Behavior of Compact Toroid Injected into the External Magnetic Field

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Abstract. Interaction of a compact toroid (CT) plasma with an external field and with a tokamak plasma has been studied experimentally on the JFT-2M and FACT devices. Fast framing camera and SX emission profile measurements indicate shift and/or reflection motions of the CT plasma. New electrostatic probe measurements indicate that the CT plasma reaches at least up to the separatrix for discharges with the toroidal field strengths of 1.0 – 1.4 T, and that there exists a trailing plasma behind the CT. We have observed a large amplitude fluctuation on ion-saturation current and magnetic coil signals. Power spectrum analysis suggests that this fluctuation is related to magnetic reconnection between the CT plasmoid and the toroidal field. The low density trailing plasma may be able to move across the external magnetic field more easily in the injector owing to the Hall effect.

1. Introduction

The injection of spheromak-like compact toroid (CT) is considered to be refueling method for fusion plasmas. The first central fueling of a tokamak plasma was demonstrated in the TdeV device [1]. Recently, we have performed CT injection experiments using the Himeji Institute of Technology-CT injector (HIT-CTI) into the JFT-2M tokamak [2, 3]. The JFT-2M has a major radius $R = 1.31$ m, a minor radius $a \leq 0.35$ m, elongation ≤ 1.7 and a toroidal magnetic field (TF) $B_t \leq 2.2$ T. CT plasmoids generated by the HIT-CTI device have a length ≈ 0.3 m, diameter ≈ 0.07m, velocity $v_{CT} \leq 300$ km/s, density $n_{CT} \leq 9 \times 10^{21}$ m$^{-3.}$ These CTs successfully penetrate into the core region of both OH and NBI heated plasmas, including H mode plasmas. After the CT injection into a target tokamak plasma with $B_t = 0.8$ T, the line averaged density in the tokamak increased by $\Delta \bar{n}_e \approx 0.4 \times 10^{19}$ m^{-3} and the particle content increases by about 0.6×10^{19}. The CT particle inventory was 1.5×10^{19}, which results in a fueling efficiency of 40 %. In order to realize central fueling by CT injection with higher efficiency into a higher field tokamak, it is necessary to understand the penetration mechanism and the dynamics of the CT as it transverses across the toloidal field and a tokamak plasma. This paper presents the behavior and characteristics of the CT plasmoid injected in an external magnetic field in JFT-2M and the FACT device at the HIT.

2. Experimental Set-up

The CT injector with the new inner electrode with 0.2-0.3 mm tungsten was installed on the midplane of the JFT-2M vacuum chamber as shown in Fig.1. The tungsten coating was applied under vacuum condition using the plasma spray technique. In this modified injector design, the space around the compression region is expanded so that the CT plasma can trap a larger amount of the bias flux before acceleration. The electrodes are baked up to 200 ^{o}C for one week before an experiment. We increased the number of the capacitor bank units driving the four gas puff valves so as to improve the uniformity of the gas injected from the ports. This has resulted in improved reproduciblity of the CT formation phase. Magnetic pick up coils (B_p1, B_p2 and B_p3) are placed at three axial positions along the outer electrode surface. Time of flight measurement between B_p2 and B_p3 provides the average CT velocity and length. A He-Ne laser interferometer measures the line averaged electron density of CT in the focus cone. We have a new diagnostic, "the complex probe" which consists of double electrostatic probe arrays and three axis magnetic pick up coils (B_x, B_y, B_z) as shown in Fig.1. This probe is inserted vertically at R = 1.62 m near the plasma separatrix at the midplane (Z = 0.03m). The probe measures ion-saturation current I_{is} and the magnetic fields of CT plasmoid reaching the separatrix of the tokamak plasma.

The JFT-2M tokamak was operated with TF from 0 to1.4 T and a plasma current between 100 kA and 150 kA, corresponding to the safety factor q-95 of 3. The line averaged electron density measured by a 130 GHz microwave interferometer was in the range of $1\text{-}2 \times 10^{19}\ \mathrm{m}^{-3}$. A fast edge magnetic coil (B_r) located at the outer toroidal section about 135^o toroidaly from the CT injection port is used to analyze MHD fluctuations of the B_r component of the magnetic field observed during penetration of the CT. A multi-chord PIN diode array measures the soft X ray emission profile with 50 μs sampling time resolution.

3. Experimental Results

3.1 Behavior of the CT Injected into a Tokamak Plasma

Recent results from the JFT-2M experiment have shown that there is evidence for the interaction between a moving CT and the toroidal vacuum field or the tokamak plasma. The injected CT is compressed to ≤ 0.1 m in length by TF (B_t =1 T) and shifts vertically as shown in Fig.1. The shift motion is caused by the $\mathbf{J}\times\mathbf{B}_t$ force on CT. Hence the direction of its shift motion depends on the direction of TF. Figure 2 shows the change of the soft x-ray emission profile (24 channels) in the shot with the deepest CT penetration. The line-averaged electron density increases by 33 % ($\Delta \bar{n}_e/\bar{n}_e \approx 0.4 \times 10^{19}\ \mathrm{m}^{-3}/1.2 \times 10^{19}\ \mathrm{m}^{-3}$). The central and edge channel signals increase rapidly after CT is injected at t = 702.90 ms resulting in a profile with double peaks. Afterwards only the central channel signal decays while the edge channel signal remains high for longer than 0.25 ms. This result indicates that the CT plasma reaches the core region and then bounces slowly back to the edge region. We note that there is no slow component of CT entering the tokamak vessel after t = 703.20 ms.

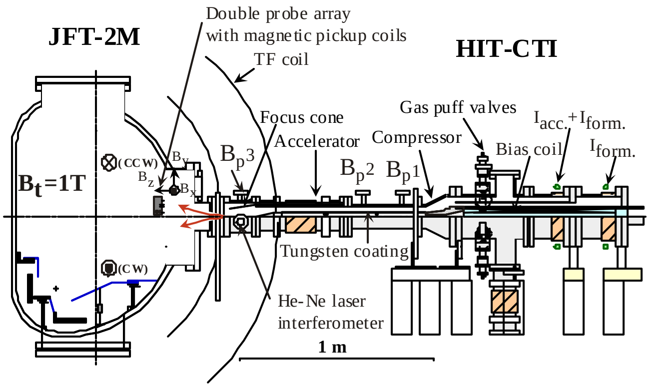

Fig.1. The CT injector and behavior of CT plasmoid injected into the toroidal vacuum field of the JFT-2M device.

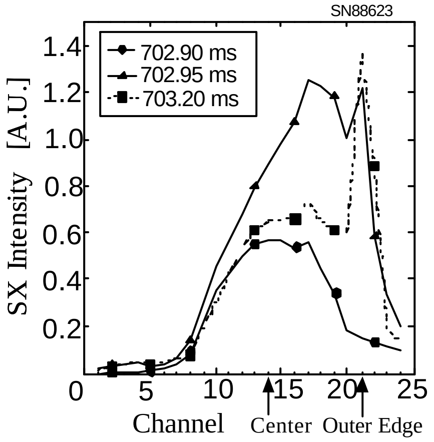

Fig.2. The temporal evolution of soft X ray emission just before and after CT injection.

3.2 Characteristics of CT Injected into a Tokamak Plasma

Figure 3 shows the time evolution of the ion-saturation current I_{si} measured by the double probe and the magnetic field B_p3 for the case of CT injection into tokamak plasmas with B_t = 1.0 T, 1.28 T and 1.4 T. Time t=0 μs corresponds the firing time of the formation bank. The I_{si} signals lasts for about 50 μs. These show that CT particles reach to the position of double probe even in the case of the higher toroidal field of 1.4 T. The average velocity of CT within the injector decreases from 138 km/s to 58 km/s as TF increases from 1.0 T to 1.4 T which indicates that the toroidal field significantly affects the acceleration of CT in the injector. The velocity of the CT ejected from the focus cone reduces from 119 km/s (at B_t = 1.0 T) to 46 km/s (at B_t = 1.4 T) between the double probe (at R = 1.62 m) and B_p3 (at R = 2.05 m). The kinetic energy density W_K of CT is estimated to be 1×10^5 J/m^3 using $v_{ct} \cong 200$ km/s and average electron density of $\bar{n}_e \cong 3\times10^{21}$ m^{-3} in the focus cone. W_K is lower than the magnetic energy density W_B of 6.5×10^5 J/m^3 (at B_t = 1.28 T). This estimation is not consistent with the penetration depth model [4] in which W_K is required to exceed W_B for successful penetration.

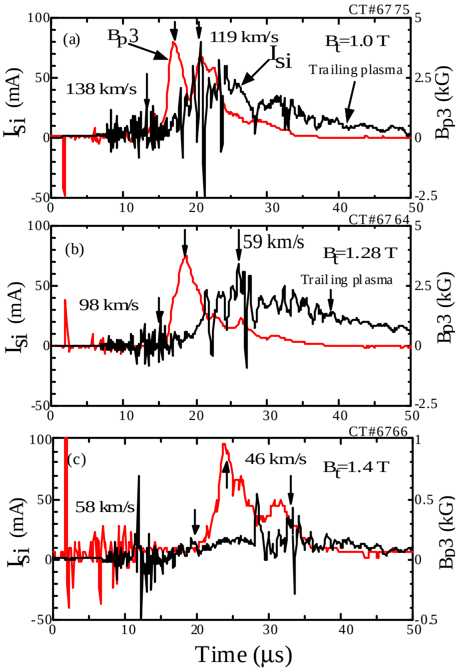

Fig.3. Time evolutions of the ion-saturation current and the magnetic field B_p3 for CT injection into a tokamak plasma with B_t=1.0 T (a), 1.28 T (b) and 1.4 T (c).

The injected CT plasma is thought to consist of a main CT plasma (t = 20-30 μs in Fig.3 (b)) and a trailing plasma (t = 30-50 μs in Fig.3 (b)) with high velocity close to the former one. A large amplitude of fluctuation in the I_{si} signal can be seen on the main CT during the initial 7-10 μs. This may imply an interaction such as magnetic reconnection between the CT magnetic field and the toroidal field. The interaction time-scale agrees with magnetic reconnection time τ_R =9-12 μs of 30 to 40 Alfvén transit times τ_A as estimated from the three dimensional MHD simulation [5]. τ_A is defined by R_{CT}/v_A, where R_{CT} is the CT diameter and v_A is the Alfvén velocity ($\equiv B / (\mu_0\rho)^{1/2}$). The large fluctuation is apparently reduced as the TF increases, but the trailing plasma appears not to be influenced by TF. The trailing plasma is not attributed to cause the rapid increase in the edge SX emission observed between t=702.95 ms and t = 703.20 ms after CT injection (Fig.2).

MHD fluctuations have been observed for about 50 μs on both the B_r signal at the wall and the B_y signal in the complex probe. The large amplitude of the magnetic fluctuation as well as the signal of the double probe lasts for about 10 μs, afterwards its amplitude decays sharply. Figure 4 depicts the power spectrum analysis of fluctuations of magnetic field signals. The same peak frequency of about 200 kHz has been observed in the fluctuation of both the B_r and B_y signals shown in Fig.4 for the B_t = 1.4 T. The dominant frequency of the fluctuation of B_y is in the range of 500 - 800 kHz and its center frequency shifts to a smaller number as TF increases. This high frequency of fluctuation indicates the local interaction of the CT

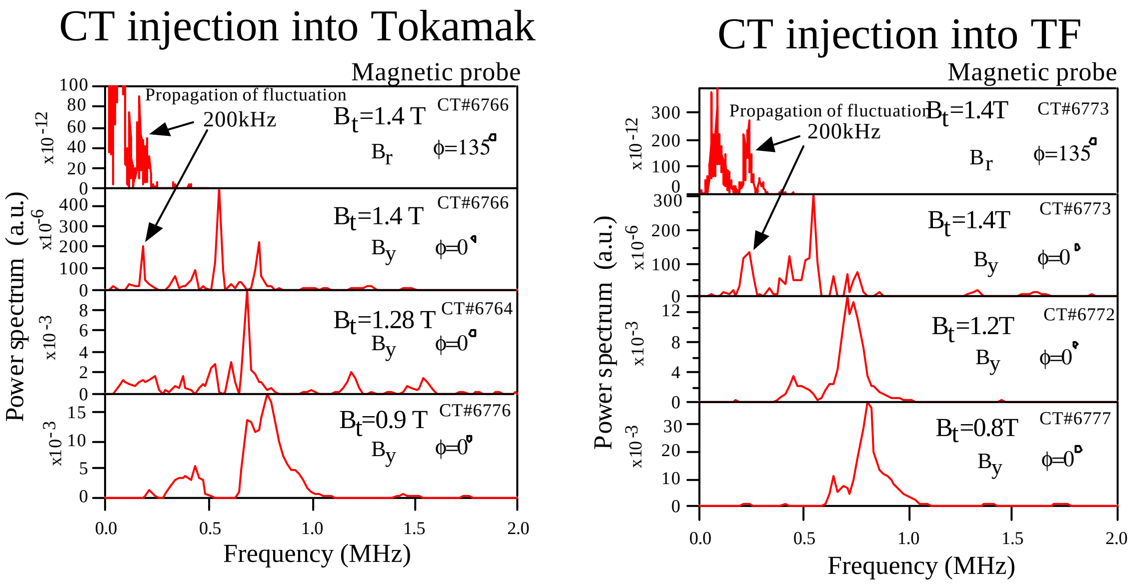

Fig.4. Power spectrum of magnetic fluctuation observed by the B_Y coil set in the complex probe and the B_r pick up coil installed on the vessel wall (B_t = 1.4 T) for CT injection into a tokamak plasma (left) and into a vacuum toroidal field (right).

plasmoid with TF near the injection port as it is not observed on the B_r signal. The low frequency spectrum of 200 kHz might be related to the toroidal propagation of particles released from the CT and a magnetic distortion produced around the injection port. We see this propagation of fluctuation for both the cases (Injection into a tokamak plasma and into a vacuum toroidal field). We do not yet understand the nature of these fluctuations.

3.3 Behavior of the CT plasmoid in the CT Injector

We have carried out experimental tests using a magnetized coaxial plasma gun (MCPG) in the FACT device for the purpose of examining CT propagation perpendicular to a magnetic field in the injector region. Figure 5 shows the time evolution of the X profile of the poloidal field B_z measured at three Y locations in the drift tube region of the MCPG. The imposed B_{ext} (= 0.8 kG) stabilizes the rotating helical distortion of the CT plasma that was observed without B_{ext} and also causes a vertical shift of the CT in the drift tube region. We note that the direction of the applied gun bias flux does not affect the shift motion, but a change of the electrode polarity or the direction of B_z reverses the motion. Those results suggest that a vertical shift motion should occur in the HIT-CT injector as well as on JFT-2M.

The behaviors of the CT propagating in the drift tube region could be explained by treating CT plasmoid produced in FACT as a low β plasma flow such as the trailing plasma. As a moving plasma with velocity **u** encounters a transverse magnetic field, a polarization electric field $\mathbf{E}_Y = -\mathbf{u}_Z \times \mathbf{B}_{ext}$ is set up in the direction of Y. The plasma is decelerated by shorting out this electric field with the external cylindrical conductor. Then a vertical polarization current $\mathbf{J}_Y$ is induced in the plasma, as shown in Fig. 5. The Lorentz force $\mathbf{J}_Y \times \mathbf{B}_{ext}$ being in the -Z direction slows the CT plasma propagation. The $\mathbf{J}_Y$ does not cause the vertical shift but bends the $\mathbf{B}_{ext}$. The $\mathbf{J}_Y \times \mathbf{B}_{ext}$ force acts as the main drag force during the CT propagation process. As already described in the section **3.2**, the penetration depth is normally predicted from the balance between W_B of $\mathbf{B}_{ext}$ and W_K of CT [4]. However, the CT plasma was able to penetrate into $\mathbf{B}_{ext}$ with W_B (3.2×10^4 J/m^3) being much larger than W_K (2.1×10^3 J/m^3) in the drift tube region. This indicates that the deceleration of the CT due to $\mathbf{J}_Y \times \mathbf{B}_{ext}$ force is effectively

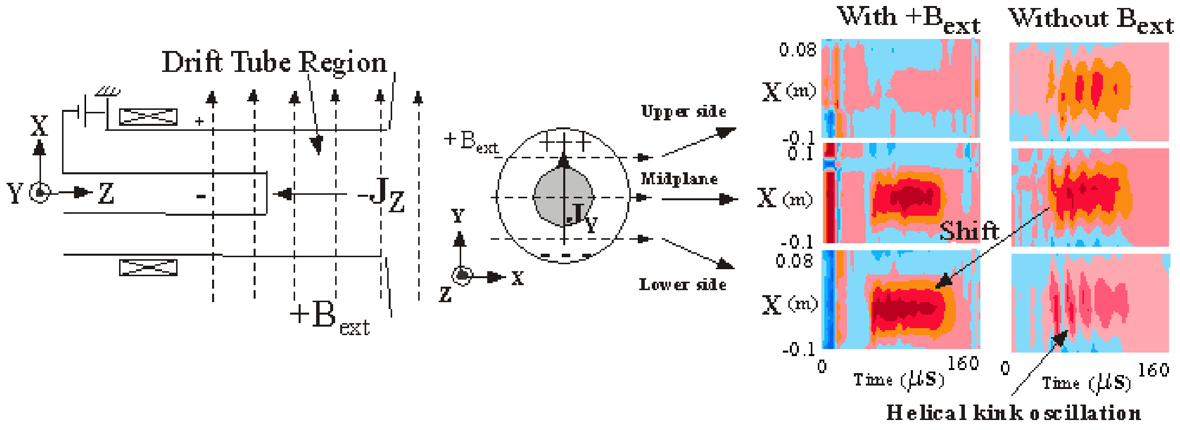

Fig. 5. Comparison of time evolutions of X profile of the poloidal magnetic field measured on three Y locations in the drift region between with +B_{ext} and without B_{ext}.

relaxed there. This could be explained by considering the Hall effect. $\mathbf{J}_Y$ is given by $\mathbf{J}_Y = \sigma \mathbf{E}_Y / (1 + h_e^2)$, where σ is the plasma conductivity, $h_e = \omega_{ce}\tau_e$ is the Hall parameter, ω_{ce} is the electron cyclotron frequency and τ_e is the electron collision time. $\mathbf{J}_Y$ is decreased from $\sigma \mathbf{E}_Y$ by a factor of $1/(1 + h_e^2)$. This means that the Hall effect makes the external field diffuse more easily into the CT plasma. For this experiment, the h_e parameter is about 25. The diffusion time $\tau_D \approx 180$ μs of $\mathbf{B}_{ext}$ is comparable to the discharge time scale as shown in Fig. 5. The Lorentz force $\mathbf{J}_Z \times \mathbf{B}_{ext}$ between the axial gun current $\mathbf{J}_Z$ and some amount of $\mathbf{B}_{ext}$ diffusing inside the CT is responsible for the shift in the Y direction. In the vacuum chamber, the plasma may continue to move across the external field by the acceleration due to $\mathbf{E}_Y \times \mathbf{B}_{ext}$ drift because the polarization electric field $\mathbf{E}_Y$ (-Y) induced by charge separation is not shorted out. This drift motion may be accompanied by the vertical shift due to $-\mathbf{E}_Z \times \mathbf{B}_{ext}$ drift.

4. Conclusions

Behavior of the CT injected into an external field and into a tokamak plasma has been investigated experimentally. We have observed interesting motions such as a shift and a reflection of the injected CT plasma. A new double probe measurement indicates that the CT plasma with a trailing portion reaches at least near the separatrix. Interaction of the CT with the toroidal field causes a large amplitude fluctuation. Power spectrum analysis of the fluctuation suggests the presence of a local magnetic reconnection event on a fast time-scale around the injection port and a low frequency non-local magnetic perturbation by the CT injection. The external magnetic field decelerates the CT plasma in the injector, but the Hall effect may be able to reduce the drag force.

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