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Multi-pulsed intense electron beam emission from velvet, carbon fibers, carbon nano-tubes and dispenser cathodes*

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Abstract The experimental results of studies of four kinds of cathode emitting intense electron beams are demonstrated under multi-pulsed mode based on an experimental setup including two multi-pulse high voltage sources. The tested cathodes include velvet, carbon fibers, carbon nano-tubes (CNTs) and dispenser cathodes. The results indicate that all four are able to emit multi-pulsed beams. For velvet, carbon fiber and CNTs, the electron induced cathode plasma emission may be the main process and this means that there are differences in beam parameters from pulse to pulse. For dispenser cathodes tested in the experiment, although there is a little difference from pulse to pulse for some reason, thermal-electric field emission may be the main process.

Key words multi-pulsed intense emission, cathode plasma, dispenser cathode

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1 Introduction

Cathodes emitting an intense electron beam are widely used in high power microwave (HPM) sources. These cathodes commonly include polymer velvet (velvet), carbon fibers and ferroelectrics. A few researchers have reported their work on velvet and carbon fiber under single pulse mode [1–5]. For velvet and carbon fiber cathodes, there are randomly distributed tips that can emit a uniform electron beam at a low turn-on electric field [1]. As described by Don Shiffler [3], there are two viewpoints on the emission from these cathodes. The first is that cathode plasma is explosively induced and the electron beam is extracted due to applied electric field. The second one is articulated by Miller. According to him, cathode plasma is induced by surface flashover at the cathode surface due to the applied voltage [2]. However, the cathode plasma is generated according to both viewpoints and this is the key. CNT cathodes and thermionic Ba-Wu cathodes can also emit an intense electron beam. CNT cathodes have been a hot research spot in the past twenty years, which has attracted considerable attention for their potential uses in field emission devices due to their nanometer scale, high aspect ratio, good conductance and high chemical stability [6, 7]. CNT cathodes have been used in many kinds of vacuum field emission devices [8], and the highest field emission current of several A·cm^{-2} was observed [9]. Therefore, they could be used to emit an intense electron beam. Thermionic cathodes are widely used in modern high-power microwave tubes. They can significantly improve the performance of the tubes. Because they can provide better reproducibility and lower emittance beams than field emission cathodes do, in recent years thermionic cathodes have also been used to generate intense electron beams, such as the device in USA, the Dual-Axis Radiograph Hydrodynamic Test (DARHT Ⅱ) in Los Alamos National Laboratory [10], which uses a dispenser cathode to generate an intense electron beam.

With the development of HPM, multi-pulsed elec-

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tron beams (MPEB) are needed to generate multi-pulsed HPM. In the MPEB mode, cathodes emit a bunch of pulsed beams with a pulse interval of less than 1000 ns and this is a little different from that of single pulse mode. In the past few years, cathodes such as velvet, carbon fiber, CNTs and dispenser cathodes have been studied under MPEB mode by our research group [11–14]. In this paper, we would like to demonstrate the work on their emission characteristics under MPEB mode.

2 Experimental setup

The experimental setup includes two pulsed power systems. Each involves a vacuum diode, a multi-pulsed power source and a beam line which is equipped with diagnostic devices. One of the two pulsed power systems can produce four pulses in a bunch (four pulse mode, FPM) and the other one can produce double pulses in a bunch (double pulse mode, DPM). While under FPM, the pulsed voltages applied on the vacuum diode are about 500 kV. And under DPM, the voltages are about 1750 kV. The pulsed beams emitted from the cathode in the test are confined by an external magnetic field and transmitted along the beam line. The beams' characteristics such as their spot size and emittance were experimentally studied in time resolved mode. The resistive wall monitors, known as beam bugs [15], were used to detect the beam current, and Cerenkov radiation generated by the interaction of the electron beam and a quartz plate was used to get the information of the beam's profile and emittance. The radiation was recorded by an 8 film streak camera through a view port. Beam bugs are placed at 3.6 m downstream from the cathode. The pepper pot used to measure the emittance is placed 3.9 m downstream and the quartz plate is placed 4.1 m downstream (refer to Fig. 1).

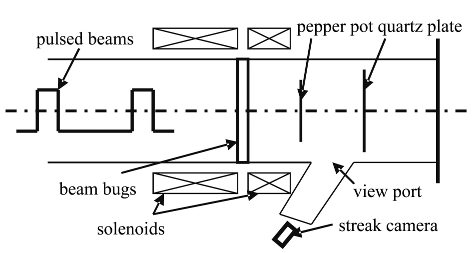

Fig. 1. A sketch of the beam line including a diagnostics system.

3 Velvet's multi-pulsed emission

As a kind of low cost and readily available cathode, velvet can emit an intense electron beam with brightness up to 10^8A/(m·rad)^2 and is widely used in the high pulsed power research field. So the device such as DARHT-Ⅰ [16] uses velvet to produce a few kilo-ampere pulsed electron beam with a pulse duration of around 100 ns. Some papers [2, 3] have demonstrated velvet's emission characteristics under single-pulsed mode. Under this mode, cathode plasma is formed while the cathode is emitting and it affects the diode vacuum little because of a very short period (usually less than 100 ns). However, under the MPEB process, the cathode plasma could seriously affect the vacuum diode. For answering the following questions can the cathode work under MPEB process? How about the beam quality? Does the cathode plasma affect the qualities of beams emitted from the cathode? Some work under the MPEB process has been done and the experimental results on velvet under FPM and DPM have been demonstrated.

As mentioned by Don Shiffler [3], especially after the cathode plasma is formed, the vacuum diode works under a space-charge limited situation. So, when the cathode plasma moves to the anode and the diode effective gap distance changes, many more pulsed beams are extracted from the cathode plasma in the later produced pulse. Fig. 2 shows the electron emission process of velvet with the emitting radius of 3.5 cm under FPM. The beam current is 1680, 1860, 2400 and 2640 A under the diode voltage of 490, 480, 454 and 440 kV, respectively. The geometrical diode gap is 95 mm.

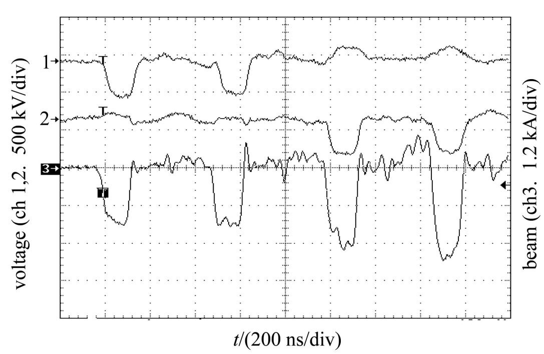

Fig. 2. The velvet's intense emission under FPM. Ch 1 is the first and the second diode voltage pulse, and ch 2 is the third and the fourth. Ch 3 is the electron beams.

It is assumed that the difference in beam amplitudes may be dependent on the velocity of the cathode plasma and the original diode gap. If the cathode plasma velocity is slow enough and the diode gap distance is long enough, the difference in the beams amplitudes may be small. Slow cathode plasma velocity means little change in the effective gap at the same time process, and the long gap means relatively little change at the same plasma velocity and the same time process.

Another experiment was conducted to verify this viewpoint. In the experiment, the setup works under DPM, the pulsed diode voltages are 1750 and 1780 kV, respectively, and the gap is 185 mm. Fig. 3 is the double pulsed beams detected by the beam bugs. The beams are 1020 and 1050 A.

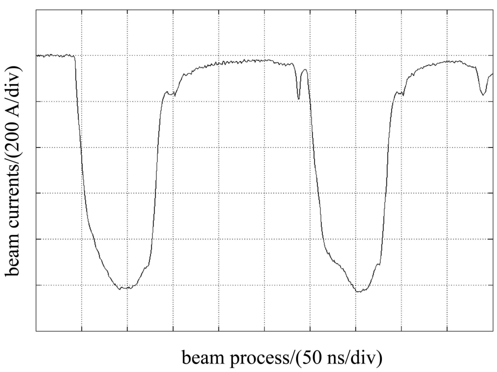

Fig. 3. The velvet's intense emission under DPM. The pulsed diode voltages are 1750 and 1780 kV. The beams are 1020 and 1050 A, respectively.

The beams' spot sizes and emittances were checked by Cerenkov radiation generated by the beam interaction with quartz in DPM. For checking the beam spot size, the pepper pot in the beam line was removed and the quartz plate was kept (Ref. to Fig. 1). The radiation was recorded by the streak camera. When the beams interacted with the quartz plate, Fig. 4 gives the time resolved beam spots for the first and the second beam. The diameters (FWHM) are about 20 mm. According to Fig. 4, one can conclude that the two beams have almost the same diameters at the same detecting position. This means that they have the same envelope at the same magnetic field.

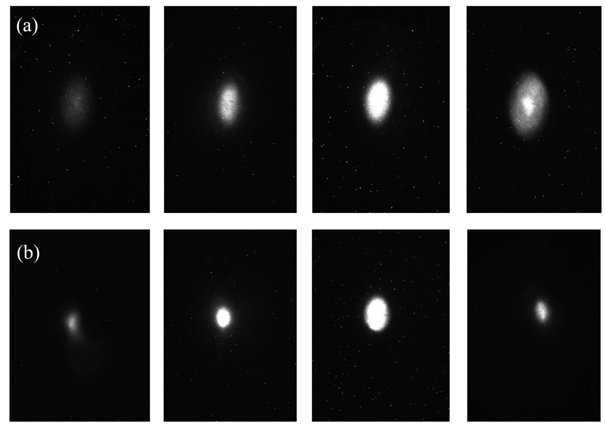

Fig. 4. The first (a) and the second (b) beam spots with the same magnetic field under DPM, 10 ns/frame.

While checking the beams' emittance, the pepper pot was kept in the beam line. In the experiment, Cerenkov radiation generated by beamlets interacting with quartz is used to determine the beams′ transverse velocity. The radiation was recorded by the streak camera, too. Fig. 5 is the time resolved emittance for the first pulse in 70 ns (a), and for the second one (b). From Fig. 5, one can conclude that the doubled beams have similar emittance of around 1400 πmm·mrad.

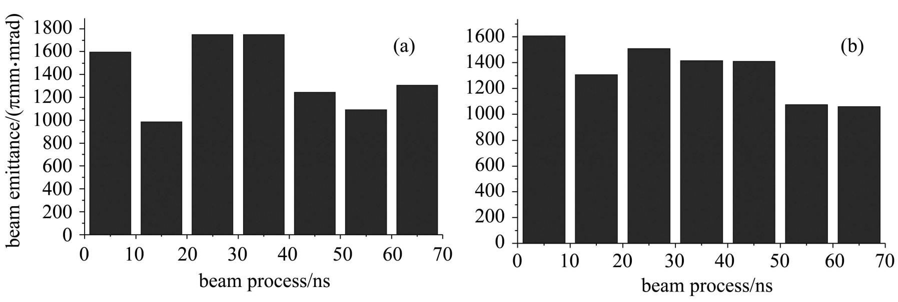

Fig. 5. The first (a) and the second (b) beam's time resolved emittance.

According to the results of the velvet cathode plasma induced emission under FPM and DPM, one can conclude that although there is a great difference in the beams' amplitude under FPM, the beams' amplitude, spot and emittance are similar under DPM. This means that with a larger diode gap and low emission density it is possible to minimize the effect of the cathode plasma's movement on the beams' parameters, such as amplitude, spot size and, more important, emittance.

4 Carbon fiber's multi-pulsed emission

Different from velvet, carbon fiber is conductive.

It does not need to form a cathode plasma to emit an electron beam. However, it is also difficult to be free from plasma in intense electron emission process. Air molecules attached to the fiber surface are released into the vacuum and ionized by the electrons, and thus plasma forms. We once observed surface flashover along a bunch of fibers while applying a DC high voltage to a bunch of fibers. After improving the vacuum and keeping the flashover for a few minutes, the flashover disappeared and the field emission was enhanced [17]. Fig. 6 is a photo of the cathode's plasma emission under FPM. The fibers' intense multi-pulsed emission process is very similar to that of velvet (refer to Fig. 2) with a much lower turn-on electric field than that of velvet.

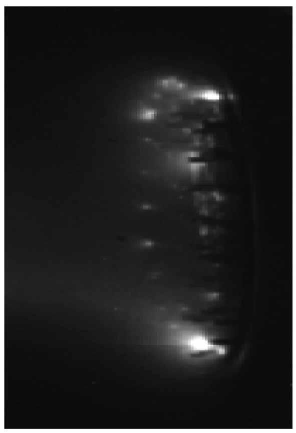

Fig. 6. The cathode during multi-pulse intense emission.

5 CNTs multi-pulsed emission

The emission characteristics were tested under DPM. The diameter of the tested CNTs cathode is 2. The CNTs were fixed to a conductive silicon slice by a thermal chemical vapor deposition (CVD) method [8, 9]. The silicon slice was fixed on a round disk. The experimental results show that CNTs are not good at intense electric field emission, although they have good prospects in field emission. When the first pulsed voltage was applied on the diode, the CNTs emitted a less than 1 kA electron beam (refer to Fig. 7). While the second pulsed voltage was applied to the diode, a more than 5 kA electron beam was derived from the cathode. The results shown in Fig. 7 are quite different from those shown in Fig. 2 and Fig. 3. A possible explanation is as follows. While in the process of the first emission of the CNTs, there are not enough free electrons and the diode worked in the source limited situation and the cathode plasma is induced and enhanced; while in the process of the second emission, the cathode plasma provides enough free electrons and more electrons can be extracted from the plasma. This also means that the cathode plasma moves to the anode and has changed the diode effective gap. Compared with the multi-pulse emission of velvet and carbon fibers, the cathode plasma plays a more important role in the process of CNTs′ intense electron emission.

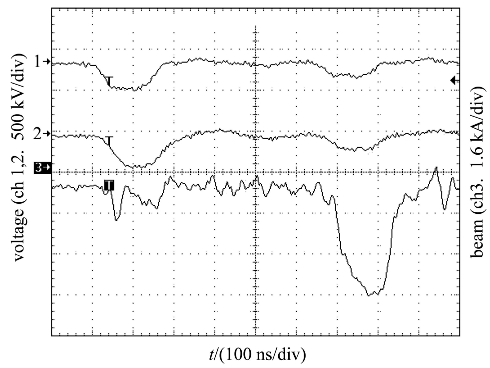

Fig. 7. The waveform of diode voltage (ch 1, 2) and emission beams (ch 3).

6 Dispenser cathode

The dispenser cathode is 100 mm in diameter. It was expected to emit a more than 1 kA electron beam. The cathode was fixed in a cathode shroud supported by three ceramic-metal columns, which were specially designed and fabricated for electric insulation. The electron beam emission from the cathode was collected by a Faraday cup attached to the anode. A piece of Wu was used as a collector of the cup to avoid gas leakage. In single pulse mode, Fig. 8 shows the pulsed voltage applied on the vacuum diode and the electron beam pulse measured by the Faraday cup (ch 3). A more than 1 kA electron beam was recorded at the cathode temperature of 1140 ℃.

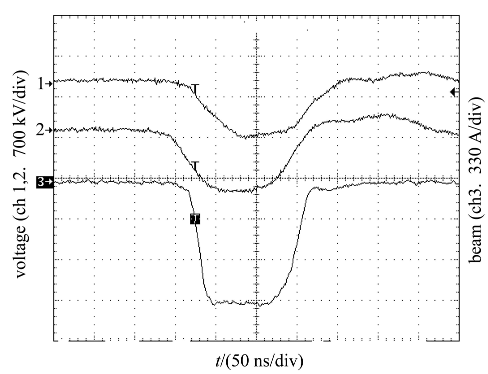

Fig. 8. The waveform of the electron beam (ch 3).

The cathode's I-V curve and I-T curve were also measured and are given in Fig. 9. From Fig. 9(a), one can see that the cathode still works in the space charge limited situation. Fig. 9(b) shows the *I-T* curve under a diode voltage of 1.95 MV. One can see that the diode works in a space-limited situation only when the cathode temperature is higher than 1050 ℃. Below that, the diode works in a temperature (or source) limited situation.

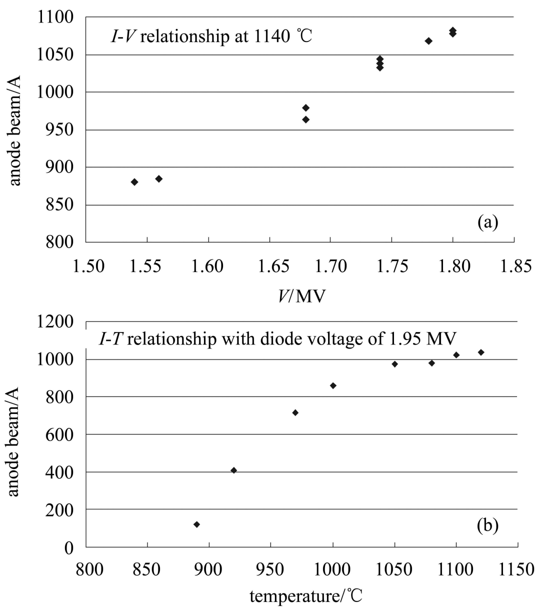

Fig. 9. *I-V* relation of the cathode (a) and *I-T* relation of the cathode (b).

With the same experimental conditions of the cathode and its temperature, diode gap and electron collector, we made the cathode emission in the double pulsed mode. The beams collected by the cup are 282 A under a diode voltage of about 850 kV (refer to Fig. 10). The data indicate that the diode is operated in the space charge limited situation. According to Fig. 10, there is somehow a small electron loss while the second beam is emitted.

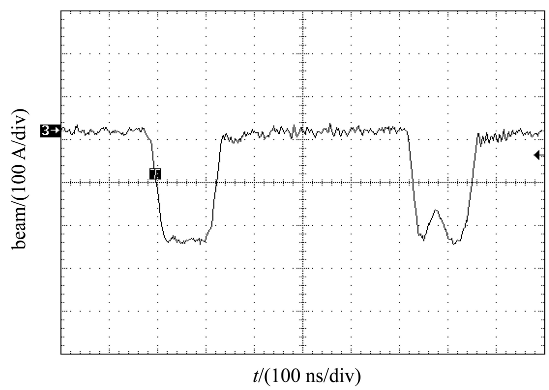

Fig. 10. The waveform of double pulsed beams emitted from the dispenser cathode.

7 Discussions

For field emission cathodes, such as velvet, carbon fiber and CNT, a cathode plasma is inevitable and plays a key role in the process of the cathode's intense emission. Without a cathode plasma, it is impossible to extract a space charge limited beam. When these cathodes emit intense electron beams in multi-pulsed mode, although a low emission density and a large diode gap could alleviate the difference, there still is some difference in beam parameters from pulse to pulse. A thermionic cathode may be a solution to be free from a cathode plasma, although there is a little difference from pulse to pulse in the experiments for some reason.

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