GRID-CONTROLLED METAL ION SOURCES FOR DE89 010657
HEAVY ION FUSION ACCELERATORS

L.K. Len, S. Humphries, Jr. and C. Burkhart
Institute for Accelerator and Plasma Beam Technology
University of New Mexico
Albuquerque, New Mexico 87131

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ABSTRACT

A variety of metal ions can be generated using vacuum arcs, but due to the nature of these arcs, the flux generated fluctuates in time. We have successfully employed electrostatically biased grids to control the plasma and to provide a well-behaved, space charge limited ion source. The grid prevents the plasma from entering the extraction gap before the main voltage pulse is applied. The extracted ion current is space charge limited, resulting in a constant output current even though the ion flux from the vacuum arc source varies considerably. There are several advantages over other conventional sources, for instance, thermionic sources are faced with heating problems especially for large area configurations, while gas-injection sources cause prefill problems because they take too long to reach equilibrium. We have performed extraction experiments with aluminum and indium arc sources. We have extracted 300 mA of pure Al^+ at 30 kV for 10 μs . The normalized beam emittance has been measured to be 8×10^{-7} m-rad.

INTRODUCTION

Metal vapor vacuum arc is one of the most versatile methods for the generation of metal ions for various research and industrial applications. Its operation is simple, reproducible and reliable. Many different types of ion can be readily generated by simply changing its cathode material [1,2]. Cathode materials that have been used successfully to generate their respective ions thus far include C, Mg, Al, Ti, Ni, Cu, Zn and In. Although it is capable of producing a respectably high ion flux, the vacuum arc by itself is nevertheless quite useless as an ion source for conventional accelerator application. This is because the flux level produced by such arcs is intrinsically very spiky, i.e., significant flux fluctuation in short time scales. The long time overall flux level is very reproducible. Figure 1 shows three typical ion flux signals for aluminum, copper and indium as recorded by biased flux cup. Each frame is a three trace overlay. Even the smoothest of them is far from being an ideal source for accelerator. The optical quality of a beam extracted

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from a plasma depends very much on the plasma anode surface. To obtain a good quality beam, one needs a plasma anode surface that is concave towards the cathode [3] and extraction condition which perfectly matches the plasma ion source. In the event there is a mismatch, the plasma anode surface will bulge one way or another thereby deteriorating the beam quality.

This paper describes an experimental technique that has been used successfully to eliminate the rapid flux variation in such sources, making them appropriate for use as ion sources for particle accelerators. The technique involves the introduction of appropriately biased grids to electrostatically separate the ions from the electrons in the plasma. A space charge limited, constant current beam can then be extracted from this grid-controlled plasma ion source so long as the extraction gap and voltage are such that the source limit is not exceeded by the space charge limit.

The basic principle of the operation of the grid-controlled ion source is illustrated in Fig. 2. The plasma grid defines the potential of the plasma and the anode grid at the extraction gap is biased to a negative potential with respect to the plasma grid. For this source to work properly, the negative bias must be large enough to turn all the electrons from the plasma. This of course is determined by the plasma electron temperature. To satisfy the above requirement, one needs a bias voltage given by

$$eV_g > (kT_e) \ln(m_i/m_e)$$

where V_g is the magnitude of the anode voltage relative to the plasma grid, T_e is the electron temperature and m_i , m_e are the ion and electron masses. For an electron temperature of 10 eV, V_g should be 100V or more for light through intermediate mass ions. This negative bias causes the electron in the plasma to turn back, allowing only the ions to enter the extraction gap as depicted in Fig. 2. Before the application of the extraction voltage, the ions that enter the extraction gap are forced to reflex because of the formation of a virtual anode. There is thus no significant buildup of particles in the gap before the arrival of the extraction voltage. The grid-controlled plasma anode thus behaves in similar manner as a thermionic anode. When the extraction voltage is applied, the ion flow is space charge limited and is insensitive to the source fluctuation. The beam optics are determined entirely on the shape of the plasma grid.

Experimental results verifying space charge limited ion beam extraction will be presented for Al^+ and In^+ . Pulsed Al^+ beam of up to 15 mA/cm² in a 1.8 cm gap at 30 kV has been produced. Beam divergence measurements showed an upper limit on normalized emittance of $\pi_{en} = 8 \times 10^{-7}$ m-m-rad.

APPARATUS

Fig. 3 shows the experimental apparatus and the electrical circuit components. A standard conical pyrex glass cross (15 cm diameter) pumped by a 6 inch ion pump provided a clean vacuum environment for performing the experiments. Typical operating pressure was 5×10^{-8} torr.

The metal vacuum arc was constructed from a stainless steel tube on which a cathode of desired material can be mounted. Inserted inside this stainless tube was a piece of rigid coax which was used as a trigger for the vacuum arc source. The anode was also made of stainless steel. It also served as a flange for mounting the source to the plasma expansion chamber. The vacuum arc was operated with a gap of 0.8 mm. We have learnt from our experience that the flux output would be reduced with smaller gaps. On the other hand, if the gap was too large, the discharge would be very erratic resulting in higher electron temperature. This in turn could lead to grid shorting at the plasma anode. The vacuum arc was triggered by the plasma generated by the rigid coax when the Krytron was fired dumping the $0.1 \mu\text{F}$ capacitor which had been charged to 5 kV. The energy was coupled to the rigid coax through a ferrite isolation transformer. Once the main arc was initiated by this trigger plasma, it was sustained by an 8-element pulse forming network (PFN). This 5Ω PFN provided a square pulse of $100 \mu\text{s}$. It could supply a constant current ranging from 100 to 500 amperes. Fig. 4 shows a typical PFN current pulse and the plasma ion flux measured behind the cathode grid. The vacuum arc cathode used in this case was aluminum.

The plasma grid was mounted at the end of the plasma chamber. All the grids used in the experiment were made from 100×100 stainless steel mesh. The mesh had a transparency factor of 0.8. All three grids can be easily replaced in the event they were damaged in the experiment. They had survived over 1000 pulses with no visible damage on any one of them. The anode grid bias was provided by a capacitor with a series resistor to protect the grids in case of a short.

The ion beam extraction voltage was provided by a pulsed transformer. The transformer was comprised of three laminated silicon steel cores. These cores had an inner diameter of 30 cm, outer diameter of 66 cm and a thickness of 5 cm, giving a total volt-second product of 0.083 V-s. An ignitron switch was used to dump the capacitor through a 5Ω resistor into the primary, which consisted of just one single turn. The cores magnetically switched out a flat extraction voltage pulse whose pulse length was dependent on the voltage in accordance with the volt-second product. The cores had to be reset after each pulse. This was done with a different capacitor charged to the opposite polarity as the extraction capacitor.

Since the cathode and its supporting flange were at high voltage, diagnostic probes were also floated up to the same high voltage. To avoid having to float the oscilloscope, the signal cables were wound around the secondary of the silicon steel cores which provided the voltage isolation. The noise level was very low. Good signal traces could be recorded on unshielded oscilloscopes.

The extracted beam angular divergence was studied using a channel-electron-multiplier-array (CEMA). Only time integrated measurements had been performed. A beam mask plate with four pinholes of diameter 0.36 mm, each 8 mm from the axis, was positioned at the cathode. The CEMA was located 37.2 cm downstream. The images of the beamlets were amplified and transferred to photographic film outside the vacuum system via fibre-optic coupler.

RESULTS

The top trace of Fig. 4 shows total driving current in the vacuum arc using an 8-element PFN. The pulselength of this PFN was about 100 μ s. The bottom trace is the plasma ion flux from an aluminum arc. The plasma flux was measured with a biased ion flux collector located behind the cathode grid. The 20 μ s time delay between the on set of the arc current and the ion flux signal was the time taken by the plasma to traverse the 18.5 cm from the plasma source to the probe. Since our source was operated at very low repetition rate, the arc had to undergo a cleaning phase at the beginning of the pulse, during which contaminants due to adsorbed gases may be present [1]. To avoid extracting these contaminants, the ion beam extraction voltage in this experiment was applied somewhere in the middle part of the pulse, i.e., 40 μ s after the initiation of the vacuum arc.

Space charge limited ion flow in the extraction gap is demonstrated in sequence of measurements in Fig. 5. All the traces displayed are 2 trace overlays. The anode grid bias voltage was set at -150 V in all cases. Only the extraction voltage was varied. In the first two frames of Fig. 5, where the extraction voltage were relatively low, the space charge limits were well below the source limits and the extracted ion currents were identical. The reproducibility was excellent. As the extraction voltage was elevated, the space charge limit approached the source limit and irregularities began to show up in the bottom traces. These irregularities occurred whenever there was a cross over between the space charge limit and the source limit. Fig. 5e in particular, shows very clearly the effect of the source fluctuation when the space charge demand could not be met.

Extensive extraction measurements had been performed on the aluminum source. The results were plotted in Fig. 6. The gap size was 1.8 cm and the anode grid bias was

-150 V. Measurements for indium plasma source has also been plotted in the same log-log graph. It can be seen that both sets of data follow the $V^{3/2}$ lines as predicted by Child's Law. It should also be noted that for the same extraction voltage, the aluminum flux is twice as high, also in agreement with space charge flow.

The beam divergence measurement was performed using an aperture plate located at the cathode and a channel electron-multiplier-array (CEMA) 37.2 cm downstream. There were 4 small holes on the aperture plate. These holes were made at a radial distance of 0.8 cm from the axis. Fig. 7 shows two sets of photographic output from the CEMA detector. Extraction voltage for both cases were 27 keV and the Al^+ ion flux was 15 mA/cm². In the case of Fig. 7a, the anode grid was biased at a relatively high voltage of -250 V. The beamlets formed well-defined images with diameter of 0.7 cm. The fact that a well-defined image was obtain for a beam implied that the anode plasma surface was highly stable. The pattern of the images was somewhat distorted when compared to the aperture pattern. This was due to space charge effect and error in the alignment of the extraction anode and cathode. The alignment was made in reference to the pyrex glass cross which is not perfectly symmetric. The normalized emittance inferred from the above measurement has a value of 8×10^{-7} π -m-rad. The beam quality can easily be improved by optimizing the shape of the plasma anode. For instance, by using a Pierce geometry.

The images in Fig. 7b were obtained with an anode grid bias of only -100 V. The images were not as well-defined as for Fig. 7a. The halos found in the images implied that the plasma anode surface was not stable. This was because of the inability of the low grid bias voltage to turn back all the plasma electron. As a result, the plasma anode surface bulged into the extraction gap thereby deteriorating the optics.

SUMMARY

The use of metal vacuum arc ion sources in conjunction with the grid-controlled technique can be used to provide a whole spectrum of ion sources which are suitable for applications in the heavy ion fusion accelerator programs. In principle, ions of any solid conductors and semiconductors can be generated. We have demonstrated the extraction of space charge limited, constant current ion beams from such sources. Al^+ beam of 15 mA/cm² (300 mA total beam current) had been extracted at 30 kV with normalized beam emittance of 8×10^{-7} π -m-rad. It should be possible to improve on the beam quality by optimizing the shape of the extraction anode.

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Fig. 1. Typical ion fluxes from metal vacuum arc sources. Note the short time flux variation.

Fig. 2. Schematics of the grid-controlled ion source. a) Grid geometry. b) Potential and particle flow with no extraction voltage. c) With extraction voltage.

Fig. 3. Experimental setup with its associated driving circuits.

Fig. 4. Total arc current and ion flux measurement with the PFN charged to 3 kV. Top: Total arc current, 200 A/div. Bottom: Available plasma ion flux measured behind the cathode grid, 12.4 mA/cm²/div., 2 μs/div.

Fig. 5. Two trace overlays of extraction voltage and extracted ion beam density for an aluminum plasma source. The anode grid voltage was -150 V for all cases. Top: Extraction voltage, 4 kV/div. Bottom: Extracted ion current density, 6.2 mA/cm²/div., 2 μ s/div.

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