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Two approaches to electron beam enhancement of the metal vapor vacuum arc ion source

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Abstract

Conclusive demonstration of electron-beam enhancement of ion charge states for the Metal Vapor Vacuum Arc (MEVVA) ion source was recently achieved using an external electron beam (E-MEVVA) in experiments performed jointly among the Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia, the High Current Electronics Institute (HCEI), Tomsk, Russia, and Brookhaven National Laboratory (BNL), USA. The E-MEVVA experiments were performed in Moscow and Tomsk with nearly the same design of ion sources. Results for lead and bismuth cathodes yielded maximum ion charge states of Pb^{7+} and Bi^{8+} for E-MEVVA, as compared to Pb^{2+} and Bi^{2+} for conventional MEVVA operation. Additional encouraging results were also obtained using a Z-discharge to produce an internal electron-beam (Z-MEVVA and LIZ-MEV).

Keywords: High charge states; Intense beams; Ion source; Vacuum arc

1. INTRODUCTION

The goal of our joint Russia–U.S.A. research effort is to develop reliable and inexpensive heavy ion sources to produce both (1) high ion charge states and (2) intense ion beam currents. While many ion sources have long been available to achieve one or the other of these goals, the combination had remained elusive—until now. Our recent results reported in Bugaev *et al.* (2001), Batalin *et al.* (2002*a*), and Batalin *et al.* (2002*b*) offer conclusive demonstrations that both goals (1) and (2) above can be realized through electron beam enhancement of the Metal Vapor Vacuum Arc (MEVVA) ion source. This work is an extension of initial E-MEVVA efforts by Batalin *et al.* (1994) in which encouraging indications of higher charge state production were achieved by combining an electron beam, a vacuum arc ion source, and a drift tube.

Two approaches to MEVVA enhancement are being studied by using either external electron beams or internal electron beams produced by a z-discharge. The E-MEVVA investigations were performed jointly at the High Current Electronics Institute (HCEI), in Tomsk, Russia, the Institute for Theoretical and Experimental Physics (ITEP), in Moscow, Russia, and Brookhaven National Laboratory (BNL), in the USA. The experiments were performed in Moscow and Tomsk with nearly the same design of ion sources. Substantially higher ion charge states were clearly observed in both experimental set-ups with two different methods of measuring the ion charge state distributions. Lawrence Berkeley National Laboratory (Z-MEVVA) and the University of California at Irvine (LIZ-MEV) working with BNL performed the z-discharge studies jointly.

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2. MOTIVATIONS AND APPLICATIONS

For many applications it is highly desirable to have a source of heavy ion beams that produces both large ion currents and high charge states. The applications which motivate this work include (a) lower-cost ion implantation facilities, (b) an improved heavy ion injector for the Relativistic Heavy Ion Collider (RHIC) at BNL, and (c) inexpensive and reliable ion sources for various approaches to Heavy Ion Inertial Fusion (HIIF).

Typical ion implantation facilities employ a low-charge state ion source and an extraction system to function as a low-energy pre-accelerator, followed by an ion acceleration column to produce desired higher ion energies. The high voltage power supplies for pre-acceleration and the accelerating column for final acceleration contribute significantly to facility size and cost. For higher-charge state beams a lower-voltage (and therefore cheaper) power supply can produce the same pre-acceleration energy. If the ion charge states are sufficiently high, then the "pre-accelerator" can reach the desired energy without the need for an additional accelerating column. Such "single-stage" acceleration would enable a more compact design for a lower cost facility.

The RHIC at BNL is now operational (http://www.bnl.gov/RHIC). Initially, the RHIC physics program will concentrate on Au + Au collisions with 100 GeV in each beam. However, Braun-Munzinger (private comm.) noted that there is physics justification for eventually colliding uranium beams in RHIC, because U + U collisions would produce significantly larger energy densities than Au + Au. The existing tandem preinjector is quite adequate and reliable for the Au + Au collision program currently in progress, but the negative ion source used as the tandem injector cannot produce sufficient uranium beam currents for use at RHIC. Electron-beam enhancement of the MEVVA ion source is a viable basis for developing a versatile heavy ion injection system for relativistic heavy ion accelerators.

Parisi *et al.* (1998) described a typical scenario for a HIIF facility using a combination of ion sources, linacs, and a storage ring as a driver. This and similar schemes involve multiple ion sources, some funneling steps through increasingly larger linacs, and then a main linac to inject the storage ring. The most numerous elements are the large number of ion sources and initial pre-accelerators. The electron-beam enhanced MEVVA is an inexpensive and compact ion source. The high charge states produced allow for higher extraction energies and the elimination of initial linacs before the first funneling step. These two factors should lead to substantial cost savings in some HIIF facility designs.

3. GENERIC MEVVA

Figure 1 illustrates two variations of the generic MEVVA, which is a prolific generator of highly ionized metal plasma from which intense beams of metallic ions are extracted. Brown (1994) described the basic MEVVA, which comprises a series of electrodes (usually concentric and separated by ceramic insulators). The commonly used configuration is a solid electrode of the desired metal, followed by a trigger electrode, an anode, and a three-grid extractor system. As indicated in Figure 1, the anode and plasma expansion regions can be either separate (left) or combined in a hollow anode (right). Triggering of the vacuum arc is accomplished by applying a short high voltage pulse between the trigger electrode and the cathode across an insulating surface. Vacuum arc discharge occurs due to formation of cathode spots, which are micron-sized spots on the cathode surface characterized by extremely high current densities. Small spots on the cathode material are vaporized and ionized, producing a plasma plume, from which ions are extracted. Although the MEVVA plasma itself is characterized by a high degree of ionization, only low ion charge states are typically extracted. Depending on the cathode material used a conventional MEVVA ion beam has a mean charge state Q of about 2+.

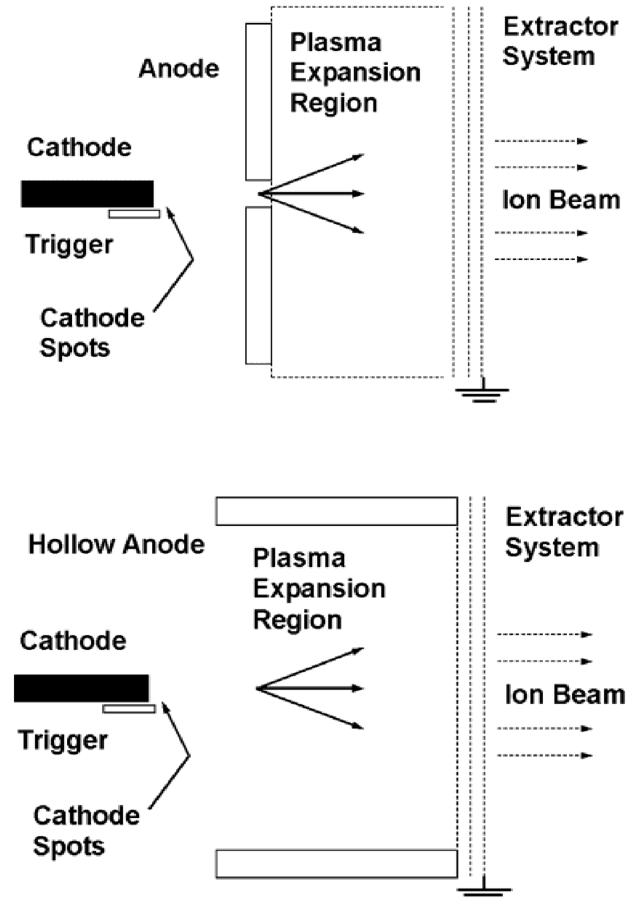

Fig. 1. Schematic layout of a generic Metal Vapor Vacuum Arc (MEVVA) ion source. The two basic variations are: (upper) separate anode and ion drift and (lower) combined anode and ion drift.

4. EXTERNAL ELECTRON-BEAM ENHANCED MEVVA (E-MEVVA)

Figure 2 illustrates two variations on the approach of using two MEVVA ion sources to construct an E-MEVVA. The first MEVVA (left) is the electron gun and the second MEVVA (right) is the ionization region. The first variation (upper) is employed in the ITEP-Moscow E-MEVVA, wherein the second MEVVA has a separate anode and plasma expansion (ion drift) region. The second variation (lower) is used in the HCEI-Tomsk E-MEVVA, in which the second

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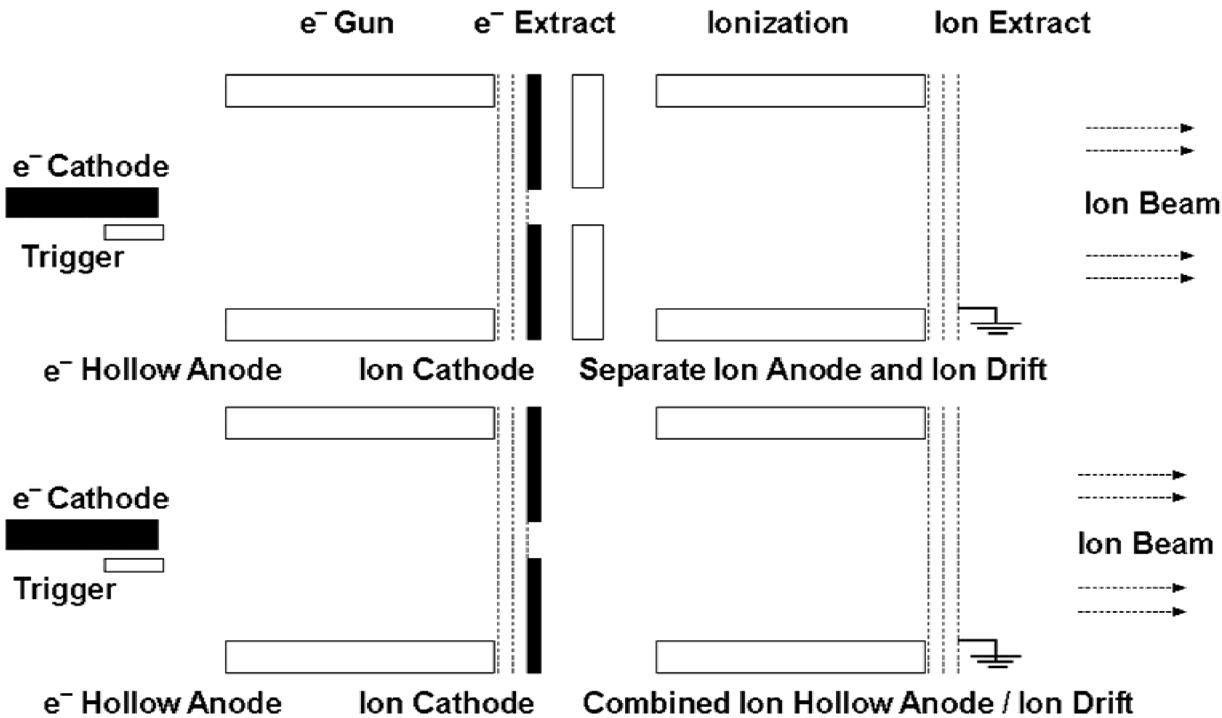

Fig. 2. Schematic layout of E-MEVVA configurations used at ITEP-Moscow (upper) and HCEI-Tomsk (lower).

MEVVA has a combined hollow anode and ion drift region. In both variations the first MEVVA (e^- gun) uses the combined hollow anode and plasma expansion region. Both ion sources use the same e^- gun MEVVA, which was developed by HCEI-Tomsk. The other difference between the two experimental approaches is that ITEP-Moscow uses magnetic analysis to measure the ion charge state distributions, while HCEI-Tomsk uses time-of-flight. Batalin *et al.* (2002*b*) gives more detailed schematic views and layouts, plus full details on the experimental arrangements and operating parameters, which are summarized here in Table 1.

Herschcovitch *et al.* (1998, 2002), and Batalin *et al.* (2002*b*) discuss the physics considerations for electron-beam enhanced MEVVA operation. Ion charge state distributions are determined by the balance of the electron stripping rate versus the electron capture rate due to charge exchange with neutrals and lower charge state ions. Optimum performance of the E-MEVVA requires sufficient intensity and energy of the electron beam to maximize the ionization rate and to overcome relevant electron binding energies to reach the desired charge states, while at the same time minimizing the production of “fresh plasma” or impurity ion production, which would increase the charge exchange rate and lower the ion beam charge states. The foremost requirement to reduce charge exchange is to improve the vacuum system and the cleanliness of surfaces inside the source to minimize background gas and outgassing. This is necessary, but not sufficient. Batalin *et al.* (2002*b*) documents that the electron gun pulse causes the impurity ion population to increase dramatically due to electrons striking the drift tube walls. Therefore, optimum source performance is achieved when the electron gun pulse is made shorter than the ion arc duration time. This also enables source output optimization by allowing for adjustment of the relative timing of the electron gun pulse within the duration of the ionization arc.

Table 1. *Typical Values of Operating Parameters for the ITEP-Moscow and HCEI-Tomsk E-MEVVA ion sources*

E-MEVVA Operating Parameter	ITEP-Moscow	HCEI-Tomsk
Electron Accelerating Voltage (kV)	18	20
Ion Accelerating Voltage (kV)	50	20
Trigger Voltage (kV)	5	7
Time-of-Flight Gate Voltage (kV)	NA	2
Electron Gun Current (A)	100	200
MEVVA Arc Current (A)	100	300
Ion Emission Current (mA)	20	100–200
Electron Gun Pulse Duration (μs)	50	100
Vacuum Arc Pulse Duration (μs)	150	450
Trigger Voltage Pulse Duration (μs)	10	20
Time of Flight Gate Duration (ns)	NA	100

The results for both the ITEP-Moscow and the HCEI-Tomsk E-MEVVA sources are impressive. Figures 3–6 show E-MEVVA spectra from the HCEI-Tomsk E-MEVVA for Cd, In, Sn, and Sm cathodes, respectively. Bugaev *et al.* (2001) showed the HCEI-Tomsk spectra for E-MEVVA operation with Pb cathode. Batalin *et al.* (2002*a*, 2002*b*) presented the ITEP-Moscow spectra with Pb cathode and

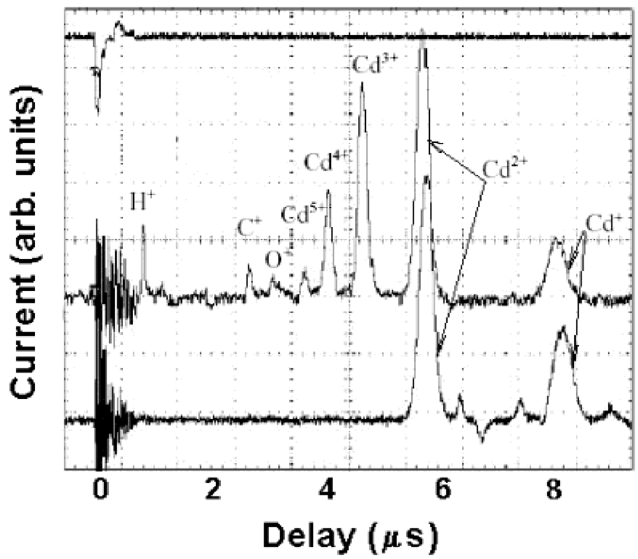

Fig. 3. TOF spectra for Cd cathode with electron beam on (middle) and off (lower). The upper trace is the signal from the TOF gate.

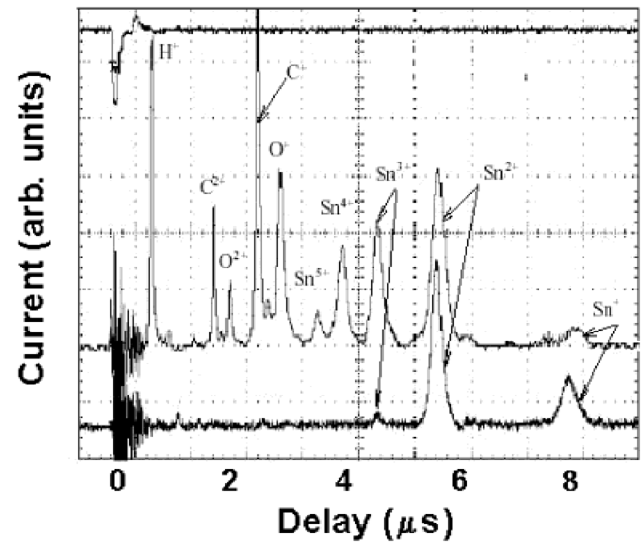

Fig. 5. TOF spectra for Sn cathode with electron beam on (middle) and off (lower). The upper trace is the signal from the TOF gate.

the HCEI-Tomsk spectra with Bi cathode. Table 2 gives a comparison of the ionic charge state fractions and mean charge states for all cathode materials studied with the HCEI-Tomsk E-MEVVA. The results are comparable to those obtained at ITEP-Moscow. As shown in the last column of Table 2, the observed increases in mean charge states for E-MEVVA versus conventional MEVVA operation ranged from 1.17 for Sm up to 2.50 for Pb.

5. Z-DISCHARGE MEVVA (Z-MEVVA AND LIZ-MEV)

An alternative approach to enhancing MEVVA charge states is to use a z-discharge plasma to produce an "internal" electron beam within the MEVVA enclosure. The basic idea is to take a conventional MEVVA with hollow anode (as illustrated in the lower portion of Fig. 1), insert a magnetized

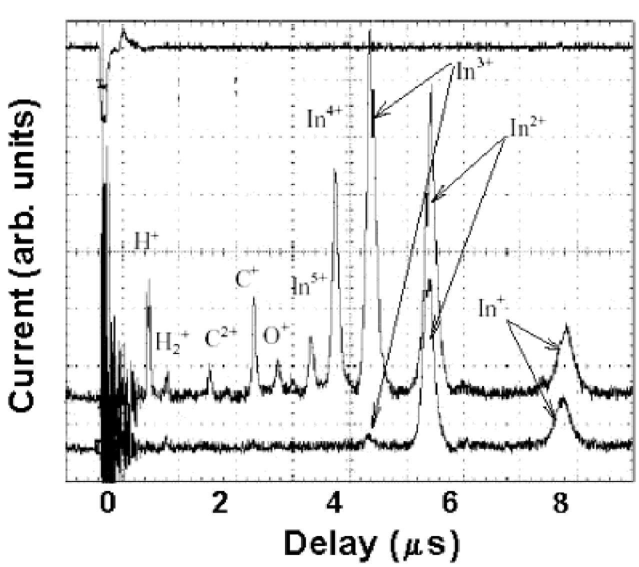

Fig. 4. TOF spectra for In cathode with electron beam on (middle) and off (lower). The upper trace is the signal from the TOF gate.

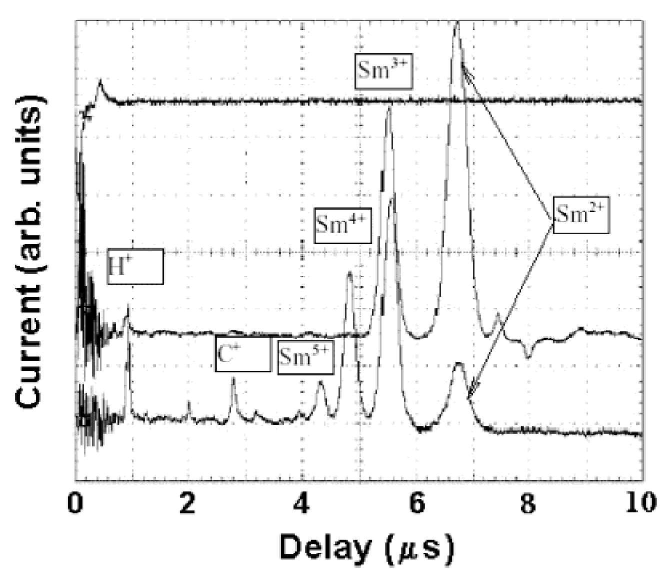

Fig. 6. TOF spectra for Sm cathode with electron beam on (middle) and off (lower). The upper trace is the signal from the TOF gate.

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Table 2. *Comparison of ionic charge state fractions (%) and mean charge states* $\langle Q_E \rangle$ *and* $\langle Q_0 \rangle$ *for different cathode materials with electron beam on (E-MEVVA) and off (MEVVA)*

Ion source	E-MEVVA									MEVVA				Ratio
Element	1+	2+	3+	4+	5+	6+	7+	8+	$\langle Q_E \rangle$	1+	2+	3+	$\langle Q_0 \rangle$	$\frac{\langle Q_E \rangle}{\langle Q_0 \rangle}$
Cd	20	42	24	11	3				2.3	44	56		1.6	1.44
In	23	39	26	11	1				2.3	42	56	2	1.6	1.44
Sn	5	52	21	16	5	1			2.6	19	76	5	1.8	1.44
Sm		35	50	12	3				2.7		67	33	2.3	1.17
Bi	10	18	23	27	14	5	2	<1	3.4	19	81		1.8	1.88
Pb	1	21	35	26	11	4	2		3.5	58	42		1.4	2.50

drift region between the anode and the ion extractor region, and then to trigger a z-discharge to produce an intense flow of high-energy electrons inside the drifting metal plasma. An ion beam is then formed through either a conventional ion extractor system or by self extraction across the plasma sheath. Hershcovitch *et al.* (1998) reported on initial attempts at LBNL-Berkeley to develop a source named Z-MEVVA. Early results with Au cathodes were limited to Au^{3+}, due the impedance of the electronic circuitry being too high. Although a 2 kV high-voltage pulse was applied to produce the z-discharge, the results indicated that the effective electron "beam" energy was only 30 eV. That is, 1.97 kV of the applied voltage was dropped across the circuit, with only about 30 V dropped across the metal plasma itself. Circuit modifications to reduce impedance resulted in the observance of significant yields up to Au^{6+}, which corresponds to a voltage drop of about 100 V across the plasma.

The Z-MEVVA work led us to a new z-discharge approach, which was pursued at UC-Irvine and given a different name: the Low Impedance Z-discharge Metal Vapor (LIZ-MeV) ion source. Debolt *et al.* (2002) presented the LIZ-MeV source layout and showed preliminary results that were encouraging, but not yet conclusive. The time-of-flight resolution was not sufficient to resolve individual charge-state peaks, but the indications were that gold ion charge states between Au^{4+} and Au^{19+} were produced with Au^{10+} as the most probable.

6. CONCLUSIONS

The external electron beam enhanced MEVVA (E-MEVVA) is clearly demonstrated to produce heavy ion beams with substantially higher charge states than a conventional MEVVA, but with similarly large ion currents. Complimentary work with internal electron beams produced by z-discharge (Z-MEVVA and LIZ-MEV) is also promising. There are many useful applications for such ion sources, including ion implantation, relativistic heavy ion accelerator injection, and heavy ion inertial fusion drivers. In Batalin *et al.* (2002*b*) we reported that performance studies indicate even higher charge state ions are produced inside the source, but are trapped in the intense electron beam. It may be possible to further optimize the source and to extract even higher charge state ions after the electron beam pulse. Possibilities for future enhancement include (a) increasing the electron beam current and density and (b) further reducing the negative effect of residual gas impurities. Future efforts are also planned to further develop the z-discharge (internal electron beam) approach to enhancing MEVVA charge states. The present results already demonstrate that electron beam enhancement of the MEVVA is a viable alternative to other much more costly and difficult to operate devices for the production of intense beams of highly charged ions.

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