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Simulations of pseudospark discharge and its generated beam to drive a THz EIO

Liang Zhang*, Alan D. R. Phelps, Kevin Ronald, Adrian W. Cross
Department of Physics, SUPA
University of Strathclyde
Glasgow G4 0NG, Scotland, UK
*E-mail: liang.zhang@strath.ac.uk

Jin Zhang, Xiaodong Chen
School of Electronic Science and Engineering
Queen Mary University of London
London, E1 4NS, UK

Jie Xie
School of Electronic Science and Engineering
University of Electronic Science & Technology of China
Chengdu, 610054, China

***Abstract*- Pseudospark (PS) sourced beams have unique features of high-current density and self-focusing by the ion channel. This paper presents the characteristics of the PS-sourced beam from PIC simulations, as well as the potential of the PS-sourced beam for driving a THz extended interaction oscillator (EIO) operating at 350 GHz.**

I. Introduction

Pseudospark (PS) discharges are low-pressure gas discharges in the range of 50 mTorr to 500 mTorr. They were first studied by J. Christiansen in 1978 [1]. A hollow-cavity structure is normally used as the cathode of the PS discharge experiments. The breakdown phase is rapid on a nanosecond scale, and the discharge current can reach tens of kiloamperes with a rise time of a few nanoseconds. This makes the PS discharge an excellent electron beam source. A centered hole on the anode can be used to extract the electrons created during the discharge process for different applications. The current density can be over 100 times higher than a thermionic cathode.

It was also found experimentally that the PS-sourced beam can be transported a long distance without the need for an external guiding magnetic field. Both the high-current density and the beam propagation features are attractive in terahertz (THz) wave generation. In THz electronic devices, one of the biggest challenges is the generation and transportation of the electron beam with high current density due to the small dimensions of the interaction circuit (its beam tunnel is even smaller) [2]. Besides the generation of the THz wave, the PS-sourced beam can be used in other applications such as material treatment, lithography, X-ray generation and plasma jet [3-6].

Many experiments have been carried out to study the discharge mechanism in the last few decades, including the diagnostics of the discharge voltage and current, measurement of the electron beam current using a Faraday cup, plasma density measured using a Langmuir probe, and electron beam profile using a phosphor scintillator. However, the PS discharge is a fast dynamic process (nanosecond scale), and there is limited space for the probes inside the discharge cavity. It is challenging to capture all the dynamic behavior from the experimental measurements during the discharge process.

The numerical simulations are an effective method to understand the temporal and spatial evolution of the discharge process. A hybrid fluid particle and Monte Carlo model was used to study the evolution of the ignition of the PS discharge, where a local field approximation was used to describe the momentum balance [7]. Particle-in-cell (PIC) simulation was also used to get a more accurate simulation, including the impact of the dimensions of the discharge cavity and the pressure of the background gas on the discharge current [8-10].

For the THz electron devices, the beam quality represented by the average beam energy, beam current, as well as energy spread is important for the beam wave interaction. For example, the previous simulations of a W-band EIO showed that the oscillation was not able to grow if the energy spread was over 30%. It is useful to study the characteristics of the PS-sourced beam and to study its limits in the application of the THz electronic devices.

II. PIC simulations of the PS discharge

Simulation of the PS-discharge was carried out using the 2D PIC code XOOPIC [11]. The following physics processes were included: (1) the elastic and ionizing collisions between the electrons and the background gas; (2) Particle re-combination to avoid the explosive increase of the particle numbers; (3) The field emission and secondary electron models; (4) A simplified external circuit model.

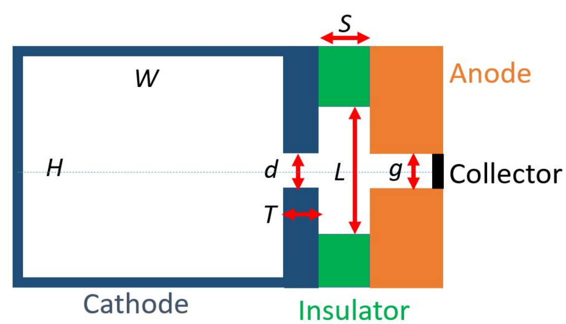

Fig. 1 2-D schematic view of the PS simulation model.

The schematic drawing of the discharge cavity used in the simulations is shown in Fig. 1, the simulations show different beam qualities are achieved at the different discharge stages [12]. The Townsend discharge (pre-breakdown) stage has the largest beam energy, which is close to the charging voltage at the anode. The energy spread is about 10%. The hollow-cathode discharge stage has the balanced performance of the beam energy spread (20%) and the beam energy swept from

70% - 30% of the charging voltage. The super-dense glow discharge stage has the largest beam current. However the beam energy is low, and the energy spread is about 40%, which is not suitable for the beam-wave interaction for the THz electronic devices.

When the electron beam transports through the gas background, the beam front will ionize the background gas to create ions and electrons. The ionized electrons are expelled by the beam electrons to leave the ions. The ion channel can compensate the space charge force from the electron beam, and can stably transport the beam under suitable conditions. Fig. 2 shows the beam propagation at different ion channel densities. The focusing effect of the ion channel is equivalent to a constant axial magnetic field. At a fixed-density ion channel n_i, if the electron beam has a small beam current, equivalently a small beam density n_b much smaller than n_i, the electron beam will be over-focused, as shown in Fig. 2(a) with $n_b/n_i = 0.2$. If the beam density is close to the ion density, the electron beam can propagate with a smaller ripple, as shown in Fig. 2(b) with $n_b/n_i = 1.0$. However, if the beam current is too large, the ion channel is not able to provide sufficient focusing, as shown in Fig. 2(c) with $n_b/n_i = 3.0$. The electrons will defocus rapidly, resulting in greater beam losses.

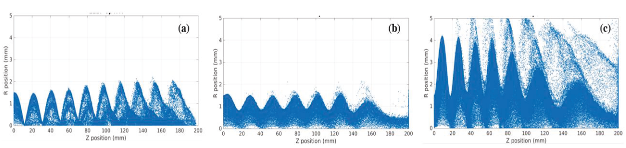

Fig. 2 PIC simulation results of electron beam with different currents

A more in-depth study of the beam transportation in the ion channel is under investigation, including the impact of the dimensions of the beam tunnel, the energy spread of the injected electron beam, as well as different current-density profiles of the electron beam.

III. The EIO structure

The extended interaction oscillator (EIO) has the advantages of high gain per unit length, high electronic efficiency, and a compact structure, which is a good match with the short-pulse duration of the PS-generated beam [13, 14]. An EIO interaction circuit operating at 350 GHz was designed and manufactured. The PIC simulation of the EIO showed a 50 W output power can be achieved taking into consideration a 20% beam energy spread, 10% of the OHFC conductivity (5.8E6 S/m) for the machined structure, and the tolerance from the wire cutting of the interaction circuit. Fig. 3(a) and Fig. 3(b) show the manufactured EIO structure and the cold measurement results using a vector network analyzer (VNA). The operating mode had a resonance frequency of 350.7 GHz, which is very close to the design value. The quality factor of the EIO in the measurement was 215. This matches with the simulation results with 10.3% of the OHFC conductivity.

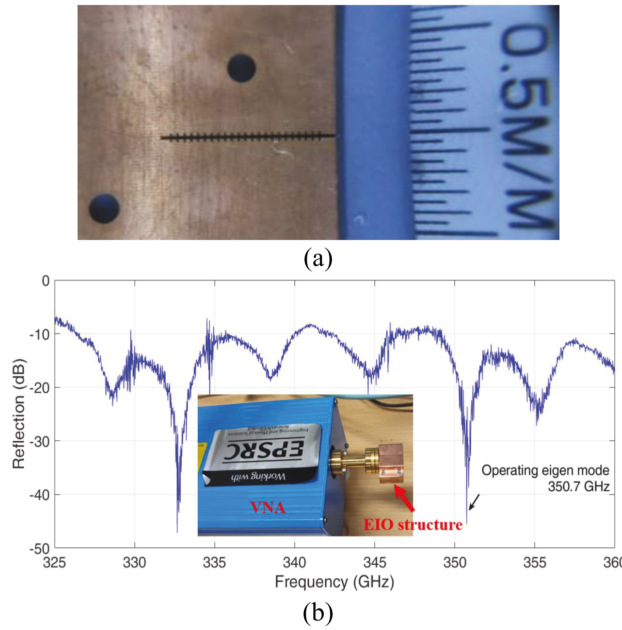

Fig. 3 (a) 2-D view of the manufactured periodic structure (b) the VNA measurement result of the 350 GHz EIO.

IV. Discussion and future work

PS-sourced beam has the advantages of larger beam current density and the self-focusing property. It is attractive for the application of high-power THz wave generation.

The drawbacks of the PS-sourced beam are the short pulse duration, and the large energy spread, compared with the thermionic electron beam source. The short pulse duration can be solved by operating the PS-discharge at a high repetition rate, which requires a stable discharge condition, especially a fast recovery and keeping a stable pressure of the background gas. The solution of the large energy spread is to post-accelerate the electron beam generated in the super-dense glow discharge stage, which will result in a more complicated power supply configuration.

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