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On the possibility of ITER starting with full carbon

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Abstract

ITER is planned to start with Be as first wall armors, and W and CFC as divertor armors. Although Be is an excellent oxygen getter, its low melting point makes it unstable to use in a burning reactor. The performance of W armor in ITER-like plasma is still quite uncertain. Moreover, operating temperature window of W would be limited due to its brittleness at lower temperatures and significant grain growth at higher temperatures. Carbon is presently the most reliable plasma facing material, if we have to allow ITER plasma more flexibility and off-normal events, which should be unavoidable to obtain physics bases to attain burning plasma. Appropriate selection of divertor structure and fine tile alignment would reduce carbon deposition significantly. And if we could keep divertor surface temperature of the deposition area above 1000 K, tritium retention could be significantly reduced. We should not exclude the possibility of carbon as PFM even in a fusion reactor. Since the operating temperature of a fusion reactor is likely be above 800 K, tritium retention in carbon is not likely the problem, and erosion could be repaired by deposition of carbon layers between shots and the deposited layers must be graphitized by a succeeding shot.

Keywords: Carbon; Plasma facing materials; Divertor; First wall; ITER; Tritium retention

1. Introduction

In the design of ITER and ITER FEAT [1–3], beryllium, carbon and tungsten are selected as armor materials of the first wall, divertor target and dome, respectively. There are several reasons for the exclusion of carbon materials; i.e. erosion, transport and deposition of carbon, tritium incorporation in the carbon deposition at remote area, production of hazardous tritiated dust, neutron irradiation effects resulting loss of thermal conductivity and dimensional changes and so on. On the other hand, carbon materials have a big advantage of non-melting [4,5]. Although tungsten is one of the best plasma facing materials (PFM) owing to its highest melting temperature and low sputtering yield, it must be proved not to kill the burning plasma due to its large radiation power when accumulated in the plasma center [6–8]. That might not be a reason to exclude tungsten and to examine how plasma behaves with high Z PFM must be one of ITER tasks. Another concern on W is the melting, which could result in

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catastrophic damage owing to cracking of re-solidified area after the melting [9,10]. To attain burning plasma in ITER, much higher energy input is requested than present tokamaks. Accordingly, heat load to PFM under off-normal events such like disruptions and giant ELMs could easily exceed the critical heat load of the material melting. If we are not able to control the off-normal event, only one off-normal event could destroy the machine. Recently, a giant ELM could load enough energy to melt the tungsten wall [11]. Of course, the damage should be quite local, but the effect for succeeding shots must be quite large. And repairing would force a long operation break.

There are some contradictions in selection of PFM materials. One may say, carbon cannot be used in burning plasma owing to large erosion and high tritium retention, so as beryllium due to its low meting point, and we should start with full tungsten. On the other hand, for the off-normal event which must be avoided in a reactor, carbon can withstand higher heat load than tungsten can. Therefore to start ITER with full carbon could be an alternative way and allow studying off-normal events and even disruptions for developing the methods to control the off-normal event before going into D–T burning discharges. In other words, we should allow plasma discharges in ITER more flexibility without caring the damage of PFM. In this respect carbon seems the best PFM.

Of course the ITER design has been carefully done and seems to employ the best selection based on the present knowledge [1–3]. Nevertheless, there are still large ambiguities in the estimation of carbon erosion and tritium retention which are the main reasons to avoid carbon in ITER.

Recent studies in JT-60U and JET indicate that carbon erosion and tritium retention in ITER could be smaller than the present estimation [12–17]. The purpose of this paper is not to deny the utilization of metallic materials as PFM but to suggest starting ITER with full carbon PFM. To do this, we have revisited the data on (1) erosion and deposition in laboratory experiments and in tokamaks, (2) tritium incorporation in the deposited layers on the divertor area and at plasma shadowed region in present tokamaks, mainly comparing JET and JT-60U and (3) neutron irradiation effects. In Table 1, recent observations in JT-60U are compared those for JET. Possibility of carbon as PFM in a reactor is also discussed.

Table 1
Comparison of JET with Mark-IIA divertor and JT-60U with W-shaped divertor

	JET	JT-60U
Deposition rate at inner divertor	5 g/h	6 nm/s
	6.5×10^{20} atoms/s	3×10^{20} atoms/s
Erosion rate at outer divertor	2.3 nm/s	0.7 nm/s
D/C in deposits	0.4–0.1	<0.04
Deposition at remote area	Louvers at inner pumping slot	Beneath outer divertor
Collected dust	1 kg	7 g
Pumping slot	Inner side	Bottom
Tile alignment in toroidal direction	A few mm step between tiles	No step between tiles
Divertor temperature	Below 500 K	Above 600 K
	Water cooled base structure	Only inertially cooled

2. Erosion and deposition

2.1. Physical and chemical sputtering

Erosion of carbon materials by physical and chemical sputtering of energetic hydrogen injection is unavoidable. If the injecting energy and flux of hydrogen ions were identified, the erosion yield of the carbon materials could be predicted precisely [18]. However, in a tokamak, the energy of impinging hydrogen ions is widely distributed and not necessarily has Gaussian like distribution. Moreover, their energy and flux are quite dependent on the location in a torous. In the divertor region, the divertor striking locations being subjected to very high particle and energy fluxes can be easily separated from other area. Moreover, sputtered neutrals (most of sputtered atoms are neutral) are immediately ionized by electrons in plasma and gyrated owing to the magnetic field, which is completely different situation from simple sputtering measurements by ion beams. Even under mono-energetic ion irradiation, flux dependence showing less erosion under higher flux is observed, of which cause is still not unclear as discussed in the next section [18,22].

Hence the estimation of erosion/deposition in tokamak is quite difficult. Of course with an aid of computer codes, the erosion/deposition as well as tritium incorporation in the deposited materials were estimated for ITER [19–22]. Accordingly, a few to a few hundreds