Particle kinetic-energy measurement in compact toroid injection into a gas neutralizer

Dazhi Liu, Yoshiyuki Ito, Naoyuki Fukumoto, Tsuguhisa Sekioka, Yusuke Kikuchi and Masayoshi Nagata

University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2280, Japan

Particle kinetic-energy measurement in the experiments of compact toroid (CT) injection into a hydrogen gas neutralizer is presented. The typical injected CT parameters are: (1 ~ 4) $\times 10^{21}$ m^{-3} in electron density and 30 ~ 70 $km \cdot s^{-1}$ in velocity. By using microchannel plate detectors, kinetic-energy of ions and neutrals after CT passing the neutralizer has been measured with an electrostatic ion energy analyzer and evaluated by time-of-flight method, respectively. The pressure in the neutralizer was scanned. At the pressure $\approx 6 \times 10^{-3}$ torr, charge exchange between CT plasma and the neutral particles with high energy has been identified, which is characterized by significant decay of CT plasma density and magnetic field profile. The velocity of the produced neutral particle flow is close to the ion velocity of the CT plasma.

Keywords: compact toroid injection, charge exchange, neutralization, microchannel plate detector.

1. Introduction

A compact toroid (CT) is a dense, well confined plasma configuration with embedded, comparable toroidal and poloidal magnetic field. Normally, CTs are formed by using a coaxial plasma gun through gas discharge between inner and outer electrodes. Once formed, a CT can be accelerated to high velocity by **J×B** force, where **J** is the radial current density and **B** the azimuthal magnetic field associated with **J**. Typical parameters of a CT are: several hundreds of $km \cdot s^{-1}$ in velocity and $10^{21} m^{-3}$ in electron density. CT injection was proposed as a promising fueling technique for reactor-grade tokamak by Perkins and Parks in 1988[1, 2]. An accelerated CT is able to penetrate into the center of a tokamak provided that the kinetic energy density of the CT exceeds magnetic field energy density of the tokamak. This can be described as: $\rho_{CT}V^2/2 > B^2/2\mu_0$, where ρ_{CT} is the CT mass density, V is the CT velocity and B is the field strength at the tokamak center. In addition, recent experiments on injection of supersonic gas jets as a new fueling approach have been successfully conducted on some tokamak facilities [3-5]. However, the ability to penetrate into tokamak plasmas needs to be enhanced for larger fueling efficiency. Thus a new technique for acceleration of plasma jet has been proposed by Rozhansky et al. [6]. The jet was accelerated to 100 $km \cdot s^{-1}$ by using a plasma gun, leading to deep penetration into plasmas in Globus-M.

In the present paper, we report a new approach to produce neutral gas jets with high velocity using a CT injector. The CT will be injected to a neutralization region filled with high pressure hydrogen gas (up to 10^{-2} torr). It is conjectured that charge-exchange collision will occur between high velocity ions and the neutral H atoms and H_2 molecules leading to the production of a high velocity neutral flow. Therefore, kinetic energy measurements of the neutrals and ions after the neutralization are crucial to clarify the charge exchange process.

author's e-mail:d-liu@eng.u-hyogo.ac.jp

2. Experimental setup

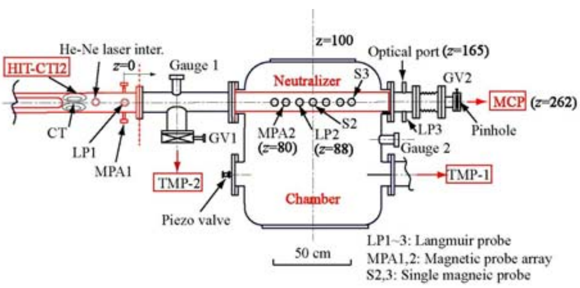

Fig. 1 Experimental setup.

The experimental setup is shown in Fig.1. A single-stage, coaxial plasma gun (HIT-CTI2) was employed to form CTs [7]. The power supply for the injector was a bank of capacitor of 10 kV/0.6 mF. Hydrogen was the working gas. The diameters of the inner and outer electrodes are 60 mm and 134 mm, respectively. A segment of stainless steel tube (length = 109 cm) was attached to the exit of the CT injector as the CT neutralizer. A set of seven holes (dia. = 42 mm) were located in the neutralizer along CT trajectory for Langmuir and magnetic probes. The neutralizer was located inside a stainless steel chamber. The pressure in the CT neutralization tube was controlled by a pulsed Piezo gas valve (PV-5020) with maximum gas output of 100 Pa·m^{3}s^{-1} for hydrogen. The inline gas pressure was 1.8 ~ 2.5 atmosphere.

The vacuum of the system was attained by using a 500 l·s^{-1} turbo-molecular pump (TMP-1). The base pressure was 1×10^{-6} torr, typically. During the experiments another turbo-molecular pump (TMP-2) with effective pumping speed 50 l·s^{-1} was used to minimize the loss of hydrogen gas.

A He-Ne laser interferometer (λ = 633 nm) and a magnetic probe array were routinely installed in the HIT-CTI2 for CT density (line-averaged) and magnetic field measurements. A monochromator was used to monitor H_β emission (λ = 486.1 nm) at the exit of the neutralization tube (z = 165 cm). Three Langmuir probes (LP1~3) were located at z = 0, 88, 165 cm to measure plasma density. Magnetic probes (MPA1, MPA2, S2 and S3) were used to measure CT magnetic field and its profile.

Microchannel plate detectors (MCP) were used to detect particles after CT passing the neutralizer. For neutral detection, a deflection coil was used to remove the charged particles in the flow; for ion detection, an electrostatic ion energy analyzer (IEA), which consists of an ion energy selection part and a MCP detector, was employed. High vacuum (< 2×10^{-6} torr) should be maintained in the MCP chamber for proper operation. To fulfill this requirement a pinhole (dia. = 0.8 mm and hole length = 3 mm) was used for differential pumping by using a dedicated turbo molecular pump connected to the MCP chamber. At the maximum pressure in the CT neutralizer, P_N = 10^{-2} torr, the pressure in the MCP chamber was 1.5×10^{-6} torr.

3. Experimental results and discussion

3.1 Observation of charge exchange process

The injection experiments were performed with the following CT parameters at the exit of the injector (z = 0): 2.5 kG in CT magnetic field, (1 ~ 4) $\times10^{21}$ m^{-3} in electron density and 30 ~70 km·s^{-1} in velocity. The CT velocity was controlled by gun discharge voltage (V_{gun}). For instance, when V_{gun}= 6 kV, the CT velocity was about 40 km·s^{-1}.

Fig.2 shows typical discharge waveforms when charge exchange occurred, from top: H_β emission, MCP intensity and the plasma density measured by Langmuir probes at z = 0, 88, 165 cm. When $P_N < 6\times10^{-3}$ torr, no charge exchange phenomena was observed. The plasma density at z =165 cm (LP3) is about 6% of that at the z = 88 cm (LP2). The peak of H_β coincides with the onset of LP3 signal.

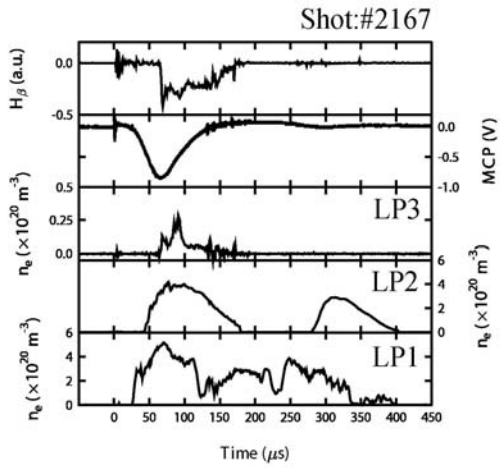

Fig.2 Typical discharge waveforms when charge exchange occurred. V_{gun}= 6 kV, P_N = 6×10^{-3} torr.

The CT magnetic filed profile in the same shot is shown in Fig.3. It clearly demonstrates that the CT still kept its integrity and field profile at this location. However, the CT-shaped profile vanished at the S3 location (z = 128 cm).

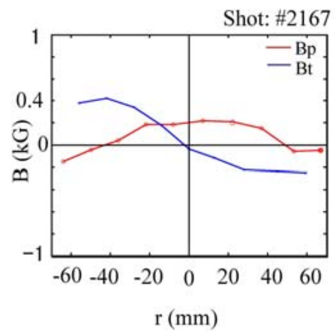

Fig. 3 Magnetic field profile of the CT at z = 80 cm.

At V_{gun}= 6 kV, a comparison of plasma density was made at different neutralizer pressure P_N, from 10^{-6} to 10^{-2} torr, see Fig. 4. At $P_N \geq 6\times10^{-3}$ torr the charge exchange (CX) occurred and the electron density decreased by one order of magnitude compared with those shots without occurrence of charge exchange. Meanwhile, the CT magnetic field also demonstrated the same trend. In Fig. 5, the field strength decays significantly, about 50%, compared with those shots in which no CX occurred. The square marker shows the value of natural decay of CT magnetic field according to Fukumoto *et al*. with magnetic field decay time τ_d = 24 µs [7].

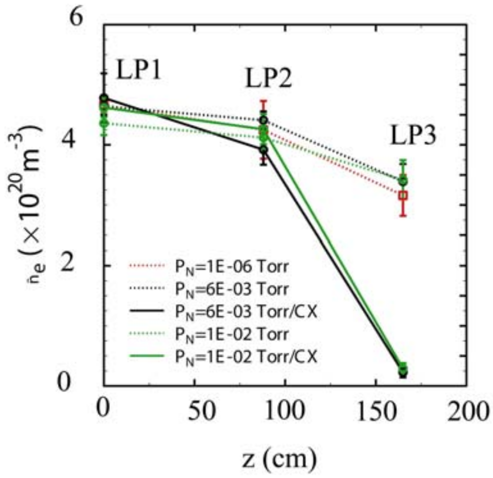

Fig. 4 Comparison of plasma density at different P_N and w/ and w/o CX occurred. V_{gun} = 6 kV.

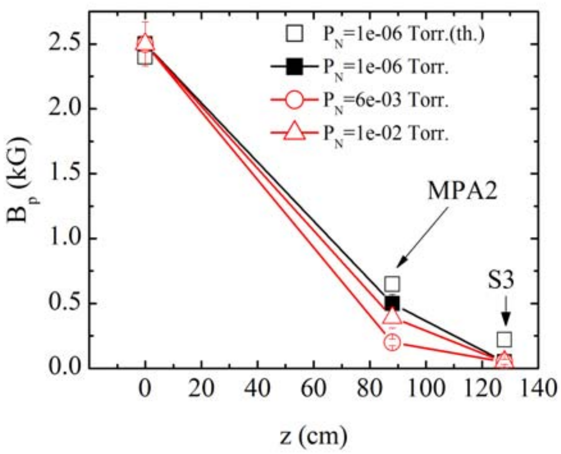

Fig.5 Comparison of CT magnetic field decay at different P_N and w/ and w/o CX occurred. Red lines are with CX. V_{gun} = 6 kV.

3.2 Particle kinetic energy measurement

Fig. 6 shows typical raw MCP signals in the neutral kinetic energy measurement. The difference in these two signals (red curve) is attributed to more production of neutrals when CX occurred. Correspondingly, the velocity of neutrals can be determined by the time of flight (TOF) method, $V_H \approx 262/68.2 = 38$ km·s^{-1}, which is close to the injection velocity of H^+ in the CT plasma at V_{gun}= 6 kV. This result also verified our observation of CX occurred in the high P_N shots.

The kinetic energy of ions was measured with IEA. Fig.7 shows the energy spectrum of ions at different P_N. V_{gun} was fixed at 6 kV in the measurement. The amplitude of the signals of high energy ions (> 200 eV) decreases with increasing P_N. This is because the charge exchange collision between the ions and neural atoms and molecules is the dominant ion momentum loss channel at high ion energy. It can be justified by the atomic cross-section data: for E_p= 200 eV, σ_m = 5×10^{-19} m^{-2} and σ_{cx} = 4×10^{-19} m^{-2}, where σ_m is the momentum transfer cross section and σ_{cx} is the charge exchange cross section for P+H collision [8].

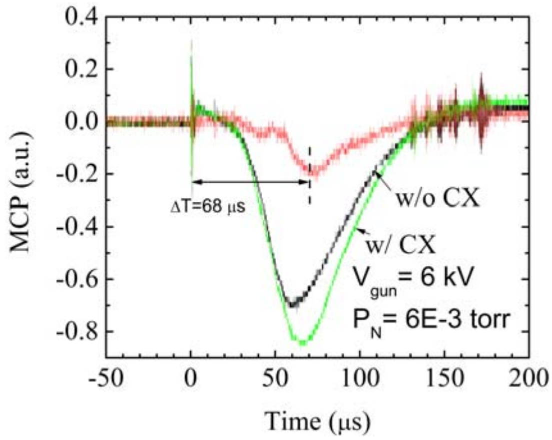

Fig.6 MCP signals for neutral kinetic energy measurement w/ and w/o CX occurred.

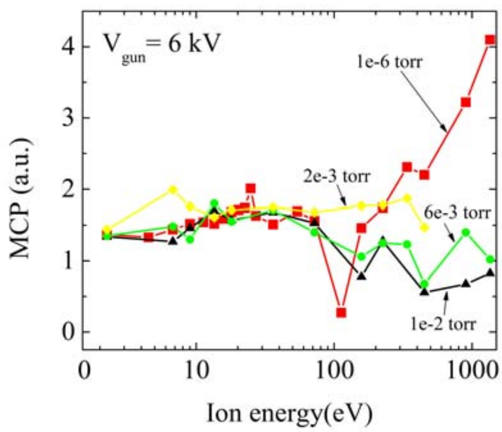

Fig.7 Ion kinetic energy spectrum at different P_N.

4. Conclusions

We have performed the injection of compact toroid into a hydrogen gas neutralizer filled with variable gas pressure. At pressure ≈ 6 × 10^{-3} torr, charge exchange process between ions in the CT plasma and the neutral particles has been identified, which is characterized by significant decay of CT plasma density and magnetic field profile.

By using microchannel plate detector, the velocity of neutral particle flow produced in the charge exchange process, has been measured. It is close to the ion directional velocity in the CT plasma prior to CX. The fraction of ions with high kinetic energy (>200 eV) decreases with increasing neutralizer pressure because of ion momentum loss mainly caused by the charge exchange process.

Acknowledgements

The author, Dazhi Liu, thanks the Japan Society for the Promotion of Science (JSPS) postdoctoral fellowship for financial support.

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