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VACUUM ARC ION SOURCES - MICRO TO MACRO\*

R.A. MacGill, M.R. Dickinson and I.G. Brown

Lawrence Berkeley Laboratory  
University of California  
Berkeley, CA 94720

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## VACUUM ARC ION SOURCES – MICRO TO MACRO

R.A. MacGill, M.R. Dickinson and I.G. Brown

Lawrence Berkeley Laboratory

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### Abstract

Vacuum arc ion sources provide a convenient tool for the production of intense beams of metal ions. The sources are relatively easy to construct and they can produce beams from all of the solid metals as well as of compounds, alloys and mixtures. We have made a number of different kinds of such sources over the course of our development work at LBL in the past decade, from very small 'thumb-size' versions to a very large one with 50-cm diameter extractor. Beam current ranges from a few milliamperes up to almost 10 amperes and extraction voltage from about 1 kV to 100 kV. Multicathode versions have been made so that one can switch between metal ion species simply and quickly. Most of the sources have been operated in a repetitively pulsed mode, and we've tested a dc version also. Here we outline some construction features of the array of vacuum arc ion sources that we've developed and used, and describe their performance and limitations.

## I. INTRODUCTION

Vacuum arc ion sources have found a widening domain of application including particularly for ion implantation and accelerator injection as well as other uses. The kinds of sources made span the range from very small up to very large, measured in terms of both the physical size of the ion source as well as the beam parameters. The principles involved are similar in all cases, and in some ways the differences between the various source embodiments are superficial.

The metal plasma formed in a vacuum arc is created at small regions on the cathode of dimension about  $10\ \mu$ , and the arc current, which is typically about 100 A or so for most vacuum arc ion source operation to-date, is concentrated at a small number of such cathode spots [1]. The plasma plumes away from the spot at which it is formed in a manner similar in some respects to a laser-produced plasma. Although the physics of plasma formation at the spots is not completely understood, many features are well known. For example, a minimum arc current is needed in order to keep the spot alive. Typically this current is of order several tens of amperes, depending on the cathode material used; if the arc current is reduced below this minimum value, the arc simply extinguishes. Also, as the arc current is increased the number of spots increases so as to maintain about the same current per spot. These characteristics of vacuum arc behavior lead to a fundamental similarity between all kinds of vacuum arc ion sources — the geometric details change, but the underlying plasma physics remains much the same.

Here we describe the construction and performance of a number of different source embodiments that we've made and used in the course of our ion source development program.

## II. KINDS OF SOURCES

The basic design approach for all our sources has been described previously in a number of publications [2,3] and we do not elaborate here. We've made sources ranging from 'thumb size' up to an embodiment with a 50-cm diameter extractor, with single cathode up to an 18-fold cathode multiplicity, with built in magnetic field for increasing the ion charge state, and with gas feed so as to incorporate gaseous ion production as well as metallic.

*Micro and small source embodiments* [2-4] can be made simply, and the lower limit on source size is probably determined by the ability to fabricate the parts. For very small sources, say less than a centimeter or so in diameter, water cooling is not possible (or only in a limited sense). On the other hand, the arc current must be maintained at its minimal value of a few tens of amperes to keep the arc alive. Therefore, the duty cycle at which small sources can be operated is limited by source heating. Voltage hold-off considerations limit the extraction voltage to low values, perhaps just a few kilovolts, depending on the actual source dimensions. The smallest source that we've made ('micro' version) has an overall diameter of about 1 cm and a length of less than 10 cm; see Figure 1. Sources smaller yet by a factor of several could be possible also, though the applications would be restricted. A slightly larger version is shown in Figure 2; we refer to this as a 'small' source [5].

*Large source embodiments* [2,6], on the other hand, call for well-designed water cooling if the beam current is to be as large as it can be. If a multi-cathode design is to be used, the concern of accomplishing good cooling of the multiple cathode assembly while retaining its freedom to rotate requires some careful thought. The extractor grids can see a considerable heat loading from the energetic ion beam 'scrape-off' region, i.e., due to imperfect beam optics, and thought needs to be given to the concern of heat removal from the grids. Our "workhorse" source has a 10-cm extractor diameter and a multicathode array holding 18 individual cathodes; see Figure 3. For very

large grids, such as our 50-cm diameter set (see Figure 4), this can be a non-trivial matter. Also, most interestingly, the electrostatic attraction between that pair of grids across which the high extraction voltage is applied (plasma grid and suppressor grid) can cause a very noticeable effect: as the source is repetitively pulsed and the extraction voltage similarly oscillates, the grids move mechanically in a drum-like fashion. The construction and mounting of the grid assembly must be able to cope with this mechanical motion.

*Magnetic fields* can be included in several different ways. We have used an array of samarium cobalt permanent magnets in a duodecapole magnetic bucket configuration so as to produce a plasma in the pre-extraction region (plasma presented to the extractor) with a radial density profile that is flat rather than the more usual gaussian, and so also to produce an extracted ion beam with a flat radial profile; this approach works [7]. More recently, we've used a small, pulsed solenoid to create a relatively high magnetic field (up to ~10 kG or more) in the arc region, as a means of increasing the ion charge states produced [8,9]. The coil was built quite stoutly, and most conveniently was powered by the same current pulse that drives the arc, thus removing the need for an additional power supply.

A *DC source* has been made and tested [2,6]. For steady state operation, very good cooling is required of both the gun assembly (anode and cathode) as well as the extractor. For our tests we used a 2-inch diameter vacuum arc cathode with direct water cooling to the back of the cathode material. Triggering was electromechanical. The d.c. Ti plasma gun was driven by a welding power supply at 100 - 150 A, sufficient to keep the arc alive for long periods of time, up to hours. The plasma ion current at a collector plate inserted at the extractor location could be varied from a low of 0.4 A to a high of over 5 A; this was the amount of plasma presented to the extractor that is available for beam formation. When the collector plate was replaced by a 2-grid extractor a dc titanium ion beam was produced. Maximum voltage and current at which we could operate was limited by the power supply that was available. We measured a dc titanium ion beam current of

approximately 600 mA at an extraction voltage of 9 kV, corresponding to a mean ion energy of about 19 keV since the mean ion charge state for Ti is 2.1. Beam diameter was about 20-cm. A photograph of this experimental set-up is shown in Figure 5.

### III. ION SOURCE PERFORMANCE

The fundamental performance characteristics of all versions of vacuum arc ion sources are similar since the plasma formation process is in all cases much the same. The plasma is born at the cathode spots and one can exercise only minimal external control over the spot plasma. Ion energy is determined by the extraction voltage and this may be limited by source design, and similarly the beam current is determined in part by the extraction area. Thus large sources may in general produce beams of higher energy and higher current. The range of metal species that can be used is of course unchanged for all source versions. Ion charge state distribution remains the same for all sources, excepting for when a high magnetic field is used [8,9]. The range of source performance is listed in Table I; the parameter values given are to be taken as indicative only.

Vacuum arc ion sources are essentially simple devices, and their design and fabrication can be simple and straightforward. It is only as the required source and beam parameters are pushed to the extremes – for example, very small or very large, very high voltage, high duty factor, or large beam size – that particular care needs to be taken in the design process. Sources have been made spanning a wide parameter regime.



## ACKNOWLEDGMENTS

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TABLE I.

Typical source and beam parameters for different vacuum arc ion source embodiments;  
values given are typical / indicative only

Source version	Diam x Length (cm)	Extractor diam (cm)	$V_{\text{extr}}$ (max) (kV)	$I_{\text{beam}}$ (max) pulse (A)	mean (mA)
micro	1 x 10	0.2	10	0.01	0.01
small	5 x 15	1	20	0.1	0.1
intermediate	15 x 40	2	75	1	10
broad beam	30 x 40	10	100	5	50
very broad beam	60 x 80	50	100	10	100

## Figure Captions

Fig. 1 (a) Miniature source.

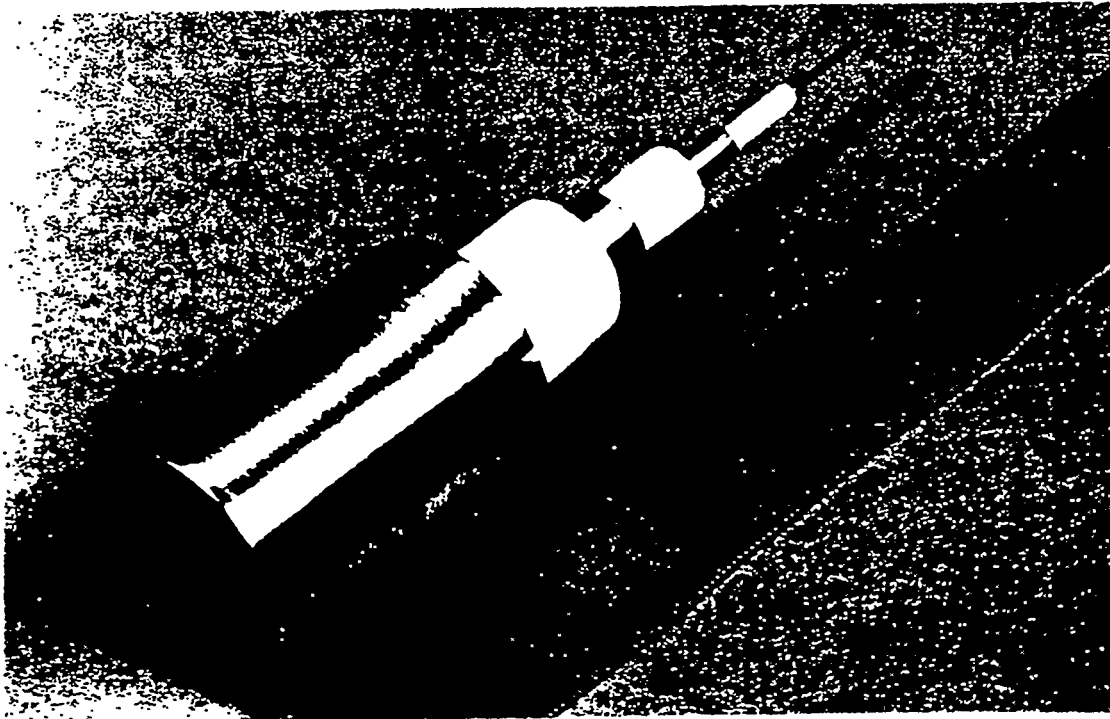
(b) Array of metal and ceramic tubes from which the miniature source is made.

Fig. 2 Small source embodiment.

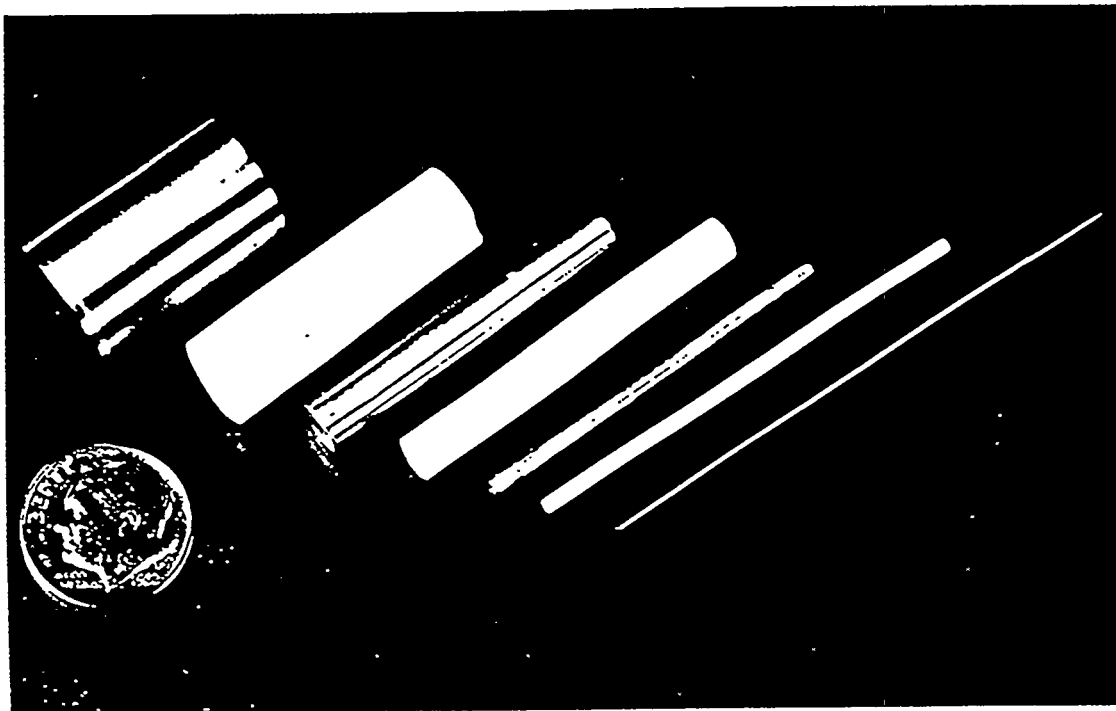
Fig. 3 Broad beam source; 10-cm diameter extractor, 18 interchangeable cathodes.

Fig. 4 50-cm diameter extractor array, together with small and miniature source versions.

Fig. 5 Experimental set-up used to test steady-state ion beam operation.



(a)



(b)

Fig. 1

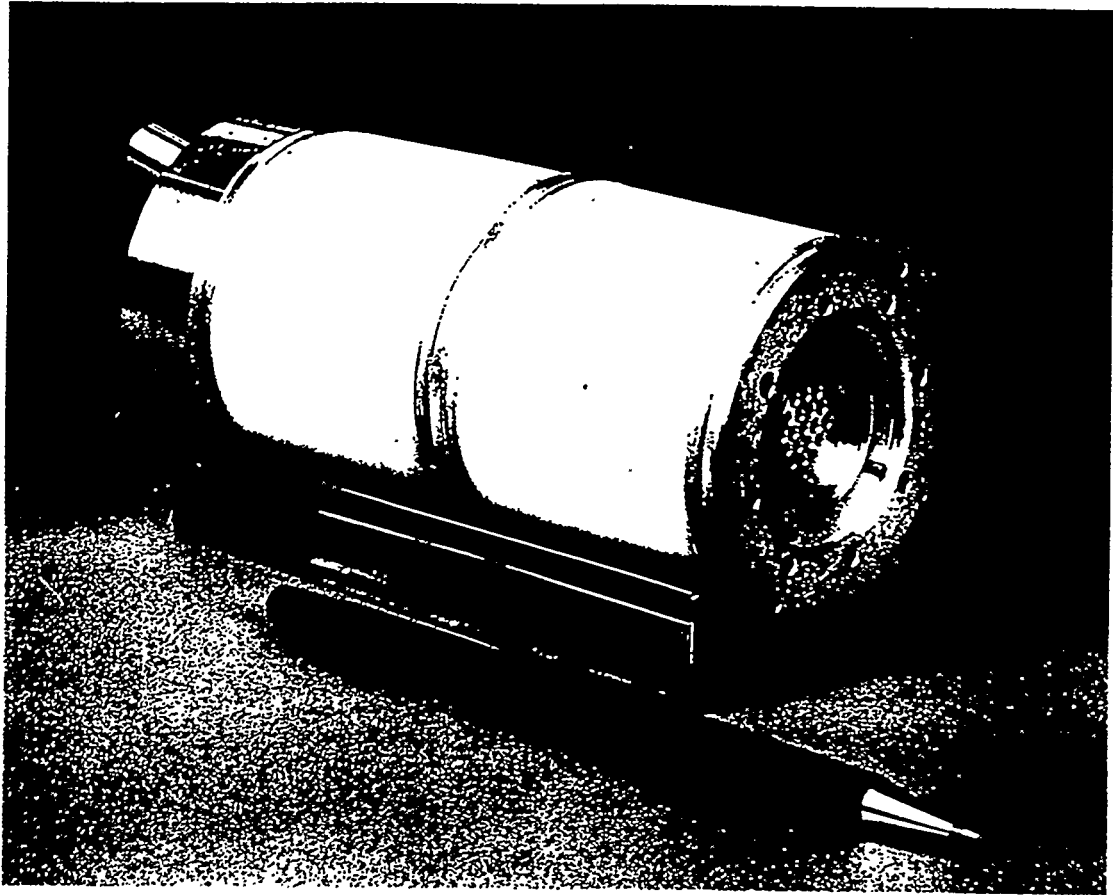


Fig. 2



Fig. 3

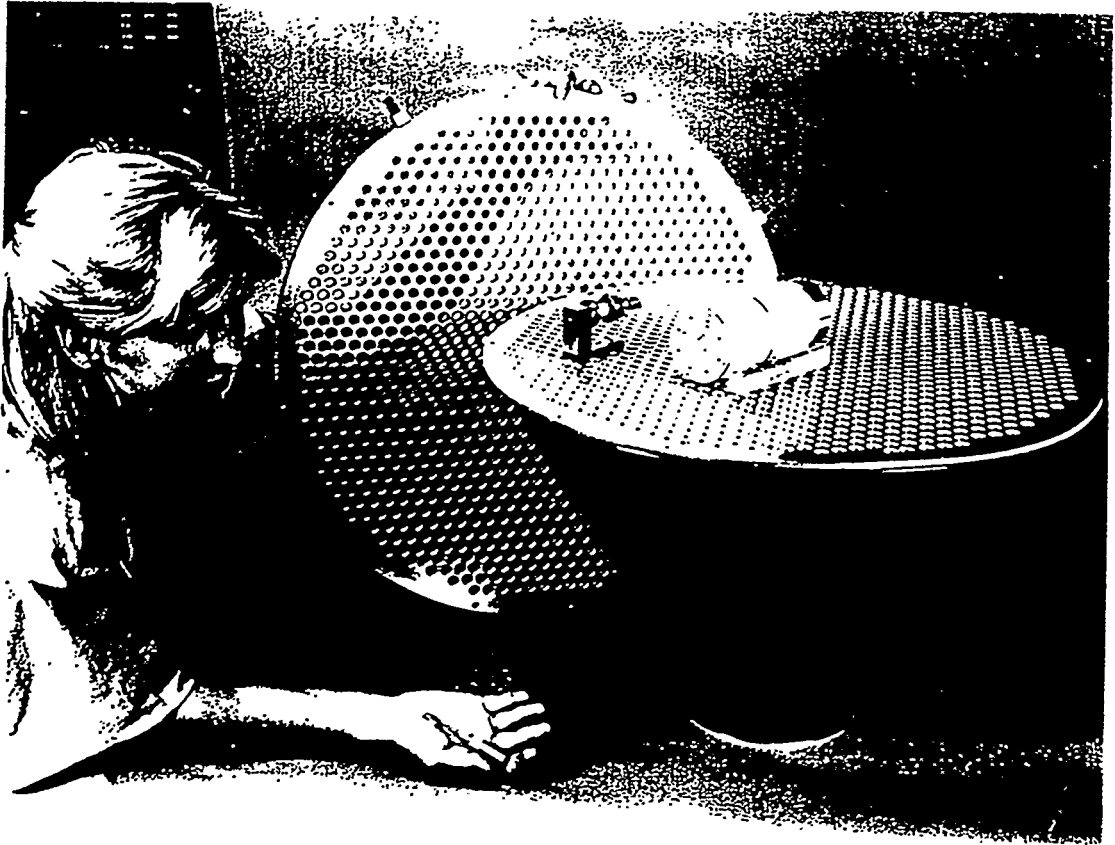


Fig. 4



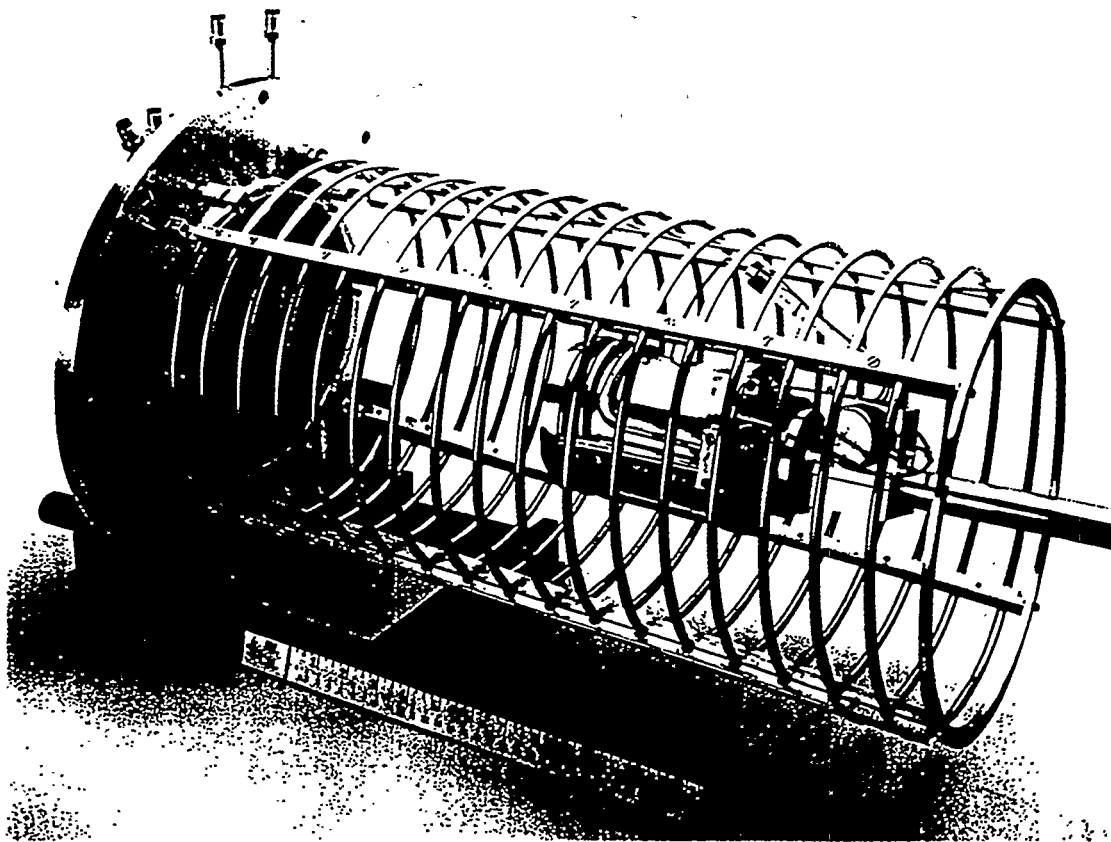


Fig. 5