Compact High Power Millimetre Wave Sources driven by Pseudospark-sourced Electron Beams

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Abstract: This article presents the demonstration of several compact millimetre wave sources driven both by a pencil or sheet electron beam from a pseudospark discharge. The millimetre wave sources include two pencil beam extended interaction oscillators (EIO) in W-band (75-110 GHz), two sheet beam EIOs in W- and G-band, two pencil beam backward wave oscillators (BWO) in W- and G-band, and one pencil beam Cherenkov maser in Ka-band. These devices can generate up to kilowatts of output power, which are very attractive for many important applications.

1 Introduction

In the millimetre-wave and terahertz (0.1-3THz) region, high power radiation sources have received increasing interest in recent years because of their many exciting applications such as in 'next 5G and beyond' high speed mobile wireless communications, new generation electron spin resonance spectroscopy, remote imaging, high resolution radar, deep-space research, and plasma science and particle accelerators [1-6]. To date, vacuum electronic technology remains still the main method to achieve kilowatt level high power broadband millimetre wave radiation. Nevertheless, when extending to THz frequencies, the radiation power of typical vacuum electronic devices (VEDs) based on thermionic cathode electron beams is often greatly reduced due to the small beam current that can be transported through the device at a particular voltage. The limited beam current is mainly due to the restriction in the electron emission current density from the thermionic emitters. In VEDs high quality intense electron beams are essential as the frequency increases, thus the pseudospark (PS) discharge has attracted a lot of attention recently as a promising source of high quality, high intensity electron beam pulses with the beam current density up to 10^8 A m^{-2} and brightness up to 10^{12} A m^{-2} rad^{-2} [7-11]. This is because a PS-sourced electron beam has the ability to self-focus due to the unique discharge structure and the formation of an ion channel generated by the beam front. This beam has a higher combined current density and brightness compared to electron beams formed from any other known type of electron source and makes it an excellent electron beam source for desirable compact millimetre wave devices. PS-sourced electron beams have been applied in many fields such as material processing, free electron lasers, x-ray sources, extreme-ultraviolet production, and microwave devices [12-19]. Microwave devices based on the PS-sourced electron beam have been experimentally studied covering various frequency bands, such as a Cherenkov maser operating at Ka band [20], extended interaction oscillators (EIOs) operating at W-band and G-band [21, 22], and a backward wave oscillator (BWO) operating at G-band [23]. In contrast to microwave VEDs based on conventional thermionic electron beams, the microwave radiation sources based on a PS discharge can generate a high current density beam that does not require an external magnetic field. In addition, as the PS discharge operates in the pulse mode, which can be driven by a compact pulse power supply, this results in a low cost, portable, sub-terahertz radiation source. It has great potential for the development of high power and compact millimetre-wave radiation sources due to the unique properties of the PS-sourced electron beam.

The PS discharge goes through various complex discharge processes and depends primarily on the PS discharge configurations [24-29]. Since its discovery in 1978, efforts have been made to understand the PS discharge phenomena for the generation of high density and energetic electron beams by theoretical, plasma simulation, and experimental studies [9, 18, 24, 29-38]. Notably, PS discharges have been studied at the University of Strathclyde since 1994 with a series of experiments conducted on beam generation and microwave and millimetre wave sources driven by PS discharges. In this paper, we will review the research conducted and recent advances made in the development of the PS-sourced electron beam and its applications in microwave and millimetre-wave devices at the University of Strathclyde.

2 PS-sourced electron beam

The PS discharge was first developed as an electron beam source in 1978 by Christiansen and Schultheiss [9]. It is an axially symmetric, self-sustained, transient, low pressure (typically 50-500mTorr) gas discharge that occurs in a special type of geometry, which consists of a hollow cathode (HC) with a centric hole and a planar and/or hollow anode in various gases such as nitrogen, argon, hydrogen and

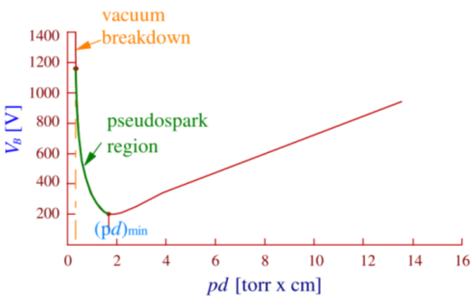

Fig. 1 Discharge *breakdown voltage V_B as a function of the parameter pd (pressure* x *anode–cathode distance).*

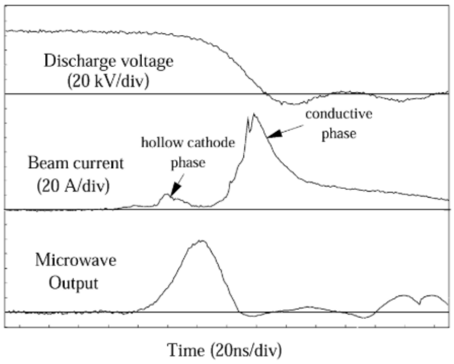

Fig. 2 *Typical waveforms of PS discharge voltage, the beam current, and the microwave pulse.*

xenon [7, 30, 39]. The HC and anode are separated by an insulator or dielectric medium. It operates on the left-hand side (with respect to the minimum) of the HC analogy to the Paschen curve as shown in Fig. 1. [7, 11]. By adjusting the distance (d) between the cathode and anode or the gas pressure (p) in the hollow cavity, the gas present will be subjected to a PS discharge, thereby obtaining a desired high density electron beam. A fast voltage breakdown together with a fast current rise is typical for this discharge resulting in a class of high-power gas-phase switches used in pulsed-power applications [40, 41]. Another remarkable feature of the PS is the complex development with different discharge phases during which bright electron beams, ion beams and extreme ultraviolet radiation can be generated. Therefore, the unusual and interesting properties of the PS discharge have led to diverse applications such as pulsed-power switching, electron beam generation and free electron masers, extreme ultraviolet (EUV) generation and microwave devices [10, 12, 15-17, 31, 42-46].

Generally, the PS discharge has a single-gap or multi-gap structure and can be considered approximately to evolve in three main phases: (1) Townsend discharge, (2) the HC discharge, and (3) the final conductive discharge. During the Townsend discharge phase, some seed electrons are generated when the trigger switch connected to the HC is turned on, which collide with the background gas molecules in the HC cavity to ionize the gas molecules, producing electrons and positive ions. At this stage, the discharge current is small, a plasma or virtual anode begins to form in the discharge gap, and gradually expands from the anode to cathode region. Only in the HC discharge stage, the collision effect is heightened significantly, the number of electrons and ions in the cavity rises sharply and an intense electron beam with high energy can be extracted from the anode. In the third

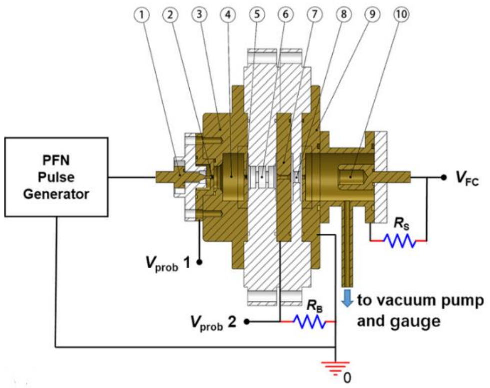

Fig. 3 *Post-acceleration configuration of the PS sourced electron beam. Trigger electrode (1), trigger gap (2), PS cathode (3), hollow cathode cavity (4), cathode aperture (5), PS discharge gap (6), PS anode with output aperture (7), post-acceleration gap (8), grounded flange with output aperture (9), and Faraday cup (FC) (10).*

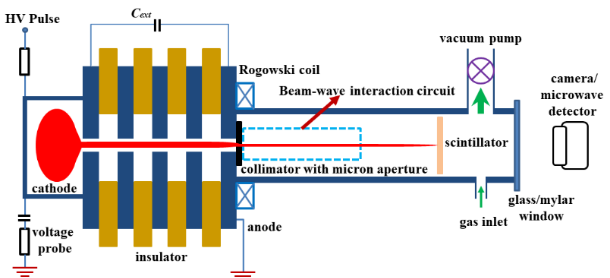

Fig. 4 *Experimental setup of the micro electron beam generation from a PS discharge.*

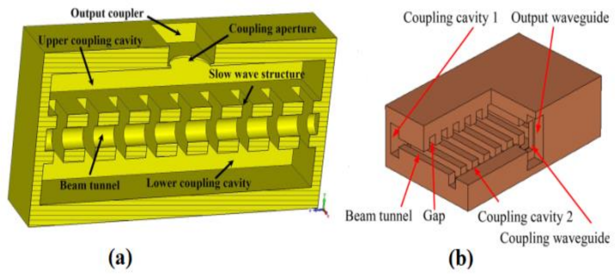

Fig. 5 *(a) Structure of the pencil electron beam EIO, (b) structure of the sheet electron beam EIO*

phase, a large number of electrons are transported in the direction towards the anode aperture, and the electrons in the front continue to ionize the background gas. Due to the comparatively large mass, the positive ions move slowly in the direction towards the cathode because of the applied electric field, providing an ion channel for the electron transport. As a result, the current density of the electron beam reaches a maximum, resulting in the formation of a high current density and bright electron beam. At the same time, the discharge voltage between the anode and cathode would gradually become zero. Similarly, the electron beam current would also decrease to zero.

As already discussed, the behaviour of a PS is very complicated and depends strongly on the internal geometry, discharge conditions and the external circuit configuration.

Therefore a large amount of research has been conducted on the PS discharge characteristics, especially with regard to the formation of an electron beam during the breakdown process. At the University of Strathclyde, Yin *et al*. had conducted an experimental investigation of a single-gap PS using a flexible discharge chamber to study the voltage breakdown characteristics under a wide range of parameters such as gap pressure, gap separation, cathode cavity depth, cathode aperture size, external capacitance and applied voltage [33]. From these experiments, an empirical formula, $V_B = (0.20 \pm 0.05) \cdot p^{-4.02\pm0.18} \cdot d^{-1.77\pm0.01}$, was obtained, where V_B is the breakdown voltage of the PS discharge in kilovolts, and p and d is the pressure in torr and the cathode-anode separation in centimetres, and an electron beam current of up to 100 A from the single gap was measured at 10 kV. Later Zhao *et al*. conducted DC PS discharge experiments with a single-gap PS discharge chamber to study the influence of the electrode-gap separation on the PS-sourced electron beam generation, where the configuration with the large electrode gap separation will generate higher electron beam current with the same discharge voltage [8].

3 Post-acceleration of PS-sourced electron beam

The experimental results demonstrated that the electron beam current in the conductive phase was greater than the beam current in the HC stage of the PS discharge, but the correlated voltage was relatively lower (as shown in Fig.2.) [16, 17]. In the conductive phase, the beam voltage is too small to have efficient beam-wave interaction. While, the high current in the HC stage should allow the production of very high power microwaves as shown in Fig. 2. It would be a great benefit for devices driven by high energy PS-sourced electron beams if the low energy electron beam in the conductive phase can be further accelerated. The first post-acceleration experiment of the electron beam in the conductive phase was carried out on a three-gap PS discharge chamber connected with an acceleration unit, where the beam was successfully accelerated from about 200 V to more than 40 kV, and the more detailed description of the experiment can be found in refs 18 and 32. In order to further simplify the configuration and size of the whole system, a simplified and compact post-acceleration circuit was proposed that could be driven by a single power supply [36]. The configuration consisted of a single gap PS discharge cavity with a post-acceleration gap, a high voltage pulse generator, two high voltage probes, and a Faraday cup used to measure the voltage pulses and the electron beam current, respectively, as shown in Fig. 3. The post-acceleration section is used to accelerate the low energy, high current electron beam to the required voltage for better beam-wave interaction. The triggering, driving of the PS discharge, and the post accelerating of the electron beam can be achieved by only one high voltage pulse. The experimental results demonstrated that an electron beam of ~20 A current, 3mm in diameter and ~180 ns duration could be obtained when a 40 kV voltage pulse is applied. With its high current density, the PS-sourced electron beam has the potential to be used for generating high power microwave radiation at sub-terahertz frequencies.

4 Generation of millimetre wave radiation

In order to demonstrate the suitability of the PS cathode as an electron beam source for high-power microwave generation, a Cherenkov maser using an 8-gap PS discharge as the electron beam source had been developed at Strathclyde University in 1998 [17]. First experimental results from the PS-based Cherenkov maser were obtained. The experimental result showed that a microwave pulse of 100 ns duration and approximately 2 kW peak power was generated by an 80 kV, 20 A beam when passed through an alumina-lined waveguide at 25.5 GHz [17] [18]. The experiment demonstrated the feasibility of generating high power millimetre-wave or even THz-radiation with the PS-sourced electron beam.

One of the most established VED sources of THz radiation is the BWO that can operate up to 1 THz with milliwatt output power. BWOs, like Free Electron Lasers and gyro-BWOs, are able to tune fully and rapidly over a very wide band (~50%) of frequencies. Nevertheless, the main advantages of BWOs driven by PS-sourced electron beams over these similar devices are portability and low cost due to not having to use either a high magnetic field or a large (>100kV) accelerating voltage. To achieve higher BWO output power levels in the THz range, the PS-sourced electron beams with highest combined beam current density and brightness satisfy the beam requirements for THz devices. Among various VEDs, the EIO as a linear beam vacuum device has gained considerable attention as a promising millimetre wave oscillator due to its high gain per unit length and compact configuration [2, 47-50]. At millimetre-wave or THz frequencies, the achievable output power of the conventional O-type VEDs is limited greatly by the electron beam current. The emergence of the PS-sourced electron beam can overcome many of these limitations. Simultaneously, when extending to THz frequencies, the conductor loss will increase greatly. The length of the EIO can be short i.e. of the order of only a few wavelengths long, which is good for reducing the power loss. Using a PS-sourced electron beam instead of the conventional electron beam produced by a thermionic cathode to drive the EIO more compact structures can be realized. A BWO and EIOs based on PS-sourced electron beams have been studied by both simulations and experiments and the relevant parameters are shown in Table 1.

The PS-based BWO experiment was conducted with a small size high current density PS electron beam at 0.2 THz and the experimental configuration is shown in Fig. 4 [23]. The BWO was excited by a PS-based pencil electron beam (PEB) with a diameter of 1 mm, a current of 10 A, and a sweeping voltage of 25-42 kV, resulting in a maximum power of 20 W at the frequency range of 186-202 GHz as shown in Table 1. In this experiment, in order to verify the viability of small-diameter PS-generated electron beams for BWO operation at THz frequencies, micro beams were investigated by using different collimators integrated within the anode of the PS chamber. The electron beam current measurements of the micro-sized beams confirmed that the PS discharge has the potential for producing micro diameter (70 μm) beams for mid-THz frequency radiation applications.

The first experiment of an EIO based on a PS-sourced PEB produced a peak output power over 38 W at W- band, as shown in Table 1 [49]. Figure 5(a) shows the 3D geometry of the EIO structure. It was found that the output microwave power is much smaller than the simulated values. A further study shows that the reduction in the radiation power is

Table 1 Comparison of experimental results for PS-based EIOs and BWO constructed at the University of Strathclyde

Device type	Beam type	Post-ac.	U [kV]	I [A]	P_{out} [kW]	F [GHz]	Ref.
BWO	PEB	No	25~42	~10	~0.02	186~202	[23]
EIO	PEB	No	~38	<4	0.038	>92	[49]
EIO	PEB	Yes	30	10	0.2	92-94	[51]
EIO	SEB	Yes	34.5	21.5	0.01	~200	[22]
EIO	SEB	Yes	32	30	1.2	104-106	[21]

mainly caused by the beam velocity spread and the current lost during the beam propagation in the beam tunnel.

To achieve better beam quality, the PS plasma electron beam has also been investigated with post-acceleration to reduce its beam energy spread [36]. For microwave devices, high energy spread will significantly affect the beam-wave interaction and reduce the output power. The post acceleration technology is able to remedy the limitation and enhance the energy of the electron beam in the conductive phase. A single gap PS discharge cavity with a post-acceleration gap was employed as shown in Fig. 3. The measured radiation power has been increased to 200 W after injecting a post-accelerated pencil PS electron beam, which was nearly 5 times higher than without post acceleration as shown in Table 1 [51]. It shows a significant improvement on the beam propagation and interaction with the EIO with the post acceleration technology.

To achieve higher output power, a sheet electron beam (SEB) EIO structure was developed based on a PS-sourced sheet beam [21, 22, 48]. The sheet electron beam is very attractive due to its enlarged beam cross sectional area and reduced space charge effect. Detailed analysis and design with respect to this SEB EIO has been presented by Shu et al. [48] and Fig. 5(b) shows the structure of the EIO. The experimental configuration is like that in Fig. 3, consisting of a single gap PS discharge cavity, an acceleration gap and planar EIO structure. In the experiment radiation pulses of ~35 ns in duration and an output power of over 10 W at a frequency of ~0.2 THz were measured. A peak output power up to 1.2 kW was also obtained in another W-band experiment [21, 22]. The specific relevant experimental parameters are presented in Table 1, respectively. The experimental results have confirmed the proposed idea that it is feasible to combine the properties of a sheet electron beam generated by a PS discharge system with that of planar EIO structures. It is a significant advance and may contribute to future development of planar VEDs.

By comparing several sets of EIO experiments based on PS-sourced electron beams, it can be found that the post-acceleration technique can overcome the influence of energy diffusion on the interaction efficiency, and improve the energy of the electron beam in the conduction phase, which can obviously improve the output power. It can be seen from Table 1 that the EIO with a sheet beam structure can significantly increase the driving current, thus providing the possibility of generating a high-power terahertz source. As regards the performance of these PS-based devices, the experiments have shown that the devices are greatly influenced by the PS discharge process. If the pressure in the system is uniformly and stably maintained at a proper value for each discharge cycle, the outputs of the devices are very repeatable. The experiments without a post-acceleration unit were carried out in a self-triggered mode by using a needle valve to maintain the system at a certain pressure level and then applying a DC voltage until the discharge occurs. The experiments with a post-acceleration unit were carried out in a triggered-mode by using a needle valve to maintain the system at a certain pressure level and then applying a pulsed voltage with a trigger switch. Great care is needed to maintain the pressure in the system. If the devices are sealed off, the performance would be greatly improved. The PS-sourced electron beam has higher current density than a thermionic electron beam, and the beam formation and focusing does not require an external magnetic field. Moreover, the PS discharge can be initialized by a pulsed voltage; therefore, the whole device including the voltage source could be fitted in a hand-held volume and weight and operated in a torch-like fashion. It is an excellent affordable, compact, and robust pulsed electron beam source to drive VEDs operating at higher frequencies with reasonably high radiation power.

5 Conclusion

In this paper, we present the research and advanced development of PS-sourced electron beams and their application in microwave and millimetre-wave devices at the University of Strathclyde during recent years. The PS has been known since at least the 1970's and has been developed for several applications including switching. Our interest in the PS is related to its ability to produce intense high brightness electron beams as drivers for free-electron sources such as the Cherenkov maser, BWO and EIOs. A Cherenkov maser, driven by the PS-sourced electron beam, operating at Ka-band was first experimentally studied. The experiments have demonstrated that the radiation power can be increased by using post acceleration techniques to enhance the electron beam energy of the PS-sourced electron beam of the conductive phase. Furthermore, it has been found that by optimizing the PS geometrical configuration and by employing micro collimating apertures, micro electron beams can be produced that are ideal for driving small structures suitable for realization of sub-THz sources. A BWO was excited by a PS-based electron beam with a diameter of 1 mm, a current of 10 A, and a sweeping voltage of 25-42 kV, resulting in a maximum power of 20 W at *G*-band. A W-band EIO millimetre wave source was designed and constructed to operate in the 2π mode. With a 35 kV discharge voltage, the EIO successfully produced W-band radiation pulses of 200W peak power and 20ns pulse duration. The experimental results of two EIOs based on PS-sourced SEBs demonstrated that the 0.1 THz and 0.2 THz EIOs could provide output powers of 1.2 kW and 10 W, respectively. These experiments establish the feasibility of generating high power millimetre-waves, or even THz-waves, with PS-sourced electron beams.

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