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Velvet's multi-pulsed emission and multi-pulsed electron beams*

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The velvet electron emission characteristics and beams' brightness are investigated with a multi-pulsed mode. The results indicate that in the multi-pulsed mode the velvet emission is not uniform and the periphery emission is much stronger than that from the centre. The periphery emission contributes much more to the formation of the cathode plasma than the centre emission, which leads to diode impendence breakdown. The relationship between the cathode plasma expansion and the initial emittance of the cathode is deduced to describe the characteristics of the multi-pulsed vacuum diode. The emittance of the multi-pulsed beams is measured to be less than 1000mm·mrad. The brightness of the electron beams is better than 1×10^8A/(m·rad)^2.

Keywords: velvet, multi-pulsed diode, cathode plasma, brightness
PACC: 2925B, 4180D, 5260, 5275P

1. Introduction

As a kind of excellent emitter, velvet can emit high current electron beam with a brightness being up to 10^8A/(m·rad)^2. So devices such as ARIX[1] and DARHT-I[2] use the velvet as a high current electron cathode to produce a few kilo-ampere pulsed beam. The beam pulse duration is around 100ns. The pulsed electron beam is extracted via a vacuum diode. Some papers[3,4] have described its emission characteristics in a single-pulsed mode. However, as the velvet emission results from a strong electric field (as high as 100kV/cm), the plasma inevitably appears around the cathode in the vacuum diode, and changes the diode gap physically. In a single short-pulsed mode, the plasma's effect due to the change of the diode gap is not significant, but in a multi-pulsed mode, it is another story. In order to investigate the velvet's emission characteristics and multi-pulsed vacuum diode physics, a multi-pulsed device is built, which can operate in a two- or four-pulsed mode.[5,6] The vacuum diode voltage can be raised up to 1MV for the two-pulsed mode and 500kV for the four-pulsed mode.

2. Multi-pulsed emission

In a single-pulsed mode, velvet's emission is quite uniform.[4] The space is "clean" and no plasma exists in the diode region before a high pulsed voltage is applied to the diode. Once a pulsed voltage is applied to the diode, the field emission shortly takes place uniformly and a thin surface plasma layer is formed. As the beam process lasts less than 100ns and the cathode plasma movement is at a speed of less than 4×10^4m/s,[3] the plasma layer changes little and there appears little effect on the beam process. An electron beam is extracted from the plasma layer and accelerated by the electric field and moves into the anode hole finally.

In a multi-pulsed mode, velvet's emission is not uniform but rather random. The first beam is extracted which is the same as that in a single-pulsed mode. After the first beam process, plasma still remains near the velvet cathode. Although the plasma layer is very thin, it is very dense. At the same time, the next pulse voltage is applied to the diode in a few hundred nano-seconds, the plasma cannot recover completely and the vacuum system cannot clean the plasma in the diode region in such a short time either. So when the second pulsed voltage is applied to the

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diode, there appear some ions, which can change the electric field distribution. The distorted field changes the second beam's extraction process. First, the effective gap of the diode is changed. Second, the electric field near the cathode surface is not uniform, which leads to a non-uniform emission. After the second beam process, there exist many more ions in the diode region, and the third beam emission process is affected more seriously. Figure 1 gives the waveforms of the diode voltages and the emission currents (the left is for the two-pulsed mode; the right is for the four-pulsed mode).

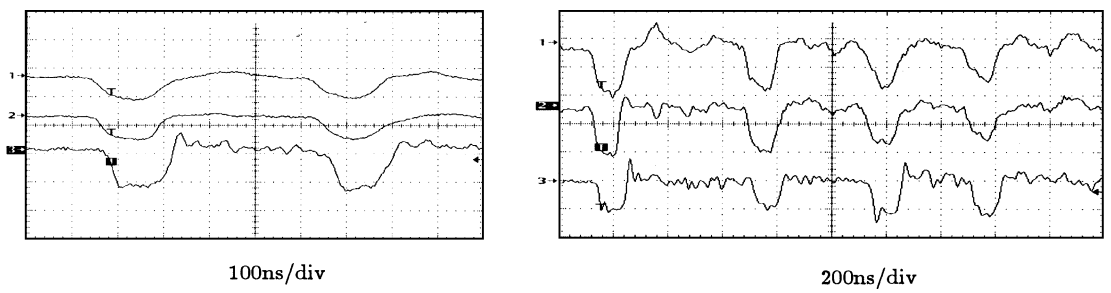


Fig.1. The diode voltages and emitting currents. Left, Channel 1: emitting beam current 1.64kA/div, Channels 2,3: diode voltages, 500kV/div; right, Channel 3: emitting beam current 0.82kA/div, Channels 1,2 diode voltages, 250kV/div.

The cathode has a diameter of 70mm, and is in contact with a copper base through conductible glue. The experiment indicated[7] that some intensified emission points appeared on the cathode surface and they were not stable. In the experiment, an interesting phenomenon was also found that the periphery of emitter was always brightest and the periphery emission was much stronger than that from the centre, which is in accord with the observation of Saveliev *et al.*[8] The periphery emission contributes more plasma than the centre emission. By diminishing the diode gap, the periphery becomes more and more bright (see Fig.2). The part of plasma however may contribute little to the effective electron emission but leads to a diode impendence breakdown.

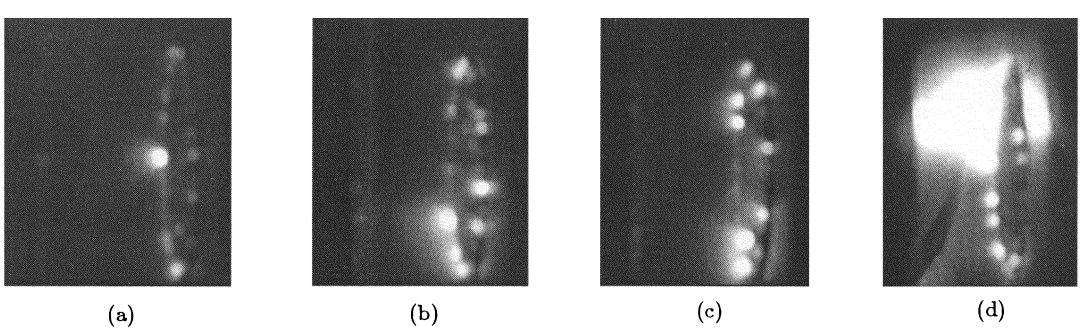


Fig.2. Plasma distribution on the cathode with different gap distances. The gap distances are 66mm for (a), 61mm for (b), 56mm for (c) and 51mm for (d), and the diode pulsed voltage is 300kV.

3. Plasma movement

Under the condition of weak ionized plasma and no effect of magnetic field, the plasma's explosion velocity is determined by the electric field, the density gradient and the temperature gradient. As discussed in Section 2, before the electron beam is extracted, the cathode plasma forms and moves forward. It is difficult to describe ions' velocity because the velocity distribution is different for different ions. The same ions' velocity can be also determined by ions' space density distribution. In order to simplify the process, a conception of effective velocity is introduced.

The Child's equation about I-V relation of vacuum diode in the space charge limitation is described as follows:[9]

$$P_i = \frac{I_{\mathrm{e,i}}}{V_{\mathrm{d,i}}^{3/2}} = \frac{4\varepsilon_0}{9}\left(\frac{2e}{m_{\mathrm{e}}}\right)^{1/2}\left(\frac{\pi r_{\mathrm{eff,i}}^2}{d_{\mathrm{eff,i}}^2}\right), \qquad (1)$$

where $P_{\rm i}$ is the diode perveance, $I_{\rm e,i}$ is the diode current, $V_{\rm d,i}$ is the diode voltage, $m_{\rm e}$ is the electron mass, $d_{\rm eff,i}$ is the effective gap distance of the diode, and $r_{\rm eff,i}$ is the effective radius of the anode.

When the first beam is emitted, plasma is formed and moves forward and changes the effective gap of the diode by

$$d_{\rm eff,2} = d_1 - v_{\rm c,1}t, \qquad (2)$$

where d_1 is the original diode gap, t is the pulse-to-pulse time separation and $\nu_{\rm c,i}$ is the effective velocity. $I_{\rm e,i}$ and $V_{\rm d,i}$ can be measured by detectors, so $P_{\rm i}$ is a known parameter from Eq.(1). With d_1, $I_{\rm e,1}$ and $V_{\rm d,1}$ fixed, we can obtain P_1 and $r_{\rm eff,1}$. P_1, $I_{\rm e,1}$, $V_{\rm d,1}$, and $r_{\rm eff1}$ are the perveance, the emission beam current, the diode voltage and the effective anode radius for the first pulse respectively.

Assuming $r_{\rm eff,1}$ to be unchanged during the second pulse emission, with Eq.(1), $I_{\rm e,2}$, and $V_{\rm d,2}$, we can obtain $d_{\rm eff,2}$ and P_2. Also according to Eq.(2), we can acquire $\nu_{\rm c,1}$. Using the same process, we can have P_3, P_4, $\nu_{\rm c,2}$, $\nu_{\rm c,3}$ and $P_{\rm av}$, $\nu_{\rm av}$. $P_{\rm av}$ and $\nu_{\rm av}$ are the average of $P_{\rm i}$ and $\nu_{\rm c,i}$ respectively.

Based on the hypothesis and the process, a series of experiments is conducted. Some statements can be made from the experiments. Under different diode conditions, the explosion velocities are between 10^4m/s$\sim 4\times10^4$m/s. When the diode distance is varied, the extracted beams' current is changed. Since a large beam current implies a larger emission density existing, one can expect a larger explosion velocity to appear in the case of a higher beams' current. However, no clear evidence can prove that. From Fig.3(a), one can see that at the same diode distance, average velocities become large as the average perveance increases, which means that if one expects the explosion velocity to be less than 10^4m/s, the vacuum diode is required to have low perveance. The explosion velocities between the first and the second pulses are less than those between the second and the third pulses. Half of the points in Fig.3(b) are in the range 0 to 10^4m/s, and most points in Fig.3(c) are in the 2×10^4m/s-to-4×10^4m/s range. So we can expect the second pulsed beam to be more similar to the first beam than to the third one.

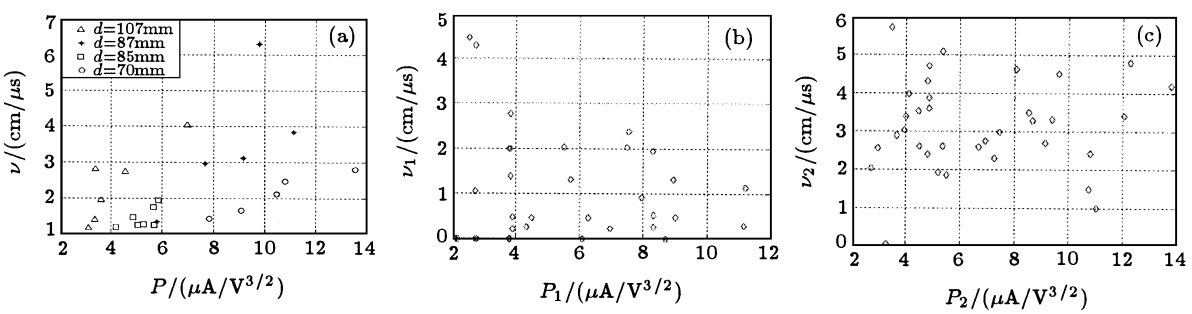


Fig.3. Relationships between average P and average ν (a), P_1 and ν_1 (b), and P_2 and ν_2 (c).

4. Multi-pulsed diode physics

There exist two equations to describe electrons' movement in a vacuum diode. They are Lorentz equation and Vlasov equation. To simplify the process, the Lorentz equation is used here:

$$\boldsymbol{F} = \frac{{\rm d}\boldsymbol{p}}{{\rm d}t} = \frac{{\rm d}(\gamma m_{\rm e}\boldsymbol{\nu})}{{\rm d}t} = e(\boldsymbol{E} + \boldsymbol{\nu}\times\boldsymbol{B}), \qquad (3)$$

where $\boldsymbol{E}$ and $\boldsymbol{B}$ are determined by Maxwell equations and boundary conditions. As discussed above, in the multi-pulsed mode, the effect of cathode plasma cannot be neglected. The plasma can change the diode characteristics by changing emission current, electron energy and beams' emittance.

The cathode's emission current density is determined by Eq.(4),[9]

$$j_{\rm e} \approx \left[\frac{2\varepsilon_0 m_{\rm e}c^3}{ed_{\rm eff}^2}\right]\left[\left(1+\frac{eV_{\rm d,eff}}{m_{\rm e}c^2}\right)^{\frac{1}{2}} - 0.8471\right]^2, \qquad (4)$$

where $d_{\rm eff}$ is determined by Eq.2, and $V_{\rm d,eff}$ is determined by Eq.(5),

$$V_{\rm d,eff} = V_0 - I_{\rm e}Z_0. \qquad (5)$$

Here V_0 is the voltage of power source without load, $I_{\rm e}$ is the emission current, and Z_0 is the interior impedance of the power source.

The electron energy E is determined by the effective voltage of vacuum diode. Different emission

currents I_e correspond to different effective diode voltages:

$$E = e\left(V_0 - I_e Z_0\right). \tag{6}$$

If the neighbour emission currents are $I_{e,i}$ and $I_{e,i+1}$, the difference in the electron energy between the two beams is described as Eq.(7),

$$\Delta E = eZ_0\left(I_{e,i+1} - I_{e,i}\right). \tag{7}$$

In order to achieve a higher brightness beam, a Brillouin design is usually used in a vacuum diode. The change in the effective diode gap implies that the magnetic field is not zero for the second pulse and the rest. When the magnetic field on the emission surface is B_s, the beam's normalized emittance ε_n is determined by Eq.(8),

$$\varepsilon_n = \varepsilon_{T,n} + \varepsilon_s = r_c\left(\frac{kT}{m_e c^2}\right)^{\frac{1}{2}} + \frac{eB_s r_c^2}{2m_e c}, \tag{8}$$

where r_c is the radius of the cathode. The above equation includes two parts. The first part is determined by the cathode's temperature T, and the second part is determined by the magnetic field B_s.

Equations (2), (3), (4), (5), (6), (8) and Maxwell equations are combined together to describe a multi-pulsed diode with the cathode plasma movement taken into account.

5. Multi-pulsed beams' emittance and brightness

In order to check the multi-pulsed beams' brightness, a pepper pot device[10] and a beam bug[11] are used respectively to measure the beam's emittance and the beam's current. A CCD camera is employed to record the light information.

For the two-pulsed mode, Fig.4 shows a CCD photo (a) and the information of angles (b) and beam envelope radius (c) deduced from the CCD photo. The first diode voltage is 589kV, and the second one is 570kV. Correspondingly the beam currents measured by the beam bug are 374A and 390A. The beam's envelope radius is 32.5mm, and beam's angle is 1.63mrad. Take the diode voltage amplitude as 600kV, then γ will be about 2.17 and β about 0.888. So we can obtain the beams' normalized integral emittance of 102mm·mrad, and the normalized integral brightness of 4.14×10^8A/(m·rad)^2.

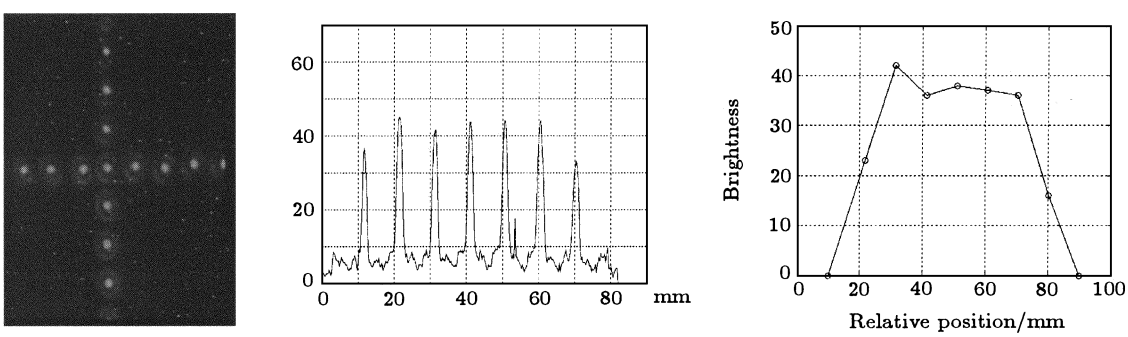


Fig.4. CCD photo of pepper pot, beam's angle and envelope for a two-pulsed mode.

6. Conclusion

Velvet is one of the best options to generate high intensive electron beams. In a multi-pulsed mode, its emission is not uniform and cathode plasma explosion velocity is less than 4×10^4m/s which is determined by the electric field, the density gradient and the temperature gradient. The multi-pulsed diode works in a process much more complicated than that of a single-pulsed mode. However, the brightness of electron beams in a two-pulsed mode is up to 4.14×10^8A/(m·rad)^2. Using velvet as a cathode, high brightness beams can be expected in a multi-pulsed mode.

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