# A GAS-FILLED CAPILLARY PLASMA SOURCE FOR LASER-DRIVEN PLASMA ACCELERATION*

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*Abstract*

The supersonic gas jet method for plasma wakefield acceleration has a limitation in acceleration distance and energy because the focused laser beam to a small spot size is diffracted severely over a very short distance (~ a few mm range). To avoid the diffraction problem, a capillary plasma source can be used, where a high power laser beam can be guided over a long distance (~ a few cm range) by a parabolic plasma density profile in the capillary plasma channel. We have developed a gas-filled capillary plasma source for generation of GeV-level electrons. In this paper, the detailed test results and the experimental plan for GeV-level e-beam generation are described.

## INTRODUCTION

The laser wakefield acceleration method can provide much higher acceleration gradient [1], compared with the RF-based conventional accelerators. In the past supersonic gas jets were widely used [2,3], but this method has an important limitation, where the focused laser beam in the supersonic gas flow is rapidly diffracted in a short distance. As a result, the laser wakefield acceleration occurs over a short distance and the gained particle energy is limited. To overcome this problem, the capillary waveguide method have been studied and it turns out that it can produce much higher electron energies up to 1 GeV level [4]. In this method, a high current is generated by gas discharge in a capillary plasma source, and after a while the plasma electrons form a kind of a parabolic density profile in the radial direction due to thermal expansion. If a laser beam is injected into the plasma column, it can be guided over a long distance just like in a waveguide. In the plasma waveguide, therefore, the laser wake field acceleration can produce much higher electron energies, compared with the gas jet method. For this purpose, we developed a capillary plasma source in collaboration with the University of Oxford team [5] and tested it. In this paper, detailed results are reported.

## RESULTS OF THE CAPILLARY PLASMA SOURCE TEST

Figure 1 shows the schematic of the capillary system, which consists of the capillary, the high voltage circuit, and the diagnostics. The capillary is made of sapphire with a hole of 200~300 μm in diameter and a length of 7~50 mm. The capillary hole is filled with a gas, which is provided by a pulsed valve opening (the opening time is about 1 second). For the gas both hydrogen and helium were used, but here test results for only helium is presented. The gas pressure is varied from 50 Torr to 300 Torr, and a high voltage pulse is applied between two electrodes to produce a discharge plasma when the capillary is filled with the gas in the capillary. For laser wakefield acceleration experiment, the laser pulse duration (about 35 fs for high power Ti:sapphire lasers) should be approximately equal to the wavelength of a plasma wave, so the plasma electron density should be of the order of $10^{18}$ cm$^{-3}$ and the gas pressure in this range is used. To generate the high voltage pulse, a simple electric circuit is used as shown in Fig. 1. In the circuit, the DC high voltage power supply charges the capacitor up to 25 kV and the thyratron switch is triggered for conduction. Then a high voltage pulse is applied between the two electrodes in the capillary, and as a result a discharge occurs and a plasma is produced. The plasma current is measured with a current transformer. The produced plasma column emits light as shown in the top of Fig. 1. We collected the plasma light from the axial direction and measured the spectrum by using a gated spectrometer, which can lead to time-resolved information about the plasma.

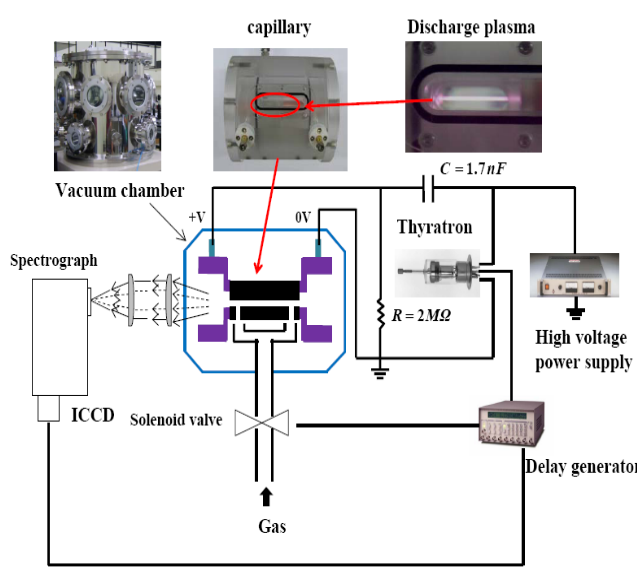


Figure 1: Experimental setup for testing the capillary plasma source.

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The discharge experiments were carried out for diverse experimental parameters. For example, the gas pressure, the charging voltage, capillary diameter and length, etc., were varied to have basic understanding of operation characteristics of the capillary system. Figure 2 shows the discharge current measurement results for different charging voltages. For these measurements the 33 and 50 mm-long capillaries and a gas pressure of 150 Torr are used. In this pressure, the atomic density is calculated as $5\times10^{18}\,cm^{-3}$. The top figure of Fig. 2 shows discharge currents for the 33-mm-long capillary. It indicates that the current increases as the charging voltage increases, as expected. At the same time, the rising time, which is defined as the time from 10 % to 90 % increase of the discharge current, is reduced for a higher voltage. For the case of 25 kV charging voltage, for example, the rising time is less than 100 ns and its peak current reaches about 275 A . When a longer capillary (50 mm in length) is used, the result is shown to have a reduced peak current, as the bottom figure of Fig. 2 indicates.

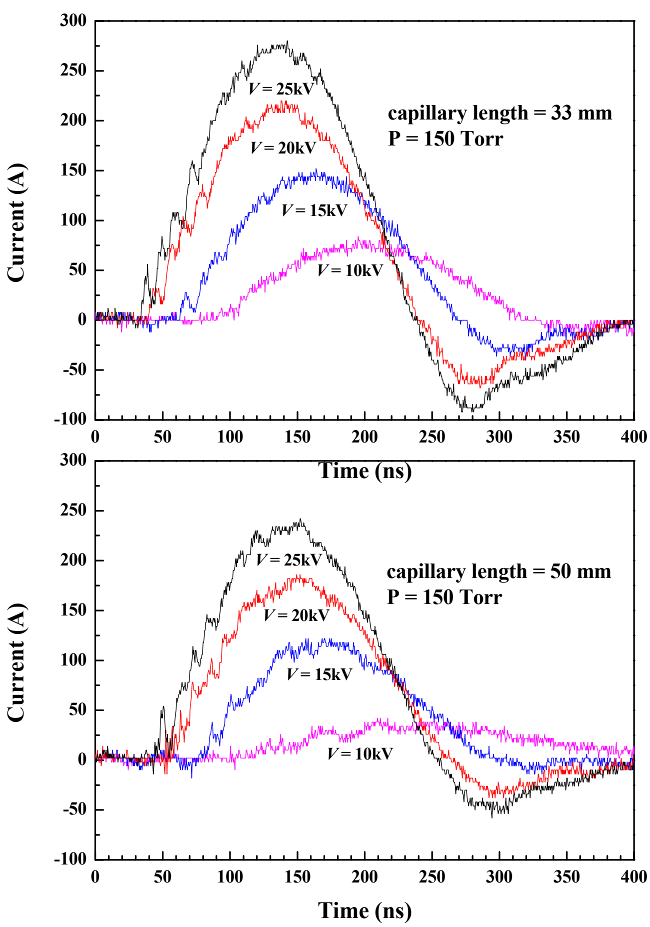


Figure 2: Discharge currents for different charging voltages. The top figure is for the 33-mm-long capillary and the bottom one is for 50-mm-long capillary.

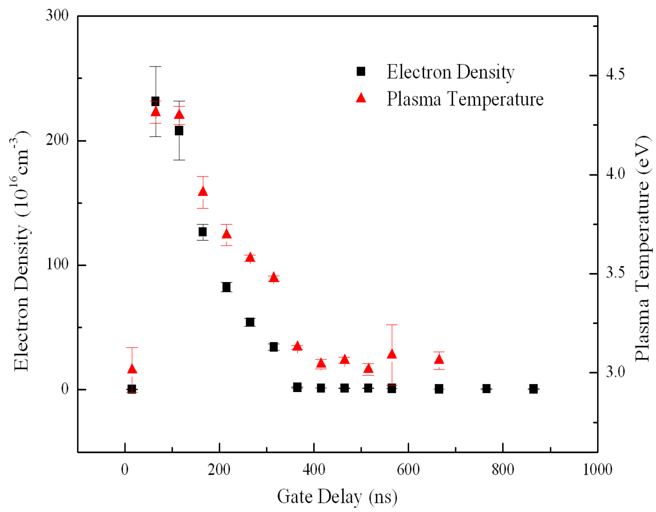


Figure 3: Electron density and temperature of the capillary discharge plasmas as a function of time. For this data helium gas was used.

When the plasma column is formed in the capillary, it changes very dynamically in its radial density profile and this is very important for choosing a right timing for injection of a high power laser pulse. Hence, time-resolved measurement of the density profile is required. This measurement using a Mach-Zehnder interferometer and analysis are under way now in our laboratory. But before dong the time-resolved measurement using the interferometer, we used a gated spectrometer with an ICCD as a first step. For this measurement, we collected the plasma light with a lens in the axial direction for a gate opening time of 50 ns and measured the spectrum. Analysis of the Stark effect on the plasma can lead to plasma density and temperature information [6]. Here, the information is spatially averaged over the capillary hole cross-section. Figure 3 shows the plasma density and temperature measurements for helium gas, where He I (587.5 nm) line is analyzed. It shows that the plasma density sharply increases and reaches a peak value of $2.3\times10^{18}\,cm^{-3}$ after about 100 ns and then it decays rather slowly. The plasma temperature can be also obtained from the assumption of local thermal equilibrium. Analysis of the spectrum gives the temperature information as Figure 3, which shows that the temperature generally follows the discharge current and density profiles. The figure indicates that the plasma temperature is between 3 eV and 4.3 eV, which is reasonable for high pressure, high current arc plasmas. Here, of course, it should be pointed out that the density and the temperature of the discharge plasma are spatially averaged, so it has limitation for understanding of the dynamics of the plasma column. The ongoing experiment for time- and space-resolved measurements with the interferometric technique is expected to give much better information about the plasma dynamics.

## EXPERIMNTAL PLAN FOR HIGH ENERGY E-BEAM GENERATION

Our institute APRI (Advanced Photonics Research Institute) at GIST (Gwangju Institute of Science and Technology) has a 100 TW/30 fs Ti:sapphire laser system and we have a plan to perform a laser wakefield acceleration experiment with the laser and capillary system. Figure 4 shows the schematic of the experimental setup for this experiment. The 100 TW laser beam with a diameter of about 7 cm in diameter is focused to a spot size of about 25 μm by using a spherical mirror with a focal length of 1.5 m. The capillary will be filled with hydrogen with about 150 Torr range and it will produce high energy electrons via laser wakefield acceleration in the forward direction. The electron beam energy and energy spread will be measured with a dipole magnet and Linex system and the charge per bunch will be measured with an ICT (intergrating Current Transformer).

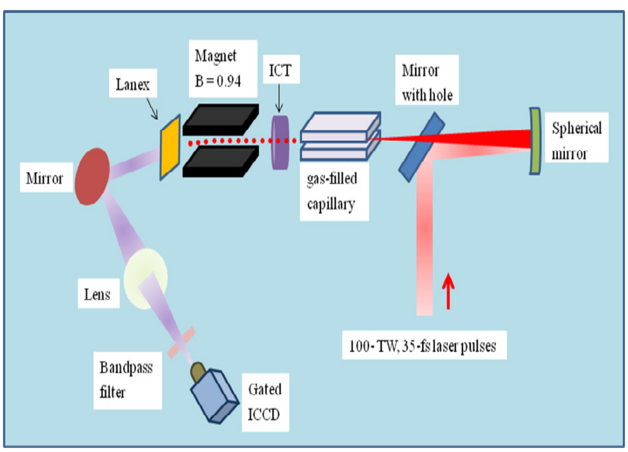


Figure 4: Schematic of the planned experimental setup for high-energy electron-beam generation, where the developed capillary plasma source will be used.

## SUMMARY

We developed and tested a cm-long gas-filled capillary plasma source for application of a laser wakefield acceleration experiment. For time-resolved measurement of the plasma density and temperature, the spectroscopic method with a gated spectrometer was used. The result shows that the capillary can produce a peak plasma density of the order of $10^{18}$ $cm^{-3}$ about 100 ns after the starting of the discharge current, which is good for the laser wakefield acceleration experiment. The plasma temperature was also measured and it is shown to be between 3 eV and 4.3 eV. For time-resolved measurement of the density profile in the radial direction is under way now and it will give more detailed information about the plasma dynamics. The developed capillary system will be used for high-energy electron generation after combining it with the 100 TW Ti:sapphire laser at APRI, GIST.

## ACKNOWLEDGMENT

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