A GAS-FILLED CAPILLARY BASED PLASMA SOURCE FOR WAKEFIELD EXPERIMENTS

Thomas Pacey*†, Oznur Mete Apsimon†,
Kieran Hanahoe†, Guoxing Xia†, The University of Manchester, Manchester, UK

Abstract

A plasma medium can be formed when a gas is discharged via an applied high voltage within a capillary tube. A high voltage discharge based plasma source for plasma wakefield acceleration experiment is being developed. Design considered a glass capillary tube with various inner radii. Glass was preferred to sapphire or quartz options to ease the machining. Electrodes will be attached to the tube using a sealant resistant to high vacuum conditions and baking at high temperatures. Each electrode will be isolated from the neighbouring one using nuts or washers from a thermoplastic polymer insulator material to prevent unwanted sparking outside of the tube. In this paper, general design considerations and possible working points of this plasma source are presented for a range of plasma densities from 1×10^{20} to 1×10^{22} m^{-3}. Consideration was also given to plasma density diagnostic techniques due to critical dependence of accelerating gradient on plasma density.

INTRODUCTION

A plasma medium can be formed when a gas is discharged via an applied high voltage within a capillary tube [1, 2]. Such a high voltage discharge based plasma source was designed to provide the plasma medium required by the plasma wakefield acceleration experiments as shown in Fig. 2. A set of glass capillary tubes are available for the tests with a inner radius ranging from 600 μm to 1200 μm in a selection of lengths between 10-30 cm. Glass was preferred to sapphire or quartz options to ease the machining. Electrodes will be attached to the tube using a sealant resistant to high vacuum conditions and baking at high temperatures. Each electrode will be isolated from the neighbouring one using nuts or washers from an organic thermoplastic polymer insulator material and the pins of the feedthrough on the vacuum side will be insulated using ceramic beads to prevent unwanted sparking outside of the tube. For the same token, a sufficient clearance between electrodes and the vacuum chamber was considered.

The whole system is kept in a vacuum chamber as shown in Fig 2. Voltage will be transferred through electrical feedthroughs, designed to function under vacuum and high voltage (30 kV, 10 mA), fitted with flanges interfacing the vacuum chamber. A 30 kV high voltage supply will be used in combination with a thyratron, triggering box and charging circuit.

In a confined volume gas discharge occurs as a function of the gas pressure, p, distance between the high voltage and earth electrodes, d, and the value of the high voltage, V. This relation, Paschen's law [3], is represented with empirical curves in Fig. 1. These empirical curves were extrapolated towards larger pd values in order to investigate the higher range of gas pressures required for plasma wakefield acceleration experiments.

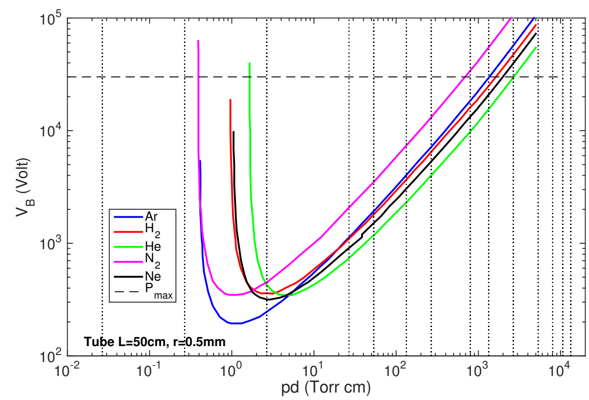

Figure 1: Empirical Paschen's curves for various gases as a function of gas pressure and the distance between the discharge electrodes. Vertical dotted lines denote the conditions given in Table 1 for a 50 cm capillary discharge tube with the radius of 0.5 mm. Horizontal dashed line denotes the limit of the high voltage source. Curves are extrapolated beyond $pd = 10^3$ Torr cm.

Table 1 summaries a range of gas number densities and corresponding pressure values. As an example, according to the Paschen's law, Ar or N_2 gas with the densities ranging from 1×10^{19} to 1×10^{22} m^{-3} can be discharged for voltages up to 30 kV by using a 50 cm long capillary tube.

One of the proposed cell modules can be seen in Fig. 3. The housings will be manufactured from Macor (Corning ®), a machinable ceramic. Macor has been machined into shapes more complex than those required for this design. A facility and costing for the machining has yet to be confirmed. A design prototype will be 3D printed with acrylic to confirm functionality.

NUMERICAL DESIGN STUDIES

Some initial simulation work has taken place to assess the cell designs. Computational fluid dynamics simulation

---

* thomas.pacey@postgrad.manchester.ac.uk
† and The Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK

ISBN 978-3-95450-147-2

Table 1: Various Operating Plasma Densities and Voltage Values Required for the Discharge to Occur in the Plasma Source for Given Distances between the Electrodes and the Gas Pressure

n (m^{-3})	Pressure (mbar)	Pd (5 cm) (mm mbar)	Pd (10 cm) (mm mbar)	Pd (50 cm) (mm mbar)
1×10^{17}	0.000533	0.002665^a	0.00533^a	0.02665^a
1×10^{18}	0.00533	0.02665^a	0.0533^a	0.2665^a
1×10^{19}	0.0533	0.2665^a	0.533	2.665
1×10^{20}	0.533	2.665	5.33	26.65
2×10^{20}	1.067	5.335	10.67	53.35
5×10^{20}	2.7	13.5	27	135
1×10^{21}	5.33	26.65	53.3	266.5
3×10^{21}	16	80	160	800
5×10^{21}	26.7	133.5	267	1335
1×10^{22}	53.33	266.65	533.3	2666.5
2×10^{22}	106.67	533.35	1066.7	5333.5^b
3×10^{22}	160	800	1600	8000^b
4×10^{22}	213	1065	2130	10650^b
5×10^{22}	266.7	1333.5	2667	13335^b

[a]No discharge can occur due to low pressure. [b] No discharge can occur due to power limit.

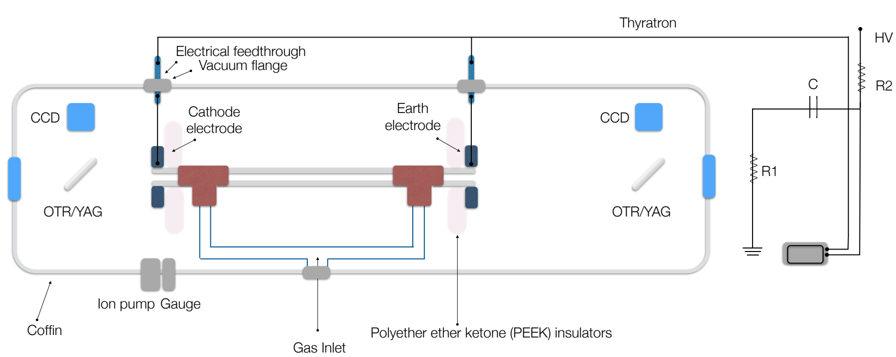

Figure 2: Capillary high voltage plasma discharge source within its vacuum chamber (not to scale).

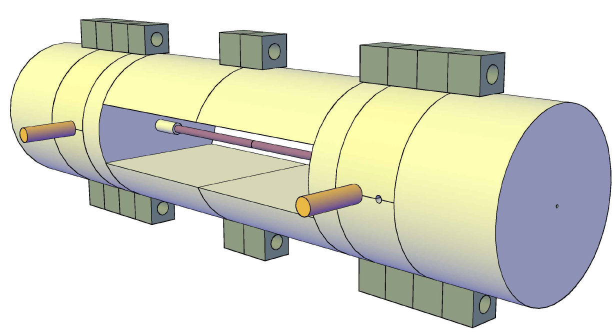

Figure 3: Preliminary design of the housing for the capillary tube.

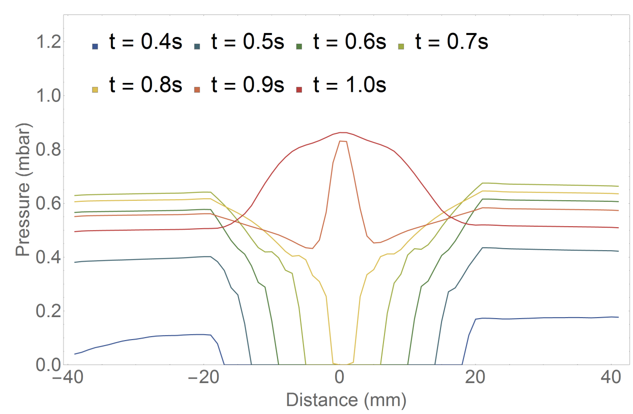

Figure 4: Result of CFD simulation for pressure distribution. Gas inlets are located at edges of the plot, with distance measured from the centre of the capillary.

was carried out in Autodesk CFD Flex [4]. This was 2D, time dependent compressible flow, with gas outflow into an environment at vacuum pressure. The result was that for two gas inlets flowing at 400 $mm^3 s^{-1}$ a pressure of ~0.1 mbar could be stably maintained in the capillary after a transient period of 20 s. The initial pressure distributions can be seen in Fig. 4. Whilst an encouraging result there are questions around the accuracy of the simulation and some detailed study will be needed for improvement.

A preliminary analysis of the discharge circuit parameters was carried out in Mathematica [5]. The discharge is capacitively coupled, with the plasma modelled as a temperature dependent resistor and a parasitic inductance included, such that an RLC circuit is formed. This was based on a paper published by the PWFA collaboration at SPARC-LAB [6]. It models the plasma resistance as a function of electron temperature using the Saha equation to describe the degree of ionisation. Numerical integration is then used to solve the coupling between the current in the RLC circuit and the ohmic heating of the cell. The evolution of electron temperature with time (and therefore gas ionisation degree) can be evaluated. No temperature loss processes are modelled. This provides an order of magnitude estimate of circuit parameters but needs further work to increase accuracy. An example result is shown in Fig. 5. Final Temperatures shown represent well beyond single ionisation, a feature of not including any loss or recombination processes.

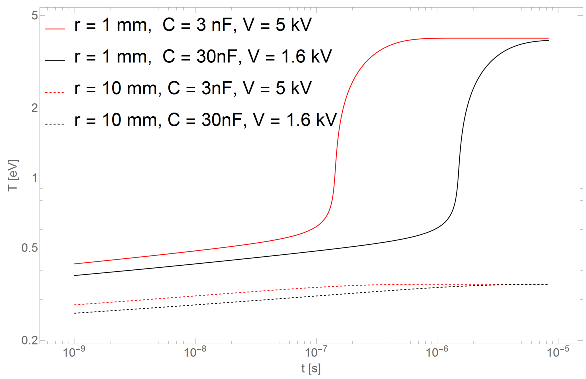

Figure 5: Results of preliminary circuit parameter analysis for electron temperature with time: Low capacitance, high current model (red) and high capacitance/low current model (black). r is cap radius, C is capacitance and V is voltage; scaled so that stored energy is constant.

DIAGNOSTICS TECHNIQUES

Understanding the plasma density is produced is important as this will impact the maximum possible accelerating gradient in an experiment. Simulation work in [7] has shown a factor of 3 increase in density leads to a drop of 62% in accelerating gradient.

Technique 1: Measuring the gas density via broadband interferometry This technique for measuring line of sight gas density dates back to 1986, detail of the method can be found in [8] The technique is an improvement on Hook interferometry, which uses a broadband source and spectrometer in a Mach-Zehnder interferometry setup. This technique has been recently improved and adapted by Max Planck Institute for Physics as part of the AWAKE collaboration. They replaced the optical line with single mode (SM) optical fibre and the Xe lamp with a white light laser. This is in order to maintain precision over long optical transport lengths required to use the technique at the AWAKE experiment. It is assumed that a more economical setup will suffice for the transport lengths required by our experiment; however fibre coupling will be beneficial. A comparison between free space and SM fibre transport will be assessed. The Max Planck group found the technique to be highly precise and reliable, with data sets showing a standard deviation of 0.2%. Comparison with vapour pressure curves lead to a measured accuracy of 5%. The Max Planck group paper can be found in [9].

Technique 2: Utilising the plasma spectrum for density measurement Collecting the light emitted from a plasma of a pure gas allows for measurement of the electron temperature and density. This is achieved through measuring the Stark broadening of characteristic emission peaks and comparison with data sets for known parameters. There are however discrepancies between density calculated for different spectral lines and with the densities calculated from the more precise techniques of laser interferometer according to [10].

CONCLUSIONS

A plasma source will be tested through discharge within a capillary tube in various lengths and radii. Whilst a specific diagnostics setup has not been formed, it should be evident that elements from both techniques mentioned could be combined to give a new measurement regime using one spectrometer. The modified Hook method would accurately measure the gas density, thus providing an upper limit on the electron density for singly ionised plasma. Furthermore, this diagnostic will be important to confirm capillary gas pressure is held stably in the vacuum environment. Once the gas is discharged spectral analysis will be able to measure electron temperature and density in the plasma state. The accuracy of this measurement can be inferred from the gas density measurement. With fibre coupling and robust analysis algorithms this technique could provide a highly flexible diagnostic technique applicable to a variety of experimental setups. A comparison between the two techniques will also be of more general scientific interest. Furthermore validation of CFD simulations can be assessed. Accurate understanding of the plasma density in a plasma wakefield acceleration experiments will be important for comparison with the simulation results in [7]. In the future it is hoped that experiments using a non-uniform plasma generated by altering the gas in flow will be carried out.

ACKNOWLEDGEMENTS

This work is supported by the University of Manchester Strategic Grant. Authors gratefully acknowledge Dr Ali Alaçakır from Turkish Atomic Energy Authority, Dr Anthony Dyson, Prof Simon Hooker, Christopher Thornton from John Adams Institute and Dr Erdem Öz from Max Planck Institute for their invaluable discussions on the plasma source set-up and plasma diagnostics. Figure 3 is produced by an Autodesk educational product.

REFERENCES

[1] D. J. Spence and S. M. Hooker, in *Phys. Rev. E*, vol. 63, p. 015401, 2000.

[2] H. Suk *et al.*, in *Proc. of IPAC'10*, Kyoto, Japan, paper TH-PEC009.

[3] F. Paschen, in *Wied. Ann.*, vol. 37, p. 69, 1889.

[4] `http://www.autodesk.co.uk/`

[5] `http://www.wolfram.com/mathematica/`

ISBN 978-3-95450-147-2

[6] M. P. Anania *et al.*, in *Nucl. Instr. Meth. A*, vol. 740, pp. 193-196, 2014.

[7] K. Hanahoe *et al.*, presented at IPAC'16, Busan, Korea, May 2016, paper WEPMY027, this conference.

[8] W. T. Hill, in *Applied Optics*, vol. 25, pp. 4476-4482, 1986.

[9] E. Oz *et al.*, to be published in *Nucl. Instr. Meth. A*, 2016, `http://dx.doi.org/10.1016/j.nima.2016.02.005`

[10] D. G. Jang, in *Journ. of Instr.* vol. 7, 2011, `http://dx.doi.org/10.1088/1748-0221/7/02/C02045`