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OPERATION OF THE BERKELEY 88-INCH CYCLOTRON

Berkeley, California

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Berkeley, California

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## ABSTRACT

The operation of the Berkeley 88-inch spiral ridge cyclotron in the past year is reviewed. Internal beam qualities and intensities, and the stability, reproducibility, and lifetime of various machine components are discussed. Examples of the use of phase diagrams obtained from I vs R curves to tune the magnetic field shape are presented.

# OPERATION OF THE BERKELEY 88-INCH CYCLOTRON*

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## INTRODUCTION

The Berkeley 88-inch cyclotron is a 3-sector AVF variable-energy cyclotron designed to accelerate protons up to 60 MeV, deuterons up to 65 MeV, and heavier ions up to comparable energies per nucleon. The shaping of the magnetic field that is required to ensure isochronous acceleration is accomplished by means of 17 trim coils. For first-harmonic shaping of the field, five sets of valley coils are used. A plan view of the pole face is shown in Fig. 1, which shows some of the important machine components. Construction details and an account of the early beam-development work were given in several papers presented at the 1962 International Conference on Sector-Focused Cyclotrons.[1]

Internal beams of protons, deuterons, and α particles have been developed, of energies up to and including maximum design energies. A summary of these is presented in Table I; α particles and deuterons are shown together in the table as no difference in the magnetic field settings is required in changing from one of these to the other. The largest internal beam currents run to date have been on the order of 500 μA, for short periods of time. The more usual internal beam current is on the order of 50 μA, of which we are able to extract 20 μA for the external beam. The area of radial phase space occupied by 90% of the deflected 65-MeV α beam is 50 millimeter milliradians (mm mrad), vertically 90 mm mrad. The amount of extracted beam obtainable is being gradually pushed upward as we learn how to make septa that will withstand large beam currents and at the same time permit efficient extraction.

## BEAM DEVELOPMENT

A history of the effort required to obtain a beam of 130-MeV α particles will illustrate the methods employed. The field shaping, which must be done by the trim coils, is most exacting for this case. The first step was the calculation of the optimum main field and trim-coil currents with a linear programming method[2] that minimizes the phase excursions of the particles, consistent with the suitable field gradients required for radial and axial stability, and with constraints imposed by trim-coil limitations. With the currents set according to this calculation, the beam was obtained out to 36.5 in. [Fig. 2(a)]. We later found a small error in the field data fed to the computer. Without this error the beam would have probably come out somewhat farther. The $H_2^+$ beam shown was found 89 kc/sec below the α resonance. This beam was from a source which had been running with helium for over 24 hours. To prevent confusion when working with a new beam, we found that it is a good idea to identify both resonances.

The phase behavior of the α beam was then deduced from records of beam current vs radius for several frequencies above and below the optimum frequency [Figs. 2(b) and 2(c)], by using a method devised by Garren and Smith.[3] Having concluded from probe measurements that the loss of beam between 35 and 37 in. is due to phase loss, it is clear that the beam particles lag the rf by $\pi/2$ in this region, as a small increase in frequency (causing additional phase lag) results in a large loss of beam at 35 in., while a relatively large decrease in frequency causes only a small loss. These changes locate points 1 and 2 on the phase diagram [Fig. 3(a)] as the limit of the beam in phase at the optimum frequency of 12.513 Mc/sec. Now when the frequency is shifted an amount $\Delta f$, each particle is shifted an additional amount in phase, given approximately by

$$\Delta \sin \phi \approx \frac{2\pi^3 m f R^2}{qV} \Delta f, \qquad (1)$$

where m is the mass and q the charge of the particle, V the dee voltage, and R is the radius. For $\Delta f = +1$ kc/sec, the particles of the beam which are lagging by $\pi/2$ are at points 3 and 4. The position on the phase diagram [Fig. 3(a)] is then found by computing $\sin\phi = (1.0 - \Delta \sin\phi)$ for each point. The edges obtained by the other positive frequency shifts are plotted in the same manner. With $\Delta f = -10$ kc/sec and less, the particles are leading the rf by $\pi/2$ when the beam disappears, and the position on the phase plot is found as $\sin\phi = -(1.0 - \Delta \sin\phi)$. In completing the diagram, use is made of the fact that the phase width remains constant with radius as long as the phase is within the $\pm\pi/2$ limits. A check on the accuracy of the data is afforded by the agreement between points obtained from the $+\pi/2$ loss with points obtained from $-\pi/2$ loss. With the phase plot thus obtained as a guide, adjustments were made to the trim-coil currents, which brought the beam to the maximum radius, 40 in. on the target probe [Fig. 3(b)].

The large decrease in beam intensity occurring inside 27 in. is not due to phase loss, however, but apparently to particles following the spiral ridges; hence we called the beam a spurious beam or "spurium." This beam does not disappear when another probe is run into the center of the machine, which of course would stop all of the orthodox beam [Fig. 3(b)]. The disappearance of this spurious beam beyond 27 in. occurs because the spiral ridge curves away from the probe track in this region. This beam was eliminated by moving the ion source and puller, while observing orthodox beam on the dee probe and spurious beam on the target probe, until a position was reached in which the spurious beam largely disappeared and the orthodox beam intensity was unimpaired [Fig. 3(c)]. A 3-finger probe record is shown in Fig. 4. The effect of lowering the dee voltage shown in Fig. 5, is to extract less beam from the center region. The flat I vs R curves show that the beam is not lost in phase as the voltage is lowered. This is a good test of isochronism.

Records made with the three probes in turn showed that the beam was off center about 1 in. toward the target probe. The direction of this off-center displacement could be readily changed to any azimuth by using the valley coils. Centering was tried by repositioning the ion source, but this was not successful. With the valley coils, however, it was possible to obtain a beam that was well centered. The method employed was to position the dee, target, and deflector probes at 20 in., then adjust the currents in valley coils 1 and 2 until all three probes read the same beam current. As the probes are symmetrically located relative to the particle orbits, this should be a good test of centering. The process was repeated by using valley coil 3 with the probe positions at 25 in., valley coil 4 with probe positions at 30 in., and valley coil 5 with probe positions at 37.5 in. The distribution of intensity on the three probes was not very sensitive to frequency when the beam was centered in this fashion.

Sparking difficulties with the electrostatic deflector have so far prevented extraction of the 130-MeV $\alpha$ beam. Extensive work has been done with the 65-MeV $\alpha$ beam to investigate properties necessary for good extraction efficiency. Typical probe records are shown in Figs. 6 and 7, and phase diagrams in Fig. 8. The 19-kV dee voltage represents an effort to achieve the maximum number of particle orbits and still get some beam out. In this machine, probably the lowest dee voltage is determined by the center-region geometry rather than by the threshold voltage for particle extraction from the ion source.

The use of valley coils doubles the extraction efficiency of the 65-MeV $\alpha$ beam. We do not understand at present why this is so. Attempts to obtain similar results without valley coils have been unsuccessful. The records of Fig. 9 show that the effect of these coils on the beam is to reduce greatly the amount of beam loss at extraction radius. The beam centering is essentially unaffected, although in this case the valley-coil tuning was done by looking at

the external beam without regard for centering. The improvement in beam is evidently in less phase loss, because a special probe which records blowup shows no significant change in intensity between the two cases. It is probable that evaluation of beam-centering studies, such as shadow measurements, would throw some light on this result, but we can report little progress so far in such attempts.

Shadow measurements made with the three probes are reproduced in Fig. 10. With a completely symmetrical centered beam, these records would be identical. They show that the beam is less than 1/2 in. off center, as well as having a different structure in the three sectors.

Being able to construct precise phase plots such as Figs. 3(a) and 8 from records that require only a few minutes to obtain allows trim-coil corrections to be made quickly and with confidence, and contributes greatly to the operator's understanding of machine operation. Also, since with fairly crude trim-coil settings the beam can be brought out to one-half or greater radius and then improved, it is possible to arrive at isochronous trim-coil settings without the aid of machine calculations.

The records of Fig. 11 show a beam that was developed by first using a simple graphical procedure to select trim-coil currents for two energies[4] (50- and 80-MeV α), where the currents were chosen to be as similar as possible in the two cases. By using the phase plots of the resulting beams, trim-coil corrections were made which brought the beams out to extraction radius. Then, working from these two cases, it was possible to obtain any energy from 25 to 80 MeV without exceeding allowable trim-coil currents or having to change polarity. Changes in the main-field shape require a new set of solutions above 80 MeV.

## OPERATING STABILITY

An important criterion in constructing the cyclotron was to secure a high degree of stability in operation so that a beam of constant intensity would be available for many hours at a time, with only occasional adjustments necessary by the operator. Of equal importance is the reproducibility of machine settings. Many man-hours of work may be necessary to achieve a particular satisfactory result, and this work can be partly or wholly wasted if the machine conditions are not precisely reproducible. These considerations are familiar to every experimenter, and the following discussion will indicate how they apply to this cyclotron.

The output with a particular beam will depend, among other things, upon the behavior of the beam in phase. Particles which have a phase shift near $\pm \pi/2$ at any radius will not be further accelerated if a frequency or field change causes a phase shift greater than $\pi/2$ or less than $-\pi/2$ to occur. The most sensitive region is in the outer few inches, for the phase shift due to such a change is proportional to the square of the radius. In addition, the greatest departure from the isochronous field (and hence the greatest phase shift) is likely to occur at the edge of the magnet, where the trim coils make the greatest contribution.

The experience with the 130-MeV $\alpha$ beam was that to maintain a beam intensity constant within 10% at 39 in. radius, the frequency had to be stable to 5 parts in $10^5$ (for corresponding stability of the 65-MeV $\alpha$ beam, about 1 part in $10^4$ is required). The main-coil current requires a corresponding stability, while the trim-coil currents must be held constant to 1 part in $10^3$. For reproducibility of a beam the trim coils require a control and readout of comparable accuracy, while the frequency and main-coil current can tolerate an order of magnitude less, since the frequency can be tuned. For beam diagnostics, however, a frequency readout accurate to 100 cycles is essential.

The 88-inch cyclotron does meet the above requirements. The main-coil-current regulation is about 3 parts in $10^5$, and the frequency regulation is about 5 parts in $10^5$. For short periods of time, under quiet conditions, a more favorable condition can be realized.

## OPERATING EXPERIENCE

The machine operating time is divided about equally between (1) physics experiments, (2) target bombardments for nuclear chemistry, and (3) beam development and maintenance (typically, one maintenance shift per week). The amount of unplanned shutdown time has been small, less than 5%.

The 88-inch cyclotron has a hooded ion source[5] with a watercooled copper anode. The filament and the oppositely positioned cathode are made from tantalum. With an average internal beam of 40-μA, 65-MeV α, the filament lasts 100 to 150 hours. The cathode is exchanged about every three filament changes. The copper anode, after 500 hours of operation, is shown in Fig. 14. Since the anode is a rather complicated mechanical piece and the slit is the only part that wears out, we inserted a tantalum piece containing the slit (Fig. 15). This insert is quickly exchanged and shows much less wear than the original copper slit.

The particles are extracted from the ion source by a carbon puller at dee potential. The puller shown in Fig. 16 was used for 500 hours of operation. The beam has eroded a lateral groove. Both the ion source and puller are positioned by remote control. Use of a telescope to see these parts is a help.

The use of three symmetrically located probes has been found invaluable in beam diagnostics, especially in centering. They are water cooled, will stand about 3 kW of beam, and can be remotely positioned to an accuracy of 0.03 in. Utility of the internal phase probe (see Fig. 1) has suffered because

of rf pickup problems and a lack of sensitivity. A different type of phase probe suggested by Homer Conzett of our Laboratory has been constructed; it uses a foil to scatter particles into a solid-state detector. So far this has been used only in the external beam. Tentative results of measurements made with the 65-MeV α beam show a phase width about one-third to one-half that of the internal beam.

A pulser for the rf system has been built and found to be useful for obtaining large instantaneous values of beam current. If run continuously, such currents would damage probes or other parts of the machine.

Since we have restricted ourselves so far to relatively modest beam currents (up to 20 μA external), neither residual radioactivity nor neutron production has been a problem. We hope to keep the residual activity inside the machine at less than 100 mr/h of β and γ after a 24-hour shutdown in order to do work inside the vacuum tank. This can be done by carefully placing carbon in front of exposed parts. An exception is the septum; activity here has been measured as 50 r at 4 in, after a 34-hour shutdown.

## ACKNOWLEDGMENT

The authors wish to express their gratitude to the 88-inch cyclotron group as a whole for their help in performing the experiments. In particular, we wish to thank Dr. E. L. Kelly for his wise guidance and Dr. Lloyd Smith and Dr. A. A. Garren for their invaluable help in interpreting results. We are indebted to the computer group and the engineering support group, especially to R. J. Cox, Arthur Hartwig, A. S. Kenney, K. F. Mirk, H. C. Owens, and Dr. B. H. Smith. Further, we are thankful that the customers allowed us the machine time for this investigation.

## FOOTNOTE AND REFERENCES

* Work done under the auspices of the U. S. Atomic Energy Commission.

1. Nucl. Instr. Methods 18, 19 (1962).
2. A. A. Garren, Calculation of Cyclotron Trim-Coil Currents for Field Optimization by Linear Programming Methods, Op. cit., p. 309.
3. A. A. Garren and L. Smith, Diagnosis and Correction of Beam Behavior in an Isochronous Cyclotron, to be presented in another paper to this conference.
4. It is our intent to issue a Lawrence Radiation Laboratory UCRL report describing this method.
5. H. A. Willax and A. A. Garren, Center Region Geometry of the Berkeley 88-Inch Cyclotron, Op. cit., p. 347.

Table I. Particle beams available at extraction radius; April 1963

| Particle | Energy (MeV) | Extraction (%) | Fig. No. | Remarks |
|---|---|---|---|---|
| Proton | 25 | - | 12 | |
| | 50 | 1.5 | 12 | Not available externally with present deflector |
| $He^{3+}$ | 25 | - | 13 | |
| Alphas (deuterium and $H_2^+$ of 1/2 energy) | 65 | 40 | 6 | 20μA maximum external beam, determined by septum heating |
| | 25 to 80 | 25 to 35 | 11 | Any intermediate energy available (max external beam ≈0.45 kW) |
| | 130 | - | 3 | Not available externally |

## FIGURE LEGENDS

Fig. 1. Plan view of pole face.

Fig. 2. Development of the 130-MeV α beam. (a) The first α beam obtained, with the corresponding $H_2^+$ beam. (b) and (c) the α beam as a function of frequency.

Fig. 3. Development of the 130-MeV α beam. (a) The phase plot deduced from the curves of Fig. 2 (b) and (c); (b) the beam obtained after trim-coil adjustments were made. The spurious beam, obtained by blocking the orthodox beam with another probe, is also shown. (c) After center region adjustment was made to eliminate spurium.

Fig. 4. Record of 130-MeV α beam made with a 3-finger probe.

Fig. 5. The 130-MeV α beam; effect of varying the dee voltage.

Fig. 6. The 65-MeV α beam with which an extraction efficiency exceeding 40% has been obtained.

Fig. 7. The 65-MeV α beam as a function of frequency.

Fig. 8. Phase plots of the 65-MeV α beam. (a) By using curves of Fig. 7. (b) By using curves made with a dee voltage of 19 kV.

Fig. 9. Use of valley coils 1, 2, and 4 with the 65-MeV α beam. Records of (a) deflector probe, (b) target probe, and (c) dee probe.

Fig. 10. Shadow measurements of the 65-MeV α beam.

Fig. 11. The 25-to 80-MeV α beam. With minor trim-coil adjustments any intermediate energy can be obtained.

Fig. 12. 25- and 50-MeV protons.

Fig. 13. 25-MeV $He^{3+}$ beam.

Fig. 14. Copper anode of ion source after more than 500 hours of operation.

Fig. 15. Ion source with tantalum insert.

Fig. 16. Puller after 500 hours of operation.

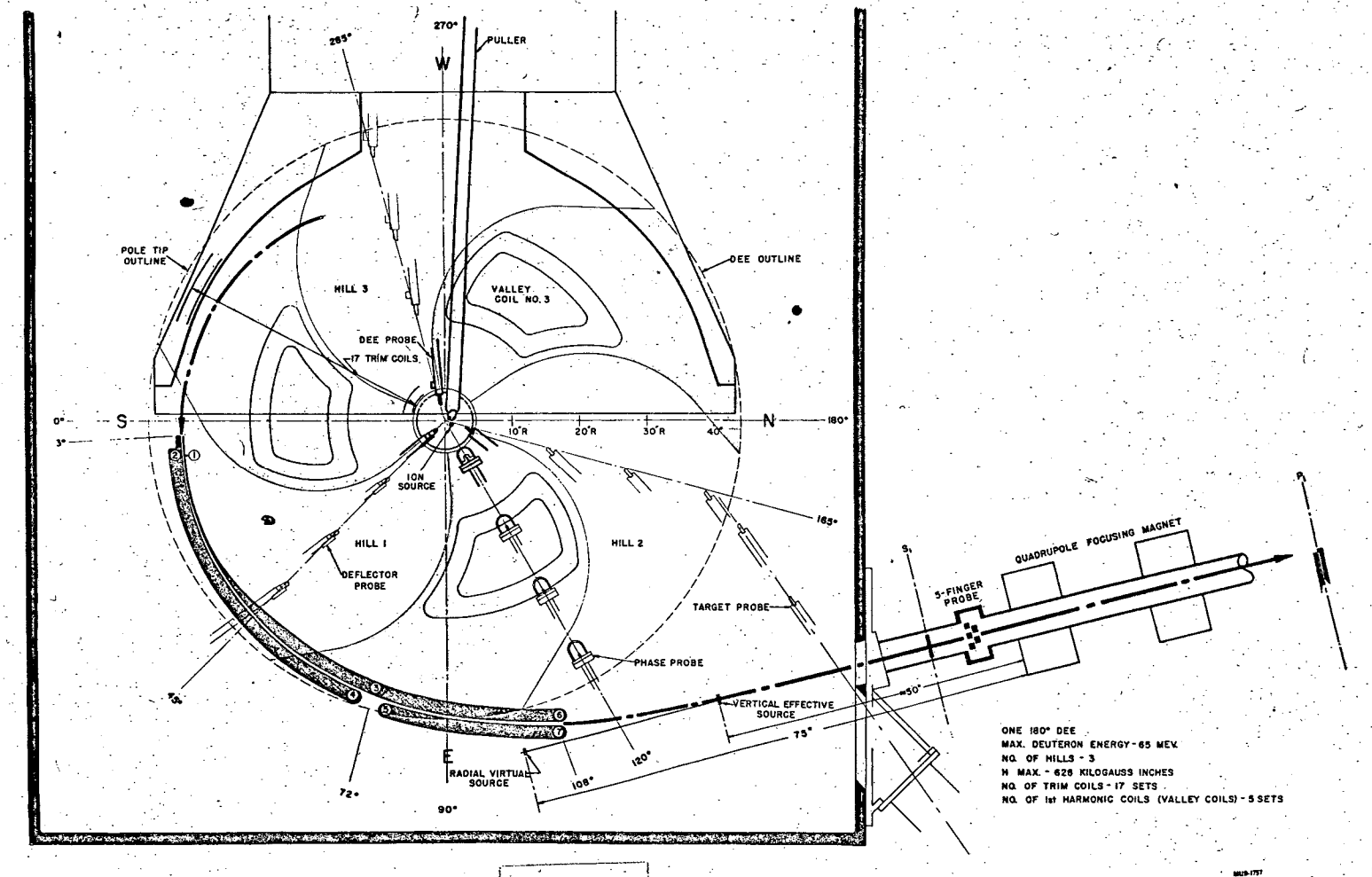
285°
270°
PULLER
W
POLE TIP OUTLINE
DEE OUTLINE
HILL 3
VALLEY COIL NO. 3
DEE PROBE
17 TRIM COILS
0°
S
N
180°
3°
10°R
20°R
30°R
40°
ION SOURCE
165°
HILL 1
HILL 2
DEFLECTOR PROBE
TARGET PROBE
PHASE PROBE
QUADRUPOLE FOCUSING MAGNET
5-FINGER PROBE
VERTICAL EFFECTIVE SOURCE
50°
75°
120°
108°
72°
RADIAL VIRTUAL SOURCE
E
90°
ONE 180° DEE
MAX. DEUTERON ENERGY - 65 MEV.
NO. OF HILLS - 3
H MAX. - 626 KILOGAUSS INCHES
NO. OF TRIM COILS - 17 SETS
NO. OF 1st HARMONIC COILS (VALLEY COILS) - 5 SETS

Fig. 1.

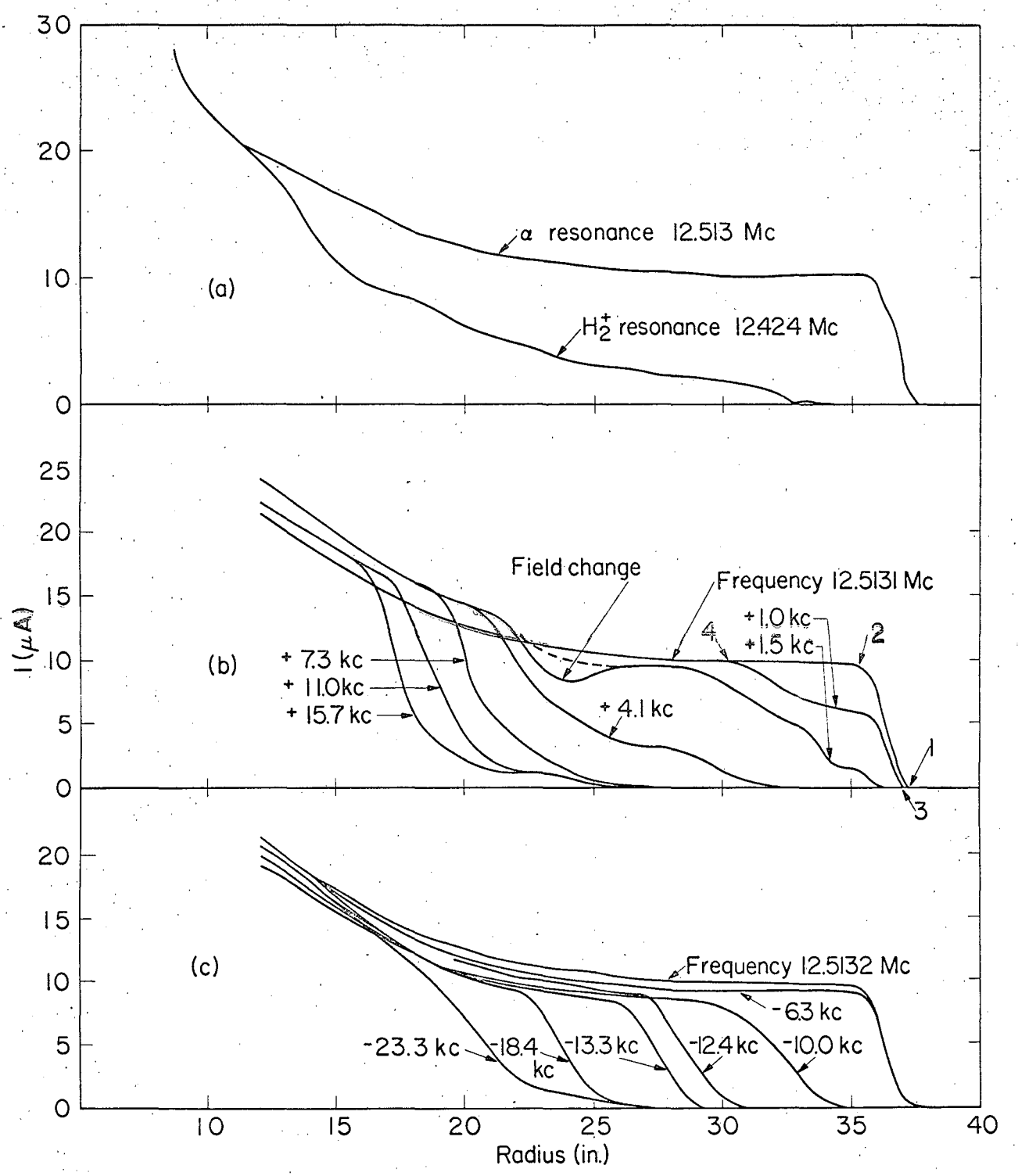
(a)
α resonance 12.513 Mc
$H_2^+$ resonance 12.424 Mc
(b)
Field change
Frequency 12.5131 Mc
+ 7.3 kc
+ 11.0kc
+ 15.7 kc
+ 4.1 kc
+1.0 kc
+1.5 kc
1
2
3
4
(c)
Frequency 12.5132 Mc
-6.3 kc
-23.3 kc
-18.4 kc
-13.3 kc
-12.4 kc
-10.0 kc
I (μA)
Radius (in.)
MUB-1719

Fig. 2.

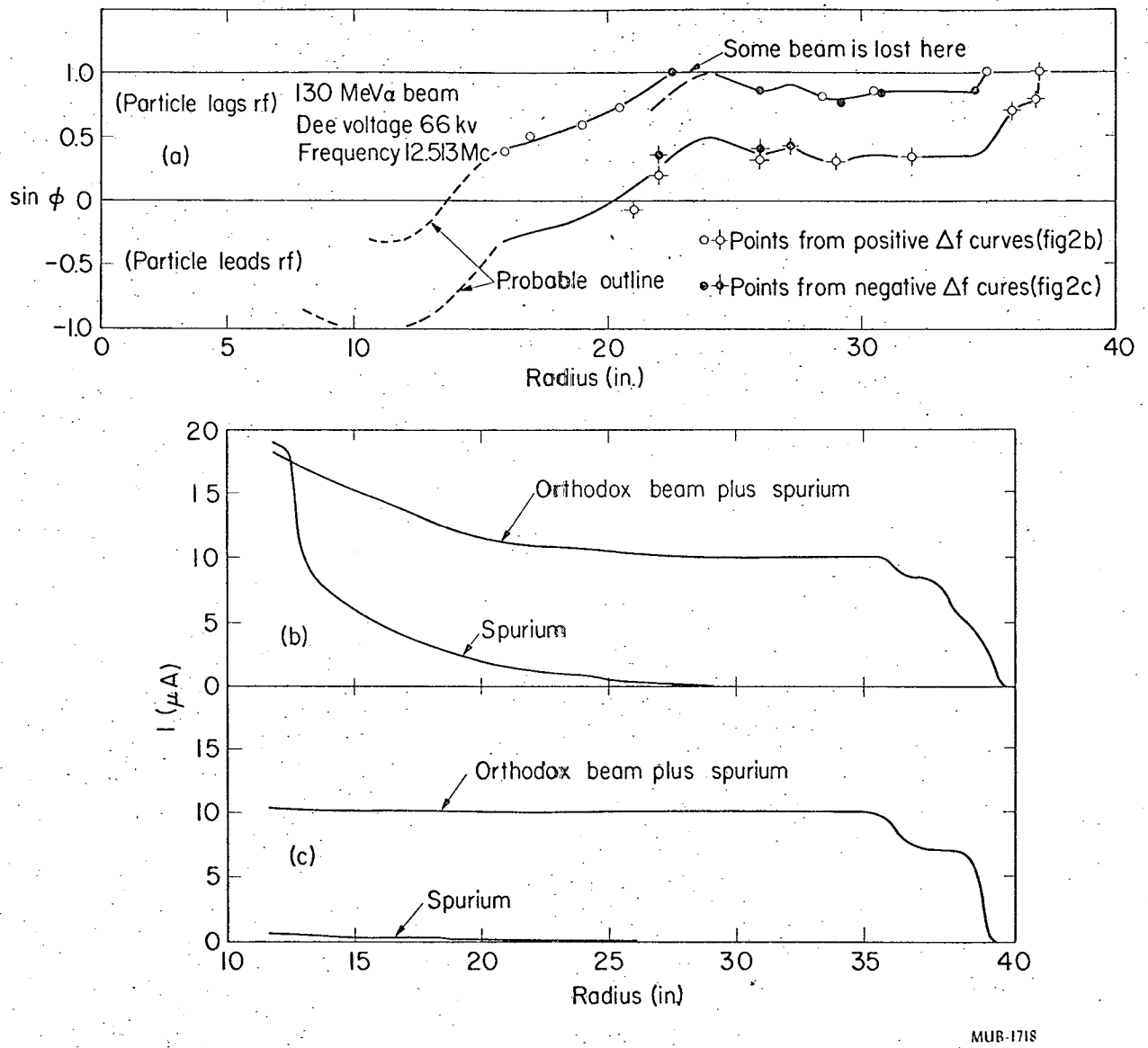
Some beam is lost here
(Particle lags rf)
130 MeVα beam
Dee voltage 66 kv
Frequency 12.513 Mc
(a)
sin φ
(Particle leads rf)
Probable outline
Points from positive Δf curves (fig2b)
Points from negative Δf cures (fig2c)
Radius (in.)
Orthodox beam plus spurium
Spurium
(b)
I (μA)
Orthodox beam plus spurium
Spurium
(c)
Radius (in)
MUB-1718

Fig. 3

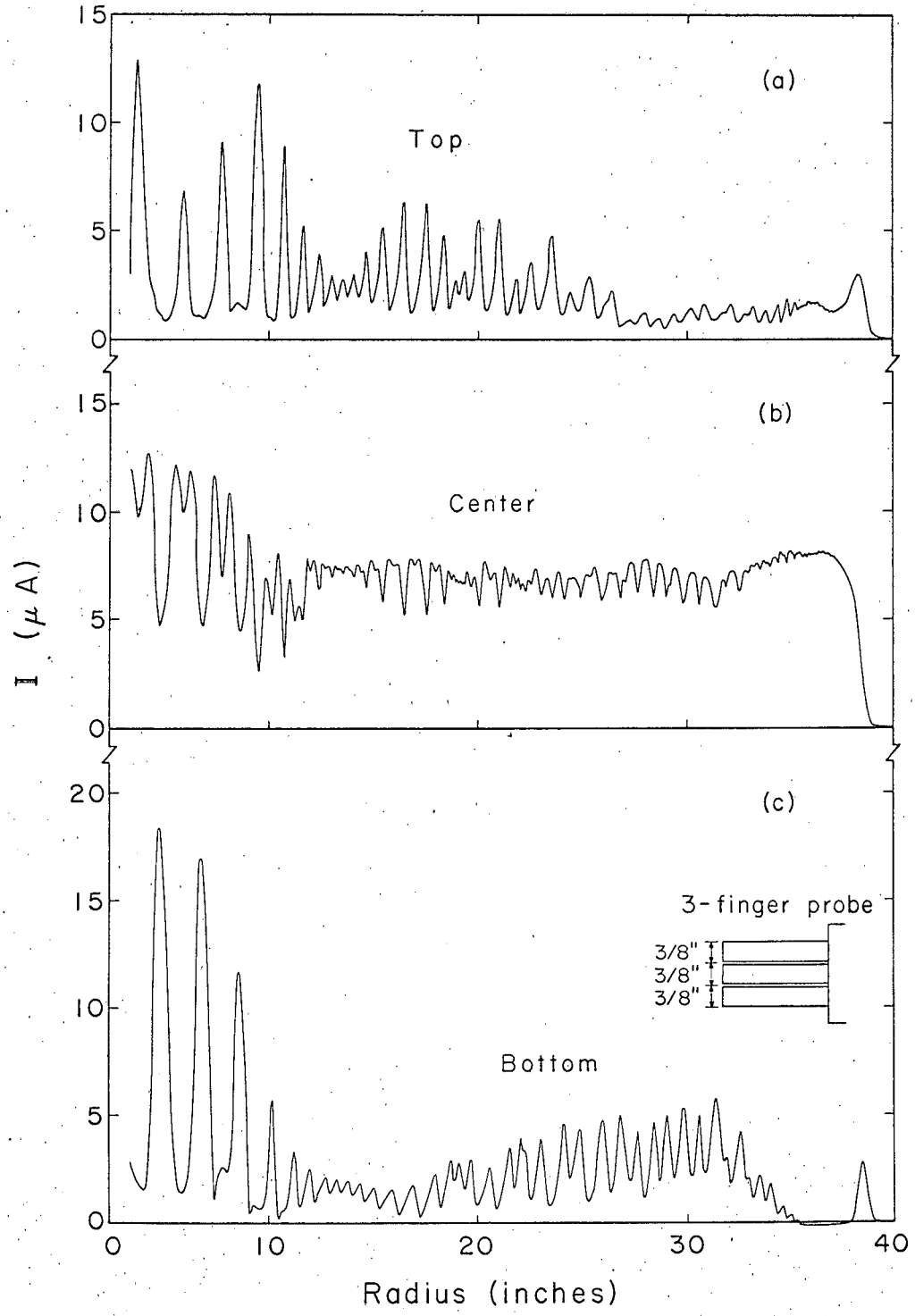
(a)
Top
(b)
Center
(c)
Bottom
3-finger probe
3/8"
3/8"
3/8"
I (μA)
Radius (inches)
MUB-1717

Fig. 4.

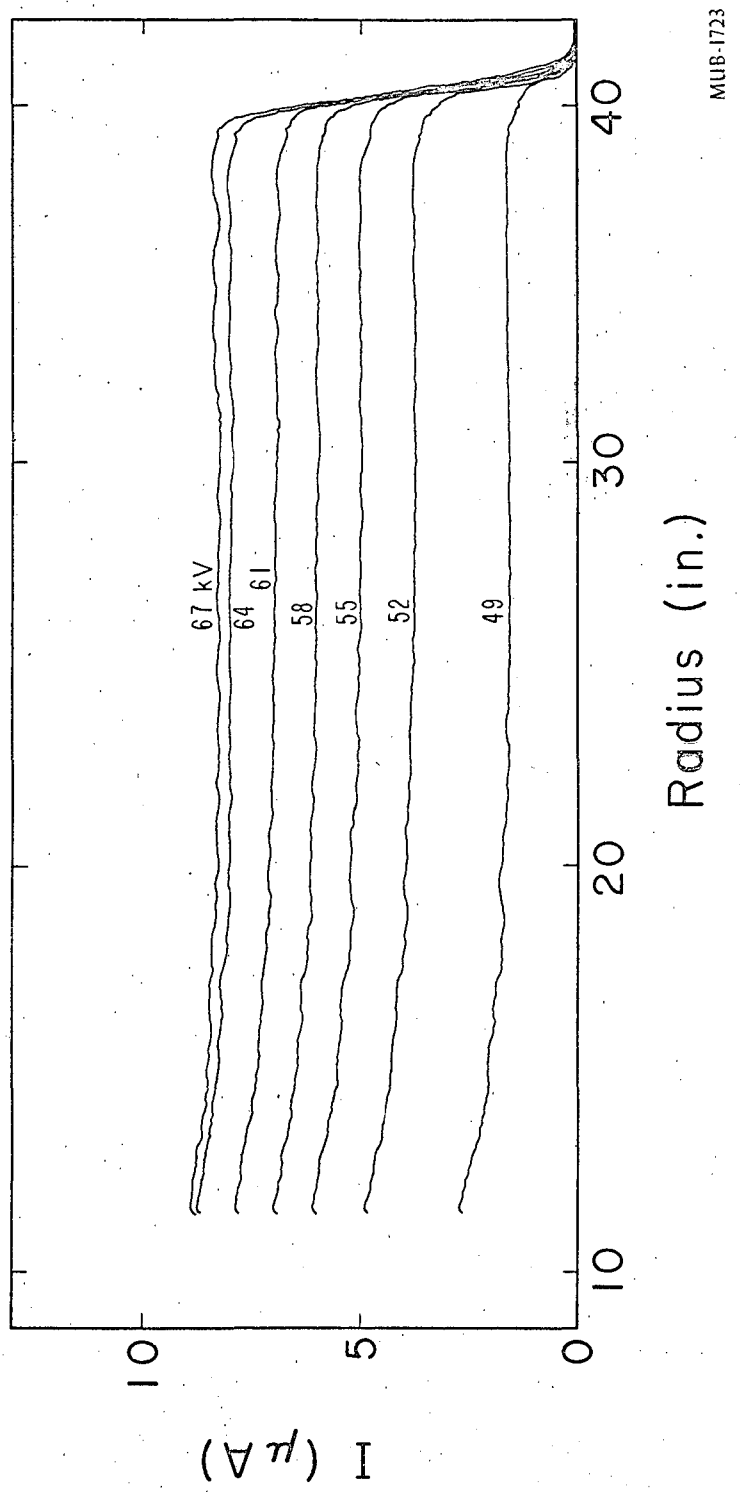


Fig. 5.

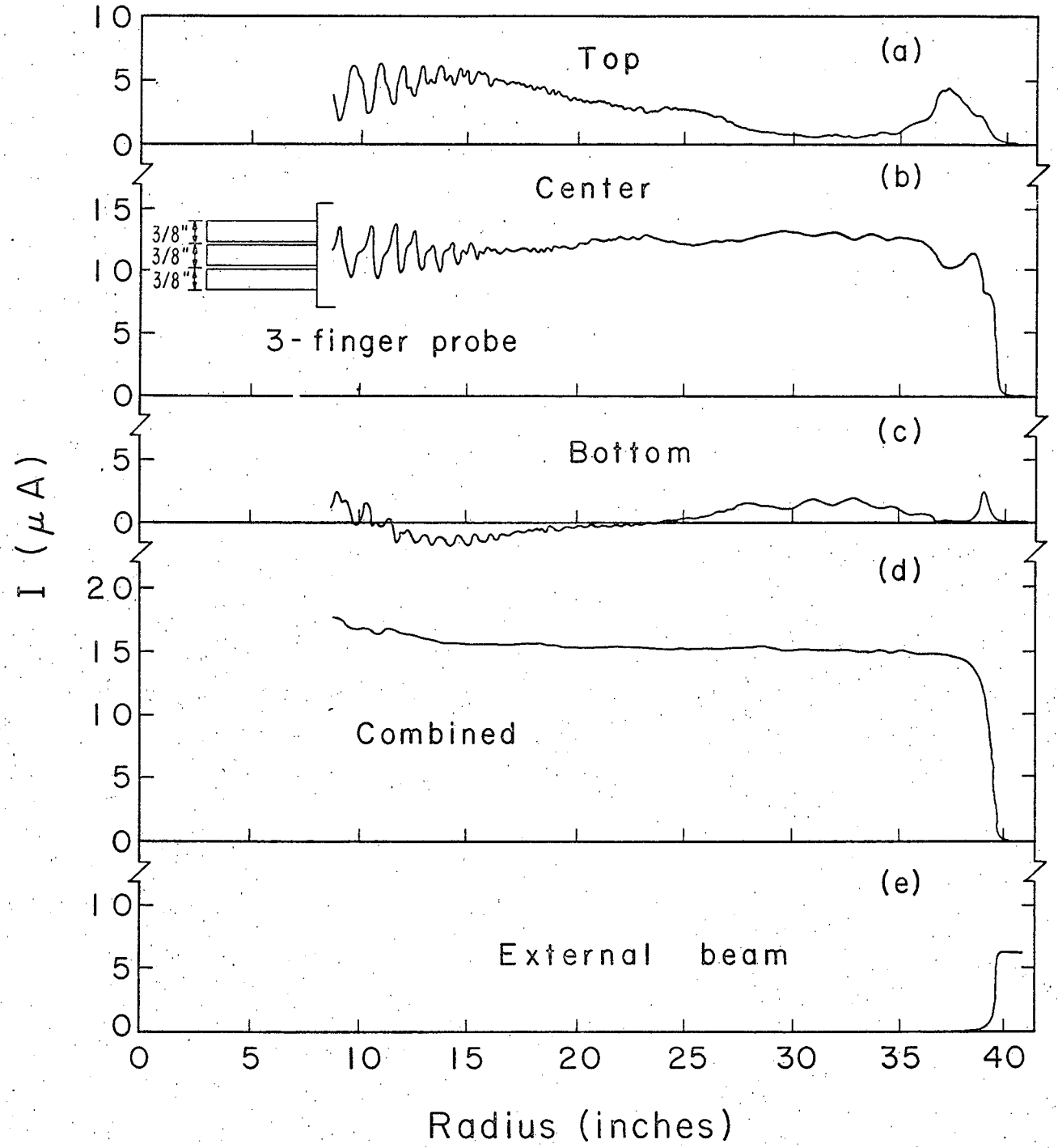
Top
(a)
Center
(b)
3/8"
3/8"
3/8"
3-finger probe
Bottom
(c)
(d)
Combined
(e)
External beam
I (μA)
Radius (inches)
MUB-1715

Fig. 6.

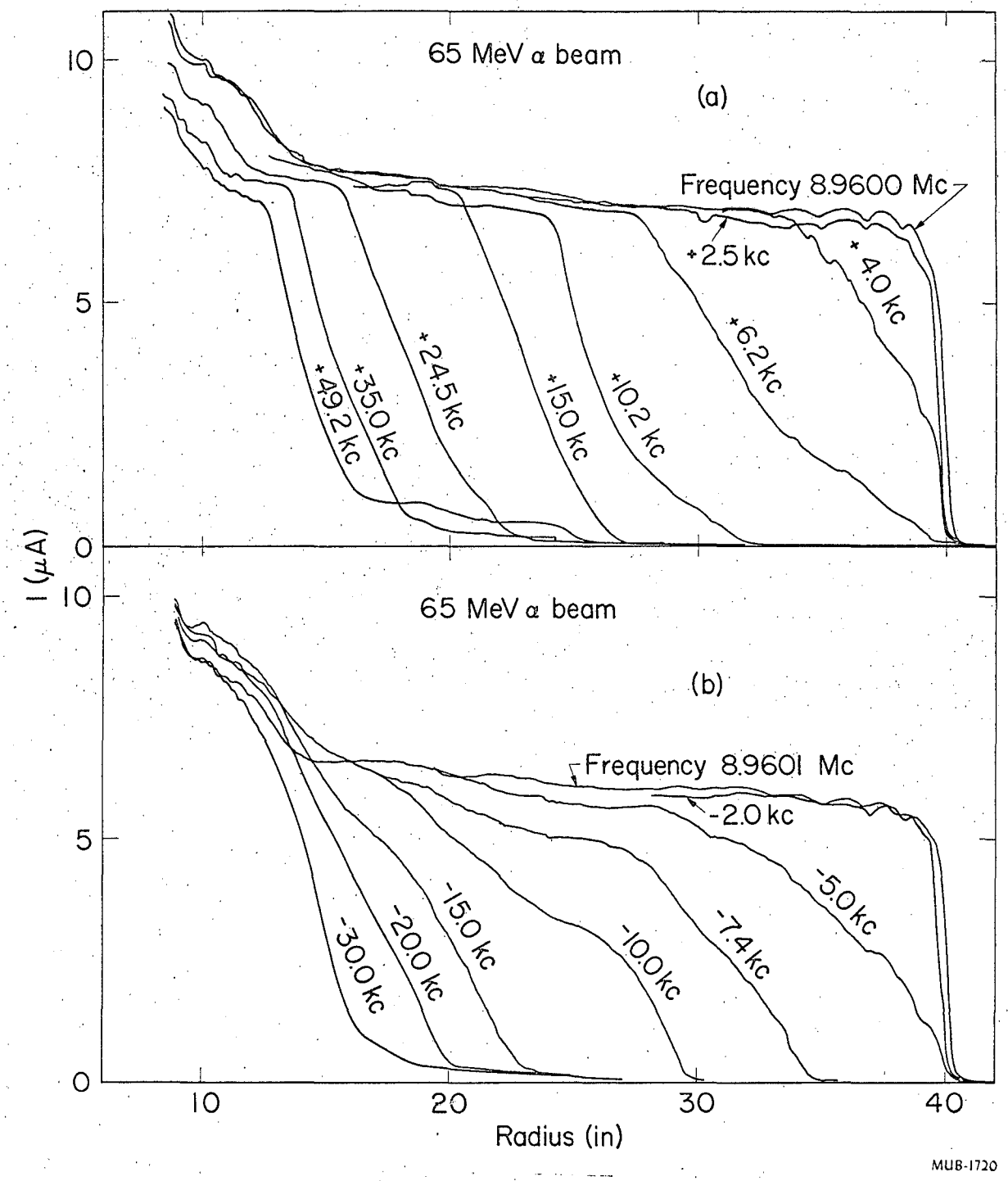
65 MeV α beam
(a)
Frequency 8.9600 Mc
+2.5 kc
+4.0 kc
+6.2 kc
+10.2 kc
+15.0 kc
+24.5 kc
+35.0 kc
+49.2 kc
65 MeV α beam
(b)
Frequency 8.9601 Mc
-2.0 kc
-5.0 kc
-7.4 kc
-10.0 kc
-15.0 kc
-20.0 kc
-30.0 kc
I (μA)
Radius (in)
MUB-1720

Fig. 7.

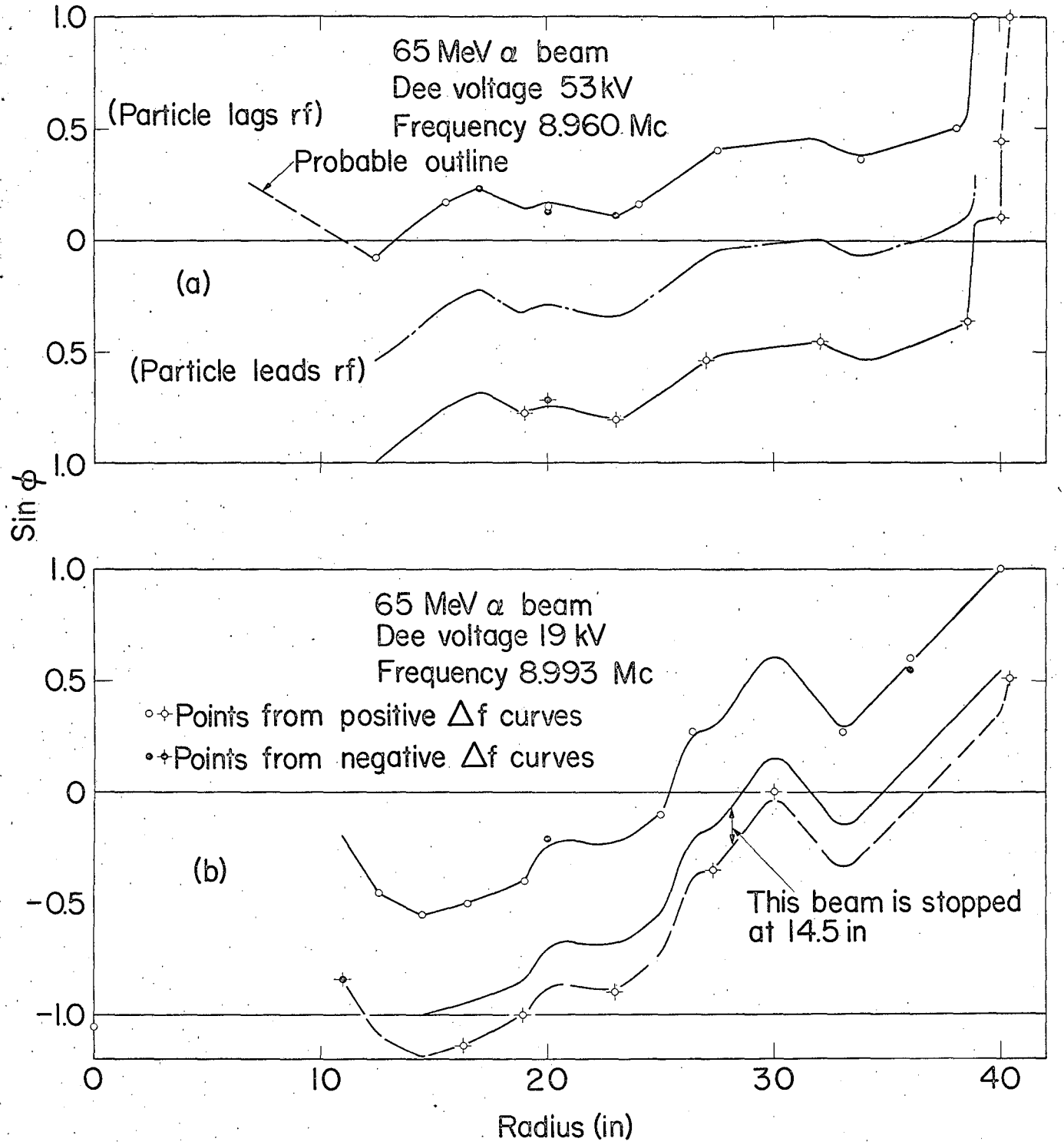
65 MeV α beam
Dee voltage 53 kV
Frequency 8.960 Mc
(Particle lags rf)
Probable outline
(a)
(Particle leads rf)
65 MeV α beam
Dee voltage 19 kV
Frequency 8.993 Mc
Points from positive Δf curves
Points from negative Δf curves
(b)
This beam is stopped at 14.5 in
Sin φ
Radius (in)
1.0
0.5
0
-0.5
-1.0
10
20
30
40
MUB-1722

Fig. 8.

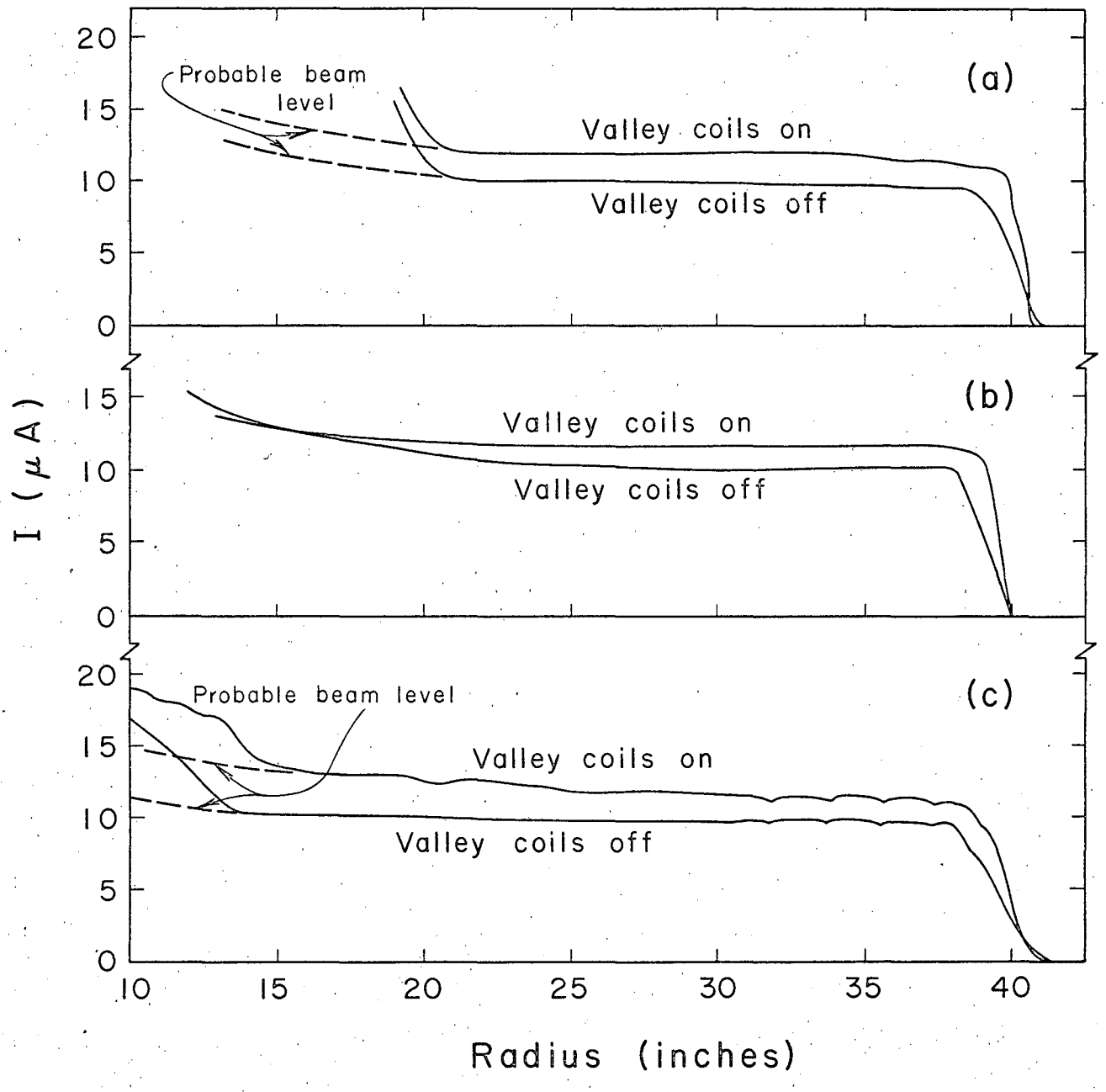
Probable beam level
(a)
Valley coils on
Valley coils off
(b)
Valley coils on
Valley coils off
Probable beam level
(c)
Valley coils on
Valley coils off
I (μA)
Radius (inches)
MUB-1716

Fig. 9.

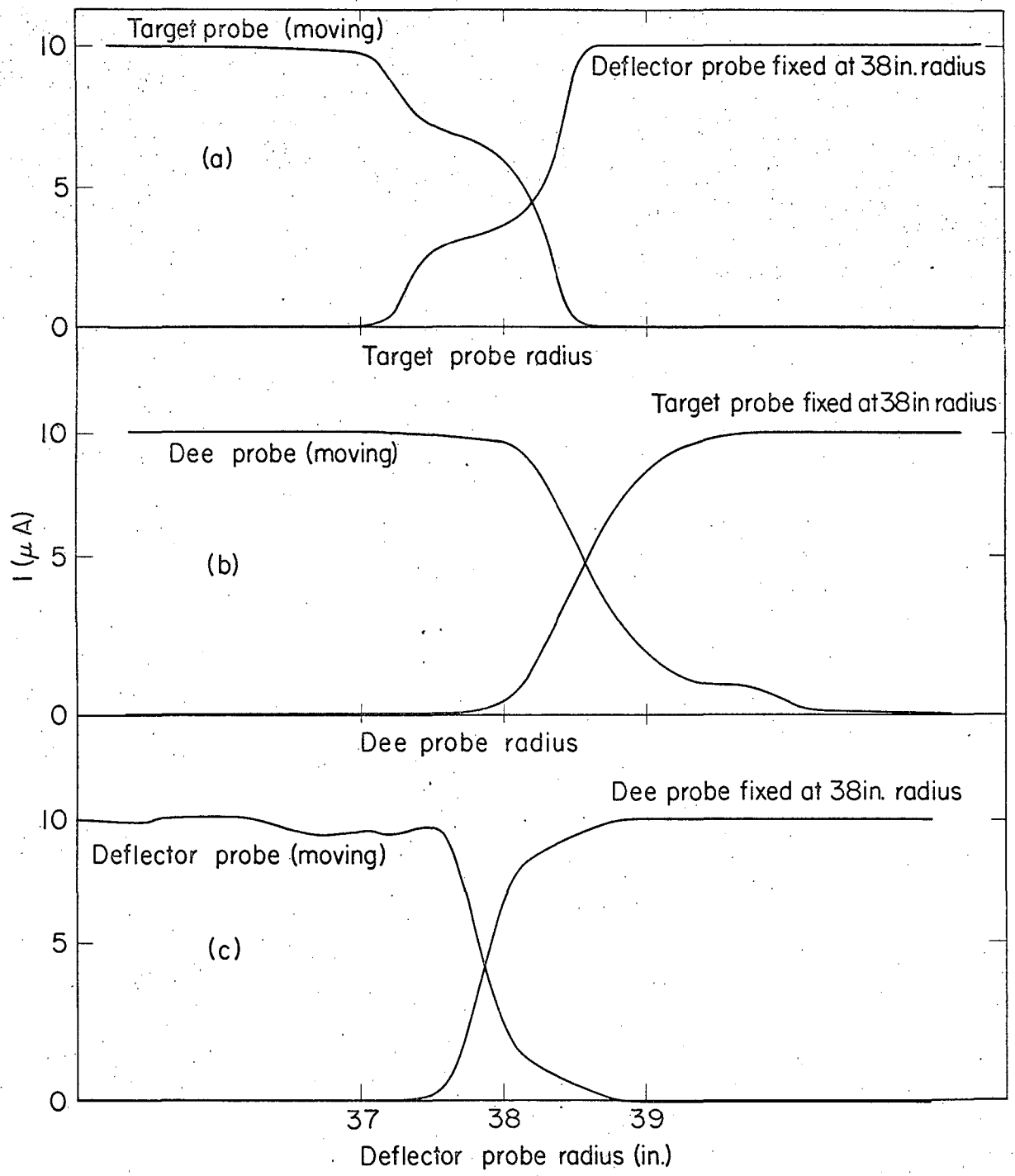
Target probe (moving)
Deflector probe fixed at 38in. radius
(a)
10
5
0
Target probe radius
Target probe fixed at 38in radius
Dee probe (moving)
(b)
I (μA)
10
5
0
Dee probe radius
Dee probe fixed at 38in. radius
Deflector probe (moving)
(c)
10
5
0
37
38
39
Deflector probe radius (in.)
MUB-1721

Fig. 10.

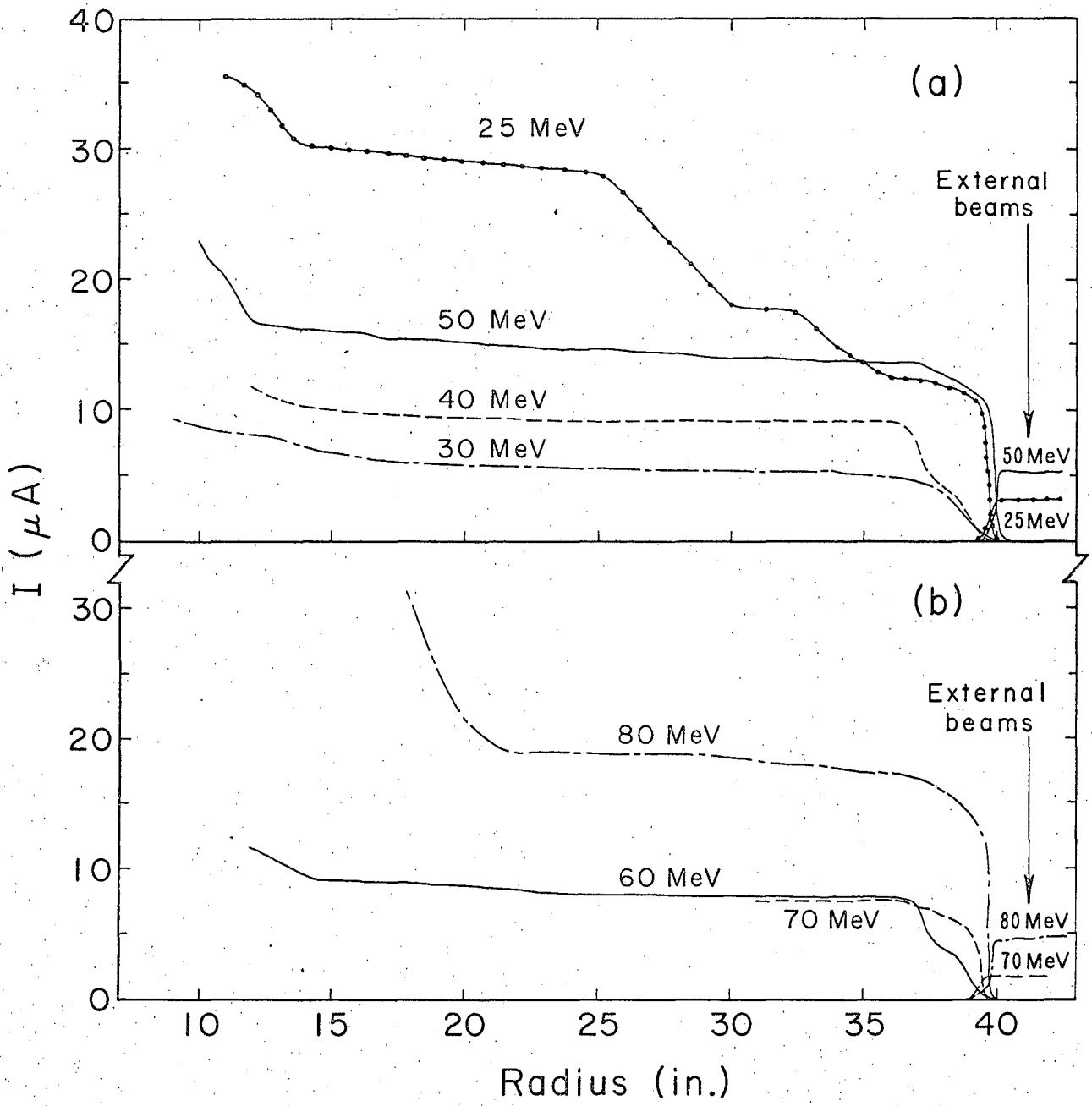
(a)
25 MeV
50 MeV
40 MeV
30 MeV
External beams
50 MeV
25 MeV
(b)
80 MeV
60 MeV
70 MeV
External beams
80 MeV
70 MeV
I (μA)
Radius (in.)
MUB-1724

Fig. 11.

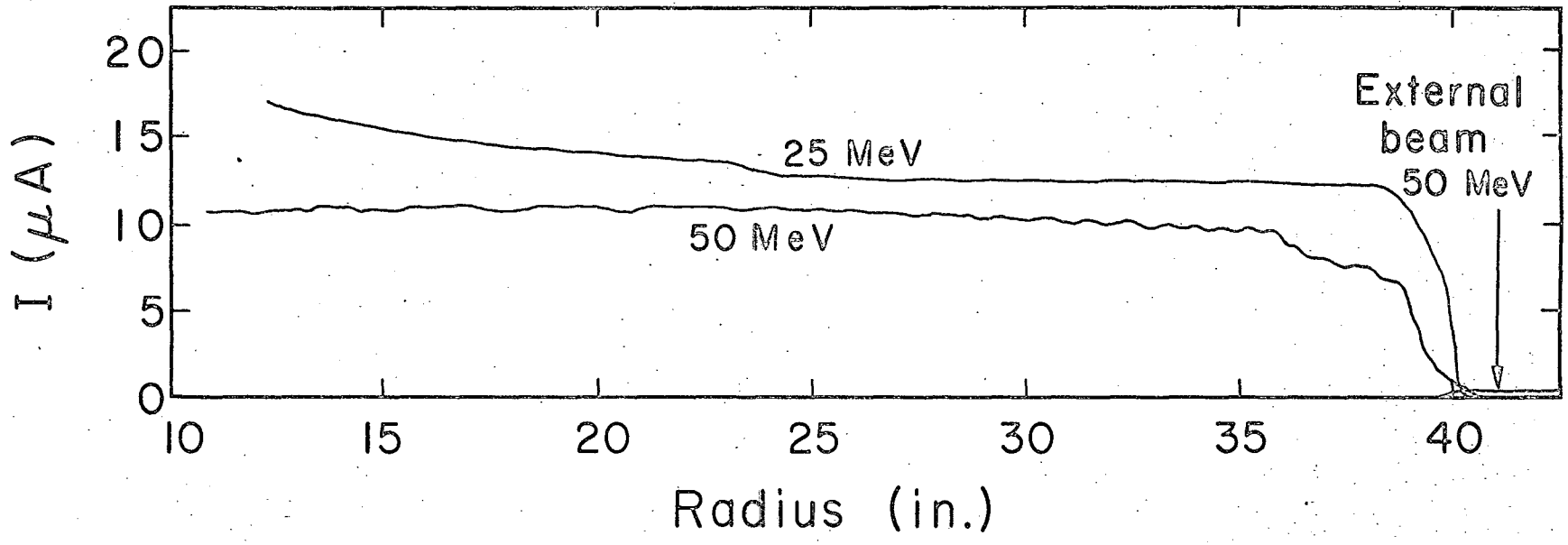
I (μA)
20
15
10
5
0
10
15
20
25
30
35
40
Radius (in.)
25 MeV
50 MeV
External beam
50 MeV
MU-30078

Fig. 12.

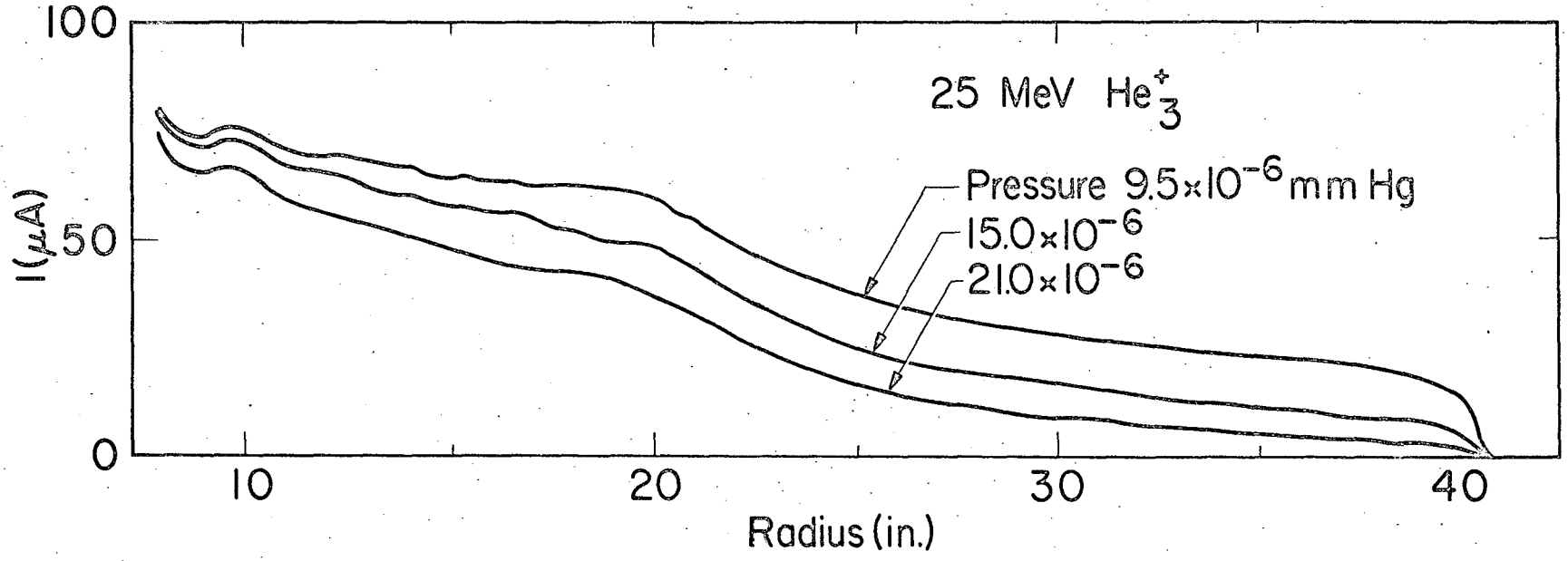
100
50
0
I(μA)
25 MeV $He^{+}_{3}$
Pressure 9.5×10⁻⁶ mm Hg
15.0×10⁻⁶
21.0×10⁻⁶
10
20
30
40
Radius (in.)
MU-30079

Fig. 13.

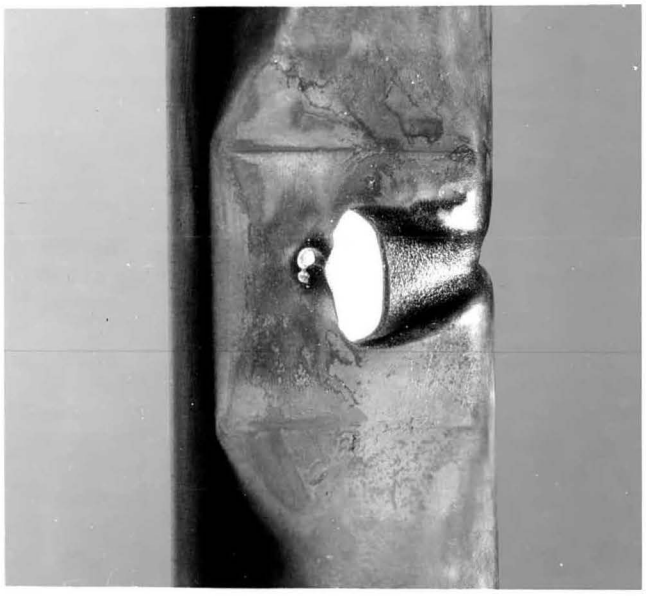

Fig. 14.

Fig. 15

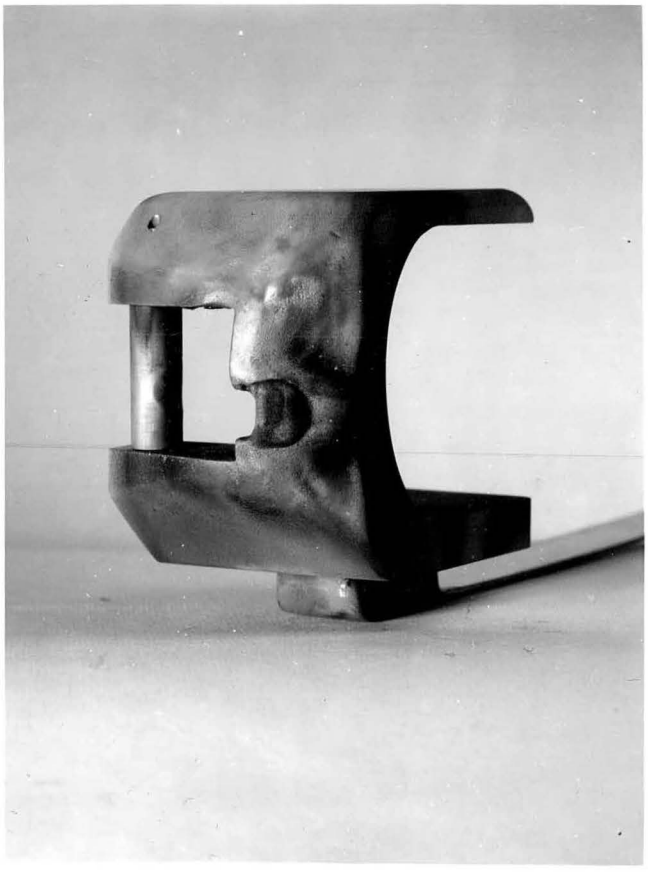

Fig. 16