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Authors
Brown, I.G.
Anders, Andre
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Publication Date
1995-07-01

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UC-426

Lawrence Berkeley Laboratory
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Accelerator & Fusion Research Division

Invited paper presented at the Ninth International Conference on Surface Modification of Metals by Ion Beams, San Sebastien, Spain, September 4–8, 1995, and to be published in the Proceedings

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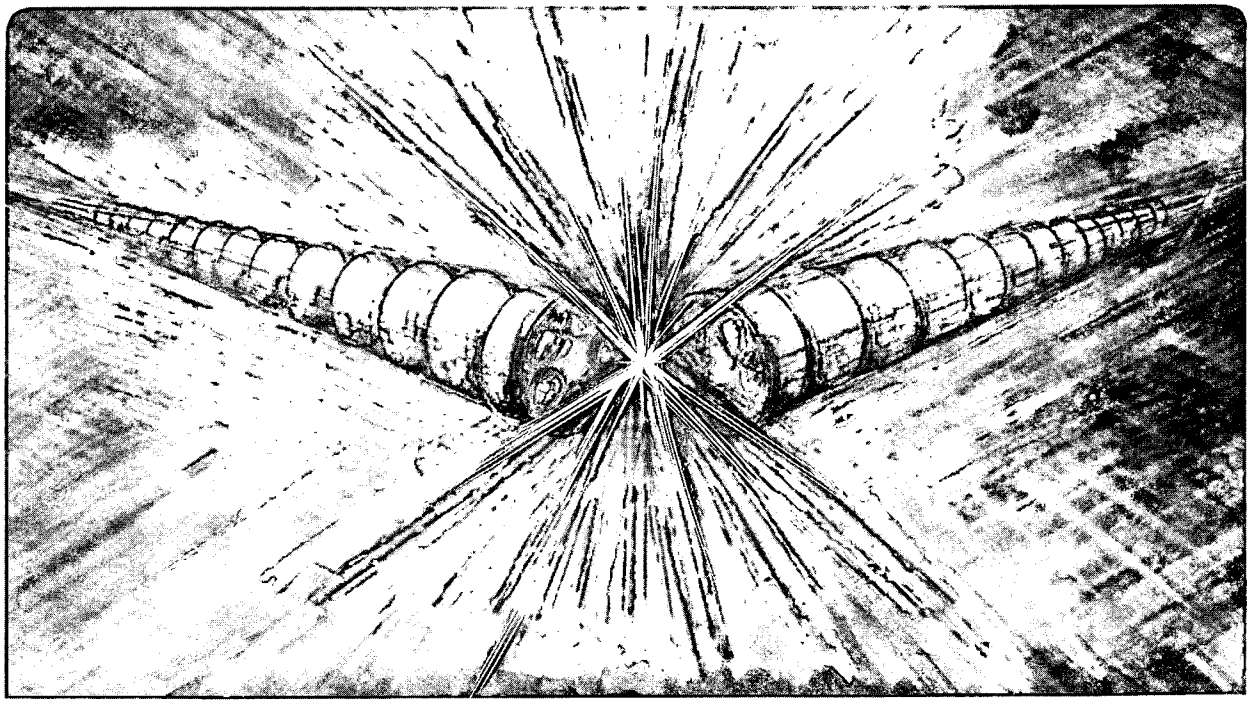
July 1995



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Invited Paper

RECENT ADVANCES IN VACUUM ARC ION SOURCES*

I.G. Brown, A. Anders, S. Anders, M.R. Dickinson, R.A. MacGill and E.M. Oks†

Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

July 1995

† Visiting Scientist from the High Current Electronics Institute, Russian Academy of Sciences, and the State Academy of Control Systems and Radioelectronics, Tomsk 634050, Russia.
* This work was supported by the Electric Power Research Institute under Award Number 8042-03, the Army Research Office under Contract No. ARO-110-93, and the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

Recent Advances in Vacuum Arc Ion Sources

I.G. Brown[a], A. Anders[a], S. Anders[a], M.R. Dickinson[a], R.A. MacGill[a], E.M. Oks[b]

[a] *Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA*

[b] *High Current Electronics Institute, Russian Academy of Sciences, and State Academy of Control Systems and Radioelectronics,Tomsk 634050, Russia*

Abstract

Intense beams of metal ions can be formed from a vacuum arc ion source. This kind of source works well for most of the solid metals of the periodic table, and because the ions are in general multiply stripped with charge states as high as 4+ to 6+, the mean energy of the ion beam produced can be 100 - 200 keV for extractor voltage in the comfortable range of about 50 - 75 kV. Broad-beam extraction is convenient, and the time-averaged ion beam current delivered downstream can readily be in the tens of milliamperes range. The vacuum arc ion source has for these reasons found good application for metallurgical surface modification – it provides relatively simple and inexpensive access to high dose metal ion implantation. Several important source developments have been demonstrated recently, including very broad beam operation, macroparticle removal, charge state enhancement, and formation of gaseous beams. We have made a very broad beam source embodiment with beam formation electrodes 50 cm in diameter (area 2000 cm^2), producing a beam of width ~35 cm for a nominal beam area of ~1000 cm^2, and a pulsed Ti beam current of about 7 A was formed at a mean ion energy of ~100 keV. Separately, we've developed high efficiency macroparticle-removing magnetic filters and incorporated such a filter into a vacuum arc

ion source so as to form macroparticle-free ion beams. Jointly with researchers at the High Current Electronics Institute at Tomsk, Russia, and the Gesellschaft für Schwerionenforschung at Darmstadt, Germany, we've developed a compact technique for increasing the charge states of ions produced in the vacuum arc plasma and thus providing a simple means of increasing the ion energy at fixed extractor voltage. Finally, operation with mixed metal and gaseous ion species has been demonstrated. Here we briefly review the operation of vacuum arc ion sources and the typical beam and implantation parameters that can be obtained, and describe these source advances and their bearing on metal ion implantation applications.

1. Introduction

The vacuum arc metal ion source provides a convenient and relatively inexpensive tool for carrying out metal ion implantation in a mode that is suitable for many different kinds of surface modification applications. High current beams of metal ions are formed from the dense, highly ionized metal plasma that is generated by a vacuum arc discharge embodied within the ion source configuration. The plasma physics of ion production in vacuum arc plasmas [1-4] and the approaches taken for incorporating this kind of plasma within an ion source [5-8] have been described in detail elsewhere. Vacuum-arc-based ion sources have been developed at many laboratories around the world [5,9], mostly for ion implantation and particle accelerator injection.

As the subfield has grown and attracted workers to the area, so also the range of application variations, hardware embodiments, and performance objectives has expanded. Sources have been developed from very small up to quite large systems and with ion beam currents from a few milliamperes up to several amperes. More recently, a number of novel and advantageous source developments have been made. Here we report on several of these advances that are of particular relevance to ion implantation application. In the following, we firstly briefly review the fundamental characteristics of vacuum arc ion sources, and then describe some of the specific advances made together with the ion beam characterization results obtained.

2. Background

The vacuum arc ion source is, in essence, simplicity itself. A vacuum arc plasma source, typically but not necessarily of cylindrical symmetry and repetitively pulsed, is appropriately located with respect to a set of beam formation electrodes ('extractor grids') in a vacuum housing. Metal plasma is produced by the vacuum arc discharge from a macroscopically cold cathode – the plasma production mechanism is neither evaporative nor sputtering, and no oven nor background gas is required. The metal plasma plume, produced at the cathode spots [1] in a way reminiscent of laser plasma production, streams toward the extractor where the ion separation and acceleration is done.

Typically a multi-aperture, triple grid extractor (plasma grid, electron suppressor grid, and ground grid) is used. The ion beam that is formed is typically 'broad beam' with diameter perhaps from a centimeter or two up to tens of centimeters, of ion energy in the range a few keV up to several hundred keV, and of (pulsed) ion current in the range from a few milliamperes up to several amperes. Pulse length might typically be a few hundred microseconds or a few milliseconds, the pulse repetition rate might be up to a few tens or a hundred pulses per second, corresponding to a duty cycle of up to several (~1 to 5) percent. A dc (continuous, steady state) source embodiment has been demonstrated and dc ion beam extracted [5], but such source versions are not yet used widely.

The metal ion species can be any of the solid metals of the periodic table [5,10], as well as metallic compounds and alloys [11,12]. Beams have been formed from Li, C, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ge, Sr, Y, Zr, Nb, Mo, Pd, Ag, Cd, In, Sn, Sb, Ba, La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, Er, Tm, Yb, Hf, Ta, W, Ir, Pt, Au, Pb, Bi, Th and U. In general the higher melting point metals provide longer operating times between needed cathode maintenance. The ions generated by the vacuum arc are in general multiply stripped with a charge state distribution having a mean between 1+ and 3+ and with components up to 5+ or 6+. For an extraction voltage of, say, 75 kV, the ion beam can thus have a mean energy of up to about 200 keV or more, with discrete ion energy components up to about 500 keV.

Vacuum arc ion sources have been used for ion implantation application by a growing number of workers at many different laboratories around the world [5,6,13]. Implantation is done in a broad-beam mode, without magnetic analysis of charge-to-mass components, and the ion trajectories are line-of-sight from ion source to target. Since the metal plasma is formed solely from the cathode material and there is no carrier gas, implantation in a non-mass-analyzed mode is for many applications (but not all) quite acceptable. An ion implantation facility of this kind consists of simply a vacuum arc ion source mounted onto an appropriate vacuum chamber, with hardware to accommodate the insertion and removal of implantation targets. The target may be introduced into the vessel through a vacuum load-lock and the turn-around time for target changes can be as short as a matter of minutes. A Faraday cup can be inserted into the beam immediately in front of the target

and the beam current adjusted prior to implantation so as to accumulate the required dose. The implantation facility developed and used at Berkeley has been described previously [14,15].

3. New Source Embodiments

A number of significant advances in source design and operation have been made recently that can be important for implantation applications. Here we limit our consideration to four separate developments that have been made at several laboratories – the High Current Electronics Institute (HCEI) at Tomsk, Russia, the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt, Germany, and the Lawrence Berkeley Laboratory (LBL) at Berkeley, California. Some of the work was done jointly between these laboratories. The developments described relate to the production of very large area beams, the removal of macroparticle contamination from the ion beam, controlled increase of the charge states produced, and production of mixed metal/gaseous ion beams.

3.1. Very large area beam production

In a conventional semiconductor ion implanter, large target areas are treated by scanning the beam electrostatically and/or the target mechanically, and the ion source usually has an initial beam size that is relatively small so that the beam can be matched to the optics of the downstream transport system and implanter post-accelerator. For non-semiconductor ion implantation of large area objects it can be convenient for the ion beam to be of large area and to irradiate the target in a direct line-of-sight from ion source to target; note that the plasma produced in a vacuum arc is comprised to a high degree of the cathode material alone, and the ion beam composition is essentially a reflection of the pure cathode metal. Broad beam operation is advantageous because of its simplicity. The essential feature of this kind of ion source is that the plasma is allowed to expand to large size prior to beam formation, preferably in a configuration such that the transverse plasma density distribution, and hence also the ion beam current profile, is relatively flat.

We've made several broad beam source versions, including our 10-cm "workhorse" source that we use for our routine ion implantation work [5,16], a 20-cm source that we used to test d.c. ion

beam extraction [5,17,18], and a source having a 50 cm diameter (2000 cm^2) extractor [5,18]. A photograph of the very large area extractor grids is shown in Figure 1. The extractor is a 3-grid, multiaperture, 50 cm diameter configuration fabricated from 4.76 mm thick aluminum. The beamlet holes are 1 cm in diameter and there are about 1000 of them; the extractor gap is ~1 cm for 50 kV operation. This extractor configuration has been tested and quantified, and used to do implantation into a large target. The radial profile of the extracted ion beam was approximately gaussian with a 33 cm FWHM. The spatially-integrated beam current was 1.5 A at 40 kV extraction voltage (~80 keV mean beam energy) and 100 A arc current, and as high as 7 A at 50 kV (~100 keV) and 300 A arc current. These measured beam currents are nicely consistent with an $I_{beam} \sim I_{arc} V_{ext}^{3/2}$ variation, as expected at or near optimal extraction conditions (ie, at perveance match).

The nature of very-broad-beam ion beam formation from a vacuum arc plasma is inherently an efficient process in terms of plasma utilization. In smaller vacuum arc ion source embodiments, it is usual that there is more metal plasma produced than can be extracted; in the large extractor embodiments, the procedure is to make sure that the geometry (plasma source, expansion region, extractor location) is such that most of the plasma that is created is presented to the extractor. In this case, the large plasma expansion is accompanied by a reduction in plasma density, and the extraction optics can be matched – i.e., if optimally designed, all of the plasma that is transported to the extractor can in fact be formed into useable beam (except of course for the factor due to extractor transparency). For the 50-cm version the extracted beam current during the current flat-top is 2.3% of the arc current, which given the 40% extractor grid transmission factor is an impressively high fraction compared to the ratio $I_{plasma}/I_{arc} \simeq 10\%$ that is universally observed for plasma production by vacuum arcs.

We conclude that vacuum arc ion source embodiments can be made of very large area, and these embodiments can be quite efficient. Extractors of a meter or more in diameter are feasible.

3.2. Macroparticle removal

It is a fundamental characteristic of vacuum arc discharges that along with the dense metal

plasma, a flux of 'macroparticles' ('macros') is also produced [1,2,19] . These are small metal globules, of dimension typically in the range 0.1 to 10 μm, formed from the cathode during the same explosive emission process that generates the plasma, initially molten and rapidly solidified in flight. Clearly the solid cathode debris might in some situations be a disadvantage, for example for the case of semiconductor processing applications. This has not been a problem for most of our implantation research, however. Macroparticle generation is observed to be less, in general, for cathode materials of higher melting point, and there also is a natural separation of the wanted plasma flux from the unwanted macroparticle flux because the plasma flux is peaked in the direction normal to the cathode surface while the macroparticle flux is peaked in a direction close to parallel (~20°) to the cathode surface [20]. The magnitude of the macroparticle flux is dependent upon a large number of operational parameters, such as arc current, pulse length, cathode material, source-to-target distance, among others. Furthermore, there is a solidification of the droplets in flight, and in many situations the solid macroparticles simply bounce off the target. Nevertheless it is in principle desirable to remove the macroparticles completely from the ion beam, and this can be done by incorporating a magnetic duct [21-25] into the ion source between the plasma gun and the extractor. We have carried out a series of experiments on duct plasma transmission and macroparticle filtering, and the results are good. A magnetic duct was installed in a modified broad beam source, thereby producing high current metal ion beams that are macroparticle free (and neutral free) [26].

The test configuration used is indicated schematically in Figure 2. The source was a modified version of our 10-cm extractor source; we used several different cathode materials, feeding a 60° duct. The arc current was varied over the range 50 to 500 A. The on-axis ion beam current density was measured at an axial location of 65 cm downstream from the extractor, the normal location of our implantation targets. As mentioned above, it is usual that macroparticle contamination of implanted targets in not a problem – mostly, the solidified macros simply bounce off the target, and residual contamination is tiny. Thus, in order to produce a measurable macro contamination so that we could quantify the effect of installing the filter, we operated for these tests with a lead cathode. Lead, being a very soft material (low melting point), is recognized as a prolific

macroparticle generator; for a lead cathode, about 90% of the on-axis flux generated is in the form of macroparticles, compared to about 3% for tungsten, for example [27].

SEM photographs of targets obtained operating with and without filter for a Pb implant into Si at a dose of 2.5 x 10^{16} cm^{-2} and energy 64 keV are shown in Figure 3. The improvement is very evident. The duct introduces a loss of plasma, and thus for given arc current the extracted ion beam is reduced. This effect is shown in Figure 4. The loss is compensated for simply by increasing the arc current, in this case (Ti at 40 kV extraction) by a factor of about 2.5, from 200 A to 500 A.

These experiments show that macroparticle removal can be incorporated into vacuum arc ion source design. There is a loss of plasma, and hence of ion beam current density, but this can be compensated for by increased arc current. For most (non-semiconductor processing) applications however, macroparticle contamination of the implanted target is not a problem.

3.3. Charge state enhancement

Ions produced in the vacuum arc plasma are in general multiply stripped. The ion charge state spectrum is distinct and different for different metals. The charge states produced vary from 1+ up to about 6+, with the mean charge state for a given metal lying in the range 1+ to 3+. Generally, metals that are low in the periodic table and of low boiling point have lower charge states, while metals higher in the periodic table and of higher boiling point have higher charge states [5,10]. There is only a weak dependence of charge state on arc current; as the arc current is increased, more cathode spots are created but the plasma physics within each spot remains much the same.

For ion implantation application, as well as for other applications, there would be considerable advantage to having upward control over the ion charge states. The ion energy can then be increased by increasing the charge state rather than by increasing the implanter operating voltage, providing an important savings in cost and size of the implanter. Some recent work has shown that the application of a strong magnetic field to the arc region can provide such charge state control.

The experiments were done using multi-cathode vacuum arc ion sources, collaboratively

between Berkeley, Darmstadt and Tomsk. The work has been described in detail elsewhere [28]; here we summarize the essence of the work and the results obtained. An axial magnetic field was established by a small, pulsed field coil mounted inside the anode region near the cathode, as shown schematically in Figure 5, producing fields of up to about 10 kG or more. Ion charge state distributions were measured using a magnetic spectrometer (GSI) [29] as well as a time-of-flight (TOF) system (LBL) [30].

It is convenient to power the field coil using the same current source as used to drive the arc; in this case the magnetic field strength and the arc current increase together. The oscillogram shown in Figure 6 is typical of the results obtained. Here the TOF charge state spectrum (electrical current into a Faraday cup) for a carbon ion beam is shown (a) for the case of no applied magnetic field and (b) for the case of an applied field of strength 3 kG and an arc current of 3 kA. For the zero field case the primary component is C^{+} with only a trace of C^{2+} and the mean charge state is close to unity; for the high field / high arc current case the primary component is C^{2+} with significant C^{3+} and the mean charge state is 2+. Results from the other end of the periodic table are shown in Figure 7 for uranium; here the charge state distribution (particle current fractions) is shown as a function of magnetic field strength. The effect of magnetic field on the charge state distribution for a number of different cathode materials is shown in Table I. It is evident that the effect can be large – the increase in mean charge state is typically by a factor in the range 1.5 to 2.5, and one or two new charge state components are added on the high side.

The measurements show clearly that upward control of the metal ion charge states produced in the vacuum arc ion source can be provided by application of a strong magnetic field. The effect is significant for implantation application – the mean ion energy can be about doubled without change in extraction voltage.

3.4. Operation with mixed metal and gaseous ion species

Although the vacuum arc ion source is usually thought of as specifically a metal ion source, it turns out that by the addition of gas to the arc discharge region under the appropriate operating

conditions, ionization of the gas can occur in the metal plasma and energetic beams of mixed metallic and gaseous species can be produced. The effect of gas on the arc plasma development has been investigated by several workers [31-33], and operation of a vacuum arc ion source at elevated background gas pressures has been reported previously [34,35]. The presence of added gas can change the charge state composition of the metal ion beam as well as allowing for mixed-species beams. Interest in this operating mode for ion implantation application of course has to do with the ability to thereby form buried layers of mixed composition such as, for example, oxides and nitrides. The versatility of the source is enhanced considerably by this capability.

For gaseous operation, it is necessary that the gas be admitted specifically into the arc region and that the arc region be embedded within a high magnetic field as described above. When the source is so modified, good operational control over the fraction of gas and metal ions in the beam can be obtained. We have modified our standard 10-cm source for operation in this way and measured the beam composition using our time-of-flight diagnostic.

An example of the kind of beam that can be produced is shown in Figure 8 for the case of a mixed Ti - N ion beam. The particle current fractions for the Ti and N ion components in the beam are plotted as a function of nitrogen gas pressure in the main vacuum chamber. As expected, the beam is primarily metallic for low pressure ($\lesssim 10^{-5}$ Torr) and substantially gaseous for higher pressure ($\gtrsim 10^{-4}$ Torr). The metal-to-gaseous ion mix ratio can be varied over an impressive range, from 100% metallic to up to as high as 80% gaseous. An oscillogram showing the TOF charge state spectrum (electrical current into a Faraday cup) for a mixed Ti-N beam is shown in Figure 9. The practical significance for metallurgical surface modification of simultaneous implantation with titanium and nitrogen is clear. We have also formed other mixed species beams, including for example Pt - N and Al - O, which we've used for carrying out some exploratory ion implantation work; this work is ongoing.

Operation with gas feed in this way also provides an important serendipitous advantage for triggering the ion source. In the presence of gas in the anode-cathode gap, the arc discharge is

initiated by a gaseous breakdown even in the absence of an applied high voltage trigger pulse; the pre-discharge anode-cathode voltage of typically 100 - 200 V is enough to cause gaseous breakdown. Then there is no erosion of the triggering system, and the ion source can be operated for many millions or tens of millions of repetitive pulses before the cathode needs to be changed.

4. Conclusions

The versatility of the vacuum arc ion source as a tool for surface modification by ion implantation is being expanded by the discovery and development of new operational modes. Here we've described several recent developments that are important in this way, related to the production of very broad beams, the removal of macroparticles, increase of the ion charge states, and operation in a hybrid gaseous-metallic ion beam mode. It is probable that the source will see yet further development along these lines and also in new ways not yet thought of, and that the versatility and utility of the vacuum arc ion source will continue to grow.

Acknowledgments

It is a pleasure to acknowledge the friendly collaborative sharing of results by workers at the High Current Electronics Institute at Tomsk, Russia, and the Gesellschaft für Schwerionenforschung (GSI) Darmstadt, Germany. This work was supported by the Electric Power Research Institute under Award Number 8042-03, the Army Research Office under Contract No. ARO-110-93, and the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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TABLE I

Charge state distributions and mean charge states, all in particle current fractions, for a range of metal ion species with and without magnetic field. Data obtained from a number of different coil configurations.

Metal	Without magnetic field							With magnetic field									$\bar{Q}_2/\bar{Q}_1$
	1+	2+	3+	4+	5+		$\bar{Q}_1$	1+	2+	3+	4+	5+	6+	$\bar{Q}_2$	B(kG)	I(kA)	
C	96	4					**1.0**	29	58	13				**1.8**	3.2	3.2	1.80
Mg	51	49					**1.5**	5	95					**1.9**	3.75	0.22	1.27
Al	38	51	11				**1.7**	5	11	85				**2.8**	1.2	1.2	1.65
Ti	11	76	12	1			**2.0**	1	6	15	58	20		**3.9**	10.0	1.3	1.95
V	11	72	15	2			**2.1**	13	31	48	8			**2.5**	3.75	0.22	1.20
Cr	14	70	15	1			**2.0**	4	9	20	53	12	2	**3.7**	6.2	0.8	1.85
Fe	28	68	6				**1.8**	6	20	34	38	2		**3.1**	2.2	2.2	1.72
Ni	43	50	7				**1.6**	1	9	19	32	27	12	**3.5**	3.4	3.4	2.18
Co	34	59	7				**1.8**	5	46	47	2			**2.5**	6.0	0.4	1.40
Cu	28	53	18	1			**1.9**	10	22	32	32	4		**3.0**	4.6	0.6	1.57
Nb	3	40	39	16	2		**2.7**	-	6	11	29	51	3	**4.3**	1.2	1.2	1.59
Mo	7	30	40	20	3		**2.8**	-	10	19	32	27	12	**4.1**	5.4	0.7	1.46
Ag	13	61	25	1			**1.9**	7	23	37	30	3		**3.0**	5.4	0.7	1.57
Hf	7	26	48	18	1		**2.8**	1	5	11	39	41	3	**4.2**	4.6	0.6	1.50
W	1	17	35	35	12		**3.4**	1	5	16	39	32	7	**4.2**	3.75	0.22	1.20
Pt	12	70	18				**2.1**	1	16	34	46	3		**3.3**	10.0	1.2	1.57
Bi	89	11					**1.1**	7	27	57	9			**2.7**	4.6	0.6	2.45
U	20	40	32	8			**2.3**	1	20	32	28	16	3	**3.5**	4.6	0.6	1.52

Figure Captions

Fig. 1 50-cm diameter extractor grids, together with a small and two 'micro-miniature' source versions.

Fig. 2 Simplified schematic of vacuum arc ion source with 60° magnetic filter between plasma source and extractor.

Fig. 3 SEM photographs of Si target implanted with Pb to a dose of 2.5×10^{16} cm^{-2} and at energy 64 keV; (a) unfiltered, and (b) filtered.

Fig. 4 Ion beam current density as a function of arc current with and without magnetic filter, on-axis 65 cm downstream, for a Ti beam at about 80 keV mean ion energy.

Fig. 5 Vacuum arc ion source with magnetic field coil surrounding the arc region, and means for gas injection.

Fig. 6 Oscillograms of TOF charge state spectra for a carbon ion beam, for the case of no applied magnetic field (upper), and for a field of 3 kG and arc current of 3 kA (lower).

Fig. 7 Measured ion beam current fractions (particle currents) as a function of magnetic field strength for the different charge states of a uranium ion beam. Arc current is given by $I_{arc} \approx 100$ Amp/Gauss (the coil is in series with the arc).

Fig. 8 Ion current fractions in a mixed Ti - N beam as a function of nitrogen gas pressure.

Fig. 9 Oscillogram of TOF charge state spectrum for a mixed Ti - N ion beam.

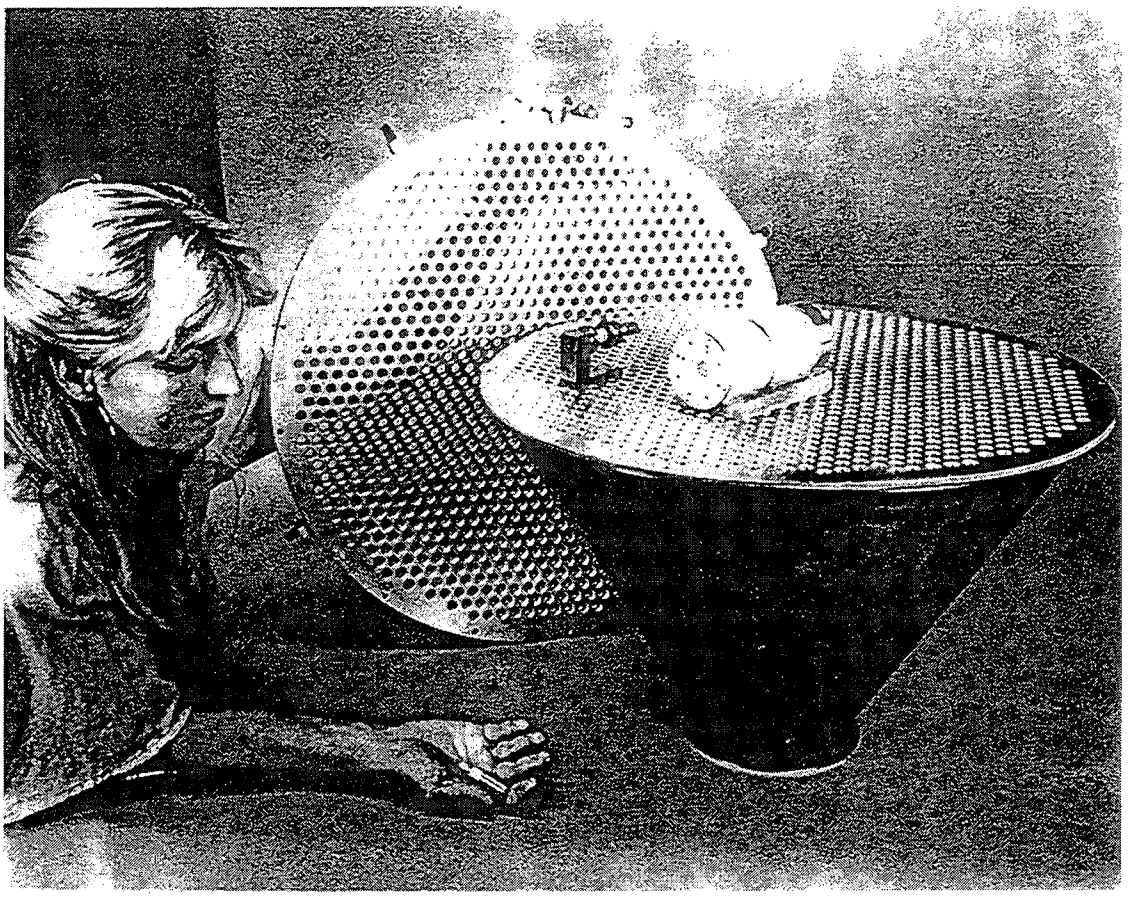


Fig. 1

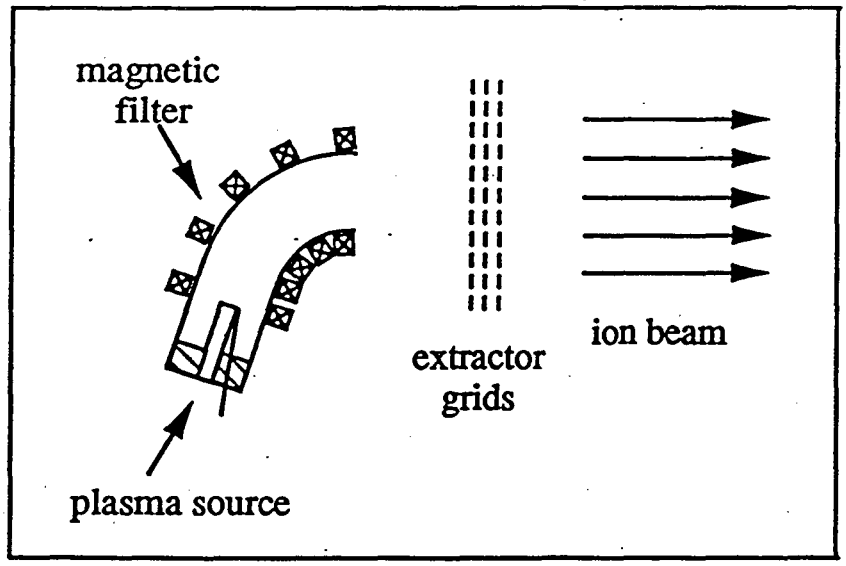


Fig. 2

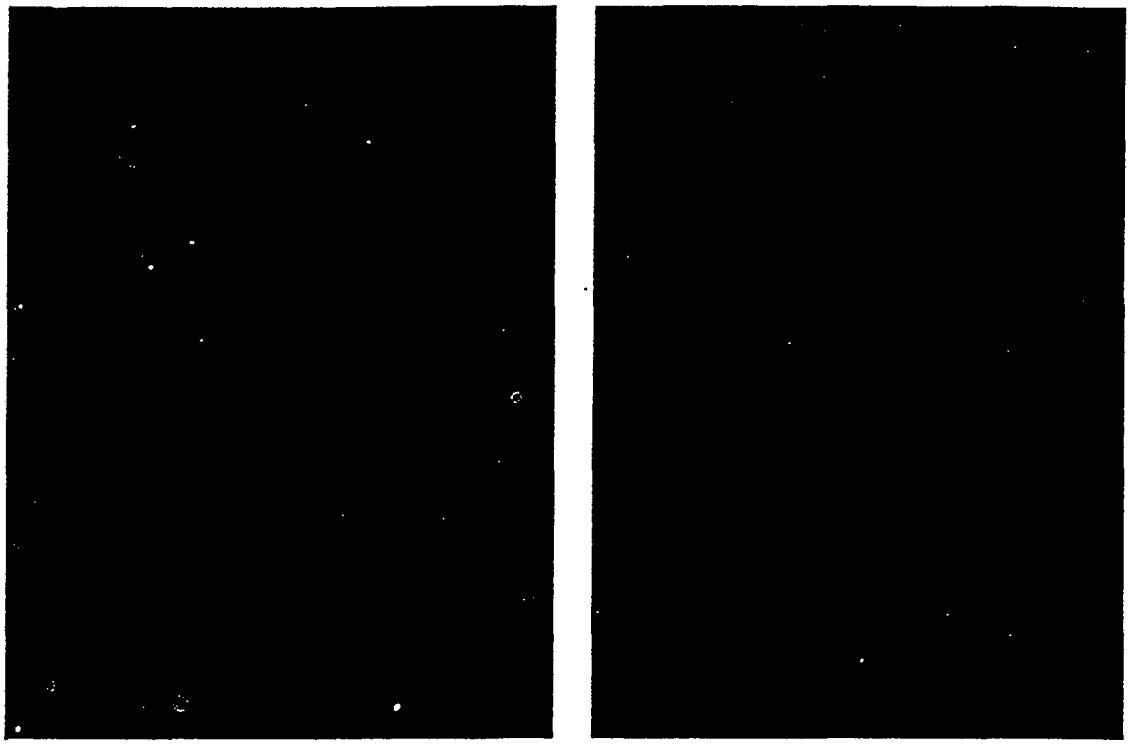
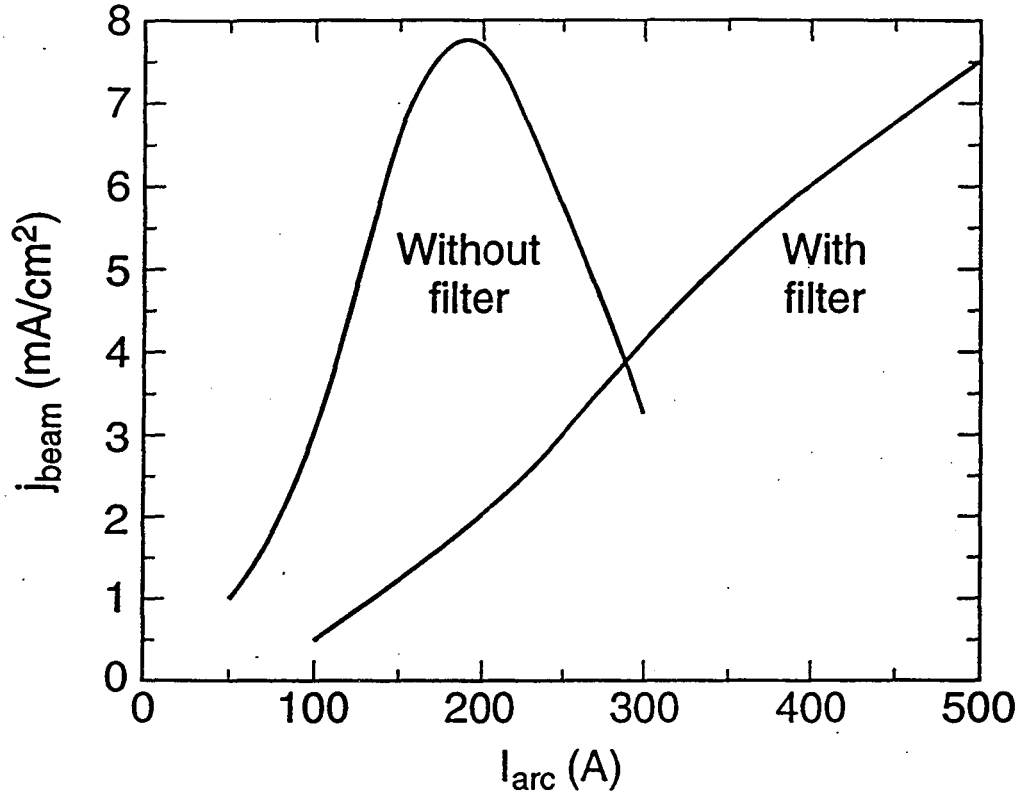


Fig. 3



XBD 9508-03786.ILR

Fig. 4

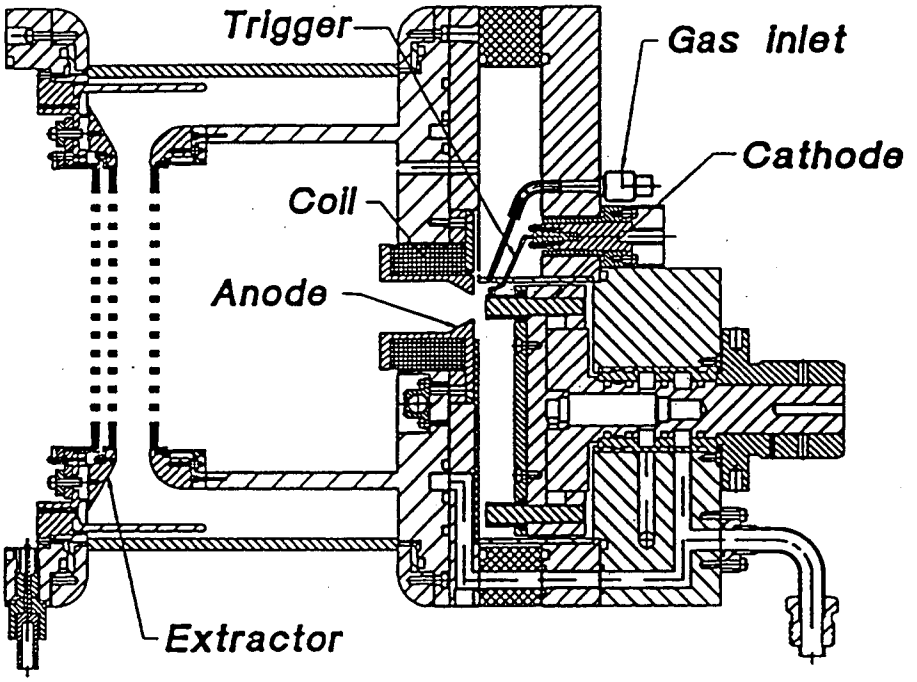


Fig. 5

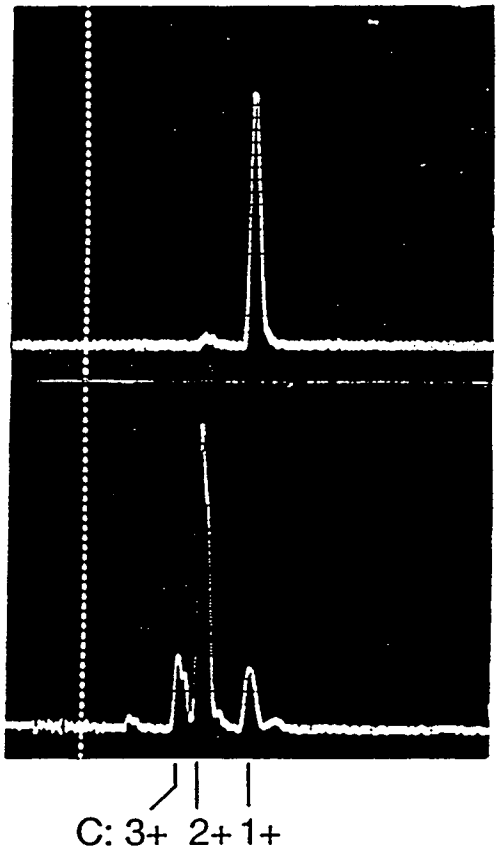


Fig. 6

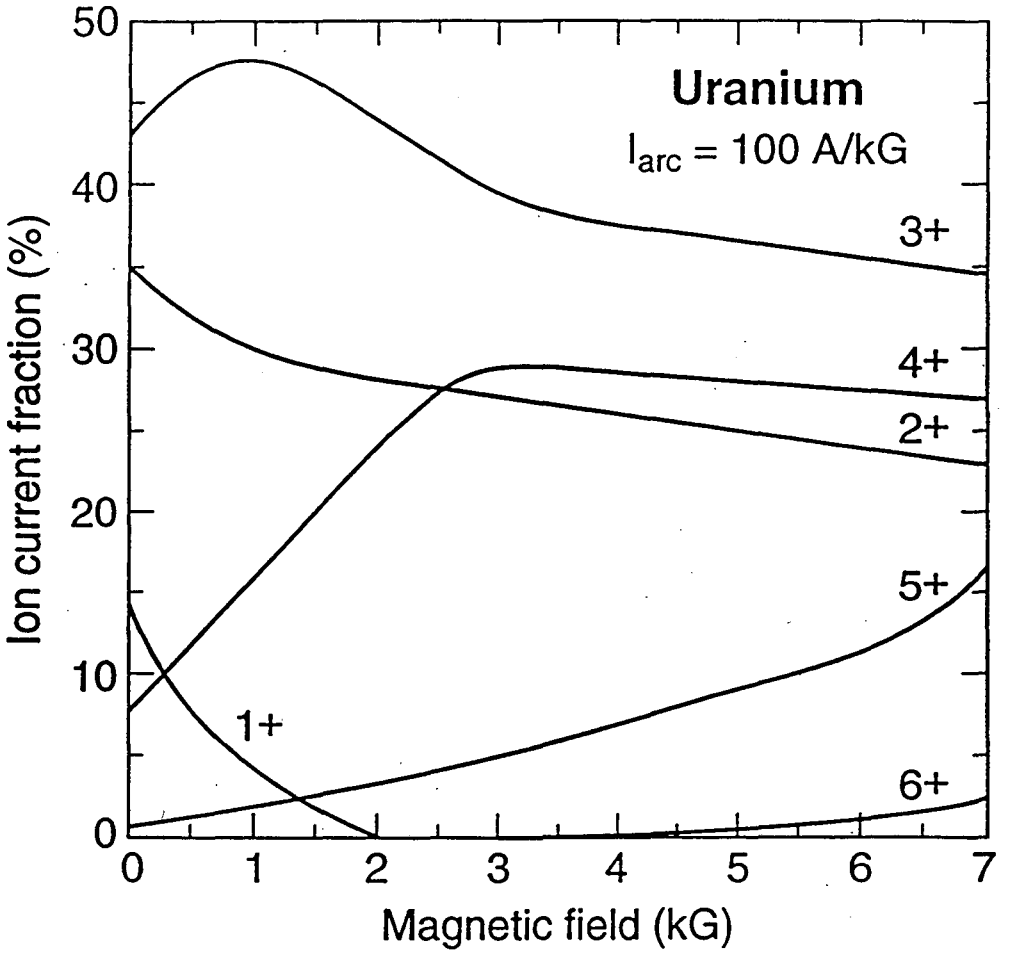


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Fig. 7

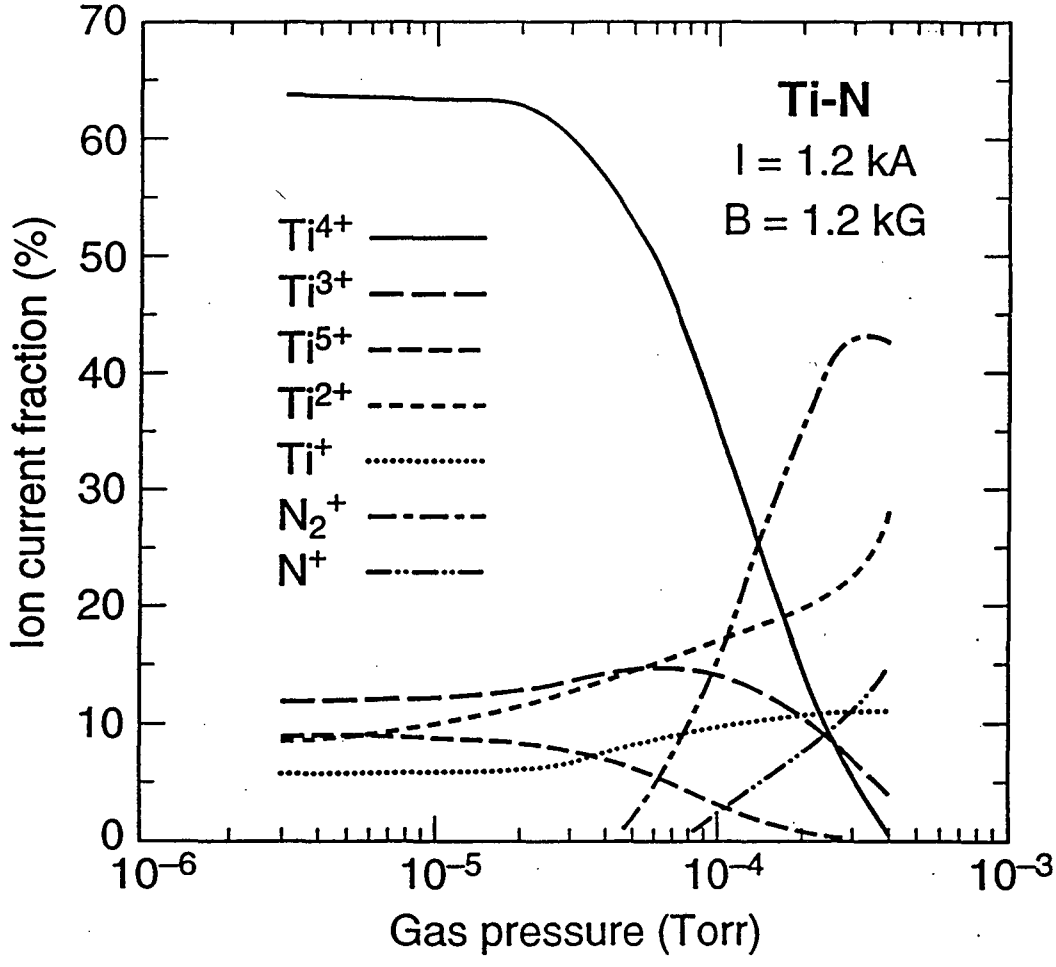

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Fig. 8

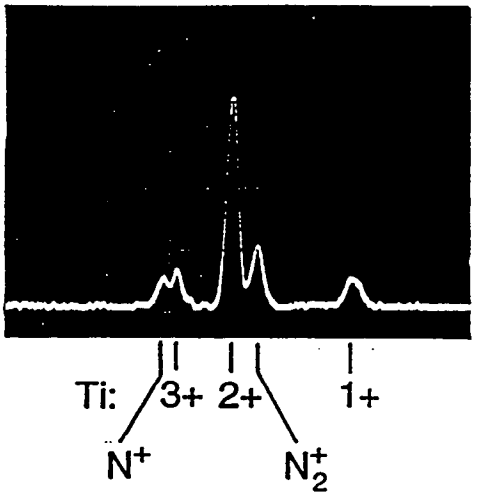

Fig. 9

LAWRENCE BERKELEY NATIONAL LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL & ELECTRONIC INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720