EXTRACTION OF A STEADY STATE ELECTRON BEAM FROM
HCD PLASMAS FOR EBIS APPLICATIONS*

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ABSTRACT

Experiments to extract high brightness electron beams from hollow cathode discharge plasmas are now in progress. A unique feature of these plasmas, which in principle can facilitate the extraction of large current low emittance electron beams, is the existence of a relatively high energy electron population with a very narrow energy spread. This electron population was identified in a self-extraction experiment, which yielded a 35 eV, 600 mA electron beam with parallel energy spread of less than 0.5 eV. Application of a very modest extraction voltage yielded a steady state extracted electron beam current of 6.5 A of which 5.7 A had a preacceleration parallel energy spread of no more than 0.25 eV. The end result of this endeavor would be an electron beam current of 6 A even though, preliminary results strongly suggest that much larger electron beam currents can be produced.

INTRODUCTION

Tentative long-range plans for the BNL heavy ion program call for the development of an electron beam ion source (EBIS) with an electron beam current of 6 A. Present day EBIS devices operate with electron beam current of less than 1 A. These beams operate steady state (or with very long pulses), and they have low emittance. Because of the later requirement, no serious considerations were given to electrons extracted from plasmas. Plasma cathodes can easily yield multi-amperes of electrons, however, at a very high emittance. Therefore, this type of electron beams have very limited use (mostly used to excite molecules in powerful gas lasers). For almost all other applications, electron beams are injected from guns utilizing either thermionic cathodes, or photocathodes. These surface emitted electrons have energy spreads of about 0.5 eV or less (as compared to plasma electrons with energy spreads of a few eV at least). But, space charge problems pose severe limitations on the total steady state (or long pulse) electron current that can be extracted from the various surface emitters. Other surface emitters, e.g., semi-conductor photoemitters have an inherent limitation to very short pulses only at high current outputs.

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Hollow cathode discharge (HCD) plasmas have two electron populations: the bulk electrons with a density of up to (and/or slightly above) 10^{14} cm^{-3} with a temperature of several eV, and fast primary electrons having a density of about 10^{11} cm^{-3} or less with an energy corresponding to the cathode potential and a thermal spread which is close to the cathode temperature of 0.17 eV. (In order to avoid confusion in terminology, it is important to note that most European researchers refer to this type of discharges as hollow cathode arcs HCA). Existence of fast electrons in HCD plasmas was either postulated¹ to explain properties of external plasmas in HCD's, or accepted as a possibility² that a minute portion (2%) of electrons emitted from a hollow cathode surface could survive their "trip" to the anode without loss of energy. Some theoretical models³ even attempt to predict HCD operation based on full thermalization of the surface emitted electrons.

To date, there is no theory which can fully explain HCD operation. As a result, there is no theory which could predict whether the electron population is a Maxwellian with a long superthermal tail, a pure Maxwellian, or whether there are two distinct electron populations.

We gambled on the existence of two distinct groups of electrons. Initial results indicate that at higher operating pressures the electron population is most likely thermal with a long superthermal tail, while at lower operating background pressures there are two electron populations, one of which has a narrow energy spread. Self extraction of this population yielded a beam current of 600 mA with a parallel energy spread of less than 0.5 eV. Application of an extraction voltage of only 100 V yielded a total electron current of 6.5 A of which 5.7 A were surface emitted electrons.

EXPERIMENTAL SET-UP AND RESULTS

In principle, this scheme is based on extracting the energetic electrons only. Schematically, the experimental configuration⁴ relied on repelling the bulk (thermal) electrons with a negatively biased grid and further selection was to be done with a magnetic mirror in case the discharge would not operate properly without a magnetic field. Fortunately, we obtained very encouraging results with unmagnetized discharges. After numerous experiments and changes, our experimental configuration evolved to that which is shown in Figure 1. The plasma is generated in a 3mm Ta hollow cathode.

Fig. 1. Schematic of the electron selection and extraction system.

The length of the discharge, i.e., the cathode-to-anode distance, was 9mm. This distance should be made as short as practically possible to minimize velocity space relaxation due to multiple small angle scattering of the fast electrons by the plasma particles. The hollow anode is followed by a negatively biased grid designed to repel the bulk electrons. Next, we have a positively biased ion repelling grid, which proved necessary in self-extraction experiments for preventing ions from reaching the target. The whole source is enclosed in a differentially pumped cylinder which can be negatively biased. The extractor and target are at ground potential.

A large number of measurements failed to show the existence of a distinct fast electron population with a narrow energy spread for "normal" modes of operation⁵ with a background pressure in the 10^{-4} Torr range. If this population existed, the electron current on target would have shown a very sharp drop or rise as the electron repelling grid bias was increased or decreased. This sharp transition was expected at a grid bias close to the arc voltage (the cathode potential). With the background pressure at about

10^{-4} Torr (or even as low as 7.2×10^{-5} Torr), target-current repelling-grid-voltage characteristics showed a gradual response. This was indicative of either a larger than expected thermal spread, or of the existence of a velocity distribution with a very long tail. Finally, when the background pressure in the discharge was reduced to 1.8×10^{-5} Torr, the desired behavior was observed. Figure 2 is a plot (on an x-y recorder) of the target current as a function of the bias on the electron repelling grid. The very sharp rise extends for 600 mA (off scale in Fig. 2). The resolution is about 0.5 V, hence the parallel energy spread is about or less than 0.5 eV. Furthermore, this sharp transition did occur at an electron-repelling grid bias of -33 V which roughly equalled the arc voltage. The plasma current was 18 A and the bias on the ion repelling grid was +42 V.

Fig. 2. Self-extracted electron current versus bias on the electron repelling grid.

Initial high voltage extraction results were performed in an experimental configuration identical to that shown in Figure 1 except for the addition of a grounding screen at the end of the source enclosure to prevent arcing between the source (floating at a negative voltage) and the pump (at ground potential). The inclusion of the screen reduced pumping which forced operation at twice the optimum pressure, for which the results from Figure 2 were obtained. Up to 1.2 A of electrons were extracted at 2.5 kV. However, the dependence of the extracted electron current on the electron repelling grid bias did not exhibit as sharp an increase/decrease as shown in Figure 2 (most likely due to the operation at non-optimal pressure).

To rectify the situation (without having to acquire expensive pumps), a slight modification of the source was made to allow for HCD operation at lower pressure. This new configuration is shown in Figure 3. The only substantial difference is that the hollow cathode is now inserted inside the hollow anode. This change facilitated HCD operation with 1.1×10^{-5} Torr pressure in discharge chamber. Best results to date are shown in Figure 4. Up to 6.5 A of total electron current was extracted with the source enclosure floating at only -100 volts, total gas flow was 0.22 ℓ/min at STP. HCD operation was in argon with an arc voltage of 36.8 V. From Figure 4, the fast electron population (the sharp increase) seems to account for 5.7 A of the extracted electron current. Based on our visual monitoring of the gauges (Voltmeter, and Amperemeter) measuring the electron current, the energy spread

Fig. 3. Modified experimental apparatus.

of the fast electron population is 0.23 eV, or lower. The most spectacular result, however, is that the plasma current in this case was only 7 A. And, as it was lowered, so was the total extracted current (roughly proportionally).

Results shown in Figure 4 coupled with the fact that the total arc current was only 7 A strongly suggest the existence of a fast electron population with a very narrow energy spread (at least in the parallel direction). Since this group of electrons accounts for 5.7 A, which is over 80% of the total arc current, the results support theories and experiments asserting that the bulk external plasma existing in a hollow cathode discharge consists of almost fully thermalized ions and electrons drifting slowly away from the cathode. Schram and his group⁶ have shown in a series of experiments that ions do indeed drift against the electric field towards the anode; a further enhancement of the assertion that the cathode emitted electron carry most of the arc current.

Fig. 4. Total extracted electron current vs bias on electron repelling grid. Bias voltage was swept manually.

FUTURE PLANS

Initial results identifying a fast electron population with a narrow parallel energy spread, which accounts for the bulk of the arc current is extremely encouraging. Since arc currents of up to 100 A have been obtained with 3 mm Ta HCD's (and up to 1 kA with larger cathodes), generation of several 10's of Amperes of steady state electron beams with low emittance may be possible.

Our next set of experiments (with smaller cathodes and lower current discharges) is designed to measure carefully the parallel energy distribution of the electrons. Following these measurements, an $E \times B$ filter to separate fast electrons from the Maxwellian tail will be built. With the filter in place, we plan to measure emittance of an electron beam consisting of the extracted fast electron population. If results meet requirements for an EBIS, experiments with long life cathodes will be performed.

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