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Production and Transport of Carbon Impurities in Fusion Plasma Devices

核融合プラズマ装置における炭素不純物の発生と輸送

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For high-heat load divertor plates, carbon materials are used in present and next generation tokamaks (such as ITER) because of their good thermal properties and low atomic number. However, erosion and redeposition of carbon materials is a concern for long operation of next generation tokamaks. In this talk, recent studies on production of carbon impurities due to chemical sputtering and transport and redeposition of carbon are reviewed, and future direction of this field is discussed.

1. Introduction

In ITER, operation with cold divertor plasmas such as partially detached divertor plasmas is considered for mitigating the severe problem of concentrated power loading of the divertor plates. Carbon material is considered to be used for the high-heat-load divertor plates: strike-point tiles, because of its high thermal shock resistance and tolerance to off-normal events (ELMs and disruptions) without melting. However, carbon has properties of strong chemical reactions with hydrogen. While the physical sputtering yield, which has been well investigated, decreases drastically in cold divertor plasmas, the chemical sputtering yield does not decrease and the chemical sputtering can reduce the lifetime of the divertor plates. Carbon impurities produced by physical or chemical sputtering are transported, and redeposition of the transported carbon impurities with tritium gives rise to operational and safety concerns for tritium inventory. Therefore, the study of production and transport of the carbon impurities is important for ITER [1-3].

In this paper, recent studies on production of the carbon impurities due to the chemical sputtering and transport and redeposition of carbon is reviewed, and future direction of this field is discussed.

2. Production of Carbon Impurity

The chemical sputtering of carbon has been studied in detail in ion beam experiments, and the sputtering yields are available as functions of incident ion energy and surface temperature. However, the high-ion-flux condition (~10^{24} $m^{-2}s^{-1}$) in ITER divertor plasmas cannot be simulated by the ion beam experiments. Therefore, it is necessary to measure ion flux dependence of the chemical sputtering yield in real divertors under high-ion-flux conditions. Using data from PSI-1, PSI-2, PISCES-B, JET, Tore Supra, TEXTOR, ASDEX Upgrade and JT-60U, the dependence of the chemical sputtering yield on the ion flux, Φ, has been determined to be $\Phi^{-0.54}$ [4]. With this flux dependence in addition to the ion energy and surface temperature dependence, the chemical erosion rate of the ITER divertor plates has been calculated. The calculated erosion rate was an order of magnitude lower than previous estimates using a constant chemical sputtering yield of 1.5 %. Here, only production of methane (CH_4/CD_4) was considered, and production of heavier hydrocarbons (C_2H_n/C_2D_n) was not investigated quantitatively. In JT-60U, the chemical sputtering yield due to C_2H_n/C_2D_n production in addition to CH_4/CD_4 production has been measured [5]. The measurement showed that the contribution of C_2H_n/C_2D_n production to the total number of the sputtered carbon atoms was ~80%. Therefore, the contribution of C_2H_n/C_2D_n production should be investigated in addition to CH_4/CD_4 production.

3. Transport and Redeposition of Carbon

In JET, D III-D, ASDEX Upgrade and JT-60U, it has been found that erosion was dominant or almost balanced with deposition at the outer divertor plates and deposition was dominant at the inner divertor plates as shown in Fig. 1 [2,6]. One of the reasons of this in/out asymmetry is considered temperature asymmetry between the in/out divertor plasmas; the temperature in the outer divertor plasma is usually higher than that in the inner divertor. The energy

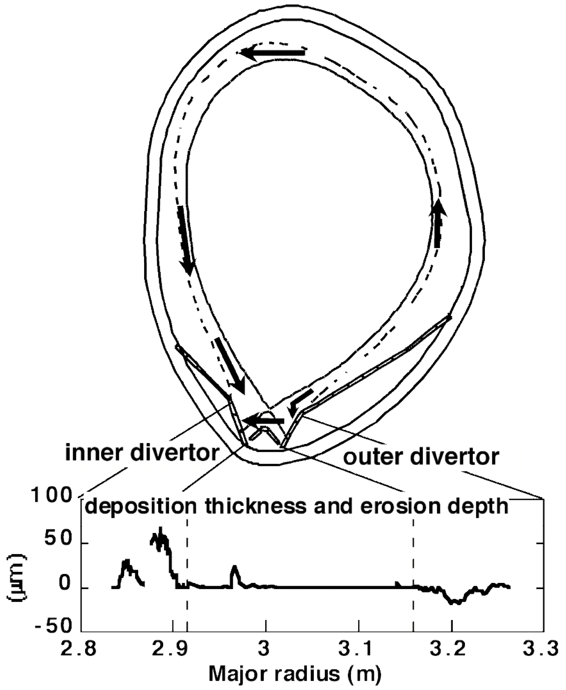

Fig. 1. Poloidal cross-section of JT-60U and deposition thickness and erosion depth in the divertor [6]. The arrows indicate the directions of the plasma flow in the SOL and the E_r x B drift flow in the private flux region [7].

dependence of the sputtering yield means that the temperature asymmetry can shift the equilibrium from net erosion to net deposition. Some of the carbon deposition in the divertor is considered to be originated from the erosion of the main chamber wall with preferential deposition in the inner divertor. In JET, $^{13}CH_4$ has been injected at the top of the machine, and it has been found that the most of the ^{13}C was deposited in the inner divertor [2]. The preferential deposition in the inner divertor may be consequence of the SOL flow towards the inner divertor plates that has been observed when the ion grad B drift was directed towards the divertor target (Fig. 1) [2,7]. In the JT-60U divertor, E_r x B drift in the private flux region has been evaluated, and the evaluation showed that the drift flow contributed to in/out asymmetry in the divertor ion flux (Fig. 1) [7]. The drift flow from the outer divertor to the inner divertor via the private region might provide a path for carbon impurity to reach the inner divertor. Quantitative investigation of carbon impurity production in the main chamber and carbon transport due to the plasma flow in the SOL and private region is required.

In JET, significant deposition has been observed on areas with no direct plasma ion impact (remote areas) in the inner divertor [2]. It was considered that hydrocarbon molecules might be released by thermal decomposition of soft hydrocarbon films formed on hot surfaces in the inner divertor and they might attach preferentially to the water cooled louver at the end of the pump ducts. On the other hand, in JT-60U, careful inspection and dust collection has shown that little deposition was appreciable in remote areas and the amount of carbon dust was very small; the total dust amount was estimated to be ~7 g [3,8]. The difference between JET and JT-60U might be attributed to difference of their divertor structures and surface temperatures of the divertor plates and walls [9]. Further study of hydrocarbon chemistry is required to understand the remote deposition.

4. Summary

For carbon impurity production, the contribution of C_2H_n/C_2D_n production should be studied in addition to CH_4/CD_4 production. For understanding of carbon transport and redeposition, quantitative investigation of carbon transport due to the plasma flow in the SOL and private region is required. In addition, carbon impurity production in the main chamber should be investigated quantitatively. Study of effects of the divertor structure and the surface temperature of the divertor plates and walls on deposition of carbon in the remote area is important.

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