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Tritium distribution in JT-60U W-shaped divertor

K. Masaki [a,*], K. Sugiyama [b], T. Tanabe [b], Y. Gotoh [a], K. Miyasaka [b], K. Tobita [a], Y. Miyo [a], A. Kaminaga [a], K. Kodama [a], T. Arai [a], N. Miya [a]

[a] *Department of Fusion Facilities, JT-60 Facilities Division II, Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, 801 Mukouyama, Naka-machi, Naka-gun, Ibaraki-ken 311-0193, Japan*

[b] *Center for Integrated Research in Science and Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*

Abstract

Detailed tritium profiles on the JAERI Tokamak-60U (JT-60U) W-shaped divertor and the first wall tiles were examined by a tritium imaging plate technique (TIPT) and full combustion method. The highest tritium level (60 kBq/cm^2) was observed at the dome top tiles. The tritium level of the divertor target was lower (2 kBq/cm^2). The result of the triton deposition simulation using orbit following Monte-Carlo code was consistent with the tritium distribution obtained by TIPT and full combustion method. These results indicate that the tritium distribution of the JT-60U W-shaped divertor reflects mainly the distribution of the energetic triton impinging on the wall. According to the simulation, the tritium atoms produced by D–D nuclear reaction in JT-60U are not loosing completely their initial energy of 1 MeV and around 1/3 of them are implanted into the wall.

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Keywords: Tritium; Tritium imaging plate technique; D–D nuclear reaction; High energy triton; Orbit following Monte-Carlo code; Ripple loss

1. Introduction

In the JAERI Tokamak-60U (JT-60U), tritium, which is produced by D–D nuclear reaction, is partially exhausted through the pumping system. A part of the tritium remains in the carbon-based first wall tiles. In early operation of JT-60U, half of the produced tritium remained in the first wall tiles [1]. However, the detailed tritium distribution, the relation between deposition layers and the tritium retention were not clear. After the use of the tritium in the Joint European Torus (JET) and the Tokamak Fusion Test Reactor (TFTR), it was found that the torus tritium inventories were accumulated at the rates of 40% and 51% of the input, respectively [2,3]. The surface and the depth distributions of the tritium have also been analyzed [4,5].

In the recent work at JT-60U, the detailed analyses of the tritium in the first wall tiles were performed. The tritium imaging plate technique (TIPT) was applied to determine the tritium wide surface distribution on the W-shaped divertor tiles [6,7]. Furthermore, absolute values of the tritium retention in the tiles were measured with the full combustion method [1]. Scanning electron microscope (SEM) analysis was also performed to determine the thicknesses of the deposition layers on each sample tile [8]. Simulation using the orbit following Monte-Carlo (OFMC) code was performed in order to understand the highly energetic triton deposition on the tile surfaces and to compare with the experimental results.

In this paper, the poloidal and toroidal tritium distribution in the JT-60U W-shaped divertor and the poloidal tritium distribution in the first wall are described taking into account the trace of high-energy tritons, particle flux and heat load.

* Corresponding author. Tel.: +81-29 270 7432; fax: +81-29 270 7449.

E-mail address: masakik@fusion.naka.jaeri.go.jp (K. Masaki).

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2. Experimental

2.1. Sample tiles

Carbon fiber composite material is applied for the divertor and the dome top tiles and a part of the baffle tiles. All other parts are covered with isotropic graphite tiles. The first wall sample tiles exposed to plasma from March 1991 to October 1998 were removed for the tritium measurement using TIPT. The sample tiles of the divertor region, which were exposed to plasma from June 1997 to October 1998, were used for the detailed tritium analyses, such as TIPT, full combustion and SEM analysis. The total number of the discharges during this period (June 1997 to October 1998) was approximately 4000 shots. The total amount of tritium activity produced during this period, which was estimated from neutron production, was 18 GBq. Fig. 1 shows the temperatures of the thermocouples installed in the divertor tiles at 6 mm depth. The thermocouple temperature of the outer divertor tile tended to be higher than that of the inner one. The finite element modeling analyses based on the temperature profile in each tile and separatrix position showed that the temperatures of the divertor tile surfaces are expected to be 200–400 °C higher than those of the thermocouples shown in Fig. 1. The highest surface temperature of the outer divertor tile is expected to be approximately 1100 °C. The dome and baffle tiles had a low temperature history, almost at a baking temperature of 300 °C.

2.2. Tritium imaging plate technique

The imaging plate (IP) is a radiation image sensor based on photo-stimulated luminescence. The IP can detect tritium distributed within the depth of about 3.5 μm from the surface of the carbon-based tile. The surface of the IP was exposed to the sample tiles with a face to face contact for a day in a dark shielded room. After the exposure, the IP was processed using an IP reader to obtain a digitized tritium intensity mapping.

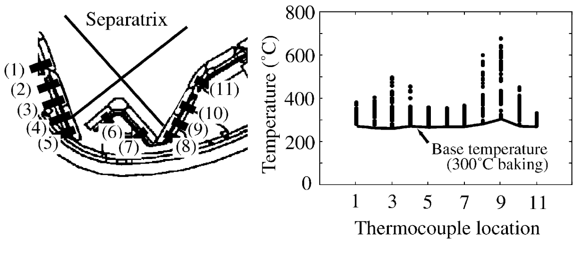

Fig. 1. Temperatures of the thermocouples installed in the divertor tiles at 6 mm depth. A typical separatrix position is shown here. These plasma experiments were performed with high power neutral beam injection in September 1998, aiming at steady-state high performance. The high temperatures of the thermocouples were observed in this experimental series.

2.3. Full combustion method

Sample pieces of 10 mm × 10 mm × 24 mm (tile thickness) were cut from the removed sample tiles. The tritium in these sample pieces was measured by burning them using air gas at 1000 °C for 6 h, converting unoxidized tritium into HTO on a hot copper bed (CuO) at 500 °C, collecting it in bubblers with water, and measuring it using a scintillation counter.

2.4. Simulation using OFMC code

An important mechanism of energetic ion loss has been understood to be the ripple transport, which is caused by the finite number of toroidal magnetic field (TF) coils, i.e. ripple loss. To assess the energetic triton loss, the OFMC code [9,10] was used for a typical plasma operation of a high β_p H-mode. Coulomb collisions between the energetic tritons and the plasma were simulated with the Monte-Carlo method tracing the triton orbits in the magnetic fields combined with the axisymmetric field calculated by a two-dimensional magneto-hydrodynamic equilibrium code and the non-axisymmetric field produced by TF ripple. The Coulomb collisions lead to pitch angle scattering and slowing down of the energetic triton. The launching points and pitch angles of triton test particles were also determined by a Monte-Carlo method. The test particles with an initial energy of 1 MeV were launched at radii based on the birth profile of the energetic tritons. The orbit of each test particle was followed until it impinged on the wall or slowed down to thermal speed.

3. Results

3.1. Experimental results

Fig. 2 shows tritium images of the divertor units and a part of the baffle plates, which were obtained using TIPT. In this figure, the tritium level is higher in the red region and lower in the blue region. The highest tritium level was recorded at the dome top tile and the outer baffle tile. Also in the full combustion analyses, the highest tritium concentration of 60 kBq/cm^2 was found at the dome top tile as shown in Fig. 3. The tritium concentration in the outer baffle tile was 20 kBq/cm^2. The tritium concentration in the inner and outer divertor tiles was at lower level of about 2 kBq/cm^2 and 250 Bq/cm^2, respectively. This poloidal tritium distribution measured by full combustion method is

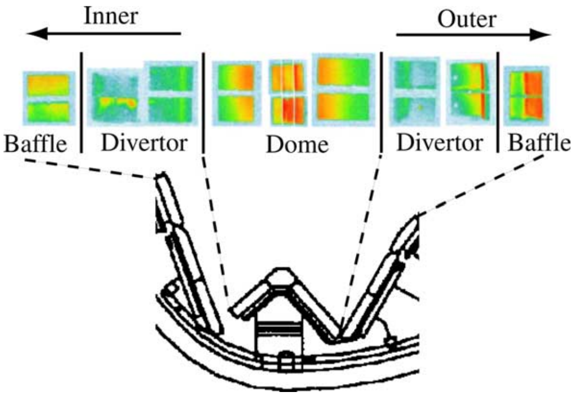

Fig. 2. Tritium images of the divertor units and a part of the baffle plates, which were obtained using TIPT. The tritium level had its maximum at the dome top tiles.

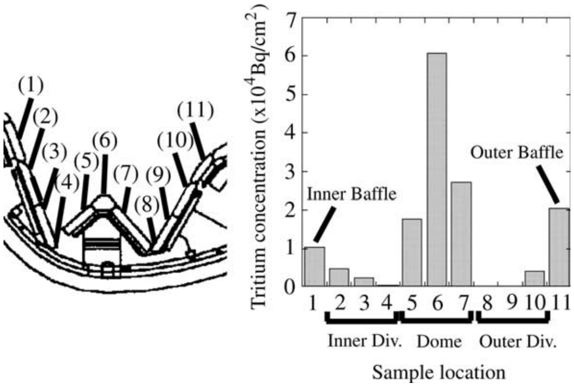

Fig. 3. Tritium poloidal distribution measured by full combustion method. The highest tritium concentration was 60 kBq/cm^2 at the dome top tile even with almost no deposition layer. The tritium in the inner divertor was lower even with thick deposition layers of about 60 μm.

consistent with that obtained using TIPT. In the SEM analyses, a thick deposition layer of ~60 μm was found on the inner divertor target tile, while the deposition layer was not obviously observed on the dome top tile and the outer divertor tile [8]. The total amount of tritium retention in this divertor region, as shown in Fig. 3, where the calculation was based on the toroidal tritium images of the dome top tiles, was approximately 10% of the produced tritium (18 GBq). This value is consistent with the previous result of the JT-60U with an open divertor [1].

The tritium of the first wall tiles in the poloidal direction and the dome top tiles in the full toroidal direction was also measured using TIPT. The tritium level of the outer first wall was high as shown in Fig. 4. In a full toroidal measurement of the dome top tiles, the tritium was distributed periodically, which was correlated to the TF coil positions, i.e. TF ripple.

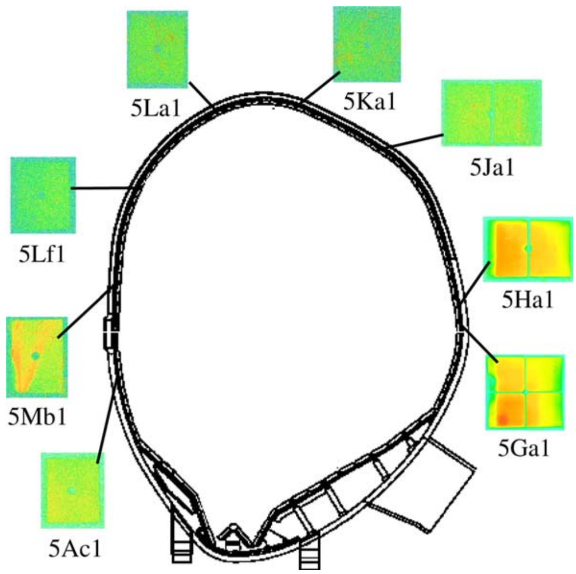

Fig. 4. Tritium images of the first wall tiles obtained using TIPT. The outer midplane first wall tiles had a higher tritium level compared with other first wall tiles.

3.2. Result of the OFMC simulation

Fig. 5 shows the heat flux distribution of the energetic tritons on the wall in a typical plasma operation of a high β_p H-mode. This plasma operation was performed aiming at steady-state high performance in the operation period described in Section 2.1. This figure is a 1/18 portion of the first wall cut under the TF coils. According to the calculation, 31% of the produced tritons (6.5×10^{14} s^{-1}) was lost and implanted to the wall. The resulting heat flux had its maximum at the dome top tiles. The heat flux on the outer midplane first wall was also relatively high. Furthermore, in the toroidal direction, the heat flux was high at the center between the TF coils. These heat fluxes were distributed periodically in the toroidal direction due to ripple loss. The tritons implanted to the divertor region (Fig. 3) were approximately 12% of the produced tritons. The average energy and particle flux of the tritons impinging on the dome top tiles were about 700 keV and 3×10^{13} m^{-2} s^{-1}, respectively. The highest energy (1 MeV) of the implanted tritons was found at the inner baffle plate, the inner and outer midplanes. However, the particle fluxes at those regions were lower (4×10^{11} m^{-2} s^{-1}). These results indicate that part of the energetic tritons produced by D–D nuclear reaction is implanted with the initial high energy to the wall surfaces.

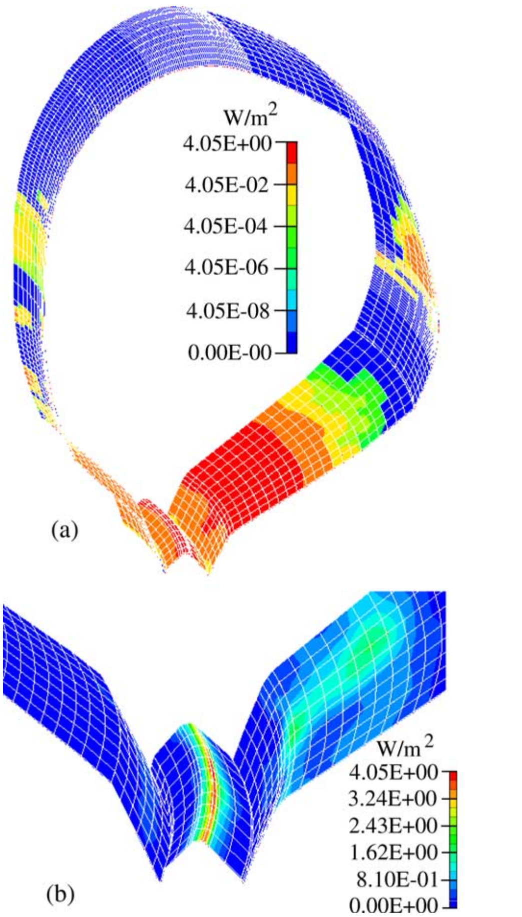

Fig. 5. The heat flux distribution of the energetic tritons on the wall in a typical plasma operation of a high β_p H-mode: (a) linear scale of the heat flux and (b) log scale of the heat flux.

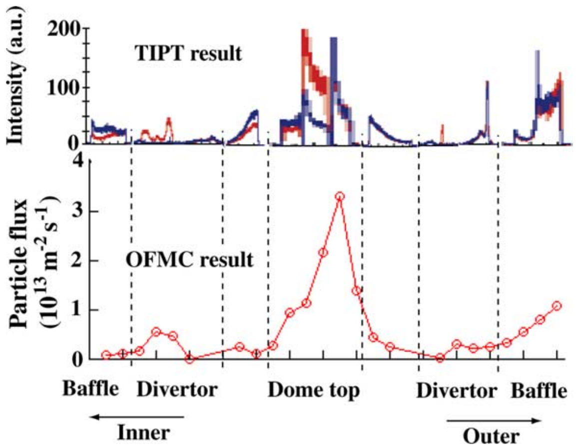

Fig. 6. A comparison between the results of TIPT and OFMC simulation in the poloidal direction. The blue line in the TIPT result shows the tritium in the upper divertor units shown in Fig. 2. The red line shows the tritium in the lower one.

4. Discussion

The tritium poloidal and toroidal distributions calculated using the OFMC code are consistent with the experimental results obtained by TIPT and the full combustion method. Fig. 6 shows a comparison in the poloidal direction between the result of TIPT and the particle flux distribution obtained by the OFMC simulation. The amount of the tritium retention in the divertor region including the dome units and the baffle plates (10%) are also reasonable compared with the simulation result (12%). These results indicate that the tritium distribution of the JT-60U W-shaped divertor reflects mainly the distribution of the energetic triton impinging on the wall. The tritium produced by D–D nuclear reaction is implanted deeply into the wall. The tritium in the divertor target tiles might be desorbed because of a high surface temperature of above 500 °C. The amount of tritium remaining in the divertor target tiles, which was measured by the combustion method, was only 1% of the produced tritium. The simulation result showed that the amount of the tritium impinging on the divertor target tiles was also small compared with other tiles. The tritium implanted to the divertor target tiles was 3% (inner target: 2%, outer target: 1%) of the produced tritium.

The result of the OFMC simulation showed that about 30% of the produced tritium was lost and implanted with high energy to the wall. The thermalized tritium distribution could not be described by this simulation, because the lowest energy of the tritons which can be taken into account in the OFMC code is the plasma temperature (10 keV in this simulation). The previous result described that approximately 50% of the produced tritium was remaining in the first wall including the divertor tiles [1]. The residual tritium (20%) is probably the tritium thermalized in the plasma. To understand the thermalized tritium distribution, the detailed tritium analyses, such as the depth profiles, are required.

5. Conclusion

Detailed tritium profiles on the JT-60U W-shaped divertor and the first wall tiles were examined by TIPT and full combustion method. Both results of the analyses were consistent. The highest tritium concentration, 60 kBq/cm^2, was found at the dome top tile. The tritium concentration in the inner divertor target tile was lower (2 kBq/cm^2). The SEM analyses showed that there is no correlation between the deposition layer and the tritium retention in JT-60U. This tritium distribution can be explained by the energetic triton loss due to ripple loss.

According to the simulation using the OFMC code, 31% of the tritons produced by D–D nuclear reaction are implanted deeply to the wall.

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References

[1] K. Masaki, K. Kodama, T. Ando, et al., Fusion Eng. Des. 31 (1996) 181.
[2] P. Andrew, P.D. Brennan, J.P. Coad, et al., Fusion Eng. Des. 47 (1999) 233.
[3] C.H. Skinner, W. Blanchard, J.N. Brooks, et al., in: Proceedings of the 20th SOFT 1998, vol. 1, p. 153.
[4] R.-D. Penzhorn, N. Bekris, W. Hellriegel, et al., J. Nucl. Mater. 279 (2000) 139.
[5] C. Stan-Sion, R. Behrisch, J.P. Coad, et al., J. Nucl. Mater. 290–293 (2001) 491.
[6] K. Miyasaka, T. Tanabe, K. Masaki, N. Miya, J. Nucl. Mater. 307–311 (2002) 1441.
[7] T. Tanabe, K. Miyasaka, K. Sugiyama, et al., Fusion Sci. Technol. 41 (2002) 877.
[8] Y. Gotoh, J. Yagyu, K. Masaki, et al., these Proceedings. PII: S0022-3115(02)01354-5.
[9] K. Tani, M. Azumi, H. Kishimoto, S. Tamura, J. Phys. Soc. Jpn. 50 (1981) 1726.
[10] K. Tobita, K. Tani, Y. Kusama, et al., Nucl. Fusion 35 (1995) 1585.