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A pseudospark cathode Cherenkov maser: theory and experiment

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Abstract

The pseudospark discharge offers the possibility of producing electron beams which are very attractive for use in high-power microwave generation. A pseudospark-based Cherenkov maser amplifier is currently under development at Strathclyde University. The electron beam source for this maser is a multi-gap pseudospark discharge. Preliminary results from recent Cherenkov maser experiments and a comparison with a numerical simulation are presented. A microwave pulse of 100 ns duration and approximately 10 kW peak power was generated by a 80 kV, 20 A beam passed through an alumina-lined waveguide when the interaction was allowed to start up from noise, which appeared to originate from the pseudospark discharge. Simulations agree well with the experimental results when a beam energy spread of 1.5% is assumed.

Keywords: Pseudospark; Cherenkov; Maser

1. Introduction

A pseudospark discharge [1] is a low-pressure, transient hollow cathode gas discharge which occurs in a special geometry in different kinds of gases, e.g., nitrogen, oxygen and hydrogen. The background gas pressure is such that *pd*, the product of the gas pressure *p* and the distance *d* between the front faces of the cathode and anode, is on the left-hand side of the Paschen curve between the Paschen minimum and vacuum breakdown. The pseudospark discharge offers the possibility of producing electron beams of high current density ($>10^4\,\mathrm{A\,cm^{-2}}$), high brightness (up to $10^{12}\,\mathrm{Am^{-2}\,rad^{-2}}$), narrow beam diameter (<4 mm), very low emittance (tens of mm mrad) and variable duration (tens of ns to hundreds of ns) [2,3]. It is therefore very attractive as an electron beam source for high power sources of microwave radiation, such as free-electron lasers (FELs), cyclotron autoresonance masers (CARMs) and Cherenkov masers. This paper describes recent experimental investigations of electron beam production from a pseudospark cathode, preliminary results from

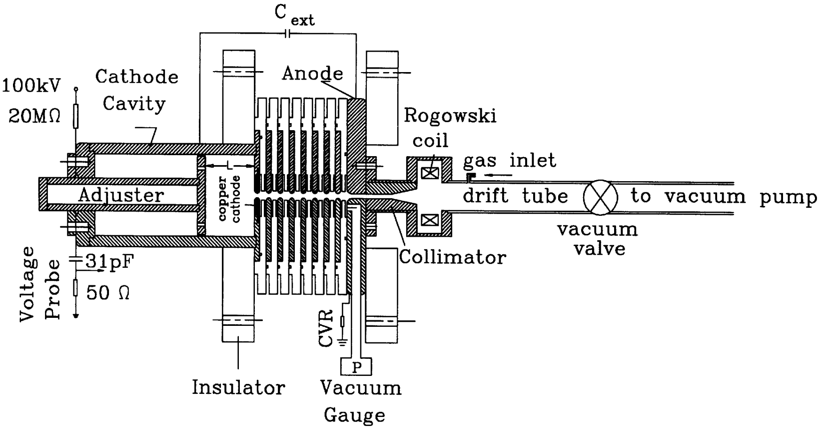

Fig. 1. The experimental set-up for pseudospark-based electron beam production.

experimental investigation of a Cherenkov maser based upon a multi-gap pseudospark discharge, and a comparison of these results with a numerical simulation.

2. Electron beam production from a pseudospark discharge

The experimental setup for the pseudospark-based cathode is shown in Fig. 1. The discharge chamber consists of a planar anode, a planar cathode with an adjustable cylindrical hollow cavity, and several sets of Perspex insulators and inter-electrodes of 6.5 mm thickness. Both the anode and cathode have an on-axis hole of 3 mm diameter. The centre of the cathode was designed to be an interchangeable structure, which allowed different sizes of cathode core and different kinds of cathode materials to be studied. The hollow cathode cavity was made of stainless-steel with outer and inner diameters of 63 and 50 mm, respectively and was length-adjustable through an adjuster. Gas pressure was measured by a digital, active Pirani gauge. The cathode side of the chamber was charged up through a 30 MΩ charging resistor and the charging voltage was measured by a capacitive voltage probe. The discharge current was monitored by a 0.066 Ω current viewing resistor (CVR). The beam current was measured by a Rogowski coil located 6 cm away from the anode and the beam brightness was measured with a 6 cm long cylindrical collimator connected to the anode as shown in Fig. 1.

Basic investigations of electron beam production were carried out on a single-gap pseudospark system for a wide range of parameters, including cathode cavity length, cathode hole size, applied voltage, external capacitance and the inductance in the discharge circuit [4–6]. These experiments showed that the pseudospark discharge phenomenon appeared when the ratio between the cathode cavity length to the cathode hole diameter was greater than 1. The discharge current approximately obeyed the relation $I_{\rm d} = U_0(C_{\rm ext}/L)^{-1/2}$, where $C_{\rm ext}$ is the external capacitance, U_0 is the applied voltage and L is the total inductance in the discharge circuit. To obtain maximum beam current the inductance in the discharge circuit should be minimized. The optimum beam current from the single-gap pseudospark discharge chamber was 100 A at 10 kV with $C_{\rm ext} = 500$ pF. Higher-energy electron beam production, more suitable for high-power microwave generation, was studied using multi-gap pseudospark systems. Fig. 2 shows the beam voltage and beam current from an 8-gap pseudospark system from which it can be seen that the electron beam consists of a high-energy, low-current section ($V \approx 70$ kV, $I \approx 40$ A) followed by a low-energy, high-current section ($V \approx 20$ kV, $I \approx 350$ A). Only the high-energy section is used in the Cherenkov maser experiments described below.

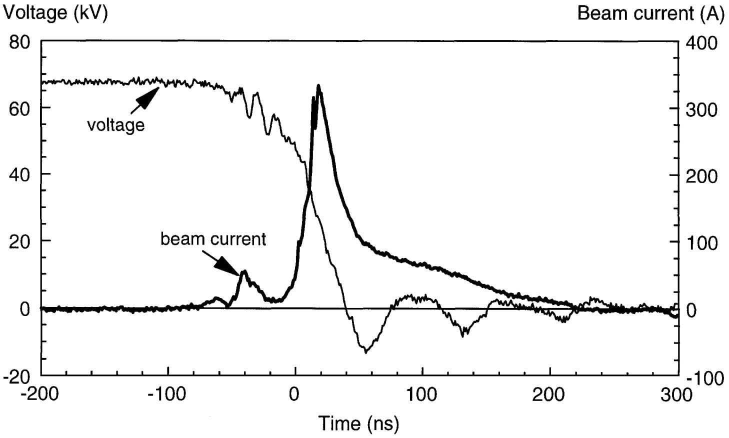

Fig. 2. The beam voltage and beam current from a 8-gap pseudospark discharge.

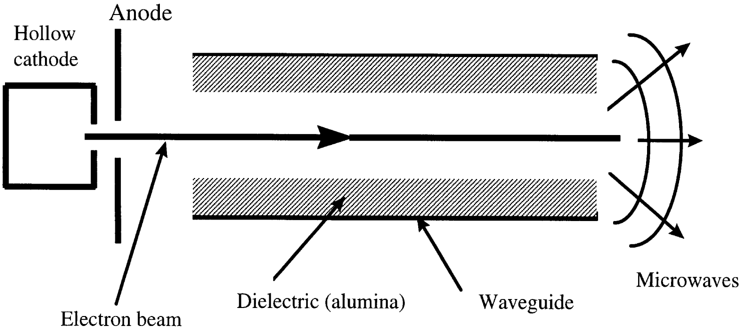

Fig. 3. A schematic diagram of the Cherenkov maser amplifier experiment.

3. Cherenkov maser amplifier experiments using a pseudospark cathode

3.1. Introduction

In order to demonstrate the suitability of the pseudospark cathode as an electron source for high-power microwave generation, a Cherenkov maser amplifier using an 8-gap pseudospark discharge as the electron beam source is being developed at Strathclyde University. In this device, the solid electron beam generated by the pseudospark discharge is passed through a section of cylindrical waveguide, 4.75 mm in radius, lined with a 1.75 mm thick layer of dielectric (alumina), as shown schematically in Fig. 3. The presence of the dielectric allows a resonant interaction to occur between a TM or HE waveguide mode and the electron beam.

For values of the beam and waveguide parameters relevant to the experiment, the force exerted on the electrons by the waveguide mode is dominated by the space-charge force, so the maser will operate in a Raman-type regime, with strongest amplification of the waveguide mode expected when it is resonant with the slow space-charge wave of the beam i.e. when the angular frequency, ω, and the axial wavenumber, k, of the waveguide mode satisfy the relation

$$\omega \approx kv_z - \frac{\omega_p}{\gamma}, \tag{1}$$

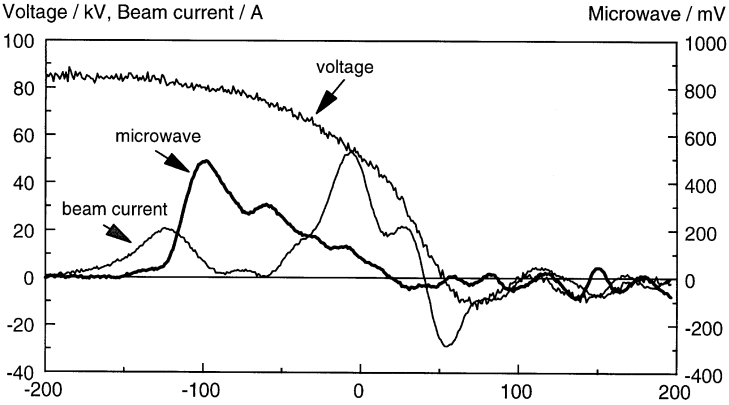

Fig. 4. Oscilloscope trace showing beam voltage, beam current and microwave detector response.

where v_z is the axial electron velocity, γ is the relativistic factor, $\omega_p = \sqrt{(e^2 n_e/\varepsilon_0 \gamma m)}$ is the plasma frequency, n_e is the electron density, and e and m are the electronic charge and mass, respectively.

3.2. Results

First experimental results from the pseudospark-based Cherenkov maser amplifier were recently obtained. The interaction length for these experiments was 60 cm and the microwave radiation was allowed to build up from noise levels. The main source of radiation background noise seems to be the pseudospark discharge itself. A background noise level of ≈ 300 W was present in the frequency range 20 GHz–50 GHz, even when no dielectric lining or guide magnetic field was present. Fig. 4 shows an oscilloscope trace of the beam voltage, beam current and the microwave power output as a function of time. As the beam voltage and current were measured before the interaction region, the microwave pulse lags behind the current pulse by ~ 25 ns. Therefore the microwave pulse occurs when the beam voltage is ~ 80 kV and the beam current is ~ 20 A making due allowance for propagation effects. The frequency of the microwaves was measured to be mainly around 25.5 GHz and the mode was identified as being TM_{01}. The duration of the microwave pulse was approximately 100 ns, with a peak power of ≈ 10 kW. The microwave output was found to be insensitive to the magnitude of the applied magnetic field, which was varied from 0.13 to 0.26 T. The observed frequency ≈ 25.5 GHz, was found to be slightly higher than that predicted by Eq. (1) for the above beam parameters and a cold alumina-lined waveguide (20 GHz). It has been suggested that this discrepancy may be due to charging of the dielectric liner [7]. Another possibility is that the transverse structure of the TM wave-guide mode is modified by the presence of the electron beam.

3.3. Comparison with simulation

A series of computer codes have been developed to complement the experimental investigations of the Cherenkov maser. These codes integrate the Lorentz equations of motion for the electrons self-consistently with Maxwell's wave equation for a TM_{0n} waveguide mode in the steady-state limit. They include the effect of space-charge forces, electron energy spread, and can simulate startup from electron beam noise. Fig. 5 shows a graph of predicted output power from the Cherenkov maser as a function of interaction length for beam voltage $V = 80$ kV and current $I = 20$ A. The microwave power at $z = 0$ was chosen to be 10 W, and the beam radius was 2 mm. The estimate of the noise power is based on an assumption that the bandwidth of the Cherenkov

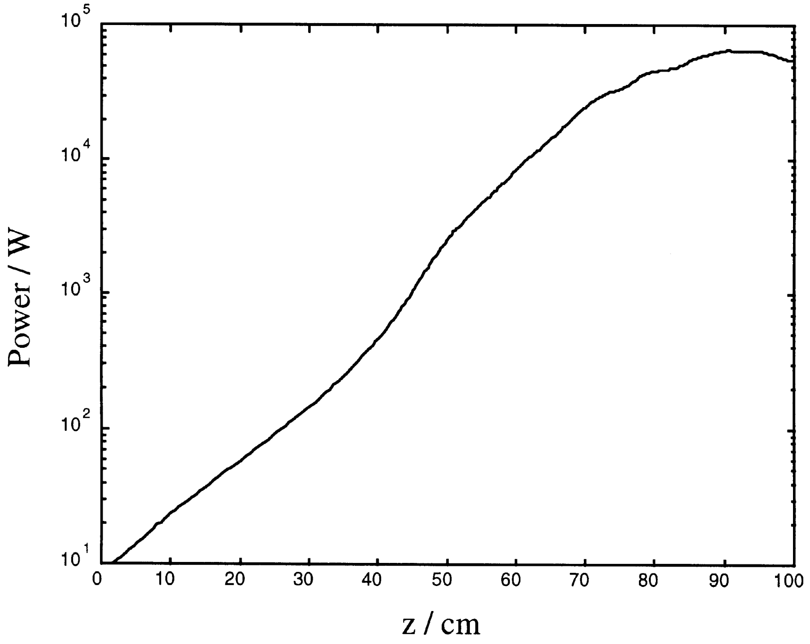

Fig. 5. Predicted output power of the TM_{01} mode as a function of z when $V = 80$ kV, $I = 20$ A, $r_b = 2$ mm, $\varepsilon = 9.6$, $\Delta\gamma/\gamma = 0.015$, $f = 20$ GHz, $k = 914\,\mathrm{m}^{-1}$.

interaction is $\approx 1\,\mathrm{GHz}$ and the noise is distributed approximately uniformly in frequency. From Fig. 5, it can be seen that the power at $z = 60\,\mathrm{cm}$ is $\approx 9\,\mathrm{kW}$ when the initial beam energy spread ($\Delta\gamma/\gamma$) was 1.5%.

Fig. 5 also shows that this Cherenkov maser amplifier is capable of producing high-power microwave radiation from noise levels if the interaction length is made sufficiently long. The predicted power of the radiation at saturation is $\approx 70\,\mathrm{kW}$, which corresponds to an efficiency of 4.4%.

3.4. Future work

The most immediate area of future experimental work involves improving the efficiency of the Cherenkov maser by extending the interaction length and/or using a seed signal. Other areas of future research involve post-acceleration of the low-voltage, high-current section of the electron beam, which should allow the production of very high power microwaves. In addition, we intend to investigate the effect of the voltage sweep across the beam (see Fig. 4) on the microwave output. Time-dependent codes capable of describing such phenomena are currently under development.

4. Conclusions

Electron beam production from a pseudospark-based cathode was studied experimentally using different configurations and external parameters. This cathode was then used as the electron source for a Cherenkov maser amplifier. Starting from noise levels, a 10 kW, 100 ns microwave pulse was produced. The main source of the noise seems to be the pseudospark discharge. Simulations predict that by varying the interaction length and/or using a seed signal, this Cherenkov maser is capable of producing microwave radiation at power levels of $\approx 70\,\mathrm{kW}$. By post-accelerating the high-current section of the electron beam, it is expected that radiation powers of hundreds of kilowatts can be produced.

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