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Studies of boundary plasmas and fueling on the JFT-2M [1]

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Abstract

In the JFT-2M tokamak, the effects of baffle plates on the divertor and the scrape-off-layer (SOL) plasma and the fueling by the compact toroid (CT) injection have been investigated, and following results were obtained. A transition-like phenomenon in the divertor plasma, which occurs at the average main plasma density of about 2–2.5 × 10^{19}m^{-3}, was observed and coincides with the abrupt drop of the temperature on the divertor plate from 9 to 3 eV. The negative biasing of both inside and outside divertor plates showed a significant improvement of the buffled divertor function, which was only observed when the direction of the $E \times B$ flow formed by the biasing in the SOL is from the inside to the outside. The particle fueling up to 3.4 × 10^{18} was observed and increase of the W_{MHD} and decrease of P_{RAD} and V_{loop} were observed in discharges with the CT injection in Ohmic heating (OH) plasmas.

Keywords: Divertor plasma; Detachment; Divertor biasing; Fueling; JFT-2M

1. Introduction

Since a divertor plasma directly interacts with a material, its temperature should be as low as possible to reduce the high heat load and the damage to the divertor material. On the other hand, the temperature of the main plasma should be kept high. Therefore, to understand and to control the scrape-off-layer (SOL) and divertor plasma is one of the most important issues in the fusion plasma research. The transport mechanisms in the SOL and the divertor region have been extensively studied over the past few years [1,2].

In the meantime, the development of a method for the core fueling is important for an experimental fusion reactor such as ITER. Degradation of H-mode confinement is problematic at high electron density with peripheral fueling by conventional methods. Recently, fast and dense compact toroid (CT) injection has been considered as a possible candidate for a core fueling for ITER. Some promising results were obtained in a few tokamaks [3,4].

In the JFT-2M tokamak, the effects of baffle plates on the divertor and SOL plasma [5,6] and the fueling by the CT injection are being studied. In this paper, the property of the divertor plasma with baffle plates, the effects of a biasing to the divertor and main plasma, and fueling by the CT injection are discussed.

2. Experimental setup

The JFT-2M is a medium size tokamak (major radius $R = 1.31$ m, minor radius $a = 0.35$ m, elongation $\kappa < 1.7$, toroidal magnetic field $B_{\mathrm{T}} < 2.2$ T). Fig. 1 shows a

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[1] The authors dedicate this paper to the memory of Dr Norio Suzuki, who was a leader of the JFT-2M group, passed away on 11 March 1998. He had devoted his life to the plasma physics and the thermonuclear fusion.

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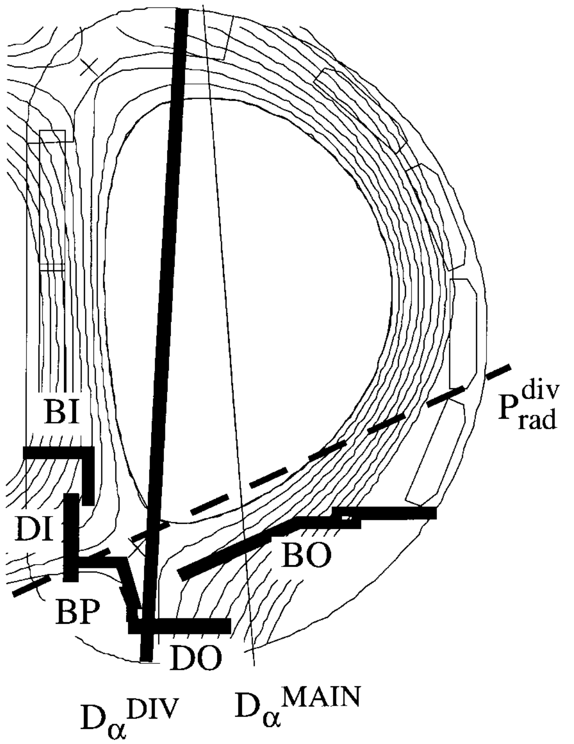

Fig. 1. JFT-2M divertor configuration. BI, BP and BO are the baffle plate of inside, private and outside divertor, respectively. DI and DO are the divertor plate of inside and outside, respectively. The thick and thin lines show the D_α line of sight at divertor and main plasma, respectively. The broken line shows the P_{rad} line of sight at the X-point.

typical JFT-2M divertor configuration. The lower divertor has been modified from an open to a closed configuration. The inside and outside divertor plates and the three baffle plates (inside and outside divertor and private region) are made of stainless steel and are toroidally continuous. All of them are electrically insulated from the vacuum vessel, and it is possible to apply a bias voltage.

The compact toroid injector, developed in Himeji Institute of Technology (HIT), was installed on the JFT-2M tokamak [7]. It is a magnetized coaxial plasma gun which consists of two coaxial electrodes (formation and acceleration) and the bias solenoid. Each electrode was connected to the power supply system which consists of capacitor banks of 20 kV for the formation and 40 kV for the acceleration. Each power supply is designed to have a very short rise time less than 10 μs.

3. Transition phenomena in a divertor D intensity at Ohmic heating

Fig. 2 shows a temporal evolution of a typical divertor discharge (the same configuration shown in Fig. 1). The plasma current is 230 kA, the toroidal field is 1.3 T and the safety factor is 2.96 in this case. The toroidal field direction is in clockwise direction (CW) viewing from the top of the torus. The X-point position is fixed from 550 ms and the deuterium gas puffing rate is constant from 380 ms. The D_α intensity at the divertor, whose line of sight is shown by a thick line in Fig. 1, shows an abrupt drop at 700 ms. However, the D_α intensity around the main plasma, whose line of sight is shown by a thin line in Fig. 1, shows a continuous increase with density. At this time the increasing rate of the density shows the change from 2.2×10^{19} to 5.3×10^{19} m^{-3}/s. This abrupt change at 700 ms is a transition phenomenon in the divertor D_α intensity. The temperature on the divertor plates measured by an

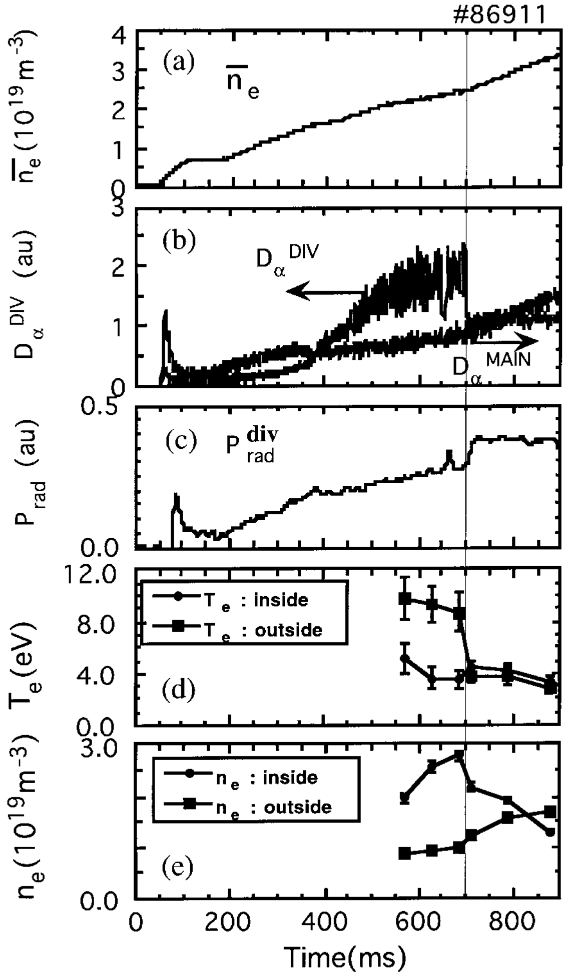

Fig. 2. Temporal behavior of a typical divertor discharge. (a) Central averaged density. (b) D_α intensity of outer divertor and main plasma. (c) Radiation around the X-point. (d) Divertor plasma temperature on the inside (circles) and outside (rectangles) divertor plate. (e) Divertor plasma density on the inside (circles) and outside divertor (rectangles) plate.

embedded Langmuir probe shows a change at this time. The temperature near the outer divertor strike point shows the gradual decrease with increasing density before 700 ms and shows the abrupt drop at 700 ms from 9 to 3 eV. Since the time resolution of the temperature measurement on the divertor is not enough, it is difficult to show the causality. However, it coincides with the drop of D_α intensity. The density at the same point shows a little increase (from 1×10^{19} to 1.3×10^{19} m^{-3}). The temperature near the inner strike point does not show a large change. At the time of 570 ms (just after fixing the X-point position), it is already below 5 eV. The density is about 3×10^{19} m^{-3} at that time and gradually decreases to the 2×10^{19} m^{-3}. The radiation, whose line of sight is shown by a dotted line in Fig. 1, shows an abrupt jump at that time. At the same time, the decrease of the radiation in a outer divertor region is observed. Those phenomena have many similarity to a partial detachment of the outside divertor leg except for the increase of the divertor density. It is considered to be a movement of an ionization front from the divertor to the main plasma. The downward spike observed in the divertor D_α intensity at 650 ms and the upward spike of X-point radiation is the rapid oscillation of this transition. Therefore, it is not a gradual change, but an abrupt change, and it may be difficult to control to keep the ionization front between divertor and main plasma.

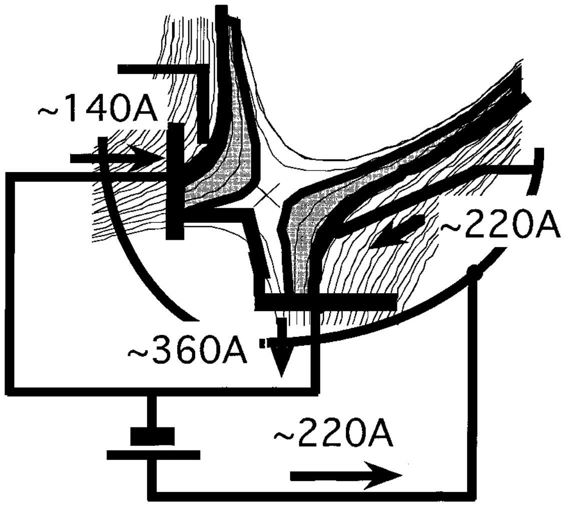

Fig. 4. Current flow in the case of the biasing is shown schematically.

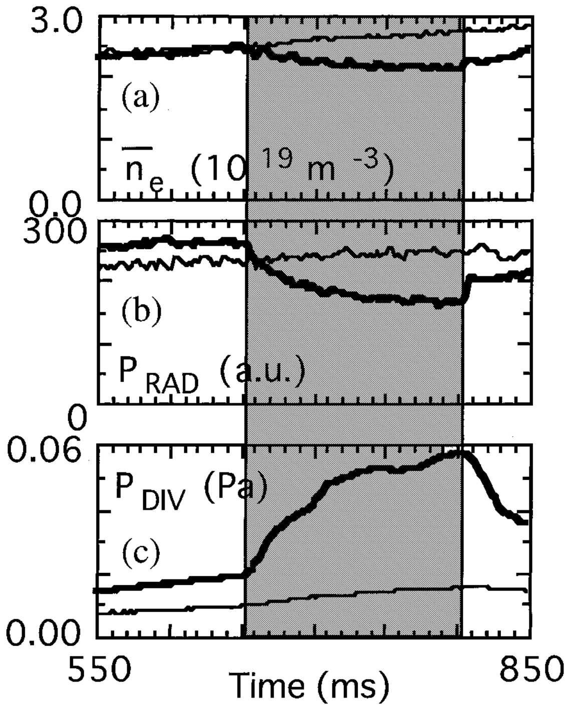

Fig. 3. Temporal evolution of the biased Ohmic discharge. Both inside and outside divertor plates are negatively biased. Thick and thin lines show the case of CCW and CW B_T direction (see text). Hatched region shows the biased phase. (a) Central averaged density. (b) Total radiation. (c) Neutral pressure in the outer divertor chamber.

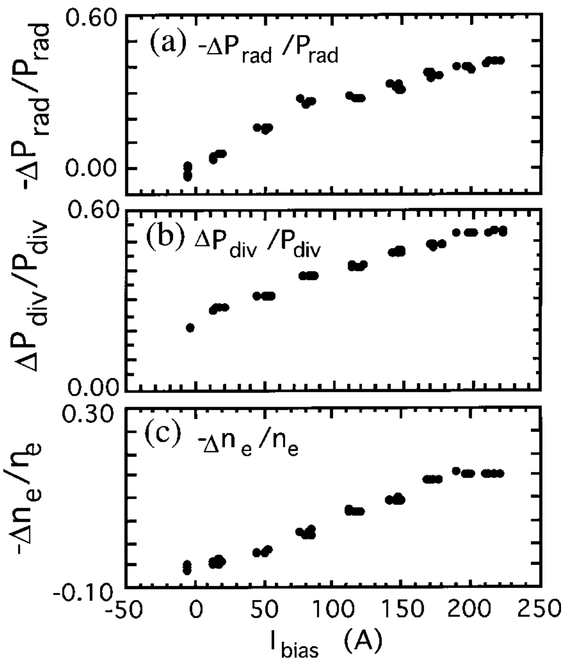

Fig. 5. Change of: (a) total radiation; (b) neutral pressure in the divertor chamber; (c) central averaged density normalized by the value just before biasing.

4. Divertor biasing experiment

When both inside and outside divertor plates are negatively biased with respect to the vacuum vessel which was a different biasing scheme compared with other experiments [8,9], we observed the significant difference of the main plasma parameters. Fig. 3 shows the temporal behavior of this discharge. A 40% reduction of the radiation loss power, 20% reduction of the line averaged electron density and about a factor 2 increase of the neutral pressure in the divertor chamber are observed at the total bias current of 220 A. The effect was observed only when the toroidal field direction was counter-clockwise (CCW) viewing from the top of the torus. Since a negative radial electric field is formed in the SOL by the biasing [10,11], the $E \times B$ flow from inside to outside makes the difference. And it was not observed before installing the baffle plates with the same biasing configuration. It means that the biasing increases the baffling effects and divertor function significantly. Fig. 4 shows the biasing current distribution schematically. The dependence of the reduction of density and radiation loss power and the increase of the divertor pressure on the bias current is shown in Fig. 5. The change of radiation, density and divertor pressure shows strong dependence on both the biasing voltage and current. At present, it is difficult to conclude which one (voltage, current or both) is important to modify the main plasma parameters.

Since we found that the biasing has a significant effect on the divertor function, then application of this biasing scheme to the H-mode was tested. Fig. 6 shows the time history of the H-mode with and without biasing. By applying the biasing, it is possible to reduce the increasing rate of density and radiation significantly. The period of the ELM-free H-mode is extended about 1.5 times compared with the case without biasing, however, it is not possible to make ELM-free H-mode steady.

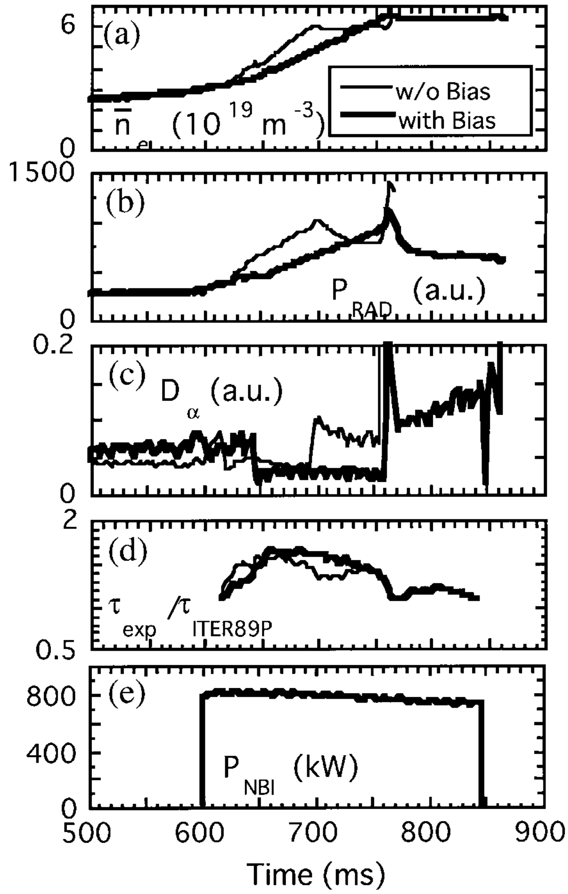

Fig. 6. Temporal history of H-modes with (thick line) and without (thin line) bias. (a) Central averaged density. (b) Total radiation. (c) D_α intensity. (d) H factor. (e) NB heating power.

5. Compact toroid injection experiment

Initial injection experiments were performed with a toroidal field of 0.9–1.3 T and plasma currents of 150–200 kA in the divertor configuration. Fig. 7 shows the time evolution of plasma parameters for discharge with CT injected into the OH plasma. In this figure, three discharges of the bank voltage for the acceleration (V_{acc}) of 30 kV (thick line), 20 kV (dotted line) and 0 kV (thin line) are shown. For the $V_{acc} = 30$ kV case the stored energy W_{MHD} increased about 30% after the CT injection. On the other hand, the total radiation loss P_{RAD} and the loop voltage V_{loop}, although the latter increased transiently just after the CT injection, decreased about 20%. These tendencies were enhanced with increasing V_{acc}, that is, CT penetration depth. The injected CT has magnetic helicity but it is too small to change the current profile in the tokamak plasma [12]. From measured velocity (100 km/s) and magnetic field strength (0.4 T), the total CT energy (kinetic plus magnetic energy) is roughly estimated to be 0.4 kJ, which is much smaller than the increment of the W_{MHD} of 2 kJ.

Fig. 8 shows a rapid increase of the electron density (2×10^{18} m^{-3}/2 ms) just after the CT injection. The line averaged electron density along the central chord increases with time and transient spike is observed in the visible Bremsstrahlung emission measured inside the separatrix ($r/a \geqslant 0.7$). These results indicate that effective fueling to inside the separatrix is performed by the CT injection. The increase of the tokamak particle inventory estimated in this discharge is 3.4×10^{18}, which is consistent with the estimated CT particle inventory of 6×10^{18}, assuming the typical CT density of 1.6×10^{21} m^{-3} obtained from the preliminary experiment using the same injector at HIT [7].

In a discharge with the CT injected into the ELM-free H-mode, the ELM-free H-mode is terminated at 5

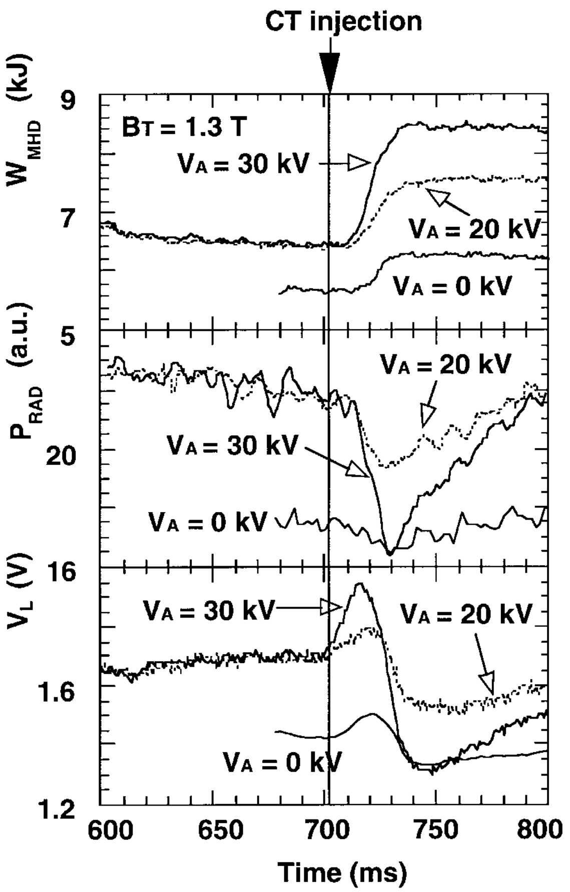

Fig. 7. Time evolution of plasma parameters for the CT injected into the OH plasma. The stored energy (W_{MHD}), total radiation loss (P_{RAD}) and the loop voltage (V_{loop}) are shown for the different CT acceleration voltage.

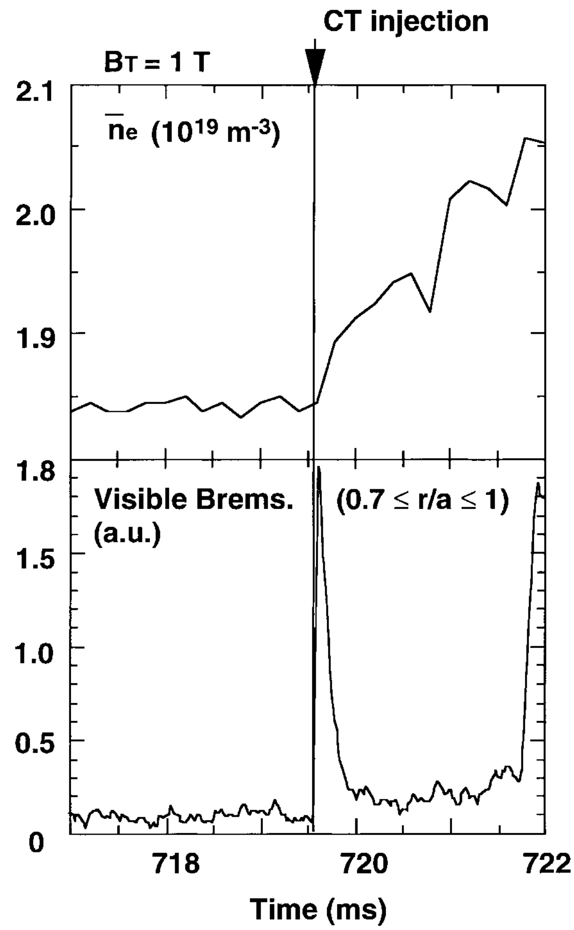

Fig. 8. The line averaged electron density (central chord) and the visible Bremsstrahlung emission at $r/a > 0.7$.

ms after the CT injection. The life time of CT plasma is in the order of several 10 µs. This results suggest that the ELM-free H-mode is not terminated immediately by the CT injection.

6. Summary

We found a transition like phenomenon in the divertor plasma. It occurs at the average main plasma density of about $2–2.5 \times 10^{19}$ m^{-3} and coincides with the abrupt drop of the temperature on the divertor plate from 9 to 3 eV. This phenomenon has the advantage of a reduction of the heat load similar to the detachment of the divertor plasma, but at relatively high density on the divertor plate.

The negative biasing of both inside and outside divertor plates showed a significant improvement of the divertor function. It was only observed when the direction of the $E \times B$ flow formed by the biasing in the SOL is from the inside to the outside. The divertor function depends both on the SOL current and the bias voltage. At present, it is difficult to separate the voltage and current effects.

The CT injector was installed on JFT-2M, and following initial results were obtained. A particle fueling up to 3.4×10^{18} was observed. Increase of the W_{MHD} and decrease of P_{RAD} and V_{loop} were observed in discharges with the CT injection in OH plasmas. The ELM-free H-mode was not terminated just after the CT injection. These results indicate the possibility of the application of the CT injector to the future tokamaks, e.g. ITER as an effective fueling system.

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