# Experimental results from backward wave oscillators driven by a pseudospark-generated electron beam

W. He, H. Yin, D. Bowes, L. Zhang, C. R. Donaldson, K. Ronald, A. D. R. Phelps, and A.W. Cross

*Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, UK*

The University of Strathclyde has investigated the applications of electron beams emitted by pseudospark (PS) discharges with an emphasis on their use in the production of radiation in the low terahertz range. To this end, backward wave oscillators (BWO), a form of vacuum tube which utilises the interaction between an axial electron beam and a slow-wave structure, have been designed and modelled using the particle-in-cell code MAGIC before construction of experiments. Successful millimetre radiation generated from BWOs at W-band (75GHz to 110GHz) driven by a 14-gap pseudospark discharge and G-band (140GHz to 220GHz) driven by a 4-gap pseudospark discharge will be presented.

## 1. Introduction

The pseudospark low-pressure discharge has long been of interest for high-speed switching applications but its production of a high current density, high brightness electron beam makes it an ideal driver for some designs of RF, microwave and millimetre-wave sources and there is the potential to extend this application further to THz production, while the formation of an ion channel following the pseudospark anode focuses the beam and eliminates the need for a guiding magnetic field.

In order for a BWO to act as an efficient generator of radiation, a high quality electron beam is necessary. A pseudospark (PS) is an axially symmetric, self-sustained, transient, low pressure (typically 50–500 mTorr) gas discharge in a hollow cathode/planar anode configuration, which operates on the low pressure side of the hollow cathode analog to the Paschen curve [1, 2, 3].

A potentially useful property of this type of discharge is the formation of an electron beam during the breakdown process. During a PS discharge, low temperature plasma is formed as a copious source of electrons and can be regarded as a low work function surface that facilitates electron extraction [4,5,6].

## 2. W-band BWO simulations

BWOs operate using the synchronism between the space-charge wave of an electron beam and the lower eigenmode of a slow-wave structure. Slow-wave structures may be of various configurations, for example an axially- or sinusoidally-rippled waveguide, or through the lining of a waveguide with a dielectric material [7].

In these experiments, a sinusoidally-rippled waveguide was used in which the mean radius was kept as close as possible to cut-off and the sinusoidal variation and period, were varied to produce an interaction in the designed frequency region. Some of the MAGIC-3D simulation results of a BWO slow wave structure in the W-band region excited by an annular 100 kV, 25 A electron beam are shown in Figures 1 and 2. The electron beams produced by PS discharges are self-focussing by the presence of an ion channel. Figure 1 shows the electron trajectories when interacting with the backward travelling wave and figure 2 shows the predicted millimetre-wave output power and frequency.

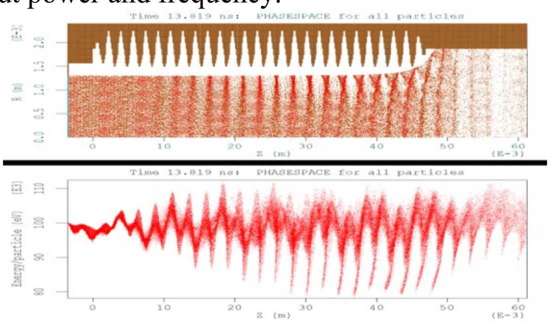


Figure 1: MAGIC-simulated BWO interaction structure showing electron beam propagation.

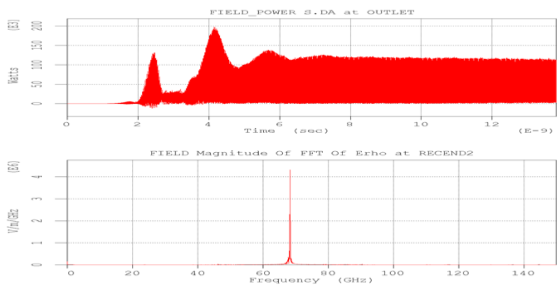


Figure 2: Predicted output power, top, and frequency of output signal, bottom.

## 3. Pseudospark-W-band BWO experiments

The W-band BWO was formed via the electrodeposition of copper on top of a precision-machined aluminium mandrel. Following copper growth, the aluminium mandrel was chemically dissolved and the structure machined to allow for use with the PS anode. The BWO interaction region was made of a corrugated copper structure of mean radius of 3.75 mm, length of 24.5 mm, period of 1.75 mm, and depth of 0.375 mm. The BWO structure was inserted directly into the PS anode aperture before the device was sealed for vacuum pumping.

W-band BWO experiments were configured using a 14-gap PS discharge chamber powered by a cable pulser capable of producing 170 kV voltage pulses of 120 ns duration, (Figure 3). The cable pulser itself can produce a nominal four times multiple of its charging voltage from a dc power supply when the load impedance is much larger than its characteristic impedance of 200 Ω.

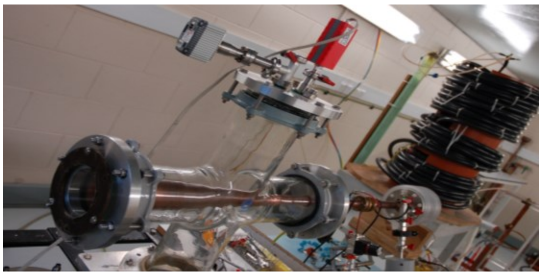

Figure 3 Experimental setup of a W-band BWO driven by a 14-gap PS discharge

Using a two-stage vacuum pumping system, the discharge chamber was evacuated to a pressure of ~ 1 mTorr and a 20 kV pretrigger pulse was applied to the hollow cathode region of the pseudospark chamber. Careful adjustment of two delay units ensured that the initiation of the PS discharge was followed by the generation of the voltage pulse by the cable pulser with both being time-correlated to produce an electron beam for subsequent millimetre-wave generation. The resultant microwave pulse was detected using a W-band detection system located downstream of the BWO output and electrically isolated. Figure 4 shows the detected time-correlated millimetre-wave pulse from the BWO with the electron beam current and voltage pulses [8].

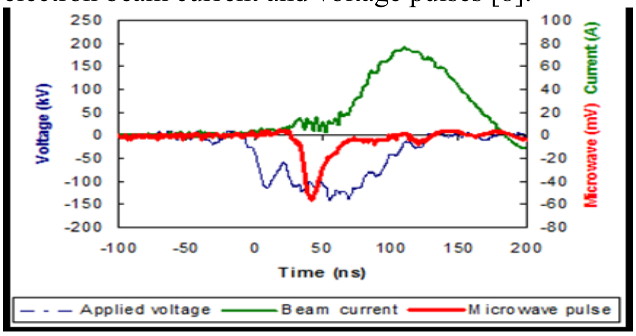


Figure 4: Electron beam voltage and current pulse and millimetre-wave pulse from the W-band BWO.

The experiment shows that the PS BWO is a very promising source for the generation of high frequency radiation.

## 4. Pseudospark – G band BWO experiments

After completion of a successful W-band BWO experiment, the design and construction of a G-band BWO structure was completed. The G-band BWO structure was incorporated into a 4-gap, pseudospark cathode which generated a 4 A, 42 kV to 15 kV, 1 mm diameter electron beam [9]. This high current, small diameter electron beam was propagated through the G-band BWO structure with 188 GHz to 202 GHz radiation measured using a harmonic mixer. Measurements of the power and frequency of the radiation generated are presented and the results compared with numerical simulations, demonstrating the potential of a pseudospark plasma-sourced electron beam to generate high frequency THz radiation.

Another potential application is to scale-down the pseudospark discharge to produce micro sized electron beams striking metal targets to serve as a point-like X-ray source for radiography of small objects [10].

## 5. References

[1] J. Christiansen and C. Schultheiss, *Z. Phys.*, **A290,** 35, (1979).

[2] M. A. Gundersen and G. Schaefer, NATO ASI Ser. B, New York: Plenum (1990).

[3] K. Frank and J. Christiansen, *IEEE Trans. Plasma Sci.*, **17**, 748 (1989).

[4] H. Yin, A.W. Cross, A.D.R. Phelps, W. He, K. Ronald, *J. Appl. Phys.*, **90**, 3212, (2001).

[5] H. Yin, A. W. Cross, A. D. R. Phelps, D. Zhu, W. He & K. Ronald, *J. Appl. Phys.* **91**, 5419, (2002).

[6] H. Yin, A.W. Cross, A.D.R. Phelps, W. He, K. Ronald, *Nuclear Instruments in Physics Research Section A* **1-2,** 378-381, (2004).

[7] H. Yin, A.W. Cross, W. He, A.D.R. Phelps, K. Ronald, *IEEE Trans. Plasma Sci.* **32,** 233-239, (2004).

[8] H. Yin, A. W. Cross, W. He, A. D. R. Phelps, K. Ronald, D. Bowes, C.W. Robertson, *Phys. Plasmas* **16,** 063105 (2009).

[9] D. Bowes, H. Yin, W. He, K. Ronald, A.D.R. Phelps, D. Chen, P. Zhang, X. Chen, D. Li and A.W. Cross, *IEEE Trans. Plasma Sci.*, **42**, 2826-27 (2014).

[10] D. Bowes, H. Yin, W. He, L. Zhang, A.W. Cross, K. Ronald, A.D.R. Phelps, D. Chen, P. Zhang, X. Chen, D. Li, *Nucl. Inst. Meth. B* **335**,74-77, (2014).