Investigation of plasma production properties of discharge capillary waveguides

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Abstract: This paper investigates the testing of plasma waveguides that are suitable for the guiding of high power femtosecond laser pulses in non-linear laser-plasma interaction experiments. Plasma is created by ionising the gas injected into the capillary using a high voltage pulse. Two waveguides were used: each is 4 cm in length but with a different capillary diameter profile. The first waveguide was a linear (straight) waveguide with a constant diameter of 288 μm and the second featured a taper in its diameter from 289 – 232 μm. To characterise the performance of each capillary, high voltage testing was undertaken using a vacuum chamber. The straight capillary produced a steady current of 320 A with a voltage input of 17kV. The tapered capillary was tested with the current flowing from the large end to the small end to produce a reasonably stable current of 300 A with an input voltage of 16 kV. In both straight and tapered capillaries, the temporal fluctuations of the current pulse demonstrates excellent stability of the plasma current.

Keywords: plasma waveguides, discharge capillary waveguides, synchronisation of the laser pulse.

Introduction

Applications for the hydrogen-filled capillary discharge waveguide for LWFA [1-3] and Raman amplification [4, 5] requires stable plasma formation for consistent and reproducible synchronisation with the laser system. The plasma only needs to exist for the short time it takes for the laser pulse to propagate through the waveguide, that is, much less than 1 ns. Therefore, pulsed systems are an efficient method both for gas injection into the capillary on the ms timescale and plasma formation on the 100s of ns or μs timescale.

Many conventional high-voltage power supply designs can be used to produce the short duration voltage pulse to form the plasma discharge [6, 7].

The hydrogen-filled capillary discharge waveguide research at Strathclyde used a pulsed power supply unit that was based on toroidal magnetic transformer technology. However, the large jitter from this power supply was problematic. Temporal fluctuations were not reproducible and were very large (many 10s of ns) at times, which made synchronisation of the laser pulse with the discharge extremely difficult, which has an impact on guiding and laser wakefield accelerator. As a solution, an all solid-state high-voltage pulsed power supply was designed and constructed [10], which helped to minimise temporal jitter for our work.

A completed capillary must undergo testing to ensure it can withstand the plasma production from a gas Temporal jitter in the induced current pulse arises from the stochastic nature of the avalanche ionisation process and is crucially dependent on the rise time of the voltage pulse, which should be minimised. It is also desirable characteristic of to minimise applied voltage for full ionisation to reduce electrical noise in the experimental environment. The goal here is to investigate the hydrogen-filled capillary discharge waveguide for the use of laser wakefield acceleration.

2 Experimental Setup

The work presented here was carried out in the TOPS laser laboratory of the University of Strathclyde. It involved testing of the waveguides to analyse their plasma discharge characteristics, which can be used in experiments such as laser wakefield acceleration [8,9].

and a high voltage source. This involved placing the capillary in holder within a vacuum test chamber and analysing its properties when the gas pressure and voltage are altered. The capillary was initially secured into a 4cm long holder between two electrodes which are contained within Perspex blocks for insulation. The capillary housing is designed to be mounted inside a motorized gimbal mount. On the top of the capillary holder are two gas inlets which direct hydrogen gas [11] into the bore holes of the capillary.

Once the capillary was secured in the Perspex housing, it was placed into the steel test chamber which was then tightly sealed shut and vacated using a rotary and turbo pump until the pressure inside the chamber is sufficiently low. The hydrogen gas is then injected through the gas inlets in which the flow rate of the gas determines the pressure within the capillary. Once the chamber pressure stabilized, the high voltage power supply was turned on and the voltage discharge was triggered by a 30 Hz pulse generator to produce a pulse with a repetition rate of ~1.0 Hz. The input voltage was varied between 0 kV and 20 kV and the backing pressure was kept constant. The effect of the change in voltage was observed on an oscilloscope which displayed the change in amplitude of the voltage of the pulse. The voltage was then kept constant and the backing pressure was varied by altering the gas flow and the effect on the pulse was again monitored on the oscilloscope.

3 Results

3.1 Straight Capillary

The straight capillary was secured in the high voltage test chamber and the vacuum pressure was reduced to 2.5 mBar. The hydrogen gas was set at a flow rate of around 33.0 scc/m (standard cubic centimetres per minute), which produced a backing pressure of 51.1 mBar. The input voltage was between 0 kV and 20.0 kV with a pulse repetition rate of ~1.0 Hz.

A photograph of the visible light emission from the plasma discharge is shown in Figure 1. Uniform emission along the entire length of the capillary is evidence of good plasma channel formation.

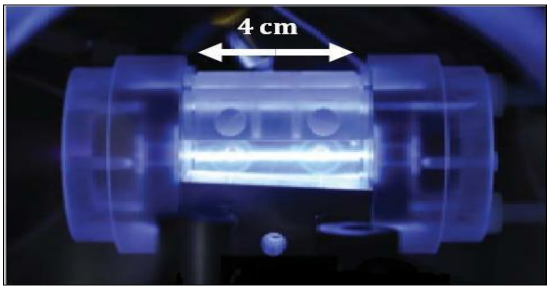

Figure 1: Photograph of plasma discharge formed by HV pulser in the capillary with gas backing pressure of 70 mbar.

Breakdown, as is evident from the current flow, is initiated for peak voltages between 6.4 and 9.1 kV. Typical current pulse is shown in Figure 2. The current reaches a maximum value of 330 A indicating a high degree of ionisation, the full-width at half-maximum pulse duration of the main peak is 900 ns and greater than 90% of the peak value is maintained for ~500 ns. The effect on the current from increasing the voltage is shown in Figure 3.

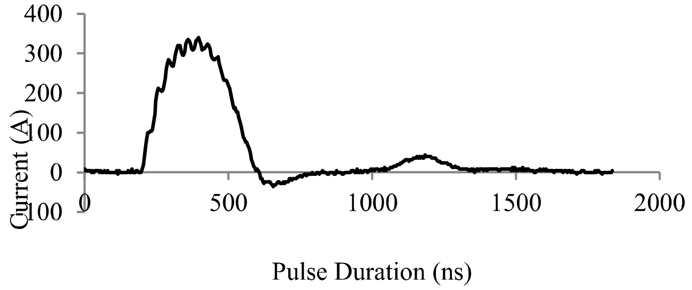

Figure 2: Typical discharge current trace for the straight capillary .

From Figure 3, it can be seen that the current was zero until around 4.0 kV where it increased to 50.0 A. it can be seen that the current was zero until around 4.0 kV where it increased to 50.0 A. This means that 4.0 kV is the threshold for the breakdown of plasma in the capillary [12]. It signifies the ionization of the hydrogen gas and is characterised by a bright violet discharge from the end of the capillary (that was clearly visible with the naked eye). The current increased rapidly from the initial plasma breakdown until 5.0 kV when it began to increase linearly with voltage from 130 A to 330A until about 16.0 kV.

After 16.0 kV, the plasma will start to become fully ionized and so the current will start to level out until it stabilizes and will remain constant. The resistance of the fully ionized gas will not change and so raising the voltage further well have no effect on the current and so it will become saturated at around 330 A. The effect of the pressure of hydrogen on temporal jitter at the maximum DC voltage has been investigated (Figure 4). There is a clear dependence with backing pressure and the lowest jitter is obtained at the highest pressure.

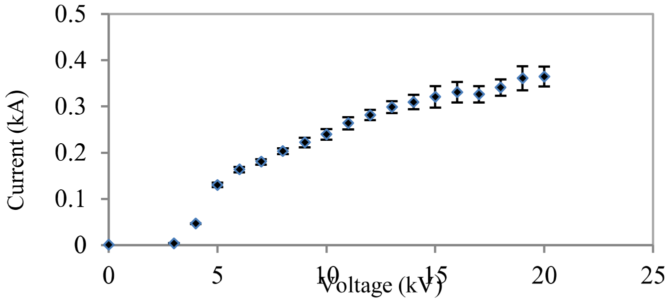

Figure 3: Current through the straight capillary as a function of the input voltage.

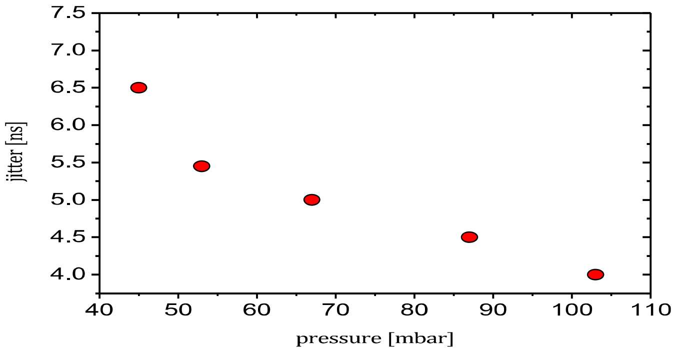

Figure 4: Current pulse r.m.s. temporal jitter as a function of gas backing pressure.

It is clear from Figure 4, that the lowest jitter occurs at around 100 mBar and so this pressure is expected to be the optimum setting for when the capillary to be used in other experiments. The jitter measurements will never be consistent due to its erratic nature, but from the results obtained for the straight capillary, allowed the most suitable testing conditions to be determined.

3.2 Tapered Capillary

In order to fully investigate the plasma production properties of the tapered capillary, it was tested in the high voltage test chamber.

The capillary was placed in the capillary holder with the cathode at the large end of the capillary channel and the anode at the small.

The chamber was vacated to 4.3 mBar and the pulse generator was set to about 1.0 Hz. The voltage was altered between 0 kV and 20.0 kV and the effects on the current were recorded and are shown in Figure 5. It is clear from Figure 5 that the plasma breakdown does not occur until 6.0 kV. This is due to the presence of a density gradient of the gas throughout the tapered channel. After 17.0 kV, the current begins to stabilize and is expected to saturate around 350 A. The optimal plasma breakdown was produced at a pressure of 63.0 mBar, with an input voltage of 16.0 kV to produce a steady current of 300 A. Figure 6 displays trace of the current through the tapered capillary with the optimal settings applied.

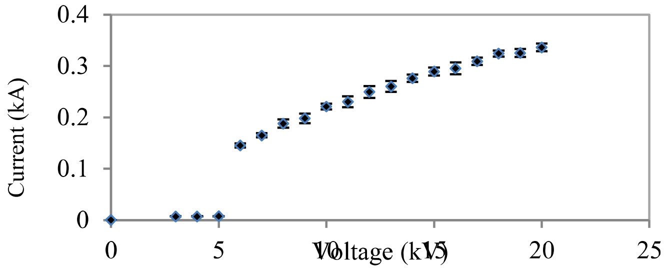

Figure 5: The effect on the current through the tapered capillary as the voltage is increased (cathode at large capillary entrance).

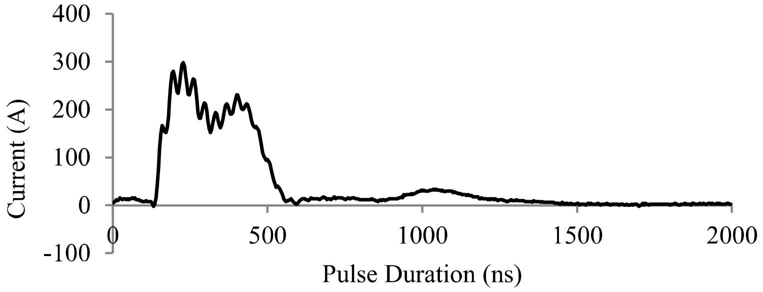

Figure 6 – Typical discharge current trace for the tapered capillary.

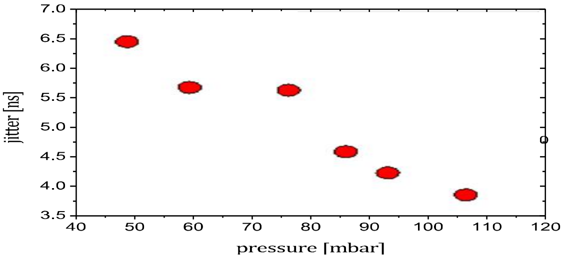

Figure 7: Jitter varying with pressure for the tapered capillary (cathode located at large end of capillary channel).

The effect of the pressure of hydrogen on the jitter has been investigated (Figure 7).Here also, as in the straight capillary, the current pulse jitter reduces at higher backing pressures, which is expected because higher densities of seed free electrons increase the ionising efficiency.

In both straight and tapered capillaries, the temporal fluctuations of the 900 ns current pulse are only ~0.4% of this period, which demonstrates excellent stability of the plasma current which is required for synchronisation with the femtosecond laser pulse.

4 Conclusions

To apply plasma channels in experiments, a pulsed power supply unit has been used. The pulser in a high voltage test chamber, provides a stable breakdown performance, which should be good for successful application in experiments. Because the experiments need stable plasma for consistent synchronisation with the high-power laser pulses arriving in the waveguide.

After testing the straight and tapered capillary in the high voltage test chamber, it is clear that Plasma generation in both capillaries has been shown to be comparable.

In the current pulse, Low temporal jitter will be good for these experiments where stable synchronisation between the arrival time of the laser pulse and the formation of the plasma channel is crucial. The time delay between the onset of the discharge current and the arrival of the laser pulse for stable electron beam generation in the LWFA, for example, can be as narrow as 10 ns [13].

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