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A HIGH BRIGHTNESS PLASMA SPUTTER HEAVY NEGATIVE ION SOURCE*

G. D. Alton

Oak Ridge National Laboratory

Oak Ridge, Tennessee 37831-6368

and

Y. Mori, A. Takagi, A. Ueno, and S. Fukumoto

National Laboratory for High Energy Physics

Ibaraki-ken, Japan.

ABSTRACT

A high-intensity, pulsed-mode, plasma-sputter heavy negative ion source has been developed; this source holds promise for a number of uses, including tandem electrostatic accelerator/synchrotron injection applications. To date, the source has been used to generate mA intensities from more than 18 sputter probes. A brief description of the source and typical performance data for a number of ion species are given. In addition, basic ion source operational data, such as intensity versus cesium oven temperature, sputter probe voltage, and discharge pressure, along with emittance data, are presented.

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I. Introduction

In recent years, the synchrotron has been used or considered for use for acceleration and storage of heavy ion beams for use in high-energy atomic and nuclear physics research. Facilities predicated on this principle have been constructed or are being constructed around the world. Noteworthy examples of such facilities are those at the Gessellschaft für Schwerionenforschung (GSI) and the Max Planck Institut für Kernphysik, West Germany, the University of Aarhus in Denmark, and the Alternating Gradient Synchrotron (AGS) facility at Brookhaven National Laboratory in the United States. Still, other facilities, such as the Heavy Ion Storage Ring for Atomic Physics (HISTRAP) at the Oak Ridge National Laboratory (ORNL), are proposed. If funded, the Holifield Heavy Ion Research Facility (HHIRF) 25-URC tandem electrostatic accelerator would serve as the injector. For this type of heavy ion accelerator, high-intensity pulsed beams of widths 50-300 μs at repetition rates of 1-50 Hz of a wide spectrum of elements are required. The low-duty-factor injection requirements of the synchrotron (typically, 10^{-3}) place a premium on ion sources with high-intensity capabilities. The specific need of the proposed tandem electrostatic accelerator HISTRAP facility for a high-brightness negative ion source with a wide range of species capabilities was the primary motivating factor which led to the present developments.

Only recently has the tandem electrostatic accelerator been considered for use as an injector for synchrotron heavy ion accelerators. Negative ion beam intensities of $\simeq$ 200 μA (peak intensity) represent a practical requirement of the ion source when the tandem accelerator is used as an injector for the synchrotron. Intensity levels of this magnitude are achievable for a limited number of relatively high electron affinity atomic and molecular species in negative ion sources based on the cesium ion sputter generation principle (see e.g., Refs. 1-3). Such intensity levels are marginally adequate at the point of injection into the synchrotron due to charge state fractionation during the stripping process and beam transmission losses in the tandem accelerator and beam transport system. Increased beam intensities from the source of a wide spectrum of negative ion species, at least to the level that the tandem accelerator becomes the limiting factor, are, therefore, desirable. The source described in this paper and other reports[4,5] has the potential of meeting the intensity and species requirements of tandem electrostatic accelerator/heavy ion synchrotron applications.

Because of the intrinsically low stored energy characteristic of the tandem accelerator and the desirability for injecting beam intensities as high as practicable into the synchrotron, the effects of high-intensity, pulsed-mode ion beams on the terminal voltage (droop) and operational stability of the accelerator are technical issues that must be addressed. The results of previous experiments performed at BNL[6] and ORNL[7] at intensity levels up to 200 μA and more recent injection experiments performed with the subject source at BNL[8] at intensity levels up to 400 μA for Au^- and 700 μA for Si^-, however, indicate no deleterious effects on the stability of operation of the large tandem electrostatic accelerators. The droop in terminal voltage induced by mA, pulsed ion beams (typically, a few kilovolts) can easily be compensated for by ion energy modulation techniques and, therefore, is not considered to be a serious problem.

2.0 Source Description

The multi-cusp magnetic field plasma surface source, routinely employed for the production of high-intensity pulsed H^- ion beams at the Los Alamos National Laboratory (LANL)[9] and at the National Laboratory for High Energy Physics[10] has recently been modified for use as a high-intensity pulsed-mode heavy negative ion source.[4,5] The design details, operational parameters, and performance characteristics for H^- generation have been reported previously (see e.g., Refs. 9 and 10), while those for heavy ion generation have been described in Refs. 4 and 5. The source modified for heavy negative ion generation, and the experimental set-up used during evaluation of the source are shown schematically in Fig. 1.

For heavy negative ion generation, a high-density plasma discharge, seeded with cesium vapor, is produced by pulsing the discharge voltage of two series connected LaB_6 cathodes maintained at ~ 1450°C. For this application, the negatively biased spherical geometry probe (converter) is made of the material of interest and as such, is a consumable item, i.e., negative ions are formed by plasma discharge sputtering of the probe itself. In order to produce higher heavy negative ion beam intensities by sputter ejection at a given probe voltage, a chemically inert, heavy discharge support gas such as Ar, Kr, or Xe, is utilized. Xe was used throughout the present measurements. Cesium is introduced into the discharge from an external cesium oven operated typically at a temperature of ~ 215°C. The sheath surrounding the negatively biased sputter probe (spherical radius, ρ = 140 mm and diameter, ϕ = 50 mm) is maintained at a negative voltage relative to housing, (typically, $\leq$ 1000 V) and serves as the first acceleration gap and lens for focusing the ion beam through the exit aperture (diameter, ϕ = 18 mm). Under pulsed-mode operation at the low duty factors utilized, (typically, 2 x 10^{-3}), the LaB_6 cathodes exhibit very little erosion after many hours of operation. With the combined long lifetimes of the sputter probe, LaB_6 cathodes, and low cesium consumption rate (~ < 1 mg/h), the source can operate stably for a few thousand hours at constant peak beam intensity levels without maintenance or cleaning.

2.1 Ion Optical Studies.

The advantage of the plasma-type sputter negative ion source lies in the fact that, when operated in a high-density plasma mode, the negatively biased sputter probe containing the material of interest is uniformly sputtered. This characteristic makes it possible to take advantage of the large area spherical geometry lens system which is formed between the spherical sector sputter probe and the plasma sheath which conforms to the geometry of the probe. Negative ions created in the sputter process are accelerated and focused through the plasma to a common focal point, usually chosen as the ion exit aperture of the source, and then pass into the field region of the extraction electrode system. Within the plasma, the ion beam is free of space charge effects. Thus, the sputtered particle energy/angular distributions and aberrations in the acceleration plasma lens system determine the beam size at the focal point of the spherical lens system. At high beam intensities, space charge effects are expected to come into play whenever the beam exits the plasma and enters the extraction region of the source. However, because the beam energy is 500 to 1000 eV upon exit from the plasma region of the source, space charge influences on the beam are reduced.

The ion optics of the ion generation and extraction regions of the source have been studied computationally. Examples of such calculations are shown in Figs. 2 and 3, which display ion trajectories for 1- and 2-mA Au^- and 3.5- and 7-mA O^- ion beams generated at the sputter probe surface and accelerated through the field-free region of the plasma and finally into the extraction lens system at energies up to 81 keV. This extraction electrode system is presently being considered for use with a source under design at ORNL and is a duplicate of the extraction system used at LAMPF.[9] The space charge effects within the two beams shown in Figs. 2 and 3, respectively, are identical. Space charge effects, of course, can be reduced by postaccelerating to higher energies. In the calculations shown in Figs. 2 and 3, no effort was made to simulate the intrinsic energy-angular distributions associated with the sputtering process. The phase spaces of ion beams from this source will be affected by the energy-angular distribution of the sputtered particles, as well as by space charge effects.

3.0 Experimental Procedures and Results.

The plasma sputter negative ion source, equipped with a chosen sputter probe, was evaluated by use of the ion source test stand displayed in Fig. 1.[4,5] In addition to the ion source, the test stand is equipped with a three-cylinder einzel lens which is used to focus the ion beam into a remotely positionable, electron suppressed Faraday cup and an automatic emittance measuring device which can be inserted into the ion beam. A permanent magnet (strength: $B \simeq 600$ G), located immediately following the einzel lens, is used to deflect residual electrons which are not otherwise trapped by the dipole magnetic field positioned at the exit aperture of the source. These provisions were made to ensure that only heavy ions were transported to and detected by the Faraday cup. Following operational parameter optimization studies, the emittance of a particular ion beam can be measured by inserting a stepping motor controlled emittance detector unit into the ion beam.

The mass distributions of total extracted ion currents were measured by altering the experimental apparatus shown in Fig. 1. The alterations to the experimental apparatus for this purpose are shown as dotted lines in Fig. 1. Basically, the magnetic field was increased to ~ 1 kG and 1-mm slits were placed at the entrance to the magnetic field and the positionable Faraday cup. The mass distribution associated with each of the sputter probes was then determined by measuring the intensity distribution as a function of Faraday cup position.

3.1 Source Operational Parameter Studies.

Sputter probes, identical in shape and size to that of the Mo converter used for H^- generation, were fabricated from chosen solid materials for the generation of ion beams. For the most part, spherical geometry sputter probes were used; however, in certain cases, planar geometry probes of equivalent diameter (ϕ = 50 mm) were evaluated. The planar geometry compromises, by an unknown degree, the ion extraction efficiency of beams produced from this probe. Based on simple geometric area ratio arguments, ion beam intensities extracted from planar probes could be lower by a factor of 7.7 in comparison to those from spherical geometry probes. The ratio of total beam intensities obtained from planar and spherical geometry Mo sputter probes approximately agree with this prediction, while for other sputter probes the factor has been found to be approximately 4.5.

Intensity versus cesium oven temperature. Negative ion beam intensity versus cesium oven flow rate was measured at fixed sputter probe voltage, Xe discharge pressure, and discharge current. Relative negative ion beam intensity versus cesium oven temperature data for a Cu sputter probe, typical of all sputter probes investigated, is shown in Fig. 4. The optimum cesium flow rate was found to occur at essentially the same temperature (~ 215°C) for all sputter probes investigated.

Intensity versus sputter probe voltage. Following the intensity versus cesium oven temperature measurements, the relationship between ion beam intensity and sputter probe voltage was determined at the optimum cesium flow rate and fixed Xe discharge pressure. Such data are shown in Fig. 5 for Pt and Si sputter probes.

Intensity versus discharge pressure. Typical relative intensity versus Xe discharge pressure data from a Ni sputter probe at a fixed sputter probe voltage is displayed in Fig. 6. As is evident from these data, beam intensity losses due to collisional detachment processes in the external region of the source increase only moderately with increasing Xe discharge.

3.2 Negative Ion Beam Intensity/Mass Distribution Data.

Intensity versus time distributions of ion beams extracted from Pt and Si probes, respectively, are shown in Figs. 7 and 8; the measurements were made at optimum or near optimum cesium flow rate, Xe discharge pressure, and at fixed sputter probe voltage. The approximate mass distributions of the respective beams are shown in Figs. 9 and 10.

Table 1 provides a partial list of total negative ion beam intensities, species and probe materials utilized during operation of the source. Also given are the approximate mass distributions of the principal negative ion species present in the total negative ion beam. Typical source operational parameters used during these measurements are displayed in Table 2.

3.3 Emittance Measurements.

Emittance measurements were made by use of the stepping motor-driven emittance detector unit shown schematically in Fig. 1. Normalized emittance ε_n is defined according to

$$\varepsilon_{nx} = \pi\, x\, x' \sqrt{E\,(\mathrm{MeV})}\left[\pi\ \mathrm{mm.mrad}\,(\mathrm{MeV})^{1/2}\right]$$

and

$$\varepsilon_{ny} = \pi\, y\, y' \sqrt{E\,(\mathrm{MeV})}\left[\pi\ \mathrm{mm.mrad}\,(\mathrm{MeV})^{1/2}\right]$$

for the respective x and y directions where x, y are position, and x′ and y′ are the angular coordinates in the respective directions. Normalized emittance versus percent total ion beam for Ni beams of 2.5 and 6 mA are displayed in Fig. 11. As noted, the emittances increase with beam intensity as expected, based on space charge effects. The normalized emittances of the Ni^- are found to have typical values for the 80% contour level of $\varepsilon_n = \sim 25\,\pi$ mm.mrad $(\mathrm{MeV})^{1/2}$. This value is only ~ 1.5 times those of cesium sputter negative ion sources when operated in pulsed mode.[11] However, the beam intensities from this source are often 30 to 100 times greater than cesium sputter negative ion sources.

5.0 Discussion.

The high-intensity, plasma sputter negative ion source has proved to be a reliable, stably operating source with an extremely long lifetime, which can provide a wide spectrum of negative ion beams suitable for a variety of applications. The intensity levels obtained are often higher by factors of 30 to 100 than those which can be generated in cesium sputter-type sources such as described in Refs. 1-3. The emittances of ion beams extracted from the source are found to be dependent on ion beam intensity as expected from the effects of space charge within the respective ion beams. The emittance values compare favorably with the calculated acceptance of the ORNL 25-URC tandem accelerator[12] and, in principle, ion beams from this source should be transportable through such devices. However, consideration must be given in designing the ion extraction, postacceleration, and low-energy transport systems of the source and tandem injector in order to reduce space charge distortion of the emittances of the ion beams. The source is well suited for use in conjunction with the tandem electrostatic accelerator as a synchrotron injector. The source holds the interesting prospect for use in producing dc, mA intensities of a wide range of species, including the commonly used semiconducting material dopants (e.g., B^-, P^-, As^-, and Sb^-), as well as O^-, for high-energy isolation barrier formation.

Acknowledgements

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References

1. R. Middleton, Nucl. Instrum. and Meth. 214 (1983) 139.
2. G. D. Alton, Nucl. Instrum. and Meth. A244 (1986) 133.
3. G. D. Alton and G. D. Mills, IEEE Trans. Nucl. Sci. NS-32 (5) (1985) 1822.
4. G. D. Alton, Y. Mori, A. Takagi, A. Ueno, and S. Fukumoto, Nucl. Instrum. and Meth. A270 (1988) 194.
5. Y. Mori, G. D. Alton, A, Takagi, A. Ueno, and S. Fukumoto, accepted for publication in Nucl. Instrum. and Meth.
6. P. Thieberger, M. McKeown and H. E. Wegner, IEEE Trans. Nucl. Sci. NS-30 (40) (1983) 2749.
7. G. D. Alton and C. M. Jones, Nucl. Instrum. and Meth. A244 (1986) 170.
8. P. Thieberger, H. Wegner, Y. Mori, A. Takagi, K. Ikegami, and G. D. Alton (unpublished).
9. R. L. York and R. R. Stevens, in Proceedings of the Third International Conference on Production of Negative Ions and Beams, edited by Krysto Prelec. (American Institute of Physics Conference Proceedings No. 111, New York, 1984) p. 410.
10. Y. Mori, A. Takagi, K. Ikegami, and S. Fukumoto, in Proceedings of Fourth International Conference on Production and Neutralization of Negative Ions and Beams, edited by James G. Alessi (American Institute of Physics Conference Proceedings No. 158, New York, 1987) P. 378.
11. G. D. Alton, Phys. Div. Progress Report, ORNL-6420, September 30, 1987, p. 222.
12. J. D. Larson and C. M. Jones, Nucl. Instrum. and Meth. 140 (1977) 489.

Figure Captions:

1. Schematic drawing of the plasma sputter negative ion source, experimental apparatus and emittance measurement device used to evaluate the source for heavy negative ion beam generation. The dotted lines show the positions of the slit apertures and alterations to the permanent magnet used to determine the mass distribution within a particular ion beam.
2. Simulation of ion optics of the high-intensity plasma sputter negative ion source for 1 mA Au^- or 3.5 mA O^- ion beams. Ion energy: 81 keV.
3. Simulation of the ion optics of the high-intensity plasma sputter negative ion source for 2 mA Au^- or 7 mA O^- ion beams. Ion energy: 81 keV.
4. Peak negative ion beam intensity versus cesium oven temperature from a Cu sputter probes. Sputter probe voltage: – 500 V.
5. Peak negative ion beam intensity versus sputter probe voltage from Pt and Si sputter probe. Cesium oven temperature: 215°C.
6. Relative peak negative ion beam intensity versus Xe discharge support gas pressure from a Ni probe. Sputter probe voltage: – 500 V; Cesium oven temperature: 215°C.
7. Intensity versus time distribution of the total ion current extracted from a Pt sputter probe at a voltage of – 1000 V and optimum cesium flow rate (cesium oven temperature ~ 215°C). Vertical axis: 2 mA/division. Horizontal axis: 50 μs/division.
8. Relative negative ion beam intensity distribution from a P_t sputter probe as a function of Faraday cup position. Sputter probe voltage: – 1000 V.

9. Intensity versus time distribution of the total ion current extracted from a Si sputter probe at a voltage of – 1000 V and optimum cesium flow rate (cesium oven temperature: ~ 215°C). Vertical axis: 1 mA/division. Horizontal axis: 50 μs/division.
10. Relative negative ion beam intensity distribution from a Si sputter probe as a function of Faraday cup position. Sputter probe voltage: –1000 V.
11. Normalized emittance ε versus percentage total negative ion beam from a Ni sputter probe.

Table 1. A partial list of total heavy negative ion beam intensities (peak) from the high-brightness plasma sputter negative ion source.

Sputter Probe Material	Sputter Probe Voltage (V)	Geometry	Total Peak Beam Intensity (mA)	Species (%)
Ag	937	Spherical	6.2	Ag^- (91)
Au	437	Spherical	10.3	Au^- (73)
Bi	937	Spherical	2.7	Bi^- (6); O^- (42)
C	937	Spherical	6.0	C^- (36): C_2^- (58)
Co	937	Spherical	6.0	Co^- (85)
Cu	438	Spherical	8.2	Cu^- (77)
CuO	438	Flat	4.5	Cu^- (40); O^- (60)
GaAs	937	Flat	3.7	As^- (20); As_2 (52)
GaP	937	Flat	1.8	P^- (44)
Mo	438	Spherical	30.0	O^- (67)
Ni	438	Spherical	6.0	Ni^- (87)
Pd	937	Spherical	7.6	Pd^- (69)
Pt	937	Spherical	8.1	Pt^- (71)
Si	937	Spherical	6.0	Si^- (75)
Sn	937	Spherical	3.6	Sn^- (67)

Table 2. Typical operating parameters of the negative heavy ion source.

Arc Current	15 - 20 A
Arc Voltage	30 - 60 V
Filament Current	130 A
Filament Temperature	1450°C
Xe Gas Pressure	1.8 x 10^{-4} Torr
Sputter Probe Voltage	–500 V –> –1000 V
Beam Extraction Voltage	–20 kV
Cesium Oven Temperature	215°C
Beams Pulse Width	100 - 200 μs
Repetition Rate	5 - 20 Hz

ORNL-DWG 88-7161R

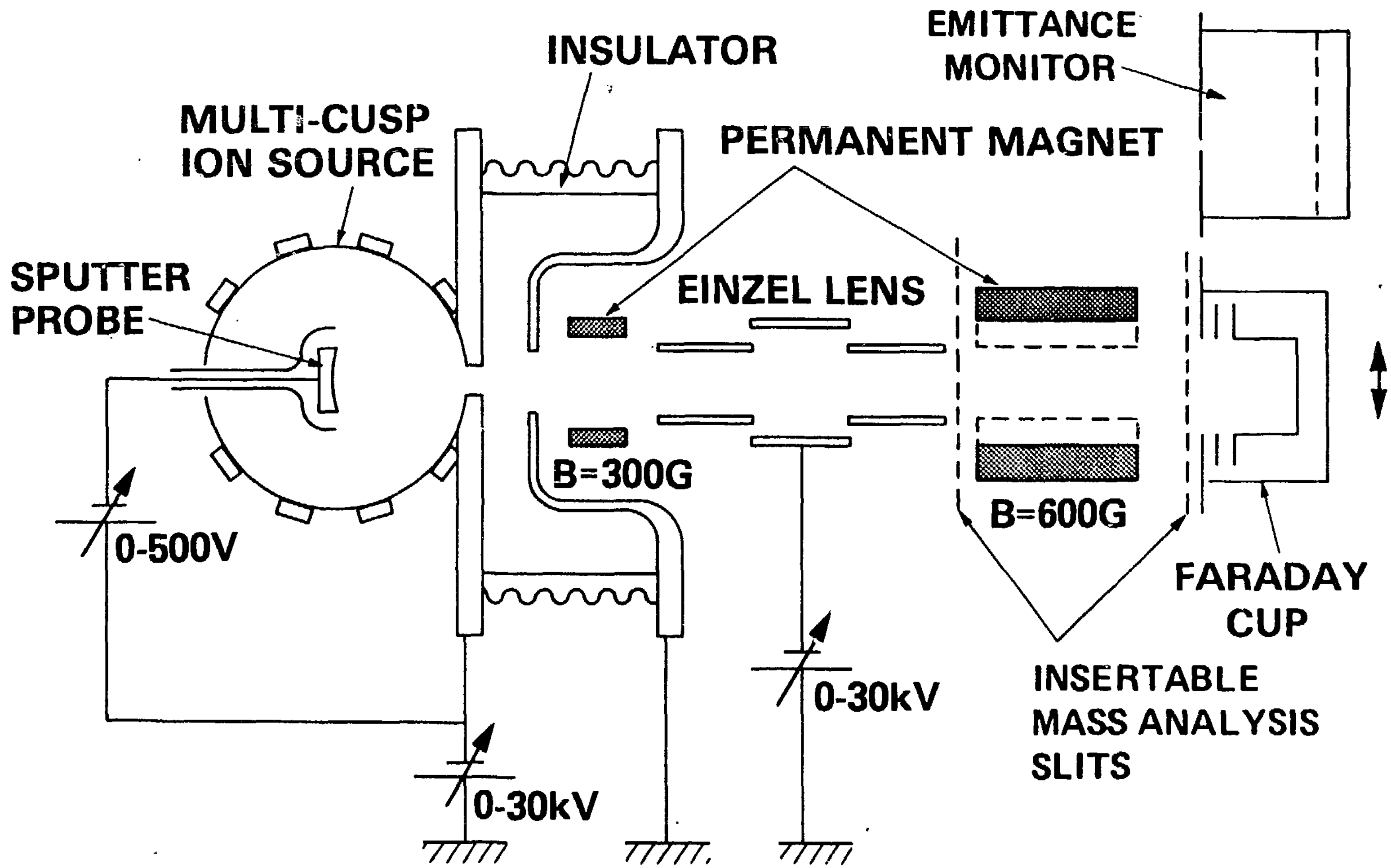

Fig. 1

ORNL-DWG 88-15269

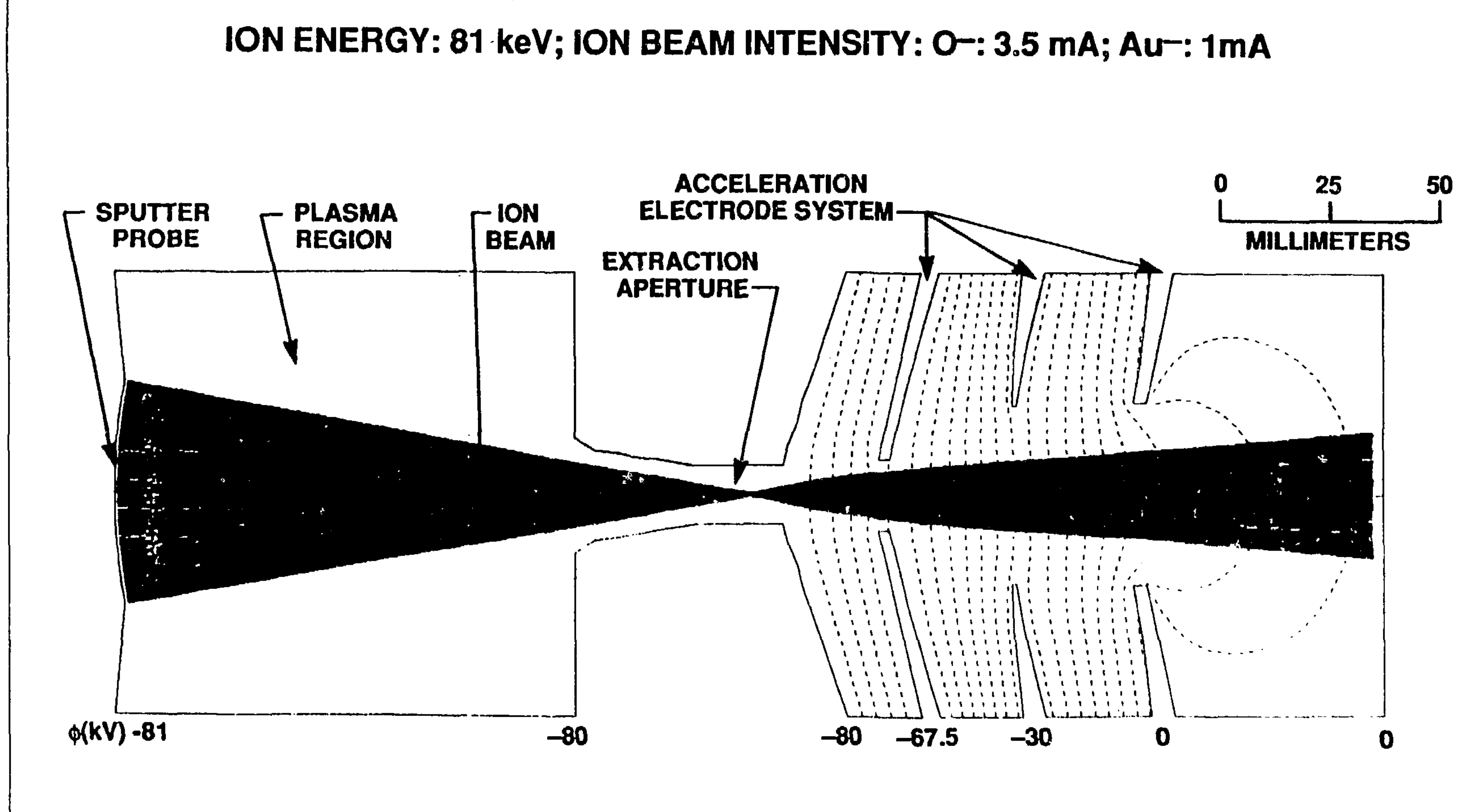

Fig. 2

ORNL-DWG 88-15268

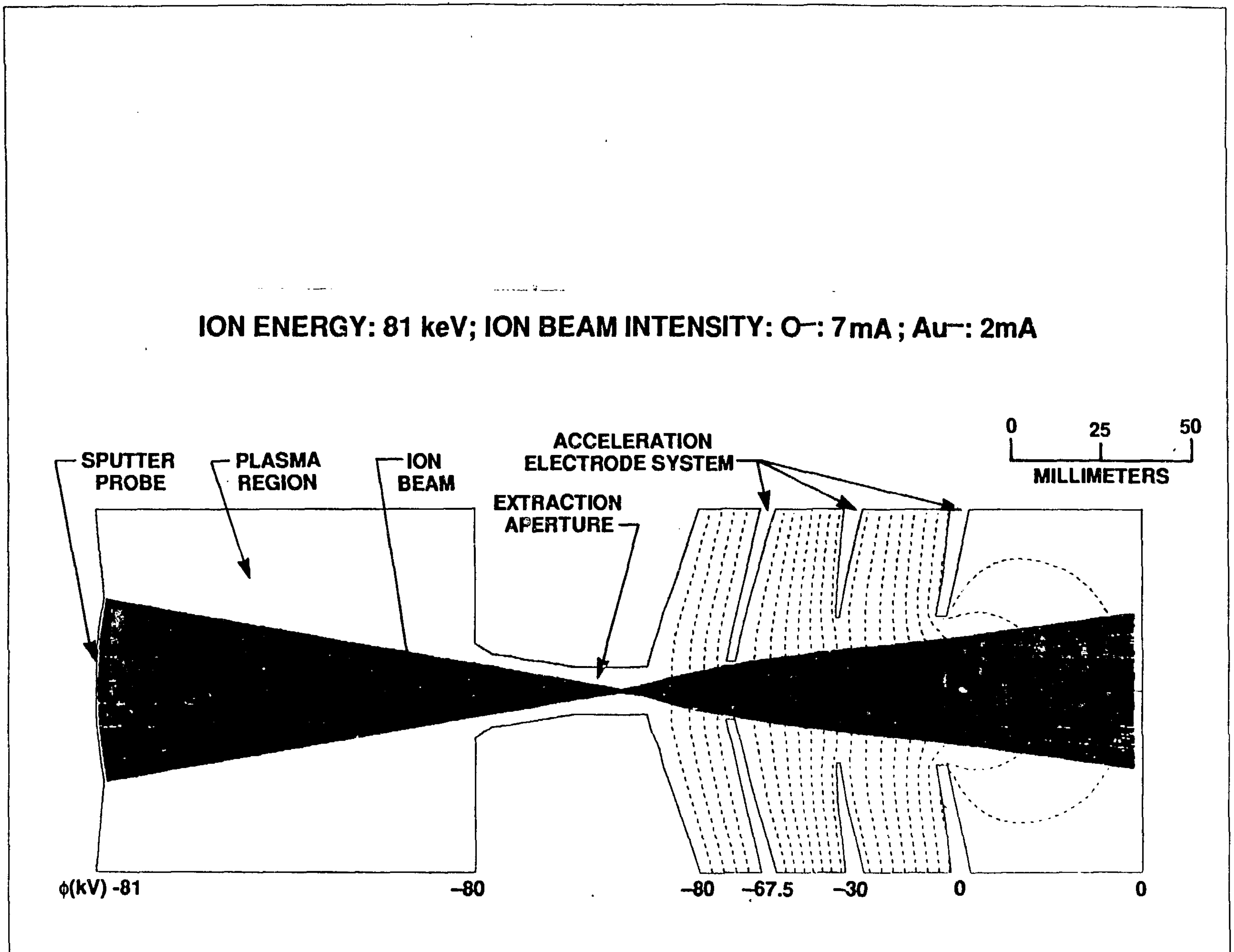

Fig. 3

ORNL-DWG 88Z-7162

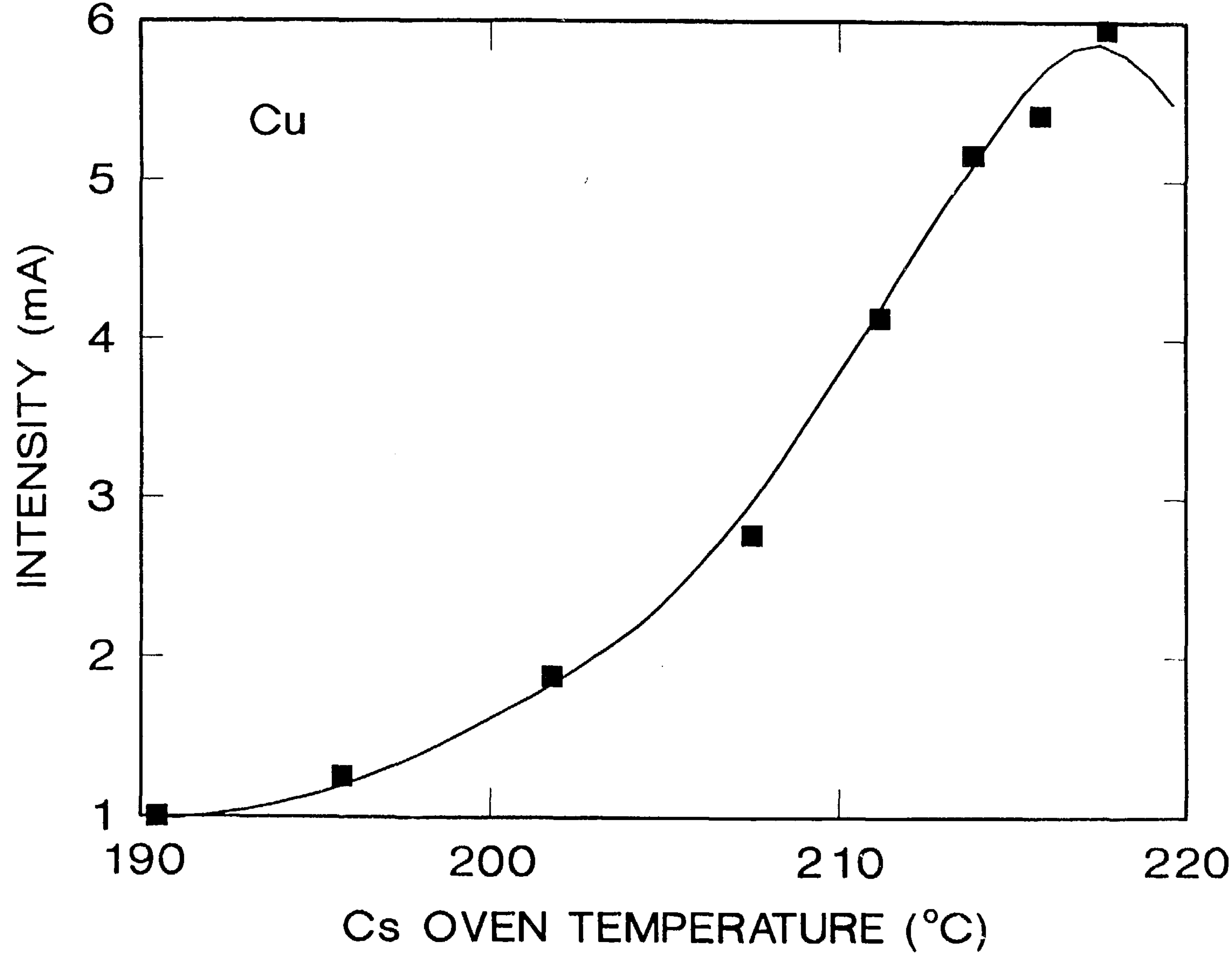

Fig. 4

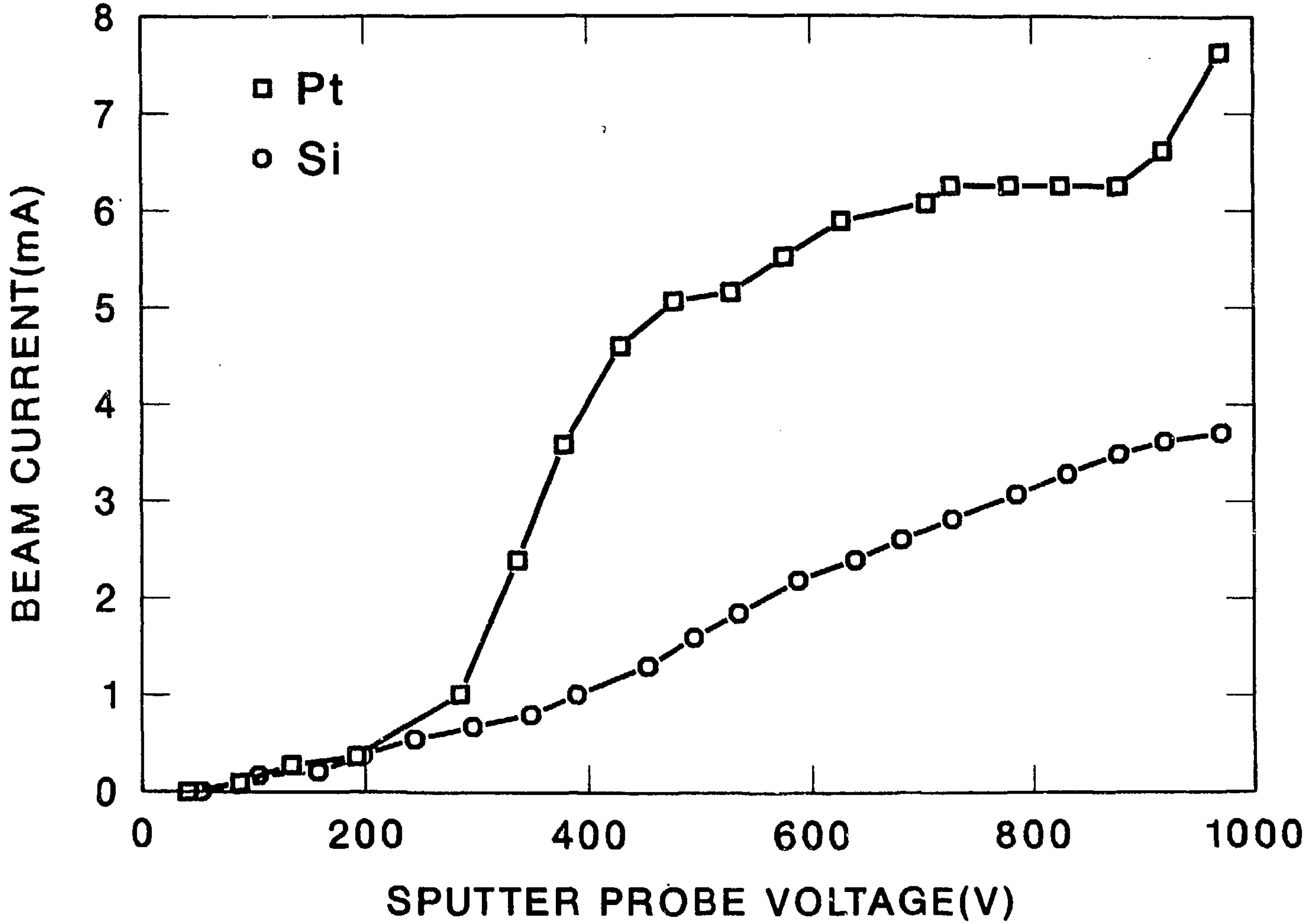
Pt
Si
BEAM CURRENT(mA)
SPUTTER PROBE VOLTAGE(V)
0
1
2
3
4
5
6
7
8
0
200
400
600
800
1000

Fig. 5

ORNL-DWG 88Z-7163

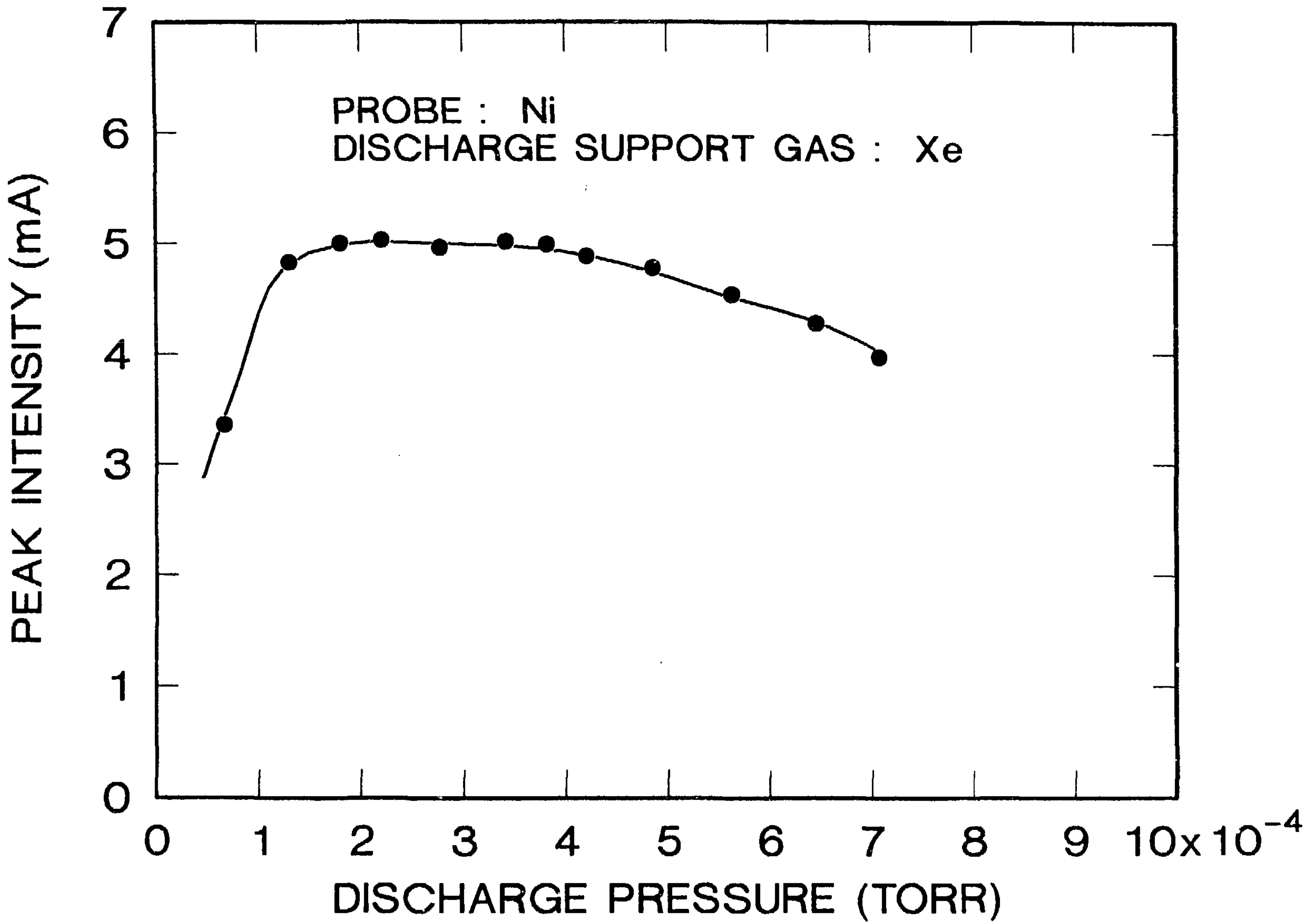

Fig. 6

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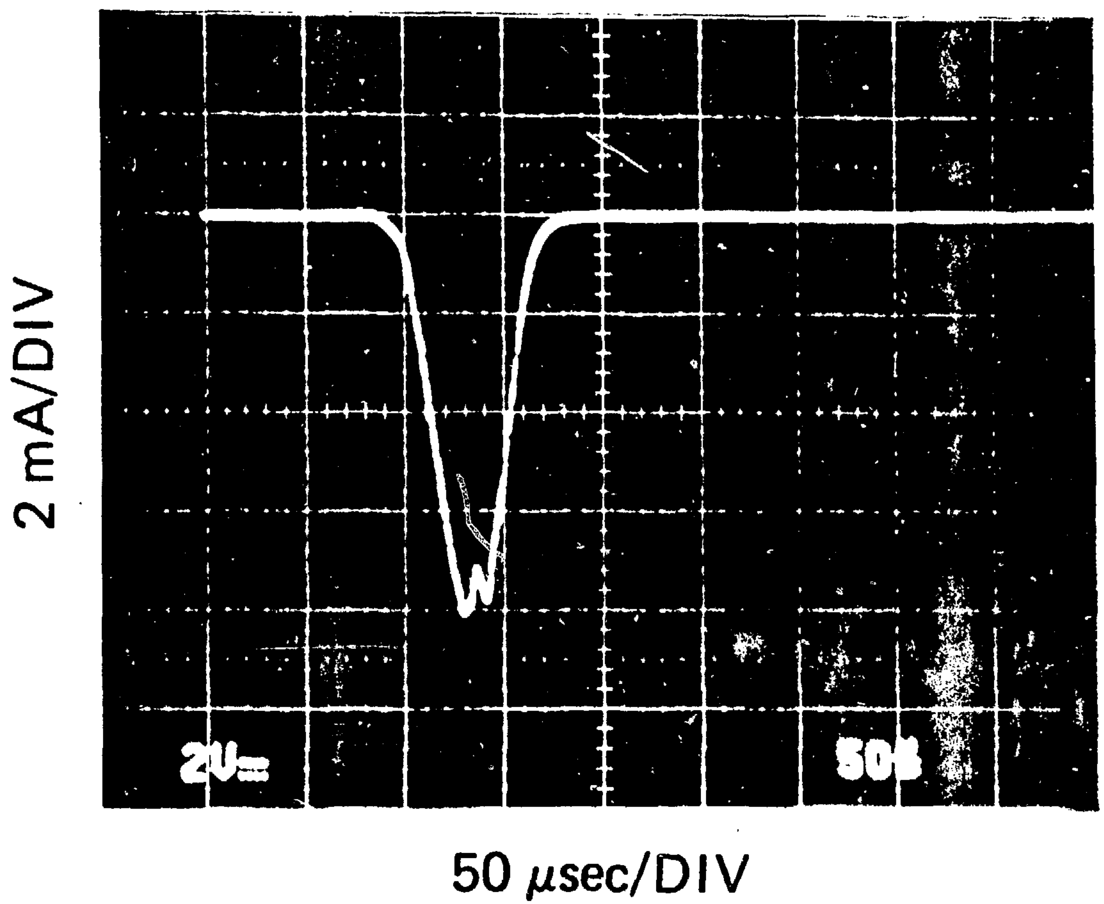

NEGATIVE ION BEAM INTENSITY VERSUS TIME
SPUTTER PROBE: Pt; GEOMETRY: SPHERICAL

Fig. 7

ORNL-DWG 88C-14828

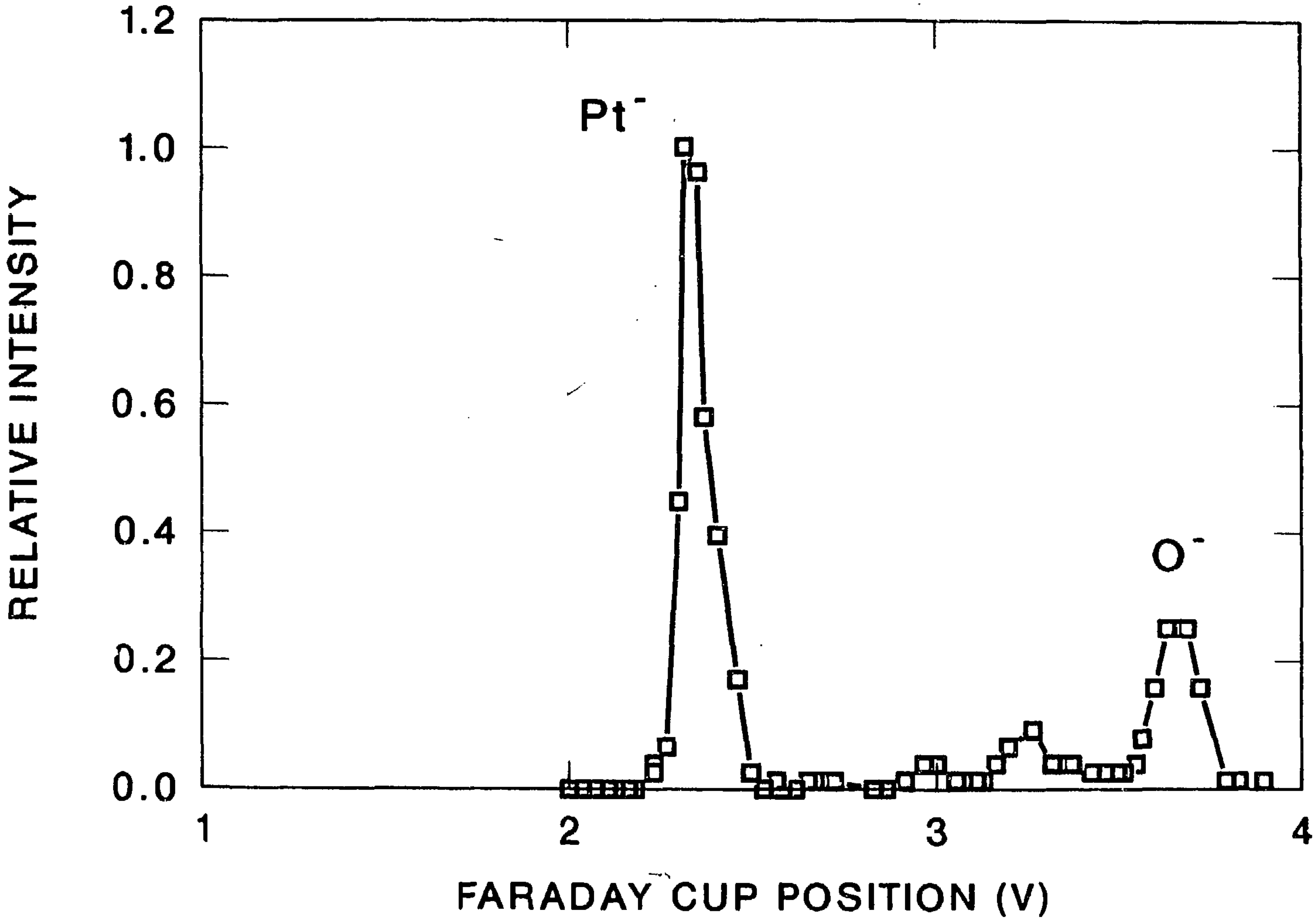

Fig. 8

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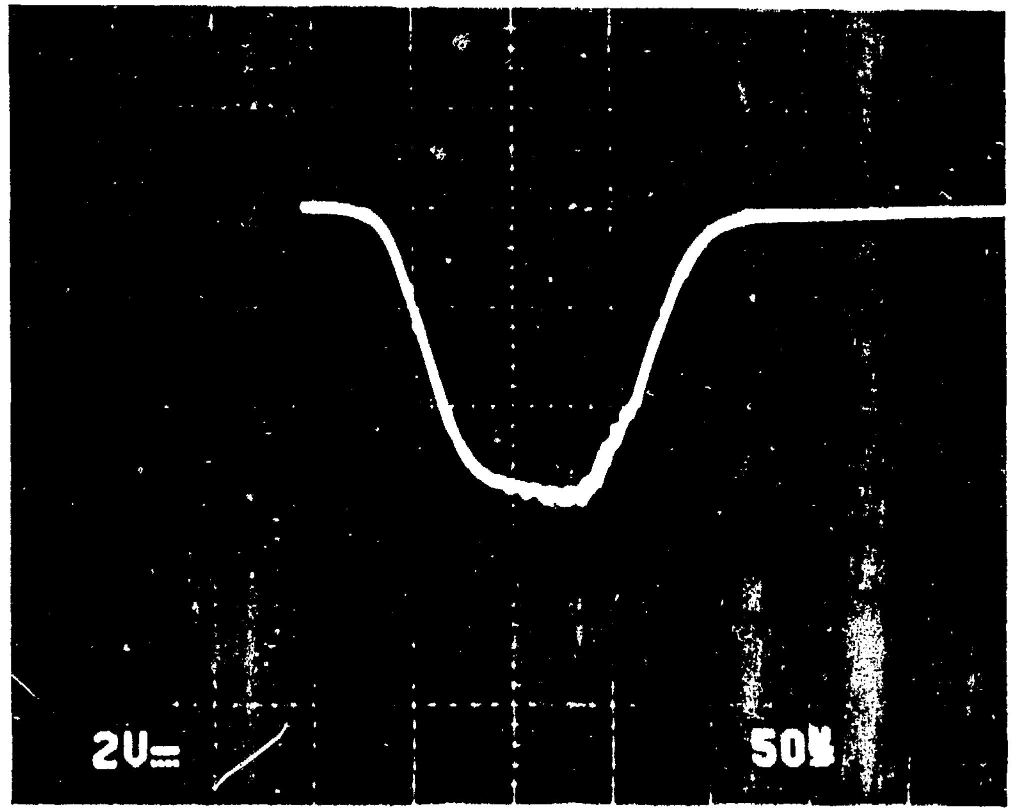
2 mA/DIV



50 μsec/DIV

NEGATIVE ION BEAM INTENSITY VERSUS TIME
SPUTTER PROBE: Si; GEOMETRY: SPHERICAL

Fig. 9

ORNL-DWG 88C-14826

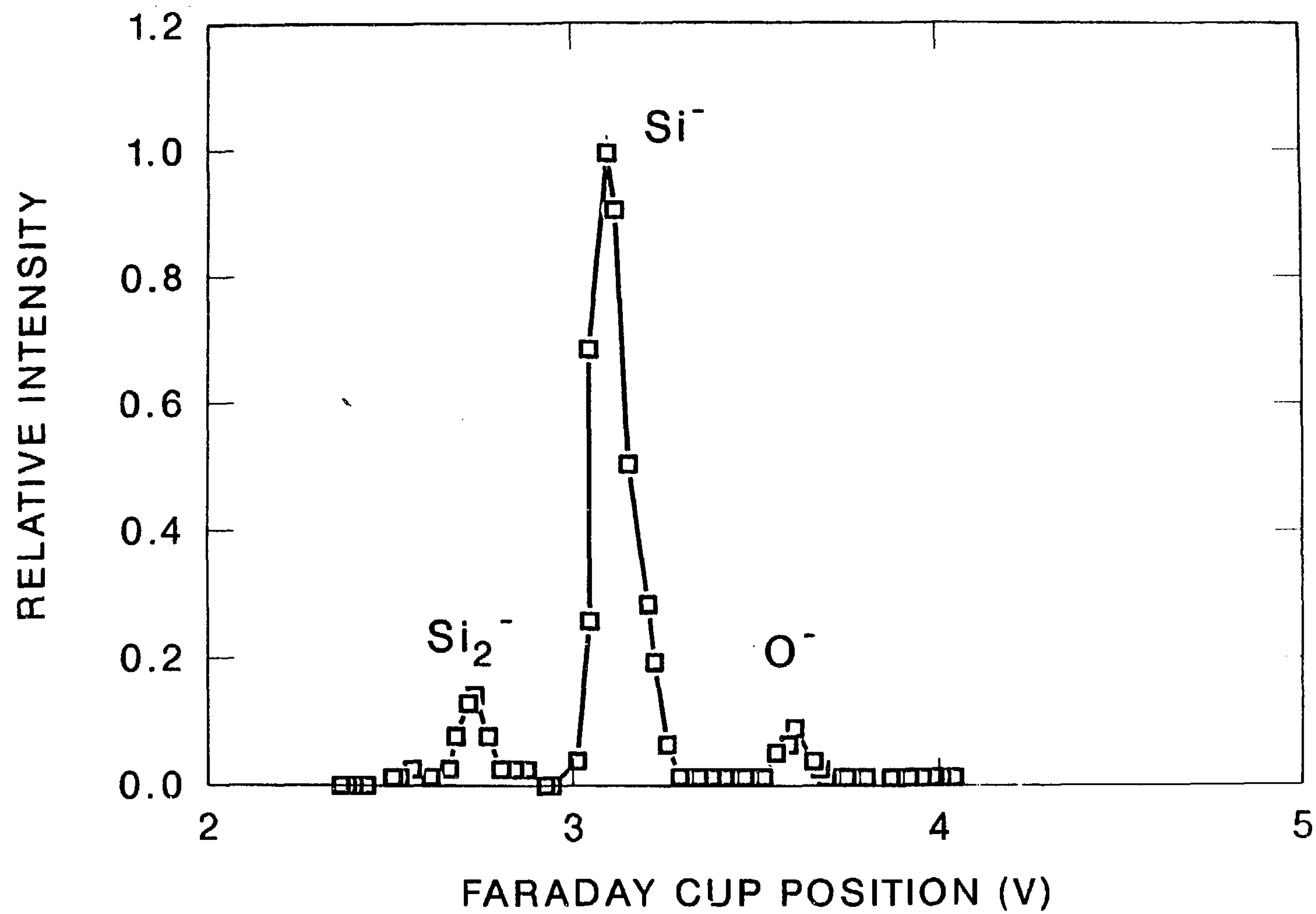


Fig. 10

ORNL-DWG 88Z-7164R

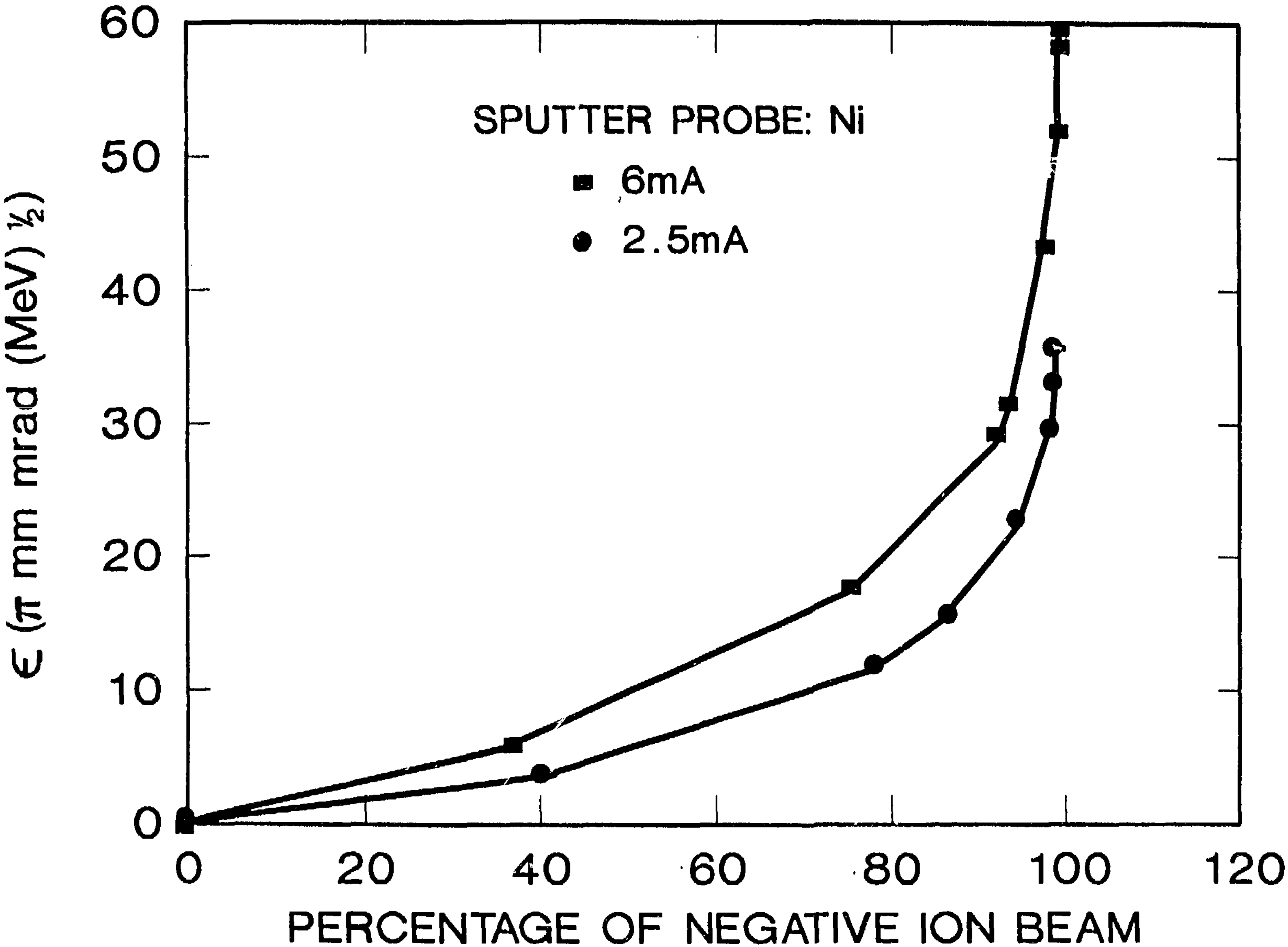


Fig. 11