A HIGH-INTENSITY PLASMA-SPUTTER HEAVY NEGATIVE ION SOURCE*

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A multicusp magnetic field plasma surface ion source, normally used for H^- ion beam formation, has been modified for the generation of high-intensity, pulsed, heavy negative ion beams suitable for a variety of uses. To date, the source has been utilized to produce mA intensity pulsed beams of more than 24 species. A brief description of the source, and basic pulsed-mode operational data, (e.g., intensity versus cesium oven temperature, sputter probe voltage, and discharge pressure), are given. In addition, illustrative examples of intensity versus time and the mass distributions of ion beams extracted from a number of samples, along with emittance data, are also presented. Preliminary results obtained during dc operation of the source under low discharge power conditions suggest that sources of this type may also be used to produce high-intensity (mA) dc beams. The results of these investigations are given, as well, and the technical issues that must be addressed for this mode of operation are discussed.

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1.0 INTRODUCTION

The demand for ion beams of higher brightness for an increasing number of applications continues to provide the impetus for ion source development. As a consequence of efforts made at several laboratories, advancements have been made in both positive and negative ion source technology during the past few years; many examples of such progress made in each of these source types can be found in the literature.

Since its discovery, the technique of sputtering a surface covered with a fractional layer of a highly electropositive adsorbate material such as cesium has proved to be a universal method for generating atomic and molecular negative ion beams from most chemically active elements. In addition to being versatile in terms of species, sources based on this concept are simple in design, easy to operate, and generally have long lifetimes. Because of these factors, such sources are utilized extensively in most tandem electrostatic accelerator heavy ion physics research laboratories, as well as for use in a growing number of other applications, including high-energy ion implantation and tandem accelerator mass spectrometry.

In recent years, the synchrotron has been used or considered for use for acceleration and storage of heavy ion beams for high-energy atomic and nuclear physics research applications. Facilities predicated on this principle have been constructed or are being constructed around the world. 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.

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 surface ionization sputter principle (see e.g., Ref. 1 for descriptions of several sources which utilize this technique). 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.

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 the Brookhaven National Laboratory (BNL)[2] and the Oak Ridge National Laboratory (ORNL)[3] at injected intensity levels up to 200 μA and more recent injection experiments performed with the subject source at BNL[4] at injected intensity levels up to 3.5 mA for Au^- and 2.5 mA for Si^-, however, indicate no deleterious effects on the stability of operation of 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.

The source description in this paper and in previous reports[5,6] has the potential of meeting the intensity and species requirements of tandem electrostatic accelerator/ heavy ion synchrotron applications. The source shows considerable promise for other applications, as well.

2.0 THE HEAVY NEGATIVE ION SOURCE

2.1 Principles of Negative Ion Beam Generation by Sputtering

Although the physio-chemical processes responsible for negative ion formation during sputtering of a low-work-function surface are complicated, the practical application of the technique for the generation of negative ion beams is quite simple. Positive ion beams, usually formed by either direct surface ionization of a Group IA element or in a heavy noble gas (Ar, Kr, or Xe) plasma discharge seeded with alkali metal vapor, are accelerated to energies between a few hundred eV and several keV where they sputter a sample containing the element of interest. The presence of a fractional layer of a highly electropositive adsorbate on the surface is critically important for the enhancement of negative ion yields during the sputtering process.[7] A fraction of the sputter ejected particles leave the adsorbate covered surface as negative ions and are accelerated through an extraction aperture in the source. While other formation processes may be responsible for negative ion formation, particularly during the sputtering of compound or alloyed materials, there is convincing evidence that the mechanism of negative ion formation during sputtering of related surfaces is a form of surface ionization.[8] Several sources based on this principle have been developed which utilize either direct surface ionization, or a plasma to form the positive ion beam used to effect sputtering of samples containing the material of interest (many of which are described in Ref. 1). The present source utilizes the plasma sputtering principle for the generation of mA-intensity-level negative ion beams.

2.2 Source Description

The multicusp magnetic field plasma surface ion source,[9,10] routinely employed at the National Laboratory for High Energy Physics (KEK) for the generation of high-intensity H^- ion beams for injection into the 12-GeV proton synchrotron,[11] has been modified for heavy negative ion generation. This type of ion source was originally developed at Lawrence Berkeley Laboratory (LBL) for neutral beam heating in fusion energy research devices[12] and improved at Los Alamos National Laboratory (LANL) for use in the Los Alamos Meson-Production Facility (LAMPF) program[9] and at KEK for H^- injection into the 12-GeV proton synchrotron.[10] The source, modified for heavy ion generation, is shown schematically in Fig. 1. Details of the mechanical design features and operational characteristics for H^- generation have been described previously in Refs. 9 and 10 and accounts of heavy ion generation in Refs. 5 and 6.

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 desirable. For the present investigations, Xe support gas was utilized. The discharge is operated in a current-regulated mode to minimize variations in the extracted ion beam intensity levels.

Cesium is introduced into the discharge from a external cesium oven operated typically at a temperature of ~215°C. The negative ion beam is formed by sputter ejection of atoms or molecules from the negatively biased spherical geometry sputter probe covered with a partial layer of cesium adsorbate material. The double sheath surrounding the negatively biased sputter probe (spherical radius ρ = 140 mm and diameter ϕ = 50 mm) which is maintained at a variable voltage (0-1000 V) relative to housing, serves as the acceleration gap and lens for focusing the negative ion beam through the exit aperture (diameter ϕ = 18 mm). At this point, the ion beam is further accelerated to an energy of 20 keV prior to passing into the chamber equipped with the experimental apparatus. Under pulsed-mode operation at the low duty factors utilized (typically 2×10^{-3}), the LaB_6 cathodes exhibit very little erosion after many hours of operation. The sputter probe is made of material containing the species of interest and thus has a very long lifetime under low duty factor usage. With the combined long lifetime of the sputter probe, sputter LaB_6 cathodes and low cesium consumption rate (~0.06 mg/h), the source can operate stably in pulsed mode for a few thousand hours at constant peak beam intensity levels without maintenance or cleaning.

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 come into play whenever the beam exits the plasma and enters the extraction region of the source. However, because the beam energy is typically 500 to 1000 eV upon exit from the plasma region of the source, space charge influences on the beam are reduced. These aspects of the source are fundamentally important for high-intensity beam transport.

3.0 EXPERIMENTAL APPARATUS, PROCEDURES, AND PULSED-MODE SOURCE OPERATION, AND PARAMETER STUDIES

3.1 Experimental Apparatus

The plasma sputter negative ion source, equipped with a chosen sputter probe, was evaluated by use of the ion source test stand described in Ref. 6. 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 or into 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, was 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.

The mass distributions of total extracted ion currents were measured by increasing the magnetic field to ~1 kG and placing 1-mm slits at the entrance to the magnetic field and the positionable Faraday cup. The mass distributions of beams extracted from each of the sputter probes were then determined by measuring the intensity distribution as a function of Faraday cup position.

3.2 Pulsed-Mode 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. 2. 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. 3 for Ag and C 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. 4. 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 pressure. The pressure in the discharge chamber during data accumulation from all sputter probes was typically 2.3×10^{-4} Torr.

4.0 SOURCE PERFORMANCE CHARACTERISTICS

4.1 Negative Ion Beam Intensity and Mass Distribution Data

4.1.1 Negative ion beam intensity data. Intensity vs time distributions of ion beams extracted from Ag and C sputter probes at optimum cesium flow rate, discharge pressure, and at fixed sputter voltage are shown in Figs. 5 and 6, respectively. A partial list of the sputter probes evaluated to date, with negative ion beam intensities and approximate mass distributions within the total ion beams produced from these probes, is shown in Table 1. Typical source operational parameters utilized during the measurements for each of the samples are given in Table 2.

4.1.2 Mass distribution data. After initial studies of each sputter probe, the experimental apparatus was equipped with the provisions described previously for estimating the mass distributions within the total ion beam extracted from a particular probe. Although the mass resolution capabilities were not adequate for separating individual isotopes, they were adequate for resolving heavy masses (e.g., Au^-, Cu^-, and Ni^-) from light masses such as O^- which was, by far, the major impurity found within the mass spectra of ion beams extracted from the elemental sputter probes. For these sputter probes, the heavy ion beams dominate the mass spectra whenever cesium is introduced into the source at optimum flow rates. Figs. 7 and 8 display relative intensity versus Faraday cup position, respectively, for beams extracted from Ag and C sputter probes. These data typify those found for elemental sputter probes which have reasonably high electron affinities, i.e., the elemental heavy ion species completely dominates the mass spectrum. Mass spectra from compound materials are much more complicated in that many molecular as well as elemental ion species are often present in the ion beam.

4.2 Emittance Measurements

4.2.1 Description of the emittance-measuring hardware. The emittance-measurement device which is used to evaluate the quality of ion beams extracted from the source is described in Ref. 13. It consists of a stepping-motor-driven detector unit for determining the emittance of an ion beam in either the x or y direction, and a control unit for driving the detector hardware. The control unit consists of a microcomputer which is interfaced to a CAMAC crate controller, a stepping-motor controller, and a 1024-channel analog signal digitizer. The CAMAC crate control modules communicate with the emittance-measurement hardware via an external electronics unit.

The ion beam diagnostic unit consists of an electrically isolated slit aperture, positioned 2.5 cm in front of a detector unit which is made up of 32 electrically isolated plates. The current striking each of the detectors is used to determine the differential angular divergence of the ion beamlet which is allowed to pass through the slit aperture. An emittance measurement consists of stepping the slit detector system through an ion beam in a chosen direction while monitoring the differential ion currents striking each of the 32 detectors at each of the positions during a selectable integration time period. The signals are integrated, digitized, and stored in memory of the micro-VAX computer for later data analysis.

4.2.2 Definitions of emittance. The conserved components of normalized emittance ε_{nx} and ε_{ny} are given by

$$\varepsilon_{ny} = \pi \int \int (dx dx'/\pi) \sqrt{E} \, (\text{x-direction}),$$

and (1)

$$\varepsilon_{ny} = \pi \int \int (dy dy'/\pi) \sqrt{E} \, (\text{y-direction}),$$

where the integrations are performed in such a manner so as to include a specified fraction of the total beam current.

In Eqs. 1, x, y are position coordinates, x′, y′ are angular coordinates, and E is the energy of the ion beam. Emittance in this prescription is usually given in units of π mm.mrad $(\text{MeV})^{1/2}$.

4.2.3 Emittance data. Normalized emittance versus percentage of total negative ion beam for 2.5 and 6 mA extracted from a Ni sputter source is shown in Fig. 9. The normalized emittance for the 2.5-mA Ni beam at the 80% contour level has a value $\varepsilon_n = \sim 11\ \pi$ mm.mrad $(\text{MeV})^{1/2}$, while the 6-mA Ni beam has a value at the same contour of $\sim\varepsilon_n = \sim 17\ \pi$ mm.mrad $(\text{MeV})^{1/2}$. The latter value is approximately the same as cesium sputter negative ion sources such as described in Ref. 1 when operated in pulsed mode. However, the beam intensities from this source are often 30 to 100 times greater than cesium sputter negative ion sources. The results of these measurements clearly indicate the presence of space charge effects within the respective ion beams. The emittance values compare favorably with the calculated acceptances of large tandem accelerators[14] and, in principle, ion beams from this source should be transportable through such devices.

5.0 PRELIMINARY DC-MODE OPERATIONAL EXPERIENCE

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. The use of this type of source for the generation of high-intensity beams of O^- is particularly attractive since the short source lifetime resulting from the chemical reaction between the O_2 feed gas and hot cathodes commonly used in volume discharge sources is avoided. In principle, the source can be operated in dc mode, provided that the source is provided with adequate cooling and that sparking problems can be avoided at the anticipated higher cesium flow rates required to maintain optimum cesium coverage on the sputter probe surface during plasma bombardment. In this portion of the paper, we describe the preliminary results obtained by operating the source under low discharge power conditions which were necessary because of the lack of cooling on the present source chamber. More details concerning this mode of operation are given in Ref. 15.

5.1 Source Modifications

In order to operate the source in the dc mode, it was necessary to modify several parts of the ion source. Compared with pulsed-mode operation, dc-mode operation requires substantially higher cesium flow rates into the source in order to satisfy the proper cesium coverage requirements on the sputter probe surface due to the constant removal of cesium by sputtering. Therefore, a new cesium oven, cesium valve, and cesium transport line for feeding more cesium vapor into the ion source were designed. The diameter of the new feed line was increased from 6 to 10 mm, while the distance between the oven and ion source was decreased from about 50 to 15 cm. The cesium oven and valve were also modified so as to fit the larger-diameter feed line. The optimum temperature of the cesium oven for pulsed-mode operation in the new oven was decreased by about 50°C compared with the previous oven. Because of the lack of cooling in the ion source chamber, the dc arc current had to be limited to less than 5 A in order to operate the source in this mode. The arc current was also limited by the maximum current capability of the beam-extraction power supply (50 kV, 10 mA) because of electron loading of the supply.

5.2 DC-Mode Results

In the present experiments, a spherical-geometry copper sputter probe was used because of its high thermal conductivity properties. The diameter of the sputter probe was the same as that used for the previously described pulsed-mode experiments. For an arc current of 3 A, the arc voltage was about 20 V during dc operation, considerably lower than typical during pulsed-mode operation. At a sputter probe voltage of -610 V, the total drain current to the sputter probe was typically 90 mA at an arc current of 2 A. A much higher cesium flow rate was required in order to provide proper cesium coverage on the sputter probe. The cesium vapor density for an oven temperature of 258°C was estimated to be ~30 times higher than required for pulsed-mode operation (~160°C). Total beam intensity versus sputter probe current observed during operation with the Cu sputter probe is displayed in Fig. 10. The beam intensity is estimated to increase almost linearly with sputter probe current. The arc discharge current affects the sputter probe current which in turn changes the beam intensity. By linear extrapolation of this data, the beam intensity would reach the same level observed during pulsed-mode operation provided that the arc current could be increased to 15-20 A. Of course, at these high arc currents, the temperature of the cesium oven would also have to be increased and more efficient cooling of the plasma chamber and the converter would be necessary. If these technical difficulties can be overcome, it is conceivable that intense dc negative heavy ion beams could be realized from this type of source. Clearly, more work with an improved source design is required in order to arrive at a definitive answer to the question of the practicality of this mode of operation.

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

Sputter Probe Material	Sputter Probe Voltage (V)	Geometry	Total Peak Beam Intensity (mA)	Species (%)
Ag	937	Spherical	6.2	Ag^- (91)
Al	937	Spherical	1.7	Al^- (9); Al_2 (64)
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)
Cr	937	Spherical	1.4	Cr^- (14); O^- (58)
Fe	937	Spherical	5.7	FeO^- (33); O^- (35)
GaAs	937	Flat	3.7	As^- (20); As_2^- (52)
GaP	937	Flat	1.8	P^- (44)
LaB_6	937	Spherical	4.5	BO^- (38); BO_2^- (62)
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)
Ta	937	Spherical	2.3	TaO^- (60); O^- (34)
Ti	937	Spherical	4.2	TiO^- (19); O^- (63)
V	937	Spherical	4.1	VO^- (17); O^- (50)
W	937	Spherical	3.9	WO^- (78)

Table 2. Typical pulsed-mode source operating parameters.

Arc current	15-20 A
Arc voltage	30-60 V
Filament current	130 A
Filament temperature	1450°C
Xe gas pressure	2.3×10^{-4} Torr
Sputter probe voltage	500 V
Beam extraction voltage	25-30 kV
Cesium oven temperature	215°C
Beam pulse width	100-200 μs
Repetition rate	5-20 Hz

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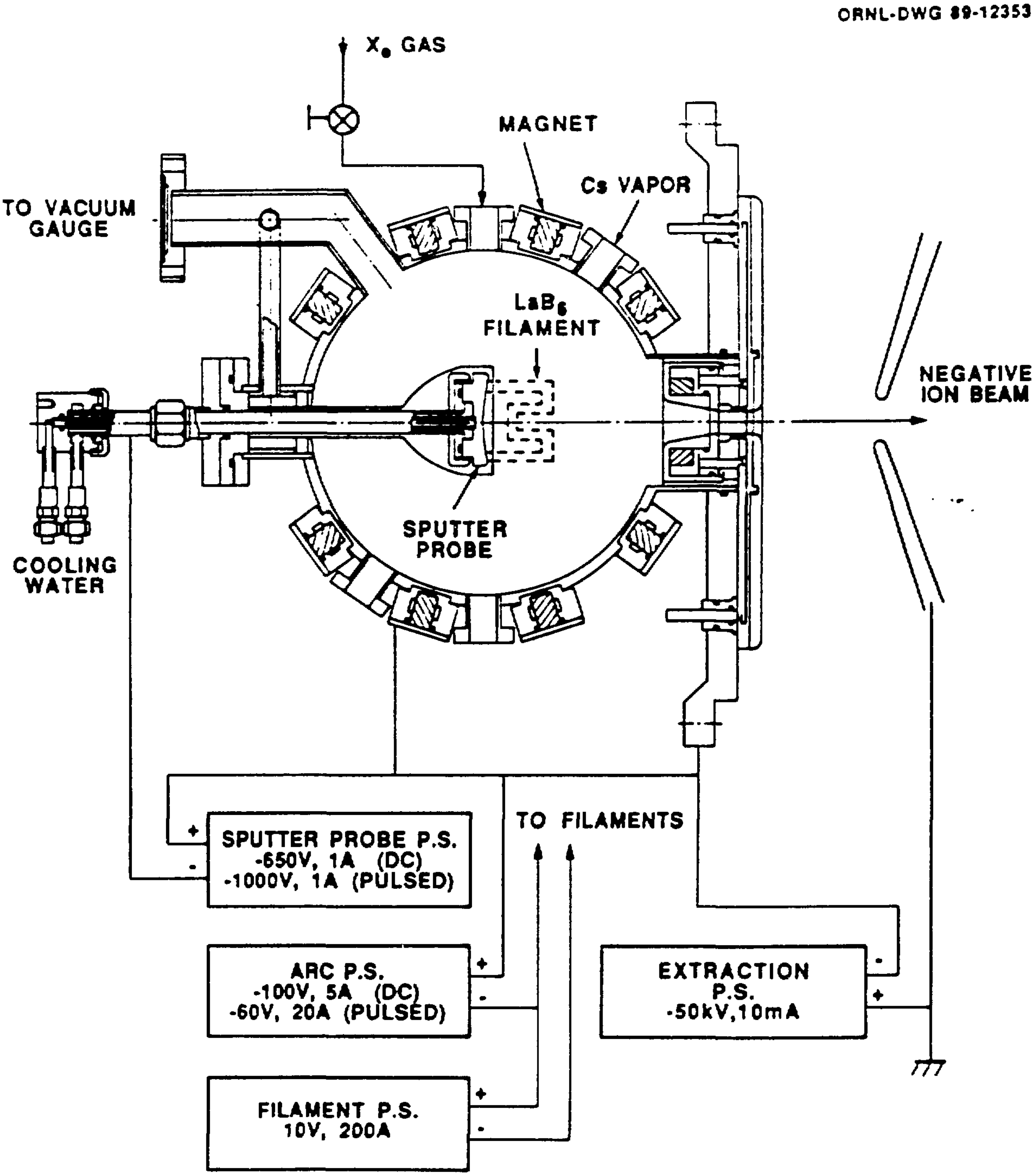
Figure Captions

1. Schematic drawing of the high-intensity plasma sputter negative ion source and the power supply arrangement used for operation of the source.
2. Peak negative ion beam intensity versus cesium oven temperature from a Cu sputter probe. Sputter probe voltage: –500 V.
3. Peak negative ion beam intensity versus sputter probe voltage from Ag and C sputter probes. Cesium oven temperature: 215°C.
4. 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.
5. Intensity versus time distribution of the total ion current extraction from an Ag 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.
6. Intensity versus time distribution of the total ion current extracted from a C 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.
7. Relative negative ion beam intensity distribution from an Ag sputter probe as a function of Faraday cup position. Sputter probe voltage: –1000 V.
8. Relative negative ion beam intensity distribution from a C sputter probe as a function of Faraday cup position. Sputter probe voltage: –1000 V.
9. Normalized emittance ε versus percentage total negative ion beam from a Ni sputter probe.

10. Extracted dc ion current versus sputter probe current from a Cu sputter probe for discharge currents of 2.3, 3.0, and 3.5 A. Sputter probe voltage: −610 V; cesium oven temperature: 258°C.



THE MULTI-CUSP MAGNETIC FIELD HEAVY NEGATIVE ION SOURCE

Fig. 1

ORNL-DWG 88Z-7162

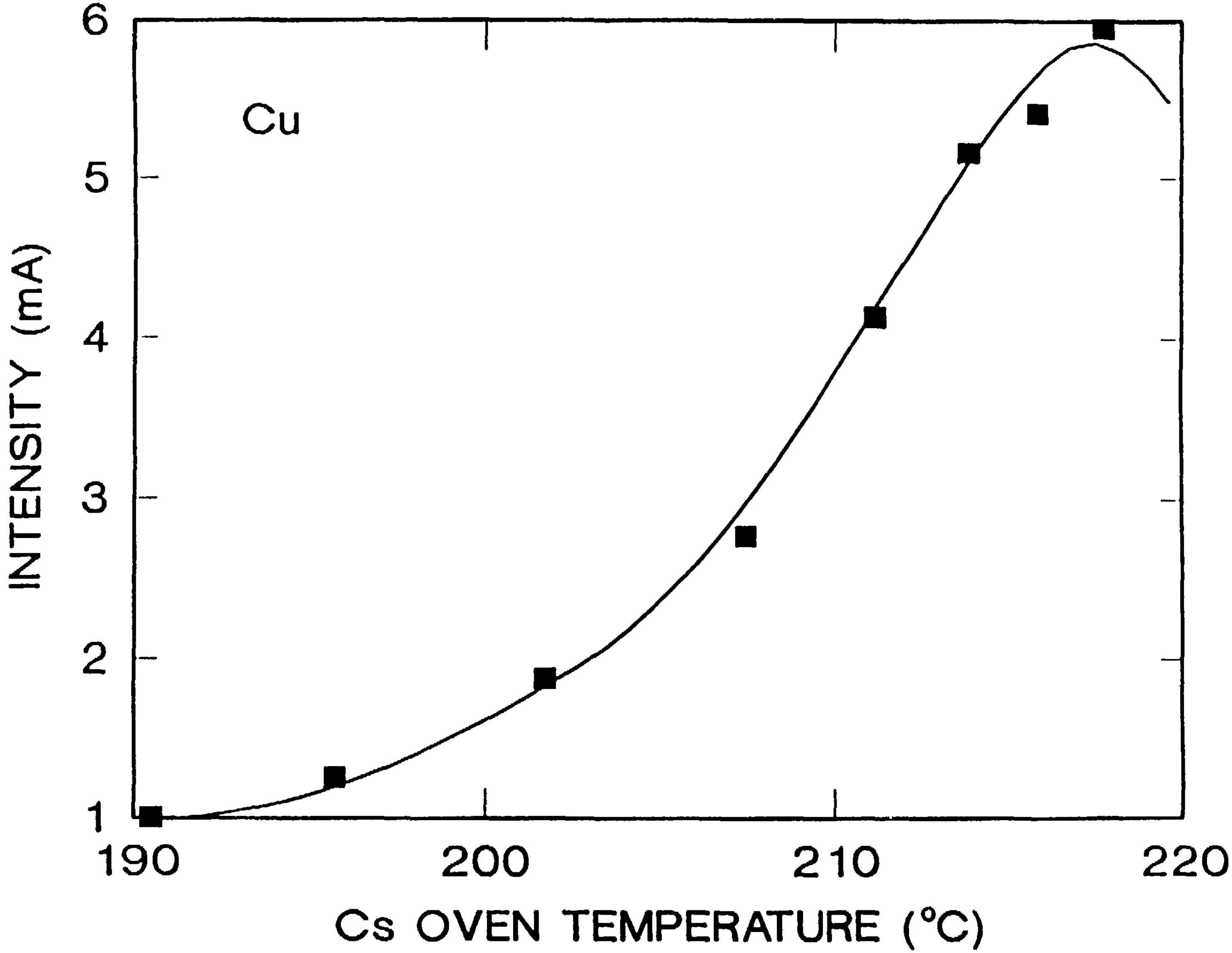


Fig. 2

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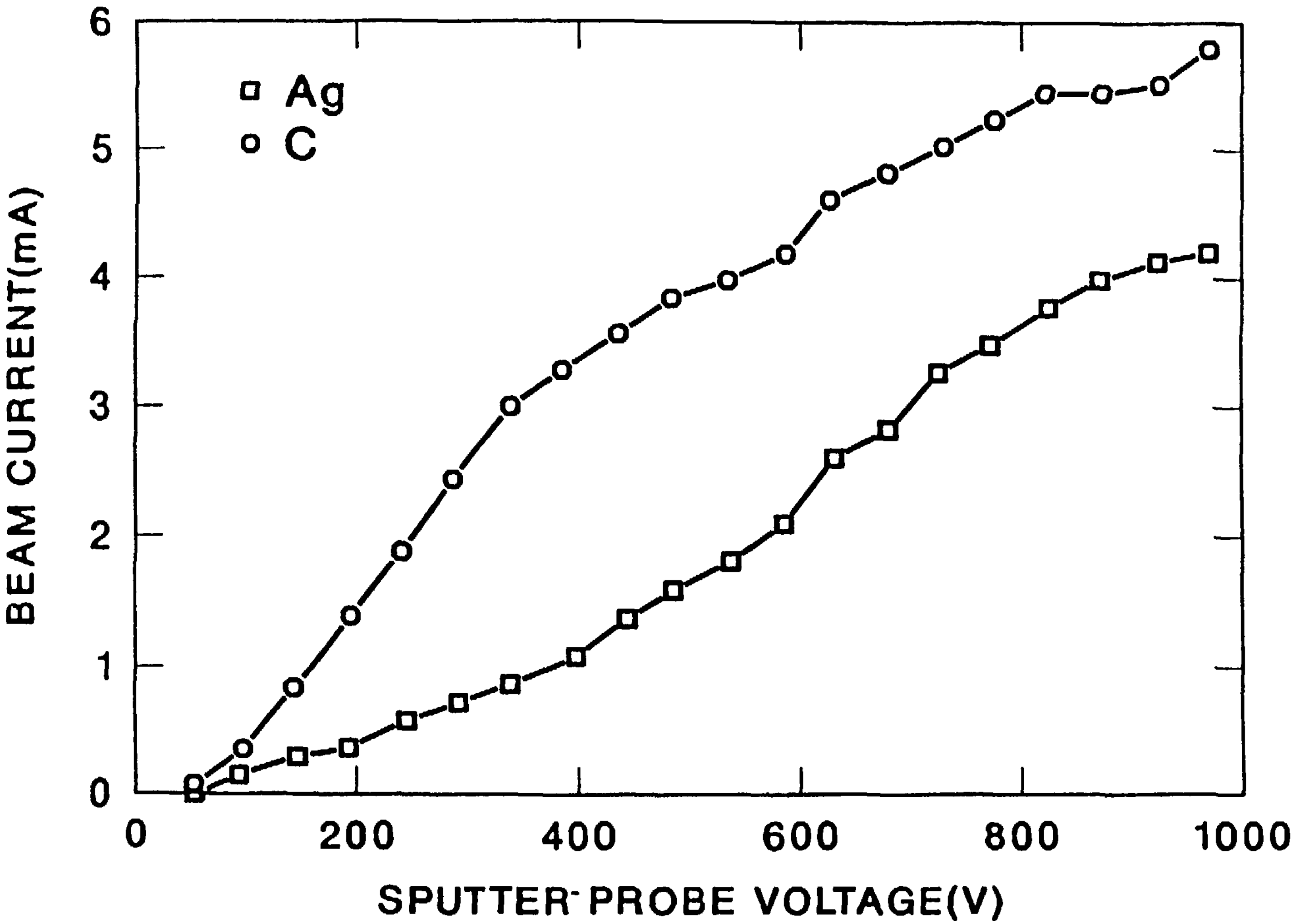

Fig. 3

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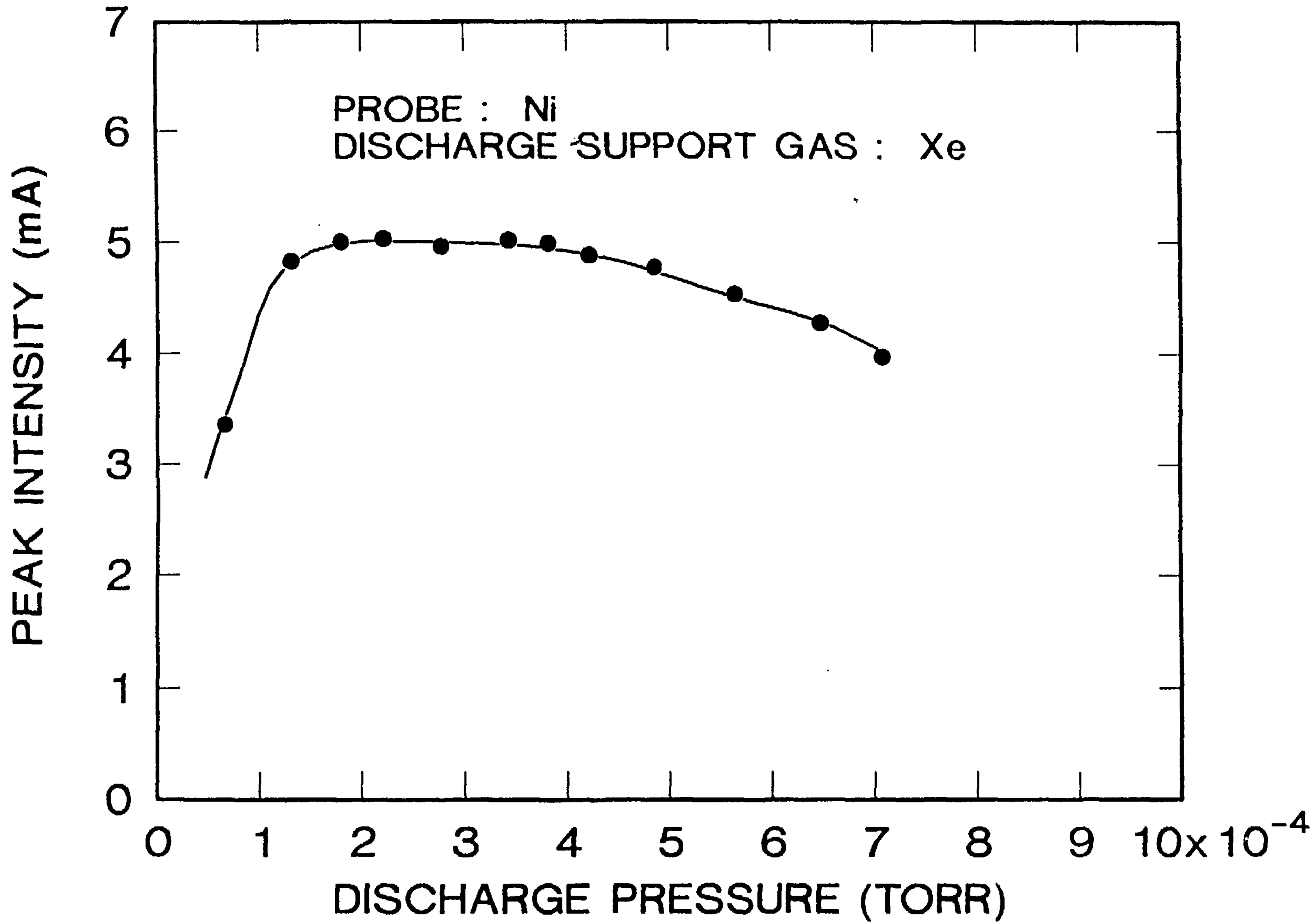

Fig. 4

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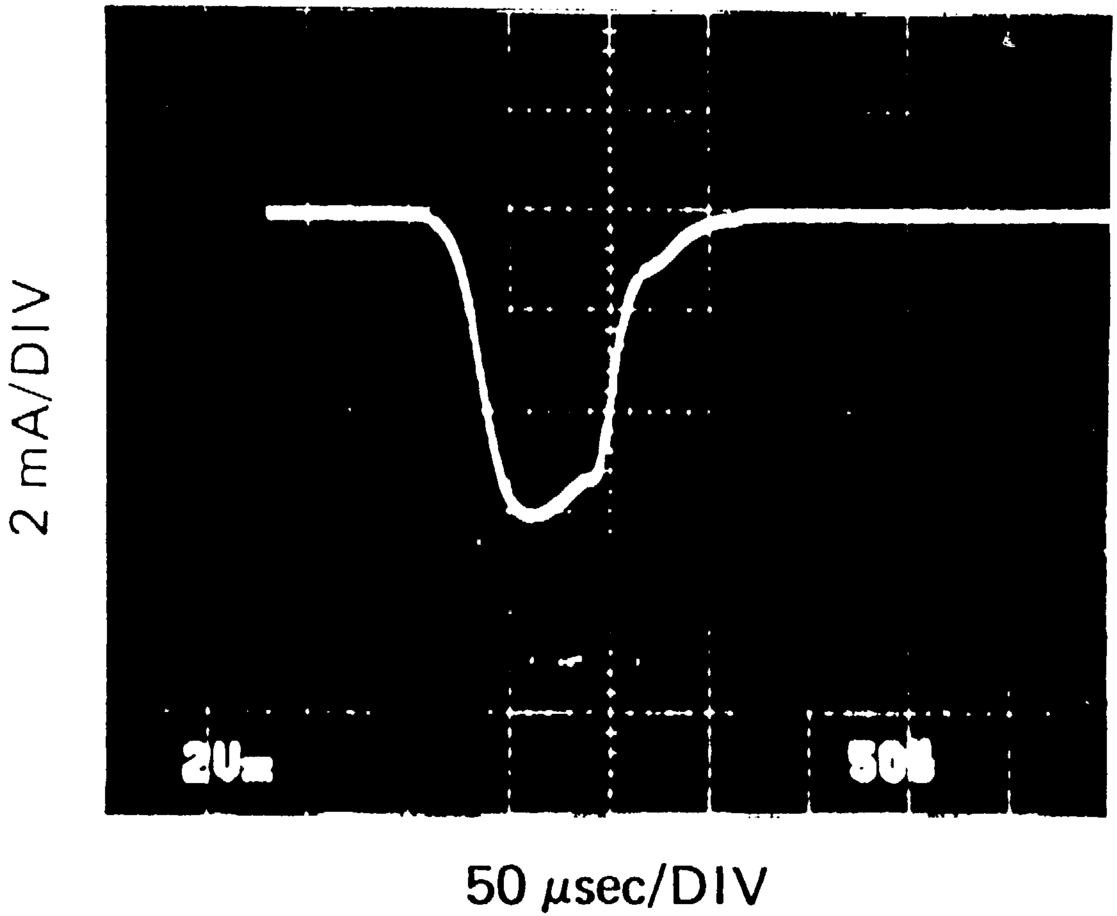

Fig. 5

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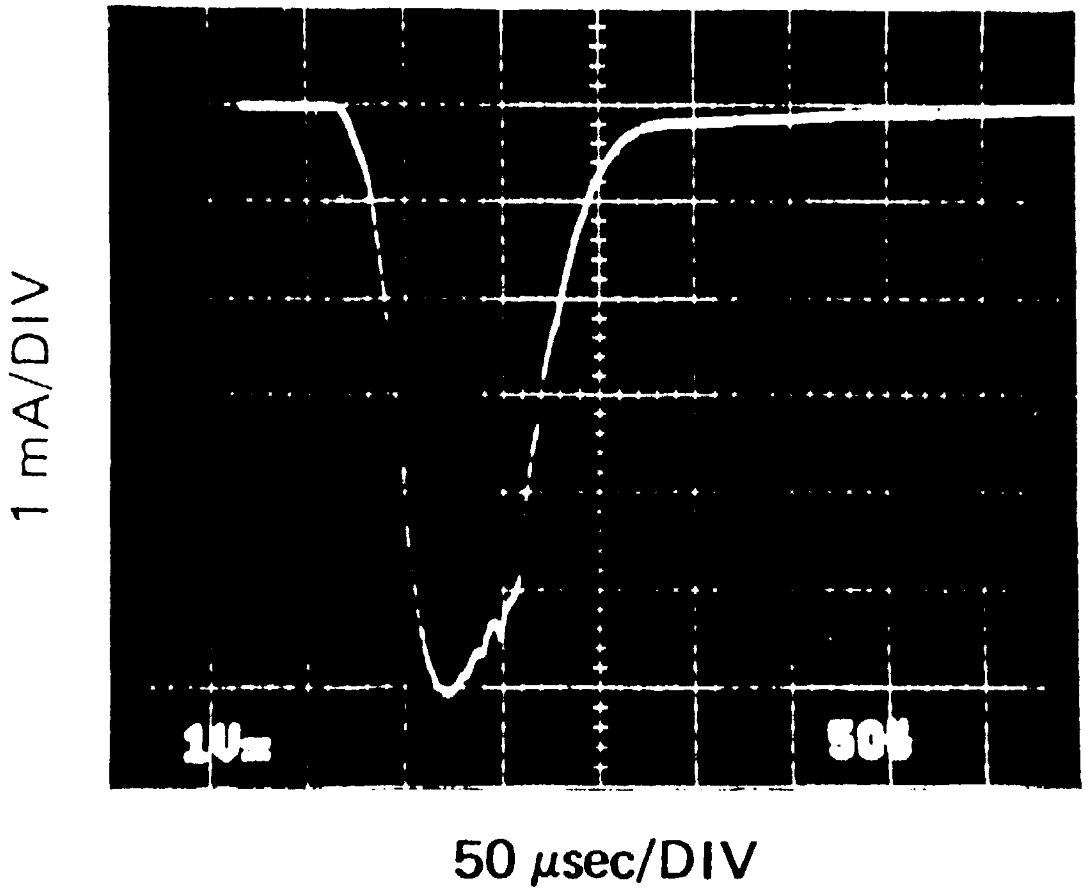

Fig. 6

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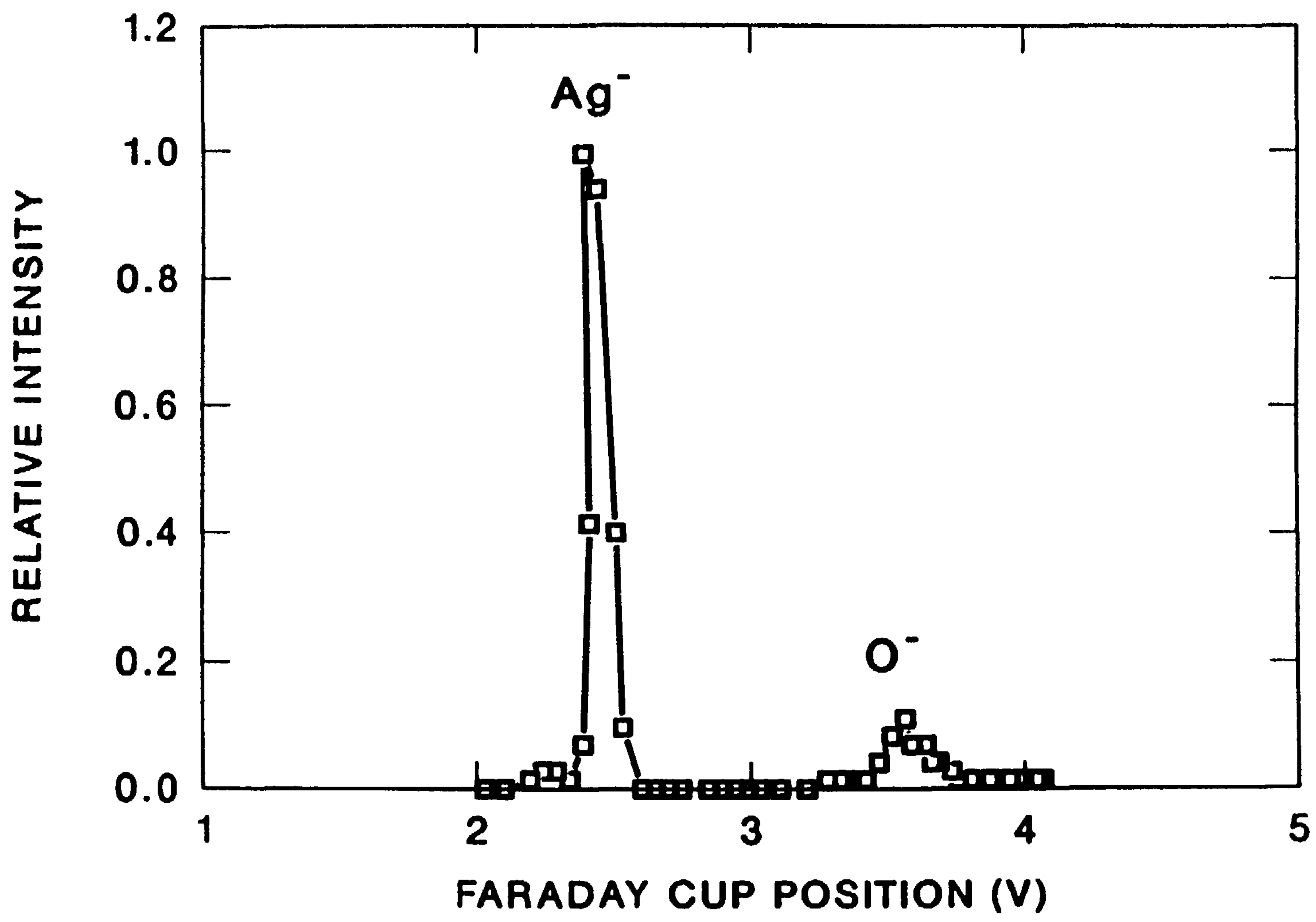

Fig. 7

ORNL-DWG 88C-14831

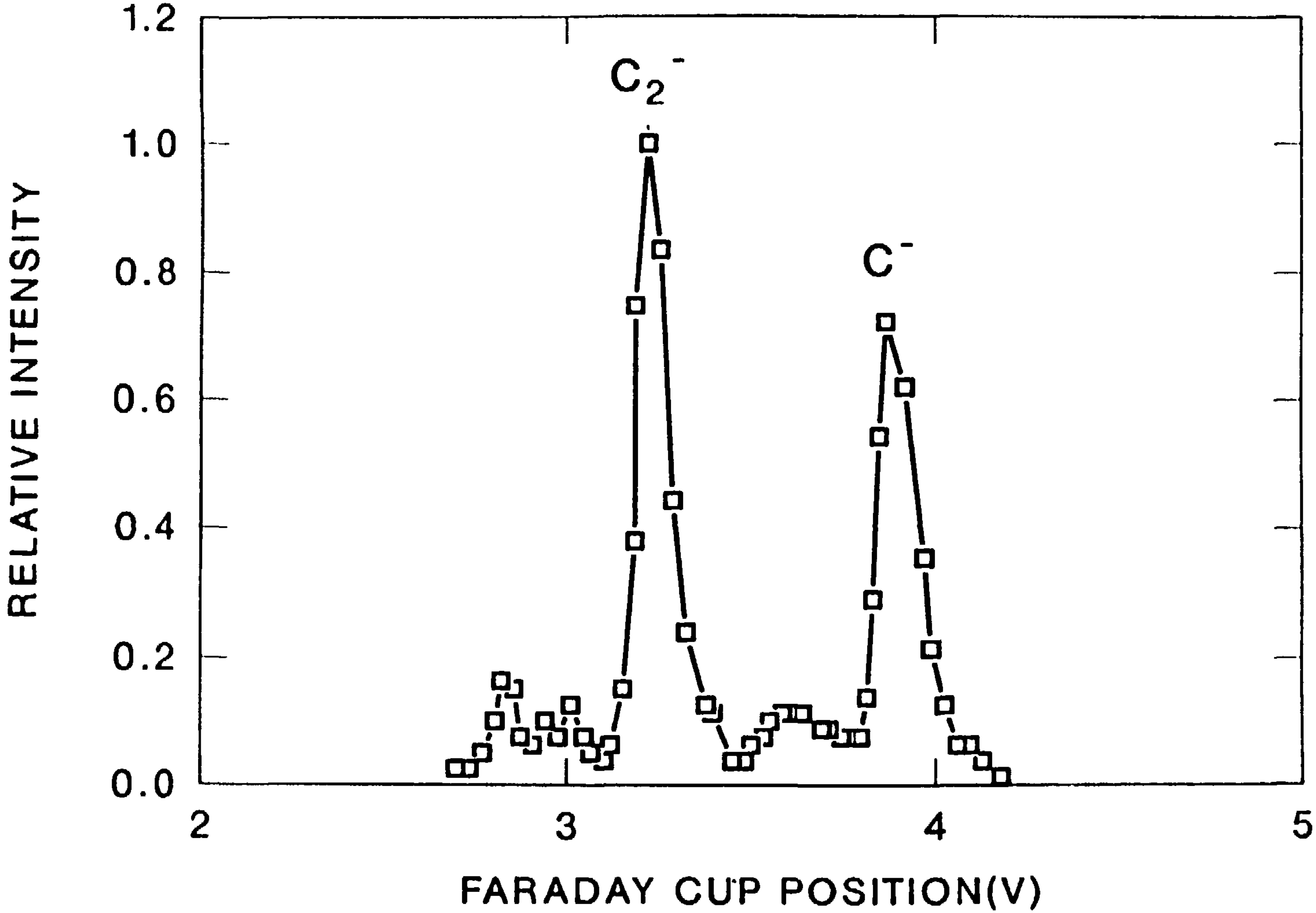

Fig. 8

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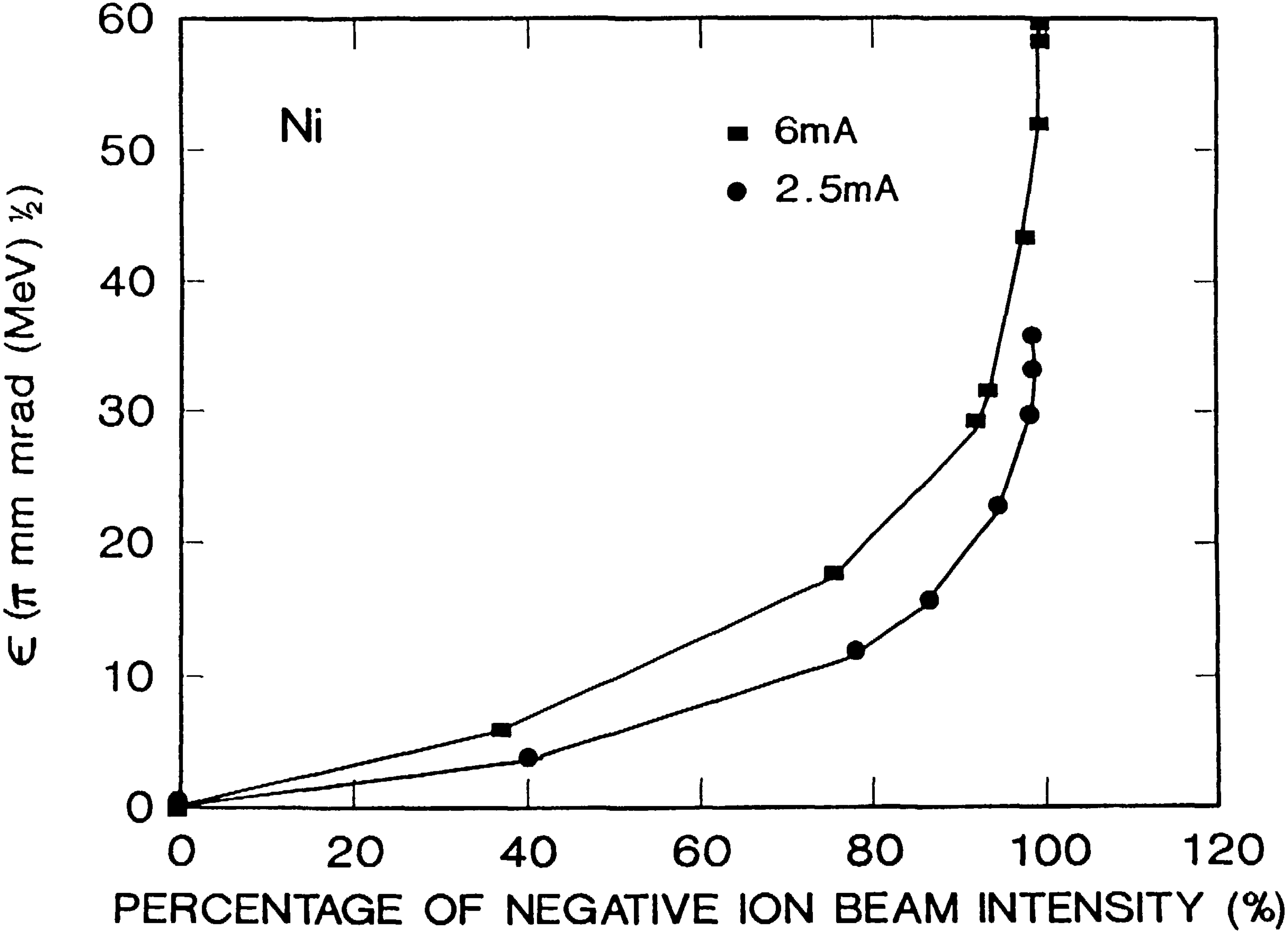

Fig. 9

ORNL-DWG 89-12354

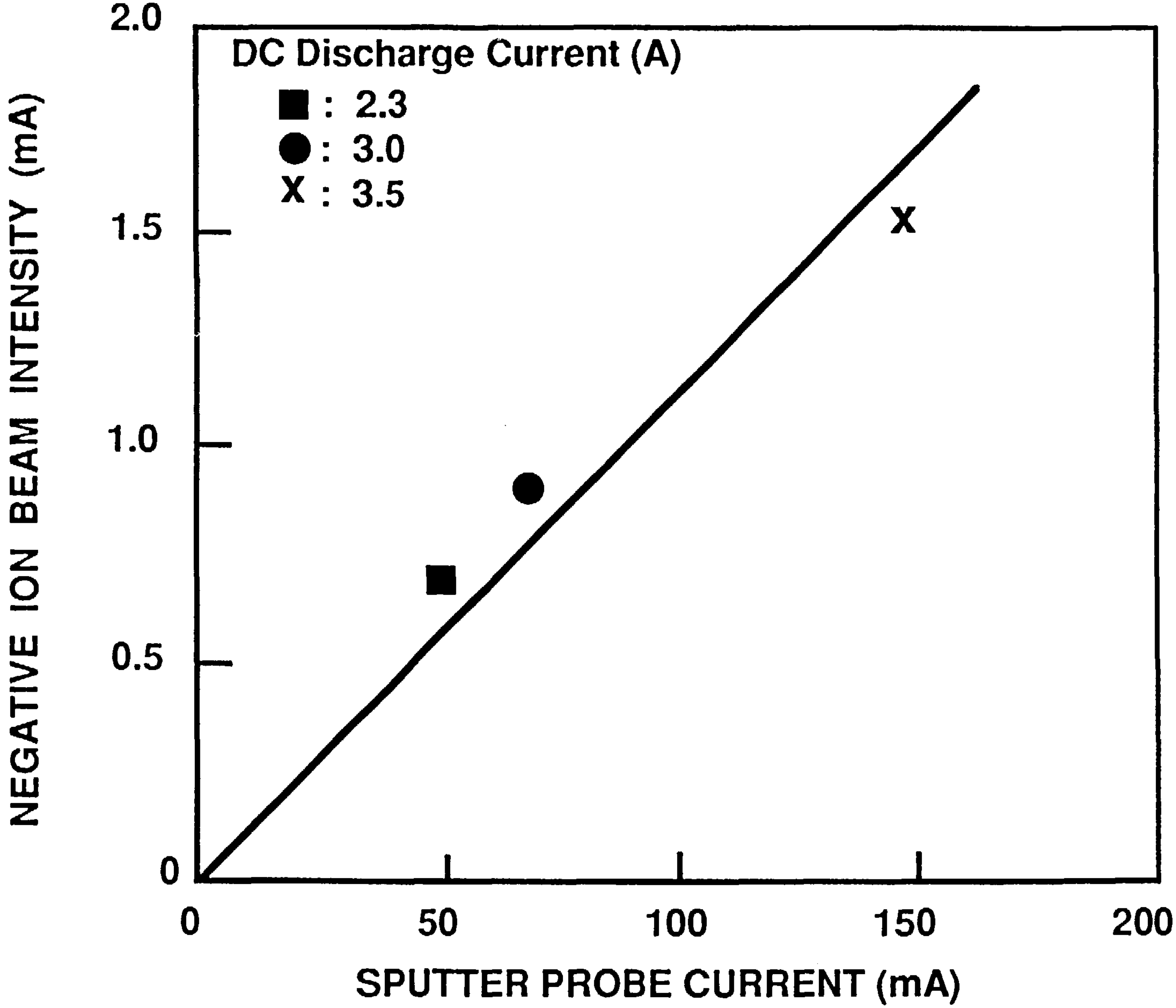

Fig. 10

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