Fuelling Effect of Tangential Compact toroid injection in STOR-M Tokamak

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Abstract

Compact torus injection (CTI) is the only known candidate for directly fuelling the core of a tokamak fusion reactor. Compact torus (CT) injection into the STOR-M tokamak has induced improved confinement accompanied by an increase in the electron density, reduction in Hα emission, and suppression of the saw-tooth oscillations. The measured change in the toroidal flow velocity following tangential CTI has demonstrated momentum injection into the STOR-M plasma.

1. Introduction

The Tokamak is one of the most promising configurations among magnetic confinement concepts to realize commercial fusion reactors. The International Thermonuclear Experimental Reactor (ITER) being constructed in Cadarache, France is the next generation tokamak. The objective of the ITER tokamak is to demonstrate the self-sustained fusion reaction with net energy gain. ITER is much larger than any existing tokamaks and the density and temperature in the ITER plasma are also significantly higher than those in the existing tokamaks. The present fueling techniques are unable to send the fuel directly into the reactor core where fusion reactions are most active. Unlike a fission reactor, fusion fuels need to be continuously injected into the fusion reactor. Pellet injection or ultrasonic gas puffing are used for fuelling the present-day tokamaks. However, they are subject to premature ablation and ionization at the edge. Compact toroid injection (CTI) is a promising technique for fuelling fusion reactors [1,2].

Fuelling a tokamak based on CTI was originally proposed by Perkins *et al.* [3] and Parks [4]. CT is a high density, axially symmetric plasmoid formed and accelerated in a co-axial plasma gun. It is confined by its own magnetic field. CT can be accelerated to a large velocity to overcome the magnetic field gradient in the tokamak and penetrate into the tokamak core. The condition for CT penetration into the tokamak core is approximately described by the following formula :

$$\frac{1}{2}\rho_{CT}v_{CT}^2 > \frac{B_t^2}{2\mu_0} \qquad (1)$$

where ρ_{CT}, v_{CT} and B_t are the CT mass density, the CT velocity and the toroidal magnetic field in the tokamak. The above equation has also been predicted in numerical simulations based on the conducting sphere [5,6] and non-slipping model [7], and qualitatively agrees with observed experimental results. The first CT acceleration was demonstrated on the RACE device at Lawrence

Livermore National Laboratory (LLNL) [8]. An improved CT accelerator as a fuelling tool was developed by the Canadian Fusion Fuels Technology Project (CFFTP) in collaboration with the University of Saskatchewan, LLNL and University of California Davis (UC-Davis). The first disruption-free CTI experiment into a tokamak was carried out on Tokamak de Varennes (TdeV) [9] and CTI into H-mode plasma was performed on the JFT-2M [10-12]. H-mode like discharges have been induced by tangential CT injection in the STOR-M tokamak using University of Saskatchewan Compact Torus Injector (USCTI) [13,14]. In addition to the Plasma Physics Laboratory at the University of Saskatchewan, active CT research is also carried out at UC-Davis for repetitive CT operation, in the National Institute of Fusion Science with a plan to examine the effect of the interaction between CT and the Large Helical Device (LHD) stellarator. CT injection into the QUEST spherical tokamak is also planned at the Kyushu University.

Since the velocity of the CT can be easily varied by changing discharge parameters for a CT injector, the fuel deposition location in a tokamak can be controlled, providing a means for density profile control. The density/pressure profile in a tokamak is one of the key parameters determining the bootstrap current in tokamaks. Bootstrap current is a self-generated plasma current sensitive to the plasma pressure profile. The high fraction of the bootstrap current is desirable since external current driving schemes require substantial power. CTI has the potential to realize fusion reactors with nearly 100 % bootstrap current which will simplify reactor design and reduce the construction and operation costs. In addition, the momentum in a CT with high velocity and density can be deposited to the tokamak discharge and drive a toroidal flow in case of tangential CT injection. Although neutral beam injection, primarily for plasma heating, is also capable of driving plasma flow, it is not an economically efficient approach. On STOR-M, CT can be injected tangentially, which is a unique feature of the CT injection experiments on STOR-M.

In this work, the effects of CTI on the STOR-M tokamak plasma are examined using various diagnostics tools. Soft X-ray (SXR) bremsstrahlung emissions are measured by a miniature imaging camera using a photo-diode array. After CT injection, SXR emission intensity increases significantly and the high emission intensity phase stays until the end of discharge. Ion Doppler spectroscopy (IDS) measurement shows that plasma flow velocity increases in the direction of tangential CT injection.

2. The USCTI injector and STOR-M tokamak

The University of Saskatchewan Compact Torus Injector (USCTI) is a co-axial plasma gun as shown in Fig. 1. The injector consists of formation and acceleration sections. A quasi-steady state bias magnetic field is generated by a solenoid coil in the formation region. The magnetic flux generated by the solenoid is typically Φ_{bias}=1.8 mWb for USCTI. The CT is formed between the inner and outer formation electrodes and accelerated along the acceleration section by two consecutive discharges. The radii of inner and outer acceleration electrodes are 1.8 cm and 5.0 cm. The formation and acceleration discharges are separately powered by a 20 μF, 30 kV capacitor bank. Hydrogen gas is injected into the circular gap between inner and outer formation electrodes by four fast electromagnetic valves. The CT plasma is confined by both toroidal and poloidal fields. This robust CT is accelerated by $\boldsymbol{j_r} \times \boldsymbol{B_\varphi}$ force, where $\boldsymbol{j_r}$ is the radial discharge current and $\boldsymbol{B_\varphi}$ is the toroidal magnetic field self-generated in CT. The typical velocity of CTs accelerated in USCTI is 150-200 km/s. CT is further compressed by and exit cone with an exit diameter of 7.5 cm. The CT lifetime estimated by the CT size and the Spitzer conductivity is 20μs[14].

STOR-M is a small tokamak housed in the University of Saskatchewan. STOR-M is presently the only active tokamak device in Canada. The major radius of STOR-M is R=46 cm and minor radius a=12 cm. The maximum toroidal magnetic field $\boldsymbol{B_t}$ is 1T. The discharge duration is usually between 30 and 40 ms and the plasma current is above 20 kA. The electron density is in the range of 10^{12} cm^{-3} and electron temperature is approximately 200 eV in typical L-mode (low confinement mode) discharges. The results presented in this paper are obtained during tangential CT injection experiments. On STOR-M, radial and vertical injection configurations are also possible. CTI research on STOR-M has been carried out for more than 15 years and important results have been obtained. H-mode (high confinement mode) STOR-M discharge phase has been induced by tangential CTI. Vertical CTI has also been demonstrated in STOR-M [14].

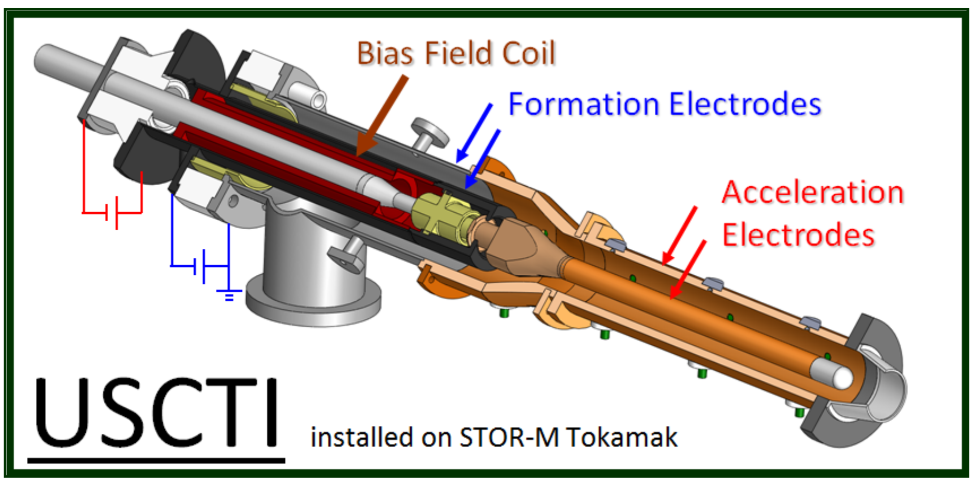

Figure 1 3D schematic diagram of USCTI. Applied voltages to the formation and acceleration electrodes are typically 18.5 kV and 17 kV respectively.

3. Effects of CT Injection on the STOR-M Discharges

Figure 2 shows waveforms of a tokamak discharge with a CT injected at t=20 ms. The CT was formed and accelerated with a formation bank voltage of V_{form}=18.5 kV and an acceleration bank voltage V_{acc}=17 kV. The Figure shows (from top) the plasma current I_p, loop voltage V_l, the electron density line-averaged along the central line of the plasma crosssection, the SXR emission intensity integrated along the central chord of a 12-channel camera looking downwards through a vertical port [15,16], and the Hα line emission integrated along a line passing through the central region of the plasma. The SXR camera covers almost an entire plasma cross-section through 12 fan-like lines of sight with the impact parameter falling in the range -8.7 cm< p < 9.0 cm, where impact parameter p is the distance from the center of the chamber to the line of sight. Obviously, p=0 represents the line of sight through the center of chamber. The negative p indicates the inboard of the chamber and positive p

outboard of the chamber. The SXR emission intensity shown in Fig. 2 is measured by a detector with an impact parameter of the line of sight *p*=1.5 cm.

The power of bremsstrahlung emission depends mainly on electron density and temperature:

$$P_{br} = 1.7 \times 10^{-38}\, Z^2 n_e n_i T_e^{1/2} \quad [\mathrm{Wm^{-3}}] \qquad (2)$$

After CT injection at *t*=20 ms, the plasma current I_p remained unchanged. The loop voltage V_l reduced slightly around *t*=22 ms, indicating an increase in the Spitzer temperature. The electron density increased from 4.0×10^{12} cm^{-3} to about 1.0×10^{13} cm^{-3}. The SXR emission starts to increase about 1ms after CT injection. Since the SXR camera port and the CT injection location are almost on the opposite toroidal sides of the tokamak chamber, the 1ms delay may indicate the time needed for redistribution of the fuel to the discharge and the thermalization time. Around the time *t*=25 ms, The SXR emission reached a maximum and saw-tooth oscillations are observed. At the same time, Hα emission intensity also decreased slightly. The change of the plasma parameters after CT injection indicates a transition to an improved confinement (H-mode) phase. In this shot, the discharge duration is slightly shorter than those without CT injection because strong MHD instability was excited around *t*=27.5 ms as indicated by the loop voltage V_l waveform. Afterwards, SXR emission decreases and Hα emission increases, indicating an H-L back transition.

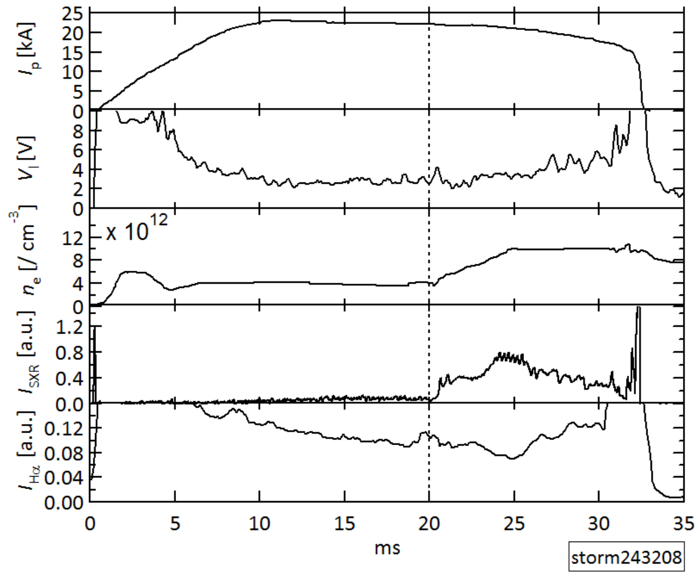

Figure 2. Typical waveform of discharge parameter of CT injected tokamak. From the top panel, Plasma current I_p, loop voltage V_l, line averaged electron density, SXR emission and Hα emission.

The plasma density after CTI becomes higher than before CTI. However, the electron temperature of CT is only 10 eV, much lower than tokamak plasma. The SXR emission in CT injected tokamak is shown in Fig.3. This contour image is the time variation of SXR emission in the same discharge as the one shown in Fig. 2. Around t=21 ms, there are two large spikes over the emission profile. After these spikes, SXR emission becomes much higher than before CTI, and tokamak confinement is improved. These spikes occur 1ms after CTI and are likely related to large scale magnetic reconnection and relaxation after CT penetration broke the robust tokamak magnetic configuration.

The profiles of SXR emissions shown in Fig.4 suggest that, the emission peak shifts outward after CTI event. SXR emission increases and also keeps high after CTI. Within 2 ms, as shown in Fig.4 (a), the emission becomes twice as high as before CTI. The profile at t=21.5 ms is asymmetric as the emission on the positive p side (outboard) is higher than on the negative p side. This profile indicates that more CT fuel is deposited in outward edge region initially as indicated by blue arrow. The peak of the profile is still shifting outwards as indicated by yellow arrow. At t=23.5 ms, as shown in Fig. 4(b), the emission at the peak becomes 3 times as high as before CTI. Eventually, steeper SXR emission gradient is generated around p=±30 mm and the profile becomes, more or less, symmetric. However, as shown at t=25.5 ms, the peak keeps shifting and the profile becomes asymmetric again. Total SXR peak shift is about 50mm outwards. Such outward shift of the emission peak has occurred in Ohmic H-mode-like operation in STOR-M tokamak, too. The physical center of torus plasma changes less than the SXR emission profile. Typical horizontal plasma position change (plasma current center) moves outwards up to 10mm when improved confinement is induced by CTI. Therefore, it is inferred that high density plasma from CT is accumulated and stay outside. Such density profile lasts for 5ms later CTI.

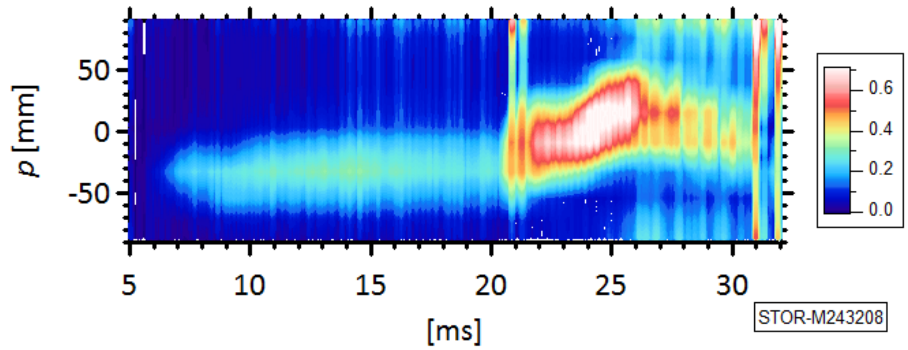

Figure 3. The time variation of SXR emission profile versus impact parameter in CT injected discharge. CTI is triggered at 20 ms.

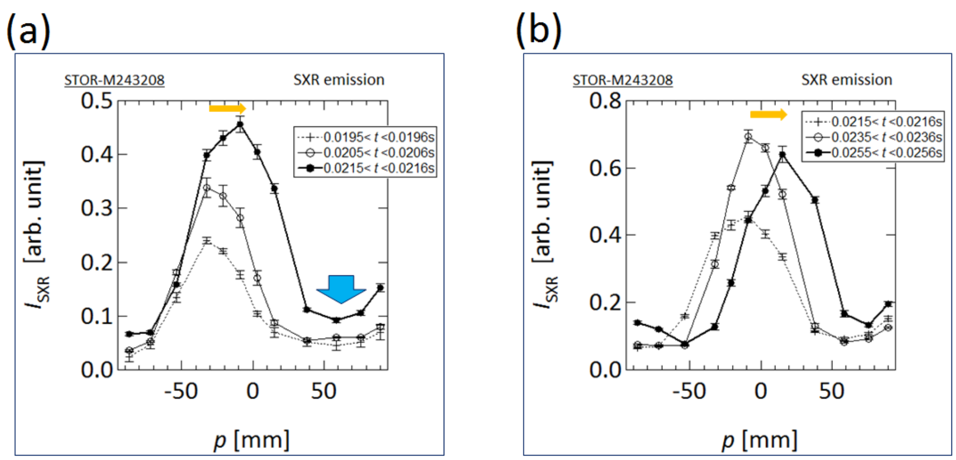

Figure.4 panel (a) is the profiles averaged for 1ms at t=19.5 ms (dashed line), t=20.5 ms (thin solid line) and t=21.5 ms (bold line), where vertical axis limit is 0.5. Panel (b) shows the profiles 2ms later than (a), at t=21.5 ms (dashed line), t=22.5 ms (thin solid line) and t=23.5 ms (bold line) where vertical axis limit is 0.8. The data of (a) and (b) are from same discharge #243208. As shown with blue arrow in (a), the emission goes up in the outer edge region, where the profile is considerably asymmetric, compared with before CTI. Such profile indicates that the density is fueled and initially deposited in the edge region.

4. Momentum injection

Momentum injection by CTI has been verified through the measurement of change in the toroidal flow velocity using Ion Doppler Spectroscopy (IDS) recently installed on the STOR-M tokamak. Intrinsic Carbon impurities are mainly utilized for this IDS measurement. Figure 5 shows the toroidal flow velocities of C_{VI} and C_{III} impurities during typical CT injected tokamak discharges. Here, the wavelength of C_{VI} and C_{III} line emissions are 5290.5 Å and 4647.4 Å. C_{VI} flow indicates the toroidal flow in the core region and C_{III} is the one at the edge region. CTI is triggered at t=20 ms. Here, positive velocity corresponds to plasma current direction, which is counter clockwise when viewed from top. Clockwise direction corresponds to negative value and opposite from CTI direction. Before CTI, C_{VI} has negative value and C_{III} (edge region) has positive value, so there is substantial shear in toroidal flow velocity in STOR-M tokamak discharges. In the discharge 244819, flow velocity in the central region goes closer to zero right after CTI. This flow change indicates that CT penetrates tokamak magnetic surfaces and injected into the core region. Then, momentum from CTI is injected and counter-current flow speed is reduced because CTI direction is co-current. In the case of C_{III} in the discharge 244717, the flow velocity increases a few km per second toward co-current direction. This co-current increase gives a proof that the flow change is indeed due to CTI which has the same injection direction as plasma current (co-current). This short term increase is coincident with strong m=2/n=1 mode and it is assumed that the momentum is transported from central region. With the strong mode, C_{VI} flow drops for 2-3 milliseconds corresponding to period with increased C_{III} impurity. Therefore, the injected momentum is inferred to be radially transported from the core region to edge region. On the other hand, such co-current C_{III} flow change is less significant when m=2/n=1 mode does not grow to a certain level.

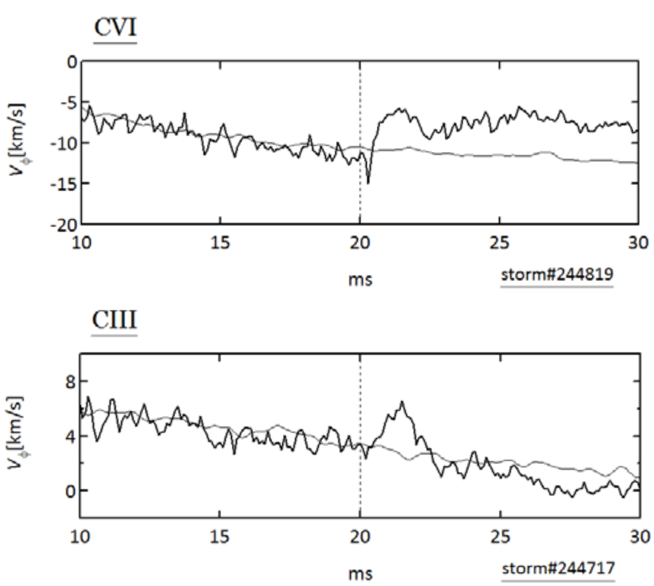

Figure.5 Toroidal flow velocities of CVI and CIII in the CT injected tokamak discharges. Thin solid lines show averaged flow velocities in typical STOR-M discharges without CTI.

5. Conclusions

Compact Torus Injection experiments have been carried out in STOR-M tokamak. In the case of gas puffing, it takes about 5 ms for the increase of plasma density to occur and too much gas puffing can induce critical MHD instability which terminates discharge. In addition, it is difficult to control the effect of external gas puffing for central fueling. With CTI, fuelling into the central part is achieved. Also, the radial location of density peak is shifted outward and the density profile was changed by CTI.

Recently installed IDS system has enabled toroidal flow velocity measurements in STOR-M. It is experimentally verified that CTI can inject momentum into the tokamak and to change toroidal flow velocity of selected impurity ions towards the CT injection direction. CTI also caused immediate density increase from 4.0×10^{12} cm^{-3} to 1.0×10^{13} cm^{-3}.

Acknowledgements

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