Experimental Study on Disk Type Cold Cathode in Weakly Relativistic Energy Region

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We study a disk cathode in the weakly relativistic region less than 100 kV by comparing the conventional tubular cathode. The disk cathode is an explosive electron emission cathode made of bare metal. The beam generated by the disk cathode has the more uniform distribution and has the higher current density compared with the tubular cathode with velvet. For the uniform emission, some surface roughness of 1 μm order is required on the emission surface. Metals such as aluminum, copper and stainless steel are tested as the cathode. Up to now, the best result is obtained by a copper cathode. In view of application to the weakly relativistic oversized backward wave oscillator, the disk cathode is superior to the tubular cathode and is effective for the high-power operation.

Keywords: disk cathode, cold cathode, explosive emission, weakly relativistic region, surface roughness, backward wave oscillator.

1. Introduction

High-power microwaves are demanded for widespread applications such as plasma heating, plasma diagnostics, telecommunication systems and radar systems. Slow-wave devices such as backward wave oscillator (BWO) can be driven by an axially injected electron beam without initial perpendicular velocity and has been studied extensively as a candidate for high-power microwave sources. For such microwave sources, it is essential to use reliable cathodes producing a high current electron beam with uniformly distributed cross sectional shape. As is pointed out in Refs. [1, 2], many high-power microwave sources in the relativistic region from hundreds kV to a few MV have relied on simple explosive emission cold cathodes to obtain annular beams. The uniformity of beam has been improved with the help of dielectrics. For example, the cathode surface is coated with a mixture of fine graphite powder and epoxy [1].

We also study BWO based on cold cathodes in the weakly relativistic energy region less than 100 keV [3-8]. The average electric field between anode and cathode gap is about 100 kV/cm or less. In the past, we used hollow tubular cathodes. In order to obtain an annular electron beam in the weakly relativistic region, velvet cloth must be put on the circular emitting edge. The velvet cathode is inexpensive and has low turn-on field for emission. To the best of our knowledge, the velvet cathode has been the only cold cathode which operates effectively in the weakly relativistic region, as presented in Refs.[3-5] and [9].

One problem with tubular geometry is that plasma is generated along the outer surface of the cathode. To avoid such unwanted plasma, an idea of disk cathode has been presented by Loza *et al*. [10]. The disk cathode is expected to reduce the unwanted plasma produced at the cathode and may be suitable for long pulse high current operations. And it has been demonstrated that the disk cathode is useful for the relativistic BWO [11]. In Refs.[6-8], it has been shown that the disk cold cathode can produce a high current electron beam without velvet, even in the weakly relativistic region less than 100 kV. An annular beam produced by the disk cathode is distributed more uniformly with a higher current density than the tubular cathode with the velvet. Any dielectric coating on the emission surface of cathode is not required. To develop practical disk cold cathodes for high-power BWOs in the weakly relativistic region, the operation conditions as well as the physical mechanisms involved should be revealed.

In this paper, we study disk cold cathodes in the weakly relativistic energy region, by comparing the conventional tubular cathode. Generation of electron beam by the disk type cathode is examined experimentally by changing the geometry, surface roughness and metal. An important point of cathode study is its availability for the realistic high-power microwave radiations. Hence, the disk type cathode is applied to a weakly relativistic BWO and discussed.

2. Experimental Setup

Experimental setup is schematically shown in Fig.1. A 10-stage, 1 kJ Marx generator has been used as a high voltage source. Electron beam diode consists of a hollow anode and a cold cathode. In our experiments, output

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voltage raging from about 30 kV up to 100 kV of the pulse-forming line is applied to the cathode. Magnetic field B_0 for beam propagation is provided by using ten solenoid coils. The position of each coil is adjusted so that the beam diode, beam transport section and beam collector lie in the uniform region of B_0. The maximum value of B_0 is about 0.9 T.

Electron beam shape along the transport section is examined by observing the burn pattern in thermally sensitive paper by intersecting the beam propagation. Unless otherwise stated, we set the anode-cathode gap at 1 cm and B_0 at 0.8 T. The beam diode, beam transport section and beam collector are installed in a stainless steel vacuum vessel. The vacuum system consists of a turbomolecular pump backed by a rotary pump. Background residual gas pressure is kept under 1×10^{-3} Pa.

For microwave generation, beam collector is removed. After beam limiter, slow-wave structure, microwave waveguide and output window are arranged. The microwave output is picked up by a rectangular horn antenna located about 600 mm away from the output window. After providing adequate amount of attenuation, the output power is detected by crystal detectors calibrated to absolute power. The detected signals are measured typically by a 350 MHz digital oscilloscope with maximum sampling rate of 1 G samples/s.

3. Cathode Geometry

Beam shapes are examined with various shapes of cathode. First, tubular cathodes shown in Fig. 2(a) are tested, which are very common in high-power slow-wave devices. The burn patterns are shown Fig. 3(a). The diameters of cathode with velvet and beam limiter are 23 mm and 26 mm, and the diameters of cathode without velvet and beam limiter are 25 mm and 28 mm. The average electric field between anode and cathode gap is about 90 kV/cm. Velvet cloth with a width of about 2 mm is put on the axisymmetric emitting edge. By adjusting velvet on the emitting area, the width and uniformity of annular beam from the hollow cathode have been improved [5]. The velvet cathode can produce a fairly uniform beam with a relatively good reproducibility. For bare metal cathodes, beam filamentation is unavoidable since the electron emission centers are formed at surface nonuniformities such as cracks or protrusions [2]. The burn pattern is composed of a discrete set of filament as shown in Fig. 3(b). Simply sharpening the tip of tubular cathode decreases the filament size with increasing its number but does not alleviate the discrete emission.

We propose to use a novel disk cathode in the weakly relativistic region less than 100 kV. In this paper, the disk cathode shown in Fig. 2 (b) is tested in the weakly relativistic region. The burn patterns are shown in Fig. 4(a). The diameters of cathode and beam limiter are 25 mm and 28 mm, respectively. The beam generated by the disk cathode has the more uniform distribution and has the higher current density compared with the hollow cathode with velvet. It can be said that the disk cathode is suitable for the weakly relativistic case as well as the relativistic case like Refs. [10, 11]. Note that any coating on the disk cathode surface is not required.

A conical shell cathode Fig. 2(c) had the same cone shape as Fig. 2(b) but is cut out the inner side. Figur 4(b) shows the burn patten for this conical shell cathode. The burn pattern is fairly uniform with a high current density compared with the velvet-tubular cathode, but is distorted slightly compared with the solid cone cathode.

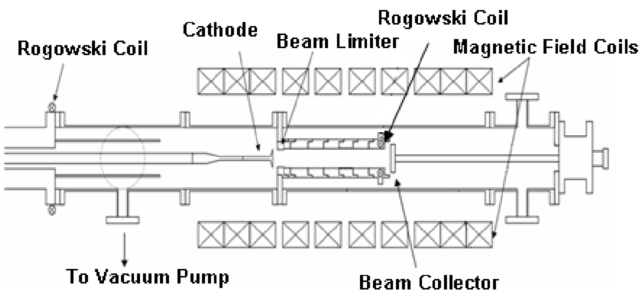


Fig.1 Schematic diagram of the experimental setup.

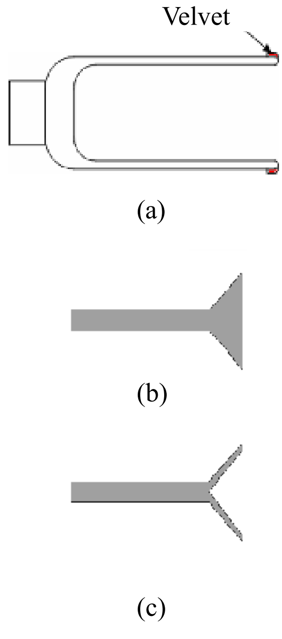
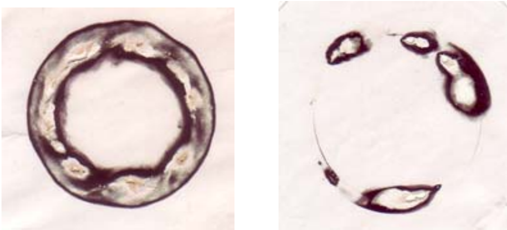
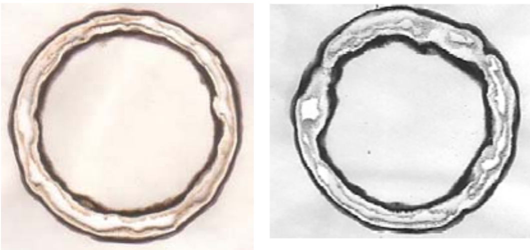


Fig.2 Cross section of (a) tubular, (b) disk and (c) conical shell cathodes.



(a) (b)

Fig.3 Burn patterns of 5-shot overlay for the tubular cold cathode made of aluminum at about 90 kV, (a) with velvet and (b) without velvet. The beam current is about 350 A with velvet and 100 A without velvet.



(a) (b)

Fig.4 Burn patterns of 5-shot overlay, (a) for the solid disk cone made of stainless steel and (b) for the conical shell made of stainless steel. Both are obtained without velvet at about 90 kV and 450 A.

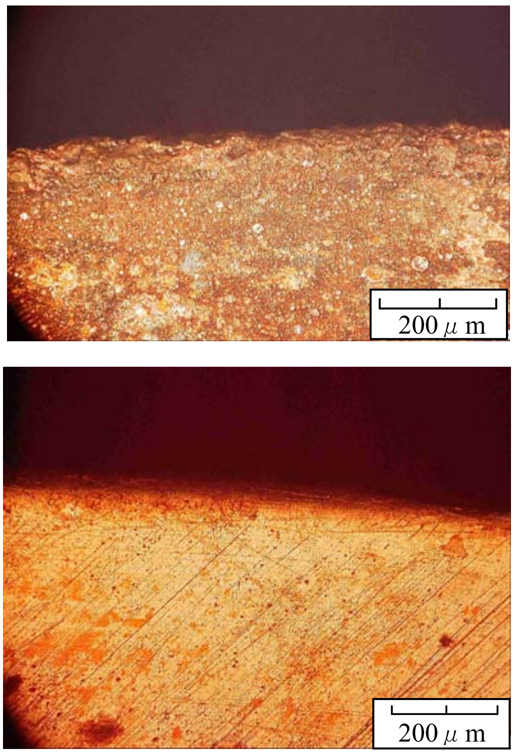
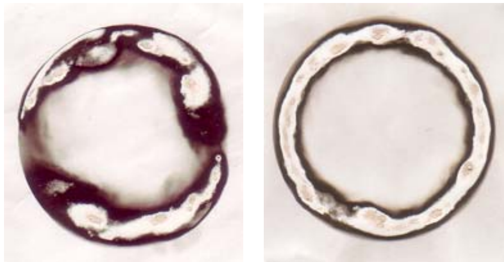


Fig.5 Micrograph of the surfaces of the lathe finished copper cathode (top) and mirror finished copper cathode (bottom).

Table.1 Surface Roughness Measurement

	Lathe Finish	Mirror Finish	After Rasp
Mean Roughness R_a [μm]	0.7～1.0	0.04～0.1	1.3～2.8
Maximum Height R_y [μm]	2.5～3.2	0.35	6.6～7
Roughness of Ten Point of Average R_z [μm]	2.1～2.4	0.31	4.7～6.2



(a) (b)

Fig.6 Burn patterns of electron beam for the mirror finished cathode made of copper: (a) is obtained with the mirror-like surface and (b) is after rasping the surface. Both are obtained by 1-shot without velvet. Beam voltage is about 90 kV. Beam current is about 400 A for (a) and about 450 A for (b).

4. Surface Roughness

We test two disk cathodes with the same solid cone geometry but with the different surface finish, one is lathe finish and the other is mirror-like surface finish. The former corresponds to the cold cathodes presented in the previous section. Figure 5 shows cathode surfaces observed by a microscope with a magnification of 350 times. The condition of each cathodes surface is completely different. Beam burn pattern with the mirror finished disk cathode is shown in Fig. 6(a). This pattern is far from the annular pattern for the lathe finished cathode of Fig. 4. The two surfaces are examined by a surface roughness meter. The surface roughness meter ticks off the surface of object by stylus made of diamond and detect the surface change and indicate the surface form as a graph. To compare the surface roughness of each cathode, there are three indexes: arithmetic mean roughness, maximum height and roughness of ten point of average. We measure the surface roughness in the area about 3mm from the cathode edge. Measured values vary to some extent depending on the measurement area. Hence, the surface roughness is measured several times changing the area. The results are summarized in Table.1. The roughness of the mirror finished surface is of the order of 0.1 μm and smaller than the lathe finished surface by nearly one order. It is the lathe finished disk that emits uniform annular beams. On the other hand, we cannot obtain uniform annular electron beams by the mirror finished disk.

Some surface roughness of the order of 1 μm is necessary to obtain a uniform annular. To roughen the emission surface of the mirror finished disk, the cathode surface is rasped by sandpaper. We first used sandpaper with #150, which means the number of mesh is 150 per inch. The way to rasp the cathode surface is that the cathode is moved with touching to sandpaper up and down 10 times, and after turned 90 degree, the same work is repeated. The burn pattern of the rasped cathode is shown in Fig. 6(b) and results of surface roughness measurement after rasping is listed inTabel.1. With this rasped cathode, we obtain uniformly distributed annular beam with a high current density, which is clearly different from the emission pattern before rasping. Table.1 indicates that the sandpaper can be made finer than #150. And the roughness of 1 μm order is required only for the emission area. To do this, the conic bottom is set on sandpaper at an angle of about 45 degree as Fig. 7 and the cone is rotated 10 times. In this case, #320 sandpaper is used to uniformly scratch the circular sharp edge. There is a possibility that #150 sandpaper may break a sharp edge. The emission areas before and after scratching are shown in Fig.8. The filed edge shows the cracks with 1 μm order.

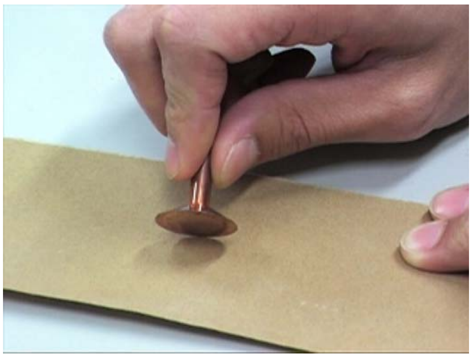


Fig.7 Rasp of the emission edge of disk cathode.

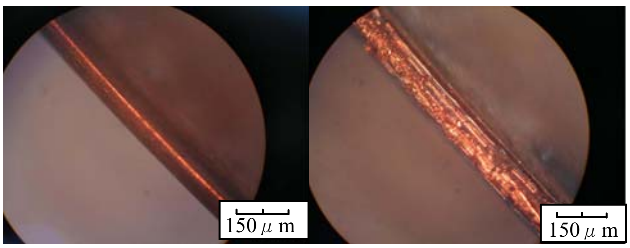
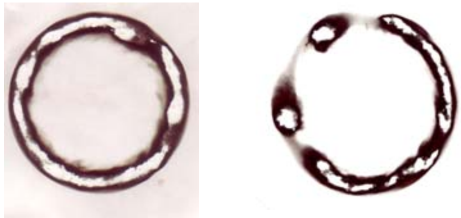


Fig.8 Micrograph of the emission surfaces. Left-side is the mirror finished copper cathode and right-side is the corresponding surface after scratching by sandpaper.

(a) (b) (c)

Fig.9 Burn patterns of (a) copper, (b) stainless steel and (c) aluminum disk cathode. They are obtained by 1-shot without velvet. Beam voltage is about 90 kV. Beam currents are around 400 A.



(a) (b)

Fig.10 Burn patterns of (a) copper and (b) stainless steel disk cathode. They are obtained by 1-shot without velvet. Beam voltage is about 60 kV. Beam current is about 270 A for (a) and about 190 A for (b).

5. Cathode Metal

We examine beam shapes for copper, stainless steel and aluminum disk cathode with the lathe finished surface as Fig.9. In Fig.9, the beam energy density is high enough and 1-shot burn patters are able to be compared at nearly the same voltage. The burn patterns show that the uniformity of annular beam for the copper disk cathode is better than the others. For the copper disk cathode, the annular thickness is about 2 mm or less. For the stainless steel cathode, the annular thickness is almost the same as the copper case. But the uniformity is slightly inferior compared with the copper cathode. For the aluminum disk cathode, the annular shape is distorted and the thickness becomes thick as compared with the copper and stainless steel cases.

As mentioned above, the copper and stainless steel disks generate fairly good annular beams at about 90 kV. We examine the burn patterns by lowering the beam voltage. The copper cathode keeps the thickness and uniformity fairly well, even about 60 kV as shown in Fig.10(a). However, the annular shape of the stainless steel cathode becomes more nonuniform than the copper case by decreasing the voltage as shown in Fig.10(b). In view of annular shape of beam, the copper disk cathode can generate the most uniform emission over a wide range of applied voltage of about 60 kV to 100 kV with several 100 A to 500 A. The stainless steel disk cathode is the second. Generation of the uniformly distributed thin annular beam is very important, since such a beam is required for the improved performance of weakly relativistic high-power BWO as reported in Ref. [6].

6. Discussion and Conclusion

For high-power microwave sources, cathodes play a very important role. Development of reliable cathode has been an important research challenge. In the relativistic region, high current electron beams are obtained by using cold cathodes based on explosive electron emission. Generally speaking, it is very difficult to realize a uniform electron beam. As the cathode voltage becomes lower to the weakly relativistic region, the uniform electron emission becomes more and more serious problem. In this paper, we propose to apply the disk type cold cathode to such a challenging area. The disk cathode comes from an idea to avoid unwanted plasma generation. Disk type sets the entire emitting surface so that it may be almost perpendicular to the guiding magnetic field. One question comes out, i.e., whether the perpendicular component of velocity becomes large or not. In Ref.[10], the pitch-angle for 500 kV and 2.5 kA beam is less than 5 degree, small enough to apply to high-power microwave devises [11]. An important point is whether the generated beam can be used for high-power microwave sources. In Refs.[6-8], the disk cathode is successfully applied to the weakly relativistic BWO, which is oversized to increase frequency and radiation power with its diameter being larger than free-space wavelength λ of output electromagnetic wave by several times or more. In such oversized BWOs, the electromagnetic fields are a surface wave which decreases sharply from the resonator wall. For an effective beam coupling to the surface wave, the beam should propagate near the wall. Hence, generation of thin walled annular beam by the disk cathode is very important. Hundreds of kW powers in K-band are obtained by improving a beam quality as well as the resonator characteristics [6]. In Ref. [10], the disk cathode can produce longer than 1 μs pulse, which is much longer than other explosive cathodes. Figure 11 shows an example of a long pulse operation of weakly relativistic oversized BWO using the disk cathode. Reducing beam scraping of the beam limiter, the pulse length is doubled compared with the typical pulse length of about 0.1μs in previous results of Refs. [3-8]. In our experiments, the pulse duration is mainly determined by the limit of our high-voltage source. The beam voltage and current change with time and have no flattop. In Fig. 10, there is no serious effect of anode-cathode gap closing or other electric discharge at the cathode. If the unwanted discharge occurred, the corresponding strong signals appeared in cathode and beam currents at a later time where the cathode voltage was decreasing. Up to now, the disk cathode is very successfully applied to the weakly relativistic BWO.

In conclusion, the solid disk cathode is an explosive cathode made of bare metal and is tested in the weakly relativistic region. The beam generated by the disk cathode has the more uniform distribution and the higher current density compared with the tubular cathode with velvet. For a uniform emission, some surface roughness of 1 μm order is required on the emission surface. Metals such as aluminum, copper and stainless steel are tested as the cathode material. Up to now, the best result is obtained by a copper cathode. In view of application to the weakly relativistic oversized BWO, it can be said that the disk cathode is very effective for the high-power operation. However, the effects of emission tip angle are still unclear and there still remains to test this explosive cathode at a good vacuum pressure less than 10^{-5} Pa. For a practical use, more definite study on the emission mechanism should be made in the future. Moreover, if well-controlled beams in both real and velocity spaces become available, some physics related to the moving electrons can be examined by a rather simple model and system [12]. In other words, microwave radiations from slow-wave devices can be used as one of the diagnostic methods.

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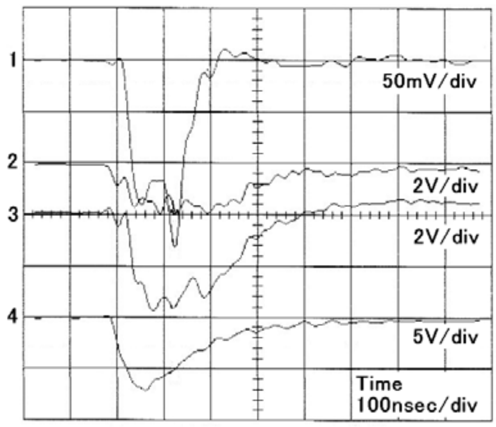

Fig. 11 An example of long-puse operation: 1 microeave, 2 cathode current, 3 beam current and 4 beam voltage. Peak values of beam voltage and beam current are about 90 kV and 400 A, respectively. Estimated microwave power level is around 100 kW.

References

[1] R. J. Barker and E. Schamiloglu, High-Power Microwave Sources and Technologies (IEEE Press, New York, 2001) Chapter 9.

[2] G. A. Mesyats, Pulsed Power (Kluwer Academic/Plenum Publishers, New York, 2005) Chapter 23.
[3] K. Ogura et al., Phys. Rev. E 53, 2726 (1996).
[4] K. Ogura et al., J. Plasma Fusion Res. SERIES 6, 703(2004).
[5] K. Ogura et al.,, IEEJ Trans. FM 125, 733 (2005).
[6] S. Aoyama et al., Trans. Fusion Sci. Tech. 51, 325(2007).
[7] K. Ogura et al., IEEJ Trans. FM 127, 681 (2007).
[8] Y. Takamura et al., Plasma Fusion Res. 3, S1078 (2008).
[9] R. B. Miller, J. Appl. Phys. 84, 3880 (1998).
[10]] O. T. Loza et al.,"Measurement of the Angular Spectrum of Electrons in a High-Current Magnetized REB with Microsecond Duration", Proc. 13th Int. Conf. High-Power Particle Beams, Nagaoka, Japan, pp.603-606 (2000).
[11] K. Han et al., IEEE Trans. Plasma Sci. 30, 1112 (2002).
[12] S. Tamura et al., Plasma Fusion Res. 3, S1020 (2008).