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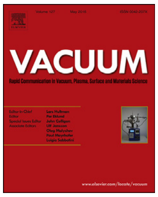

Design and experimental study of Penning discharge plasma anode for high current pulsed electron beam source

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ABSTRACT

The Penning discharge structure was designed to produce plasma anode used in a high current pulsed electron beams source. The cylindrical anode of diameter 80 mm and height 30 mm was powered by a pulse voltage of ~5 kV. The plasma discharge characteristics were investigated by means of oscilloscope, current sensor and digital camera. The results show that the plasma discharge goes through two main stages, a high-voltage, low-current stage and a high current discharge stage. There exists an anode voltage threshold to ignite the high current discharge. With the higher working pressure and magnetic field intensity, the Penning discharge operates more quickly and steadily. The time accuracy can be controlled under ±0.5 μs The peak discharge current increases proportionally with the anode voltage. The HCPEB emissions were realized with the optimized parameters including working pressure 7×10^{-2} Pa, anode voltage 5 kV, magnetic field 2000 Gauss and ballast resistor 200 Ω.

1. Introduction

Recently, the high current pulsed electron beam (HCPEB) technique has been developed rapidly and proven to be a powerful method for surface modification of materials [1–7]. When the incident electron flux of extremely high energy density (~10^7 Wcm^{-2}) transferring into surface layer (10^{-5}–10^{-6} m) of metallic material within a very short period (~several μs), the rapid heating ($10^{9\sim10}$ Ks^{-1}) to melt or even evaporation, thermal dynamic stress impact (~GPa) and self-quenching ($10^{8\sim9}$ Ks^{-1}) processes occur intensively, which give rise to the formation of non-equilibrium surface microstructure accompanied by the modified physical and chemical properties [8–15]. Also, the HCPEB sources of low accelerating voltage (20–30 kV) and large beam diameter (>Φ60 mm) can provide much more convenience for their radiation safety, simple configuration, high efficiency and long lifetime.

Since the first generation of HCPEB facilities originated in Tomsk Institute of High Current Electronic of Russian in the 1990s, the design of electron gun with plasma anode and explosive-emission cathode, i.e. plasma-filled diode structure has been widely adopted [16–18]. When the diode and the beam drift space are preliminarily filled with plasma of density ~10^{12-13} cm^{-3}, the accelerating voltage is localized within a narrow near-cathode layer of ionized space charge and the electric field will be strengthened enormously to a huge value of ~10^{7-8} Vm^{-1}. As a result, the explosive electron emission can be initiated at the cathode surface, leading to the formation of double sheath structure between the cathode and anode plasmas where the electron beam is produced. Thereafter, the plasma present in the drift space helps to transport the high current electron beam over a significant distance (normally 10–20 cm) onto the target surface [19]. It is clear that the plasma anode component plays a vital role for the HCPEB emission and influences the beam diameter, energy uniformity and even safe running of the whole system.

Up to now, there are two methods generally used for the production of plasma anode in HCPEB sources. One is based on the multiple-point discrete plasma sources (vacuum sparks discharge) and another is to realize bulk ionization in the working space (Penning discharge). It was reported that the plasma anode generated by Penning discharge could provide substantial advantages as compared with the vacuum sparks method, including the elimination of erosion contaminations, improvement of uniformity of radial plasma distribution and long transportation distance [16,17].

In this work, the Penning discharge structure was designed and

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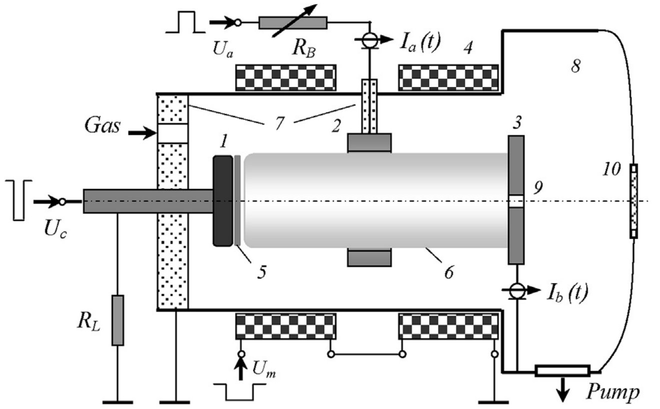

Fig. 1. Schematic diagram of HCPEB source with Penning discharge plasma anode. (1) cathode, (2) anode, (3) collector, (4) solenoid, (5) cathode plasma, (6) anode plasma, (7) insulator, (8) vacuum chamber, (9) observation hole, (10) inspection window, U_c - accelerating voltage, U_a - anode voltage, U_m - magnetic field voltage, $I_a(t)$ - anode current, $I_b(t)$ - collector current, R_B - ballast adjustable resistor, R_L - leakage resistor.

built up on a HCPEB source in our laboratory. The discharge characteristics and phenomena were experimentally studied to obtain the ideal condition of plasma anode. The HCPEB emission was successfully realized with the optimized working parameters.

2. Experimental procedures

The schematic diagram of HCPEB source is shown in Fig. 1. The Penning discharge cathodes are consisted of the graphite cathode and beam collector. The diameter of the graphite cathode is 60 mm. The cylindrical anode is made of 316L stainless steel of inner diameter 80 mm and height 30 mm. The anode is fixed at the centre position between the graphite cathode and collector of distance 70 mm in each side. The sectioned Helmholtz solenoids of diameter 300 mm and 325 loops were utilized to provide magnetic field of strength up to 3000 Gauss. The chamber is evacuated by turbo molecular pump to a base pressure of 7×10^{-3} Pa, then the pure argon gas is inlet through D08-1F flow controller to a stable pressure in the range of $3–9 \times 10^{-2}$ Pa.

At the peak value of magnetic field, the anode was powered by a pulse voltage generator of positive polarity ~5 kV. The anode discharge current was limited through a ballast adjustable resistor ~500 Ω. The anode voltage and discharge current were real-time measured by Tektronix 2024 oscilloscope on a resistive divider and D6-300 A current sensor. The discharge phenomena were recorded by phantom V611 digital camera. For the HCPEB emission, the accelerating voltage of 27 kV was applied on the graphite cathode and the electron beam irradiation was tested with stainless steel plates.

3. Results and discussion

The characteristics of a typical Penning discharge are shown in Fig. 2. After the loading of pulse voltage, the discharge goes through two main stages (Fig. 2a). Firstly, the anode voltage rises up to a setting value and maintains, i.e. high-voltage, low-current stage, there is no visible discharge phenomenon. After a period of time T_a, the intense fluctuations appear in the measurement signals. The anode voltage falls down to several hundreds volts, at the same time, the anode current increases quickly to the maximum value and then descends slowly, i.e. high current discharge stage. At the beginning of high current discharge, numerous small bright spots emerge at the edge of cathode (Fig. 2b). With the increasing anode current, the small bright spots agglomerate and move towards the center region of cathode. When the anode current increases intensively, the plasma discharge develops in the entire working space and emits a glaring lightening (Fig. 2c). With the decrease of anode current, the plasma discharge diminishes and only some dispersed bright spots maintain until extinction (Fig. 2d).

According to our experiments, the pulse voltage applied must exceed a certain high value, i.e. anode voltage threshold, to ignite

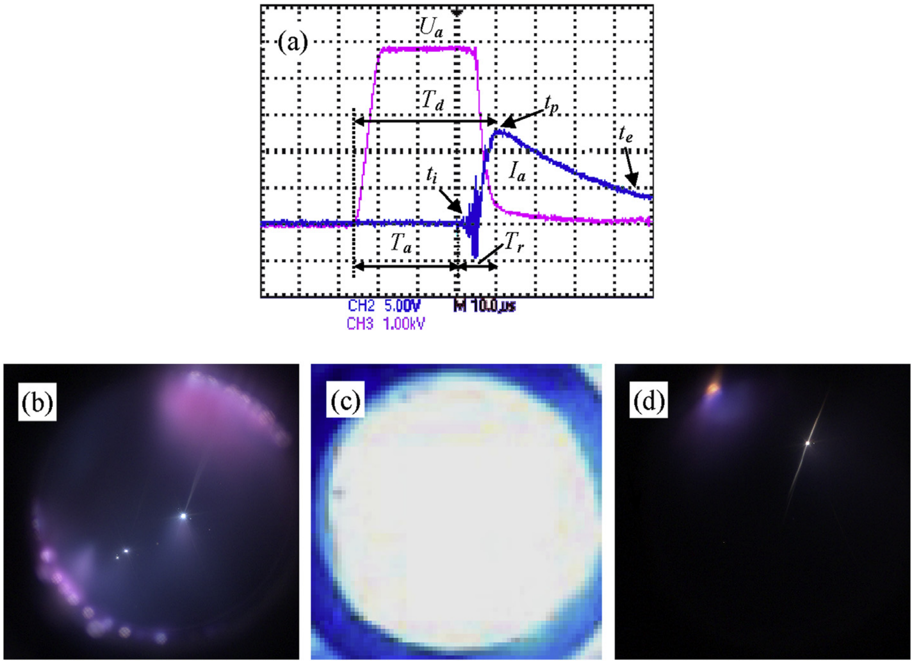

Fig. 2. Oscillograph of a typical Penning discharge process (a), and photographs taken at different moments, (b) t_i, (c) t_p, (d) t_e. U_a - anode voltage, I_a - anode current, T_a - activating time, T_r - rise time of anode current, T_d - delay time of peak current, t_i—ignition moment, t_p—peak current moment, t_e—extinction moment.