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Irradiation Experiments of Extremely High-Power-Density Helium Ion Beams to Plasma Facing Candidate Materials in ITER

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1. Introduction

In the nuclear fusion plant as ITER, the thermal flux due to the disruption and edge localized mode (ELM) to the plasma facing materials can cause sever damages such as heat conductivity and mechanical properties. Generally, heat road test using a high-power-density electron beam has been conducted to plasma facing candidate materials to study the effects of disruption or ELM. However, plasma facing materials are exposed to not only electrons, but also hydrogen isotopes and helium [1]. It has been found that the surface modification by hydrogen and helium beam heating is completely different from that by electron beam heating [2]. Recently, it was also found that helium plasma affected on light reflection properties of the metallic mirror [3]. Therefore, it is very important to irradiate the materials by the high-power-density helium and hydrogen beams.

At National Institute of AIST, high-power-density neutral and ion hydrogen beam was successfully developed [4]. It is also possible to extract a high-power-density He^+ beam by this neutral beam system using helium gas instead of hydrogen gas without gas puffing into the neutralization cell. In the present study, this high-power-density He^+ beam with disruption heat load level is irradiated to plasma facing material candidates (tungsten and ferritic steel), as initial tests.

2. Experimental setups

Figure 1 shows a schematic drawing of a strongly focused ion beam system having concave electrodes with large-area (ϕ345 mm) [4]. The designed focal length is 1860 mm. The diameter of extraction aperture in the concave acceleration electrode with a meniscus structure is 4 mm at the ion-source side. The transparency of each electrode is ~50 %. The distance between the acceleration and deceleration electrodes is 5.5 mm, and that between the deceleration and grounded electrodes is 2 mm. The thickness of all electrodes is 2 mm. The plasma is produced using a bucket type ion source with cusped magnetic fields. A power supply (PS) system using capacitor banks is adopted. Specifications of PSs are 30 kV and 50 A for the acceleration, -5 kV and 6 A for the deceleration, and 300 V and 1 kA for the arc. The filament PS of DC operation has the specifications of 20 V and 2700 A. In the case of the maximum beam current of ~90 A with 25 keV energy, the beam power of

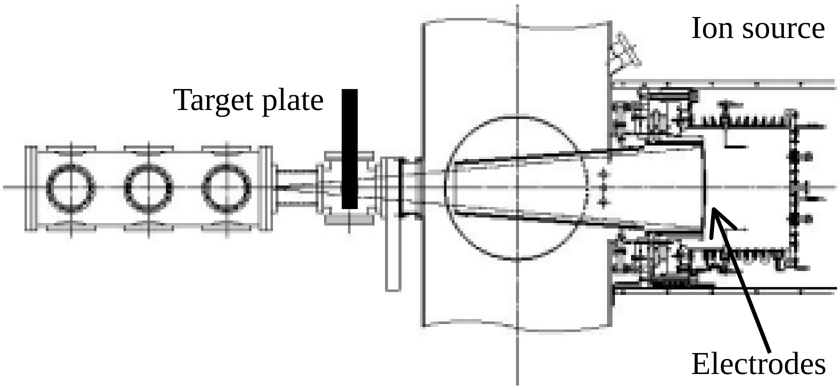

Fig. 1. Schematic drawing of ion beam system.

~2.1 MW is achieved. The beam with a diameter of 345 mm at the electrode is focused to a diameter of ~36 mm at the focal point with a small divergence angle of about ±0.8 deg. As a result, a power density as high as ~1 GW/m^2 is attained at the focal point of the neutral beam.

Figure 2 shows time evolutions of acceleration voltage, extracted He$^+$ beam current and beam power, respectively. He$^+$ beam of ~22 kV and ~40 A is obtained. At 1530 mm from the electrode, the diameter of focused He$^+$ beam becomes ~70 mm which is estimated by the melting trace of the target plate [5]. Then, power-density, flux and total flux are estimated as Γ =248 MW/m^2, 6.2 x 10^{22} m^{-2}s^{-1} and 1.9 x 10^{21} m^{-2}/shot (beam duration, τ, is 30 ms), respectively. (It is possible to increase the power-density to put the materials at the focus point of the beam.)

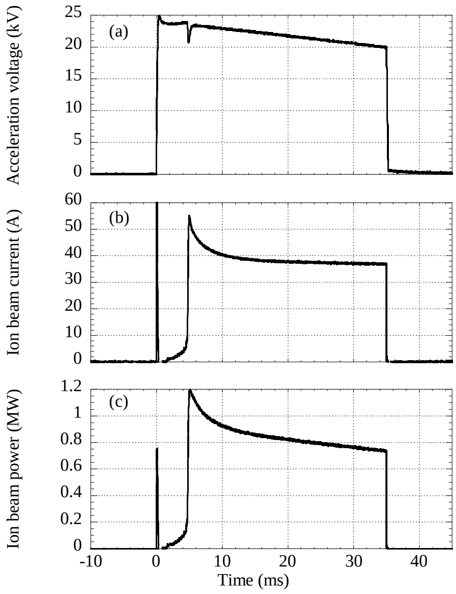

Fig. 2. Time evolutions of (a) acceleration voltage, (b) extracted ion beam current and (c) ion beam power.

3. Experimental results

This high-power-density He$^+$ beam with disruption heat load level in ITER is irradiated to both the bulk powder metallurgy (PM) tungsten (purity ~99.99 %) which is one of the plasma facing candidate materials with low erosion yield and high temperature properties, and ferritic steel. Materials (16.6 x 16.6 mm^2) are put on the copper plate and fixed bolts as shown in Figs. 3(a), (b) and (c). The tungsten thickness at the center part is 1 mm with the diameter of 3 mm for tap screw, the thickness of other parts is 3 mm. It is easily recognized that the surface of the ferritic steel is completely melted as shown in Fig. 3(c).

Figure 4(a) shows a scanning electron microscope (SEM) image of the tungsten surface before the irradiation. Figure 4(b) and (c) show the SEM images of the tungsten surface which are indicated in (i) and (ii) of Fig. 3(b), in the case of 1 shot He^+ beam irradiation (= 1.9 x 10^{21} m^{-2}). Surface modification and production of some small holes are shown. In this case, tungsten surface temperature is estimated as ΔT~2689 K using the relation of $\Delta T = 2\Gamma\{\tau/(\pi\rho c\kappa)\}^{1/2}$. Here, ρ, c and κ indicate material density, specific heat and thermal conductivity, respectively.

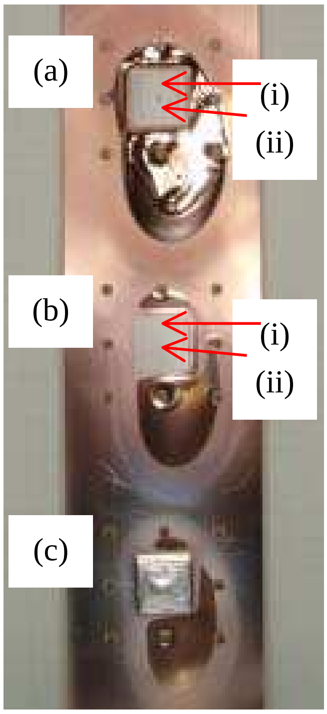

Fig. 3. (a) 5 shots to tungsten, (b) 1 shot to tungsten and (c) 1 shot to ferritic steel.

Figure 5 shows the SEM images of the tungsten surface which are indicated in (i) and (ii) of Fig. 3(a), in the case of 5 shot He^+ beam irradiation (= 9.5 x 10^{21} m^{-2}). The beam is irradiated every 9 minutes. Figures 5(a) and (b) show wide scale modification and the production of very small holes (< ~100 nm). Figures 5(c) and (d) show that many small holes (ϕ~200 nm) are produced (The center part of the tungsten material in Fig. 3(a) looks black). We can understand that the damage becomes more terrible, as the thickness of the material becomes thin. It indicates that temperature of the material is important for the production rate of holes and the size of holes. Thermal conductivity may become worse as the number of beam pulse increases, since the material surface gradually becomes rough.

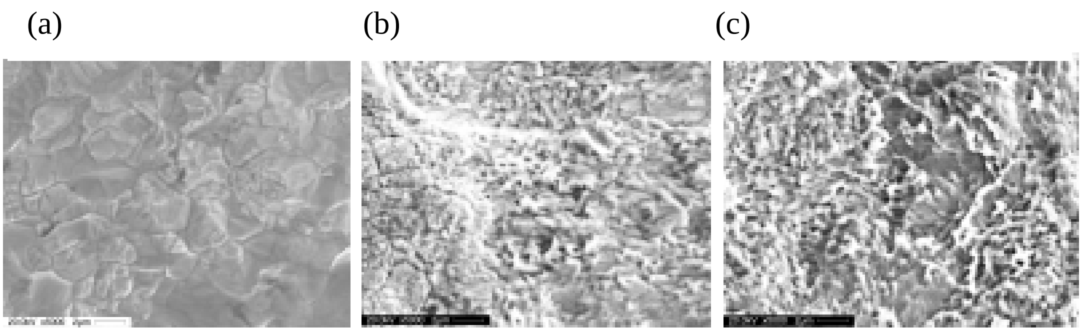

Fig. 4. SEM images (x 5,000) of the tungsten surface, (a) before the irradiation, (b) location (i) in Fig. 3(b) and (c) location (ii) in Fig. 3(b).

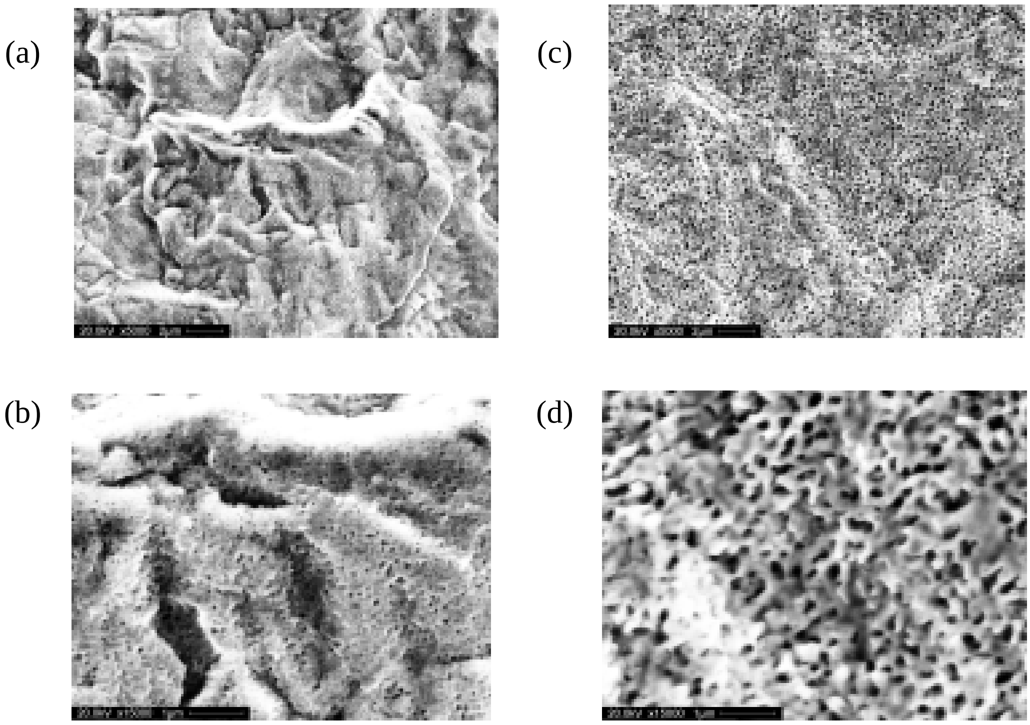

Fig. 5. SEM images of the tungsten surface, (a) x 5,000, (b) x 15,000 at location (i) in Fig. 3(a),and (c) x 5,000, (d) x 15,000 at location (ii) in Fig. 3(a).

4. Summary and future plans

High-power-density He^+ beam of ~248 MW/m^2 is successfully extracted using the beam system with large-area concave electrodes. This high-power-density He^+ beam is irradiated to PM tungsten and ferritic steel. Even in the case of 1.9 x 10^{21} m^{-2} flux, this high-power-density He^+ beam causes sever damages on the surface of tungsten material. It is also found that hole sizes on the surface depend on the amount of total flux and thickness of the material. This damage might influence thermal properties, mechanical properties and tritium retention. It is easily recognized that the surface of the ferritic steel is completely melted at one shot.

As future plans, following things are considered; irradiation experiments by hydrogen beam, hydrogen and helium mixture beam and electron beam, cross section image observation by transmission electron microscope (TEM), and continuous irradiation experiments by short pulse beam (a few ms) with high-power-density (ELM simulator), etc.

References

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