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ABSTRACT

A Von Ardenne-type ion source and lens system has been developed for use as a preinjector to the 18-Mev strong-focusing linear accelerator. Proton beams of 120 ma at an ion production efficiency of 83% have been obtained.

A magnetic beam-confining system has been built, and a beam of 85 ma has been transported 82 in. The beam energy was 370 kev, and its emittance was 100 mrad-mm. The beam diameter was 1 cm. This is within the linear accelerator's calculated acceptance of 179 mrad-mm.

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I. INTRODUCTION

The interest of physicists in low cross section reactions has emphasized the necessity of increasing the beam intensity of high-energy accelerators. The recent development of strong-focusing linear accelerators has made it possible to achieve these intense beams.[1,2,3]

A major problem has been the production and focusing of intense low-energy proton beams, in the linear accelerator's pre-injector. As part of the Bevatron improvement program, a high-intensity ion source and lens system has been developed.

Results of this program, reported here, indicate that a pre-injector can be built that will inject 85 ma of protons into an 18 Mev linear accelerator. Emittance measurements show that this beam will be accepted with a 1-cm-diam drift-tube bore.

These tests were performed using a 350 kev Cockcroft-Walton accelerator, and a magnetic-beam confining system.

II. SOURCE ASSEMBLY AND CHARACTERISTICS

A duo-plasmatron ion source, designed for pulsed operation, has been constructed. This source is especially adaptable for use on large accelerators. All of the internal parts, including the extraction electrode, can be removed from the rear of the assembly; removal, in this fashion, does not affect the pre-injector electrode alignment.

Figure 1 is a cross section of the source. Five subassemblies are used:

A. Source body
B. Aperture and extractor cone
C. Middle electrode (snout)
D. Filament assembly
E. Extractor electrode

A. Source Body

In Fig. 1, the source body consists of a mild-steel face plate (1) which has a stainless steel tube (2) welded into it. A solenoid (3) slips over this tube and is held in place by a split-ring clamp (4) which is recessed, providing alignment of the snout assembly.

The source body bolts onto the Cockcroft-Walton lens tank and is held in close alignment by a protruding lip. The face plate is threaded to receive the aperture assembly.

B. Aperture Assembly

This assembly is a cone-shaped invar disk (5) with a molybdenum cathode button (6) pressed into it. This button has a 0.020-in. -diam and 0.024-in. -deep aperture. The disk is aligned by a shoulder joint in the source body.

A spanner wrench, with a holding magnet, can be inserted in the disk to remove it. This wrench fits into the source body, and the assembly can be changed without removing the source body from the lens system.

C. Middle Electrode (Snout)

A mild-steel electrode (7), mounting plate (8), and an alumina insulator (9) form this assembly. The steel electrode is threaded into the mounting plate, then welded in place. Two "O" rings and the insulator slip over the electrode, forming vacuum-tight joints between the mounting plate, insulator, and the rear of the source holder. Because of filament heat, Viton "O" rings must be used. It should be noted that this is the weakest part of the design. We feel that having the "inside" parts of the source readily accessible justifies this complicated multiple "O"-ring seal.

The snout assembly is aligned by the precise fit of the alumina insulator in the source split ring. This insulator is ground to ± 0.0005 in. on all diameters.

The magnetic path from the solenoid is through the source plate (1) and the invar disk (5), across a 0.060-in. gap to the snout electrode (7), through the mounting plate (8), across a small air gap, and then back to the solenoid through the split ring (4).

Fiber sleeves and washers insulate clamping bolts (A) from the electrode. Voltage is applied from a divider to mounting plate (8).

D. Filament Structure

The filament (10), a 0.035-in.-diam, 1/2-in. loop of tantalum, is mounted on two insulated copper rods (11). The ceramic seals (12) are soldered into the filament mounting plate (13). Alignment of this structure is insured by a recessed joint similar to that described above.

To change a filament, one removes bolts (B) and pulls off the mounting plate. The filament wire is setscrewed to the supports; a new one can readily be substituted.

Arc voltage is applied to the filament and, as mentioned above, the snout. Since the filament mounting plate is at snout potential, hydrogen—from a palladium leak—is fed to the source through an insulated joint on this plate.

E. Extractor Electrode

The extractor (14) is mounted on a spider (15). It can be replaced by removing the filament, snout, and aperture assemblies, then inserting a collet extracting tool into the source body. The spider is rigidly mounted and, once aligned, will not move when the extractor is removed. Voltage is applied to the extractor through a vacuum feedthrough. The extractor is invar and the spider is No. 316 stainless steel. A lens gap of 0.070 in. is normally used; this gap has held 100 kv for extended periods. Normal operating voltage is 70 kv. Figure 2 is an equipotential plot of the extracting field.

III. SOURCE OPERATING CHARACTERISTICS

Figure 3 is a simplified circuit diagram of the source and electrode connections. The arc power supply is all solid state and uses two triggered diodes. This supply is essentially a one-shot multivibrator and is triggered on and off. The output is 250 v at 25 amp. Pulse length is variable, but is usually set at 1 msec. The repetition frequency is 2 pps.

The maximum axial field of the arc magnet is 3 kgauss. Normal operation is at about 1.2 kgauss. The magnetic flux in the snout aperture gap has not been measured, but may be quite high here.

Figure 4 shows a family of arc volt-ampere curves for various magnetic field settings. Note that the arc impedance can be raised by increasing the magnetic field.

Figure 5 shows the effect of filament current on arc impedance. Normal volt-ampere shape is represented by the 68-amp curve. No adequate measurement of filament life has been made yet. Maximum life appears greater than 48 hr.

The dependence of proton efficiency on arc current has been studied. Table I shows the results.

Neutral-atom efficiencies have not been measured. Normal operation is at 20 amp.

Table II shows the beams obtainable from various apertures. At 20 amp arc current, an ion density of 60 amp/cm^2 is obtained.

In operation this source has been very stable, and proton beams of 100 ma are readily obtainable.

IV. COCKCROFT-WALTON LENS DESIGN AND PERFORMANCE

A. Computational Methods

When it was decided to construct a high-intensity injector, it was apparent that the present electrostatic lens system would not handle the beam required.

The best way of obtaining beam orbits appeared to be the use of a wedge tank and a digital computer. Accordingly, a tank was constructed and calibrated using the method developed by Fechter and Striegl.[4] The tank was 24 in. $\times$ 20 in. and was accurate to 0.1% in the center and 1% near the walls, with a wedge angle of 2.5 deg. Electrode shapes were approximated by plane sections made of 1/16 in. copper.

Beam orbits were computed using an IBM 650 computer. In all cases a homogeneous beam of protons was assumed. The differential equation solved was

$$r'' + V'/2V\, r' + V''/4V\, r + \frac{20.58\, I}{V^{3/2}\, r} = 0,$$

where r is in centimeters, V in kilovolts, and I in amperes. Primes indicate derivatives with respect to Z.

In practice, the electrode system was modeled in the tank, and then the potential variation along the axis was obtained. This was fed into the computer, and the necessary derivatives were calculated, using finite-difference expressions. In addition, the beam radius and divergence at the second field point was assumed. From the orbits obtained and an equipotential plot we were able to get the desired lens shapes.

B. Column Design

Two types of accelerating columns were investigated. These were the standard linear-gradient column and the power-law column of Harrison.[5] Theoretically the Harrison column will confine an intense beam; however, it would be difficult to construct one for 500 kev. Therefore we decided to use the linear accelerating tube, and to design a lens that would match the source and column.

The beam characteristics were studied by ray-tracing backwards through the column.[6] The final energy was 480 kev, and the entrance energy was set at 60 kev. This was determined by the expected voltage stand-off characteristics of the new injector. Figure 6 shows some typical orbits.

Results of the calculations for a 76-cm column indicate that a large (approx 6-cm-diam) convergent beam is required.

C. Matching Lens Design

Figure 7 shows the lens used to match the source and column. It is a four-electrode accel.-accel.-decel.-accel. type. The beam emerging from the source is accelerated to about 100 kev by the extractor and focus electrodes. Then the beam is decelerated by the E_1-focus gap to increase its radius. This gap is converging, so that a balance can be obtained between the lens focusing forces and the beam blowup, thereby allowing control of the radius. The E_1-E_2 gap and the first column gap give the beam a radially inward push, causing it to become slightly convergent, while accelerating it to the proper column-injection energy.

Figures 8 and 9 show the lens equipotentials, as well as the axial potential and its first and second derivatives. The large curvature of the off-axis equipotentials helps to keep the beam well confined.

Typical beam orbits are shown in Fig. 10. The currents all have the same initial conditions (R_0 = 0.25 cm and R_0' = 7 deg). At the voltages used there is no crossover.

D. Lens-System Performance

This lens has performed well. We have achieved a total beam of 150 ma at 1 in. from the column exit. The waist diameter was 1.6 cm, and 80% of the beam was within a diameter of 1 cm. The beam profiles show some loss on E_2; this has been observed experimentally. However, 90% of the beam is transmitted through the lens. To achieve this, lens concentricity is held to ± 0.002".

V. BEAM TRANSPORT SYSTEM

Because space-charge effects are still large at 500 kev, it was necessary to construct a beam-confining system. We used solenoidal focusing because of its simplicity. This, of course, has the disadvantage of requiring high-power magnets.

Figure 11 is a layout of the transport system. Two solenoids are used. The first one is an integral part of the column assembly. It is located as close to the column waist as possible. This magnet is 10-3/4 in. long and has an inside diameter of 3 in. It is wound in eight layers with 23 turns per layer. The coil leads are brought out to permit maximum cooling. In winding, considerable care must be used to insure coil uniformity, otherwise the lens will have large aberrations. This magnet has a coil resistance (series connection) of 29 mohm and a peak field of 9.8 kgauss at 1 ka.

The second magnet is placed 33 in. from the exit of the column solenoid. This magnet is 20 in. long and has a 2-in. inside diameter. It has a coil resistance of 21 mΩ. The peak field is 7 kgauss at 1 ka.

With these magnets we have achieved 85 ma of protons 82 in. (point 1, Figure 10) from the exit of the first solenoid.

VI. BEAM QUALITY MEASUREMENTS

Matching of the Cockcroft-Walton beam to the linear accelerator is done by measuring the emittance of the beam. This technique has recently come into wide use in several laboratories.[7, 8, 9]

At the foci of the two solenoids we have determined the emittance of the beam and its proton content.

Our emittance measurement was made in a manner analogous to that of Marsicanin and Tallgren.[7] Figure 11 shows a typical setup. The beam homogenity was checked by using various apertured cups and calculating the ion density. The beam was homogeneous to within 5%. We determined the center of gravity of the beam by scanning at points (1) and (2) with two Faraday cups. The beam was focused slightly ahead of point (1). The cup apertures were 1-mm diam. A 1-mm aperture was inserted at point (1) and moved along the X and Y axes of the beam. At each aperture position the beam zeros were measured by the cup at point (2). Then the divergence of the beam was calculated by transforming the aperture location from point (1) to point (2) and dividing by the cup separation.

The emmittance is obtained by plotting the divergences as a function of radius. The area under the curve is then determined. Then the beam emittance is given by

$$E = \frac{\text{area under curve}}{\pi},$$

since the emittance plot of a perfect beam is an ellipse.

Figures 12 and 13 show the X and Y emittances, respectively, for the second magnet focus.

Dr. Hugh Hereward at CERN has calculated that the acceptance of their linear accelerator is 179 mrad-mm,[10] and our beam appears to be within these limits. Ninety percent of the beam is within a diameter of 4.3 mm and has an emittance of 73 mrad-mm.

All measurements were made at the stable voltage limit of the test stand (370 kev). The maximum voltage run with beam was 410 kev. This limit is due to room geometry and not to the column structure, e.g., sparkdown occurred from the shell to the room floor.

A mass spectrograph has been set up and the beam purity determined at the second focus. Figure 14 shows the results. The instrument had a resolution of ± 1 amu at mass 30. Identification of the proton peak was done by wire-orbiting. The deflection angle was 20 deg.

It is of interest to note that the solenoids apparently analyze the beam. We have obtained similar curves with a source efficiency of 60%. The first small peak is probably low-energy protons, created by the dissociation of H_2^+ in the column.

We have obtained 120 ma of protons at the first focus, with an arc current of 20 amp.

Beam intensity has been measured using a shielded Faraday cup and a beam transformer. The cup and transformer agree, as long as the cup is 4 in. or more downstream from the transformer; otherwise, secondary electrons from the cup face cause the transformer to read high. Measurements with the cup biased gave a plateau at -10 v.

In addition, a calorimetric measurement has been made. With 80-ma p^+ incident on the cup, the beam current—measured thermally—was 106 ma. This seems to indicate that some neutral atoms are present in the beam.

ACKNOWLEDGMENTS

Many people participated in this project. We especially would like to thank Dr. Hugh Hereward for freely giving us the benefits of his experiences with the CERN injector, and Dr. Malcolm McGregor for checking our field-plotting methods with his iteration program. Robert Force and John Barale, from the Bevatron Engineering Group, gave us invaluable assistance with our electronics. Many of the Bevatron operators have helped us in assembly and data reduction.

Table I. Proton efficiency as a function of arc current.

I_{arc} (amp)	Efficiency (%)
4	63
8	69
14	73
16	80
20	83

Table II. Beam extracted for various apertures.

Aperture		Probe	Arc current	Beam
Diam. (in.)	Depth (in.)	(kv)	(amp)	(ma)
0.020	0.090	70	17	45
0.020	0.024	70	20	120
0.028	0.090	70	20	84

FOOTNOTES AND REFERENCES

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

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10. Dr. Hugh Hereward (CERN, Geneva) private communication.

Figure Captions

Fig. 1. Source detail.

Fig. 2. Equipotential plot for the extraction electrode.

Fig. 3. Source and electrode connections.

Fig. 4. Plot of arc and snout voltage versus arc current for a filament current of 63 amp.

Fig. 5. Plot of arc and snout impedance versus arc current for various filament currents.

Fig. 6. Column backtrace-beam envelopes as a function of output convergence R_0', where R_0 is 0.5 cm and Δ is 0.762 cm.

Fig. 7. Four-electrode lens assembly.

Fig. 8. Equipotential plot for injector four-electrode lens.

Fig. 9. Potential plots for injector four-electrode lens. Extractor potential is 70 kv; focus potential, 100 kv; $E_1 = 21$ kv; and $E_2 = 55$ kv. $\Delta = 0.25$ cm. Symbols denoting V, dV/dz, and d^2V/dV^2 are ●, ▲, and ■ respectively.

Fig. 10. Beam envelopes for injector four-electrode lens. Extractor potential is 70 kv; focus potential, 100 kv; $E_1 = 21$ kv; and $E_2 = 55$ kv. $\Delta = 0.25$ cm.

Fig. 11. Typical beam transport system.

Fig. 12. X emittance of second focus for 80-ma proton beam.

	375 kev	500 kev
Emittance of total beam	105 mrad-mm	91 mrad-mm
Emittance of 93% of total beam	67 mrad-mm	58 mrad-mm

Fig. 13. Y emittance at second focus for 80-ma proton beam.

	375 kev	500 kev
Emittance of total beam	127 mrad-mm	110 mrad-mm
Emittance of 92% of total beam	73 mrad-mm	63 mrad-mm

Fig. 14. Plot of beam current versus spectrograph magnet current at the second focus. Solenoids M 1 and M 2 are adjusted for maximum H^+ beam into 3/4-in.-diam cup. Beam energy is 370 kev. The M1 solenoid current is 376 amp. The M 2 solenoid current is 570 amp.

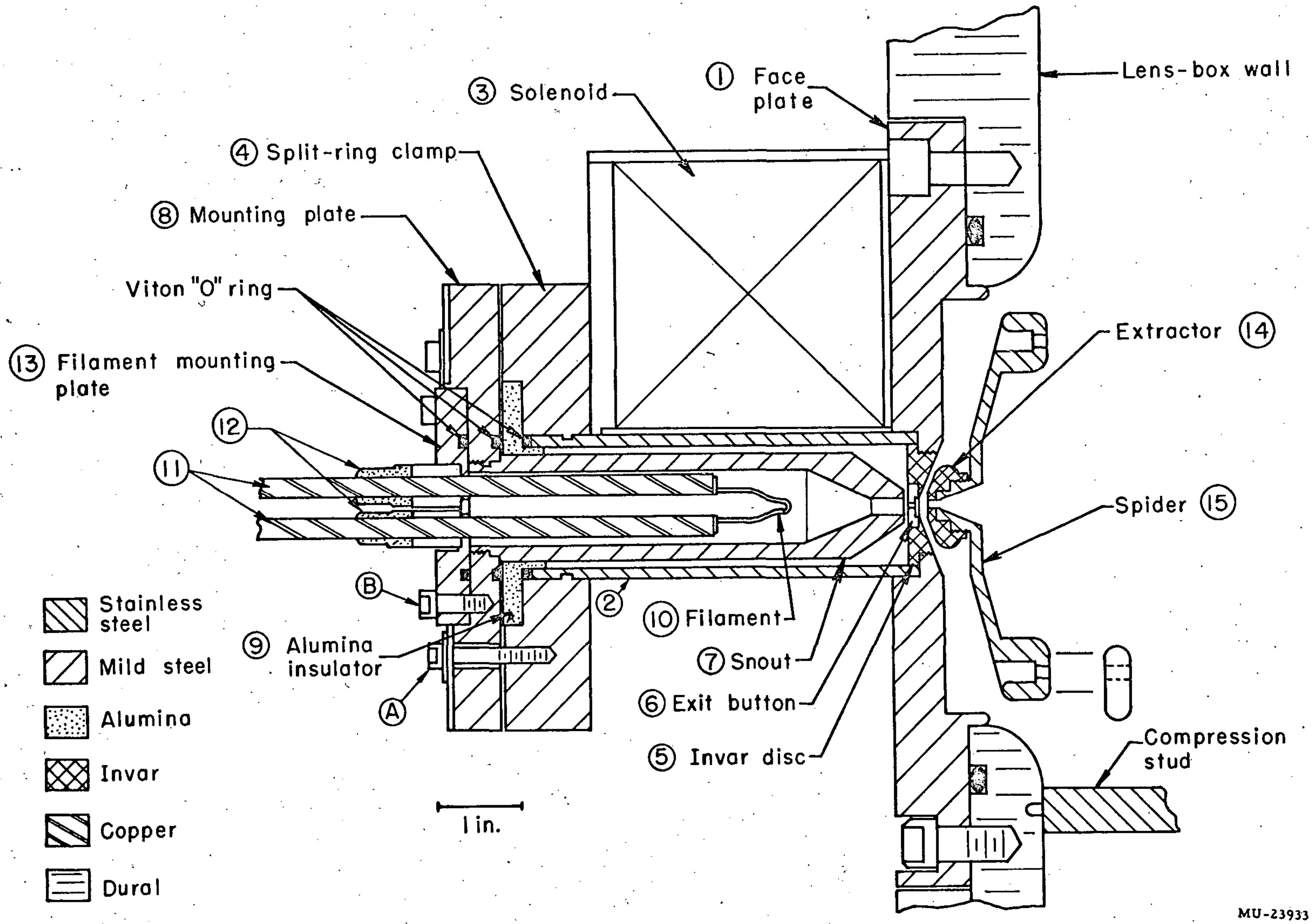

Lens-box wall
① Face plate
③ Solenoid
④ Split-ring clamp
⑧ Mounting plate
Viton "O" ring
⑬ Filament mounting plate
⑫
⑪
Extractor ⑭
Spider ⑮
Ⓑ
②
⑩ Filament
⑨ Alumina insulator
⑦ Snout
⑥ Exit button
Ⓐ
⑤ Invar disc
Compression stud
Stainless steel
Mild steel
Alumina
Invar
Copper
Dural
1 in.
MU-23933

Fig. 1

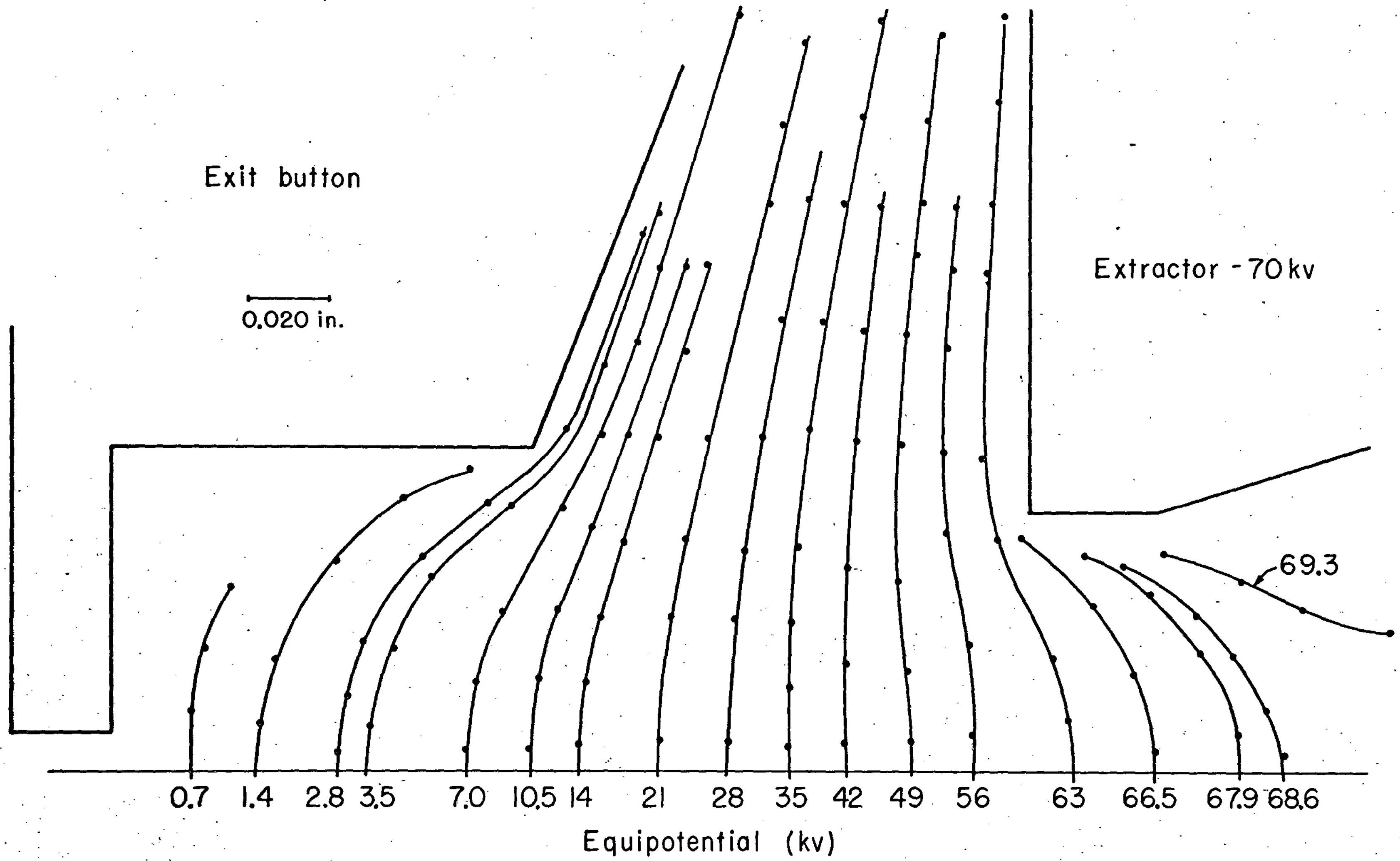

Exit button
0.020 in.
Extractor - 70 kv
69.3
0.7
1.4
2.8
3.5
7.0
10.5
14
21
28
35
42
49
56
63
66.5
67.9
68.6
Equipotential (kv)
MU-23934

Fig. 2

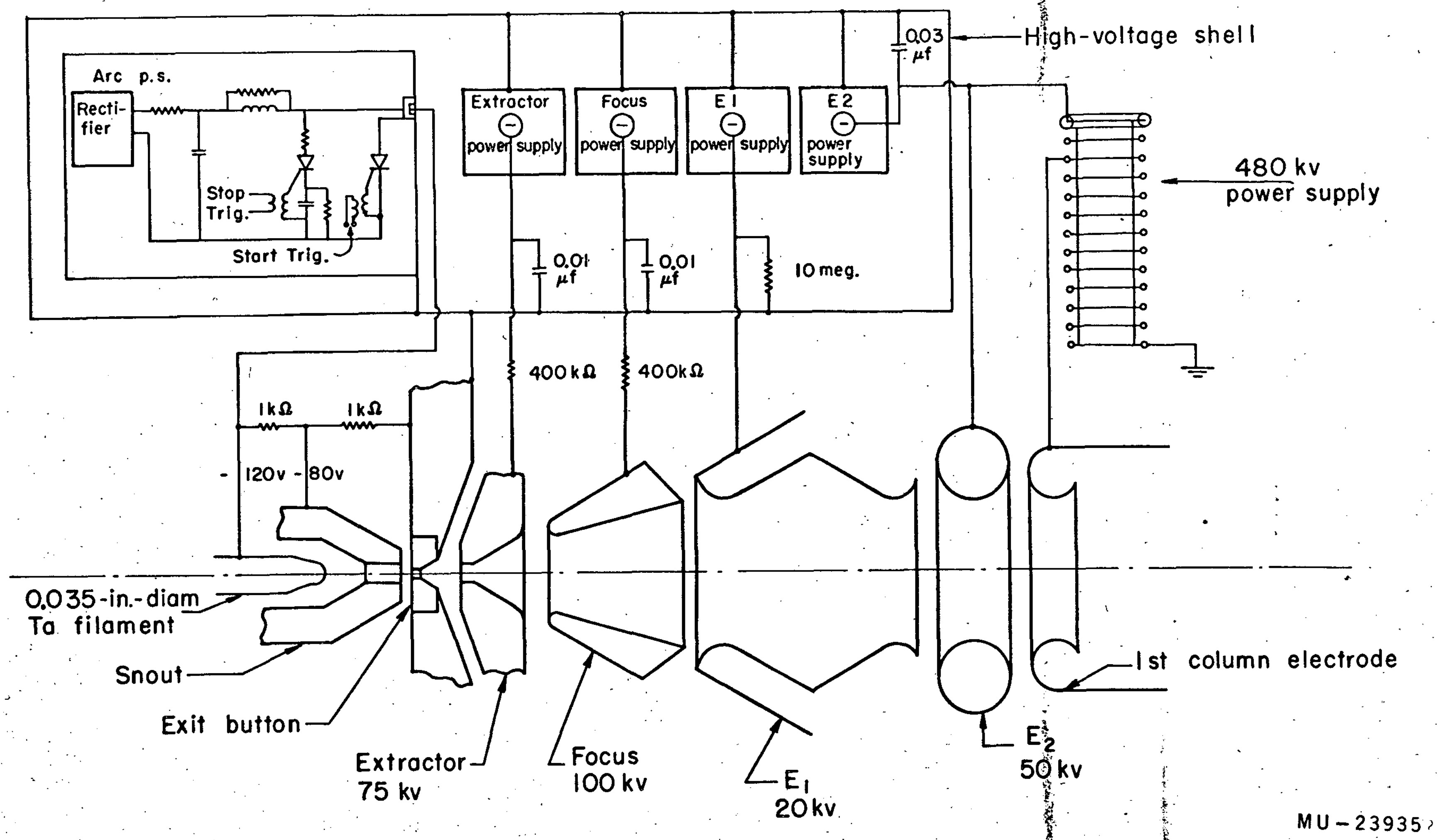

Arc p.s.
Recti-fier
Stop Trig.
Start Trig.
Extractor power supply
Focus power supply
E 1 power supply
E 2 power supply
0.03 μf
High-voltage shell
480 kv power supply
0.01 μf
0.01 μf
10 meg.
400 kΩ
400 kΩ
1 kΩ
1 kΩ
-120v
-80v
0.035-in.-diam Ta filament
Snout
Exit button
Extractor 75 kv
Focus 100 kv
E1 20 kv
E2 50 kv
1st column electrode
MU-23935

Fig. 3

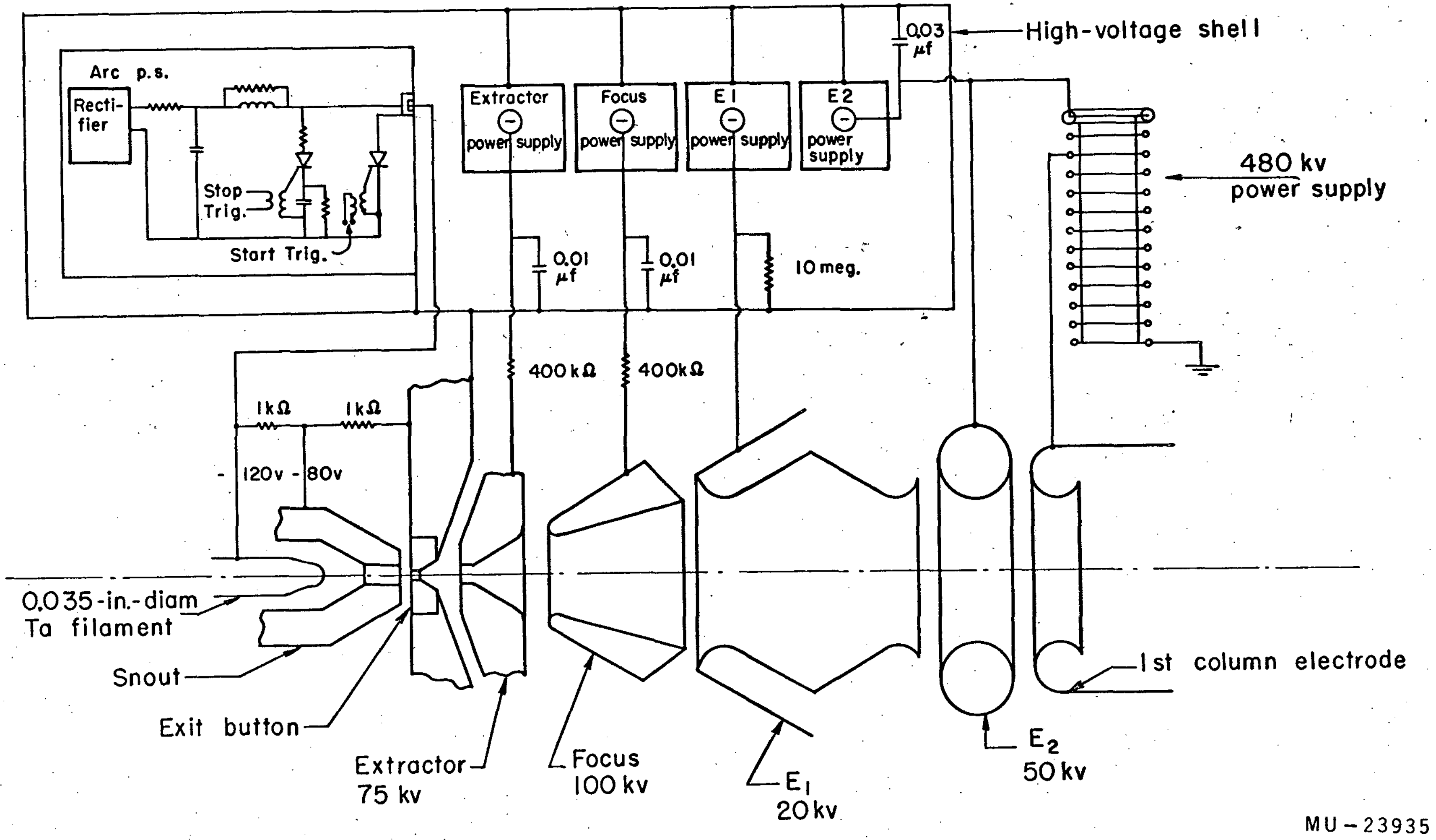

Arc p.s.
Recti-fier
Stop Trig.
Start Trig.
Extractor power supply
Focus power supply
E1 power supply
E2 power supply
0.03 μf
High-voltage shell
480 kv power supply
0.01 μf
0.01 μf
10 meg.
400 kΩ
400 kΩ
1 kΩ
1 kΩ
- 120v
- 80v
0.035-in.-diam Ta filament
Snout
Exit button
Extractor 75 kv
Focus 100 kv
E1 20 kv
E2 50 kv
1st column electrode
MU-23935

Fig. 3

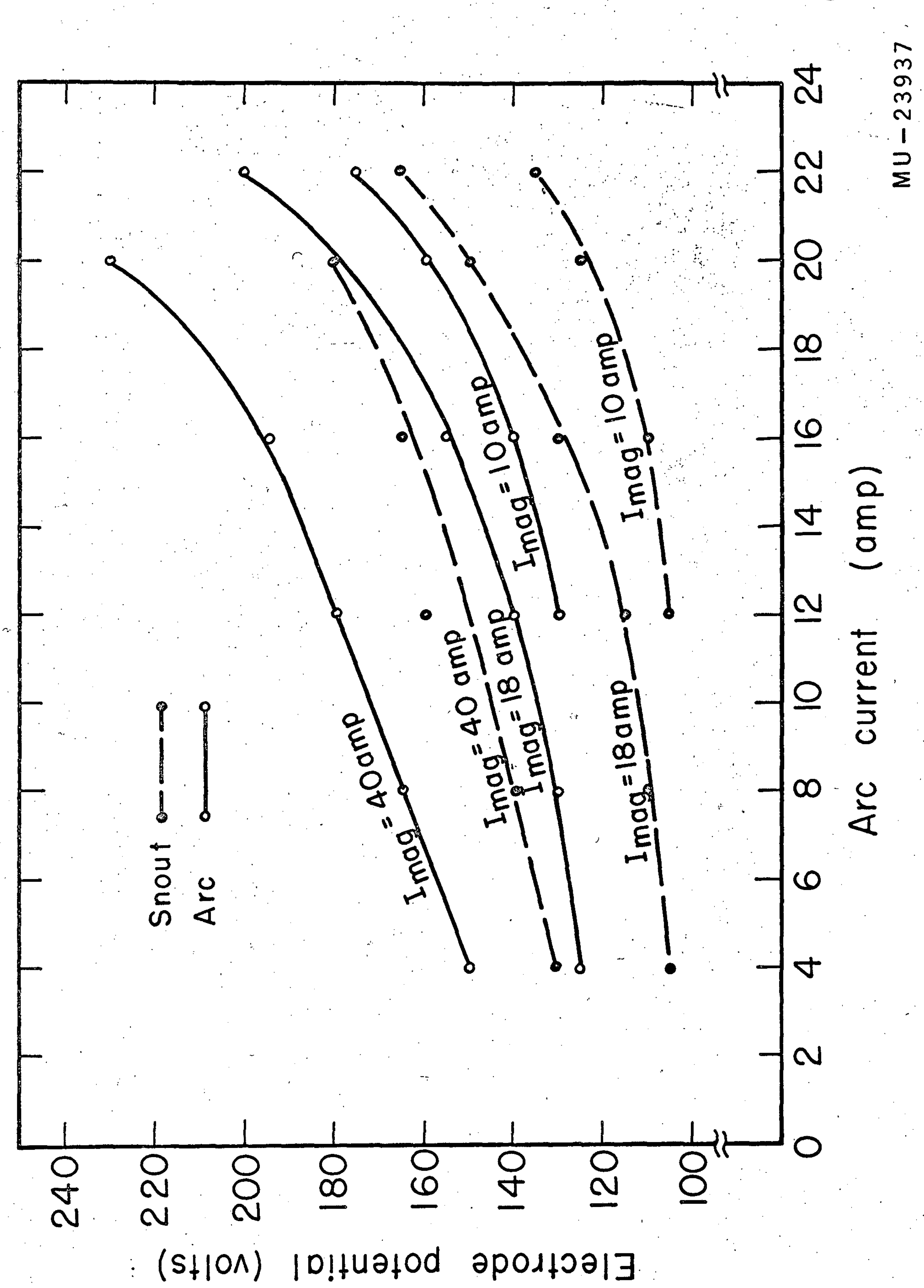
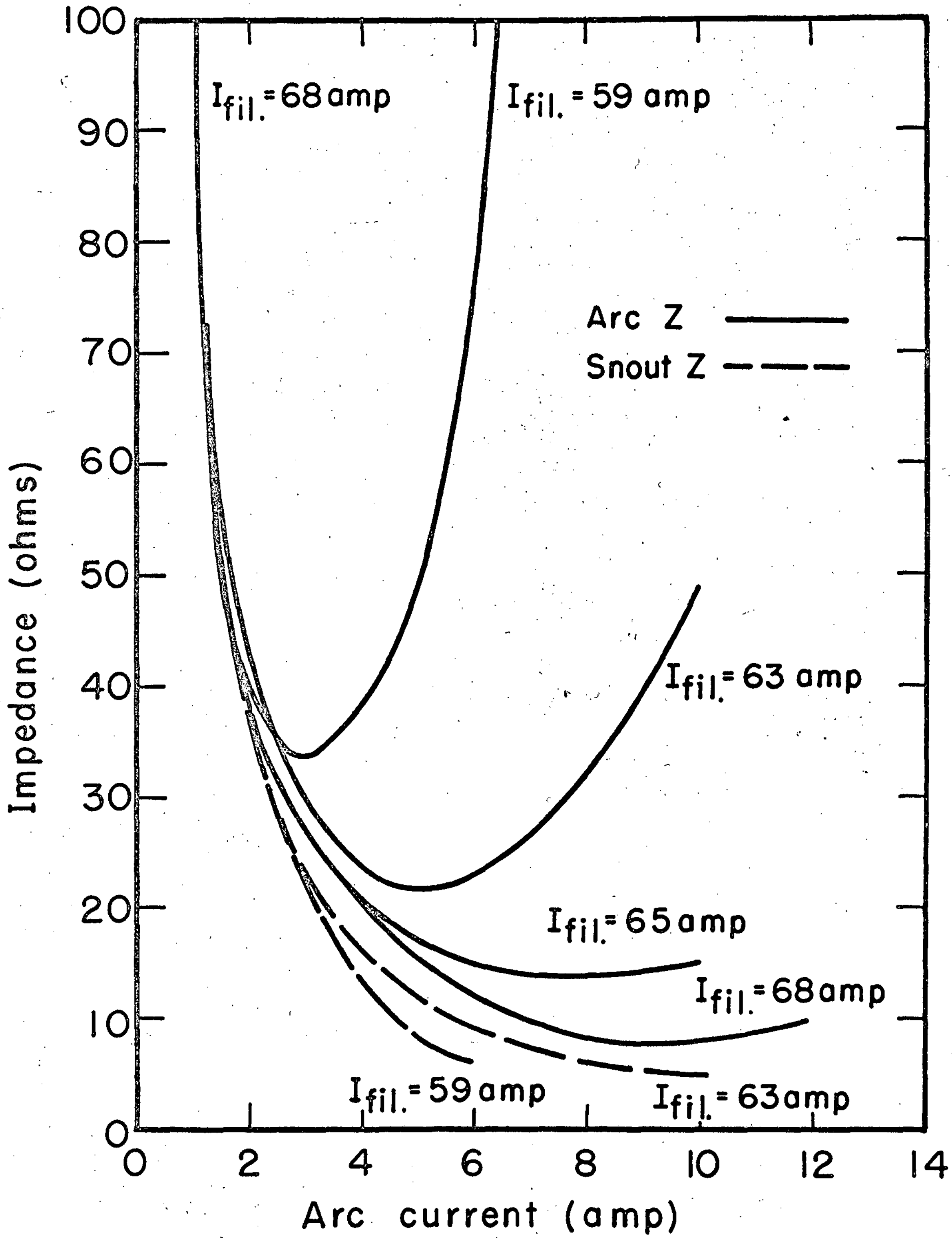
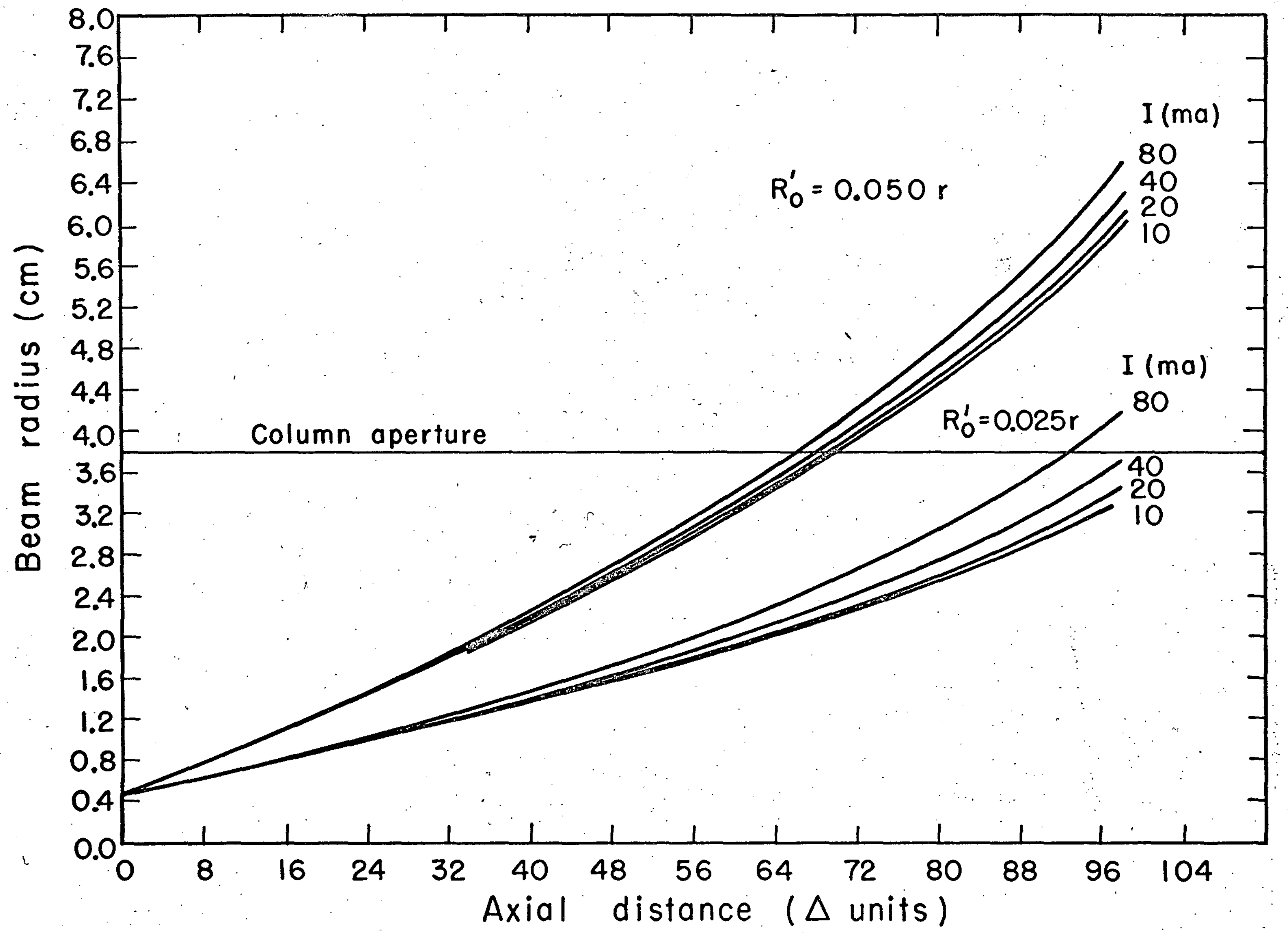

Snout
Arc
Imag = 40amp
Imag = 40 amp
Imag = 18 amp
Imag = 10amp
Imag = 18amp
Imag = 10amp
Electrode potential (volts)
Arc current (amp)
240
220
200
180
160
140
120
100
0
2
4
6
8
10
12
14
16
18
20
22
24
MU-23937

Fig. 4



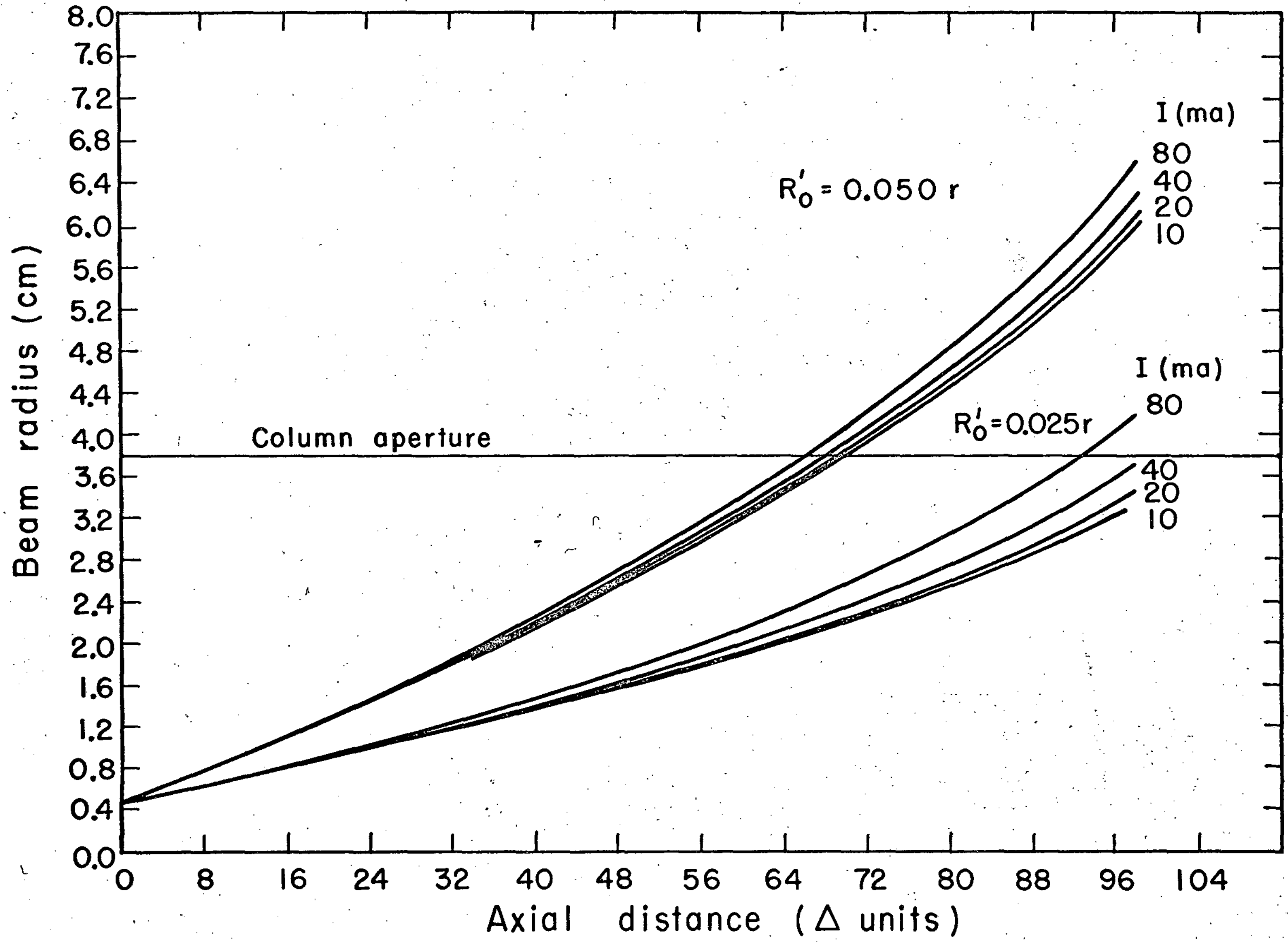
MU−23939

Fig. 5



MU-23940

Fig. 6



MU-23940

Fig. 6

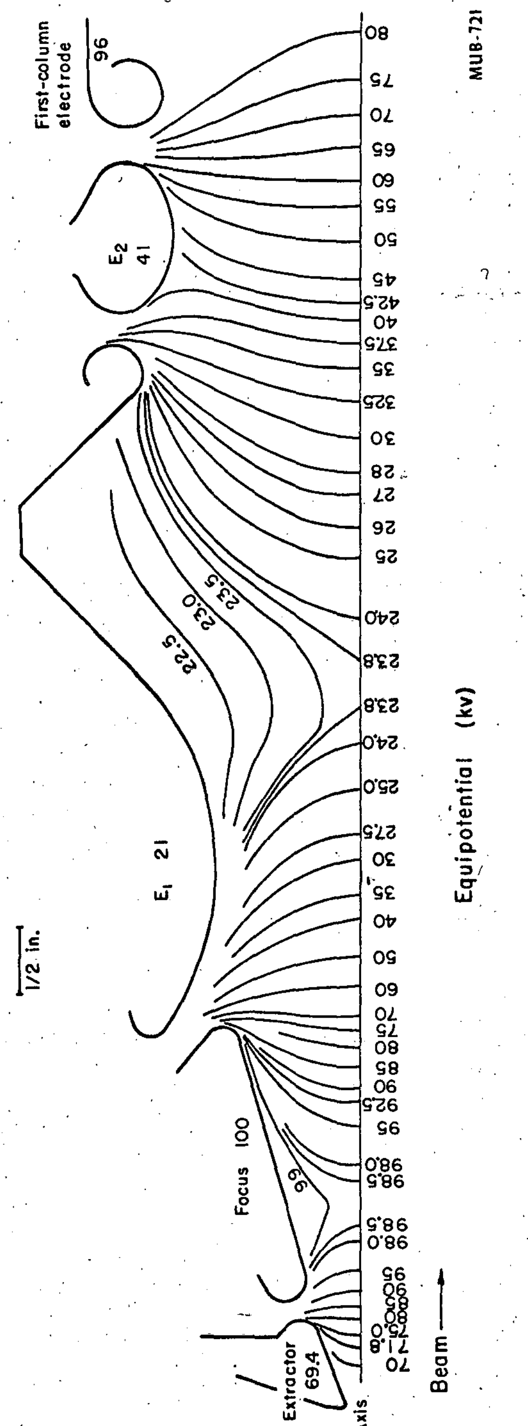
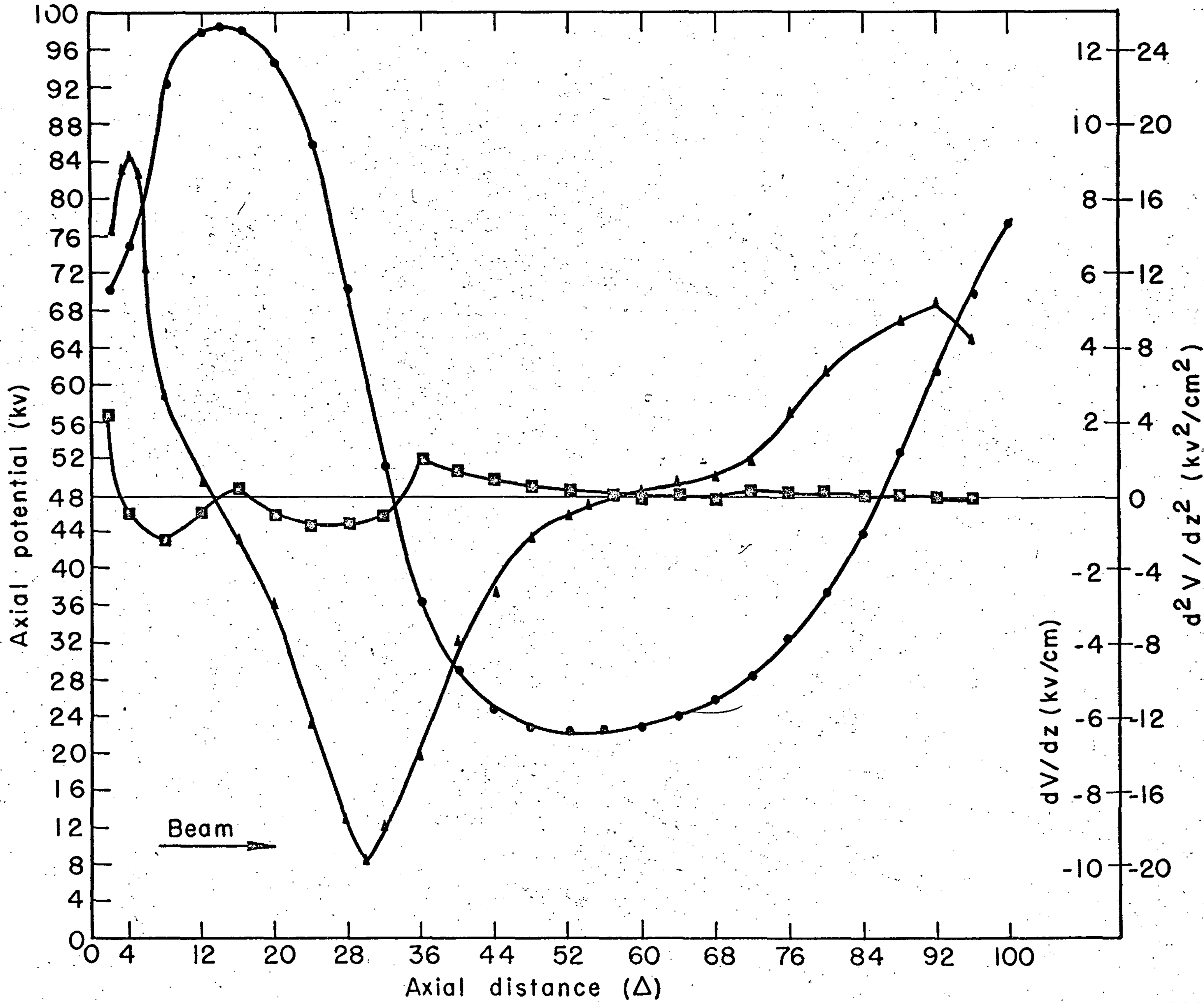

First-column electrode
96
E2 41
E1 21
Focus 100
99
Extractor 69.4
Axis
Beam
1/2 in.
Equipotential (kv)
MUB-721

Fig. 8



MU-23941

Fig. 9

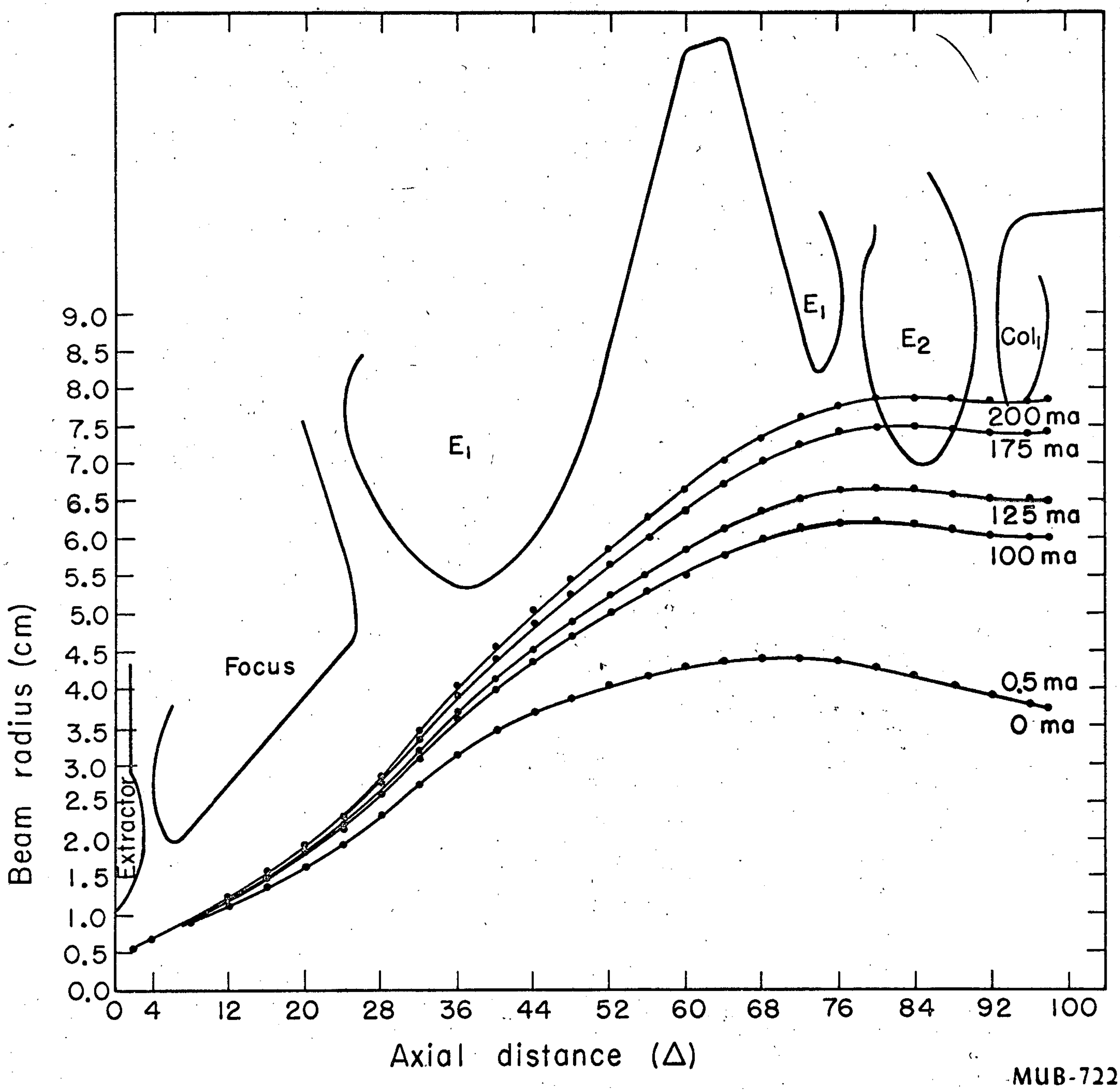
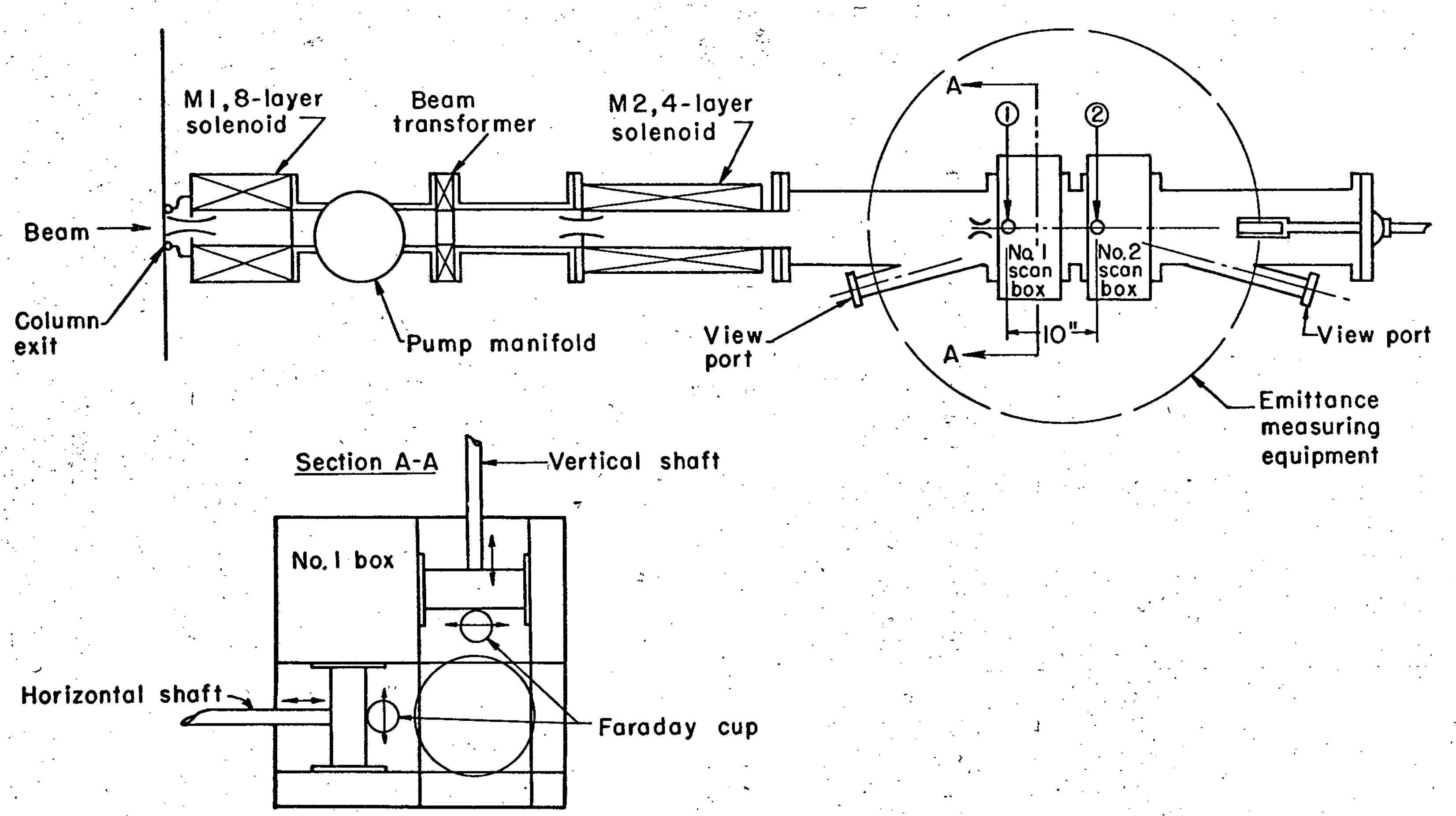

Beam radius (cm)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 4 12 20 28 36 44 52 60 68 76 84 92 100
Axial distance (Δ)
Extractor
Focus
E_1
E_1
E_2
Col_1
200 ma
175 ma
125 ma
100 ma
0.5 ma
0 ma
MUB-722

Fig. 10



MU-23942

Fig. 11

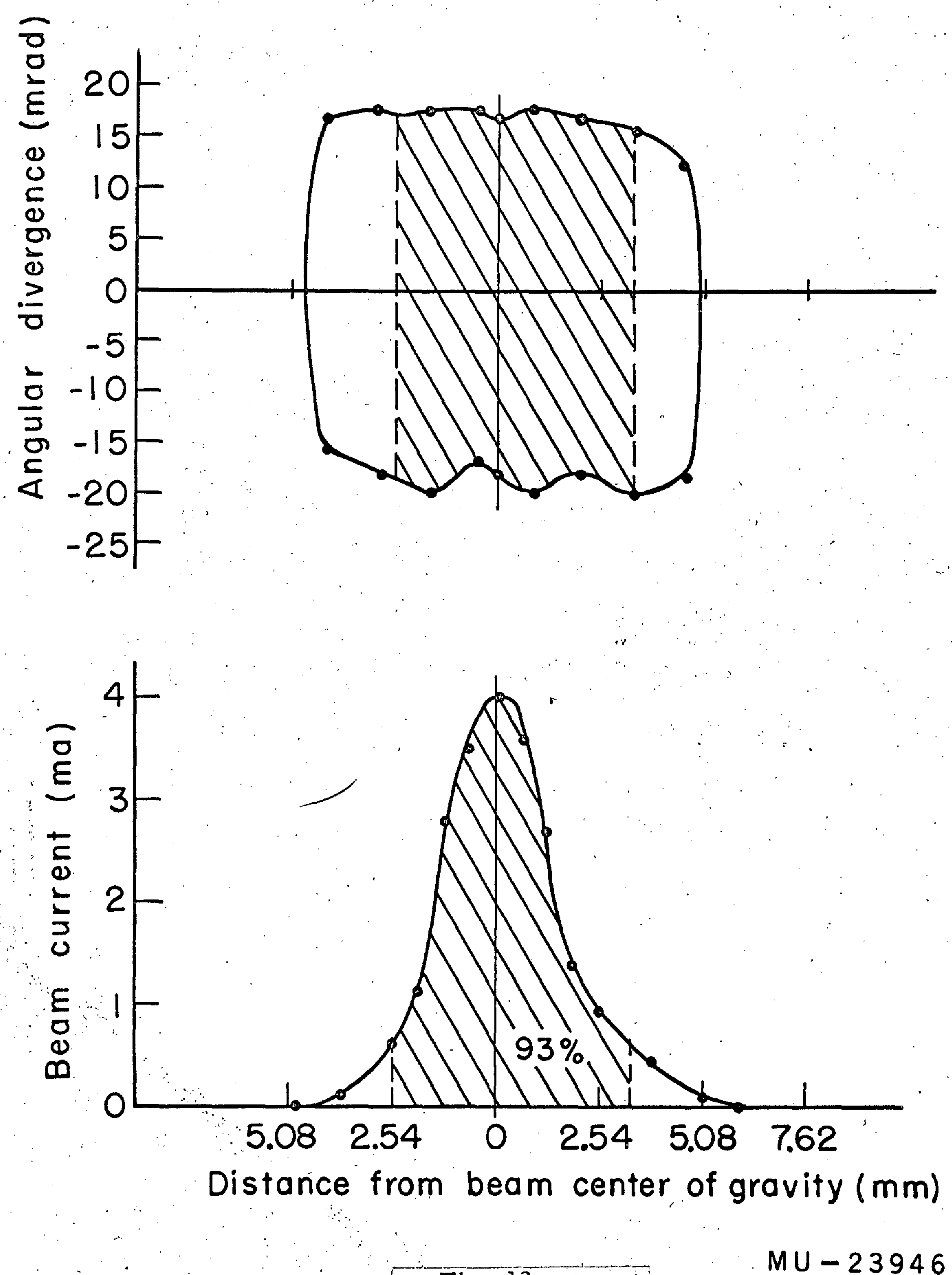
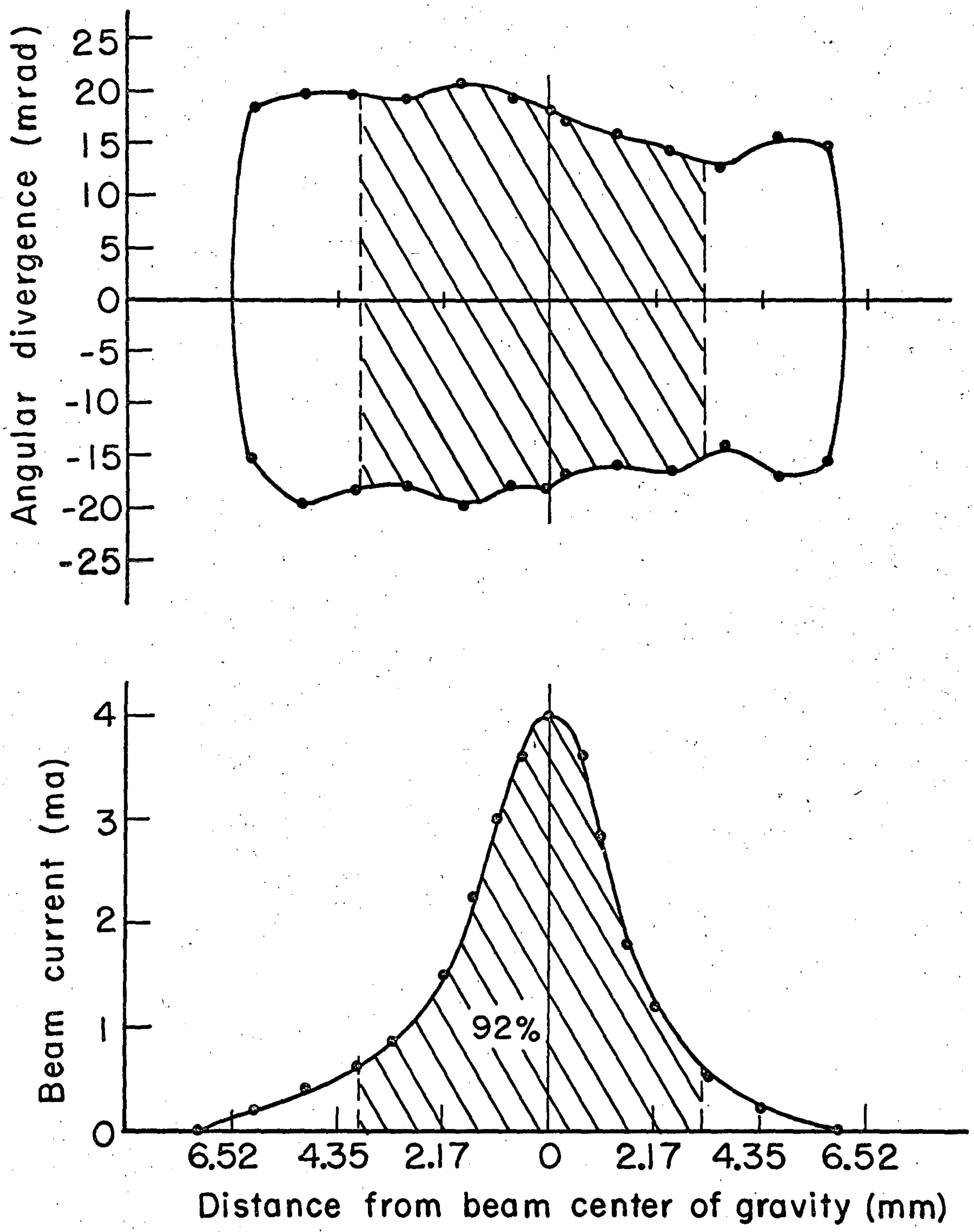
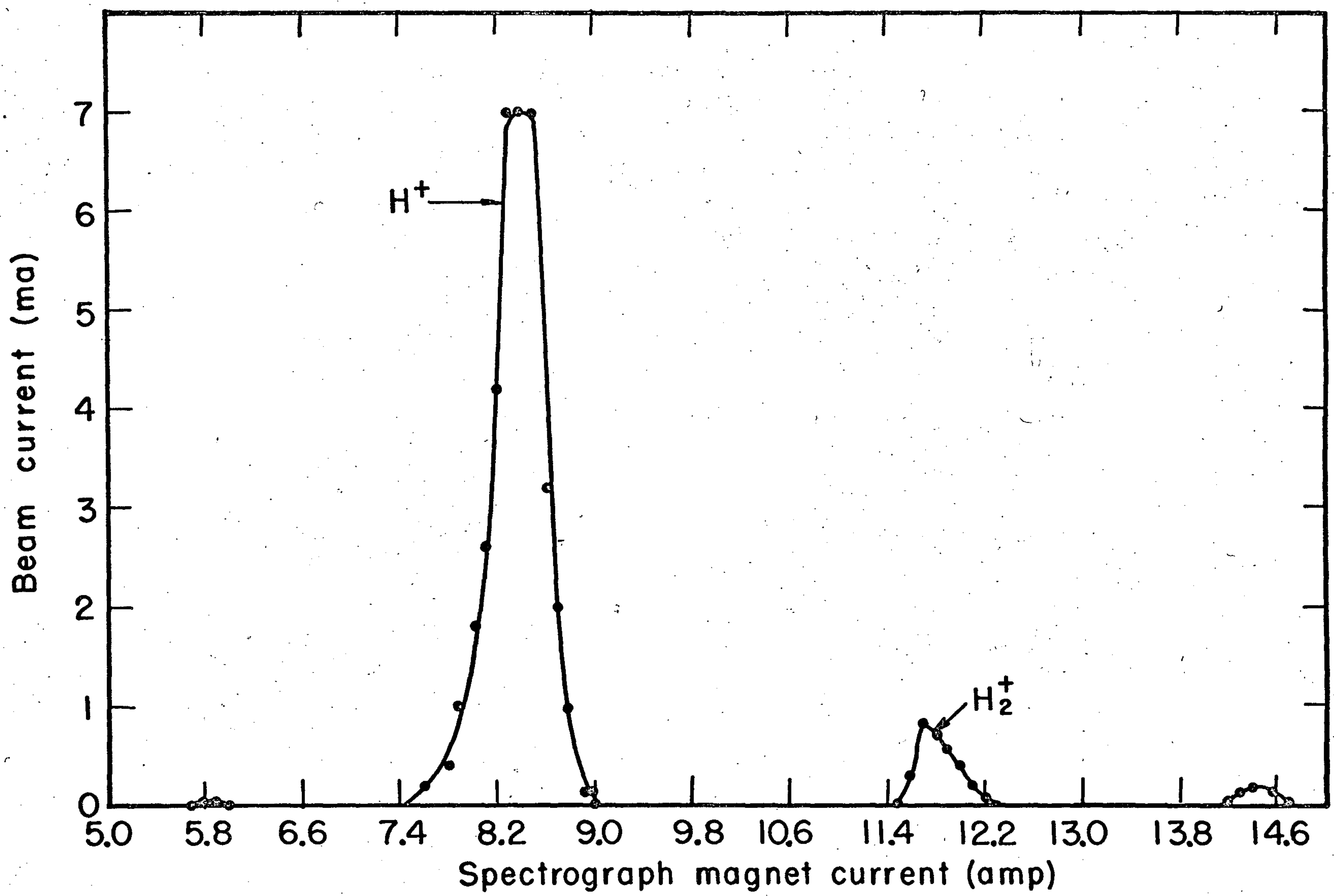

Angular divergence (mrad)
20
15
10
5
0
-5
-10
-15
-20
-25
Beam current (ma)
4
3
2
1
0
93%
5.08 2.54 0 2.54 5.08 7.62
Distance from beam center of gravity (mm)
MU-23946

Fig. 12



MU-23947

Fig. 13



MU-23950

Fig. 14