Capillary Discharge for Laser Beam Guiding


Abstract – The report describes the work done in the last two years in our laboratories to develop and characterize the laser beam guiding through a plasma channel created by a current discharge in a capillary. This work is carrying out for a project aimed to the laser-driven plasma-wave electron accelerator. In this way electrons are accelerated by the field associated to intense plasma waves driven by an intense laser pulse. It offers the prospect of extremely compact sources of energetic electrons.

The plasma channel was formed in a 200–300 mbar hydrogen-filled capillary discharge unit with a capillary of 200–300 μm. The unit is placed in a vacuum chamber. The electrical circuit consists of a capacitor 1–4 nF charged up to 20–30 kV which is triggered with a thyratron on 6 m long 25-Ohm cable ended by the capillary. It gives us the discharge current about 500 A for the charge voltage 20 kV.

A frequency doubled Nd:Yag laser (@532 nm) with a full width half maximum (FWHM) duration of 5 ns and a pulse energy of 5 mJ was used for the guiding in the capillary plasma discharge of length 15 and 33 mm.

1. Introduction

Many applications of high-intensity laser pulses require an optical guiding to increase the length of interaction with the laser radiation. In the absence of guiding, the interaction length is limited by diffraction to distance of about of the Rayleigh range which is in a practical case close to 1 mm. This limitation was overcome by employment a hydrogen-filled capillary discharge waveguide: guiding of laser pulses with an intensity in excess of $10^{18}$ W/cm² though a distance of few centimetres [1]. The hydrogen-filled capillary discharge waveguide is an example of a plasma waveguide, i.e., guiding is achieved in a plasma column due to a special electron density radial profile. In an ideal plasma waveguide it has a parabolic profile. Plasma with a radial density gradient operates as a converging lens on the laser pulse, opposing the effect of diffraction and keeping the laser beam focused.

In conventional accelerators, energy from RF electromagnetic waves in vacuum is transformed into kinetic energy of particles driven by the electric field. Theses accelerators are limited to relatively low accelerating fields 10–50 MV/m, requiring tens to hundreds of metres to reach the level of a few-GeV electron beam energies.

Laser-wakefield accelerators produce electric fields of the 10–100 GV/m, which is at least a thousand times bigger, when a laser pulse of intensities higher than $10^{18}$ W/cm² is propagating through plasma. To achieve higher energy particle beams one needs lower density plasmas and longer plasma channels. Intense laser pulses guided in the plasma channel excite plasma waves (wakefields) with phase velocities approximately equal to the group velocity of the drive laser pulse. These plasma waves can trap background plasma electrons and accelerate them to relativistic energies of a GeV level on distance of a couple centimetres [2].

Our work deals with this prospect of a new generation of extremely compact particle accelerators based on this idea. The work was motivated by experiments performed at Laboratoire d’Optique Appliquée (LOA) in France by the group of V. Malka. The experiments used a 30 TW, 33 fs laser focused on the plume of a gas jet. A narrow energy spread bunch was observed at 170 MeV [3].

2. Experimental setup operation and guiding test

Figure 1 shows the design of our gas-filled capillary discharge waveguide. Only one electrode part and the capillary plates holder are presented. The capillary was constructed from two sapphire plates of size $20 \times 6 \times 15$ (33) mm³, each with a half-cylindrical groove in its surface like it was proposed in [4]. The experiments have been carried out with the capillary diameters 200 and 300 μm. Hydrogen gas is introduced through two slots $0.6 \times 0.6$ mm² made 2 mm from the capillary ends with help of a pulsed valve at upstream pressure of up to 600–800 mbar. Usually the gas-filled capillary discharge waveguide was operated with a pulsed gas flow of duration 0.5 s. The both

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sapphire plates were placed into rectangular housing tooled in a Plexiglas cylinder sawed on two halves, which were squeezed up with two screws. The stainless steel electrodes 2 with a hole of Ø2 mm were removed about 0.1 mm from the capillary entrances. Well polished plate surfaces and two seals (one 3 close to the capillary entrance and another 4 between outside diameter of electrode and internal wall of the Plexiglas none shown cylindrical insulator) allow assuring any leak of gas and help to prevent any breakdown outside of the capillary channel. The elements presented in Fig. 1 are enclosed into Plexiglas cylinder (none shown) of external diameter 100 mm and length 120 mm. The unit is placed in vacuum chamber diameter 550 mm and height 600 mm which can be pumped up to $10^{-3}$ bar.

The discharge circuit (Fig. 2) comprises small storage 1–4-nF capacitance $C_0$ charged to between 15 and 30 kV. A high voltage pulse is initiated by switching the high voltage side of the capacitor to the ground by a thyratron. A cable with an impedance $\rho = 25$ Ohm and a length 6 m is used to transport a HV pulse to the capillary electrodes. A special HV 25-Ohm vacuum connector, developed in the Centre d’Etude de Gramat (France), was employed to enter the cable into the vacuum chamber. It allows avoiding any perturbation of wave regime for the HV pulse. The use of this cable transport is an important difference with previously built circuit, based on simple LC circuits [1]. The resistance $R_0 = 12.5$ Ohm is used to protect the thyratron and to damp electrical oscillations. When the pulse arrives to the capillary electrode it doubles its amplitude as it happens in the case of open cable output end. It means that, say, with $U_0 = 30$ kV charge we have 40 kV on the capillary ends. When the thyratron is closed, the capacitor $C_0$ is discharging with the characteristic time $\tau_1 = (R_0 + \rho)C_0$ during the time $2\tau_2 = 2L_{\text{cable}}/v = 60$ ns corresponding to returning back of reflected wave from the cable end. With 50–100 ns time delay after the voltage pulse coming to the capillary electrodes, a gas breakdown appears. It gives rise to a current which depends of this delay. In general, its amplitude can be estimated as $U_0/(\rho + R_0)$. In fact, it strongly depends on $C_0$ value and the gas breakdown delay as well (Fig. 3).

The system operation is controlled by measuring of the voltage signal on the cable input with a simple resistive voltage divider and by measuring of the current through the capillary by the current monitor Stan-genes Pulse Current Transformer model 0.5–0.1. The typical current plots are presented in Fig. 3 for the storage capacitances 1, 2, and 4 nF in the case of 15-mm length, 200-µm diameter capillary. One can see that the current amplitude reaches about 500 A with 2 and 4 nF charged to 20 kV.

Operation with the 15-mm length, 200-µm diameter capillary is characterised by the delay between applied voltage and the current 70–98 ns when the charged voltage is 15 kV and the gas pressure changes between 190 and 100 mbar correspondently (Fig. 4). Breakdown of gas-filled capillary gap is a statistical process which introduces delay variation between the thyratron trigger and current flow through the discharge, so called jitter. Its value is required to be rather limited in guiding experiments since the temporal window in which one can guide. Rather high rise time value of the applied voltage pulse of 1.6 kV/ns, in comparison with a simple LC circuits, allows to reach the jitter as small as 0.4–1.8 ns. While operating with 20 kV charge theses parameters are correspondently 47–64 ns delay, 1–6 ns jitter with gas pressure 190–110 mbar. In fact, the delay and jitter parameters depend naturally on voltage charge, capillary length and gas pressure.

The operation with the 33 mm, 300 µm capillary is characterised by the delay between applied voltage and the current about 60 ns and the jitter which can reach ~1 ns when the charge voltage is 25 kV while...
gas pressure is close to 140 mbar. When one operates with 20 kV charge these parameters correspond to 75 ns delay, and ~ 1 ns jitter with the same gas pressure. It’s interesting to note that operation with higher pressure gives shorter jitter. Higher pressure makes operation more stable and more reliable.

Fig. 4. Delay between applied voltage and the current in dependence of gas pressure for the capillary 15 mm length and 200 µm diameter.

Theses characteristics are degrading during experimental work. For example, operation with 200 µm × 15 mm capillary and 4 nF capacitor charged up to 20 kV becomes not acceptable (jitter > 5 ns) after 400–500 shots. We have identified at least two sources of the degradation: 1) the electrodes erosion and 2) an appearance of non regular metal layer on the capillary wall due to electrodes evaporation. We have found that a female thread of the electrode holes allows straightening out the jitter. The pollution of the capillary walls can be reduced by reducing the charged capacitor. Ultra-sound and chemical treatment of the sapphire plates can help as well.

Another problem of our experiments lies in a choice of operation regime. In fact, it’s important to keep vacuum level better than 10⁻² bar at the discharge moment. At higher pressure we observe some current leak outside the capillary due to corona and partial discharge onto close situated chamber wall. With our vacuum chamber and a turbo-molecular pump 600 l/s it’s possible to work at the rate 1 shot per 3 s if the gas pressure inside the capillary is less than 60 mbar. But 150÷300-mbar regime requires a delay 20–40 s between the shots to have pressure 2·10⁻⁴ bar at the shot moment.

3. Experimental guiding

A frequency doubled Nd:Yag laser (@532 nm) with FWHM duration of 5 ns and a pulse energy of 5 mJ was used for guiding experiments. The beam size can be chosen between 50 and 15 µm. The exit plane of the capillary is imaged by a short focal length lens and a microscope (× 25) mounted on a 12 bits CCD camera.

Figure 5 presents a typical guiding result in a capillary of length 15 mm and diameter 200 µm, with \( C_0 = 2 \text{nF} \), \( U_0 = 20 \text{kV} \) and a hydrogen pressure of 200 mbar. This pressure corresponds to an on axis electronic density of \( 5 \times 10^{18} \text{cm}^{-3} \).

![Guiding result](image)

**Fig. 5.** Guiding of a laser pulse in a 15 mm, 200 µm capillary: a – capillary entrance; b – capillary exit, without discharge; c – capillary exit with discharge (delay of 70 ns)

Image a) represents the focal spot at the entrance of the capillary. The laser spot size here \( w_0 = 23 \mu\text{m} \). Image b) represents the exit of the capillary without discharge. The light diffused by the capillary walls is easily visible. On the other hand, when the discharge is fired (here the laser arrives 70 ns after the discharge firing), it is possible to guide the laser. The exit size of the beam is \( w_0 = 19 \mu\text{m} \).

Figure 6 represents the measured pulse-energy transmission as function of delay between the discharge and laser arriving time for the beam \( w_0 = 27 \mu\text{m} \). It is necessary to wait approximately 50 ns after the beginning of the discharge so that the laser is correctly guided. This can be explained by the dynamics of the formation of the density channel. During the following 50 ns, transmission is high, above 80%. Afterwards, the transmission decreases and follows the current curve.

![Transmission versus Delay](image)

**Fig. 6.** Laser energy transmission (beam size 27 µm) as a function of the delay between the discharge and the laser arriving time. Capillary \( L = 15 \text{mm} \), O200 µm, \( C_0 = 2 \text{nF} \), \( U_0 = 20 \text{kV} \) and Hydrogen pressure is 200 mbar

The guiding of beams with waist as small as \( w_0 = 23 \mu\text{m} \) is demonstrated: during 50 ns, it is possible to obtain a high transmission and a good spatial quality. Here the beam is smaller at the exit plane than at the entrance plane, which seems to indicate that smaller beams can be guided.

The operation with \( C_0 = 4 \text{nF} \) storage capacitance allows guiding for larger delay range between the discharge and laser arriving time. Unfortunately, the time parameters (delay and jitter) are degrading quicker.
Work with 1-nF capacitance allows guiding in fairly narrow delay range. That’s why operation with 2-nF capacitance seems to be optimal for our case.

References