Behavior of a Tracer-Containing Compact Toroid in a Transverse Magnetic Field*)

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Studying impurity behavior in a magnetically confined plasma is essential for fusion reactor developments. A tracer-containing compact toroid (TCCT) injection have been developed as a new tracer injection technique for studying impurity accumulation and behavior in magnetically confined fusion plasmas. We generated and ejected the TCCT using a compact toroid (CT) injector that had successfully demonstrated CT injection fueling into a large field-reversed configuration (FRC). Tracer ions, e.g., tungsten, copper, and aluminum, are supplied by an independently controlled tracer source attached to the CT injector. The plasma containing tracer ions is accelerated and ejected by Lorentz self-force as the TCCT. To investigate whether tracer ions can be injected into the plasma without separation from the TCCT, we experiment by injecting the TCCT injection into a transverse magnetic field, emulating a confinement magnetic field of the FRC plasma.

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1. Introduction

Studying impurity behavior in a magnetically confined plasma (MCP) is essential for fusion reactor developments. To study impurity transport, a small amount of tracer particles is injected as an impurity, and their behavior is tracked using optical measurements. Gas puffing [1], laser blow-off [2], and pellet injection [3] have been used to inject tracer particles so far. As a new tracer injection method, we have proposed a tracer-containing compact toroid (TCCT) injection [4] to expand the experimental range of impurity transport studies. It consists of a compact toroid (CT) doped with tracer ions.

In a previous experiment, we generated CTs doped with tracer ions using a magnetized coaxial plasma gun (MCPG) that has an inner electrode made of conductive tracer elements, e.g., aluminum, tungsten, manganese, and zirconium [4]. The inner electrode is sputtered during discharge and tracer ions are integrated into the CTs. The velocity of the ejected TCCT was optically measured in the drift tube of about 1 m in length. The tracer ions and CTs had the same velocity. Experimental results show that the tracer ions and CTs do not separate while the TCCT passes through a drift tube.

To realize tracer injection into MCPs, an ejected TCCT must penetrate a confinement magnetic field without the separation of tracer ions from a CT. In this experiment, we generated and accelerated a TCCT using a CT injector that had successfully demonstrated particle fueling on a large field-reversed configuration (FRC) device C-2/C-2U [5]. This CT injector can eject a deuterium CT with enough velocity to penetrate a confinement field of an FRC.

To dope tracer ions in the CT, a newly developed tracer source was installed in one of the gas injection ports of the CT injector. An ejected TCCT was injected into a transverse magnetic field, which emulates the confinement field of a target plasma. Using optical and magnetic measurements, we observed the behavior of the TCCT in the transverse field. The rest of this study is organized as follows. Sections 2 and 3 explain the CT injector and newly developed tracer source, Sections 4 and 5 discuss the experiment and results, and finally, Section 6 concludes this study.

2. Compact Toroid Injector

The CT injector was developed for the large FRC facility of the C-2/C-2U, primarily for particle refueling. The CT injection experiments demonstrated a success-

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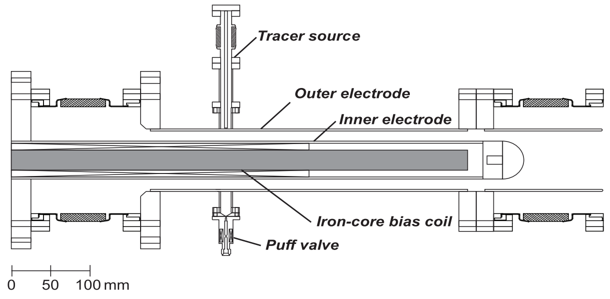

Fig. 1 Schematic of compact toroid (CT) injector with tracer source.

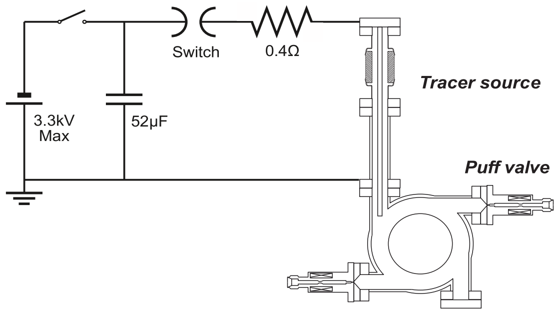

Fig. 2 Schematic of the tracer source on the cross section of the gas port.

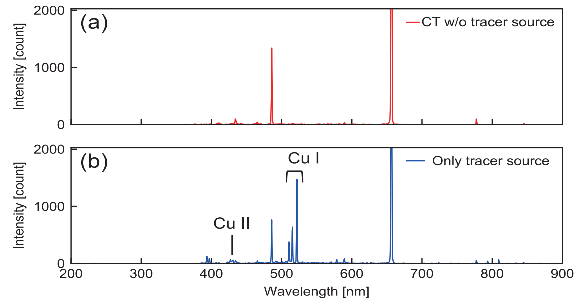

Fig. 3 Line spectra of (a) a CT (deuterium) and (b) the plasma generated by only the tracer source (copper).

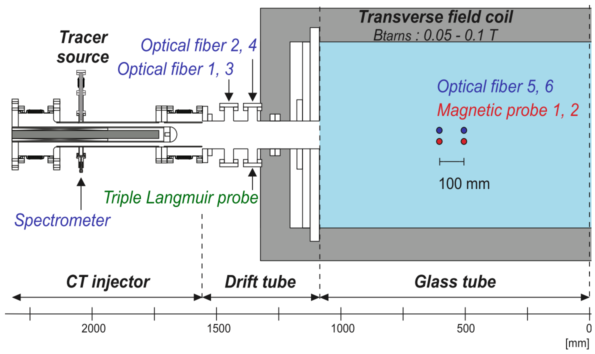

Fig. 4 Schematic of the test stand and diagnostic setup.

ful refueling with the density build-up of 20% - 30% for the FRC particle inventory without any serious effects. The CT parameters of electron density, electron temperature, and ejection velocity are ~5×10^{21} m^{-3}, ~30 eV, and ~100 km/s, respectively [5]. Using the CT injector, the TCCT could be accelerated to enough velocity to penetrate the confinement field.

The CT injector is an MCPG that consists coaxially arranged inner and outer electrodes, a bias coil, and puff valves as shown in Fig. 1. A deuterium gas puffed between the electrodes is ionized by the discharge of the MCPG. The plasma is accelerated by the Lorenz self-force of the discharge current. During acceleration, the plasma captures bias magnetic flux and is ejected as a spheromak-like CT from the MCPG [6].

3. Tracer Source

The tracer source, consisting of a coaxially arranged rod electrode and a cylindrical electrode, was mounted on the cross section of the gas port of the CT injector as shown in Fig. 2. The rod electrode (O.D. 6.35 mm) is made of conductive tracer elements, e.g., tungsten, copper (Cu), and aluminum. We can adjust the inventory of tracer ions, independent of the CT parameters, because the tracer source is separately driven from the CT injector.

The working gas diffuses from the gas puff valves on the CT injector (−3.25 ms); the gas is ionized by the discharge of the tracer source, and tracer ions are integrated into the plasma by the sputtering of the rod electrode (−0.05 ms). Finally, the plasma containing the tracer ions is accelerated by the discharge of the CT injector (0 ms).

We measured the spectra of (a) the CT and (b) plasma generated by discharging only the tracer source near the gas port, where the tracer source is mounted as shown in Fig. 3. In this study, the gas used is deuterium, and the tracer element is Cu. When the CT was ejected without a tracer source discharge, we observed only deuterium lines. Moreover, when only the tracer source was discharged, we observed Cu and deuterium lines.

4. Experimental Setup

Figure 4 is the schematic of the test stand and diagnostics setup. The test stand consists of the CT injector with the tracer source, a drift tube, and a glass vacuum tube. The set of transverse field coils is installed on both sides of the glass tube, and it can create a magnetic field, which acts perpendicular to the CT ejecting axis.

The velocity of the CT and tracer ions at the drift tube are inferred by the time-of-flight (TOF) method [7] using collimated fibers and photomultiplier tubes (PMTs) with optical filters (Fibers 1, 2, 3, and 4 in Fig. 4). Using the optical and magnetic measurements, the behavior of the injected TCCT was observed in a transverse field in the glass tube (Fibers 5 and 6 and Magnetic probes 1 and 2 in Fig. 4).

5. Experimental Results

Figure 5 shows the waveform of electron density and optical signals in the drift tube. We measured the optical signals of the CT using PMT1 and PMT2 with a neutral-density filter (NDF). We measured optical signals of Cu using PMT3 and PMT4 with a bandpass filter (BPF) (CWL 522 nm: Cu I, FWHM 10 nm). Both the CT and Cu optical emissivity peak at the same time, i.e., after 20 μs. The velocities of the CT and Cu inferred by the TOF method were the same (~60 km/s). Tracer ions are accelerated without separation from the CT after ejection. We successfully ejected the TCCT using the tracer source.

Figure 6 denotes the magnetic and optical signals at the glass tube. The magnetic signals measured using the

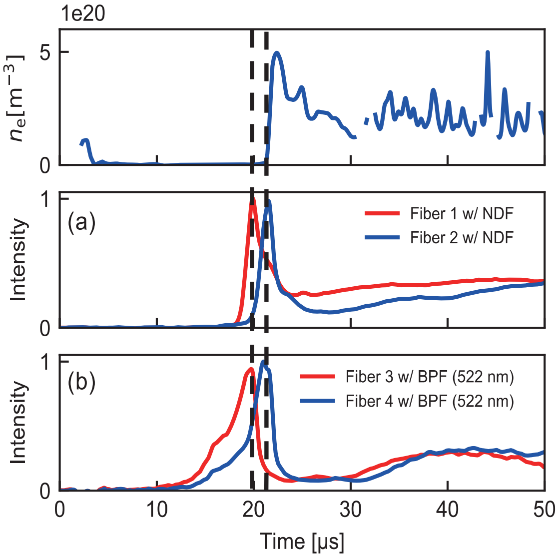

Fig. 5 Waveform of electron density and optical signals at the drift tube, (a) CT, (b) tracer (copper).

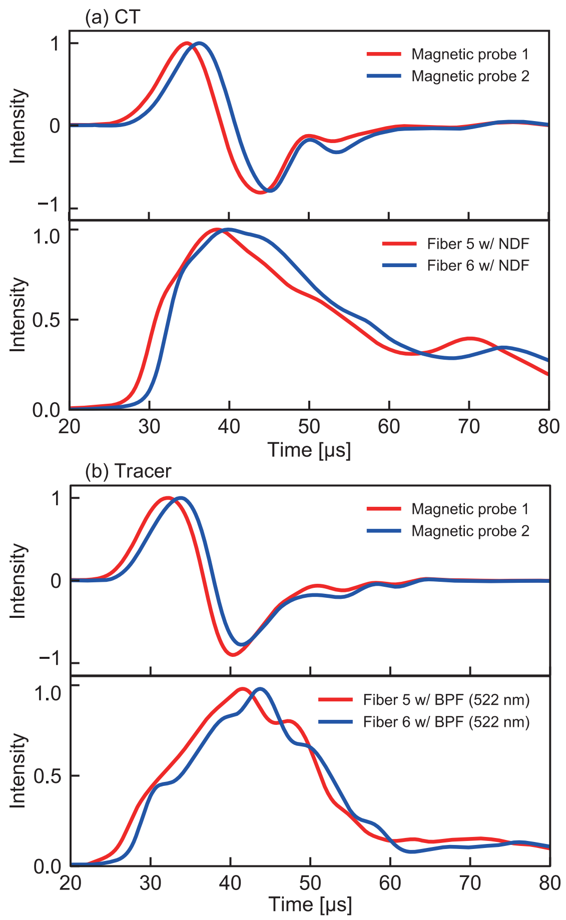

Fig. 6 Magnetic probe signals and photomultiplier tube signals in a transverse field, (a) with a ND filter, (b) with band pass filter (522 nm).

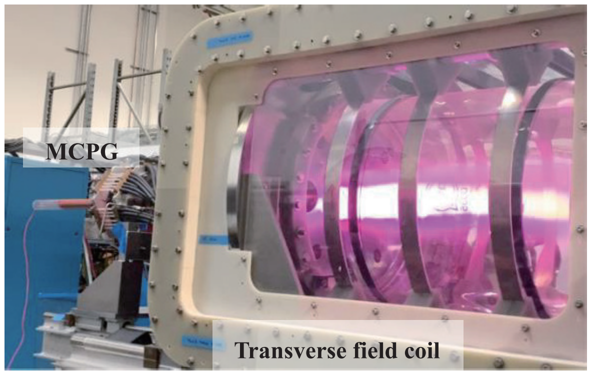

Fig. 7 Image of the typical trajectory of a CT injected into a transverse field.

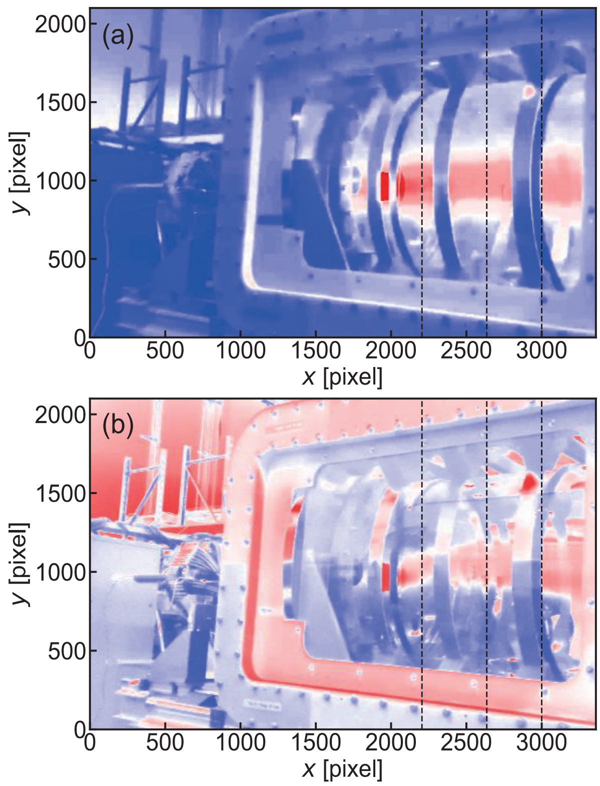

Fig. 8 Contrast corrected images of the CT injected into a transverse field, (a) with a bandpass filter (BPF) (656 nm: Dα), (b) with BPF (522 nm: Cu I).

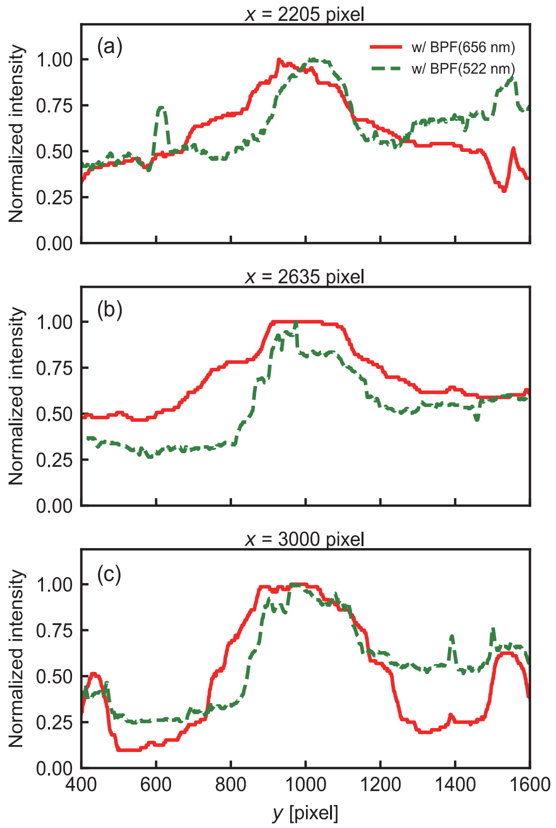

Fig. 9 Normalized intensity of (a) x = 2205 pixel, (b) x = 2635 pixel, and (c) x = 3000 pixel.

magnetic probes attached to the outside of the glass tube indicated the fluctuation of a transverse field. When the CT penetrates a transverse field, magnetic signals fluctuate with optical signals of the CT (Fig. 6 (a)). The optical signals of Cu rose synchronously with the magnetic signals (Fig. 6 (b)). It seems that the tracer ions were sparsely located in the CT. Tracer ions travel with CTs in a transverse field.

Figure 7 is the image of the typical trajectory of a CT injected into a transverse field. The radial expansion of the ejected CT is suppressed by a transverse field in the glass tube. Figures 8 (a) and (b) are the processed images of the trajectory of a TCCT injected into a transverse field. A normal camera with BPF was used to obtain images ((a) 656 nm: Dα, (b) 522 nm: Cu I). The trajectory of the CTs is in the red area of the glass tube (Fig. 8 (a)). The trajectory of Cu is in the same area as that of the CTs (Fig. 8 (b)). The trajectory of injected CTs and tracer ions is almost the same. Figure 9 traces the normalized optical intensities at x = (a) 2205, (b) 2635, and (c) 3000 pixel. It seems that the intensity distribution of the tracer ions and CTs are concentrated in the center axis of the glass tube (y = 1000 pixel). We have successfully injected tracer ions and a CT into a transverse field without their separation.

When the magnitude of Lorentz self-force on deuterium and tracer ions with different mass is same, the tracer ions separated from the CT because of more mass. The tracer ions might have been accelerated by the collision with the deuterium ions in the CT.

6. Summary

We have proposed TCCT injection as a new tracer injection technique to expand the experimental range of impurities transport studies. The TCCT was injected into a transverse field, which emulates the confinement field of MCPs using a CT injector and a newly developed tracer source. The tracer ions integrated into the CT accelerated without separating from the CT. We have successfully injected CTs doped with tracer ions into a transverse field.

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