Pulse-Width Increase of Reflex Triode Vircator Using the Carbon Fibre Cathode*

LIU Lie(刘列), LI Li-Min(李立民)**, ZHANG Xiao-Ping (张晓萍), WEN Jian-Chun(文建春), WAN Hong(万红)

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

(Received 16 August 2005)

We present the investigation on the reflex triode virtual cathode oscillator in which performances of carbon-fibre and stainless-steel cathodes are compared with each other. The experimental results and analyses show that surface tracking induces the electron emission of the carbon fibre cathode. There are electron emission phenomena observed not only from the top of the carbon fibre but also from its side surface. Compared with the case of the stainless steel cathode, the plasma expansion velocity for the carbon fibre cathode is slower, and using the carbon fibre cathode can widen the pulse width of output microwave. The output microwave pulse width reaches an increase of about 20%. This mechanism is different from the conventional explosive emission of metal cathodes.

PACS: 52. 70. Dw, 84. 70. +p

Intense pulsed electron beams have been generated by high-power diodes. In the commonly used high-power diodes, the electron beam extraction depends on the cathode plasma covering on the cathode surface. The cathode plasma, on the one hand, as a kind of zero working functions of electron sources, is the foundation of intense electron beam generation. On the other hand, because of different kinds zero working functions, the temperature and density, especially expansion, have direct impact on beam current properties, which restricts technique targets of intense pulsed electron beams. These technique targets include the beam current intensity, flat-top property, pulse width, beam current spread, energy spread, brightness, the repeat-run feasibility, etc.

The rf pulse shortening has already become a common problem in all HPM tubes and a primary obstruction of HPM technique development. Most kinds of pulse shortening are attributed to the plasma and the plasma expansion is a sort of mechanism bringing the pulse shortening.

We present the investigation on the reflex triode virtual cathode oscillator, in which performances of carbon-fibre and stainless steel cathodes are comparable with each other. Both the cathodes were operated in the same diode geometry in the same vacuum and under high-voltage pulse driver conditions at the beam current of 9–11 kA and diode voltage of 350–400 kV respectively.

We experimentally investigated the effect on the output microwave pulse width by using the carbon fibre cathode, as shown in Fig. 1. The pulse width for the stainless steel cathode was approximately 150 ns. Under the condition of the same magnitude, the microwave pulse width, in the case of the carbon fibre and stainless steel cathode, was increased to about 200 ns. The widening of the microwave pulse width is to a great extent attributed to the improvement of the electron beam quality. It is demonstrated that the interaction time between the electron beam and microwave field can be prolonged by using the carbon-fibre cathode. The microwave pulse widening is favourable for enhancement of the reflex triode efficiency.

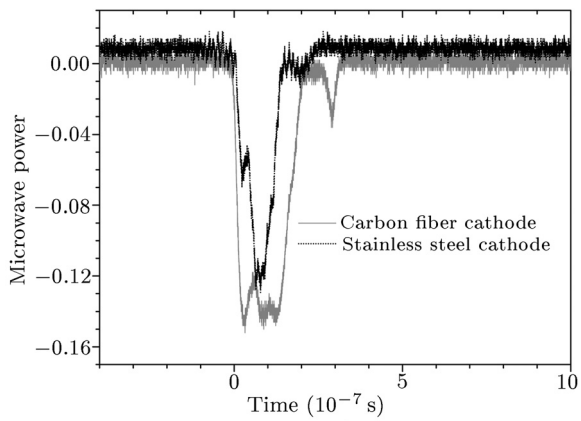

Fig. 1. Comparison of the output microwave signals using carbon fibre and stainless steel cathodes respectively.

The explosive emission cathode has many virtues such as briefness, easy using, needing less accessorial facility, and being the only cathode that can offer emission current density of several kA/cm^2. However, they also have severe limits such as the cathode surface plasma expansion. Cathode surface plasma expansion will make the anode–cathode (A–K) gap closure, cause the pulse shortening, and limit the pulse

* Supported by the National 863-803 Programme of China.
** Email: newages1979@yahoo.com.cn
©2006 Chinese Physical Society and IOP Publishing Ltd

width and energy. In pulse duration, severe changing of the diode impedance will cause severe changing of microwave power.

Several materials have been used as cold cathode explosive emitters in a variety of cathode configurations. A limit factor of all these cathodes is that they typically suffer impedance collapse. For pulse width in excess of several hundreds of nanoseconds, the diode impedance collapse can often lead to rf pulse shortening in HPM tubes. The impedance collapse is usually attributed to closure of the anode-cathode (A–K) gap by either radial expansion of the cathode plasma, axial expansion of the cathode plasma, or a combination of them. Either effect can be enhanced by large amount of gas evolving from the cathode or anode surface. The resultant plasma speeds in these situations are on the order of 1 to 5 cm/μs. This impedance collapse effectively limits the pulse width and thus total energy that an HPM tube can deliver.

Typical explosive field emission cathodes suffer from large amounts of outer gassing, non-uniform emission, and very high emittance. However, the carbon fibre cathode can overcome the above disadvantages of the explosive field emission cathodes. Thus, it is necessary to compare the electron emission process of the carbon fibre cathode with that of the stainless steel cathode. In general, the electric field at the needles on the cathode, no matter whether cathode material is either stainless steel or carbon fibre, is hundreds of times larger than the externally applied electric field. In this case, the plasma is formed on the surface of the cathode, and then the electrons are emitted from the cathode plasma sheath due to the field emission or explosive emission mechanism.

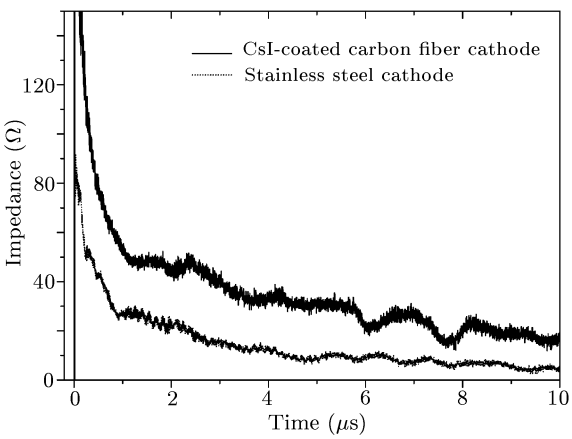

Fig. 2. Temporal behaviour of diode impedance with stainless steel and carbon fibre cathodes.

Among many physical problems involved in relativistic diode, the cathode plasma expanding is prior to be investigated, which is the foundation of the long pulse intensive electron beam accelerator. It is emphasized that, because of the Debye screen effect, cathode plasma will keep neutrality, its expansion does not depend upon the electric field force, but upon the pressure gradient variance. In the long-pulse diodes, diode closure time (breakdown time) is decided by the cathode plasma expansion velocity, that is to say, the cathode plasma expansion velocity restricts the beam current pulse width. In addition, the cathode plasma expansion has important impact on the diode impedance. Figure 2 shows the impedance versus the time for both the stainless steel and carbon fibre cathode diodes. As can be seen from Fig. 2, the impedance of the carbon fibre cathode diode was higher than that of the stainless steel cathode diode. The increasing impedance and longer closure time of the carbon fibre cathode diode strongly imply that the plasma expansion velocity is decreased obviously.

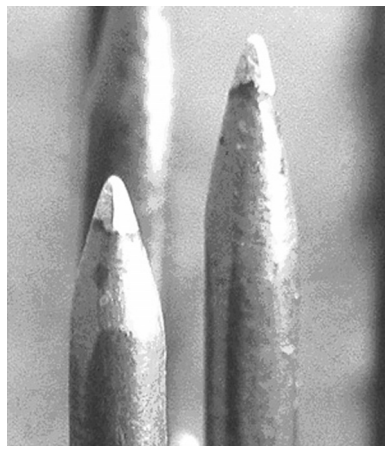

Fig. 3. Photo of the needles on the surface of the stainless steel cathode after electron emission.

Figure 3 shows the micrographs of the needles on the surface of the stainless steel cathode after electron emission. It is obvious that after the electron emission, the tips of the needles are ablated but there is no ablation on the side surfaces of the needles. The tips of the needles become flatter after the electron emission, which implies the plasma formed explosively at the tips of the needles but not on the side surfaces of the needles. We conceive a process of plasma formation at the tips of the needles of the cathode, in which the tips of needles become flatter and the needles are depleted gradually. The electron emission is mainly concentrated on the tips of the needles on the cathode, which could lead to the cathode destruction and affect the lifetime of the stainless steel cathode. Particularly, the electron emission not only is concentrated on the tips of the needles but also is not uniform. In other words, there are emission differences between these needles on the stainless steel cathode, which shows the high threshold field of the stainless steel cathode.

As far as a carbon fibre cathode is concerned, the process of plasma formation is quite different, which is related to the microstructure of the carbon fibre material. It has been understood that the carbon fibre consists of three layers, which are the surface, crust, and the core.[1−4] The surface, which is parallel to the axis of the fibre, is a layer of graphite. The medium crust layer includes carbon granules that are distributed randomly. Manders[4] investigated the carbon fibre microstructure by using the electrolytic etching to show the three layers of carbon fibre. The complexity of carbon fibre microstructure shows that the electric polarization of the carbon fibre is not uniform,[2,5] which could be favourable for occurrence of flashover and thus for the formation of a plasma.[6−8]

Figure 4 gives the comparison between the carbon fibre tips before electron emission and those after electron emission. Figure 5 illustrates the comparison between the side surfaces of carbon fibres before electron emission and those after electron emission. As can be seen from Figs. 4 and 5, there are some spots at the tips and on the side surfaces of the carbon fibres after the electron emission. These spots only could be attributed to the flashover discharge along the side surfaces of the carbon fibres and field emission at tips of carbon fibres. Therefore, we believe that the plasma can be formed not only at the tip of carbon fibre but also on its side surface, which has been demonstrated in Ref. [9].

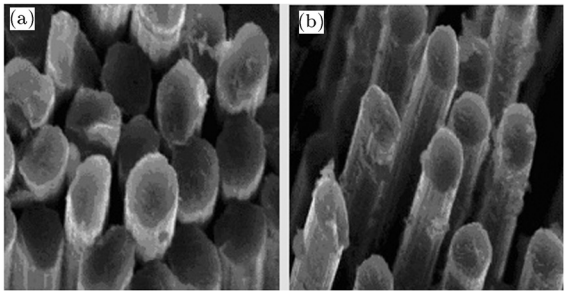

Fig. 4. Electron-scanning micrographs of the tips of carbon fibre cathode before (a) and after (b) the emission.

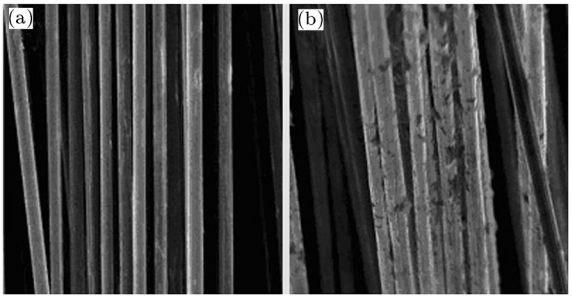

Fig. 5. Electron-scanning micrographs of the side surface of carbon fibre cathode before (a) and after (b) the emission.

The mechanism of plasma formation for the carbon fibre cathode could be attributed to the field enhancement at the tip of the fibre and the surface flashover along the length of the fibre. The surface flashover discharge plays an important role in the plasma formation on the surface of the carbon fibre cathode. The surface flashover makes the plasma form on the whole surface of the carbon fibre, which increases the electron emission area and the uniformity of the cathode plasma sheath. Therefore, it is expected that the plasma formed on the surface of a carbon fibre cathode is more uniform than that formed on the surface of a stainless steel cathode. Therefore the electron beam generated by the carbon fibre cathode has a better quality, which is favourable for generating high-power microwaves by the vircator.

Experimental results indicate that the plasma formed on the carbon fibre cathode is more uniform as a result of the surface flashover discharge along the whole surface of the carbon fibre. However, the electron emission of the metal cathode is confined to the tips of the emitters on the cathode, which obviously differs from the electron emission mechanism of the carbon fibre cathode. The electron beam extracted from the carbon fibre cathode has a higher quality than the case of the stainless steel cathode.

Therefore, the diode impedance increases with the decrease of plasma expansion velocity. The collapse of impedance for the diode using the carbon fibre cathode is in a slower speed, which is favourable for the increase of voltage pulse duration. Thus, it is significant for the enhancement of the microwave power because the slow expansion velocity of the cathode plasma could be beneficial for increasing the interaction time between electron beams and microwave fields.

The carbon fibre cathode has higher melting point and larger resistance than metal cathode, and so its electron emission mechanism differs from the explosive emission mechanism of metal cathode. After the explosive emission, the typical metal cathode will be ablated, the tiny protuberances will vanish, and the surface will become sunken. While the carbon fibre will be blasted and occur new tiny protuberances with field buildup after the explosive emission. The experiments show that the carbon fibre cathodes have lower emission threshold field and form less plasma than the metal cathode. In long pulsed high-power diodes, the plasma reducing can availably keep the impedance stable, especially by using of the CsI carbon fibre cathodes.

It should be pointed out that the electron emission mechanism of the carbon fibre cathode is mainly the result of surface flashover along the fibre surface. In general, the mechanism of the plasma initiation for the

dielectric fibre cathodes can be attributed to field enhancement at the tip of the fibre, or surface flashover (it is called the surface tracking strictly) along the side surface of the fibre, or both. However, in our experimental condition of long pulse (300 ns), the electron emission mechanism of the carbon fibre cathode can only be both the surface tracking and the field emission at the tip of carbon fibre.

Thus, we can conclude that an optimized cathode should have several electron emission mechanisms, and thus the uniformity of the whole electron emission surface of the cathode may be increased.

The application of the carbon fibre cathode in high power diode can obviously improve the interaction between the electron beam and the microwave field due to the existence of the surface flashover during the process of the electron emission. Using the carbon fibre cathode, in addition, makes the expansion velocity of cathode plasma slower and then the closure time of the diode A-K gap longer than the case of the stainless steel cathode, which is favourable for the increase of the microwave pulse width. As a final point, the pulse duration of output microwave is increased by approximately 50 ns, which can illustrate advantages of the carbon fibre material. It follows that the carbon fibre cathode has broad perspective in the field of high power diode.

References

[1] Latham R V and Wikson D A 1981 *J. Phys. D: Appl. Phys.* **14** 2139
[2] Johnson D J 1987 *J. Phys. D: Appl. Phys.* **20** 286
[3] Watt W and Johnson W 1975 *Nature* **257** 210
[4] Manders P W 1978 *Nature* **271** 142
[5] Owston C N 1970 *J. Phys. D: Appl. Phys.* **3** 1615
[6] Blasie G 1993 *IEEE. Trans. Electron. Insult.* **28** 437
[7] Blaise G and Gressus G L 1991 *J. Appl. Phys.* **69** 633
[8] Miller H C 1993 *IEEE Trans. Electron. Insul.* **28** 512
[9] Krasik Ya E, Dunaevsky A, Krokhmal A, Felsteiner J, Gunin A V, Pegel I V and Korovin S D 2001 *J. Appl. Phys.* **89** 2379
[10] Shiffler D, Lacour M et al 2000 *SPIE* **4031** 144