Back-Surface Temperature Measurements of Thin Tungsten Materials during Plasma-Gun Generated Pulsed Plasma Irradiation using a Fast Two-Color Pyrometer

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A fast two-color pyrometer system was developed to measure the back-surface temperature of thin tungsten materials during plasma-gun generated edge localized mode-like pulsed plasma irradiation. The developed pyrometer system had a time resolution of ~ 5 µs and the lowest measureable temperature was ~ 1600 K. We observed that the back-surface temperature of the thin tungsten material during the pulsed plasma irradiation reached ~ 3280 K. The absorbed energy density and the pulse width of the pulsed heat load estimated by the measured time evolution of the back-surface temperature and 3D heat analyses using ANSYS code were ~ 0.52 MJ m^{-2} and ~ 1.6 ms, respectively.

Keywords: ELM-like pulsed plasma, plasma gun, two-color pyrometer, tungsten, divertor

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Transient heat loads, such as type-I edge localized modes (ELMs), and disruptions are critical problems for lifetime of plasma-facing components in future tokamak devices. In the ITER divertor, the energy density and pulse length of type-I ELMs are predicted to be 0.2 - 2 MJ m^{-2} and 0.1 - 1 ms, respectively [1]. Simulation experiments of pulsed heat loads using electron beams, lasers, and plasma guns have been conducted to investigate allowable heat load limits of type-I ELMs in ITER [2]. Furthermore, we have investigated the surface damage of tungsten (W) materials due to ELM-like pulsed plasma heat loads using a magnetized coaxial plasma gun (MCPG) device at the University of Hyogo [3]. The material damage caused by pulsed plasma exposure has been characterized in terms of the energy density absorbed on the material surface, which was measured with a calorimeter. In contrast, a surface temperature measurement during the pulse heat load is also required to clarify dynamic behaviors of plasma–material interactions. In this study, a two-color pyrometer with a fast response time was newly developed to measure a material surface temperature during the pulsed plasma irradiation.

A schematic of the two-color pyrometer developed in this study is shown in Fig. 1. The pyrometer detected thermal emission at 750 and 800 nm wavelengths from the material surface heated by the pulsed plasma load using interference filters with bandwidths of 11 and 12 nm. Si photodiode amplifiers (Tholabs, DET36A/M) were used as the detectors, and output currents of the photodiodes were translated to voltage signals using load resistances (51 kΩ). The temporal resolution of the pyrometer system was ~ 5 µs, which was sufficient for the temperature measurements in the MCPG experiment.

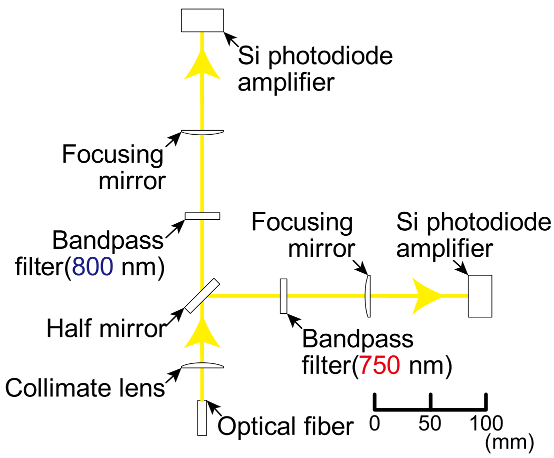

Fig. 1 Schmatic of the two-color pyrometer.

For the pyrometer system, the absolute temperature T was analyzed as shown in Ref. [4]. The emission intensities $I_{1,2}$ at two wavelengths $\lambda_{1,2}$ can be described according to Planck's law

$$I_{1,2}(\lambda_{1,2}, T) = A\Omega K_{1,2}\varepsilon_{1,2}(\lambda_{1,2}, T)\frac{2\pi hc^2}{\lambda_{1,2}^5}\cdot\frac{1}{e^{hc/\lambda_{1,2}kT}}, \tag{1}$$

where A, Ω, K, ε, h, c, k are the surface area, solid angle, constant loss term of the pyrometer at the chosen wave-

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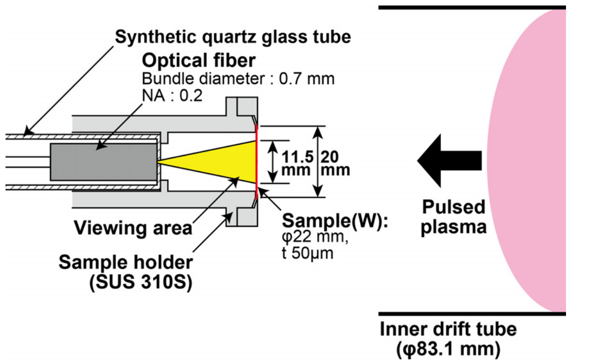

Fig. 2 Schematic of the sample holder for pyrometer measurements. A thin tungsten (W) sample was mounted, and an optical fiber was installed behind the sample to collect the thermal radiation.

length, emissivity at the wavelength, Planck constant, the speed of light, and Boltzmann constant, respectively. Assuming $\varepsilon_1 = \varepsilon_2$ at two wavelengths (750 and 800 nm), T can be derived by the following equation:

$$T = \frac{hc}{k}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) / \ln\left[\left(\frac{V_1}{V_2}C_{\mathrm{v}}\right)\left(\frac{\lambda_1}{\lambda_2}\right)^5\right], \qquad (2)$$

where V_1, V_2, and C_{v} are the measured photodiode voltage signals and a calibration factor. The value of C_{v} $(= (V_2/V_1)(K_2 I_1/K_1 I_2))$ was experimentally obtained by calibrating the pyrometer system with a standard spectral calibration lamp. The deviation between the true and measured temperatures due to the assumption of $\varepsilon_1 = \varepsilon_2$ has been analyzed using surface emissivity data [5]. In this study, the error of the measured temperature was estimated to be ~ 2% of the true temperature (2000 K), where ε_1 and ε_2 at 750 nm and 800 nm are 0.4218 and 0.4166 [6].

A target material was mounted on the sample holder, which was located at the center of the target chamber (Fig. 2). The thermal emission from the target material surface during the pulsed plasma irradiation was disturbed by emission from the plasma and impurities. Thus, thin W discs (22 mm diameter, 50 μm thick) were used as target materials to measure back-surface temperature T_{bs}. The surface temperature was almost the same as T_{bs} because the 50 μm thickness was much shorter than the heat penetration depth (~ 670 μm) in the present condition. The thermal radiation from the back-surface of the W disc was collected by an optical fiber (numerical aperture: 0.2) embedded inside the sample holder and transmitted into the pyrometer housing. The diameter of the viewing area of the pyrometer was ~ 11.5 mm.

In the present study, two capacitor banks (fast: 3.5 kV/2.88 mF, slow: 0.7 kV/280 mF) were used to produce the pulsed plasma. Helium was used as the discharge gas. Figures 3 (a) and (b) show time evolutions of the gun discharge current I_{gun} and singly ionized helium ion emission (He II, 468.58 nm) I_{HeII}. The pulsed plasma was initiated by the fast capacitor bank, and then the slow capacitor bank was turned on to sustain the discharge. The plasma diameter determined by an MCPG inner drift tube was 83.1 mm.

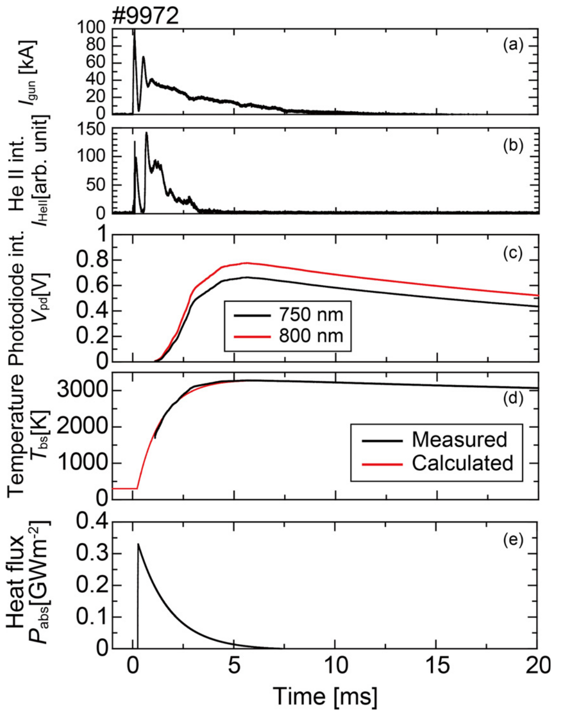

Fig. 3 Time evolutions of (a) I_{gun}, (b) I_{HeII}, (c) V_{pd} (black: 750 nm, red: 800 nm), (d) T_{bs} (black: measured, red: calculated), and (e) P_{abs}.

Figures 3 (c) and (d) show time evolutions of the photodiode output signals V_{pd} and T_{bs}. Here, T_{bs} is plotted only for $T_{\mathrm{bs}} > 1600$ K because of the lower temperature limit caused by the background noise level. T_{bs} reached ~ 3280 K at $t \sim 5.5$ ms.

The absorbed power density P_{abs} on the W disc was estimated by the measured time evolution of T_{bs} and 3D heat analyses using the ANSYS code. A spatially uniform heat flux in a circular area was used in the simulation. Furthermore, radial heat transport and the temperature dependence of the thermomechanical properties of W were included. In the simulation, the time evolution of P_{abs} was adjusted so that the calculated T_{bs} agreed with the measured T_{bs}. As shown in Fig. 3 (e), P_{abs} had a steep rise time and a peak value of ~ 0.33 GW m^{-2}. The pulse duration of P_{abs} defined by the time constant of exponential decay was ~ 1.6 ms. The absorbed energy density given by time integration of P_{abs} was ~ 0.52 MJ m^{-2}. Consequently, measurements of T_{bs} of thin W materials during ELM-like pulsed plasma irradiation were successfully conducted using the developed two-color pyrometer.

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[1] G. Federici *et al.*, Plasma Phys. Control. Fusion **45**, 1523 (2003).
[2] V. Phillips *et al.*, J. Nucl. Mater. **415**, S2 (2011).
[3] Y. Kikuchi *et al.*, J. Nucl. Mater. **463**, 206 (2015).
[4] J. Hanna *et al.*, Rev. Sci. Instrum. **77**, 123503 (2006).
[5] B. Müller *et al.*, Rev. Sci. Instrum. **72**, 3366 (2001).
[6] R.D. Larrabee, Technical Report 328 (Research Laboratory of Electronics, Massachusetts Institute of Technology, 1957).