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Wall conditioning for performance improvement in the divertor reversed field pinch TPE-2M

K. Hayase [*], Y. Sato, S. Kiyama

National Institute of Advanced Industrial Science and Technology, Tsukuba Central 2, 1-1-1, Umezono, Tsukuba, Ibaraki 305-8568, Japan

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Abstract

A divertor reversed field pinch machine, TPE-2M ($R/r = 0.87$ m/0.28 m), has been operated at AIST. The wall conditioning is one of key issues for the divertor study in this unique machine. Boronization on the shell inner surface (plasma-facing wall), titanium gettering on the vacuum wall and divertor plate surfaces and pulsed gas injection with glow-discharge pre-ionization are developed and applied successfully. They are indispensable to the analysis of divertor plasma behaviors and to the improved plasma operation

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1. Introduction

The divertor discharge of reversed field pinch (RFP) has been operated in TPE-2M ($R/r = 0.87$ m/0.28 m) to examine the validity of axisymmetric poloidal divertor for control of plasma–wall interaction in the RFP configuration [1,2]. The engineering aspect of this unique machine is described in [3]. The characteristic feature of the device is that the aluminum stabilizing shell of circular cross-section with an axisymmetric poloidal cut ~18°) is installed in the rectangular SUS vacuum vessel to ensure both a good shell to plasma surface proximity and a diverting space. The vacuum condition of this complicated vacuum vessel/shell assembly is poor, since many organic or inorganic components for high voltage electrical insulators, vacuum sealing, divertor plates and magnetic sensors are mounted inside the vessel. The plasma-facing material is the aluminum, which must be carefully protected from plasma sputtering. Besides, the ambient gas pressure must be minimized to alleviate the interaction of main plasma with it for the good plasma sustenance. In the present divertor experiment, the radiation cooling of divertor plasma is not aimed, but the main objective is to study the effect of divertor field on particle behaviors and plasma stability. The effused particle from the divertor is observed at the divertor plate, then the ambient gas pressure should be minimized. For these purposes, some wall conditioning techniques such as Ti-gettering, boronization and gas control by short-pulse gas puffing are necessary. The conditioning of wall surface, mainly boronization, had already been applied successfully in other RFP devices [4–6]. Here the development, experience and results of these conditionings in our device of complicated structure and of particular purpose are described.

2. Conditionings

The cross-sectional view of the vacuum vessel, stabilizing shell and coil assembly and a cutaway photo of the vacuum vessel and shell are shown in Figs. 1 and 2 respectively. An array of double probes is mounted on the divertor plate surface and many sets of magnetic search coils are mounted on the inner surface of the

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[*] Corresponding author. Tel.: +81-298 61 5763; fax: +81-298 61 5754.

E-mail address: k.hayase@aist.go.jp (K. Hayase).

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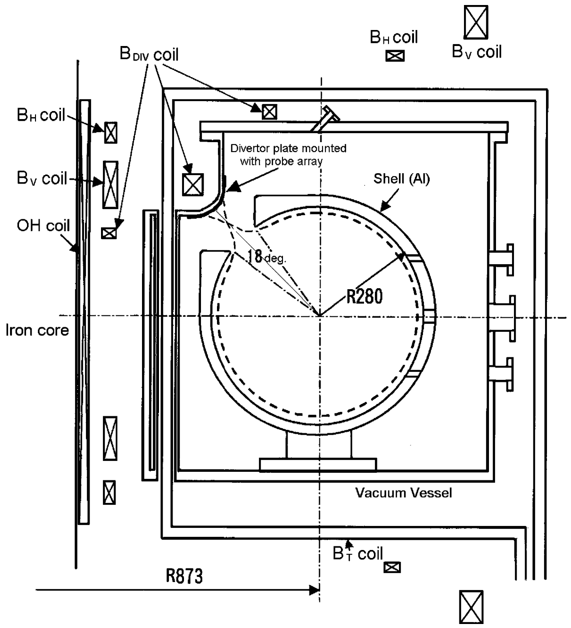


Fig. 1. Cross-sectional configuration of the divertor RFP, TPE-2M.

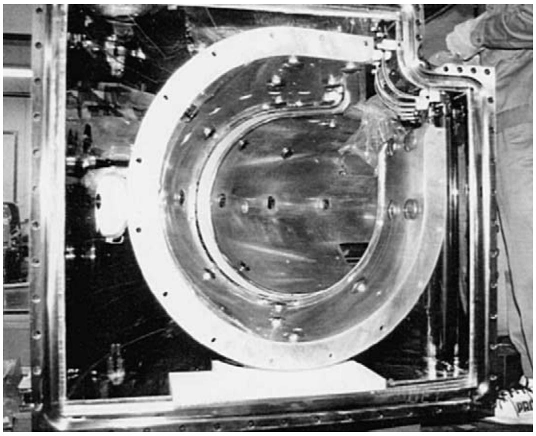
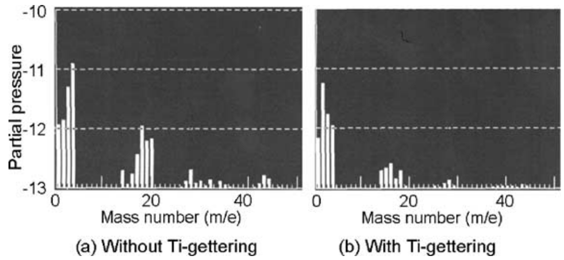


Fig. 2. Inside view of V/V and shell. The divertor is at the 45° upside in the right side of the cross-section.

shell. Here Ti-gettering is applied to the inner wall surface of vacuum vessel including the divertor plate surface and the outer surface of shell. Boronization by glow discharge is performed on the inner surface of shell (the plasma-facing wall). A fast acting short-pulse gas puff with an intense glow-discharge pre-ionization, instead of a quasi-steady puffing, is also developed.

2.1. Ti-gettering



(a) Without Ti-gettering (b) With Ti-gettering

Fig. 3. Residual gas mass analysis after the main deuterium discharge with and without Ti-gettering.

Ti-gettering filaments (ULVAC Co., Japan) are inserted from two ports into the space between the vacuum vessel and shell. The base pressure is reduced to one third to fifth after 1 min flashing (to 3×10^{-8} Torr). The main plasma shots are discharged for every 5 min and the Ti-gettering is done between shots. The Ti-activated surfaces of the divertor plate and vessel wall are effective to adsorb effused plasma particles. However, it is only effective for a few shots of main plasma discharge due to adsorption saturation. Then Ti-gettering is repeated for every 3–5 main plasma shots in the present experiment. To observe the conditioning effect, the residual gas mass analysis data measured at $\sim 10^{-6}$ Torr after a main plasma discharge are compared with and without Ti-gettering in Fig. 3. It is seen that hydrocarbons emitted by the plasma interaction are significantly reduced. They are well adsorbed on the Ti-activated divertor plate and vessel wall surfaces.

2.2. Boronization

The inner surface of shell (plasma-facing wall) is boronized by a discharge of mixed trimethyl-boron (10%) and helium (90%) gases. By ~20 shots of the boronizing discharge (at $I_p \sim 10$ kA), the water component in base pressure level is reduced to 0.1, hydrocarbons to a negligible level. The base pressure is also reduced to 1/3–1/5 (5×10^{-8} Torr). The boronized surface remains active for typically ~30 D_2 main plasma shots. The mass analysis data of residual gas after a main plasma discharge with and without boronization is similar to the Ti-gettering case. The suppression of impurity component is estimated by the optical multichannel analyzer (OMA) spectroscopy and its reduction ratio is shown in Fig. 4. The oxygen component is reduced to ~0.1. The carbon component is slightly suppressed. The aluminum component is suppressed also (the signal intensity is around a background level). Then the impurity contamination itself is greatly suppressed by boronization of shell inner surface (plasma-facing surface) in the setup phase of main RFP discharge. The reduction of oxygen impurity generally leads to the enhancement of plasma conductivity. In the present experiment, no direct measurement of plasma conductivity or plasma energy has been done, however, the enhancement

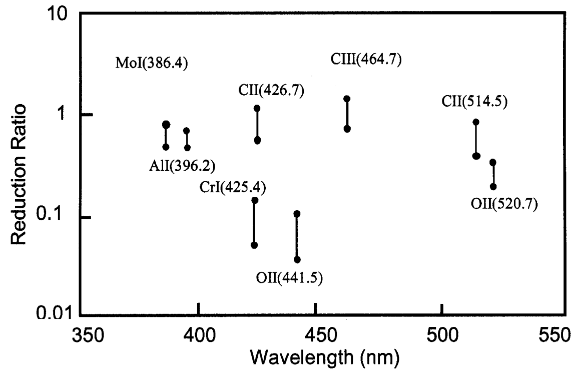


Fig. 4. Impurity reduction ratio by boronization estimated by OMA spectroscopy.

of CV radiation (227.1 nm) intensity (almost doubled) and the extension of discharge duration by ~20% are observed. The boronization is exploited in the daily experiment; the boronization shots are discharged in the morning before the plasma experiment, and the main plasma experimental shots (30–40 shots) in the afternoon. The combined application of Ti-gettering and boronization is proven more effective.

2.3. Fast gas puffing with pre-ionization

The discharge D_2 gas is injected by a fast acting puff with a glow-discharge pre-ionization instead of a quasi-steady injection. The schematic diagram is shown in Fig. 5. In this type of vessel/shell structure, the electron-emitting filament is not enough for the initiation of discharge. It delays by ~ms or even the discharge does not initiate. The idea is that the short-pulse gas is ionized in the passing ceramic tube. Both ends of the tube are connected to a capacitor charged to ~500 V. When the injected gas from the fast valve passes between electrodes, a glow discharge easily starts automatically between them and extinguishes after passing away. The method ensures the exact start of main discharge without delay. The pre-ionization tube should be as close as to the shell. The system is very simple and cost-effective. The introduction of fast pulse puff is important to reduce the ambient gas quantity around the divertor region and to keep the divertor surface fresh during the main RFP discharge. Lately the method is improved; the valve is replaced by another one (the opening duration as small as a few hundred μs) and the glow-discharge tube is replaced by a small coaxial plasma gun, which ensures more powerful pre-ionization.

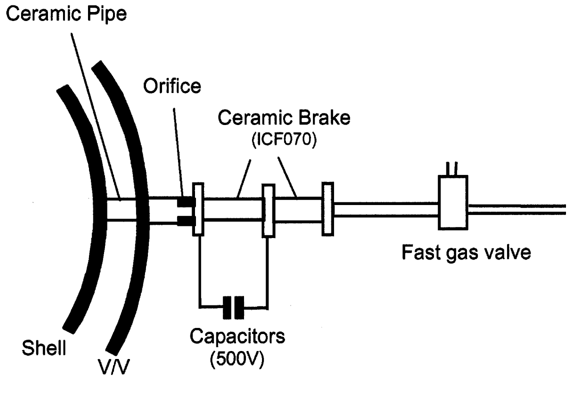


Fig. 5. Fast pulsed gas injection with pre-ionization. Glow discharge initiates spontaneously as the injected gas passes the ceramic tube, which is biased at 500 V between two electrodes.

With a normal slow gas injection, the divertor field effects on Dα radiation in the divertor region and the probe current at the divertor surface are small probably due to a less direct interaction of effused plasma with the divertor surface; the effused plasma interacts more with a higher density neutral deuterium there. In addition, the Ti-activated surface becomes inactive even with a single main shot.

Combined application of Ti-gettering, boronization and a fast pulsed gas puffing with pre-ionization results in a successful operation of divertor discharge of RFP; the divertor effect has been observed more clearly as described in the following section, and a general RFP plasma performance has been greatly improved as well.

3. General properties of discharge and divertor plasma

After above-mentioned wall and gas conditionings, the discharge characteristics are compared without conditioning. The plasma current is 50–70 kA and its duration is typically ~5 ms. With conditionings, the duration is extended by 20% at the same plasma current presumably by the reduction of radiation loss due to suppression of impurities and ambient neutral gas.

The global plasma behaviors are observed in the divertor configuration. In Fig. 6 are shown the plasma current, Dα line in the divertor plate surface region seen from the oblique port and the saturation current of Langmuir probe at the divertor plate surface with and without the divertor field. The plasma current decays faster due to a slight increase of loop voltage in the case of divertor operation. The Dα and probe signals indicate that the plasma effuses out from the main plasma to the divertor region through the poloidal shell cut to a great extent in the early stage of the discharge, however, they decay faster in the normal discharge without the divertor field. This observation shows that the plasma particles go out more to the divertor plate and are neutralized more with the divertor field, that is, the divertor effect is evidently seen in the later stage of the discharge. If the gas is injected by a slow puff instead of the presently developed one, the difference is much smaller, that is,

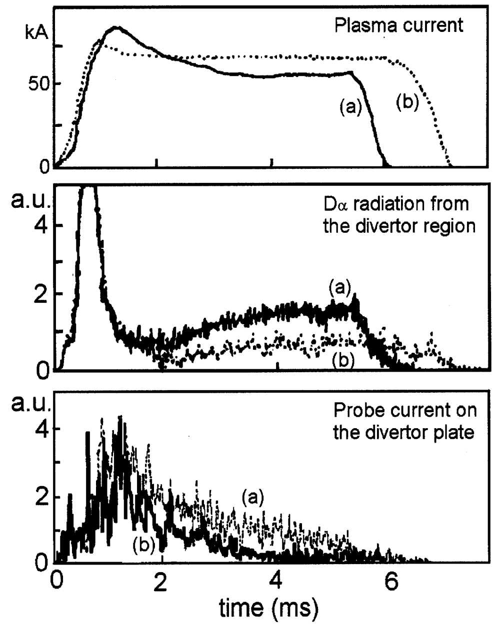


Fig. 6. Plasma current, Dα line intensity from the divertor plate surface and the saturated probe current on the divertor plate surface. (a) and (b) correspond to the divertor and non-divertor discharges, respectively.

the divertor effect is only obscurely observed. AlI line (surface material) is also observed at the main plasma surface. However, the reduction by the divertor field is quite small (less than 20%). If the boronization is intense, the reduction is further less.

In Fig. 7, the electron saturation current profile on the divertor plate surface is plotted, where the value from the pure divertor effect is estimated by subtracting the value in the non-divertor discharge from that in the divertor discharge. The observed current (nearly proportional to the plasma density) profile is not doubly peaked, but rather it is a single hump. In a normal divertor, a clear scrape-off layer is formed and the plasma particles from the main plasma surface effuse out mainly along the separatrix field line. Since the separatrix line hits the divertor plate surface at two symmetric points, the measured density profile on the divertor plate surface should have two peaks, each at the point. If the magnetic fluctuation intensity is high enough, the separatrix line of field will be chaotic. In this case, the clear scrape-off layer cannot usually be formed and the density peaks at the divertor surface will also be not formed because of chaotic particle trajectories. This may be our case, since the magnetic fluctuation intensity measured near at the X-point is unusually high (more than 10%). We consider this is the characteristic behavior of RFP. In a tokamak divertor operation in the same device, we really observe a profile with two peaks at ±5 cm. The details of these characteristic divertor behaviors are discussed in others [2,7].

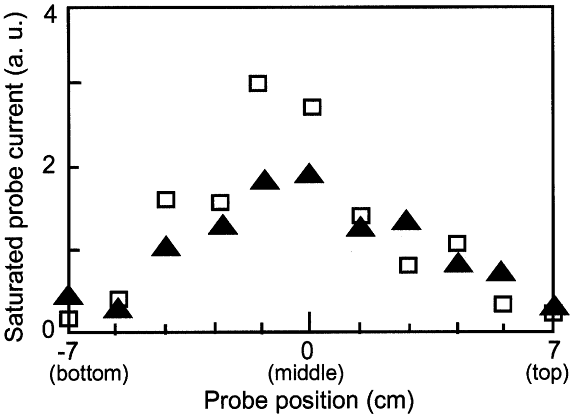


Fig. 7. Saturated probe current profile on the divertor plate surface. Full triangle marks; X-point at 4 cm from the originally circular plasma surface. Vacant rectangular marks: X-point at 8 cm from it (4 cm from divertor plate surface)

4. Conclusion

It is shown that the wall and gas conditionings such as Ti-gettering, boronization and short-pulse fast gas puffing with glow-discharge pre-ionization are very useful and applied successfully in the divertor RFP experiment of TPE-2M. The divertor effect is more clearly observed with these conditionings. A characteristic behavior of divertor particles has been found in this poloidal divertor RFP, TPE-2M.

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