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Longitudinal controllable capillary discharge plasma for laser wakefield acceleration

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The laser wakefield acceleration (LWFA) enables the production of high-energy electron beams on a centimeter scale, offering significant potential for the development of future compact accelerators and next- generation X-ray radiation sources. To generate high quality electron beams, various injection schemes have been demonstrated such as self-injection, ionization injection, density down gradient injection.[1,2] Recently, a high quality electron beam with a narrow energy spread has been produced from density down gradient injection using gas-jet with a sharp blade, which has been applied to free electron lasers.[3]

In the gas jet, a sharp density transition can be effectively generated by a shock wave from a sharp blade. However, the acceleration length in the gas jet is limited to achieve GeV-scale electron beams. An 8 GeV electron beam has been demonstrated using a discharged capillary plasma waveguide with a laser guiding structure over a length of a few tens of centimeters.[4] Therefore, to achieve a GeV-scale energy electron beam with good quality, a capillary plasma waveguide with controllable density shaping is required.

We have developed an innovative segmented capillary plasma source with a plasma density gradient for LWFA. The SC gas cell is composed of sapphire blocks joined together, each with a 1 mm hole created using a diamond drilling.[5] To make density gradient, we inserted a thin sapphire plate with a thickness of 300 μm and a 0.5 mm hole diameter between sapphire blocks to separate pressures. By injecting different pressures into each gas-feeding line, the pressure becomes different as separated by the thin plate, creating a pressure gradient. This SC gas cell facilitates the shaping of longitudinal density profiles within the plasma and is also accompanied by a transverse guiding structure during discharge.

With this segmented capillary (SC) gas cell, without discharge, we conducted experiments using a 150 TW laser system at IBS in GIST. Figure 1 shows the comparison of energy spectra between self-injection and down-gradient injection in the SC capillary gas cell. The energy spread was reduced from 51% to 26% with the density gradient in the SC gas cell. These experiments led to a noticeable reduction in the energy spread of the electron beam.

To measure the density gradient profile, we used discharged plasma in the SC gas cell by pulsed high voltage using a solid-state switch. The density profile was measured by the Stark broadening of hydrogen gas. Figure 2 shows the clear down density gradient formation with a length of around 600 μm which agreed well with a CFD simulation results.

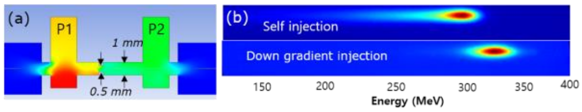

Figure 1. (a) The static gas pressure distribution in the segmented capillary gas cell, with two different pressures P1 and P2, as obtained from CFD simulation. (b) Experimentally measured energy spectra of electron beams from self-injection (top) and down-gradient injection (bottom).

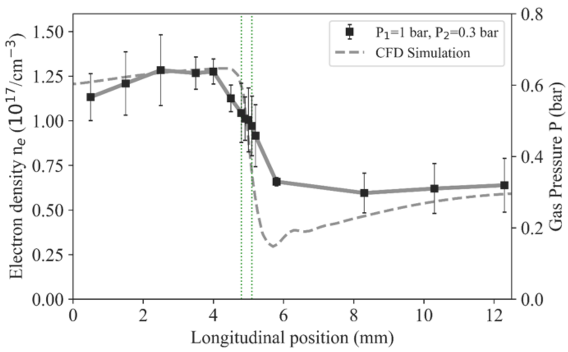

Figure 2. Plasma density profile measured by Stark broadening of hydrogen molecules during discharge. The dotted green line indicates the location of a thin sapphire plate with a smaller hole. The dashed gray line represents the CFD simulation, which agrees well with the experimental results.

We present the development of the segmented capillary (SC) plasma source for LWFA, and its future applications. This work is supported by NRF of Korea under grand no. NRF-2022R1A2C2009768.

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