Time-and-space resolved measurements of the emission uniformity of carbon fibre cathode in high-current pulsed discharge*

Liu Lie(刘 列)†, Li Li-Min(李立民), Xu Qi-Fu(徐启福), Cheng Guo-Xin(程国新), and Chang Lei(苌 磊)

College of Photoelectric Science and Engineering, National University of Defense Technology, Changsha 410073, *China*

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The remaining challenges, confronting high-power microwave (HPM) sources and pulsed power generators, stimulate the developments of robust relativistic electron beam sources. This paper presents a carbon fibre cathode which is tested in a single pulsed power generator. The distribution and the development of cathode plasma are observed by time-and-space resolved diagnostics, and the uniformity of electron beam density is checked by taking x-ray images. A quasistationary behaviour of cathode plasma expansion is observed. It is found that the uniformity of the extracted electron beam is satisfactory in spite of individual plasma jets on the cathode surface. These results show that carbon fibre cathodes can provide a positive prospect for developing a high-quality electron beam.

Keywords: cold cathode, emission uniformity, x rays, time-and-space resolved measurement

PACC: 2925B, 4180D, 5250D, 5270K

1. Introduction

There is continuous interest in a pulsed high-current electron beam with current amplitude of a few tens of kA (current density of kA/cm^2 levels), electron energy of several hundreds of keV, and pulse duration of less than μs.[1−5] The high-current electron beam is mainly utilized for high-power microwave (HPM) tubes, pumping gaseous lasers, the modification of solid surfaces, and otherwise.[6−9] Unfortunately, field emission or thermionic cathodes, although they are employed extensively for electron emission, are unable to meet such technological requirements.[10,11] However, it is entirely possible to use explosive emission cathodes at a strong accelerating electric field exceeding 100 kV/cm. Explosive emission cathodes have advantages in that they emit electrons without requiring any cathode heater for operation, so they are called cold cathode. Explosive emission cathodes can cause a large amount of outgassing, which loads the diode vacuum system and results in the shutdown of the diode and high emittance.[12−14]

It is generally accepted that the efficiency of converting the electron beam energy to the microwave field is to some extent determined by the quality of the intense electron beam extracted from explosive emission cathodes.[15,16] In the majority of electron beam applications, one of the main requirements for electron beam quality is its uniformity or low divergence.[17] The general idea of how explosive emission cathodes operate is that plasma is rapidly formed, thereby providing an electron emission sea.[18−20] Therefore, the electron beam extraction is under the influence of the uniformity of cathode plasma covering on the cathode surface. Thus the uniformity of the electron beam mainly relies upon the properties of electron emission sources.

At present, several materials have been used as a cold cathode explosive emitter in a variety of cathode configurations. These cathodes are made of metal, velvet fabric, and carbon fibre.[21−26] In particular, the explosive electron emission from velvet cathodes is initiated by a surface flashover mechanism.[19] Additionally, carbon fibre is considered to be one of the best materials for manufacturing explosive emission cathodes because of its ability to generate highly uniform plasma across a large area at a plasma expansion rate of less than 1 cm/μs which is the lowest among the plasma expansion rates available.[27−29] Carbon fibre can be alternative to polymer velvet due to the absence of organic components in this cathode material and long lifetime ($> 10^6$ shots).[30] Notably, the surface flashover participates in the electron emission

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†Corresponding author. E-mail: fmin.lee@gmail.com

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process of carbon fibres, thereby resulting in impure explosive electron emissions. However, the physical mechanisms governing the electron emission (field or explosive emission, or flashover plasma) from the carbon fibre cathodes are still questionable.

In the present paper, to begin with, we discuss the experimental configuration involving the types of cathodes used in experiment and the diagnostics for evaluating these cathodes. The experimental results include the electron beam uniformity and the characterization of the plasma on these cathodes, and they are obtained by time-and-space-resolved diagnostics. Finally, we conclude this paper with a discussion of the results and the future research.

2. Experimental setup

The experimental setup is shown in Fig. 1. We investigate a cathode made of carbon fibres. This cathode had an emitting surface area of 28.3 cm^2. We also tested a cathode design based on carbon fibre emitters. Each emitter represented a bundle of carbon fibres with the total number of ∼1000. Each fibre bundle had a length of 5 mm and a diametre of 1.5 mm. The emitters were fixed to the aluminum plate and interspaced with 5 mm between two neighbouring emitters. This design was also fixed inside the same screening ring.

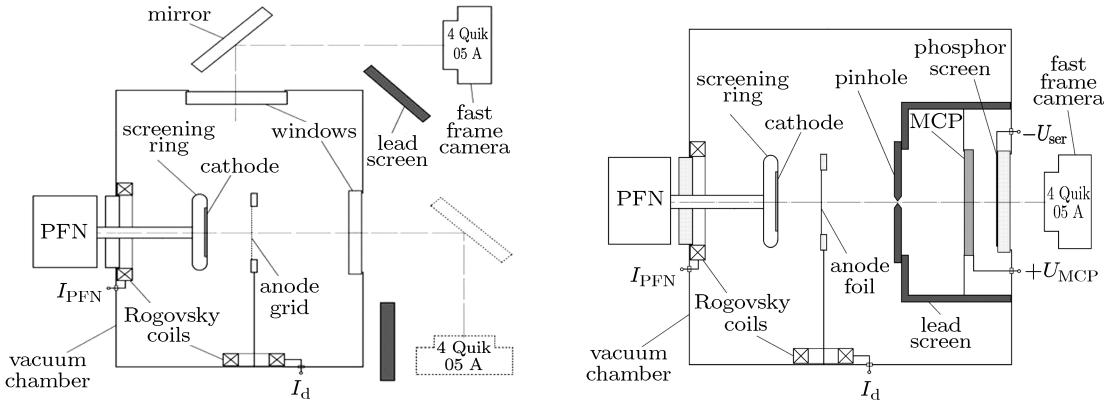


Fig. 1. Experimental setup for the measurements of emission uniformity (a) and beam quality (b).

The cathodes were placed at different distances of 20–60 mm from the anode. The anode had a diameter of 160 mm and was made of a stainless steel disk or a stainless steel mesh having a transparency of ∼50%. The measurement of the anode mesh transparency was performed by using a cylindrical (∼160 mm diameter) low-inductance Faraday cup (FC) having a resistance of 0.047 Ω. This FC was placed at a distance of 1 cm from the anode mesh. It was shown that the amplitude of the electron current detected by the FC was approximately equal to the amplitude of the anode current and that the sum of these currents was equal to the cathode current.

The electron diode was powered by a high-voltage (HV) pulse generator. The HV generator consists of 12 stages of pulse forming network (PFN) generators connected in the Marx scheme. Each PFN generator consists of six stages, each with two capacitors connected in parallel and a 1.5 μH inductance. The impedance of each PFN generator is 7 Ω which corresponds to an impedance of 84 Ω for the whole HV generator. The duration of the output voltage pulse is 250 ns. We used a bipolar scheme to charge the PFN generators (< 45 kV).

In order to obtain an output voltage pulse with 250 ns duration, all the PFN generators should be required to simultaneously discharge. Therefore we used six gas spark-gap switches that were placed in a common tube and triggered by a Maxwell trigger generator. By adjusting the pressure and the flow of dry air inside the tube, the generator could be operated for more than 4 h with a repetition rate up to 5 Hz and time jitter of less than 10 ns.

The diode voltage and current were measured by

an active voltage divider and two self-integrated Rogowski coils (RCs) (see Fig. 1(a)). The use of two RCs allowed us to account for possible electron losses in the cathode holder. A fast framing camera 4Quik05A (frames > 0.2 ns) was used to observe the light emission from the cathode and anode surfaces. To protect the framing camera from being influenced by the x-ray flux, we placed the camera behind a lead wall and used a mirror (see Fig. 1(b)). We believe that the observed light was irradiated by the plasma. By changing the time delay between the beginning of the gating pulse of the camera and the start of the accelerating pulse, we obtained a set of framing photographs of the emitted light. The photography of the plasma light emission was taken from both front and side views which allowed us to follow the development of the surface plasma and its propagation inside the diode gap with temporal and spatial resolutions. The uniformity of the electron beam was checked by the x-ray imaging of the anode. In order to increase the x-ray output, we used a Ta foil anode with a thickness of 125 μm. To obtain x-ray images with time resolution we used a Pb-made pinhole (1 mm diameter, 8 mm thickness) which was placed at a distance of 34 cm behind the anode. A gated multichannel plate (MCP) with a gating pulse duration of 40 ns and a phosphor screen behind it, was placed at a distance of 15 cm from the pinhole in a Pb-made cylinder which protected the MCP from being influenced by the background x-ray flux. The image produced on the phosphor screen was detected by the 4Quik05A camera. We determined the space resolution of the pinhole to be 63 mm. Experiments were performed in a vacuum of $(2.5\text{–}5)\times10^{-3}$ Pa which was maintained by a diffusion pump. The vacuum deterioration was checked by a conventional inverse magnetron gauge.

3. Results and analysis

Figure 2 presents the typical waveforms of the diode voltage and the cathode current for the carbon fibre cathode. In Fig. 3(a) we observe that light emission is not uniform over the whole cathode surface, or rather, it appears as many individual bright spots in the case of the carbon fibre cathode with the screening ring. In the case of the 30 mm gap, the light emission from the cathode without the screening ring mainly distributed at the cathode edge, resulting in the emission pattern similar to an annular cathode as shown in Fig. 3(b). Then the electron beam may be a hollow electron beam, certainly causing the degradation of electron beam. In particular, there also existed strong light emission from the inside of the carbon fibre cathode, rather than only from the cathode perimeter. Namely, in the case of the carbon fibre cathode with the screening ring, the light emission is more uniform over the whole cathode surface than that without the screening ring. Independent of the cathode materials and the external electric field, brighter emission centres on the perimeter of cathodes always appeared as a result of the edge effect.

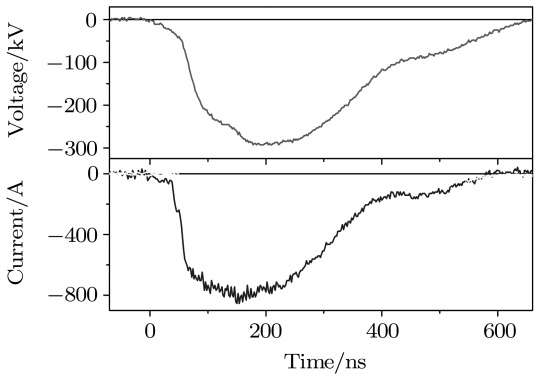


Fig. 2. Typical waveforms of diode voltage and current at a diode gap of 30 mm.

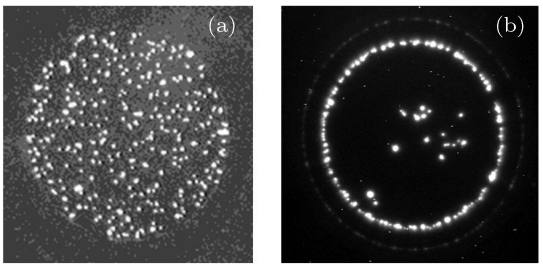


Fig. 3. Front images of light emission for carbon fibre cathodes with (a) and without (b) screening ring.

The electron emission cross-sectional uniformity is an important characteristic of any electron beam source. Figure 4 shows the front images of the light emission from the carbon fibre cathode which were observed at several values of $\tau_{\rm d}$ with respect to the beginning of the accelerating pulse. Framing images from the carbon fibre cathode show the appearance of bright spots from the individual emitters. Here the diode gap is 30 mm. One can see that the distribution of bright spots is random on the cathode surface. Further, the number and the brightness of light spots on the surface increased as the pulse proceeded. Most notably, the larger and brighter light spots always appeared along the periphery of the cathode surface, mainly due to the edge effect.

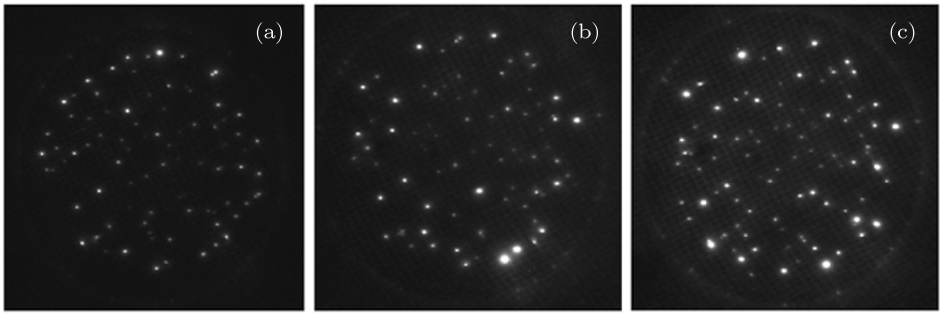


Fig. 4. Front images of the light emission from the carbon fibre cathode at different values of time delay $\tau_{\rm d}$ with respect to the beginning of the accelerating pulse, i.e. $\tau_{\rm d} = 50$ (a), 150 (b), and 250 ns (c).

To further understand the edge effect, the distribution of the electric field on the cathode surface was simulated in the case with the screening ring. The distribution of the electric field on the cathode surface with the screening ring is presented in Fig. 5. Here the simulation was made at the diode gap of 25 mm and the 200 kV voltage. One can see that the intensity of the electric field, close to the cathode surface, is uniform from the cathode edge to the centre. Thus, the addition of the screening ring can significantly improve the distribution of electric field on the cathode surface, providing a possibility of uniform electron emission. This also further supports the experimental observation in the two cases with and without the screening ring.

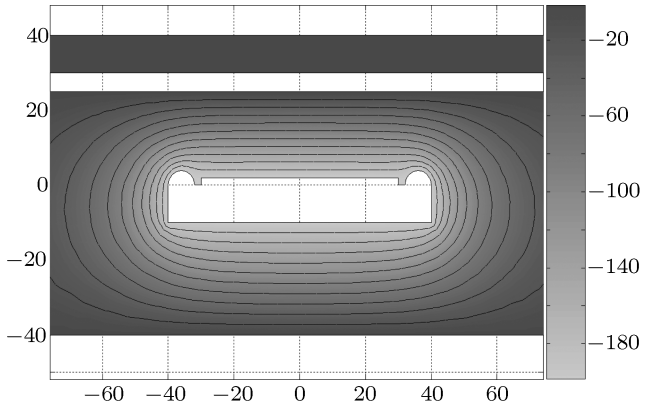


Fig. 5. Distribution of electric field on the cathode surface with the screening ring.

We observe that light emission is more or less uniform over the whole cathode surface, or rather, it appears as many individual bright spots. In fact, later in the accelerating pulse, we can observe light emission from a larger cathode surface area. In this case the strongest electron emission was also extracted from individual bright spots. These bright spots are separated from each other by a spacing of several millimeters, and the dimensions of the bright spots each are less than 3 mm. Also, it was observed that the intensity of the light emission from these bright spots was closely related to the amplitude of the cathode current. That is, with the decrease of the emitted current, light emission reduced. The number of the emitting spots is related to the increasing rate of the accelerating electric field as shown in Fig. 6. One can see that the higher the increasing rate of the accelerating electric field is, the more the spots will occur. As a whole, the uniformity of electron emission tends to be related to the number and the brightness of the emitting spots on the cathode surface.

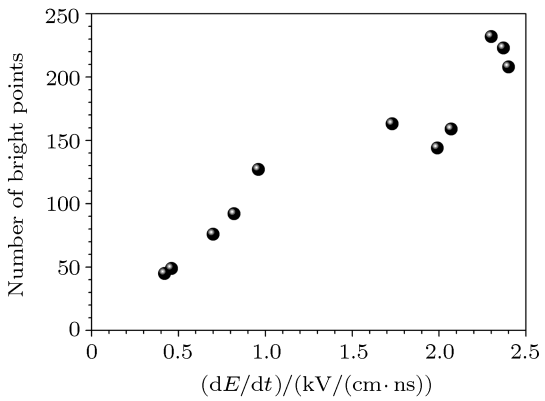


Fig. 6. Dependence of the number of bright points on the derivative of the accelerating electric field.

The formation of the individual plasma jets rather than a plasma sheath on the cathode surface is mainly due to the screening effect. That is, ignition of an emission centre retards the formation of new emission centres in its vicinity. The space charge from an emission centre can screen the electric field in its immediate neighbourhood. A small reduction in electric

field strength can produce a large delay in electron emission of a microprotrusion. Thus an emission centre can retard the formation of its nearby emission centres. Such a 'screening effect' should be independent of cathode materials. Additionally, the formation of individual plasma spots will give rise to an important effect on the effective emitting area. Figure 7 shows the evolution process of the effective emitting area. At $\tau_{\rm d} < 50$ ns, the effective emitting area increased quickly and then relatively slowly, and at $\tau_{\rm d} \sim 150$ ns, the emitting area reached its maximum value ~ 35 cm^2. However, at 150 ns$< \tau_{\rm d} <$230 ns, the emitting area decreased slightly, which most likely was due to the quenching of some emitting centres.

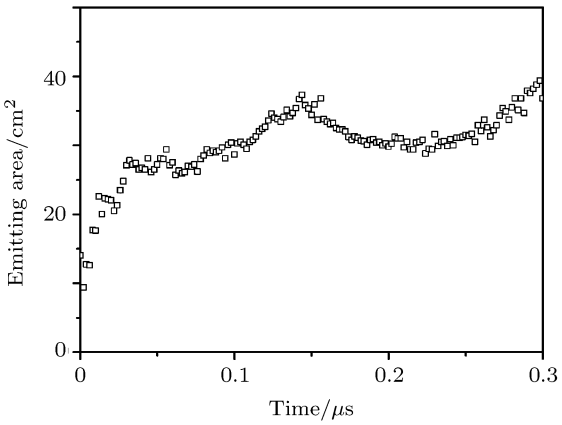


Fig. 7. Evolution process of effective emitting area at a diode gap of 30 mm.

Side-view observation of the light emission from the diode gap with different values of time delay $\tau_{\rm d}$ are shown in Fig. 8. Side view fast framing images showthat a structure of individual light emission sources with dimensions of 1–2 mm appears on the cathode surface. This structure of the light emission indicates that individual plasma jets are ejected.

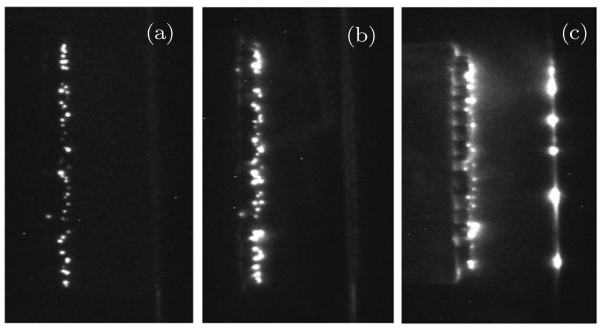


Fig. 8. Side images of the light emission from the carbon fibre cathode with different values of time delay $\tau_{\rm d}$ with respect to the beginning of the accelerating pulse (cathode on the left and anode on the right), i.e. $\tau_{\rm d} = 50$ (a), 150 (b), and 250 ns (c).

One can see that during the accelerating pulse the light emission occurs only from the narrow cathode region, which has a width of < 3 mm, almost in the absence of the expansion of the cathode light-emitting bright spots. Side-view framing photographs also show a structure of the emitting area in the form of separate bright spots. There also exists light emission from the anode at $\tau_{\rm d} > 200$ ns, while the cathode plasma significantly expands into the vacuum gap. The observed data can indicate the existence of quasistationary boundaries in the cathode plasma during the main pulse.

This explosive process causes the formation of a neutral cloud which is simultaneously ionized by electrons, leading to the formation of a plasma layer on the cathode surface. However, the ensuing expansion of plasma into the diode gap reduces the diode impedance, ultimately resulting in the diode shorting of the driving pulse. Actually, the evolution of the expanding plasma turns out to be a rather intricate problem of nonequilibrium plasma physics and has not been fully characterized. Fortunately, the expansion velocity $v_{\rm p}$ has been suggested as[31]

$$v_{\rm p} = \frac{\sqrt{\gamma_{\rm i}}2}{\gamma_{\rm i}-1}\sqrt{\frac{kT_{\rm i0}}{m_{\rm i}}}\int_x^1 \sqrt{\left(1+z\frac{\gamma_{\rm e}T_{\rm e0}}{\gamma_{\rm i}T_{\rm i0}}\,(x')^{\frac{2\gamma_{\rm e}-2\gamma_{\rm i}}{\gamma_{\rm i}-1}}\right)}{\rm d}x', \tag{1}$$

where k, z and x are the Boltzmann constant, the ionic charge and the relative electron density, respectively; $\gamma_{\rm i}$ and $\gamma_{\rm e}$ are the ionic and the electronic polytropic exponents, respectively; $T_{\rm i0}$ and $T_{\rm e0}$ are the ion and the electron initial temperatures, respectively. Clearly, the light elements in plasma are leading contributors to the plasma expansion. Thus, a high concentration of these light elements is deleterious to long-pulse microwave emission. Most microwave sources do not have wall cleanliness sufficient to prevent the plasma within the diode or the interaction region from being produced by explosive emission. The surface layers of water and hydrocarbons are disassociated into hydrogen and other light elements. Therefore, the lightest ions are likely to determine the plasma expansion. Equation (1) also indicates the possibility of $v_{\rm p} = 0$ at $x = 1$. It should be noted that $x = 1$ means the equality between the plasma saturation electron current and the space-charge limited current. That is, the dynamics between plasma saturation electron current and the space-charge limited current is likely to determine the expansion process of cathode plasma.[2]

Figure 9 shows a typical set of framing photographs obtained with time and space resolutions by using a carbon fibre cathode in a diode gap of 20 cm, at an average electron current density of ∼400 A/cm^2 and electron energy of 470 keV. One can see that the patterns of the x-ray image appear as islands or circles. Thus, it can be supposed that these rays are images of the electron beamlets emitted from the individual plasma sources located on the cathode surface. The brightness and the uniformity of x-ray images depend on the magnitude of the accelerating voltage. Namely, the x-ray image has the highest brightness and uniformity around the maximum voltage, shown in Fig. 9(2). One can observe that the brightness and the uniformity of the x-ray image decreased as the pulse proceeded. Taking into account the fact that each x-ray image is produced by electrons having almost the same energies, we hold that the observed uniformity of the x-ray images corresponds to the uniformity of the electron current density. Most notably, the electron current density is satisfactory in spite of the individual plasma sources on the cathode surface. There are two factors that can be responsible for the above phenomenon. The first factor may be related to the electron-beam divergence, and the second one is related to a fast radial expansion of the cathode surface plasma that serves as an electron source. As a whole, the quality of the electron beam with the screening ring excels that without the screening ring. Further, from the x-ray image without the screening ring, the edge effect plays a significant role in determining the uniformity of electron beam. Therefore, the screening rings can be used to improve remarkably the uniformity of electron beam.

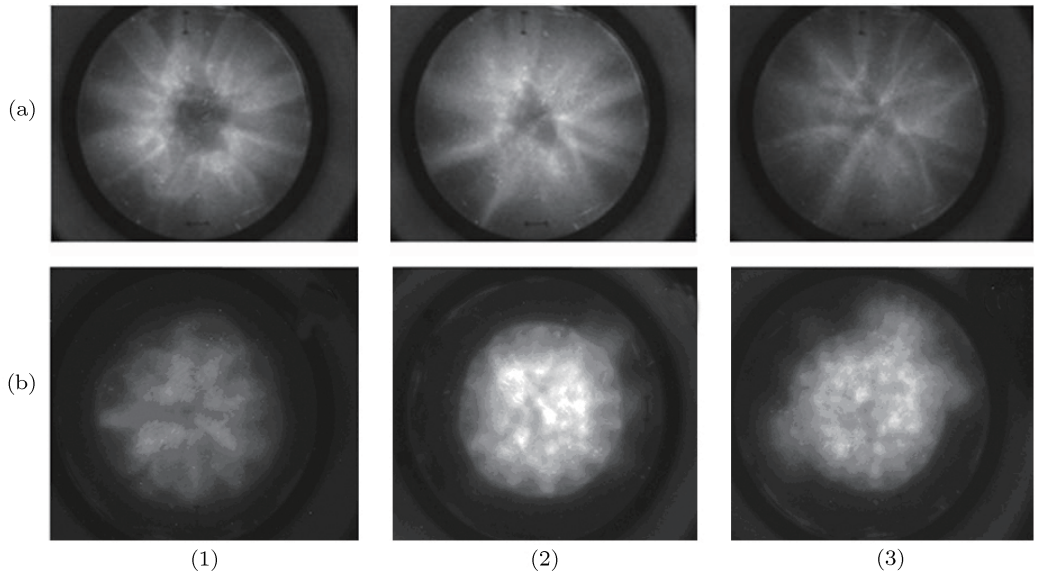


Fig. 9. Typical x-ray images of the anode foil obtained with the phosphor screen for different values of time delay $\tau_{\rm d}$ with respect to the beginning of the accelerating pulse, i.e. $\tau_d = 50(1)$, 150(2), and 250 ns(3), without (a), and with (b) the screening ring.

4. Conclusions

The generation of relativistic electron beams is based on electron emission from the plasma which is produced on the cathode surface as a result of the significant enhancement of microscopic electric field. Thus, the above emission mechanism induces unavoidably the intense desorption of cathode materials during their operation. This is accompanied by the deterioration of emission properties, namely, the reduction in the amplitude of emission current and the appearance of time delay in the electron emission. These drawbacks stimulate a continued interest in groping for robust cathode materials.

The major content of this research is the determination of the electron beam quality and the emission uniformity from the carbon fibre cathode as a plasma source. Most notably, the light mission from the carbon

fibre cathode surface indicates that the electron emission occurs from individual bright spots rather than from the whole cathode area. It may be caused by a process termed screening effect of cold cathode. That is, the ignition of an emission centre retards the formation of new emission centres in its vicinity. The space charge from an emission centre may screen the electric field its immediate neighbourhood. A small reduction in the electric field strength can produce a large delay in the vaporization of a protrusion on the cathode surface. Therefore an emission centre should retard the formation of nearby emission centres. Thus it becomes hard for a few bright spots with small dimensions to merge into a large one. However, due to the transverse component of the electric field in the vicinity of the emission centre, the bright spot is prone to becoming larger and larger. Surprisingly, it is found by taking x-ray images that the uniformity of the electron beam is satisfactory. There are two factors involved in this result, i.e. the beam divergence and the increase in emission area as the pulse proceeds.

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