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Characteristic Plasma Behaviors in the Divertor Reversed Field Pinch TPE-2M

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Abstract

The behaviors of RFP plasma with a poloidal field divertor are studied in the TPE-2M Reversed Field Pinch to establish and evaluate the divertor as a means of plasma-wall interaction controls in RFPs. The divertor plasma is measured by Langmuir probe, visible spectroscopy and magnetic probe. The characteristic behaviors in the RFP divertor are the plasma burst into the divertor region at the RFP field setup stage and the strong magnetic fluctuation in the divertor region. The latter may cause the anomalous effusion or loss/scattering of particles through the X-point region and the additional helicity loss which leads to the enhanced loop voltage.

Keywords:

RFP, reversed field pinch, divertor, dynamo, plasma-wall interaction, PWI, PSI, TPE-2M

1. Introduction

The fusion plasma confinement concept based on the reversed field pinch (RFP) is considered to be one of simple and economic fusion reactor core concepts, in which it is claimed that the ignition may be attained with Ohmic heating alone as well as with a normal conductor magnet [1,2]. Many works are now devoted to confinement improvement and/or physics understanding. While, the control of plasma-wall interaction (PWI) will be quite important for a high current and long time discharge in the near future, for which pioneering works had been carried out with the magnetic divertor in [3,4]. To pursue it more elaborately, TPE-2M (R/r = 87 cm/28 cm) has been working for the divertor RFP discharge [5]. The global stability had already been confirmed [6]. In the recent series of experiment, the characteristic behaviors of diverted plasma and the global effect on the main discharge are investigated. Here, the wall conditioning is proved essential to reduce the neutral gas effect on PWI study. The density profile of effused plasma on the divertor plate surface is measured by a Langmuir probe array. The observed unique divertor plasma profile and the increased toroidal loop voltage are discussed in relation to the enhanced magnetic fluctuation in the divertor region.

2. Device Structure and Wall Conditioning

The cross-sectional view of the vacuum vessel, shell and coil assembly is shown in Fig. 1. The engineering aspect of device is described in ref. [7]. The aluminum stabilizing shell of circular inner cross-section (28 cm in I.D. and 2 cm in thickness) with an axisymmetric poloidal cut (approx. 18 degrees wide) is installed in the rectangular SUS vacuum vessel (10 mm/20 mm thick) to ensure both a good shell-plasma surface proximity and a diverting space. The minimum distance between the divertor plate surface and the shell inner surface is 12 cm. The position of X-point is controlled by varying the plasma to divertor coil current ratio. Typical calculated separatrix surfaces are drawn in the

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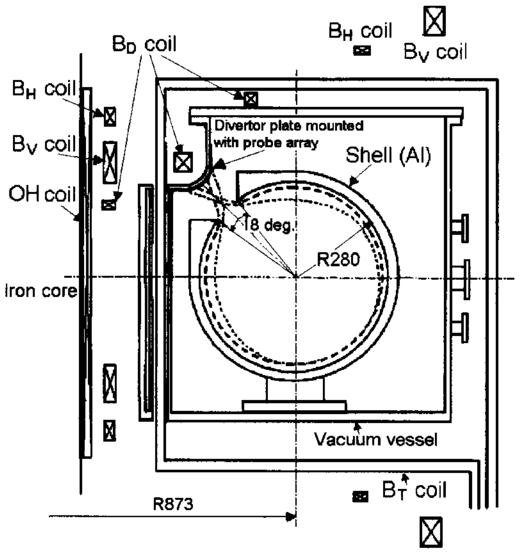

Fig. 1 Cross-sectional view of vacuum vessel, shell and coils of the divertor RFP, TPE-2M. Two separatrix lines are shown for different X-point locations; 4 cm from the divertor plate surface and 3 cm from the shell inner radius.

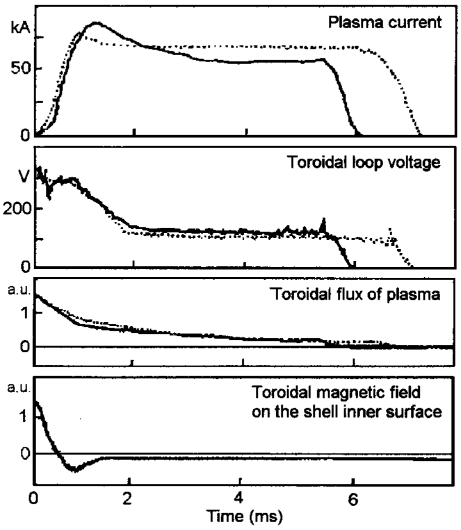

Fig. 2 Typical waveforms of discharge with divertor (full lines) and without divertor (dotted lines) field.

same figure. An array of 11 double probes (14 cm from top to bottom positions) is mounted on the divertor plate surface The divertor plasma and the edge plasma of main core are also observed by a visible spectroscopy, an inserted Langmuir probe and inserted/pre-installed magnetic probes.

In order to reduce the effect of neutral gas on the divertor plasma and its interaction with the divertor plate surface, the inner wall surface of vacuum vessel including the divertor plate surface and the outer surface of shell are activated by Ti-gettering for every 3–4 shots. The discharge D_2 gas is injected by a fast acting short-pulse puff with an intense glow discharge pre-ionization, instead of a quasi-steady puffing, to reduce the surrounding neutral gas density and to keep the divertor surface fresh. Besides, the inner surface of shell (the plasma-facing wall) is boronized by mixed discharge of trimethyl-boron and He gases. The boronization is very effective to suppress the impurity contamination of especially oxygen and aluminum in the setup phase, and leads to the overall enhancement of plasma conductivity [8].

3. Experimental Results

3.1 General Properties of Discharge

The experiment is carried out typically with a plasma current of 50–70 kA, the duration of around 5 ms, and the loop voltage of 100 V. The duration is limited usually by the volt-second capacity of OH circuit, however, the discharge terminates earlier in some cases, presumably due to the uncompensated error fields. To alleviate it, the external DC horizontal and vertical fields are elaborately added as well as the pulsed vertical field.

Typical signals of plasma current, toroidal loop voltage, etc are shown in Fig. 2. The plasma current decays faster and the loop voltage is slightly higher in the divertor discharge. The higher loop voltage implies a larger helicity loss. The helicity loss comes from the normal and anomalous resistivities of plasma, and the latter is considered to originate from such as anomalous magnetic fluctuation. The presently observed loop voltage is rather high even in the non-divertor operation compared with usual spatially closed shell devices of similar radius and plasma current (normally 20–50 V). The specific character is that the magnetic fluctuation level is much higher in the open shell region than in the shell-covered region as is described later. The magnetic fluctuation in the open shell region is more intensive in the divertor discharge, which may lead to an additional helicity loss. So that the difference of loop voltage may qualitatively be explained by the existence of X-point in the open shell structure. We, however, need a detailed physical calculation to estimate it quantitatively. The current terminates much earlier (< 4 ms) and sharply when the X-point approaches to the shell inner radius.

In Fig. 3, some spectroscopic lines are shown. AlI (396.2 nm) and CIII (464.7 nm) lines are from the edge region of main plasma, and D_α from the divertor region.

This is the case without boronization. With boronization, the AlI intensity is below the background level and the CIII intensity is also slightly reduced even without the divertor field. Comparing the divertor and non-divertor discharges, all the intensities are nearly the same at the beginning of the discharge immediately after the setup. As far as D_α intensity outside the shell in the divertor region is concerned, the peak in the initial stage may come from a burst of plasma particles effused out from the main plasma through the open shell portion even without the divertor field, when the RFP magnetic configuration sets up. This burst of particle is observed also by an inserted Langmuir probe in the divertor region. The burst is further steeper in the case of divertor discharge. The D_α line intensity in the later stage, however, is smaller in the non-divertor operation, which indicates that the plasma effuses out more due to the divertor field. The impurities, Al and C, from the wall surface seem to be suppressed by the divertor field. In Fig. 4, profiles of ion saturation current of arrayed probes on the divertor plate surface are plotted for the early stage immediately after the set-up (~2 ms) and the later stage (4–5 ms). The divertor effect is evidently seen in the later stage. The difference of signals with and without the divertor field is taken as the signal from the divertor effect.

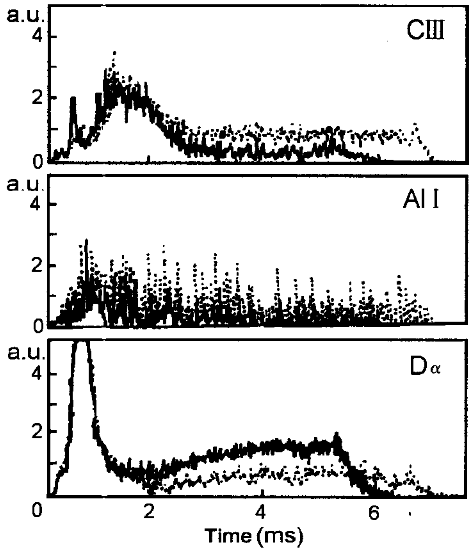

Fig. 3 Spectroscopic line intensities with divertor (full lines) and without divertor (dotted lines) field.

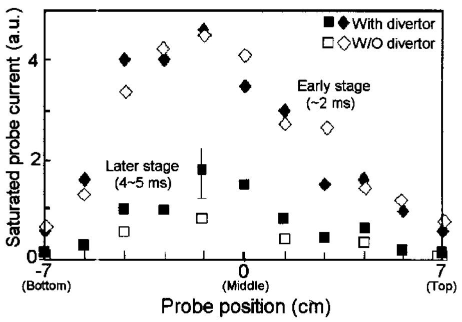

Fig. 4 Profiles of saturated probe current on the divertor plate surface at early and later stages of discharge. The full and empty marks correspond to divertor and non-divertor discharges, respectively.

3.2 Divertor Plasma Profile

In Fig. 5, the spatial profiles of saturated probe current on the divertor plate surface in the later stage are compared for two X-point positions; 4 cm from the divertor plate surface and 4 cm from the shell inner radius. Although the data are largely scattered, the observed density profile is not doubly peaked, but rather smoothed to a single hump, which seems unexpected in the present divertor magnetic field configuration. When the X-point lies at 4 cm from the divertor plate surface, the profile is sharply peaked. As the X-point moves toward the plasma surface (4 cm from the shell inner radius), the profile becomes broader. The observed single hump may be explained by overlapping of two widely spread humps, which seems to be caused by anomalous particle scattering due to a large amplitude fluctuation of magnetic field in the divertor region. In Fig. 6, typical plots of B_r at 5 cm outside from the shell inner radius in the open shell region with and without the divertor field and on the shell inner surface (horizontally outboard) are shown. It is much higher in the open shell region than on the shell-covered surface. It is further enhanced with the divertor field. To estimate

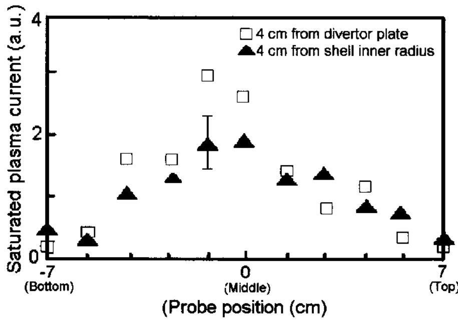

Fig. 5 Spatial profiles of saturated probe current on the divertor plate surface for two positions of X-point; 4 cm from the divertor plate (□) and 4 cm from the shell inner radius (▲).

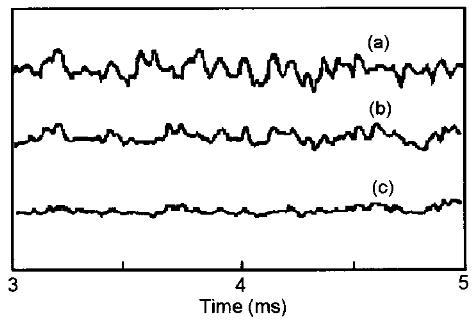

Fig. 6 B_r signals (a) at 5 cm outside from the shell inner radius (slightly outside the X-point) with the divertor field, (b) at the same position with (a) but without the divertor field and (c) on the shell inner surface (shell-covered region).

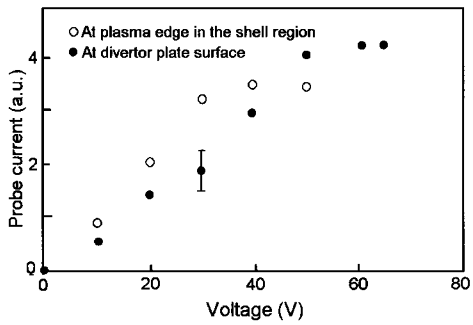

Fig. 7 Probe characteristics for estimating the electron temperature at the divertor plate surface and the plasma edge of shell-covered region.

the level of B_r fluctuation, the B_p fluctuation level is also measured in the shell-covered region. It is ~ 2 %. The high level of magnetic fluctuation in the divertor region will lead to the excess loss and/or additional scattering of effused particle through the divertor and then the peak of profile may be smoothed more.

When the X-point moves further toward the plasma surface, the discharge usually terminates earlier (< 4 ms) not by the increased volt-second consumption (the loop voltage is further slightly increased) but probably by an instability. In this case, a very large amplitude magnetic fluctuation (sometimes spiky) is seen in the divertor region. The plasma may be less stable since the shell proximity of the whole plasma surface is deteriorated (a complete shaping is not possible by the shell and vertical and horizontal coils outside the vacuum vessel alone, see Fig. 1). On the other hand, we can consider another possibility of sudden intensive flux loss that leads to the destruction of RFP configuration, since the X-point becomes nearer to the reversed field surface of main plasma core and the magnetic fluctuation is more intensified.

The parameters of divertor plasma are estimated. The temperature is estimated from V-I characteristics and saturated current of double probe signal as shown in Fig. 7. It is as high as ~50 eV, while the temperature at the edge of main plasma of the shell covered region is around ~30 eV irrespective with divertor field (The core temperature is assumed at a few hundred eV from the I_p-T_e scaling). The fact suggests the effusion of hot plasma through the X-point region is significantly large. The density of divertor plasma is only a few times smaller than the edge density of main plasma. The relatively high density on the divertor surface may be accounted qualitatively by the large amplitude fluctuation of local magnetic field in the divertor region and/or by the short connection length of magnetic field line ($B_t \ll B_p$ in RFP).

4. Conclusion

In summary, the divertor discharge of RFP has been operated in TPE-2M, and some characteristic behaviors are newly found. An anomalous particle effusion due to a strong magnetic fluctuation through the X-point region is suggested. This feature of magnetic fluctuation also explains the slight increase of toroidal loop voltage by the additional helicity loss. The appropriate positions of X-point are limited in the present geometrical configuration due to a kind of instability.

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