

Investigation of the Dynamics of Accelerated Compact Toroid Injected into the JFT-2M Tokamak Plasmas

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Abstract. We present the first results from recent compact toroid (CT) injection experiments in the JFT-2M tokamak using the improved CT injector and diagnostics with fast time resolution. We have observed that the core line density increases rapidly at a maximum rate of $\sim 1.3 \times 10^{22} \text{ m}^{-3}/\text{s}$ after a delay of 100 - 200 μs . This increment rate of the core density is about several times larger than that obtained so far. Interferometry measurement along the peripheral line chord of $R = 1.1 \text{ m}$ in the inboard side indicates that CT plasma reaches near to the core region beyond separatrix. Time-frequency and space distribution analyses of edge magnetic probe signals show that the magnetic fluctuation induced by the CT has the spectral peak of 250 - 350 kHz and propagates at the Alfvén speed of the order of 10^6 m/s in the toroidal direction. These results indicate the excitation of Alfvén wave by CT injection. We have interestingly observed that the fluctuation level of the ion saturation current in divertor and the D_α spectral line intensity decrease significantly after CT injection. Corresponding increase in the soft X-ray signals in the core region may suggest that the CT causes a transition to H-mode-like discharges.

1. Introduction

Conventional particle fuelling schemes such as continuous gas puffing and pellet injection are not considered to be adequate for central fueling in fusion reactors. Compact toroid (CT) injection is expected to have capabilities to achieve it as one of the advanced particle fuelling methods for fusion plasmas. So far, CT injection were carried out in TdeV [1], TEXT-U [2] and STOR-M tokamaks [3] in the past and has been developed in the JFT-2M tokamak ($R = 1.31 \text{ m}$, $a \leq 0.35 \text{ m}$, $k \leq 1.7$, $B_T \leq 2.2 \text{ T}$) for several years [4-8]. In recent CT injection experiments [9] in the JFT-2M tokamak using the improved CT injector, rapid increase in the core electron density within about 60 μs was clearly observed. The fuelling efficiency is estimated to be about 25 %, which is deduced from the increment of the line averaged electron density, $\Delta \bar{n}_e \sim 0.2 \times 10^{19} \text{ m}^{-3}$ and the CT particle inventory of $\sim 1.5 \times 10^{19}$. This is the first measurement of the density increase on such a fast time scale, which is an encouraging demonstration for deep fueling of a medium size tokamak discharge by CT injection.

A high density CT plasmoid is accelerated to high velocity and injected into tokamak plasmas with the toroidal vacuum field TF. The dynamics of the CT as it transverses the tokamak are predicted to be determined by the tilting motion, magnetic reconnection, excitation of waves, and expansion/contraction due to the TF [10]. However, three-dimensional interaction of a high speed CT with low magnetic Reynolds number R_m ($\sim 4 \times 10^2$) with a tokamak plasma with high R_m ($\sim 2 \times 10^7$ for JFT-2M) has not yet been studied experimentally. It thus becomes a pioneering work in laboratory reconnection experiments to find the complex mechanism of CT particle fuelling process. This paper presents results of fast measurements using edge

magnetic probe arrays, Langmuir probe in the divertor region, two laser interferometers (core and edge line chords) and a fast camera to study the interaction of the injected CT with the JFT-2M tokamak plasmas.

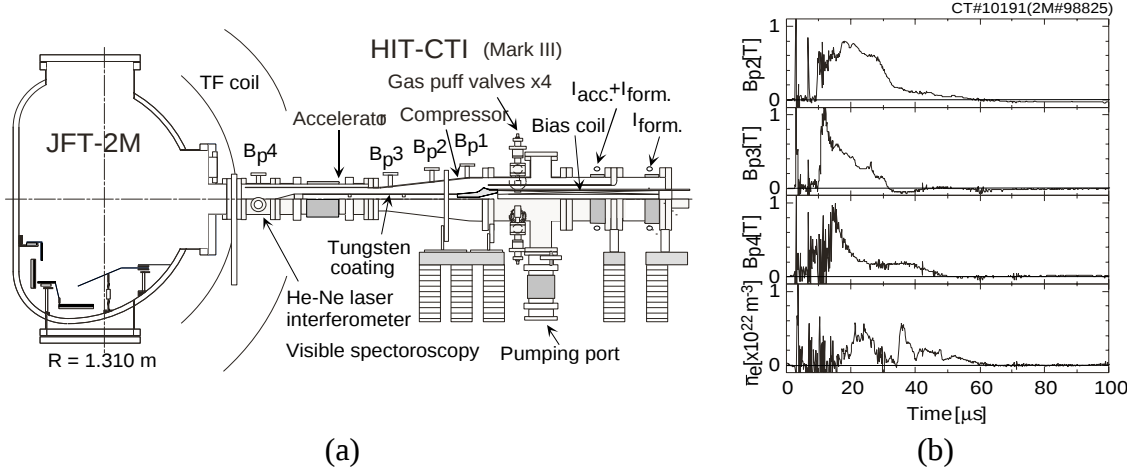


Figure 1. (a) Schematic drawing of the HIT-CT injector (mark III) and the JFT-2M vacuum vessel. (b) Typical time evolutions of CT parameters; magnetic fields of B_{p2} , B_{p3} and B_{p4} , and averaged electron density measured by the He-Ne laser interferometer.

2. Experimental Set-up

The HIT-CT injector (mark III) modified newly to improve injection efficiency was installed on the midplane of the JFT-2M vacuum chamber as shown in Fig.1 (a). The focus corn of the injector was replaced to straight type at the nozzle and the tapered shape of the pre-compression region became gentle to avoid strong deceleration due to rapid compression. The detail performances of this CT injector are described in the reference [11]. The tungsten coating with thickness ~ 0.25 mm was applied under vacuum condition using the plasma spray technique. The electrodes are baked up to 200°C for one week before an experiment. Magnetic pick up coils (B_{p1} , B_{p2} , and B_{p3}) are placed at four axial positions along the outer electrode surface. B_{p4} magnetic coil is inserted in a port frange on a tube before the gate valve. Time of flight measurement between B_{p3} and B_{p4} provides the average CT velocity and its length. He-Ne laser interferometer measures the line averaged electron density of CT in the drift tube. A sample shot for velocity and density measurement with the tokamak toroidal field $B_T = 0.8$ T is shown in Fig. 1 (b). In this shot, the average velocity is estimated about 180 km/s. The peak value of the electron density and the magnetic field strength of the CT is $n_{CT} \sim 5 \times 10^{21} \text{ m}^{-3}$ and $B_p \sim 1$ T, respectively. The typical CT parameter values obtained without B_T are $\bar{n}_e = 0.7 - 0.9 \times 10^{22} \text{ m}^{-3}$ and $v_{CT} = 230 - 300$ km/s at the acceleration bank voltage V_{acc} ranging from 25 to 30 kV. The kinetic energy W_{CT} of CT $\sim 700 \text{ kJ/m}^3$ at $V_{acc} = 30$ kV is larger than the magnetic energy $W_B = 400 \text{ kJ/m}^3$ for $B_T = 1$ T so that a deep penetration of the CT can be expected in experiments.

The JFT-2M tokamak was operated for the CT injection with TF ranging from 0.7 to 1.4 T and a plasma current of about 100 kA, corresponding to the safety factor q_{95} of 3. Figure 2 depicts the arrangement of the diagnostics for fast measurements on JFT-2M. Note that the fast time resolution of key diagnostics makes it possible to analyze the CT behavior on the time scale of μ s. A 130 GHz microwave and a FIR interferometer measure the central and

peripheral ($R = 1.1$ m) line density with $1 \mu\text{s}$ sampling time, respectively. Fast edge poloidal and toroidal magnetic pick-up coil arrays measure MHD fluctuations induced by CT injection. A multi-chord PIN diode array measures the soft X-ray (SX) emission profile with $50 \mu\text{s}$ sampling time resolution. Electrostatic probe array is mounted in the inner and outer divertor plates. The new 2D spectroscopic system using the fast CCD camera (maximum frame rate: 40500 frames/s) with a D_α or He-II line filter is set up in order to investigate fast behavior of deuterium or helium CT plasmas in the tokamak plasma.

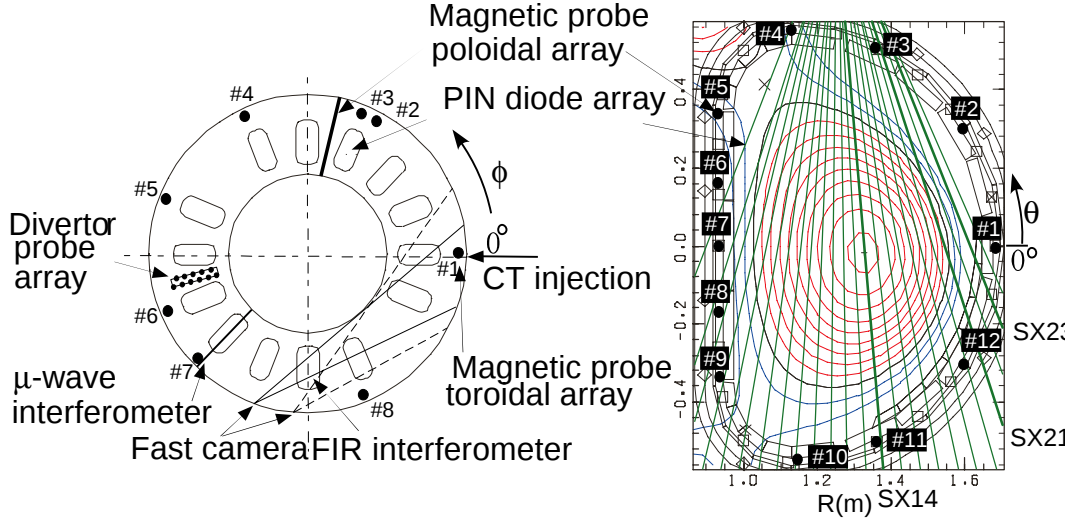


Figure 2. Arrangements of the diagnostics for fast measurements on JFT-2M.

3. Experimental Results

Two types of MHD fluctuations have been observed after CT injection as shown in Fig. 3. The first fluctuation lasts for $30 - 40 \mu\text{s}$ which agrees well with the time scale Dt_{inj} of CT injection. Time-frequency analysis shows that the magnetic fluctuation induced by the CT has the maximum spectral peak of around $250 - 350$ kHz. The estimation of Alfvén frequency f_A indicates the excitation of Alfvén wave by CT injection [12]. Alfvén frequency is given by $f_A = v_A / (2\pi q R)$, where q is safety factor and v_A is Alfvén speed $B / (\mu_0 r)^{1/2}$. In a typical case of $v_A \sim 6 \times 10^6$ m/s, $q = 2 - 3$ and $R \sim 1.5$ m, f_A is $210 - 320$ kHz. The latter fluctuation with larger amplitude but lower frequency < 100 kHz has been often observed about 1 ms after CT injection and is identified as the $m=2/n=1$ tearing mode. This mode activity causes a plasma disruption after a mode conversion to the $m=1/n=1$.

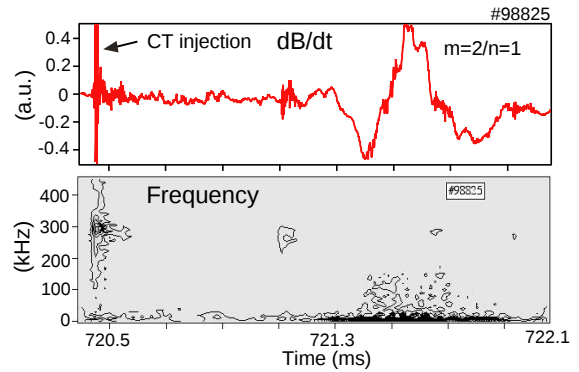


Figure 3. Time evolution of the edge magnetic fluctuation induced by CT injection and its time-frequency spectrum analyzed by Wavelet transform.

Figure 4 is the toroidal and poloidal profile contours of edge magnetic fields. Results of the edge magnetic probe arrays show that the fluctuation excited by the injected CT propagates at

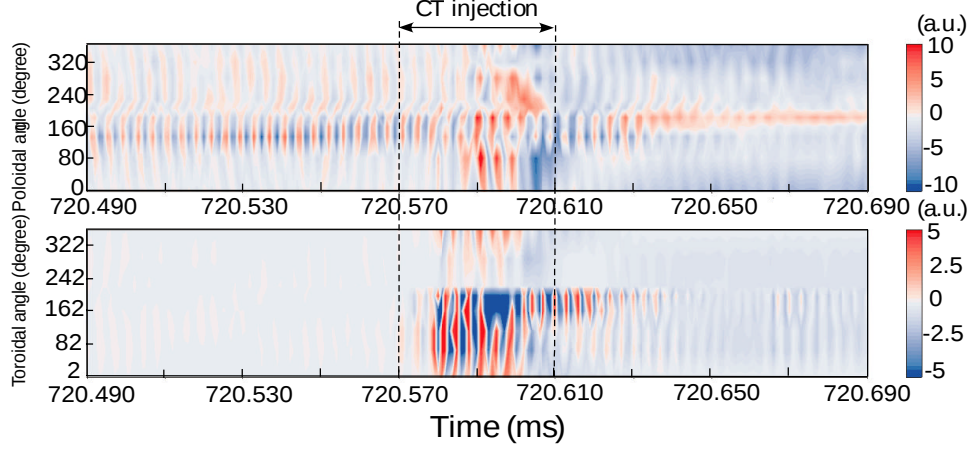


Figure 4. Time evolution of poloidal (upper) and toroidal (lower) profile contours of the edge magnetic fluctuations before and after CT injection.

the Alfvén speed of $\sim 3 \times 10^6$ m/s first in the toroidal direction and then after 10 μ s in the poloidal direction also. The fast toroidal propagation time of within a few μ s in the torus (length $2\pi R = 8 - 10$ m) cannot be explained by slow speeds such as the ion thermal speed v_{th} of CT $\sim 3 \times 10^4$ m/s. MHD activities seen in the poloidal direction appears to be suppressed after CT injection.

Figure 5 illustrates temporal evolutions of central and peripheral line integral densities $n_e L$ and soft X-ray emissions (core, edge and SOL) for the NBI heated discharge with $B_T = 0.8$ T, $I_p = 100$ kA with CT injection at $t = 720.43$ ms. A sharp rise of the peripheral line density within 10 μ s was observed after ~ 30 μ s from the firing time of the acceleration banks. On the other hand, the core density starts to increase rapidly after a delay of about 150 μ s. The density increment rate in this shot is about 0.7×10^{22} m $^{-3}$ /s ($D \bar{n}_e \sim 0.2 \times 10^{19}$ m $^{-3}$, the rise time ~ 300 μ s) which is higher than that in the past experiments [4, 5]. Note that the peripheral density exhibits a gradual increase correspondingly as the core density starts to rise. The SX emissions in both the edge and core chords show a response to CT injection, and the SX signal at SOL remains near the base line. The density rise due to CT injection appears to complete until around $t = 721$ ms. After then, the SX signal in the core region increases largely and correspondingly the edge SX signal

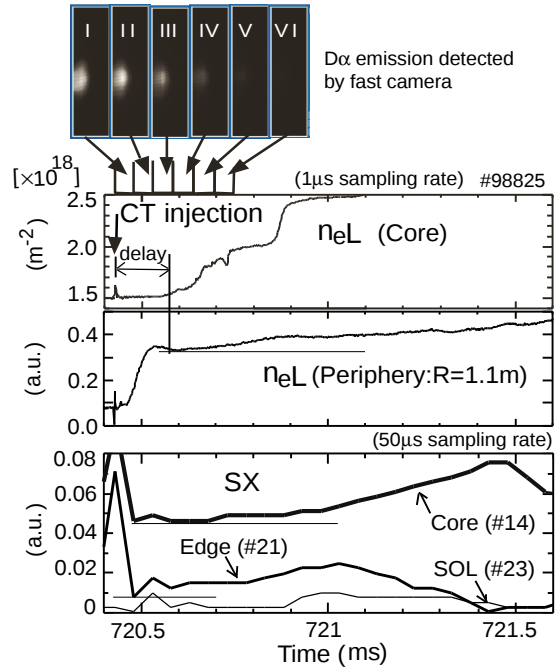


Figure 5. Time evolution of the line electron densities (core and periphery), soft X-ray signals (Core, Edge and SOL) and CT images (D_α emission) obtained by a fast camera

decreases so that the peaked profile becomes steep. Then the $m=2/n=1$ tearing mode begins to occur from around $t = 721.4$ ms, and so the core SX signal goes down rapidly. The reason for the time delay of the core density increase is not yet understood. As one possible explanation, we are speculating the fact that if the reconnection time is much slower than the reconnection time scale $(t_A t_R)^{1/2} \sim 2 \mu\text{s}$ estimated by Sweet-Parker model, where t_A is Alfvén time and t_R is the resistive diffusion time of CT plasma, only partial release of CT particles may occur instantly. During the delay time, the relatively long CT (length $v_{CT} \times D t_{inj} \sim 4$ m), as compared to the minor radius, may lay locally between the magnetic flux surfaces ($q = 2 - 3$) of the tokamak until full reconnection occurs or decays there in such a slow time scale due to the resistivity.

The fast image camera (18000 frames/s) measures D_α emission from CT plasmoids. Camera images displayed in Fig. 5 show that the D_α emission is detected at first frame I just after CT injection, and it is most intensified at the frame II. Thereafter it is almost disappeared at the frame IV. This evolution happens within $\sim 200 \mu\text{s}$. This emission time is almost the same as the delay time of the core density rise, which may support one of the speculations that the CT dissipates resistively in such a slow rate in the tokamak plasma without a rapid magnetic reconnection.

Figure 6 shows that the D_α signal decreases after CT injection and the fluctuation of the ion saturation currents I_s in the divertor is clearly reduced in 400 – 500 μs . Correspondingly the SX signals in the core region appear to increase significantly from around $t = 721$ ms as already shown in Fig. 5, suggesting that the confinement may be improved by CT injection. The reason is because the CT may assist NBI with L-H transition [3]. The fluctuation level of I_s does not change significantly in comparison to just before and after CT injection, which means that the CT initially reaches a peripheral region at least beyond the separatrix.

4. Conclusions

The dynamics of CT injected into the JFT-2M tokamak have been investigated by means of diagnostics with fast time resolution. We have verified that the CT plasma penetrates directly near the central region (at least $R = 1.1$ m) beyond separatrix. The MHD fluctuation excited by the CT is identified as Alfvén wave. We have observed for the first time that CT injection causes the decrease in the D_α signal and the suppression of the density fluctuation in the divertor region. This result may suggest that the CT has capabilities to produce H-mode-like tokamak discharges. The delay in the core density rise may be closely related to the 3D

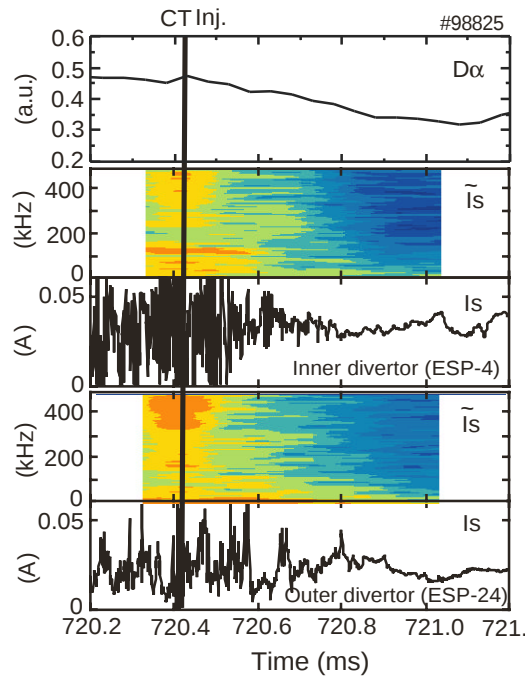


Figure 6. Time evolution of D_α spectral line, fluctuations of I_s signals detected on divertor plates and its frequency spectrum.

dynamics of the CT in the tokamak plasmas. Further studies are required to explore the complex mechanism of CT particle fuelling process.

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