Development of High-Power-Density Ion Beam System with High-Repetition Pulse Operation

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A high-power-density ion beam system with high-repetition pulses was successfully developed. In the ITER (International Thermonuclear Experimental Reactor), it is anticipated that an intermittent thermal flux, due to the edge localized mode (ELM), to the plasma facing materials causes severe damage of the mechanical properties. Therefore, it is very important to study the effect of ELM phenomena. We already developed an ion beam system with a power density as high as ~1 GW/m^2 around the focal point of the beam. In order to imitate the intermittent high-power-density pulsed flux, we modified the beam operation method and part of the acceleration power supply. A pulsed helium ion beam with the beam width of 2 ms and 4 ms intervals between pulses was successfully extracted. In this case, beam energy, current and power were ~22 keV, ~40 A, and ~0.88 MW, respectively. This high-repetition pulsed helium ion beam with high power density (~300 MW/m^2) was irradiated to a tungsten material. It was found that this repetitive short-pulse irradiation caused less surface damage compared with long-pulse irradiation, even when the total amount of irradiation fluence (1.5×10^{22} particles/m^2) was the same for each condition. This would provide important data for the design of ITER diverter.

Keywords: high-power-density ion beam, high-repetition pulsed ion beam, ITER, edge localized mode (ELM), ELM simulator, plasma wall interaction, pulse beam irradiation, nanostructure

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1. Introduction

The ITER (International Thermonuclear Experimental Reactor) has been constructed in Cadarache to achieve a self-burning plasma. In the nuclear fusion plant, it is anticipated that the thermal flux due to the edge localized mode (ELM) or plasma disruption to the plasma facing materials causes severe damage of the mechanical properties. Therefore, it is important to study the effect of ELM phenomena using fusion plasma devices and also alternative devices that simulate the ELM behavior. Generally, heat road tests using a high-power-density electron beam have been conducted on plasmas facing candidate materials, and recently, pulsed electron beams or lasers have been used to demonstrate the ELM behavior. However, wall materials are exposed to not only electrons, but also hydrogen isotopes and helium [1]. It has been found that surface modification by hydrogen and helium beam heating is completely different from that by electron beam heating [2, 3]. It has also been found that helium plasma affects the light reflection properties of a metallic mirror [4]. Therefore, it is very important to irradiate the high-power-density ion beam to materials. Typical ELM conditions that we aim are power density of ~500 MW/m^2, pulse repetition of 1-10 Hz, and pulse width of several hundred μs, respectively.

A high-power-density ion beam system with a concave-type electrode was developed for the purpose of hydrogen neutral beam injection (NBI) through a narrow port in the vacuum vessel of the reversed field pinch (RFP) fusion plasma device [5–9]. The beam was strongly focused to a diameter of ~36 mm around the focal point, with a divergence angle of about ±0.8 deg. A power density as high as ~1 GW/m^2 was attained around the focal point of the beam. One of the applications of this focused beam is in irradiation experiments of materials, particularly the inner wall candidate material in ITER [10]. It was found that high-energy and high-flux helium irradiation on tungsten induced serious surface erosion [11]. In order to imitate the intermittent high-power-density pulsed flux, our beam system was modified, and a pulsed helium ion beam with the beam width of 2 ms and 4 ms interval (250 Hz) between pulses was successfully extracted.

In this paper, we describe in detail the modification method of the beam system to establish the pulse operation. Moreover, irradiation results of a repetitive short-pulse beam to tungsten material are presented.

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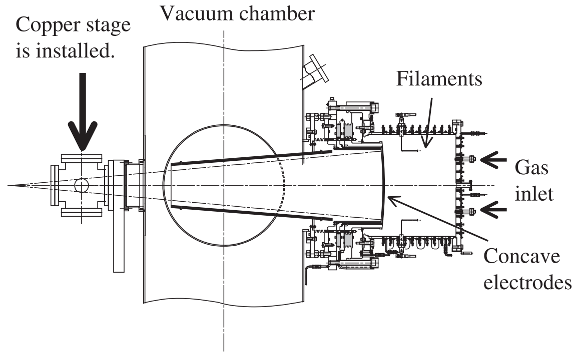

Fig. 1 Ion beam system.

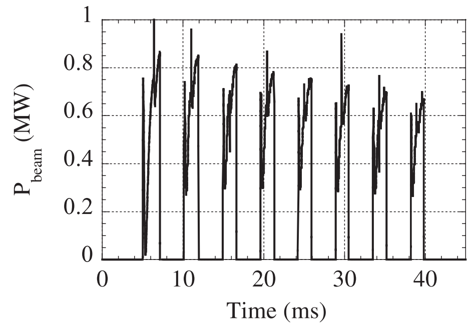

Fig. 2 Time evolution of repetitive short-pulse ion beam obtained spontaneously in the case of brakedown.

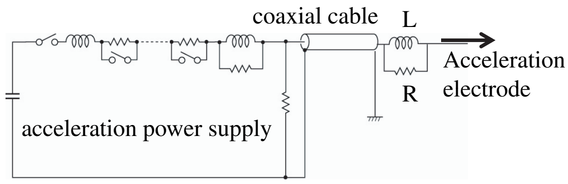

Fig. 3 Acceleration power supply system after modification. Inductance L is inserted between the electrode and long coaxial cable from the power supply.

2. Ion Beam System and Pulse Operation Results

The ion source of our beam system is a bucket type with a cusped magnetic field, as illustrated in Fig. 1. This magnetic field is larger than 0.15 T at the inside surface of the chamber, and the residual magnetic field in the plasma region is smaller than 0.5 mT. Narrow hairpin tungsten filaments of 2 mm diameter are adopted as cathodes [12], and inserted a few mm inside the plasma region. To focus the beam, three sets of concave copper electrodes (acceleration, deceleration and grounded electrodes) are adopted. The effective diameter of the electrode is 345 mm. The extraction aperture on the acceleration electrode is 4.0 mm in a diameter on the ion-source side, and the transparency of the electrode is ~50 % (the total number of apertures is ~3,700). The thickness of all electrodes is 2.0 mm. A power supply (PS) system with capacitor banks is adopted, except for the filament PS. The PS specifications are 30 kV and 50 A with voltage ripples of less than 5 % for the acceleration PS, −5 kV and 6 A for the deceleration PS, and 300 V and 1 kA for the arc PS. The filament PS of DC operation (30 s) has the specifications of 20 V and 2700 A (= 180 A × 15 sets of filaments), and a programmed constant-voltage control property with a setting accuracy of 0.1 %. The designed beam duration is 30 ms. The extracted ion beam was successively focused to the focal point of the electrode (which was ~1450 mm from the electrode) with a diameter of ~36 mm. In the case of an acceleration voltage V_{acc} of 25 kV and extracted current I_{ext} (= acceleration current I_{acc}-deceleration current I_{dec}) of 50 A for the hydrogen ion, the power density is more than 1 GW/m^2 around the focal point [6].

In the case of exceeding the limit value of the acceleration current, such as during a breakdown between acceleration and deceleration electrodes, acceleration and deceleration power supplies are automatically switched off by the programmed controller using the IGBT unit. Moreover, it is possible to set IGBT switches on for the purpose of restarting the beam up to 10 times. Figure 2 shows an example of repetitive short-pulse ion beams obtained spontaneously in the case of brakedown, as a benefit of the restart mechanism. This restart operation was originally designed to conduct discharge cleaning of the electrodes.

To obtain arbitrary pulse waveforms to demonstrate the ELM behavior, we modified the circuit between the acceleration PS and electrode, and part of the beam control system. In the former modification, inductance L (= ~2 mH) was newly inserted in the circuit, as shown in Fig. 3. Figure 4 (a) shows the helium ion (He^+) beam power P_{beam} of ~22 keV, ~40 A. Arc current I_{arc} is also shown in Fig. 4 (a). In this case, an arc efficiency (= beam current /arc power) of 1 A/2 kW was attained. To keep acceleration voltage constant as possible, six resistances of 16.7 Ω each connected in series in the circuit are successively bypassed utilizing IGBT switches. Hence, the six-step recovery of acceleration voltage is possible. Each waveform of V_{acc}, I_{acc} and I_{dec} at the start-up period is expanded in Figs. 4 (b)-(d). V_{acc} gradually increases during Phase I, and rapidly increases into Phase II. At the transition to Phase II, I_{acc} drops to the nominal current, and I_{dec} also decreases since the increment of V_{acc} might contribute to the reduction of beam divergence. If ΔV is chosen so that V_1 becomes the nominal voltage, V_{acc} will be kept nearly constant afterwards. This condition is attained by selecting the R value such that ΔV equals $R\,\Delta I$. Here, R indicates the parallel resistance to the inductance.

In the latter modification, it may also be possible to switch IGBT on or off by inputting an external arbitrary timing on/off signal. Then, a square wave of 2 ms width and 4 ms interval between pulses is generated using a function generator. As shown in Fig. 5 (a), the waveform of V_{acc} (~22 kV) is completely controlled, and is the same as

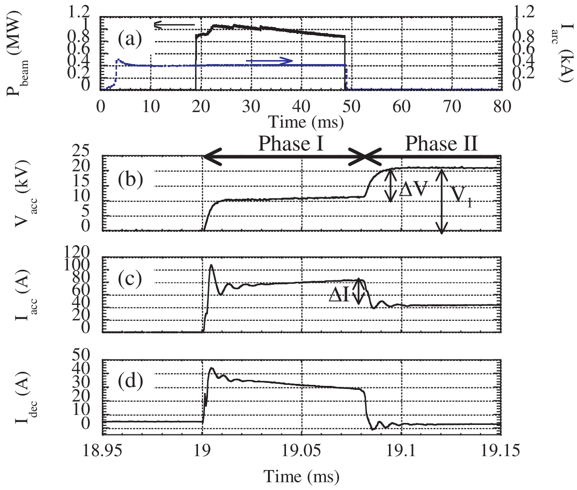

Fig. 4 Time evolutions of helium ion beams: (a) P_{beam} and I_{arc}, (b) V_{acc}, (c) I_{acc}, and (d) I_{dec}.

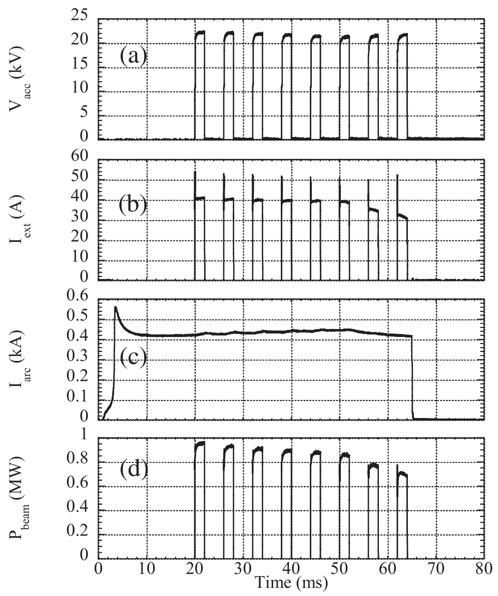

Fig. 5 Time evolutions of short-pulse helium ion beam: (a) V_{acc}, (b) I_{ext}, (c) I_{arc}, and (d) P_{beam}.

the waveform generated by the function generator. Figures 5 (b), 5 (c) and 5 (d) show time evolutions of the extracted He^+ beam current (~40 A), arc current and beam power, respectively. We successfully extracted controlled repetitive short-pulse beams. Here, I_{arc} decreases after t =~50 ms, this causes the reduction of I_{ext} and P_{beam}.

3. Pulsed Ion Beam Irradiation Experiments

High-purity (~99.95 %) powder metallurgy (PM) tungsten specimens of $10 \times 5 \times 1$ mm^3 are mounted on the copper stage around 1530 mm from the electrode, as shown in Fig. 1, where the diameter of the beam is estimated to be ~60 mm [11]. Four specimens are set on the stage. Figure 6 shows one of four specimens, and the irradiation area

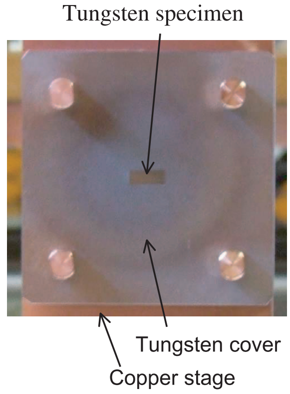

Fig. 6 One of four specimens mounted on a copper stage set around 1530 mm from the electrode. PM tungsten specimen of $10 \times 5 \times 1$ mm^3 is fixed between the copper stage and tungsten cover. Irradiation area on specimen is limited to 8×3 mm^2. Surface color of the tungsten cover became gray after irradiation.

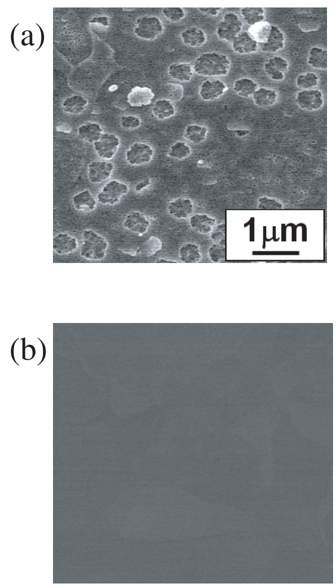

Fig. 7 Tungsten surface images obtained by SEM after beam irradiation: (a) long pulse irradiation [11] and (b) repetitive short-pulse beam irradiation (it is difficult to identify the change due to the limitation of contrast).

on the specimen is limited to about 8×3 mm^2 by the tungsten cover. In the case of a He^+ beam of ~22 keV, ~40 A and ~0.88 MW, power density and flux are calculated to be ~300 MW/m^2 and 8.8×10^{22} particles/m^{2}s, respectively. It is noted that almost 25 % of the He^+ beam is changed to a neutral helium beam by the gases from the ion source [13]. It is also considered, from past experimental results [5], that the beam power at the target might become less than 90 % of the extracted beam, namely, ~0.88×0.9 MW. Two kinds of beam pulses were irradiated to the tungsten. One (case I) is a ~30-ms-long-pulse beam in one shot, as shown in Fig. 4 (a), and 6 repetitions of irradiation with 6 min intervals, for total irradiation time and fluence of 171 ms and

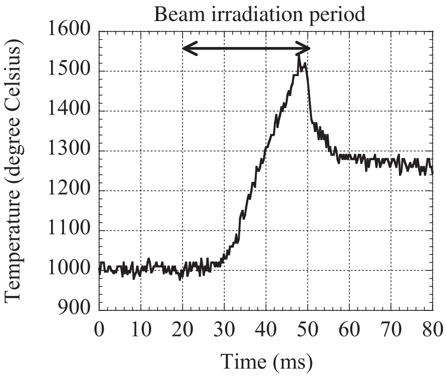

Fig. 8 Time evolution of tungsten surface temperature measured with fast optical pyrometer with a sensitivity of more than 1,000 degree Celsius.

1.5×10^{22} particles/m^2, respectively. The other (case II) is 8 short pulses of 2 ms width and 4 ms intervals in one shot, as shown in Fig. 5 (d), with the total irradiation time and fluence being adjusted to be the same as those in case I.

Figure 7 (a) shows the tungsten surface image obtained by scanning electron microscopy (SEM) after the beam irradiation of case I [11]. Large blisters with the diameter of ~500 nm were densely observed. For in case II, it was observed that the surface morphology after repetitive short-pulse beam irradiation did not show marked deformation, as shown in Fig. 7 (b). In the case of repetitive short-pulse irradiation, it was thought that the damage would be worse than with long-pulse irradiation, owing to repetitive thermal stress. However, it was found that this repetitive short-pulse beam irradiation caused less surface damage. In the present experimental series, helium gas has been used, then it is considered that the affects of other ions are very small [13]. In the case of short-pulse beam irradiation, the surface temperature of tungsten was less than 1,000 degree Celsius, while in the case of long-pulse irradiation, it became ~1,500 degree Celsius, as shown in Fig. 8. Reduction of the surface damage might be related to the low temperature state of the material surface during beam irradiation. Here, surface temperature was measured using a fast optical pyrometer with a sensitivity of over 1,000 degree Celsius.

4. Summary

A high-power-density ion beam system with high-repetition short pulses was successfully developed to simulate the ELM behavior. This was achieved by the modification of both part of the acceleration power supply and the beam operation method. A pulsed He^+ beam of ~22 keV and ~40 A was extracted with the beam width of 2 ms and 4 ms intervals between pulses. This high-repetition pulsed He^+ beam with high current density was irradiated to the tungsten material to study the effect of the pulsed heat load of ion particles. It was found that this repetitive short-pulse beam irradiation caused less surface damage and lower temperature compared with the long-pulse irradiation, even when the total amount of irradiation fluence was the same for each condition. This might be related to the reduction of the material surface temperature during irradiation as it has been reported that surface temperature is one of the important factors behind the nanostructure of tungsten material [14]. Therefore, a short-pulse irradiation experiment of the tungsten material while controlling the material temperature should be conducted in the future. The results would provide important data for the design of ITER diverter plates.

Acknowledgements

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