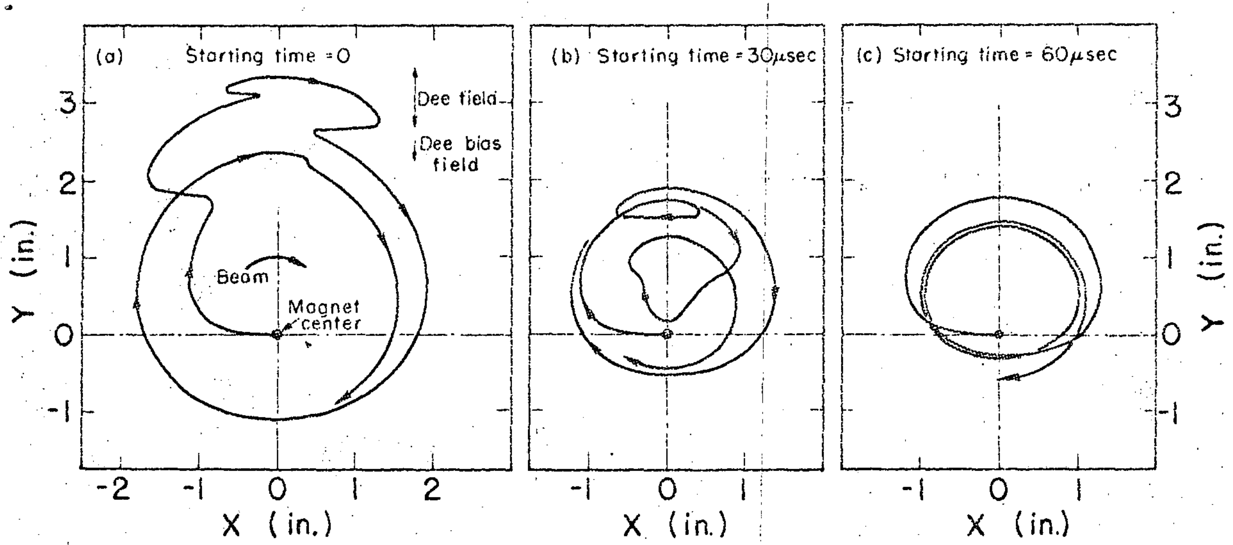
(a) Starting time = 0
Dee field
Dee bias field
Beam
Magnet center
(b) Starting time = 30μsec
(c) Starting time = 60μsec
Y (in.)
X (in.)
-2
-1
0
1
2
3
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Fig. 6

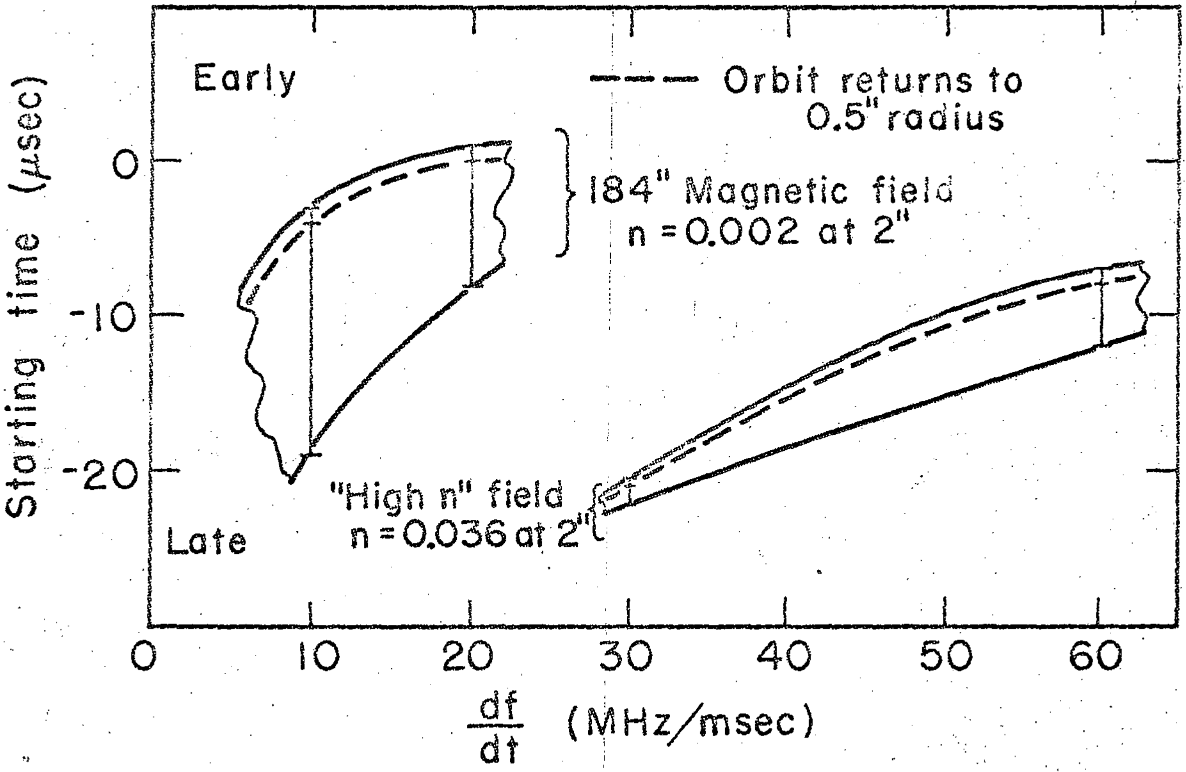

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Fig. 7