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A low-outgassing-rate carbon fiber array cathode*

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In this paper, a new carbon fiber based cathode — a low-outgassing-rate carbon fiber array cathode — is investigated experimentally, and the experimental results are compared with those of a polymer velvet cathode. The carbon fiber array cathode is constructed by inserting bunches of carbon fibers into the cylindrical surface of the cathode. In experiment, the diode base pressure is maintained at 1×10^{-2} Pa–2×10^{-2} Pa, and the diode is driven by a compact pulsed power system which can provide a diode voltage of about 100 kV and pulse duration of about 30 ns at a repetition rate of tens of Hz. Real-time pressure data are measured by a magnetron gauge. Under the similar conditions, the experimental results show that the outgassing rate of the carbon fiber array cathode is an order smaller than that of the velvet cathode and that this carbon fiber array cathode has better shot-to-shot stability than the velvet cathode. Hence, this carbon fiber array cathode is demonstrated to be a promising cathode for the radial diode, which can be used in magnetically insulated transmission line oscillator (MILO) and relativistic magnetron (RM).

Keywords: high power microwave, magnetically insulated transmission line oscillator, carbon fiber array cathode, low outgassing rate

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1. Introduction

Cathodes with ideal shot-to-shot stability, low outgassing and long lifetime have been one of the main pursuits in high power microwave (HPM) field,[1–3] especially in the repetitive operation HPM systems.[4–6] In order to obtain ideal cathodes, researchers have done lots of work to study various cathodes made from different materials,[7–11] among which carbon fiber and velvet are two kinds of the most popular materials.

Carbon fiber cathodes and velvet cathodes have been widely used in HPM tubes,[12–19] especially in tubes where large area emission cathodes are needed, such as magnetically insulated transmission line oscillator (MILO)[12–18] and relativistic magnetron (RM).[19] Correspondingly, a lot of research[20–27] has been done to study the characteristics of these cathodes. As a widely used source of high-current electron beams, the velvet cathode [23–26] has a very uniform emission at a relatively low field level, has a low gap closure velocity, and is inexpensive and widely available. However, the velvet cathode has a short lifetime and suffers from high outgassing rate during the beam pulse because this cathode discharges a significant quantity of matter in the electron emission process.[26] If a velvet cathode is in a repetitive operation, the pressure rise in the background resulting from this outgassing may limit the achievable pulse reprate,[25,26] which depends on the vacuum system specifications and the desired pulse duration. Also, high outgassing rate could enhance the plasma formation in the anode–cathode (A–K) region, and the plasma expansion could cause the closure of the A–K gap, thus resulting in the impedance collapse of the diode.[21] The impedance collapse can often lead to the shortening of the radiofrequency (RF) pulse in HPM tube, so the high-outgassing-rate cathode limits the microwave pulse-duration and the achievable pulse repetition rate of the HPM tubes.[25,26] As reported previously,[21,22] the carbon-fiber-based cathode (carbon velvet cathode) not only has a low threshold field and a low gap closure velocity, but also can have a uniform emission. Besides, this cathode has a lower outgassing and longer lifetime than the velvet cathode.[24,27] However, the carbon velvet cathode is not so available as the polymer velvet cathode because of the relatively complicated manufacturing process,[3,7,12,22] especially in the radial diode. The fabrication of radial-emission carbon fiber cathode[3,7,12] has not reached an ideal level and hence more research should be done to apply carbon fibers to radial-emission cathodes.

In this article, aiming at its application in MILO[13–16,18] or in RM,[19,28] a new carbon fiber based cathode — a radial-emission and large area emission carbon fiber array cathode — is constructed and experimentally compared with a velvet cathode in a radial diode. During the experiments, both cathodes are operated in similar conditions. What we are mainly concerned with is the outgassing rates of cathodes, but the shot-to-shot stabilities are also discussed briefly. Some research has been done to study the outgassing rates of carbon fiber cathodes or velvet cathodes. In Ref. [22], the "uncoated carbon-on-epoxy"-type carbon fiber cathode has an outgassing rate of 4.7 atoms/electron; in Ref. [23], the authors found

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that the velvet cathode has an outgassing rate which is about four times as great as the carbon fiber cathode; in Ref. [29], the carbon nanotube cathode has an outgassing rate of 153 atoms/electron. However, in the previous research, the two kinds of cathodes were not compared with each other directly nor in detail; and the outgassing rate varies with working condition. Here in this paper, we present a direct and detailed comparison between the outgassing rates of the two cathodes.

The rest of the present paper is organized as follows. In Section 2 the experimental configuration is introduced, including the pulsed power system, vacuum system, diode geometry, diagnostics, and the structure of the two cathodes. In Section 3, the experimental results are presented and discussed, including outgassing characteristic and shot-to-shot stability at tens of Hz operation. Finally, in Section 4, the conclusions are drawn from the present experimental results and the future research in this field is suggested.

2. Experimental configuration

The experimental configuration is shown in Fig. 1. A radial diode was designed to investigate the two cathodes. The anode–cathode gap (from the fiber tip to the inner side of the anode) is about 1.2 cm. An annular trough was excavated in the anode for water flowing. When the system worked in a repetitive mode, continuous pulses will bring about a large amount of heat; a water pump (see Fig. 1) was used to pump the water to accelerate the release of heat that was produced on the inner wall of the anode.

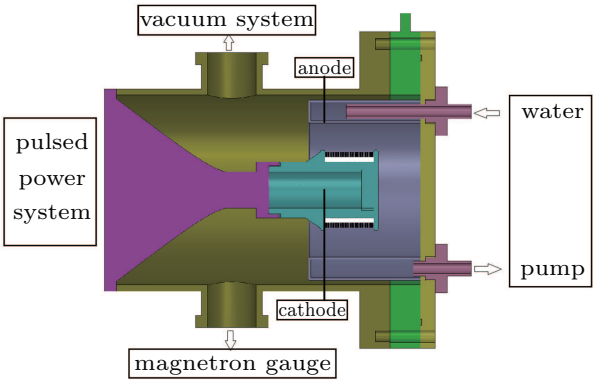


Fig. 1. (color online) Experimental configuration (model of the radial diode).

The pulsed power system can provide a diode voltage of about hundreds of kV and pulse duration of about 30 ns at a repetition rate of tens of Hz. In the experiments, the diode voltage was about 100 kV and the system worked at repetition rate of 10 Hz or 20 Hz. The base pressure in the diode chamber was maintained at 1×10^{-2} Pa–2×10^{-2} Pa by a vacuum system which consisted of a turbo molecular pump and a backing pump. The pumping rate of the turbo molecular pump was 240 l/s, and the cylindrical tube which connected the diode chamber to the vacuum system had a diameter of 4 cm and a length of 80 cm. Pressures were measured by a magnetron gauge. The magnetron gauge remained switched on in repetitive operation process and its output voltage data was used to acquire time-resolved pressure data. The diode voltage and current were measured by a capacitance voltage divider and a Rogowski coil respectively, and both were recorded by an oscilloscope. The micrographs (Figs. 11–14) of fiber surface morphology were taken by a scanning electron microscope (SEM, Hitachi S-3700N).

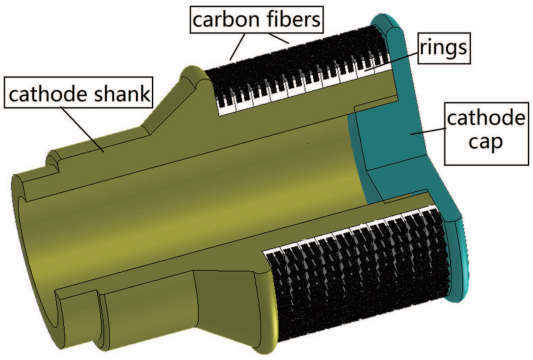


Fig. 2. (color online) Model of the carbon fiber array cathode.

Figures 2 and 3 show the models of the radial carbon fiber array cathode and the velvet cathode, respectively. The carbon fiber array cathode consists of cathode shank, cathode cap and metal rings with carbon fibers. Firstly, aluminum rings are fabricated, and holes are drilled on the lateral surfaces of these rings. Secondly, bunches of carbon fibers are inserted into the drilled holes on the cylindrical surface of the metal rings, and are fastened with polyacrylic ester. Thirdly, after metal rings with carbon fibers are made, these rings are placed on the cathode shank one by one and fastened by the cathode cap. The metal rings are made of aluminum, and the cathode shank and cathode cap are made of stainless steel. This carbon fiber array cathode has several advantages as follows. 1) It has a good flexibility because the basic units, metal rings with carbon fibers, are easy to install or demount, which is beneficial for application in MILO or RM. 2) Its density can be adjusted by altering the density of the drilled holes. 3) Its vacuum could be improved with very few volatile polyacrylic esters. The carbon fibers are produced by Toray Industries. Inc, and a small bunch consists of about 3k fibers. A single carbon fiber has a diameter of about 5 μm, a bunch of carbon fibers has a diameter of about 1 mm, and the length of the parts of bunches above the ring surface is about 4 mm. The velvet cathode consists of cathode shank, cathode cap and velvet, and the velvet cloth is attached to the surface of the cathode with polyacrylic ester. The diameter and length of a single velvet

fiber are about 12 μm and 1 mm, respectively. After fastening, the two cathodes, carbon fibers and polymer velvet, will roughly have the same diameters (from fiber tip to tip). The cathode surface area is about 117 cm^2 for both cathodes.

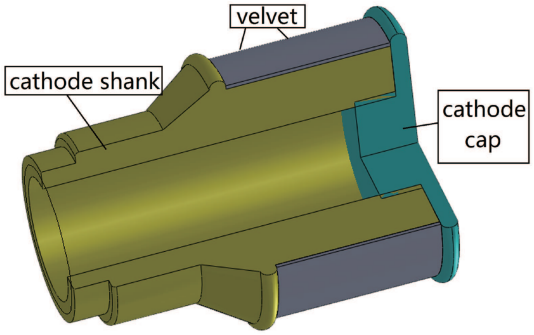


Fig. 3. (color online) Model of the velvet cathode.

3. Experimental results and discussion

In the experiments, the diode voltage is about 100 kV and the system works at a repetition rate of 10 Hz or 20 Hz. Typical waveforms of diode voltage and current in a single pulse of the two cathodes are shown in Fig. 4. The diode current and the calculated current density (diode current divided by cathode surface) for the carbon fiber array cathodes are around 8.3 kA and 70.9 A/cm^2, respectively, while they are 9.9 kA and 84.6 A/cm^2 for the velvet cathode. Under the same peak voltage (100 kV), the current of the velvet cathode is bigger than that of the carbon fiber array cathode, which may be due to the fact that the actual diameter of the velvet cathode is a little bigger than that of the carbon fiber array cathode though they are designed to be the same.

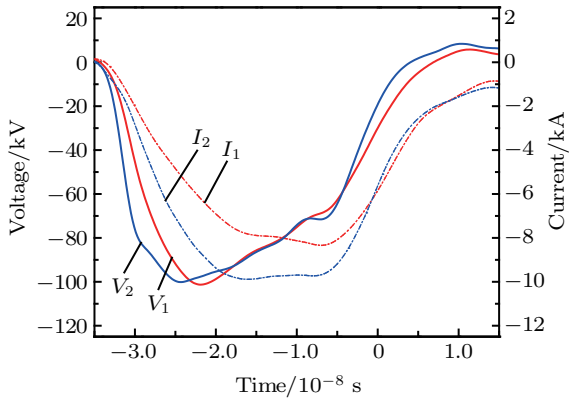


Fig. 4. (color online) Waveforms of diode voltage and current in a single pulse (V_1, I_1-carbon fiber array cathode; V_2, I_2-velvet cathode).

Typical waveforms of the diode voltage and diode current in a repetitive operation of the carbon fiber array cathode and the velvet cathode are shown in Figs. 5 and 7, and Figs. 6 and 8, respectively. The shot-to-shot stabilities of the two cathodes can be observed from the stabilities of the waveforms. If we take

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\mathrm{mean}}} \times 100\% \quad (1)$$

as a measure of the instability extent of the waveform, where $I_{\max}$, $I_{\min}$, I_{mean} are the absolute values of the maximum, minimum, and average value of current peak values which are recorded by an oscilloscope, then δ values in Figs. 5–8 are 2.7%, 2.9%, 9.8%, and 11.0%, respectively. One can see that the instabilities of the waveforms of the carbon fiber array cathode are smaller than those of the velvet cathode (especially in the experiment of 100 pulses), which means that the shot-to-shot stability of the carbon fiber array cathode is better than that of the velvet cathode. In the process of continuous pulses in repetitive operation, the vacuum will become worse gradually (to the level of 10^{-2} Pa and 10^{-1} Pa for carbon fiber array cathode and velvet cathode, respectively) because of the outgassing of the early pulses. Hence the gas (plasma) density will increase and influence the possibility of electron collisions with gas molecules, resulting in the fluctuation of current in the later pulses. The outgassing of the velvet cathode is larger than that of the carbon fiber array cathode, which is to be mentioned later, so the instability extent of the former is larger than the latter.

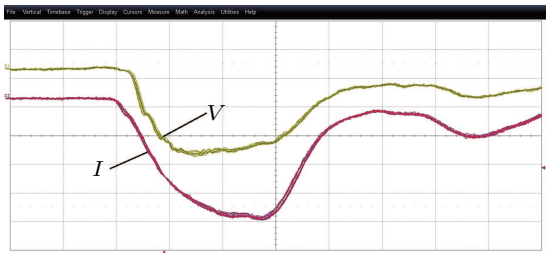


Fig. 5. (color online) Diode voltage, current of carbon fiber array cathode (10 pulses at 20 Hz).

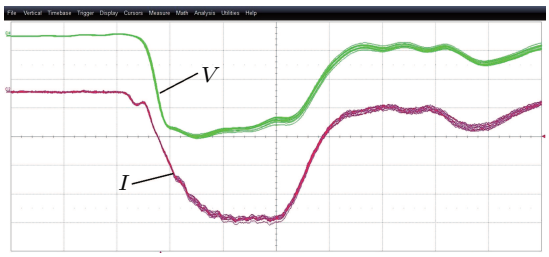


Fig. 6. (color online) Diode voltage, current of velvet cathode (10 pulses at 20 Hz).

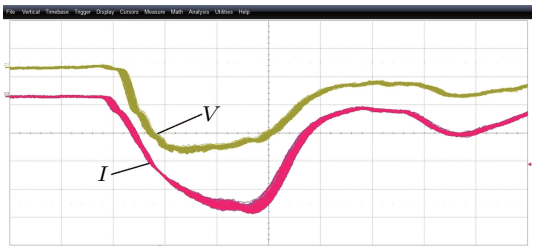


Fig. 7. (color online) Diode voltage, current of carbon fiber array cathode (100 pulses at 20 Hz).

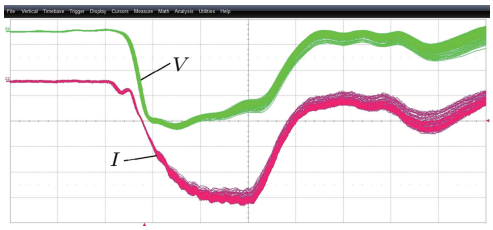


Fig. 8. (color online) Diode voltage, current of velvet cathode (100 pulses at 20 Hz).

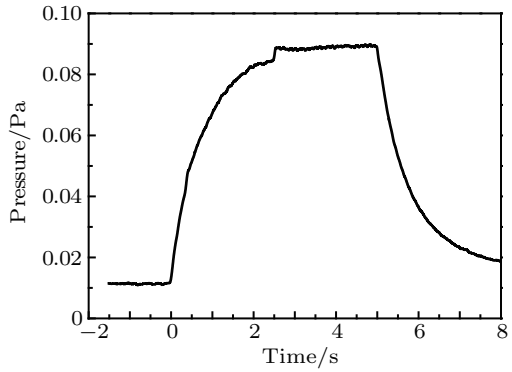


Fig. 9. Pressure evolution caused by the outgassing of carbon fiber array cathode at 20 Hz (100 pulses).

The pressure evolution data are obtained from the output voltage of the magnetron gauge, and the outgassing characteristic of cathode can be analyzed from pressure evolution data of the diode chamber. It is found that the outgassing rate of the cathode decreases gradually in the initial tens to hundreds of pulses of the experiments, but tends to reach a relatively stable value after a number of pulses. This may be due to the fact that some contaminants or water vapors are absorbed on a fresh cathode surface, and in the initial pulses, these absorbed contaminants or water vapor were desorbed and then extracted out by the vacuum pump; these contaminants or water vapor get "cleared up" to some extent after a number of pulses, at which time, the outgassing rate tends to reach a stable value. In a stable state, typical variations of the pressure data of carbon fiber array cathode and velvet cathode in experiments are shown in Figs. 9 and 10, and the base pressures are 1.1×10^{-2} Pa and 1×10^{-2} Pa, respectively. Normally, at a higher repetition rate, for the same cathode, more pulses are needed to reach the equilibrium pressure and higher equilibrium pressure will be reached as well. However, neither the repetition rate nor the number of pulses has an influence on the following calculation of outgassing rate as long as the equilibrium pressure can be reached. A pressure evolution curve caused by the outgassing of the velvet cathode in 50 pulses at 10 Hz is presented here to compare with a curve of carbon fiber array cathode in 100 pulses at 20 Hz because the peak pressure of the velvet cathode in 100 pulses at 20 Hz exceeds the working range of the magnetron gauge. One can see from Figs. 9 and 10 that the equilibrium pressure of the velvet cathode is much higher than that of the carbon fiber array cathode even at a lower repetition rate.

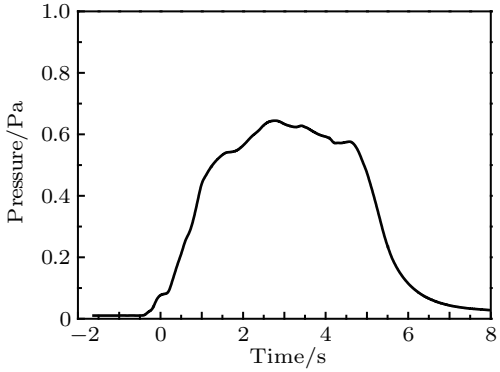


Fig. 10. Pressure evolution caused by the outgassing of velvet cathode at 10 Hz (50 pulses).

According to Ref. [30], if the base pressure is sufficiently low, then the equilibrium pressure will be approximately given by

$$P(\mathrm{Pa}) = \frac{133.3N_{\mathrm{p}}(\mathrm{atoms/pulse})R(\mathrm{pulses/s})}{[3.5\times10^{19}\ \mathrm{atoms/l/Pa}]S_{\mathrm{eff}}(\mathrm{l/s})}, \qquad (2)$$

where N_{p} is the number of the molecules liberated from the cathode during a pulse, R is the repetition rate, and S_{eff} is the effective pumping speed of the vacuum system. The effective pumping speed S_{eff} depends on system conductance C according to $S_{\mathrm{eff}}^{-1} = S^{-1} + C^{-1}$, and a useful approximation for the vacuum conductance of a cylindrical tube with diameter D and length L is given by (with dimensions in unit cm) $C(\mathrm{l/s}) = 12.1D^3/L$. Here $D = 4$ cm, $L = 80$ cm, and $S = 240$ l/s, the equilibrium pressure of the carbon fiber array cathode and velvet cathode are 0.088 Pa and 0.65 Pa, respectively; the repetitive rates are 20 pulses/s and 10 pulses/s, respectively. Solving Eq. (2) for N_{p}, then N_{p} values of carbon fiber array cathode and velvet cathode are 1.07×10^{16} atoms/pulse and 1.59×10^{17} atoms/pulse, respectively. Considering the fact that the current may influence the outgassing characteristic, if we take atoms/electron as the unit of the outgassing rate (the number of electrons in a pulse is calculated by integrating the current), then the outgassing rates of the carbon fiber array cathode and velvet cathode are 6.9 atoms/electron and 85.8 atoms/electron, respectively. It is worth mentioning that the carbon velvet cathode investigated in Ref. [22] has an outgassing rate of 4.7 atoms/electron (the "uncoated carbon-on-epoxy" type), which is a little lower than this carbon fiber array cathode. The reason may be that the base pressure in Ref. [22] (4×10^{-5} Pa) is much lower than that in our experiments (1.1×10^{-2} Pa), as the amount of outgassing partly depends on the base pressure.[29] Actually, the value of cathode outgassing rate depends on experimental condition, such as base pressure, anode material, pretreatment, etc. What we are really concerned with is not the absolute value, but the relative value, of outgassing rate. Here in this paper, under a similar

condition, the outgassing rate of the carbon fiber array cathode is an order smaller than that of the velvet cathode. So this carbon fiber array cathode is positive for repetitive operation and long-pulse MILO in which the repetitive and long-pulse operation is limited by the velvet cathode to some extent.

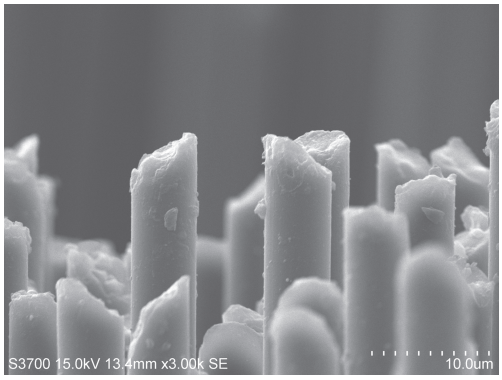


Fig. 11. Surface morphology of carbon fibers before 10000 pulses.

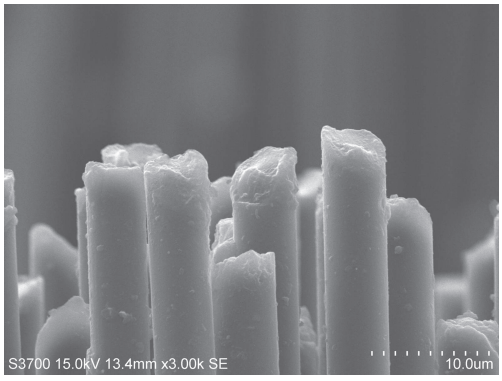


Fig. 12. Surface morphology of carbon fibers after 10000 pulses.

In experiment, it is impossible to precisely measure the outgassing singly from the cathode because there is outgassing from other parts of the chamber inevitably (outgassing from anode surface caused by the electron bombardment, leakage, etc.) and we cannot discriminate them from the outgassing of the cathode either. Thus the measured outgassing rate is usually the whole outgassing in the diode chamber. However, because the anode and other parts of the diode are the same for the two cathodes, the reason for the difference in outgassing rate should be attributed to the cathodes themselves. The outgassing from the cathode is determined by the original materials and the fabrication technique. When cathodes are exposed to atmosphere, a large number of neutrals can be absorbed on their surfaces, of course, the specific numbers are different for surfaces of different materials and surfaces with different planeness. When cathodes are put into work, there will be high temperature around them because of the current heating, and the material that cannot withstand high temperature will tend to release matters easily. The micrographs of the surface morphologies of carbon fiber and velvet fiber are taken by an SEM (Figs. 11–14). From Figs. 11 and 12, we can find that there is no obvious damage on the carbon fiber surface. However, some of the velvet fibers are damaged after about 2000 pulses. In Fig. 14, comparing the damaged velvet fibers in it with the undamaged velvet fibers in Fig. 13, one can see the surfaces of some velvet fibers are cracked. The cracked or missing part of the velvet fiber may contribute to the outgassing, but there is no such crack in the carbon fiber surface (this may be because carbon fiber has a higher melting point than the velvet fiber). Therefore, we think, this may be a reason why the outgassing rate of the carbon fiber cathode is much smaller than that of the velvet cathode. One can also find from Figs. 11–14 that the stiffness and planeness of the carbon fiber are better than those of the velvet fiber, so the velvet fiber may tend to absorb neutrals more easily than the carbon fiber, which makes the outgassing larger. Besides, in the manufacturing process, much more polyacrylic esters (volatile) are used in the velvet cathode, which may be another reason for the different outgassing rates.

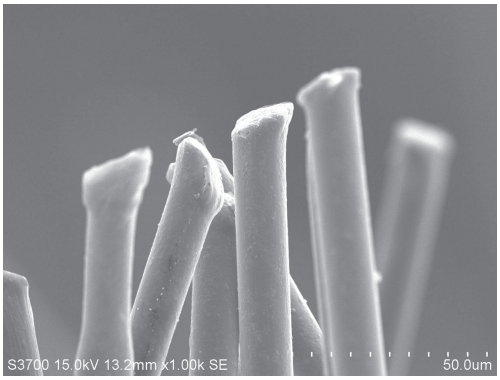


Fig. 13. Surface morphology of velvet fibers before 2000 pulses.



Fig. 14. Surface morphology of velvet fibers after 2000 pulses.

4. Conclusions

A low-outgassing-rate carbon fiber array cathode is fabricated and experimentally compared with a polymer velvet cathode in a radial diode. Experimental results show that the shot-to-shot stability of the carbon fiber array cathode is better than that of the velvet cathode when the cathodes work under a diode voltage of around 100 kV. The outgassing rate of

the carbon fiber array cathode is an order smaller than that of the velvet cathode (the outgassing rates are 6.9 atoms/electron and 85.8 atoms/electron for the two kinds of cathodes, respectively). In general, the carbon fiber array cathode is a promising substitution for the velvet cathode for MILO repetitive operation. To make sure the performance of carbon fiber array cathode is better than that of traditional velvet cathode, our further work will concentrate on the applications of this carbon fiber array cathode in a MILO for repetitive operation.

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