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HIGH CURRENT, LOW EMITTANCE, STEADY STATE ELECTRON GUNS WITH PLASMA CATHODES*

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Major limitations of plasma cathodes have been overcome in an electron gun based on extraction of superthermal electrons from a discharge characterized by a large component of high energy electrons with a low thermal spread. A grid is employed to select these electrons for extraction while retaining the bulk electrons in the discharge. Steady state extraction of electron beams corresponding to over 60% of the total arc discharge current has been observed. A perveance of over 280 microperv was reached with the extraction of 9A at 1 keV from a 6 mm aperture. Some of the characteristics of the electron gun described in this paper are very attractive for electron beam melting.

Introduction

A plasma cathode is an electrical discharge device producing a plasma, from whose boundary electrons are extracted for further acceleration. Plasma cathodes are easier to fabricate and are more efficient than thermionic sources. Therefore, these cathodes were viewed as potential alternatives to thermionic cathodes about thirty years ago. However, present day plasma cathodes have some serious shortcomings. A major drawback of present day plasma cathodes is a high electron temperature¹ resulting in large emittance electron beams. Additionally, there is a severe limitation on the pulse length² of extracted current from these cathodes, as well as fundamental difficulties in controlling their emission current.^{1,2} Consequently, plasma cathodes have only a few limited applications (although considerable research interest remains^{3,4,5}).

Shortcomings of present day plasma cathodes arise from problems associated with fundamental plasma properties. High emittance is a result of high electron temperature. In plasma cathodes, it ranges from a few eV to as high as several keV compared with about 0.1-0.2 eV of most thermionic cathodes. Difficulties in controlling current emission from plasma cathodes, as well as limitations on the pulse lengths stem from fundamental problems^{1,2} with electron extraction from a plasma boundary. If the extracted current density is lower than the thermal flux, the plasma expands into the gap.² Extraction of

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current density equal to the thermal flux causes velocity-space anisotropy, which leads to instabilities.² In addition, electron emission from a plasma changes the plasma potential (as well as other plasma parameters), which in turn affects electron emission.

In this paper, a new concept for a plasma cathode, which is based on selective generation and extraction of low temperature electrons, is described. The underline principle is to generate a plasma with a substantial component of high energy, low thermal spread electrons, which can then be extracted through a hollow anode to form an electron beam. Extraction of these superthermal electrons, which otherwise just strike the anode, does not affect any discharge parameters; and, their low thermal spread yields a low emittance electron beam. The end result is a plasma cathode without the shortcomings of present day plasma cathodes, i.e., a plasma cathode capable of generating low emittance, steady state, high current electron beams.

Electron guns with plasma cathodes have a rugged constitution and are easy to fabricate and to replace components in. These electron guns can generate high power electron beams with lower extractor voltages (but higher current levels). Hence, they can operate at higher pressures. Additionally, contaminants (from backstreaming gas, ions, and metal chips) have negligible effects on the electron gun, since the plasma density is far larger than that of the contaminants. Hence, such an electron gun has many of the advantageous features of a plasma torch, yet, its beam can be rastered like any electron beam. Consequently, this type of electron gun may be very attractive for use in electron beam melting (EBM), electron beam casting (EBC), and physical vapor deposition (PVD).

The Electron Gun Development and Plasma Cathode Performance

Figure 1 shows a hollow cathode discharge (HCD) based electron gun, which demonstrates this concept. This electron gun evolved from a series of experiments,^{6,7,8} with a plasma based, high current, low emittance, steady state electron beam source. First, a retarding potential technique was employed to select electrons for extraction from a hollow cathode discharge, from which the electron energy distribution was inferred. From these measurements,⁶ it was shown that at conventional operating pressures, the parallel (to the direction of extraction) electron energy distribution function is Gaussian-like with a superthermal tail. At low operating pressures (of 1.8×10^{-5} Torr or below), the central core of the external HCD plasma is characterized by two electron populations: bulk electrons having a thermal spread of several eV and a population of fast electrons with a very narrow energy spread. This additional distinct component of electrons has an energy corresponding to the cathode potential and a very low energy spread of 0.13 eV. Although no satisfactory explanation for these phenomena exists,⁶ it was concluded that the fast electron population can become the basis for an excellent e-beam source. A negatively biased grid (to a potential whose magnitude is slightly lower than the energy of the fast electrons) can repel

the bulk electrons and ExB filter can be used to separate the fast electrons from the tail of the distribution function.

Next, attempts were made to evaluate the emittance of electrons extracted from the HCD plasma using a profile monitor.⁷ From the beam profile measurements and the beam envelope equation, the beam emittance was evaluated, and the beam transverse temperature calculated.⁷ The results indicate that the perpendicular thermal spread is very small and is comparable to the parallel spread; however, the error bars on the perpendicular temperature of the fast component were larger than the value of the temperature. A combination of low thermal spread and of high current density beam renders the thermal contribution to the total value of the emittance negligible.

Finally, an operation mode at the lowest pressure range ($6-8.5 \times 10^{-6}$ Torr), which is characterized by the extraction of very large electron currents, was identified.⁸ Up to 9 A were extracted with only 1,000 V.⁸

A schematic of the electron gun and of the beam current measuring devices is shown in Figure 1. The operation principle of this electron gun is to generate a plasma with a substantial fraction of fast electrons, and to use a negatively biased grid to repel the bulk (thermal) electrons toward the cathode while allowing the fast low thermal spread electrons to enter the extraction gap. The plasma is generated in a 3-mm Ta hollow cathode. The hollow cathode tip is slightly inserted inside a hollow anode. This hollow anode is followed by a negatively biased grid designed to repel the bulk electrons. The whole plasma generation and electron selection region is enclosed in a differentially pumped cylinder that is negatively biased during extraction to give electrons the desired energy. The extractor and extraction gap have a classical Pierce geometry. Source enclosure and extractor apertures are 6 mm each. The extractor gap is 8.12 mm. Electron beam extraction is achieved by biasing the source enclosure with a 1000 V, 25 A, Universal Voltronics power supply. Measurements of the extracted electron beam currents were done with both a dc current transformer (DCCT) and by monitoring the current collected on the beam dump shown in Figure 1.

In Figure 2, extracted current I_x as measured by the DCCT and/or the beam dump is displayed as a function of the arc current I_{arc} at a source pressure of 8×10^{-5} Torr and extraction voltage of 1000 V. Also shown is the total current load on extractor power supply, I_{ps} , for the same conditions and parameters. It should be noted that saturation occurs in Figure 2 at an arc current of 35 A due to power supply limitation. The DCCT saturated at 3 A, hence, only the beam dump was used to record I_x values greater than 3 A. In all these measurements, the bias on the electron repelling grid was 0.5 V less negative than the arc voltage V_a in order to allow for extraction of only the fast low thermal spread electron population. The current collected on the extractor, as measured by the voltage across a grounded resistor, was always close to $I_{ps} - I_x$ for the configuration shown in Figure

1 (within about 7%). I_x measurements by DCCT and beam dump agreed within about 2% for currents of up to 2.5 A, and within 5% for currents of 2.5-3 A.

For the conditions of Figure 2, the arc voltage (not shown) displayed V-I characteristics that are typical for an HCD,^{9,10} where the arc voltage has a very weak dependence on the arc current. However, as it was noted in Reference 8, the arc voltage has a very strong dependence on the source pressure where it almost tripled as the pressure was decreased by a factor of three. An interesting feature of this figure is the almost linear dependence of the power supply load, which corresponds to the total current exiting the source enclosure, on the arc current (up to power supply saturation at 25 A). The weaker raise in I_x with I_{arc} is probably due to space charge effects at low extraction voltage.

Affects of variations in the repelling grid bias on the extracted currents (I_x on beam dump and total extraction from source enclosure I_{ps}) and on the arc voltage V_a are displayed in Figure 3. The Figure 3 data was taken at a source enclosure pressure of 8×10^{-6} Torr and an arc current of 35 A. As it can be seen from this figure, the arc voltage is almost independent of the repelling grid bias, while the extracted current does depend on the repelling grid voltage exhibiting dramatic changes at a bias close to that of the arc voltage.

Resistivity of a highly ionized plasma like an HCD has a very strong temperature dependence. Based on the Figure 3 data, all indications are that the plasma resistivity, and hence the plasma temperature, does not change as the repelling voltage (and hence, the extracted current) are varied, since the arc voltage almost does not change (the arc current was kept constant at 35 A). In Figure 3, the arc voltage seems to decrease slightly as the repelling grid voltage (absolute) decreased below about 10 Volts. At this repelling grid bias, a significant portion of the bulk electrons can be extracted since their energy exceeds the grid bias. However, their extraction causes changes in the plasma potential,¹ which in turn affects the arc voltage.

At a source enclosure pressure of 8×10^{-6} Torr, the neutral particle density is about $3 \times 10^{11} \text{cm}^{-3}$. The plasma density inside the anode is not significantly different. Therefore, the mean free path of the fast electrons is a few meters, i.e., much larger than the experimental apparatus. In an HCD with a solid anode, these superthermal electrons would travel the length of the discharge and be lost to the anode. Therefore, extraction of superthermal electrons through the hollow anode in the Figure 1 electron gun should not affect any plasma parameters.

Maximum contribution of the bulk electrons to the total extracted current is given by

$$I = \frac{1}{4} envA \quad (1)$$

where e , n , v , and A are the electronic charge, electron density, thermal velocity, and extraction area respectively. This current is referred to in the literature as either the thermal flux² or the chaotic current.¹ For a typical HCD electron temperature^{9,10} of about 10 eV and a source enclosure aperture diameter of 6 mm, Equation (1) yields a current of 0.43 A. Compared with an extracted current (on beam dump) of 9 A and total extractor power supply load of 25 A (9A on beam dump and 16 A striking the extractor), the contribution of the bulk electrons is negligible.

Electron beam extraction was also performed by biasing the source enclosure with a Universal Voltronics power supply capable of reaching 12 kV and 3 A. Displayed in Figure 4 are the extracted current and power supply load versus the extraction voltage. The extraction was done in 350 msec long pulses every second in order not to exceed by too much the steady state cooling capability of the extractor and beam dump (each designed to handle only 10 KW). This is one case where a plasma was rather generous in facilitating electron current extraction which far exceeded original expectations of about 1 to 2 A.

A very interesting feature of the Figure 4 data is the large factor by which the extracted current exceeds that which the Child-Langmuir Law predicts. This factor diminishes as the extraction voltage is increased. One interpretation of this phenomenon is that plasma ions enter the extraction gap and partially neutralize the plasma. At higher extraction voltages, these ions penetrate a shorter distance into the extraction gap. Some preliminary results at low extraction currents (100s of mA) indicated that a two-electrode extraction system may retain the large factor by which the Child-Langmuir Law is exceeded to high extraction voltages as well. This concept will be, hopefully, further explored in future endeavors.

Conclusion

Extraction of superthermal electrons from a plasma can result in a high current low emittance steady state electron beam. Generation of plasmas with a large components of superthermal electrons can form the basis for superior plasma cathodes that do not have the shortcomings of pulse length limitations and large emittances. These cathodes have features which make them very attractive for use in EBW, EBC, and PVD. Additionally, HCDs operate well with odd shaped non-circular cathodes.¹¹

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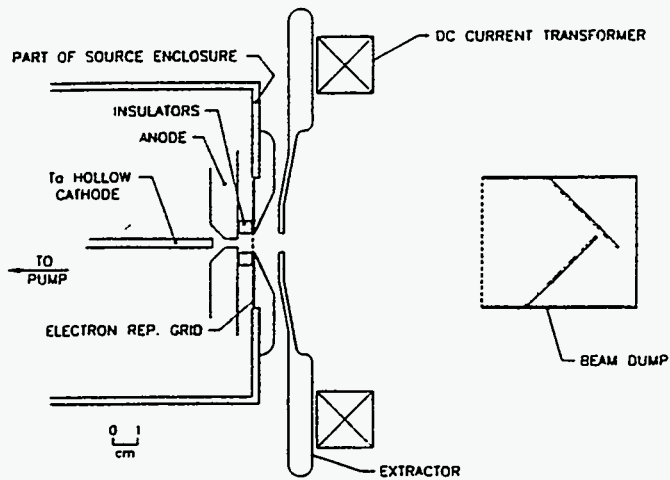


Figure 1

Schematic of the electron gun. Only the gun is drawn to scale. The DCCT has an I.D. of about 7 inches. The beam dump, located 35 cm downstream, has an I.D. of 10.5 inches.

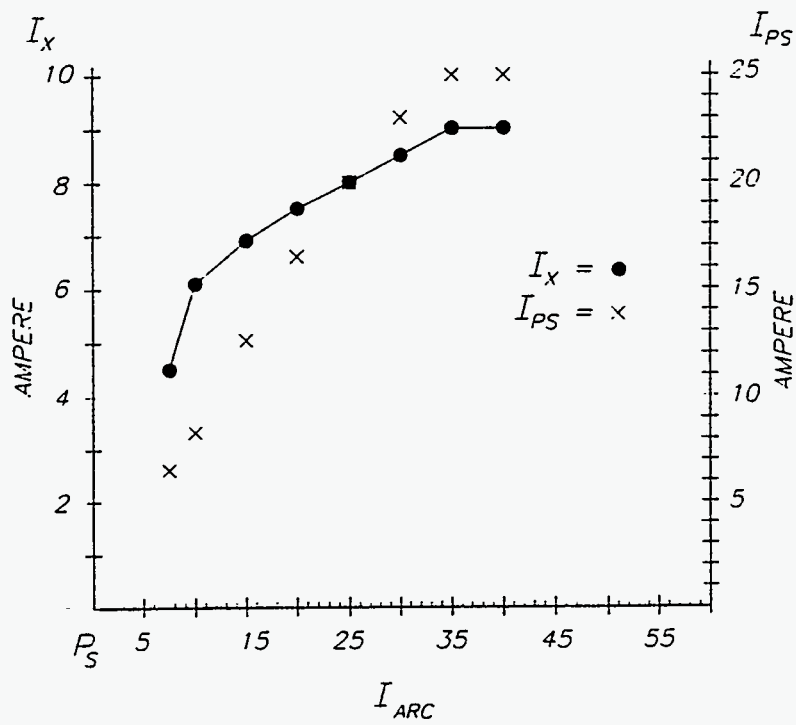


Figure 2

Extracted electron current, I_x (denoted by solid dots), and power supply load I_{ps} (denoted by x's), versus arc current, I_{arc} . The line through the solid dots is only to guide the eye.

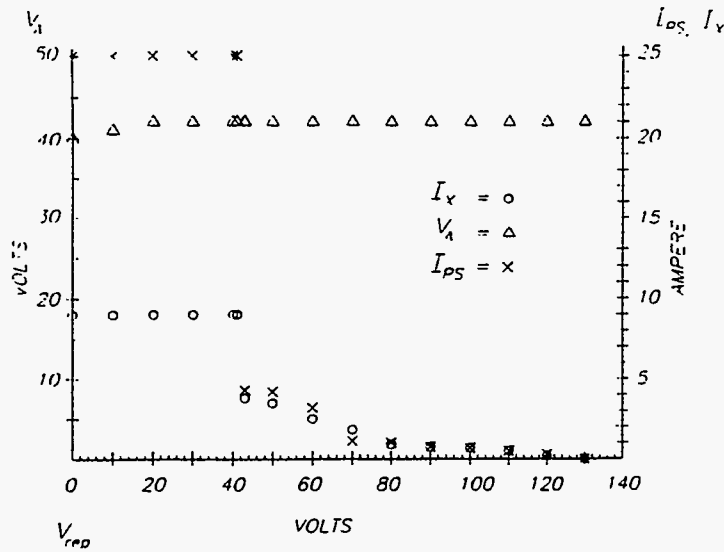


Figure 3

Arc voltage (denoted by triangles), and extracted I_x and power supply I_{ps} currents (denoted by circles and x's, respectively) versus the repelling grid bias V_{rep} .

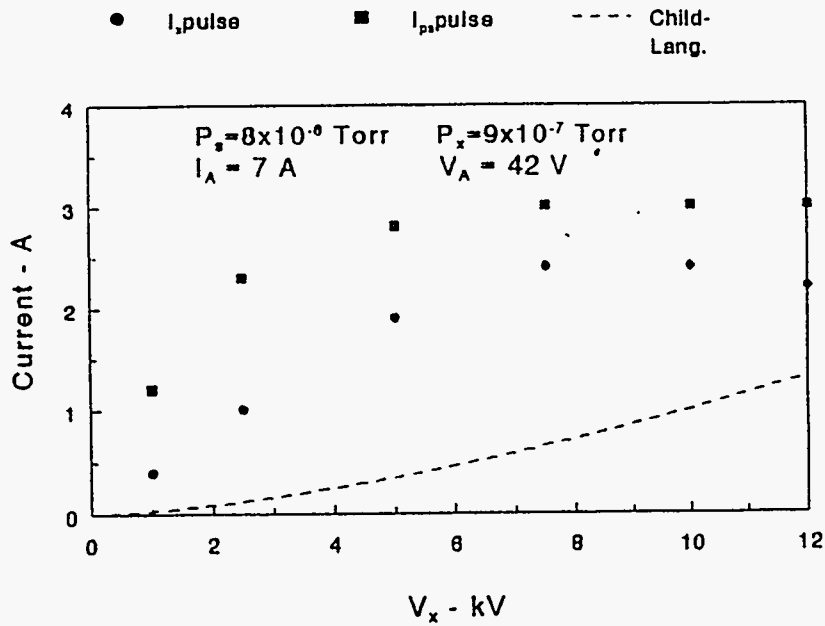


Figure 4

Extracted current I_x and power supply load I_{ps} versus extractor voltage. Dashed line is the extracted current predicted by the Child-Langmuir Law.