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EFFECT OF PLASMA FORMATION ON ELECTRON PINCHING AND MICROWAVE EMISSION IN A VIRTUAL CATHODE OSCILLATOR

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Abstract

Time and spatial evolutions of anode and cathode plasmas in a vircator diode are observed with a streak camera. A cathode plasma appears immediately after the rise of a beam current and is followed by an anode plasma typically after about 30 ns. Both plasmas expand with almost the same speed of order of 10^4 m/s. The anode plasma was confirmed as a hydrogen plasma with an optical filter for H_β line and study of anode-temperature rise. Electron beam pinching immediately followed by microwave emission is observed at the beam current less than the critical current for diode pinching in the experiment and the simulation. The electron beam current in the diode region is well characterized by the electron space-charge-limited current in bipolar flow with the expanding plasmas between the anode-cathode gap. As a result, electron bombardment produces the anode plasma which makes electron beam strongly pinched, resulting in virtual cathode formation and microwave emission.

Introduction

Electron pinching immediately followed by microwave emission was observed in the virtual cathode oscillator (vircator) with a large aspect ratio, when a electron beam current exceeded a critical current for electron beam pinching[1,2]. On the contrary, the experiment in Himeji showed the strong microwave emission associated with electron pinching at the beam current below the critical current [3,4]. And the electron beam current in the diode region was found to be well characterized by the electron space-charge-limited current in bipolar flow, suggesting the presence of anode and cathode plasmas expanding between the anode-cathode gap. In this paper we report the experimental observation of plasma formation at the anode and cathode surfaces with a streak camera and the simulation results of strong electron pinching due to the presence of anode plasma.

Experiment

The vircator diode consists of an annular cathode with its outer radius R_c of 1.5 cm and thickness of 1.0 mm and an aluminum foil anode of 15 μm in thickness. The A-K gap length d was varied from 0.2 to 0.7 cm. Electron beam currents were measured using a ns-response Rogowskii coil at the upstream (1.1 cm from the anode) and downstream (0.1 cm from the anode). The diode voltage was measured by a resistive divider at the location close to the anode. The emitted microwave propagated along a circular waveguide (radius R = 2.25 cm and 2 m in length) and emitted into a free space through a conical horn. The microwave signals were detected by an open-ended rectangular waveguide antenna (WRJ-10) located at the distance of 1 m from the conical horn. The total microwave power was calculated by numerically integrating the radiation pattern. The microwave frequency was determined with a long waveguide dispersive delay line (WRJ-10, cutoff frequency f_c = 6.55 GHz, and length L=105.7 m). The light from the anode and cathode plasmas was imaged onto the slit of the streak camera (HAMAMATSU C1587) through a quartz window of the wall at the diode region and a focusing lens. X-rays radiated from the anode due to electron beam bombardment were measured using a scintillator (BaF_2) and a photomultiplier, where the spatial resolution for X-ray measurement was ±7 mm which is less than the cathode radius.

Results and Discussion

The typical time evolution of electron beam current, microwave emission and X-ray from the anode center for d = 5 mm is shown in Fig. 1. As seen in Fig. 1, microwave emission appears at the same time of the strong radiation of X-ray from the anode center after about 70 ns of rise of beam current. The beam cross-section measured with an X-ray pinhole photograph was typically 8 mm in diameter. When the axial magnetic field of 0.14 T is applied, the beam cross section was an annular with almost the same diameter as the cathode and there was no microwave emission. These results indicated that strong beam pinching is essential for microwave radiation. The critical current for diode pinching is estimated to be 35 kA with the present experimental parameters (beam energy = 350 kV, R_c = 1.5 cm and d=5mm) which is larger than the observed diode current of 27 kA at the maximum of microwave emission in Fig. 1.

Figure 2 shows the typical time history of diode voltage, beam current, microwave emission, and plasma luminosity at both surfaces of anode and cathode for d = 5 mm. As seen in Fig. 2, a cathode plasma appears on the cathode surface immediately after the rise of a beam current. After about 30 ns of the rise of beam current, an anode plasma on the anode surface is formed. The cathode and anode plasmas in the initial phase expand with approximately the speed of 1.8×10^4 m/s and 2.6×10^4 m/s, respectively. The A-K gap is

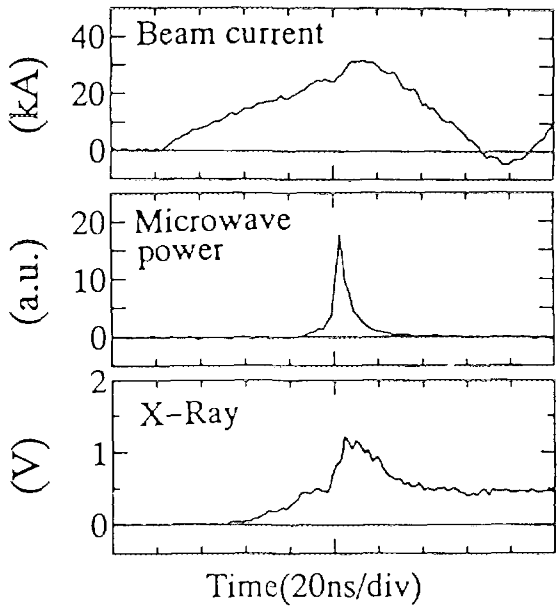

Fig. 1. Time history of beam current, microwave emission and X-ray radiated from the anode.

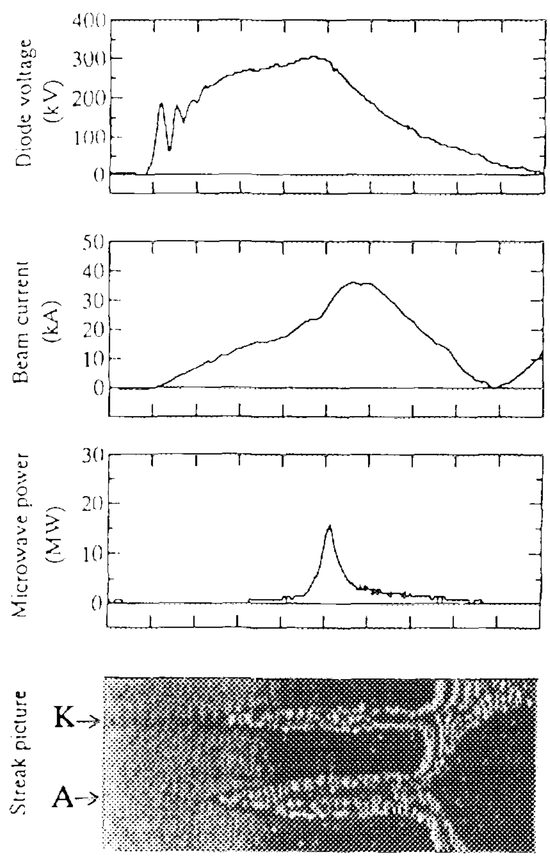

Fig. 2. Time history of diode voltage, beam current, microwave emission and luminosity of anode and cathode plasmas.

closed by both plasmas after about 140 ns from the onset of anode plasma. The maximum microwave emission occurs after 80 ns of the rise of beam current before the gap closure. The microwave peak power was 15 MW with the frequency of 11 GHz and pulse duration of 10ns.

To identify the source of anode and cathode plasmas, the plasma luminosity through an optical filter for H_β line (wavelength: 487 nm and band width: ±5nm) was examined and is shown in Fig. 3. After passing through the optical filter, the luminosity of anode plasma remains, but that of the cathode plasma disappears. This suggests that the anode plasma source is the impurities such as water and oils adhered or absorbed on the anode surface , while the cathode plasma is the ionized metal of cathode material. To estimate the temperature rise caused by electron beam bombardment to the anode, we assume that electrons pass through the anode foil once before microwave emission, because the potential of virtual cathode is not enough to repel incoming electrons to the anode. As the electron range X in the aluminum is much larger than the anode thickness δ, we also assume that δ/X of the beam energy E deposits in the anode. Then, the temperature rise of the anode is written as

$$\Delta T = \frac{\delta}{X} \frac{E J_b t \times 10^{-9}}{\rho C_p X} \quad (^\circ C) \tag{1}$$

where J_b is the beam current density, t is time, and ρ and C_p are the mass density and the specific heat of the anode material, respectively. The electron range in the aluminum is given by [5]

$$X = \frac{0.407 E^{1.38}}{\rho} \quad (cm) \tag{2}$$

Substituting the values of beam energy and beam current in Fig. 2 into eqs. (1) and (2), the anode temperature rise is estimated with ρ=2.69 g/cm^3 and C_p=0.81J/g・℃ for aluminum, the result of which is shown in Fig. 4. Here the annular beam cross section of the same dimension as the cathode was assumed to estimate the beam current density from the beam current in the diode region, since the electron beam should be annular before its pinching. As

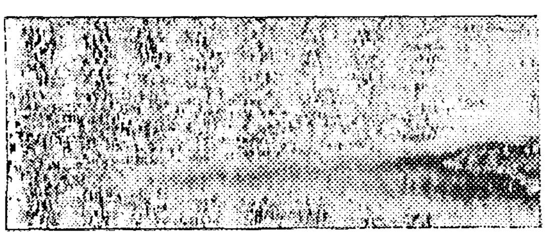

Fig. 3. Streak picture of plasma luminosity through an optical filter for H_β line.

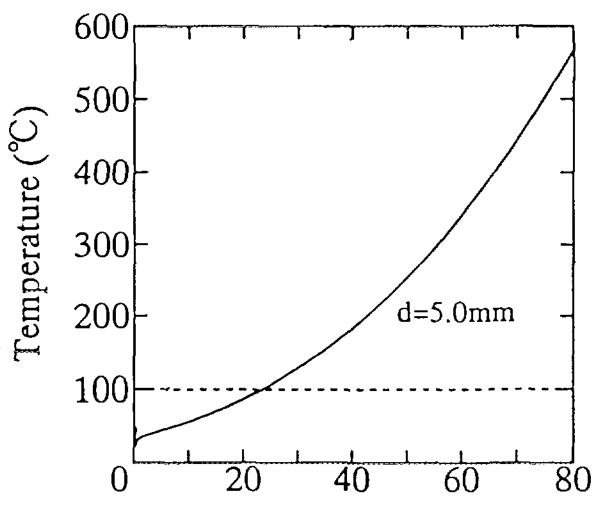

Fig. 4. The anode temperature rise due to electron bombardment.

seen in Fig. 4, at the onset of anode plasma (t=30ns) the anode temperature is 130 ℃ which is enough to vaporize the impurities such as water or oils adhered on the anode surface, but less than the melting point of aluminum (660.4 ℃). These temperature studies support our conclusion that the impurities on the anode surface form the anode plasma.

The trajectory plot of the cathode electrons by MAGIC simulation code is shown in Fig. 5 (a) for non-ion emission from the anode and (b) for ion emission from the anode, where the anode plasma is assumed to expand with the speed of 0.85cm/μs. As seen in Fig. 5, the strong pinching of electrons is observed with the presence of anode plasma.

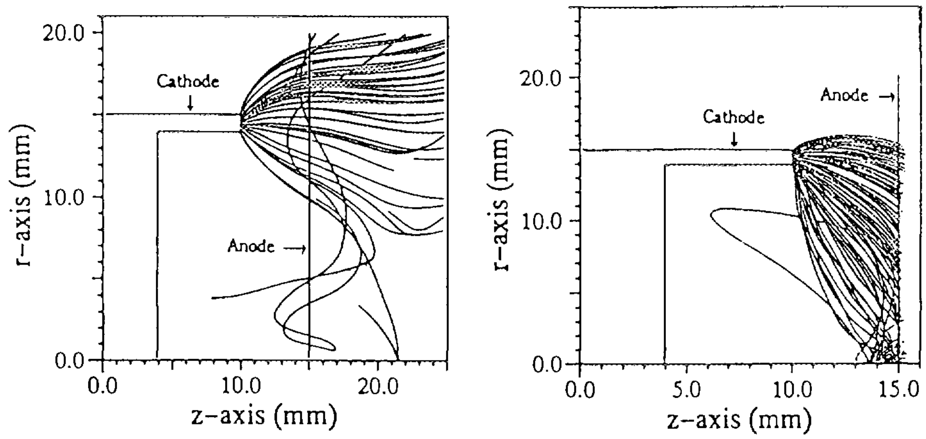

Fig. 5. The trajectory of electrons (a) for non-ion emission and (b) for ion emission.

Conclusion

A cathode plasma appears on the cathode surface immediately after the rise of beam current. After about 30 ns of the rise of beam current, an anode plasma is formed. Both plasmas expand with approximately the same speed of 2 cm/μs. After 30 ns, the anode temperature is estimated to be approximately 130 ℃ which is enough temperature for releasing adsorbed gases such as H_2O from the anode, but is less than the melting point of aluminum. The anode plasma was confirmed as a hydrogen plasma with plasma observation through an optical filter for H β line as well as anode-temperature rise. The MAGIC simulation of electron trajectory shows the strong electron pinching with the presence of anode plasma.

In summary, electron bombardment to the anode produces the anode plasma which makes electron beam strongly pinched, resulting in virtual cathode formation and microwave emission.

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