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Development of a Compact Toroid Injector for C-2 FRC Plasmas
大型FRC実験（C-2）への燃料供給を目的としたCT入射装置の開発

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A Compact Toroid (CT) injector has been developed for a particle fueling to C-2 FRC plasmas. The CT is produced by a Magnetized Coaxial Plasma Gun (MCPG) and has a magnetic field structure similar to Spheromak plasma. The developed MCPG consists of coaxial cylindrical electrodes, whose outer diameter of the inner electrode and inner diameter of the outer electrode are 54 mm and 83.1 mm, respectively. The surface of the inner electrode is coated with tungsten in order to reduce impurities coming out from the electrode. The bias coil is mounted inside of the inner electrode. In the test experiments we have obtained following CT performances: translation speed of the CT up to ~100 km/s, electron density ~5×10^{21} m^{-3}, electron temperature ~40 eV, and particle inventory of ~$0.5\text{-}1.0\times10^{19}$.

1. Introduction

A spheromak can be generated using a Magnetized Coaxial Plasma Gun (MCPG). The conventional MCPG incorporates a set of coaxial electrodes (inner and outer electrodes) and can be easily accelerated over hundreds km/s by the Self-Lorentz force. To produce a spheromak-like plasmoid by the MCPG, at first, the biasing poloidal magnetic field is applied and the working gas is injected between electrodes, and then the MCPG formation bank is triggered for breakdown between electrodes and to ionize the gas. After that, a radial current $\boldsymbol{J}$ is produced through the plasma and it generates the magnetic field $\boldsymbol{B}$ itself. Finally, $\boldsymbol{J}\times\boldsymbol{B}$ Lorentz force pushes out the spheromak-like plasmoid away from the MCPG.

A Compact Toroid (CT) injection has been considered and implemented for one way of fueling to small and middle size tokamaks [1]. The CT can be injected deeply into confined plasma, compared to a gas puff method [2] and a pellet injection [3]. The objective of this study is to develop a new MCPG for FRC particle fueling in the C-2 device [4,5]. This paper describes the design and characteristics of newly developed MCPG and its test experimental results.

2. Developed MCPG and Experimental Setup

Figure 1 shows a schematic view of the developed MCPG on the test stand and a cross-section of gas puff port. The MCPG consists of coaxial cylindrical electrodes, whose outer diameter of the inner electrode and inner diameter of the outer electrode are φ~54 mm and φ~83.1 mm, respectively. Thicknesses of these electrodes are 3 mm. The inductance between electrodes is 86 nH/m. The length of formation and acceleration region between gas port and muzzle of outer electrode is approximately 190 mm. The inner electrode and outer electrode is made of stainless-steel 304L. The surface of the inner electrode is coated with tungsten in order to reduce impurities coming out from the electrode by discharge. The head of inner electrode is machined hemisphere shape, made of solid tungsten. This tungsten head can be replaced with a longer one to extend the length of the acceleration region. Therefore, there is an extension-tube of the outer electrode inside of the ceramic break on the gun muzzle. Moreover, this extension-tube has other importance roles; preventing the ceramic break from a breakdown/discharge, and suppression of a magnetic field diffusion generated by plasmoid.

The two gas valves are located off-axis (tangential, 180° apart) on the outer electrode to prevent a wearing of the inner-electrode surface from localized discharges, and they operate together. In addition, they produce a uniform circumferential diffusion of the gas. Parker valves are used in the test experiment and isolated from the outer electrode with a ceramic break.

The MCPG power supplies are 12 μF of fast bank for the CT formation/acceleration and 50 mF for the bias-field generation. The operating voltages of these banks are 20 kV and 100-300V, respectively. The power supply for the main fast bank is using a crowbar circuit. The bias coil (2 layers of 30 turns) is installed inside of the inner electrode. Magnetic field B_z produced by the bias coil is ~133 G at V_{bias} ~100V (current ~200 A) on the axis.

There are diagnostics for ejected CT/plasmoid measurements in the test stand as shown in Fig. 1: triple probe located at r~3 cm (wall radius ~5 cm), He-Ne laser interferometer (single pass, along the diameter), 6 photo-diodes (unfiltered, #1 and #2 are only shown in the figure), ionization gauge, quad-camera (end-on), and survey spectrometer (end-on). The axial views of those end-on camera and spectrometer can see inside electrodes.

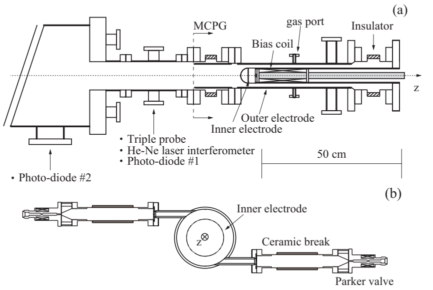

Figure 1. (a) Schematic view of the MCPG attached on the test stand, and (b) cross-section drawing of the gas puff port.

3. Experimental Results

Figure 2 shows the time evolution of typical waveforms of the gun voltage and current. The nominal main charging voltage is 20 kV and the produced current (gun current) between the electrodes is ~250 kA near the peak. The gun trigger time is set to t=0 in the test experiment, and the gas puff timing for different operating gas pressures are as follows: -5 ms (40 psia), -6 ms (30 psia), and -8 ms (20 psia).

Figure 3 shows the bias voltage (field) dependences on the produced CT/plasmoid performance. Translation speed of ejected plasmoid is estimated from photo-diodes. The plasmoid velocity slows down as increasing the bias voltage (i.e., more poloidal flux). On the other hand, as for the gas pressure, more gas-puffed case indicates faster translation speed than that of lower pressure case. One can explain that in low pressure cases, the puffed gas diffuses more in the axial direction due to the gas-puff timing, comparing to higher pressure case. Therefore, the plasmoid velocity tends to decrease in the low gas pressure operation. In other words, in order to produce the faster velocity, it is necessary to have high enough gas pressure locally. The ejected plasmoid particle inventory is estimated form triple probe and He-Ne laser interferometer. It has a wide range of particle inventories (N ~0.1-1.0x10^{19}), which can be controlled by the gas-puff pressure and the bias field.

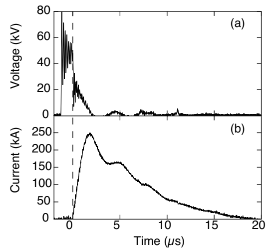

Figure 2. Typical waveforms of discharged gun (a) voltage and (b) current. Dashed line is t=0. This shot charged 20 kV and gas pressure was 40 psia.

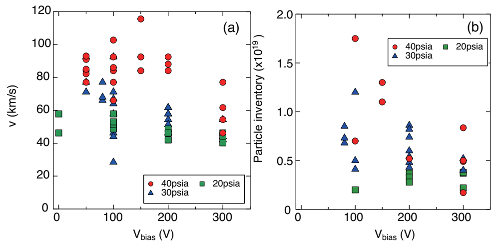

Figure 3. Bias voltage dependences on (a) CT/plasmoid velocity and (b) particle inventory for different gas puff pressures.

Summary

A CT injector has been newly developed and tested on the test stand, planned mainly for FRC particle fueling in the C-2 device. Under optimum operating condition, the CT velocity achieved up to ~100 km/s. The particle inventory can be widely controlled: N ~0.1-1.0x10^{19}.

Acknowledgments

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