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In–out asymmetry of low-Z impurity deposition on the JT-60U divertor tiles

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Abstract

Low-Z impurity (^{7}Be) on the JT-60U divertor tiles was analyzed to study the impurity behavior in the divertor region. The amount of the ^{7}Be increased approximately one hundred times after B_4C-tile installation in the outer divertor. The ^{7}Be was probably produced by $^{10}B(p,\alpha)^{7}Be$ nuclear reaction on the divertor tiles in the hydrogen experiment with ion cyclotron range of frequency heating. The ^{7}Be was distributed asymmetrically in the poloidal and the toroidal direction. The highest ^{7}Be concentration was found at the inner divertor whose boron content ($B/(B+C) \sim 20\%$) was lower than the B_4C tiles ($B/(B+C) \sim 80\%$) of the outer divertor. This result may imply impurity transport from the outer divertor to the inner divertor.

1. Introduction

For future fusion devices, studies of erosion/redeposition and impurity transport are very important to understand the plasma surface interactions. In particular, interactions between plasma and carbon-based materials have been intensively studied so far. A remarkable erosion/deposition asymmetry between the inner and outer divertor targets was observed in many tokamaks [1,2]. Also in JT-60U, the erosion/deposition asymmetry was observed. The inner divertor was a redeposition-dominated region, whereas the outer divertor was an erosion-dominated region [3]. However, the carbon impurity behavior in the divertor region is not fully understood yet.

In JT-60U, carbon fiber composite (CFC) and isotropic graphite are used as armor tiles on most plasma facing components. Various radioactivity elements (tritium, beryllium (^{7}Be), cobalt (^{60}Co), etc.) were detected in radioactivity analyses of the armor tiles. With respect to the tritium in the plasma facing wall, the distribution and the retention processes were already reported [4]. The cobalt is believed to originate from the vacuum vessel and in-vessel component materials (Inconel 625 and SUS316). In JT-60U, radioactive beryllium (^{7}Be) was found on all plasma facing tiles. In particular, installation of the B_4C tiles, which were selected in order to reduce chemical sputtering of CFC tiles as well as oxygen impurity [5,6], increased the amount of ^{7}Be approximately one hundred times. The ^{7}Be was probably produced by the $^{10}B(p,\alpha)^{7}Be$ reaction. Furthermore, the ^{7}Be was distributed asymmetrically in the poloidal and toroidal direction. This ^{7}Be distribution may give useful information on impurity behavior. For the study of the impurity behavior, i.e. in–out asymmetry of the impurity deposition on the divertor targets, we focused on the radioactive beryllium.

In this paper, results of ^{7}Be analyses of the divertor tiles are described. In addition, mechanism of ^{7}Be production and impurity transport in the divertor region are discussed.

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2. Sample tiles

Samples for the analyses of beryllium (^{7}Be) were the divertor tiles removed from the open divertor (1991–1997) and the W-shaped divertor (1997 onwards). In JT-60U, boronization using decaborane as one of the wall conditioning techniques to reduce oxygen impurity has been performed since 1992 [7–9]. The open divertor had eight rows (a, b–h) of tiles in the poloidal direction. In December 1992, CFC tiles with a B_4C-converted layer (i.e. B_4C tiles) of ~100 μm thickness were installed in the outer divertor row-f [5]. CFC tiles having a B_4C-converted layer of ~300 μm thickness were installed in the outer divertor row-e in December 1993 [6]. The sample tiles of the open divertor were removed in November 1992, 1993 and 1994. Accordingly, the 1992-year samples experienced only the boronization. The thickness of the boron layer formed by the boronization was ~100 nm [7]. The samples removed in 1993 and 1994 experienced B_4C-tile operation and boronization. The sample tiles of the W-shaped divertor, which has no B_4C tiles, were removed in November 1998. These samples experienced boronization forming a boron layer of ~several 100 nm [9].

Table 1 shows experimental conditions in each year. The heating parameters of ion cyclotron range of frequency (ICRF) are those in hydrogen experiments performed in the last phase of each year-long experimental campaign. In 1993 and 1994, hydrogen experiments with relatively high ICRF heating power of 3–5 MW and integrated injection times of 100–200 s were performed. In 1998, the ICRF power and integrated injection time in the hydrogen experiments were ~3 MW and ~50 s, respectively.

The ^{7}Be content of each tile was measured without cutting samples, using a germanium semiconductor detector and a NaI scintillation detector.

Table 1
Experimental conditions in each year

Operation year	1992	1993	1994	1998
Average ICRF power (MW)	2.1	4.7	2.5	2.9
Integrated ICRF injection time (s)	86	218	103	55
Number of ICRF shot (shots)	53	162	98	46
Number of boronization	1	2	1	1
B_4C-tile operation		Row-f ~100 μm	Row-f ~100 μm, row-e ~300 μm	

The ICRF heating parameters are those in hydrogen experiments performed in the last phase of each year-long experimental campaign. After the B_4C tile (300 μm) installation in December 1993, boron impurity in plasma was increased.

3. ^{7}Be distribution in open divertor and W-shaped divertor

Fig. 1 shows beryllium (^{7}Be) poloidal distribution of the open divertor tiles removed in November 1992, 1993 and 1994. These data were estimated values for end of each year-experimental campaign, because of the relatively short half-life (53.3 d). After the installation of B_4C tiles, the ^{7}Be concentrations of the divertor tiles increased from ~10 to ~10^3 Bq/cm^2. In particular, the samples removed in 1994, which experienced thick B_4C tile (~300 μm) operation, had a high ^{7}Be level. The highest ^{7}Be concentration of 16 kBq/cm^2 was found at row-c of the inner divertor. The ^{7}Be concentration at the inner divertor was always higher than that at the outer divertor. Moreover, ^{7}Be levels of row-e increased after B_4C-tile installation in row-e. Full toroidal measurement of row-e tiles showed that the ^{7}Be was distributed peri-

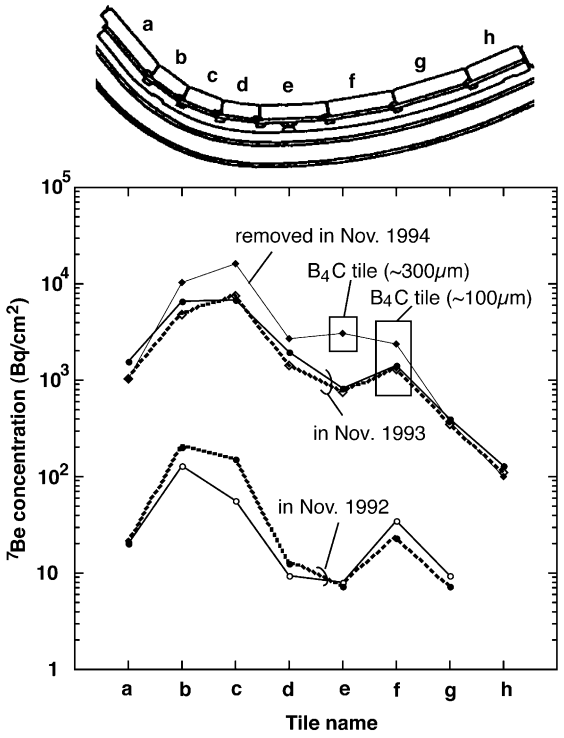

Fig. 1. Beryllium (^{7}Be) poloidal distribution in the open divertor tiles removed in November 1992, 1993 and 1994. The dot lines are sample tiles removed from different toroidal positions. The ^{7}Be was measured using a germanium semiconductor detector.

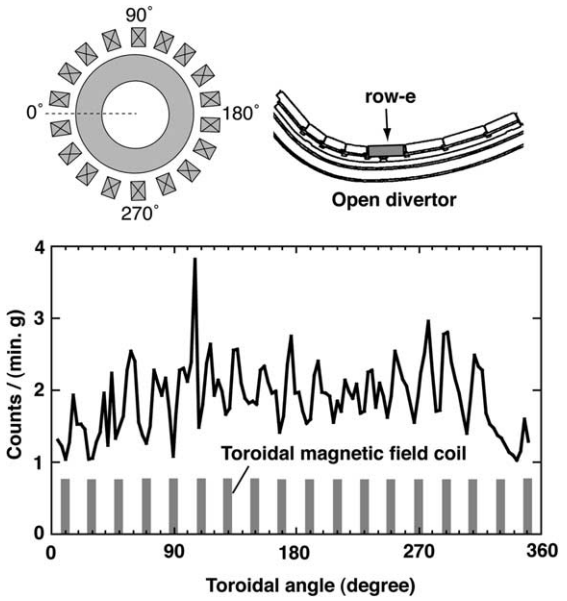

Fig. 2. ^{7}Be toroidal distribution in the divertor tiles (row-e) removed in November 1993. Since the dominant radioactive impurity in the divertor tiles was ^{7}Be, full toroidal measurement of row-e was performed using a NaI scintillation detector without nuclide identification.

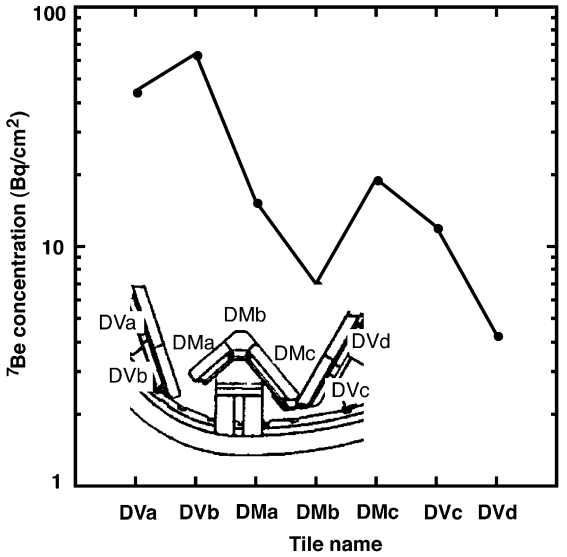

Fig. 3. ^{7}Be poloidal distribution in the W-shaped divertor tiles removed in 1998. The ^{7}Be was measured using a germanium semiconductor detector.

odically in the toroidal direction as shown in Fig. 2. This distribution was correlated to the toroidal field coil (TFC) positions. Fig. 3 shows ^{7}Be poloidal distribution in the W-shaped divertor tiles removed in November 1998. The ^{7}Be concentration decreased to $\sim$10 Bq/cm^2 after the divertor modification. Also in the W-shaped divertor, the ^{7}Be concentration at the inner divertor was higher than that at the outer divertor.

4. Discussion

4.1. Production of ^{7}Be

After the B_4C installation, the ^{7}Be concentration increased drastically approximately one hundred times. In the W-shaped divertor without B_4C tiles, ^{7}Be decreased to the level before the installation of the B_4C tiles. This result must indicate that ^{7}Be in JT-60U originated from boron. Most probably, ^{7}Be was produced by the $^{10}B(p,\alpha)^{7}Be$ reaction. The cross section at the resonance peak (1.5 MeV) is 0.21 barn. In JT-60U, high energy protons are produced by D–D nuclear reactions and in a hydrogen plasma with ICRF heating performed in the last phase of a year-long experimental campaign. The energy of the proton produced by D–D nuclear reaction is 3 MeV. The integrated amount of the proton production was $\sim 1\times10^{19}$ in each year (average $\sim 3\times10^{15}$/shot). According to the simulation using an orbit following Monte Carlo code [10], roughly 30% of the produced protons were implanted into the divertor tiles (rows a–h) with average energy of $\sim$1.5 MeV. Taking account of the proton production in the deuterium experiments and the ^{7}Be production yield [11] and the half-life of ^{7}Be (53.3 d), the total amount of the ^{7}Be at the divertor region was estimated to be $\sim 10^{6}$ Bq even assuming that a thick boron layer of 30 μm exists on the divertor tiles, which is equal to the penetration depth of 1.5 MeV protons. This amount of ^{7}Be was very low compared with that of the samples removed in 1993 and 1994 ($\sim 10^{8}$ Bq). In the hydrogen experiment with ICRF heating, the hydrogen ions are accelerated to several MeV [12]. The number of high energy protons produced by ICRF heating is expected to be larger ($\sim 10^{16}$ m^{-3} [13]) than the number of protons produced by D–D nuclear reaction. This suggests that most of ^{7}Be was probably produced by the $^{10}B(p,\alpha)^{7}Be$ reaction in the hydrogen experiments with ICRF heating and B_4C tiles.

Furthermore, the following two cases should be considered for the ^{7}Be production. (1) Boron on the tile surface was bombarded by high energy protons due to ripple losses. (2) Boron reacted with high energy proton in the plasma. The periodic ^{7}Be distribution in the toroidal direction, which was correlated to TFC positions (i.e. ripple loss), and increase of ^{7}Be at row-e after B_4C-tile installation (row-e) in 1993 probably reflected the high energy proton bombardment of the tile surface.

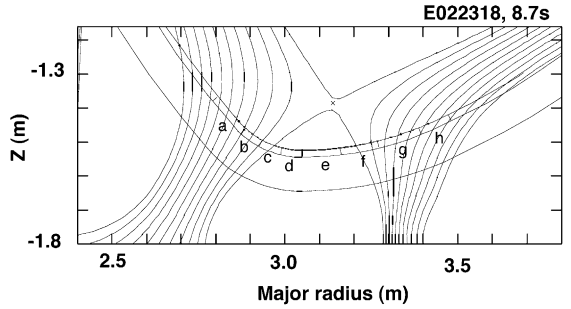

Fig. 4. Typical divertor configuration in 1994 hydrogen experiments. The ICRF heating power and plasma current were 2.5 MW and 2.5 MA, respectively. The inner and the outer strike points were located at row-c and row-f, respectively.

4.2. Transport of ^{7}Be

With respect to the poloidal distribution, ^{7}Be in the inner divertor was always higher than that in the outer divertor. Fig. 4 shows a typical divertor configuration in 1994 hydrogen experiments. In this case, it is expected that the high energy protons impinged on the tiles of the private region and the outer divertor region, because the ripple rate of the toroidal magnetic field was high on the low field side. However, the highest ^{7}Be concentration was found at row-c, whose boron content (B/(B+C) $\sim$ 20%; X-ray photoelectron spectroscopy analysis) was lower than B_4C tiles. In the scanning electron microscope analyses of the divertor tiles removed in November 1994, a thick deposition layer of $\sim$60 μm was found on the inner divertor tile (row-b), whereas no continuous deposition layer was observed on the outer divertor tiles. Also in the W-shaped divertor, it was reported that the inner divertor was a deposition-dominated region, whereas the outer divertor was an erosion-dominated region [3]. These results may imply impurity transport from the outer divertor to the inner divertor.

5. Conclusions

In JT-60U, various radioactive elements (tritium, beryllium (^{7}Be), cobalt (^{60}Co), etc.) were detected in radioactivity analyses of the armor tiles. For the study of the impurity behavior in the divertor region, ^{7}Be on the divertor tiles was analyzed. Furthermore, in–out asymmetry of the ^{7}Be and the impurity transport in the divertor region were discussed.

Beryllium (^{7}Be) produced by the ^{10}B(p,α)^{7}Be nuclear reaction in the hydrogen experiment with ion cyclotron range of frequency heating was distributed asymmetrically in the poloidal and toroidal directions. The ^{7}Be was periodically distributed in the toroidal direction, which was correlated to toroidal field coil positions, i.e. ripple loss. Therefore, ^{7}Be was believed to be produced by proton bombardment of the tile surface. With respect to the poloidal direction, the ^{7}Be concentration in the inner divertor was higher than that in the outer divertor (B_4C). This result may imply impurity transport from the outer divertor to the inner divertor.

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