A Variable Pulse-Length Electron Beam from the Back-Lighted Thyratron*

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Abstract
A variable pulse-length electron beam source capable of 100's μsec pulse to DC operation is reported. Long-pulse electron beam generation was based on the steady-state hollow cathode discharge mode of operation of the back-lighted thyratron and achieved by modification of circuit parameters that control the discharge. Three different discharge circuits were used in the experiment. An RC circuit (16 nF, 1 kΩ at -20 kV) was used to generate an electron beam with duration ≈ 100 μsec. The energy of the beam is associated with the cathode voltage and a current density ≈ 10 A/cm^2 was measured. To further increase the pulse-length a discharge circuit with 100 μF and 500 Ω was used. The pulse-length was extended to 50 msec FWHM. The third circuit was a pulse forming network which generated an non-decaying amplitude electron beam with a duration of 200 msec FWHM. DC operation has also been achieved. The results demonstrate the feasibility of controlling the electron beam pulse-length with modifications of external circuitry. The device is simple, robust, and compatible with a plasma environment. Applications include electron beam ionized lasers, electron beam ion trap, electron beam assisted atomic layer epitaxy and plasma-filled microwave generators.

INTRODUCTION

Plasma compatible electron beam sources are of interest in current research areas that include plasma-filled microwave generation, electron beam ionized lasers and a long duration electron beam is also essential for electron beam ion trap (EBIT) experiments.[1-6] Electron beam generation is usually achieved through using thermionic cathodes, field emitters or photocathodes. The plasma cathodes are of particular interest in the generation of long pulse electron beam. In a glow discharge, electrons can be generated by ion bombardment and then accelerated through the cathode fall.[7,8] This feature makes glow discharge a promising candidate for applications mentioned above.

Recently the back-lighted thyratron (BLT) and pseudospark have been developed for high current pulsed power switching applications.[9] The BLT and pseudospark have several modes of operation, including a mode that is essentially a hollow cathode discharge (HCD).[10] This is achieved with electrodes that are parallel discs, each with a circular central hole and separated by insulators. With the application of sufficiently high voltage, a very low current (typically < 10^{-6} A) Townsend discharge develops on axis due to the focusing effect of the electric field. A positive space charge builds up inside the hollow cathode region (HCR) as a result of low mobility of the ions produced by electron-neutral collisions. The release of a sufficient number of starting electrons inside the hollow cathode initiates a *transient* HCD. The short-pulse (~10-100 nsec) electron beam generation during this transient HCD has also been subjected to some extensive studies.[11-14] In the process towards a high discharge current operation, the increasing plasma density eventually shields the electric field from the HCR. The discharge current will then be taken over by the cathode surface at the aperture, the HCD ceases and the super-emissive process becomes dominant.[15-17] In this work the BLT was running under a HCD condition (low current) and not the super-emissive condition. The low current condition prevents the BLT from entering into the super-emissive mode of operation and a *steady-state* HCD is achieved.

II. RESULTS AND DISCUSSION

A. Experimental Setup

Figure 1 shows the experimental setup. A single-gap BLT was directly built on a standard 2-3/4" conflate flange and mounted on a 15 cm diameter vacuum chamber. The HCR is a copper cylinder, with a cathode on one end and a quartz window on the other. The HCR is 3 cm in both the diameter and length. The cathode central hole size and cathode-anode gap are 3 mm and 5 mm. The cathode-anode gap spacing is maintained with a 44-mm glass insulator.

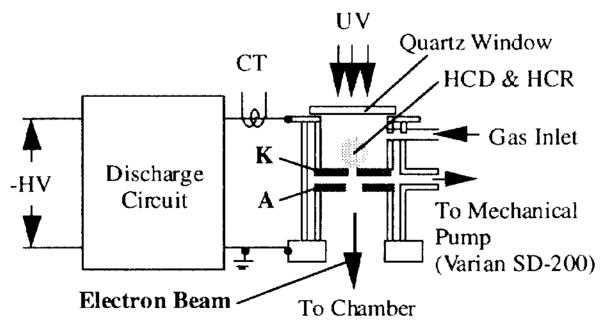

FIG. 1 Experimental setup. The chamber is evacuated with a Varian 80 liters/sec turbo pump. Beam current was measured with a Faraday cup.

The discharge (and therefore the electron beam emission) is initiated with UV light illuminated on the cathode back surface through the quartz window. During the experiment a working gas will flow into the cathode back space and be evacuated through the cathode hole. The cathode-anode gap is evacuated with a Varian SD-200 mechanical pump and the chamber a V-80 Turbo pump. Pressure in the chamber was monitored with a cold cathode gauge. Time-resolved beam current was measured with a Faraday cup which could be moved along the discharge axis. The Faraday cup has a resistance of 0.25 Ω and a rise time ≤ 2 nsec. The area of

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Faraday cup is ≈ 1.25 cm^2. The electron beam is self-extracted with no extraction voltage nor axial guiding magnetic field (except for the DC operation). Cathode voltage is monitored with Tektronix P 6015 high voltage probe. Various discharge circuits have been used to generate electron beam with different pulse-length.

B. 100 μsec pulse-length Electron Beam Generation

An RC circuit (16 nF, 1 kΩ) operated at -20 kV was used to generate the electron beam with pulse-length of 100 μsec. The 1 kΩ resistor was chosen as a ballast resistor to limit the discharge current so that a prolonged HCD can be sustained.

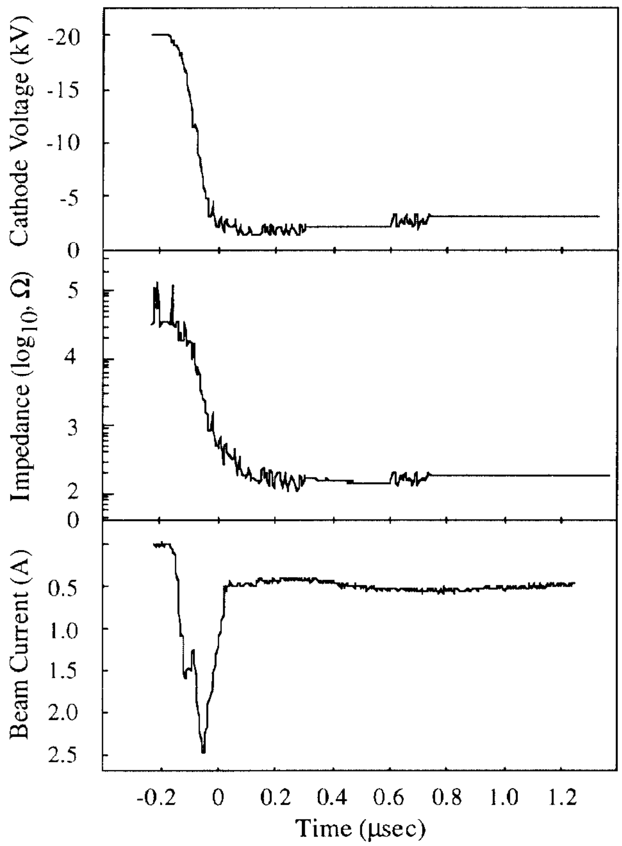

FIG. 2 The cathode voltage, BLT cathode-anode impedance, and the beam current at 2 cm behind anode for a 100 μsec pulse electron beam generation with both the transient and steady-state phases shown.

The top trace of Figure 2 shows the BLT cathode voltage. The discharge voltage drops from the initial -20 kV to -2 kV in about 170 nsec; roughly equals to the duration of the transient electron beam. The discharge voltage then decays with a time constant of ≈ 12 μsec. The BLT impedance was determined from the ratio of discharge voltage to discharge current. This varies from a blocking state (order of MΩ) to about 200 Ω during the voltage transient. Since the BLT is maintained in a low discharge current operation the impedance is much higher than what was usually found in a typical high current operation (order of 10 mΩ.). On the same time axis also shown is the electron beam current measured at 2 cm behind anode. A correlation between the discharge voltage and the electron beam currents is clearly seen. The transient electron beam had a wide energy variation, from an initial 20 keV down to 2 keV. The long-pulse electron beam on the other hand had a much slower energy variation in time. The measurements indicate a two-phase operation. The transient phase of electron beam has a peak current ≈ 2.5 A and duration ≈ 130 nsec FWHM. The steady state phase of the electron beam has shape and duration follow the discharge current. The discharge current is highly overdamped with peak current ≈ 16 A and duration ≈ 100 μsec. The long-pulse electron beam has a duration of ≈ 100 μsec and current of several hundred mA. The minimum current density is estimated to be ≈ 10 A/cm^2 with the beam area assumed to be anode aperture. The ratio of electron beam to discharge current is ≈ 4% at the peak of discharge current.

C. 100 msec Electron Beam Generation with RC Discharge

An RC circuit with 100 μF capacitor and 500 Ω resistor was chosen to extend the pulse-length. Figure 3 shows the electron beam current, discharge current and the cathode voltage when operated at -2 kV (capacitor rating : 2.5 kV).

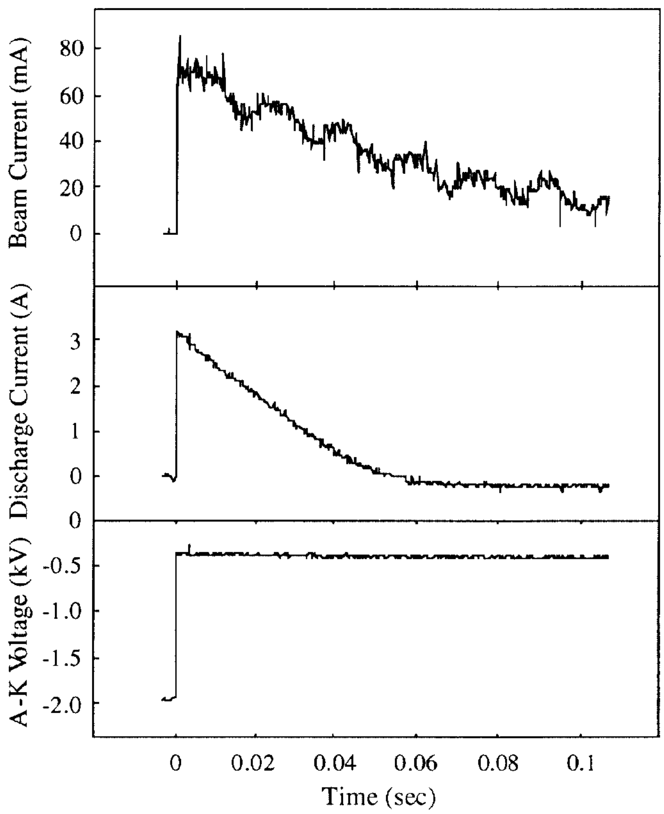

FIG. 3 Electron beam generated with a low-voltage RC discharge circuit (100 μF, 500 Ω). Beam current was measured at 5 cm behind anode.

The discharge current is overdamped with a peak current of ≈ 3 A. With ≈ 800 mTorr H_2 in HCR and ≈ 8 mTorr inside the chamber the self-extracted electron beam has peak current of 75 mA and FWHM pulse-length of 50 msec. The beam current to discharge current ratio is ≈ 2.5%. The cathode voltage drops from an initial applied voltage of -2 kV to ≈ -400 V and remains at that value for the rest of the discharge. This behavior is similar to the familiar "normal glow discharge" between two planar electrodes where the discharge voltage is found to be constant with a wide range of discharge current.[18]

Visual observation of cathode-anode gap through the glass insulator indicates that discharge near the cathode side is confined within a radius about the size of the cathode hole. This fact confirms that electron emission comes solely from the HCR as expected. In this case the cathode hole acts like an electron beam focusing lens which brings the broad-area electron beam from HCR to a much smaller dimension with a compression ratio more than 400. The present geometry presents a simple device which, together with a proper magnetic guiding field, can produce electron beam density on the order of 100 A/cm^2.

D. 100 msec Electron Beam Generation with PFN Discharge

A pulse forming network consisted of four 100-µF capacitors and two 5-H inductors was used to generate electron beam with FWHM ≥ 200 msec with an applied voltage of -2.5 kV. A beam current of 70 mA was measured at 2 cm behind anode with a 2-A discharge current. The self-extraction efficiency was ≈ 3.5%. The beam energy is confirmed with a retarding field measurement to be ≥ 400 eV as indicated from the cathode voltage measurement. Beam currents measured with Faraday cup at various positions indicate a beam divergence half-angle of ≈ 13^o.

A DC operation has also been achieved. An axial magnetic field of ≈ 200 Gauss was used to guide the low-energy electron beam. At 2 cm behind anode the efficiency is ≥ 90%. The beam energy spectrum was measured at 18 cm behind anode. The majority of the electrons have energy ≤ 40 eV. Since electrons with energies more than a few eV play an important role in electron-enhanced chemical reactions on surfaces, it is of interest to apply this BLT DC electron beam in an electron beam assisted atomic layer epitaxy experiment (EBALE) to locally assist the growing processes.[19]

CONCLUSION

In conclusion, we have demonstrated the generation of a long pulse electron beam (from 100 µsec to DC) from a simple device. The self-extracted beam current density is on the order of 10 A/cm^2. The results indicate that the electron beam pulse-length can be controlled through the modification of the external circuit, i.e. the discharge current pulse. Future work will seek to increase the beam current through proper differential pumping, magnetic guiding, and extraction structure. The device is simple, robust and compatible with a plasma environment. Possible applications include electron bean ionized lasers, plasma-based microwave generation where a plasma compatible electron beam source may be preferred, EBIT and EBALE.

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