Lawrence Berkeley National Laboratory

Title
ON THE CURRENT INTENSITY LIMIT OF A VACUUM ARC ION SOURCE

Permalink
https://escholarship.org/uc/item/08s7556c

Author
Brown, I.G.

Publication Date
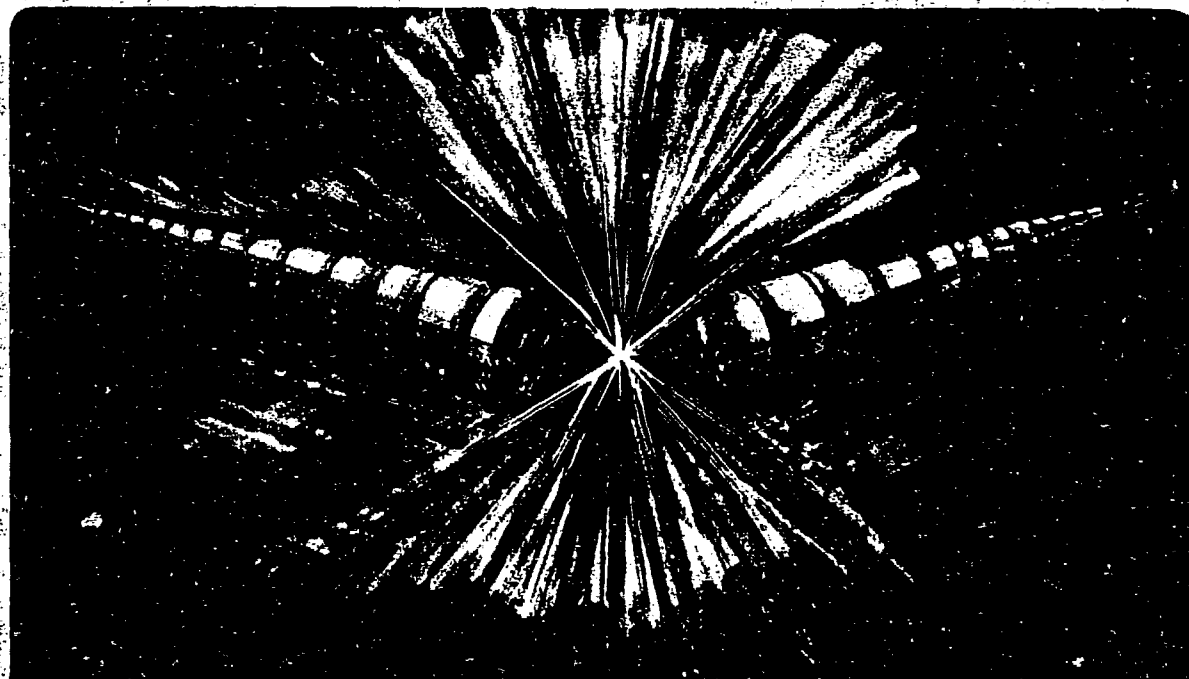1987-03-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

**ON THE CURRENT INTENSITY LIMIT
OF A VACUUM ARC ION SOURCE**

I.G. Brown

March 1987

ON THE CURRENT INTENSITY LIMIT OF A VACUUM ARC ION SOURCE*

Ian G. Brown

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

ABSTRACT

The maximum ion current that can be produced as a high energy beam from a metal vapor vacuum arc ion source is considered. Results are presented of measurements of the plasma ion current in the MEVVA II ion source. It is shown that this source is an efficient generator of metal ions, an intense flux of which is efficiently transported to the beam extractor. The maximum metal ion current that is available for extraction at the extractor location is 5% of the arc current. The limitation to the intensity of the metal ion beam that can be produced by this kind of ion source is in the extractor design.

INTRODUCTION

The metal vapor vacuum arc is a prolific source of highly ionized metal plasma. Ion production in this kind of discharge has been investigated by a number of authors [1-11]. This way of creating a high density metal ion plasma can be used to make a high current metal ion source. One of the earliest attempts to incorporate the vacuum arc into an ion source was done as part of the Manhattan Project [12], but this work was not successful and was not pursued. Revutskii et al [13] made a source of this kind, but this also was not pursued. More recently, vacuum arc ion sources have been made and investigated by several groups [14-22].

A series of sources of this kind have been developed at Lawrence Berkeley Laboratory, which we've called MEVVA ion sources as an acronym for the metal vapor vacuum arc plasma discharge employed. These sources have been described in detail elsewhere [19-22]. With the MEVVA source we have produced beams of metal ions at voltages up to 100 kV and with ion current of hundreds of milliamperes. The source operates well with a wide variety of cathode materials spanning the periodic table from lithium up to uranium.

It is of some interest to consider what the upper limit is to the ion beam current that can be produced by the MEVVA ion source. Several workers have addressed the more fundamental question of ion production in the basic vacuum arc plasma source, and we have drawn upon this work. In the present work results are presented of measurements of ion current in the plasma plume within the MEVVA geometry. This can be related to the maximum ion beam current that can be drawn from the MEVVA ion source.

EXPERIMENT

The version of the source that we've used for these experiments is the MEVVA IIb source. A photograph of this source is shown in Figure 1, and an outline of the arc and extractor region is shown in Figure 2. In the MEVVA ion source, the intense plume of highly ionized metal plasma that is created at the cathode spots of the vacuum arc discharge plumes away from the cathode toward the anode, persisting for the duration of the arc current drive. The anode of the discharge is located on axis with respect to the cylindrical cathode and has a central hole in it through which a part of the plasma plume streams; it is this component of the plasma that forms the medium from which the ions are extracted. The plasma drifts through the post-anode region to the set of grids that comprise the extractor - a three grid, accel-decel multi-aperture design. A small axial magnetic field of up to about 200 Gauss, produced by a simple coil surrounding the arc region, serves to help duct the plasma plume in the forward direction, but this is not an essential ingredient to the operation of the source. The various components and features referred to can be seen in Figures 1 and 2. The extractor diameter is 2 cm, as is the initial beam diameter. For these experiments we have used titanium as the cathode material. Vacuum pressure is typically in the mid-10^{-6} Torr range; there is no significant gas load.

The arc is driven by a simple LC pulse line of impedance 1 Ohm and pulse length 250 microseconds. The line is charged to a voltage of up to several hundred volts with a small, isolated, dc power supply. A high voltage pulse applied to a trigger electrode initiates a surface spark discharge between the trigger electrode and the cathode, which in turn causes the main anode-cathode circuit because of the plasma established by the spark, and the vacuum arc proceeds.

-3-

When the device is used in its usual mode of operation - ie, as an ion source - the arc circuit and the first grid are biased up to full extractor potential, which may be as high as 100 kV or more. For the present set of experiments we have removed the grids completely, and replaced the middle grid with a plane metal plate which serves as a current collector. The arc is biased to a low positive voltage, around 100 V, and the current that is received by the collector plate is measured by the voltage drop across a 1 Ohm resistor to ground. In this way, the current that is monitored by the collector plate represents precisely that ion current that could be extracted by the MEVVA ion source if we had a perfect method of extracting beam. The experimental configuration is shown in Figure 3.

RESULTS

The collector plate is being used as a kind of Langmuir probe [23], and as with any Langmuir probe, it is important to confirm that the current collected is all ion current (since that's what we're interested in here), with no electron current component. The I-V characteristic of this probe has been measured, and the results are shown in Figure 4. Here the collector current is plotted as a function of arc bias voltage for three different values of arc current; note that the arc bias voltage is approximately equal to the voltage drop between the plasma plume and the collector plate. The shape of the curves is as expected for a current collecting probe immersed in a plasma. In the measurements reported below, the bias voltage was kept sufficiently high so as to be always in the ion saturation region, safely beyond the knee of the characteristic. Thus the collector current measured is indeed ion current.

The titanium ion current that can be drawn from the plasma plume, I_{ion}, has been measured as a function of arc current, I_{arc}, for a number of different values of magnetic field strength, B. The results of these measurements are shown in Figure 5. The plasma ion current is proportional to the arc current, and the constant of proportionality increases with magnetic field strength.

For a fixed value of arc current, I_{arc} = 270 A, the plasma ion current has been measured as a function of magnetic field, and the results of this measurement are shown in Figure 6. The ion current increases with magnetic field strength up to a saturation value of 15 A. A field of only about 100 gauss is needed for saturation.

The ratio I_{ion}/I_{arc} is of interest, as it represents the efficiency with which current dissipated in the arc is made available as extractable ion current. This factor is also indicated in Figure 6. The efficiency varies from a low of about 0.5% for the case of no applied magnetic field, up to a maximum of 5.6% for fields over about 100 gauss.

DISCUSSION

The ion current generated in a vacuum arc has been measured by Kimblin [2,3] and by Heberlein and Porto [7], who have obtained a value of approximately 10% as the fraction of arc current that is available as metal ion current. In this light, the value of 5% that has been measured here (Figure 7) is not surprising and constitutes no new information about vacuum arc behavior. What is interesting and surprising, however, is that so much of the ion current that is produced is transported to the collector plate: of an amount $0.1I_{arc}$ that is maximally available, an amount $0.05I_{arc}$ is measured

at the location of the extractor, for the case when the applied magnetic field is maximally effective, B > 100 gauss. This implies that 50% of the ions generated at the cathode are ducted by the magnetic field to the extractor and are available there for extraction.

The effect of the magnetic field is evidently to duct the plasma plume that is created at the cathode to the collector plate. In the absence of magnetic field, the angular distribution of the ion flux emitted from the cathode is roughly a cosine peaked in the forward direction [6,24]. The current at the extractor is in this case determined by the geometry of the source – the solid angle at the cathode subtended by the extractor. As the magnetic field is increased, the angular distribution of ion flux becomes more peaked forward than cosine, and for sufficiently high field strength, B > 100 gauss here, the effect saturates with 50% of the plasma born at the cathode being ducted by the field to the extractor.

It is another matter, however, to be able to make use of the high plasma ion current at the extractor. For extraction of an ion beam from a plasma by a set of extractor grids, the plasma density must be matched to the extractor geometry so as to form a plasma meniscus (sheath) that is of the appropriate curvature [25-27]. When the plasma density is properly matched to the extractor, ions falling through the sheath are accelerated into a tight beam. This is the usual and preferred condition. In the case that the plasma density is overdense with respect to the extractor geometry and voltage, the shape of the plasma meniscus is such that ions are accelerated into the second (accelerating) grid, or else the plasma itself extends to the second grid. In either case the result is that breakdown occurs across the grids, and no energetic ion beam is produced. In the MEVVA source this effect is particularly

clear; when the arc current, and thus the plasma density, is increased too high, grid breakdown occurs. Similarly breakdown occurs when the magnetic field is too high, as is expected from the data shown in Figures 5 and 6. The solution is to increase the voltage applied across the grids (so that the high rate at which ions are flowing through the sheath is matched by a high rate of transport of ions away from the sheath). One then soon runs into a new limit, which is the maximum voltage that can be supported across practical grid structures. This is the factor that limits the extractable ion beam current. The maximum current that we have been able to extract from the MEVVA II geometry is approximately 1.1 Amperes.

CONCLUSION

The vacuum arc is a prolific source of metal plasma, and the MEVVA ion source geometry provides an efficient means of presenting the dense metal plasma to a set of ion extracting grids. The magnetic field of the MEVVA source enhances the efficiency by about an order of magnitude. In the MEVVA II configuration of this ion source concept, the maximum ion current that is potentially available for extraction is about 5% of the current driving the vacuum arc. The limitation to actually achieving these very high current beams is in the extractor design and inherent limitations, and this is where further work needs to be done in order to take full advantage of the copious source plasma that is available. Development in this direction would have significant implications for the application of the MEVVA ion source to heavy ion fusion and to large scale ion beam modification of metallurgical surfaces, as well as for more efficient operation of the source as an injector for particle accelerators.

REFERENCES

1. For an excellent review see "Vacuum Arcs – Theory and Application", edited by J. M. Lafferty, (Wiley, New York, 1980).

2. C. W. Kimblin, Proc. IEEE $\underline{59}$, 546 (1971).

3. C. W. Kimblin, J. Appl. Phys. $\underline{44}$, 3074 (1973).

4. A. A. Plyutto, V. N. Ryzhhov and A. T. Kapin, Sov. Phys. JETP $\underline{20}$, 328 (1965).

5. W. D. Davis and H. C. Miller, J. Appl. Phys. $\underline{40}$, 2212 (1969).

6. J. E. Daalder and P. G. E. Wielders, in Proceedings of the 12th International Conference on Phenomena in Ionized Gases (North-Holland, Amsterdam, 1975), Pt. 1, p. 232.

7. J. V. R. Heberlein and D. R. Porto, IEEE Trans. Plasma Sci. $\underline{PS-11}$, 152 (1983).

8. J. W. Robinson and M. Ham, IEEE Trans. Plasma Sci. $\underline{PS-3}$, 222 (1975).

9. J. E. Daalder, J. Phys. D $\underline{8}$, 1647 (1975).

10. J. L. Hirshfield, IEEE Trans. Nucl. Sci. $\underline{NS-23}$, 1006 (1976).

11. J. E. Daalder, J. Phys. D $\underline{9}$, 2379 (1976).

12. "Electromagnetic Separation of Isotopes in Commercial Quantities", edited by R. K. Wakerling and A. Guthrie (McGraw Hill, New York, 1951), p.324.

13. E. I. Revutskii, G. M. Skoromnyi, Yu. F. Kulygin and I. I. Goncharenko, in Proceedings of the Soviet Conference on Charged-Particle Accelerators, Moscow, 9-16 October 1968, edited by A. A. Vasilev (USAEC), Vol. 1, p. 447.

14. C. Burkhart, S. Coffey, G. Cooper, S. Humphries, Jr., L. K. Len, A. D. Logan, M. Savage and D. M. Woodall, Nucl. Instrum. Methods B, 10/11, 792 (1985).

15. S. Humphries, Jr., C. Burkhart and M. Savage, Particle Accelerators 17, (1986).

16. L. K. Len, C. Burkart, G. W. Cooper, S. Humphries, Jr., M. Savage and D. M. Woodall, IEEE Trans. Plasma Sci. PS-14, 256 (1986).

17. R. J. Adler and S. T. Picraux, Nucl. Instrum. Methods B 6, 123 (1985).

18. I. G. Brown, IEEE Trans. Nucl. Sci. NS-32, 1723 (1985).

19. I. G. Brown, J. E. Galvin and R. A. MacGill, Appl. Phys. Lett. 47, 358 (1985).

20. I. G. Brown, J. E. Galvin, B. F. Gavin and R. A. MacGill, Rev. Sci. Instrum. 57, 1069 (1986).

21. I. G. Brown, J. E. Galvin, R. A. MacGill and R. T. Wright, Appl. Phys. Lett. 49, 1019 (1986).

22. I. G. Brown, J. E. Galvin, R. A. MacGill and R. T. Wright, 1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.

23. F. F. Chen, in "Plasma Diagnostic Techniques", edited by R. H. Huddlestone and S. L. Leonard (Academic Press, New York, 1965).

24. J. E. Galvin, paper presented at the Workshop on Metal Vapor Vacuum Arc Ion Sources, Lawrence Berkeley Laboratory, Berkeley, CA, September 1985.

25. J. R. Coupland, T. S. Green, D. P. Hammond and A. C. Riviere, Rev. Sci. Instrum. 44, 1258 (1973).

26. T. S. Green, Rep. Prog. Phys. 37, 1257 (1974).

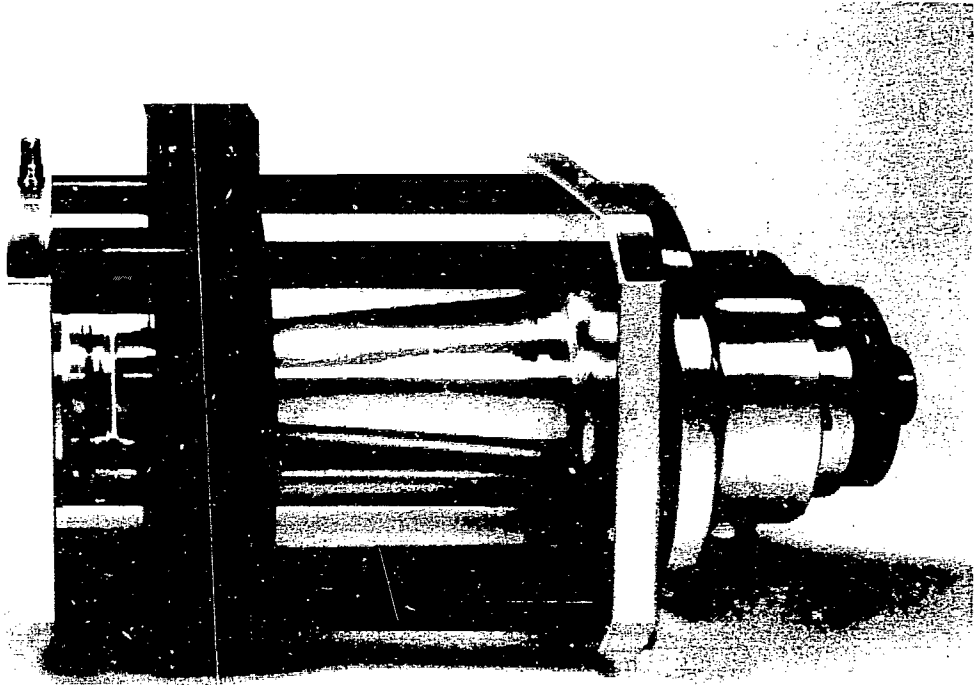27. T. S. Green, IEEE Trans. Nucl. Sci. NS-23, 918 (1976).

Fig. 1   CBB 850-9007

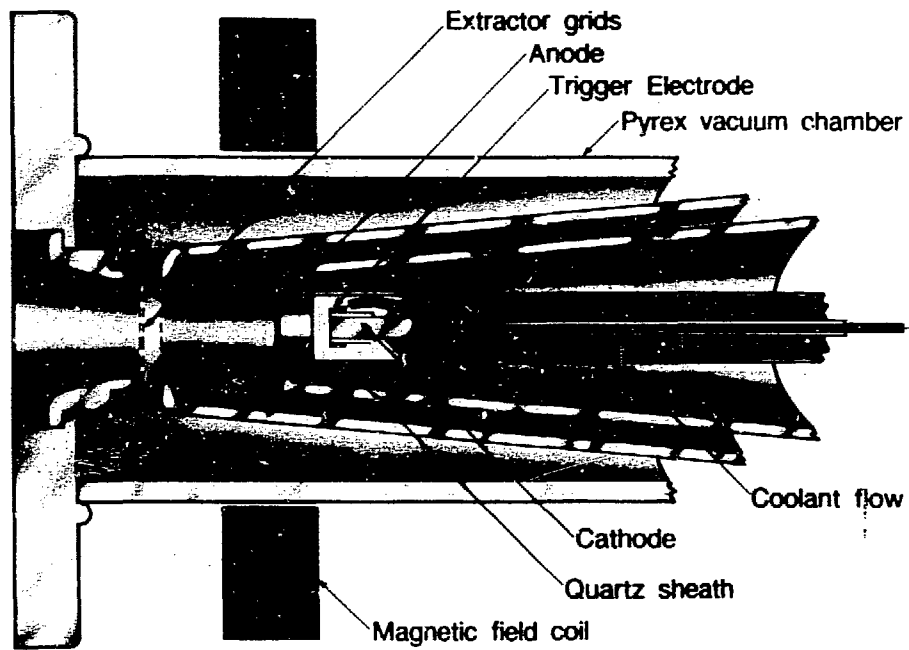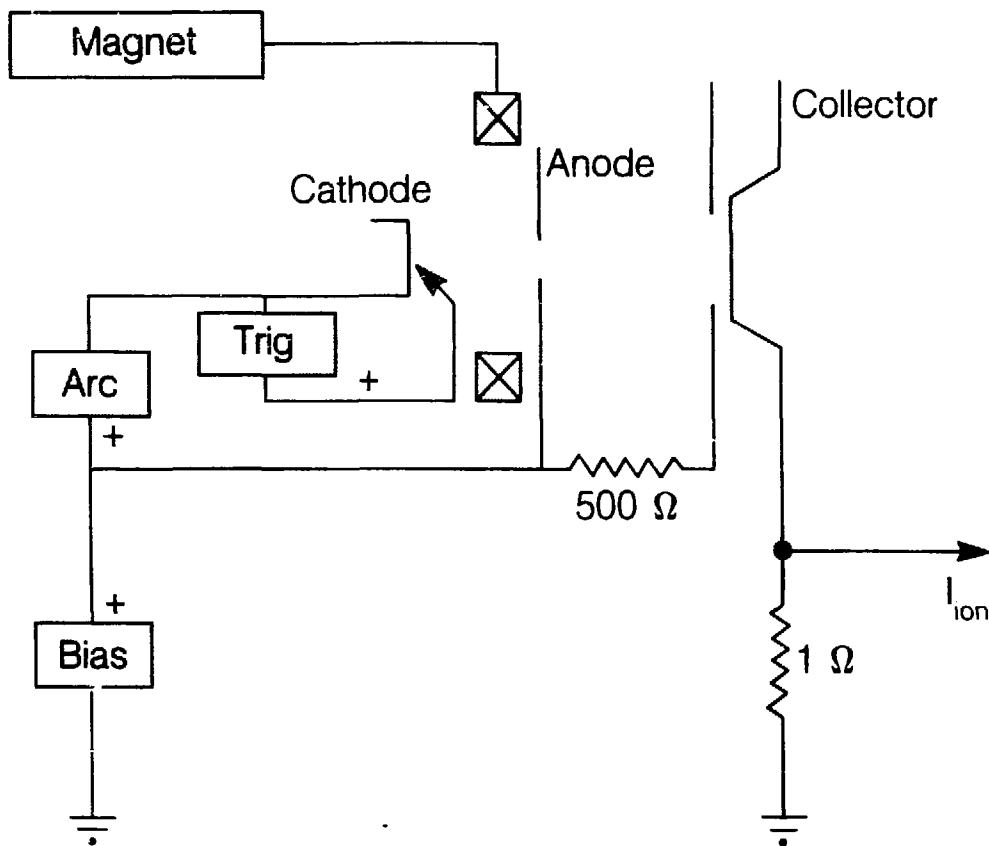Photograph of the MEVVA IIb ion source. Overall length is 16 inches.

Extractor grids
Anode
Trigger Electrode
Pyrex vacuum chamber
Coolant flow
Cathode
Quartz sheath
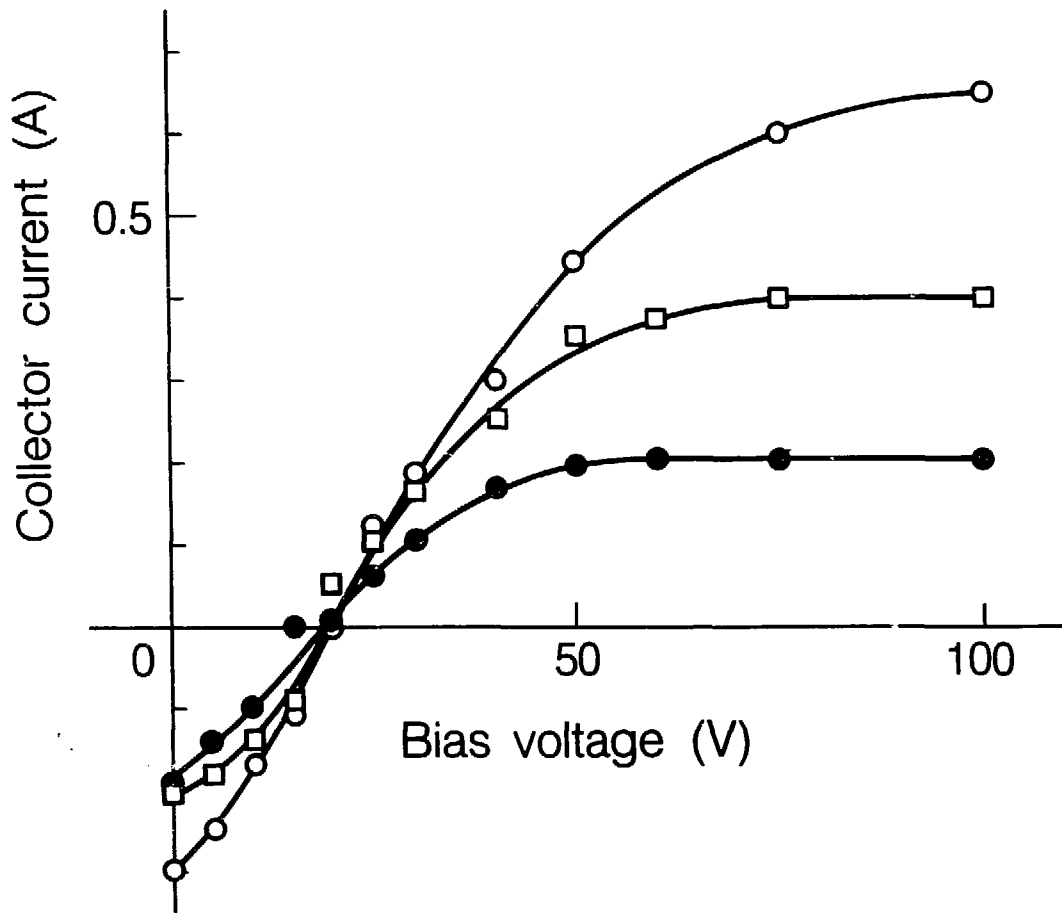Magnetic field coil

Fig. 2

CBB 862-1326

Outline of the arc and extractor region of the MEVVA IIb source.

Fig. 3

XBL 858-9895B

Schematic of the experimental configuration.

XBL 873-8938

Fig. 4

Current-voltage characteristic of the plasma ion current collecting plate, for three different values of arc current, (60 A, 110 A, and 150 A).
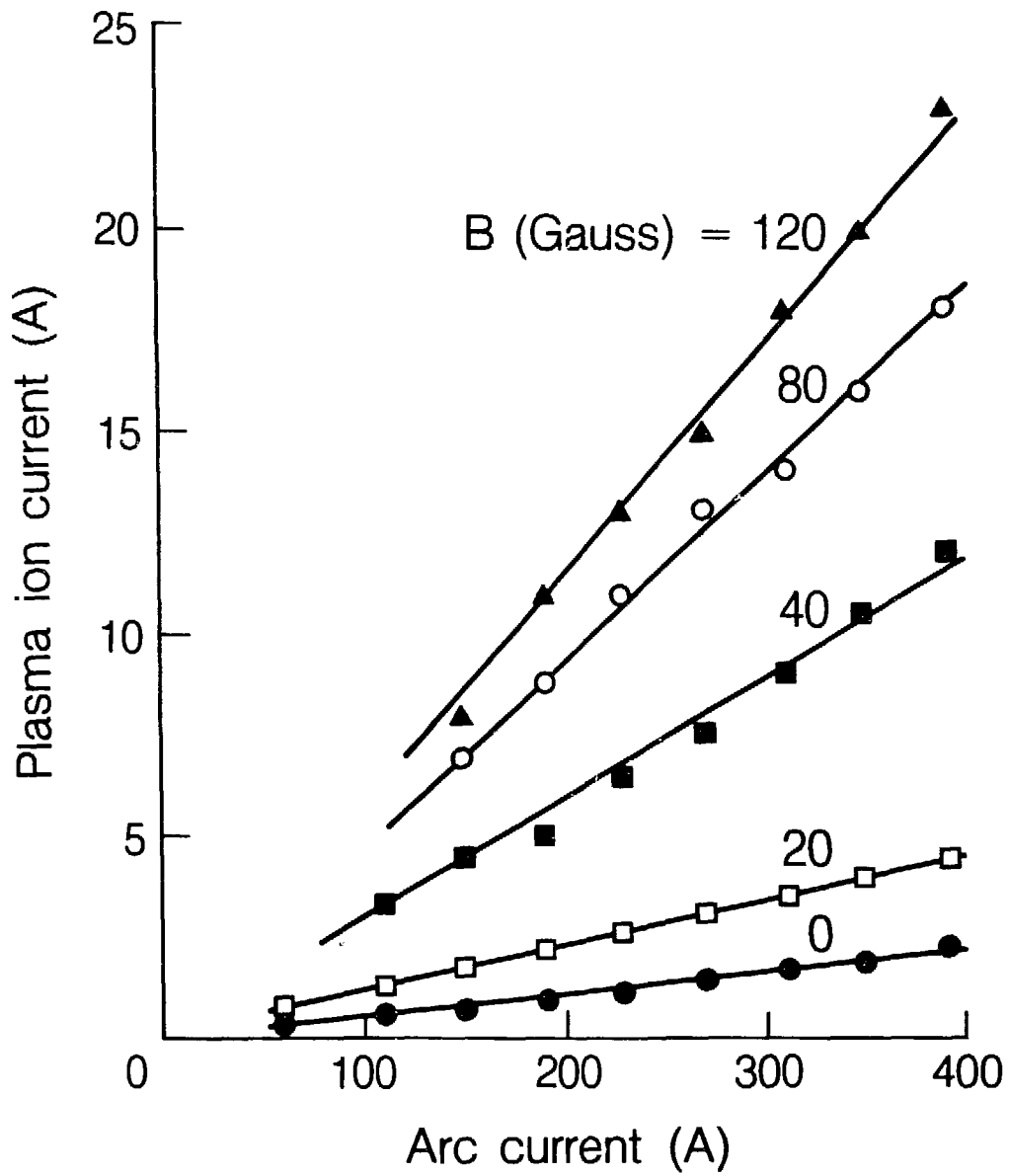
Fig. 5   XBL 873-8939

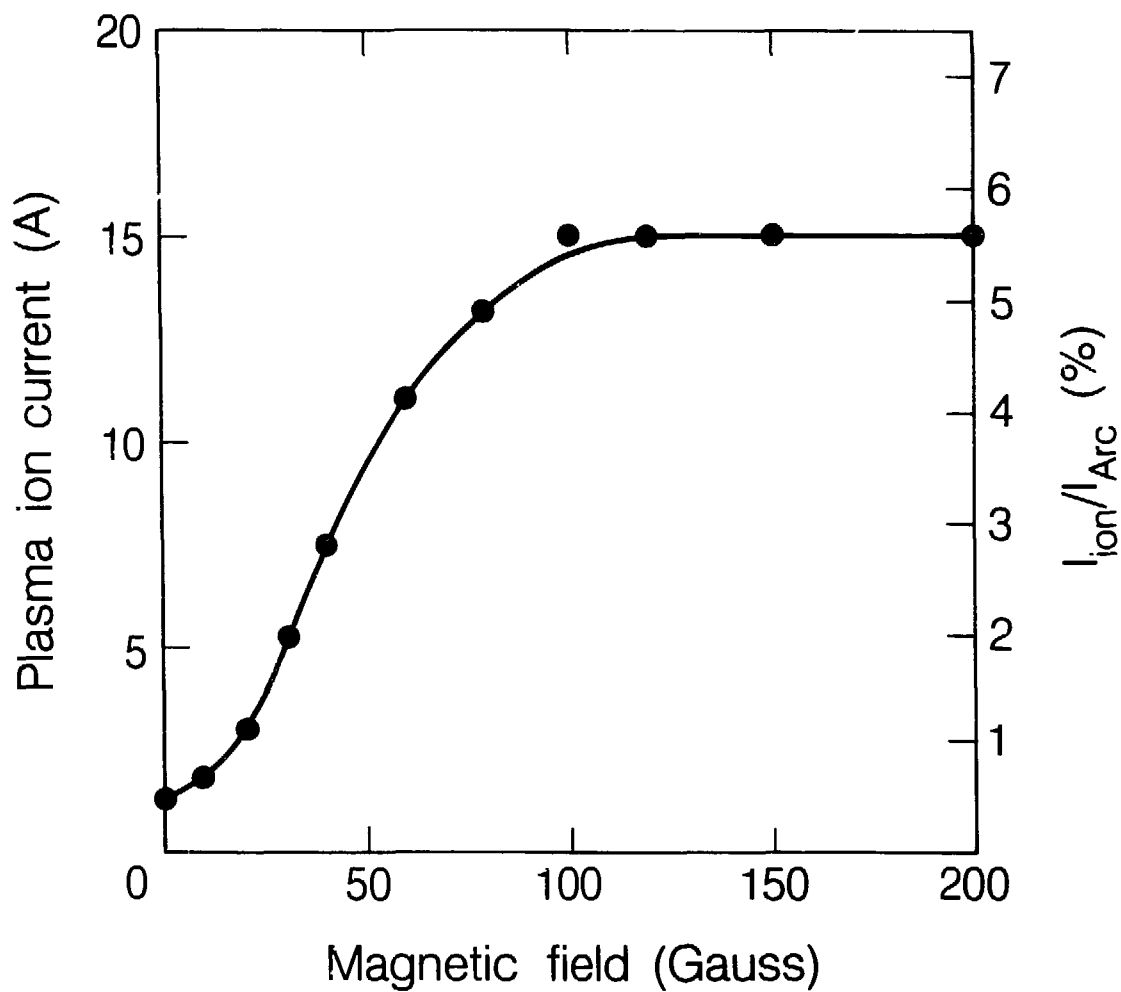Plasma ion current as a function of arc current for several different magnetic field strength.

-14-

Fig. 6

Plasma ion current, I_{ion}, and "efficiency factor", I_{ion}/I_{arc}, as a function of magnetic field strength. I_{arc} = 270 A.