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Compact toroid injection as fueling in the JFT-2M tokamak

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Abstract

Compact toroid (CT) injection experiments have been carried out in JFT-2M for the understanding of the physics of CT injection as means of tokamak fueling. An increase in the line averaged electron density $\Delta\bar{n}_e \approx 0.4 \times 10^{19}$ m^{-3} was obtained in the case of a CT velocity of 300 km/s and a toroidal magnetic field of 0.8 T. The fueling efficiency is roughly 40%. An asymmetric radial profile with a peripheral second peak in the soft X-ray emission was produced for ~0.4 ms by this CT injection and resulting in a tokamak disruption.

Keywords: Compact toroid; Tokamak fuelling; Electron density

1. Introduction

A compact toroid (CT) injection is considered as one of advanced refueling methods for fusion plasmas [1]. CT plasma is formed by a magnetized coaxial plasma gun and accelerated to high velocity by $\mathbf{J} \times \mathbf{B}$ force from a capacitor bank discharging [2]. The first successful refueling experiment by a CT has been demonstrated in the TdeV tokamak [3]. Himeji Institute of Technology has developed a CT injector (HIT-CTI) to demonstrate CT fueling and study CT behavior in the JFT-2M high confinement plasma. The CT injection experiments were performed with toroidal fields of 0.8–1.3 T in both OH and NBI heated plasmas, demonstrating the fueling with the CT velocity less than 200 km/s [4,5]. In this paper, we present more remarkable results from the CT injection experiment with the CT velocity up to 300 km/s.

2. Experimental setup

The HIT-CTI is installed perpendicularly to the magnetic axis on the midplane in the JFT-2M tokamak (Fig. 1). Four fast electromagnetic valves placed azimuthally around the injector outer formation electrode are used to inject the gas between the inner and outer electrodes for CT formation. These valves are powered in series by capacitor banks of 5 kV (4 kJ) with 130 μs rise time. Typically 2 Torr-liters gas are puffed into the formation region and roughly 10% of the injected gas is trapped by the CT with particle inventory order of $\sim 1 \times 10^{19}$. Some amount of the unused gas flow into the tokamak chamber and contribute to edge fueling. Experimentally, the effect of the diffused gas was observed to be dominant a few milliseconds after the CT injection [5]. The CT plasma is formed at the first coaxial electrodes, accelerated in the second coaxial electrodes and compressed to a diameter of 70 mm in the focus cone at the end of the accelerator. Three magnetic pick-up probes (B_P-1–B_P-3) along the outer electrode with 196 and 620 mm interval provide time of flight measurements to estimate the CT velocity and length. A He–Ne laser interferometer measures the averaged electron density horizontally. An optical fiber for a spectroscopic measurement is mounted at the bottom port of the same radial position as the B_P-3 probe and the He–Ne interferometer.

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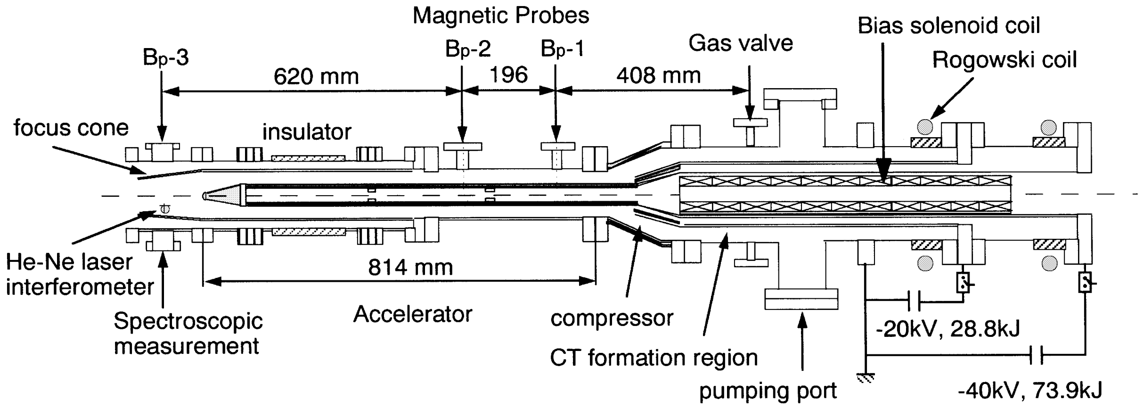

Fig. 1. Schematic of the CT injector.

The JFT-2M tokamak has a D-shaped vacuum vessel with a major and a minor radius of $R = 1.31$ m and $a = 0.35$ m in vessel size, respectively. Fast magnetic probe located at the toroidal section $\varphi = 123.8°$ from the CT injector has effective domain of frequency up to 500 kHz with a 1 μs sampling time. A 130 GHz microwave interferometer measures the electron density integrated along the horizontal center chord at $\varphi = 135°$. A multichannel visible bremsstrahlung measurement has tangentially horizontal chord at $\varphi = 145°$ with a 20 μs sampling time. A multichord PIN diode array measures the soft X-ray (SX) emission profile with a 50 μs sampling time at $\varphi = 67.5°$. A thin beryllium window of 5 μm in thickness can pass through the X-ray energy above 500 eV.

3. Experimental results

3.1. CT injection into vacuum field

Compact toroids have been injected into a toroidal magnetic field without tokamak plasma. Fig. 2(a) shows time traces of the CT plasma parameters.The CT velocity is 150 km/s and the averaged density is $\sim 4 \times 10^{21}$ m^{-3}. Rapid increase in the tokamak density

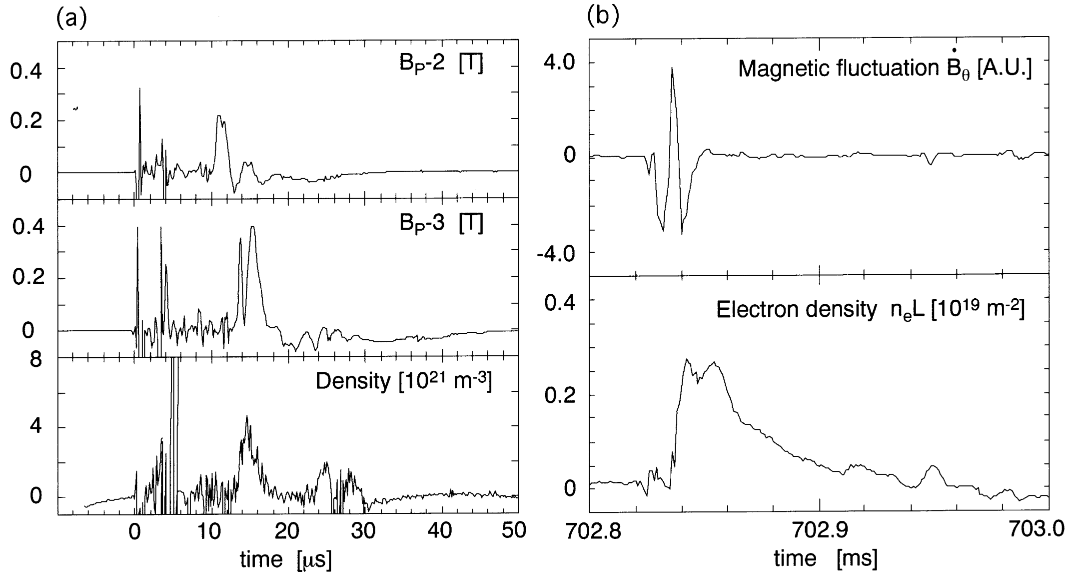

Fig. 2. CT injection into a vacuum field with $B_T = 0.8$ T. (a) Time traces of CT magnetic probe signals B_P-2, B_P-3, and He–Ne laser interferometer signal (electron density). The CT velocity is estimated 150 km/s and the length is 0.25 m from the magnetic probe signal. (b) Time traces of magnetic fluctuation B_θ and line-integrated electron density of JFT-2M plasma.

with bursts of magnetic fluctuations was observed at $B_T = 0.8$ T (Fig. 2(b)). In this experiment, the fast digitizer with 1 MHz sampling rate was used for this density measurement. This figure shows quick rise of the line-integrated density up to $\sim 2.5 \times 10^{18}$ m^{-2} with ~ 10 μs rise time. The injected CT plasma expands along the field lines quickly and the density is decreased in ~ 50 μs. The interferometer does not respond up to 1 MHz so that the measured density should be less than the real value. The tokamak particle inventory is $\sim 1.5 \times 10^{18}$ on the assumption that the CT penetrates inside the tokamak main chamber ($R \leqslant 1.625$ m) maintaining the CT radius of 70 mm equivalent to a diameter of the focus cone. The difference from the CT inventory $\sim 3.8 \times 10^{18}$ may be caused by the limited response time of the interferometer and/or the penetration depth of this CT plasma into toroidal magnetic field.

Spectroscopic measurements of CT plasma have been carried out without toroidal magnetic field. Fig. 3 shows the time traces of magnetic probes B_P-1 and B_P-3, D_β intensity and the discharge current for the CT formation without acceleration discharge. The CT formation current generally oscillates and vanishes within 150 μs. Magnetic probe B_P-1 shows clear CT poloidal field at the entrance of acceleration electrode but the B_P-3 signal shows no CT reaches at the focus cone. The interferometer shows no thick plasma ($n_e > 10^{20}$ m^{-3}) at this position. D_β radiation is observed during formation current oscillating. This indicates formation current makes non-magnetized plasma or exited neutral gas which flow at least till the focus cone. This may be related to the trailing plasma following the CT plasma.

The electron temperature of the CT plasma is estimated by the spectroscopic measurements of impurity lines. The carbon ion lines such as CII and CIII are observed but CIV and lines from higher charged ions are not. This experimental result suggests that the ionization time of C^{2+} ion is longer than several 10 μs. The characteristic time of electron impact ionization ($\tau = 1/n_e Sij$, Sij: ionization rate coefficient) is estimated by using measured electron density. The coefficient Sij of C^{2+} ion strongly depends on the electron temperature below 30 eV. The time range of t is about 10 s or longer at $T_e = 10$ eV. Then the electron temperature is estimated as around 10 eV.

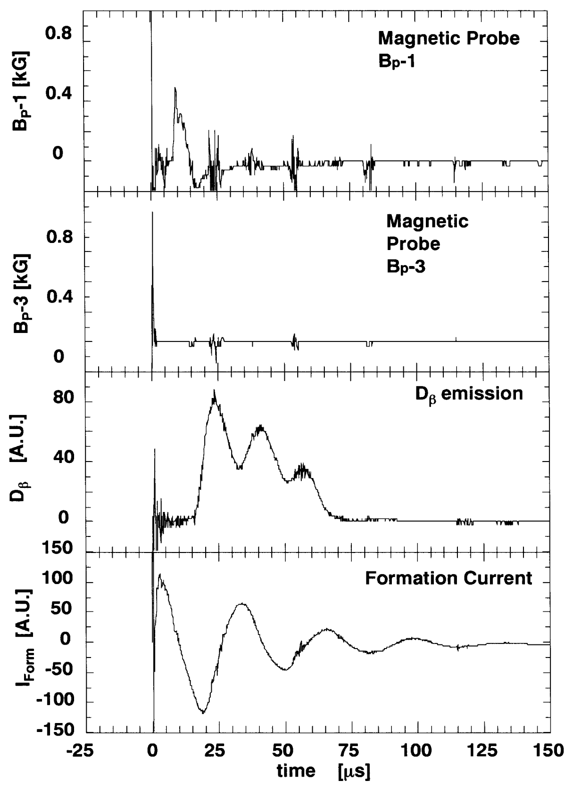

Fig. 3. Time traces of CT magnetic probe B_P-1, B_P-3, D_β radiation and formation current for CT formation discharge in vacuum with $V_A = 0$ kV.

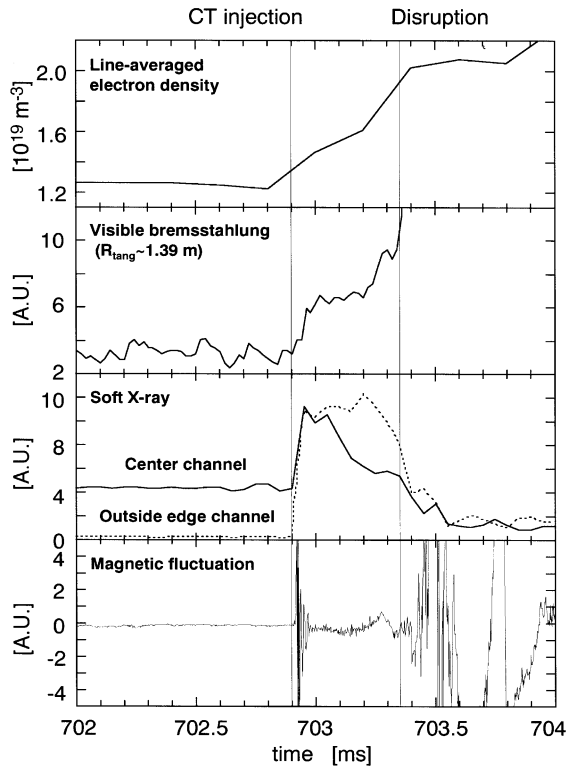

Fig. 4. Time trace of the line-averaged electron density, visible bremsstrahlung signal, the SX emission and magnetic fluctuation for the discharge with $B_T = 0.8$ T. The CT injected at 702.95 ms.

3.2. CT injection into tokamak plasma

The optimum CT plasma with velocity 300 km/s was injected into the JFT-2M plasma at $B_T = 0.8$ T (Fig. 4). Sharp rise of SX emission was observed along the center chord as well as the edge chord. The SX intensity is sensitive to electron temperature, electron density and impurity contamination. The electron temperature should not increase by CT injection because the CT plasmas temperature $T_e \sim 10$ eV is much lower than the tokamak plasma temperature. Therefore, the rise in the SX emission is mostly related to the increase in plasma density including impurity by the CT penetration. On the other hand, the fall time of this signal will depend on the temperature drop and the particle diffusion loss. Bursts of magnetic fluctuations occur at the CT injection and last ~50 μs. This magnetic fluctuation is stabilized for ~400 μs and the instability suddenly grows at 703.35 ms, resulting in a disruption. This duration of stabilization becomes longer with less CT penetration. In Fig. 4, the density plot rises slower than the other because the sampling rate is 5 kHz in this shot which is not fast enough comparing to the phenomena of the CT fueling. The visible bremsstrahlung emission rises at $t = 702.95$ ms and stays for 200 μs. The increase in the density agrees with this bremsstrahlung emission till $t = 703.2$ ms. The density data after the disruption should have miscounted by fringe jumps. Therefore, we estimate the fueling rate from the line-averaged electron density increased from 1.2×10^{19} m^{-3} to 1.6×10^{19} m^{-3} at a rate of 1.0×10^{22} m^{-3}/s. This rate 1.0×10^{22} m^{-3}/s is five times as large as the rate at $v_{CT} \sim 185$ km/s previously reported [5]. The fueling efficiency is estimated roughly 40% from the increment of the density $\Delta\overline{n_e} \approx 0.4 \times 10^{19}$ m^{-3} and the CT particle inventory $\sim 1.5 \times 10^{19}$. The SX emission points to a strong change in the density profile after CT injection but the profile almost returns to the base at $t = 703.2$ ms except the peripheral second peak. There is no other diagnostic to estimate the density profile with fast temporal resolution. So the tokamak particle inventory after the CT injection was evaluated using the same ratio of the line-averaged density to the volume-averaged density.

Fig. 5(a) shows the time trace of the SX emission profile due to CT injection measured by the 24 channel PIN diode array. The vertical chord of the PIN diode array in the poloidal cross-section is shown in this figure. All the channel including the edge channel in the high field side increase within 50 μs just after the CT injection. Fig. 5(b) shows the time slices of the SX emission profile. Asymmetrical profile in SX is produced with the center peak channel moving to outside and the second peak appearing at outside edge. The SX emission in the core returns to a slightly higher level than the base level within 0.4 ms, but the second peak stays at much higher level. This second peak is not caused by diffused gas

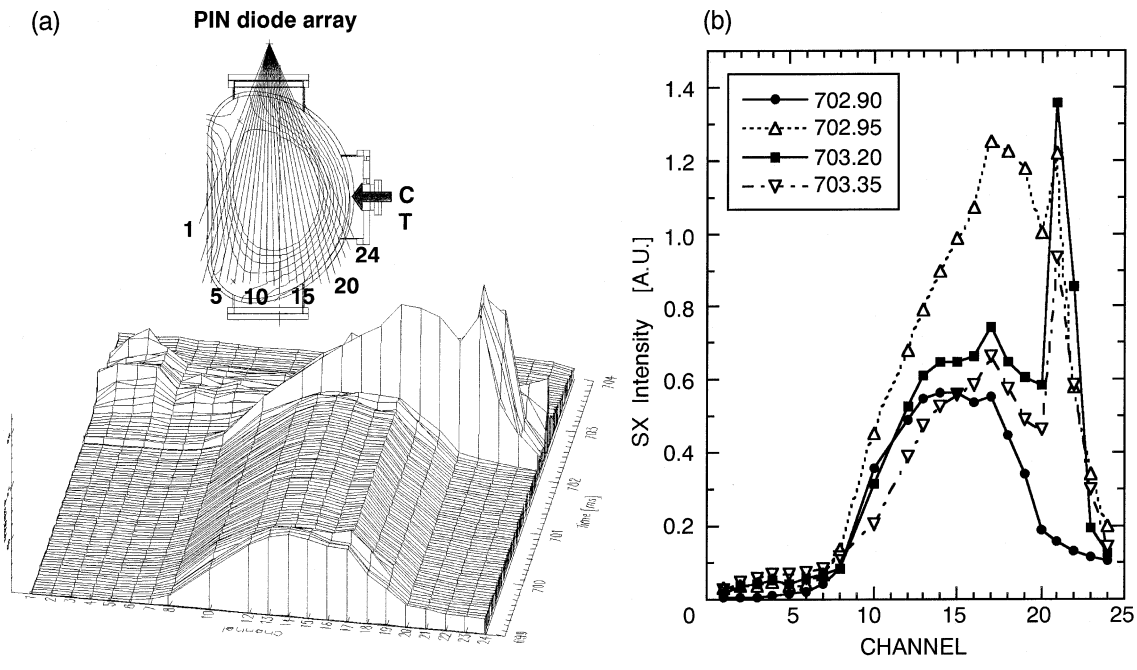

Fig. 5. (a) The SX emission radial profile of the same shot in Fig. 4. Poloidal cross-section of the JFT-2M tokamak showing the vertical chord of 24 channel PIN diode array for SX measurement. (b) Time slices of the SX radial profile. The CT injected at 702.95 ms.

from the CT injector because it takes a few milliseconds for the gas to flow into the tokamak plasma. Trailing plasmas or fast neutral gas following the CT plasma accelerated by the formation and/or acceleration discharge have a possibility to make this SX second peak. In spectroscopy measurements at the focus cone, however, D_α, D_β and impurity lines are observable only for a period within ~0.1 ms. This period of existing trailing plasma is too short to explain that the second peak remains for 0.4 ms. Furthermore, toroidal rotation effect should be accounted because the SX emission is measured at the toroidal section 67.5° from the CT injector. The CT behavior in the tokamak plasma such as the CT bouncing back from the core region is another possibility to explain this SX profile. The CT length is almost same as tokamak plasma radius with complex profile. This radial profile makes the effect of CT fueling more complicated.

All discharges with asymmetric SX profile accompanied with tokamak disruption. The reason for the disruption is not yet well understood. We have already installed fast PIN diode arrays on the top port and the horizontal side port of the CT injector section. This measurement will give us some new information to understand the CT behavior in the tokamak plasma and the reason of the disruption.

4. Conclusions

The CT fueling efficiency was roughly 40% from the line-averaged electron density increased by $\Delta\overline{n_e} \approx 0.4 \times 10^{19}$ m^{-3} with the CT injection at the velocity of 300 km/s. Asymmetrical radial profile in SX emission is produced and second peak appearing at outside edge kept for 0.4 ms. This SX profile may reflect the CT behavior in the tokamak plasma. CT temperature is estimated around 10 eV from observation of CII, CIII emission. Further study using faster diagnostics is planning to understand CT behavior in the tokamak plasma and the cause for disruption.

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