Performance Improvement of a Magnetized Coaxial Plasma Gun by Adopting Iron-Core Bias Coil and Pre-Ionization Systems*)

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A magnetized coaxial plasma gun (MCPG) is utilized to generate a compact toroid (CT). An MCPG-type CT injector had been developed as a particle refueling system for C-2/C-2U field-reversed configuration (FRC) plasmas. To inject CTs repetitively for a long-lived plasma, the injector has been upgraded. Iron-core bias coil system has been adopted to generate stationary bias magnetic field. Typical MCPG systems use excess neutral gas to produce a breakdown; therefore, the excess gas tends to flow into the confinement vessel and cool off the edge plasma as well as the target plasma. This negative effect is more serious for repetitive CT injection so that a pre-ionization (PI) system is required to reduce initial gas amount. By injecting the initial plasma using the PI system, amount of the neutral gas for the injector can be reduced. The combination of these systems also expands operating range of the injector. By moving the iron-core bias coil, the radial magnetic field can be controlled. The PI system can easily produce breakdown; therefore, the MCPG can be operated at lower gas pressure, reduced by approximately 40 %. The optimum CT has higher velocity (>100 km/s) and ion temperature (>70 eV), increased by more than 40 %.

Keywords: magnetized coaxial plasma gun, compact toroid injection, stationary magnetic field, iron core, pre-ionization

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1. Introduction

A magnetized coaxial plasma gun (MCPG) is utilized to generate a compact toroid (CT), which has a spheromak-like configuration. It typically consists of a set of coaxial cylindrical electrodes, a bias coil, and gas-puff valves. In a typical MCPG operation, bias magnetic field is firstly applied by the bias coil, and neutral gas is injected between the electrodes. Then, a plasma is generated within the gap by applying a high voltage between electrodes and can be accelerated by $\boldsymbol{J} \times \boldsymbol{B}$ Lorenz self-force; where $\boldsymbol{J}$ is gun current and $\boldsymbol{B}$ is magnetic field which is generated by the gun current. The accelerated plasmoid captures interlinkage bias flux, and the captured poloidal flux induces a toroidal current. Finally, a magnetized plasmoid that has toroidal and poloidal fields is ejected from the MCPG.

MCPG-type CT injectors had been developed as a particle refueling system for C-2/C-2U field-reversed configuration (FRC) experiments [1–3]. The CT injection demonstrated successful refueling with a significant build-up of 20 - 30 % of the total particle number per single CT injection without any disruptive effects on the target plasma [3].

To inject CTs repetitively for a long-lived plasma, a quasi-stationary bias magnetic field is required. By using bias coil with an iron-core, a stationary bias field, without capacitor discharge, is generated; i.e., it does not require a large current. By moving the iron-core bias coil, the distribution of magnetic field between the electrodes can be easily controlled; therefore, a CT proceeds while gathering magnetic field so that the amount of poloidal flux can be controlled.

The neutral gas necessary to produce a breakdown is excessive for generating a CT; the excess neutral gas flows into the confinement vessel and cools off the edge plasma as well as the target plasma; the excess gas also remains inside the MCPG. The CT is generated with the bulk of the gas, while the remaining neutral gas cools the CT. These negative effects are more serious for repetitive CT injection due to the inflow of neutral gas so it is necessary to reduce initial gas amount; thus, a pre-ionization (PI) system is required to solve this issue. By adopting the PI system, the injected neutral gas can be ionized efficiently, and

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the MCPG can break down reproducibly under even lower gas pressure; the PI system can reduce the amount of neutral gas and generate somewhat hotter CTs without cooling target plasmas by the interaction with retained neutral gas.

In this paper, we report the design of these new techniques and the effects of iron-core bias coil and the PI system. The combination of these systems can fulfill requirements for repetitive CT injection and expands the operating range of the CT injector.

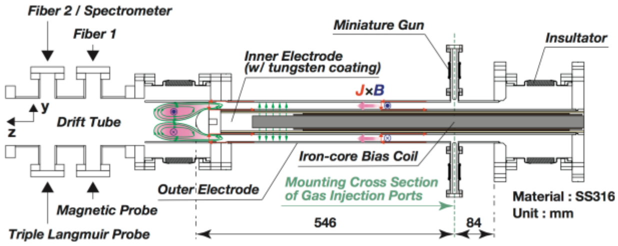

Fig. 1 Schematic drawing of the developed MCPG.

2. Experimental Apparatus

Figure 1 shows a schematic drawing of the developed MCPG. It consists of a set of coaxial cylindrical electrodes, iron-core bias coil, gas injection ports, and a miniature gun [4] as a PI system. The outer diameter of the inner electrode is φ 54.0 mm, and the inner diameter of the outer electrode is φ 83.1 mm. The inner electrode is coated with tungsten to reduce the impurity influx. Energy storage for the main discharge is a capacitor bank of 125 μF with 9.5 kV charging voltage; the inner electrode is negatively biased. The peak value of gun current is approximately 150 kA, its rise time is ~ 10 μs, and the half width is ~ 15 μs.

To evaluate CT performance, the MCPG is mounted onto the drift tube, which has the following diagnostics; collimated fibers, magnetic probes, triple Langmuir probe, and spectrometer. The CT velocity is estimated using time-of-flight (TOF) method from the signals of collimated fibers; the distance between fibers is 9.5 cm. The axial magnetic field B_z and azimuthal magnetic field B_t are measured by the magnetic probes located at just inside of the drift-tube inner wall. The electron density and temperature on the edge of the CT is measured by the triple Langmuir probe located by the inner wall as well. The ion temperature is estimated from Doppler broadening of the divalent carbon (C III) line at 464.7 nm using the spectrometer.

2.1 Iron-core bias coil

An iron-core bias coil has been developed to generate a stationary bias field. The solenoid coil is wound on an acrylic tube (φ 31.8 mm O.D.), which has 1000 turns across two layers and the coil length of 565 mm. It is covered by another acrylic tube (φ 44.5 mm O.D.) to be isolated from the inner electrode. The iron-core (φ 24.5 mm, magnetic permeability: 5000) made of cast iron is inserted into the solenoid coil. A complete set of iron-core bias coil is inserted inside the inner electrode. The solenoid coil and iron-core are also movable independently in the axial direction. By inserting iron-core, an equivalent magnetic field is generated with a much smaller current; even a current of a few amperes produces the required bias field of a few milli-Teslas. The designed bias coil generates approximately 0.25 mWb of magnetic flux at 1 A of bias current. As mentioned above, DC power supply is employed for the bias coil so that the discharge system can be more compact and created easily.

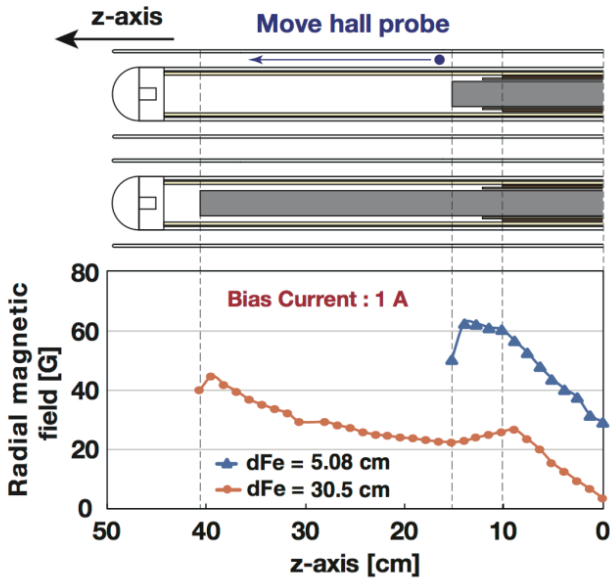

Fig. 2 Axial distribution of radial magnetic field B_r measured by a hall probe at the middle of the gap between electrodes.

Figure 2 shows the axial distribution of the radial magnetic field B_r measured by a hall probe. The edge of the bias coil is fixed at 10.2 cm in z-axis, and only the iron-core is varied from 5.08 cm to 30.5 cm. The maximum B_r is different in both cases. By making a short length between the end of iron-core and coil, B_r is increased compared to the long iron-core case. On the other hand, the distribution of B_r is spread over a spatially wide range by the iron-core length protruding from the edge of the bias coil, and this result is similar to a calculation result by COMSOL Multiphysics modeling software [5]. From this result, the bias magnetic field can be easily controlled by changing the iron-core length and coil position.

2.2 Pre-Ionization system (miniature gun)

A miniature gun [4] has been developed as a new PI system to reduce excess neutral gas. Figure 3 shows the diagram of the experimental setup of the miniature gun with the discharge circuit. It has coaxial cylindrical electrodes and bias coil. The outer diameter of the inner electrode is φ 8.0 mm, and the inner diameter of the outer elec-

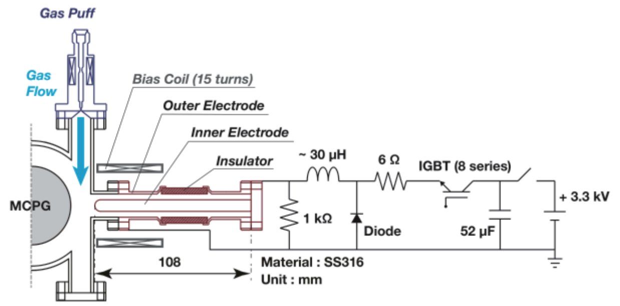

Fig. 3 The diagram of the experimental setup with the discharge circuit. This cross-section corresponds to the dashed line in Fig. 1.

trode is φ 16 mm. The miniature gun is installed radially at the same cross-section as the gas injection ports. The discharge method is similar to MCPG's; neutral gas flows into the gap between the electrodes, and a plasma generated by a high-voltage breakdown in the miniature gun is accelerated/ejected by Lorenz self-force. A bias field is also applied to assist breakdown between miniature gun's electrodes. The inverter circuit, consisting of 8 IGBTs in series, switches the discharge current on the miniature gun. The inverter unit is protected from the surge voltage using a charging-type snubber circuit. A diode and inductor also installed for protection from high voltage and large current of the MCPG. The charging voltage of the 52 μF capacitor bank is 3.3 kV, and the inner electrode is positively charged. Typical waveform of the discharge current has a flattop with approximately 550 A at the peak, and the rise time is ~ 14 μs. The miniature gun starts to discharge at 40 μs before the main discharge of MCPG, and the duration of current is 30 μs; the duration can be adjusted arbitrarily. The impurity influx should be negligibly small because of its low current. By adopting the miniature gun, MCPG breakdown can occur at lower gas pressures than that of without the PI system.

3. Experimental Results

Figure 4 shows the variation of CT parameters while changing iron-core length (*dFe*) and coil position (*dCoil*) without the PI system, where *dFe* is the length between the edge of the coil and the end of iron-core, and *dCoil* is the distance between the edge of the coil and the gas port. Here, the bias current is 1.85 A and the gas pressure is 0.276 MPa.

By changing *dCoil* and *dFe*, the bias magnetic flux and the bias field distribution in the area where the plasmoid accelerates can be controlled; consequently various CT parameters can also change. According to the experimental result seen in Fig. 4, the CT velocity can be affected by both the coil position and the iron-core length. While, B_z depends more strongly on the coil position than on the iron-core length. In the cases of *dFe* = 0 and 40.6 cm for

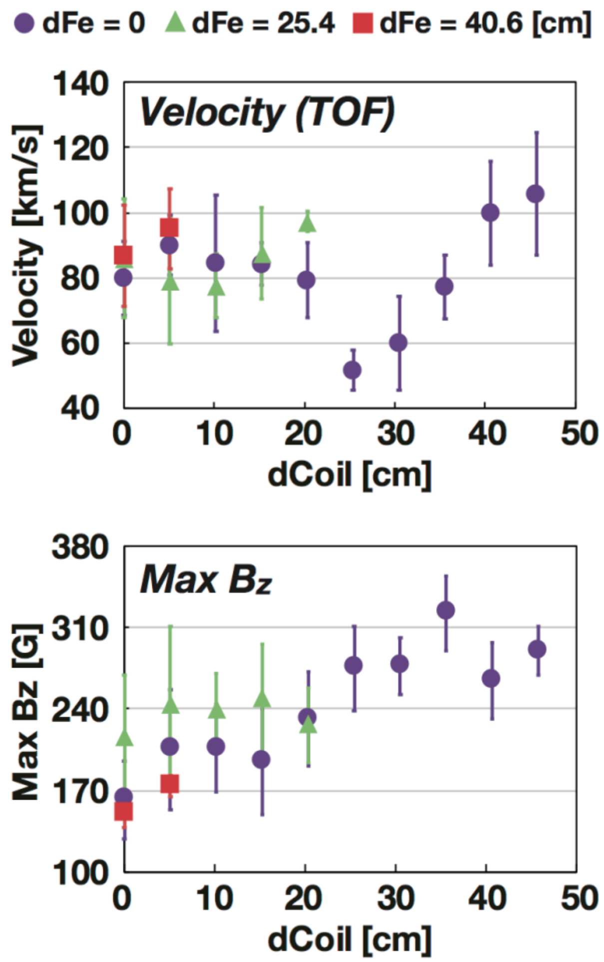

Fig. 4 Dependency of CT parameters on iron-core length (*dFe*) and coil position (*dCoil*) without the PI system.

example, B_z is higher at *dCoil* = 35.6 and 5.08 cm, respectively. As *dCoil* becomes longer, the interlinkage magnetic field distributes wider in the axial direction in the area where the plasmoid accelerates. The plasmoid accelerates while gathering more magnetic field so that the poloidal magnetic field (B_z) of CT's can be affected by the bias coil position. By changing the bias flux and the bias filed distribution, the amount of poloidal flux and the velocity of the generated CT can be controlled.

Figure 5 shows the evaluation of the CT parameters at lower bias current and gas pressure with the PI system. Here, the bias current is 1 A and gas pressure is 0.172 MPa. The iron-core is fully inserted and fixed in each case, and only the bias coil is moved. The PI system can efficiently produce breakdown, thus the MCPG can operate at a lower gas pressure, reduced by approximately 40 %. By reducing the amount of neutral gas, the generated/ejected CT has a faster velocity; more than 100 km/s in *dCoil* = 0, 5.08, and 45.7 cm cases. It also reached approximately 140 km/s in *dCoil* = 0 case. From edge probe measurements, the electron density is lower than the typical value ($\sim 5 \times 10^{15}$ cm^{-3}) of the CT injector developed for the C-2U FRC [3].

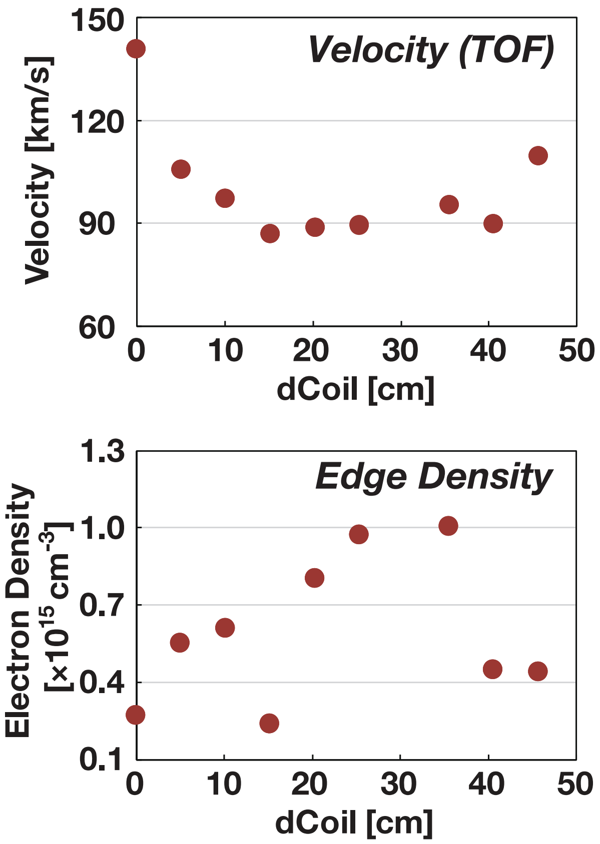

Fig. 5 CT parameters at lower bias current and gas pressure with the PI system.

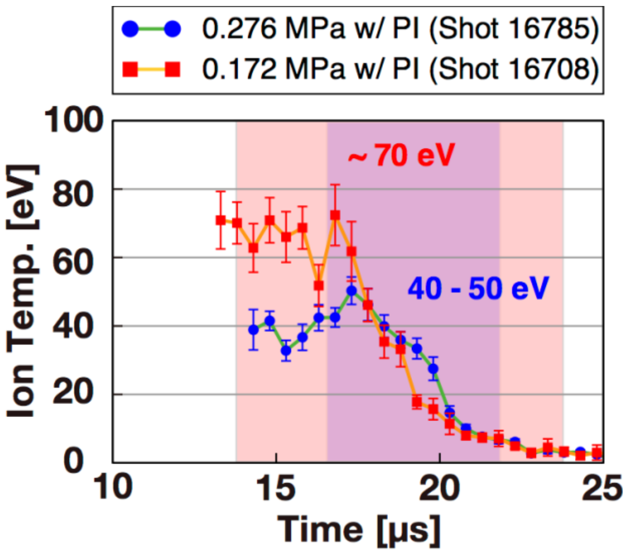

Fig. 6 Typical ion temperature estimated by Doppler broadening of C III line at 0.276 MPa and 0.172 MPa with the PI system. The darkened areas are full width at half maximum (FWHM) at each case in the signal of the collimated fiber at the same cross-section of the spectrometer.

Figure 6 shows the typical ion temperature T_i at 0.276 and 0.172 MPa gas pressure operations with the PI system. Here, $t = 0$ is the start time of the MCPG's current. It clearly shows that the ion temperature is increased from 40 - 50 eV level to ~ 70 eV by reducing the amount of initial gas. As a result, the ejected CT is not cooled by the neutral gas, and the CT performance is improved at low gas pressure operation.

4. Summary

We have examined two newly adopted techniques for a MCPG: iron-core bias coil, and miniature gun as a new PI system. The iron-core bias coil can generate an equivalent stationary bias magnetic field with a much smaller current. By changing iron-core length and coil position, the amount of poloidal flux and velocity of the generated CT can be easily controlled. Also, the PI system can efficiently and certainly produce breakdown of the MCPG; therefore, the MCPG can operate at lower gas pressure, reduced by approximately 40 %. CT performance is improved due to the lowered gas pressure operation; the CT has a higher ejection velocity and ion temperature without being cooled down by excess neutral gas.

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