DEVELOPMENT OF A VACUUM ARC METAL ION SOURCE FOR HEAVY ION ACCELERATORS

P. Spädtke, H. Emig, C. Mühle
Gesellschaft für Schwerionenforschung mbH, Planckstr. 1, D-64291 Darmstadt, Germany,
E.M. Oks
High Current Electronics Institute, Russian Academy of Sciences and
the State Academy of Control Systems and Radioelectronics, Tomsk 634050, Russia,
and I.G. Brown
Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA

1 INTRODUCTION

Multiply charged ion beam generation is an active field of research for a number of technological applications including injectors for heavy ion accelerators. High current broad metal ion beams can be formed by a vacuum arc ion source [1]. This kind of ion source has been developed at Berkeley [2] and at many laboratories around the would over the last ten years [3]–[7]. The metal arc discharge occurs between "cold" electrodes. After arc ignition by a high-voltage, short-duration spark discharge, plasma is generated by ionization of metal vapor from the cathode spots formed on the surface of the negative electrode.

In normal operation vacuum arc ion sources provide, depending on the extraction system, a few hundred milliamperes of ion current with pulse length from 50 microseconds to steady-state, generally containing ionization states between Q = 1+ and Q = 5+ with a mean charge state from 1+ to 3+ depending on the metal used as the cathode of the arc. Further upgrade can be achieved by application of a magnetic field in the arc gap. In the vacuum arc all ionization processes take place quite close to the cathode spots. Thus the magnetic field is important only in this small region. This simplifies the production of a strong magnetic field to confine not only the plasma electrons but also the ions. It has been shown that the combination of a magnetic field of up to 1 kG together with a small metal grid increases ion beam current [8] improves the uniformity of beam current density [9], reduces the noise of the beam current [10], and allows simultaneous gaseous-metal ion beam generation [11].

A strong magnetic field gives rise an to enhancement of the high charge state fractions [12, 13] in the vacuum arc plasma. This result reduces the nesseccary dc acceleration voltage for injection to rf-accelerators even for heaviest elements. Here, we present experimental results on the influence of a strong magnetic field on the charge state distribution of ions in the vacuum arc ion source. This work was carried out between GSI Darmstadt, HCEI Tomsk, and LBL Berkeley in a collaboration.

2 EXPERIMENTAL SET-UP

The experiments reported here were done using multi-cathode vacuum arc ion sources, both the MEVVA-4 GSI version [14] and the MEVVA-5 developed at LBL [15]. Model experiments concerning the influence of magnetic field on the emission parameters of the ion source were made in Tomsk with the "TITAN" ion source [16]. In the first two cases a magnetic field was induced by a small pulsed field coil mounted inside the anode region near the cathode.
A schematic of the GSI source, as modified to include the magnetic field coil, is shown in Fig. 1. A detailed description of the basic design of this ion source has been presented elsewhere [3]. The coil, 3 cm in diameter and 4 cm in length,

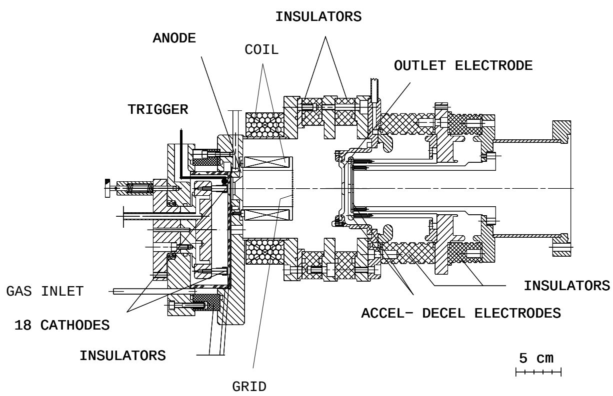

Figure 1: MEVVA with grid and magnetic field(s).

contains about 250 turns of copper wire of 1.05 mm diameter with a total resistance about 1 Ω, and produces 40 G per ampere of coil current. These coil parameters are well matched to the arc power supply, so we used a duplicate supply as designed at GSI for the MEVVA discharge. It was also possible to use only a single power supply with a parallel connection of the arc and coil but separation of their currents by resistors. In the Berkeley experiments we connected the arc and coil in series. It is important to note that two power supplies provide independent variation of the arc current and the magnetic field. The coils produce a magnetic field of up to 6 kG (GSI experiments) and up to 10 kG (LBL), repectively. Compared to the conventional large coil for the MEVVA 3 using the small coil, we obtain a rather narrow field distribution, and the field at the extraction system is 100 times less than the maximum field. This fully removes any influence of magnetic field on the beam extraction. As shown in Fig.1, in this modification of MEVVA ion source the internal surface of the coil serves as the arc anode, allowing increased plasma density, which is inversely proportional to the anode space volume. The anode was terminated by a metal grid; we used two meshes made from Ta (0.75x0.75 mm^2 and 0.25 mm thickness).

Ion charge state distributions were measured using a magnetic spectrometer (GSI) [3] and a time of flight system (LBL) [17] . The first method provides an analysis of m/q ratios within the beam, while the second gives an analysis of the particle velocities within one single beam pulse. All experiments were done at a background gas pressure of about 10^{-6} torr.

3 EXPERIMENTAL RESULTS

A strong influence of the magnetic field on the ion beam charge state distribution was observed. Similar results were obtained in both the GSI and LBL experiments, confirming the validity of both sets of experiments.

Increasing the magnetic field strength up to a few kG increases the intensity of the high charge state components and decreases the low charge states in the vacuum arc plasma. This result was observed for more then 30 different cathode materials used in our experiments. In the case of an Ag cathode, for example, the Ag^{4+} fraction increases by a factor of 30 from about 1% to 30%, Ag^{5+} increases from zero to 3%, while at the same time the lower charge state components decrease from 61% to 23% (Ag^{2+}) and from 13% to 7% (Ag^{+}). All data are in particle current fractions. There is an important difference in arc voltage behavior also; thus as an example, for a titanium cathode without magnetic field increasing the arc discharge current from 100 to 700 A is accompanied by an arc voltage increase from 18 to 32 V, while with a magnetic field increase from 1 to 7 kG the voltage increases from 32 to 78 V.

Measurements of the effect of arc current on the surface of the anode mesh allow us to estimate the current density and plasma density. Thus with a strong magnetic field the average plasma density increased about 16 times, and its value at 20 mm distance from the cathode spot can be as high as 10^{14} – 10^{15} cm^{-3}. One can conclude that a dense plasma exists relatively far from the cathode spot when a magnetic field is present.

It is important to note that with a high magnetic field new high charge state components can be formed that are not present in the zero-field case (C^{3+}, Ti^{5+}, Ni^{5+}, Ni^{6+}, Cr^{5+}, Pt^{5+}, Mn^{4+}, Ba^{3+}, Ba^{4+}, Bi^{4+}, Mo^{6+}, U^{6+}, and others). Enhancement factors in the mean charge state were between 1.2 and 2.45 depending on the magnetic field and cathode materials. Comparison of charge state distributions without and with magnetic field for some cathode materials are shown in Table 1.

Because of the series connection of the coil and the arc in some of the LBL experiments it is important to separate the influence of magnetic field from that of the arc current itself. Experiments show that for up to 1 kA of discharge current the dependence of charge state distribution on arc current is negligibly small. For arc current above 1 kA however, together with the "pure" influence of magnetic field the charge state distribution was also influenced by increase of discharge current. Comparison of the charge state distribution at high arc current with and without external magnetic field shows that both arc current and magnetic field have a similar influence, but higher current is required to obtain the same effect in the case of zero external B-field. Simple estimates indicate that the influence of the discharge current is connected with the self magnetic field of the arc. This fact leads us to the hypothesis that the magnetic field alone is the explanation for the enhancement of higher charge state fractions in the vacuum arc plasma.

4 CONCLUSION

The experimental results on the influence of a strong magnetic field on the charge state distribution of ions in the vacuum arc plasma can be explained by increased power input into the near-spot plasma. This provides an increase in ionization by plasma electrons. Increased plasma density and improved ion confinement, with associated increase in the electron-ion collisions in the plasma, are two additional factors which enhance the multiple ionization processes. There is a correlation between the value of ionization potential of the highest charge states in the vacuum arc plasma and the maximum value of the discharge voltage. This implies that in order to increase the limits of multiple ionization in the vacuum arc plasma one should find a method to increase the arc discharge voltage.

For the planned high current injector at GSI U^{4+} is the design ion. From the desired electrical current of 15 mA already 8 mA could be transported and analyzed at the test bench. The beam emittance was measured with $\epsilon_n = 0.2\ \pi$·mm·mrad. However, the reduction of noise is still a topic of further development.

5 ACKNOWLEDGMENTS

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Table 1: Charge state distribution and mean charge state (all in particle current fractions) for a range of metal ion species. For comparison, data of ”conventional” operation mode without magnetic field (I_{arc} = 220 A) are included. The total extracted current as well as the beam emittance depend on the used extraction system.

	Without magnetic field							With magnetic field									
Metal	1+	2+	3+	4+	5+	6+	Q	1+	2+	3+	4+	5+	6+	Q_B	kG	kA	Q_B/Q
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	3.7	0.2	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	1.0	1.95
V	11	76	12	1	–	–	2.1	13	31	48	8	–	–	2.5	3.7	0.2	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	39	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	3.7	0.2	1.20
Pt	12	70	18	–	–	–	2.1	1	16	34	46	3	–	3.3	10	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

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