Review of Scientific Instruments

Sensitivity improvement of infrared imaging video bolometer for divertor plasma measurement

Cite as: Rev. Sci. Instrum. **92**, 063521 (2021); https://doi.org/10.1063/5.0043664
Submitted: 10 January 2021 • Accepted: 04 June 2021 • Published Online: 18 June 2021

K. Mukai, B. J. Peterson, N. Ezumi, et al.

Sensitivity improvement of infrared imaging video bolometer for divertor plasma measurement

Cite as: Rev. Sci. Instrum. 92, 063521 (2021); doi: 10.1063/5.0043664
Submitted: 10 January 2021 • Accepted: 4 June 2021 •
Published Online: 18 June 2021

View Online Export Citation CrossMark

K. Mukai,[1,2,a)] B. J. Peterson,[1,2] N. Ezumi,[3] N. Shigematsu,[3] S. Ohshima,[4] A. Miyashita,[5] and R. Matoike[5]

AFFILIATIONS

[1] National Institute for Fusion Science, National Institutes of Natural Science, Toki, Gifu 509-5292, Japan
[2] SOKENDAI (The Graduate University for Advanced Studies), Toki, Gifu 509-5292, Japan
[3] Plasma Research Center, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan
[4] Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan
[5] Graduated School of Energy Science, Kyoto University, Uji, Kyoto 611-0011, Japan

Note: Paper published as part of the Special Topic on Proceedings of the 23rd Topical Conference on High-Temperature Plasma Diagnostics.
[a)] **Author to whom correspondence should be addressed:** mukai.kiyofumi@nifs.ac.jp

ABSTRACT

The sensitivity of an infrared imaging video bolometer (IRVB) was improved for the measurement of relatively low energy plasma radiation from the viewpoint of the metal foil absorber material. The photon energy of the radiation was considered up to 1 keV for the divertor plasma measurement. The thickness of the foil absorber was evaluated not only for conventional heavy elements, e.g., platinum, but also for light elements by the relation between the photon energy and attenuation length and by mechanical strength. A heat-transfer calculation using ANSYS suggested that light elements with practical foil thickness provide a higher temperature rise of the foil absorber compared with heavier elements with practical foil thickness. The maximum of the temperature rise was evaluated using He–Ne laser irradiation onto absorber samples. The material dependence of the temperature rise has a similar tendency between calculations and experiments. Experimentally, the sensitivity of the IRVB improved from 280 to 110 μW/cm^2 using titanium with 1 μm thickness compared with conventional platinum with 2.5 μm thickness. Consequently, the signal-to-noise ratio of the IRVB could be improved from 2.8 to 9.1.

I. INTRODUCTION

In fusion reactors, radiative cooling using impurity seeding is a common scenario to reduce the divertor heat load. In ITER, 50%–60% of the heating power should be dispersed as plasma radiation. The requirement of the fraction increases to 80% in JA-DEMO.[1] Linear devices, e.g., GAMMA10/PDX,[2,3] have important roles to investigate the mechanism of detachment, e.g., energy balance, and to improve simulation codes. For the study, not only the spectroscopic measurement but also the plasma radiation measurement is essential. Resistive bolometers are commonly used for the plasma radiation measurement mainly in large devices.[4] However, it is too costly, especially for the radiation profile measurement with a number of channels. On the other hand, InfraRed imaging Video Bolometers (IRVBs) can realize a multi-dimensional measurement using only a foil absorber and an infrared (IR) camera.[5–9] Preliminary results of an IRVB on GAMMA10/PDX suggested that the sensitivity of the IRVB should be improved to realize the sensitivity comparable to that of the measurement on the Large Helical Device (LHD). For the foil absorber, platinum is conventionally used to detect plasma radiation with high energy from the core plasmas.[10] However, the material of the absorber has not been investigated for the plasma radiation with low energy only from divertor plasmas. Therefore, in this paper, the sensitivity of the IRVB was improved by focusing on the divertor plasma measurement. In GAMMA10/PDX, the targeted ion temperature is 20–500 eV and the targeted electron temperature is 100 eV in the E-divertor region.[2,3] The ion temperature in the central cell is up to 10 keV.[3] By considering that the IRVB has been installed in the upstream region of the E-divertor region, plasma radiation with the photon energy up to 1 keV is considered. The schematic and the sensitivity of the IRVB are shown in Sec. II. The foil absorber thickness appropriate for the low energy radiation is investigated in various materials in Sec. III. The temperature rise of the foil absorber is evaluated by using a heat-transfer calculation and using He–Ne laser irradiation experiments onto absorber samples in Sec. IV.

II. INFRARED IMAGING VIDEO BOLOMETER

A. Schematic of IRVB

The IRVB consists of a pinhole camera and an IR camera. Plasma radiation through an aperture is projected onto a foil absorber inside a vacuum vessel. The two-dimensional temperature distribution due to plasma radiation is observed using an IR camera. A foil absorber has three layers as shown in Fig. 1. Both sides of a thin metal foil are blackened by carbon. Radiations in the range of far infrared, visible, and ultraviolet are absorbed in the carbon layer on the plasma side. Radiations in the range of soft x rays are absorbed in the metal layer. The carbon layer on the IR camera side can increase emissivity to improve sensitivity.

B. Sensitivity of IRVB

The following equation indicates the sensitivity of the IRVB measurement as the Noise Equivalent Power Difference (NEPD):

$$\sigma_{IRVB} = \frac{\sqrt{10}kt_f\sigma_{IR}}{\sqrt{f_{IR}N_{IR}}}\sqrt{\frac{N_{bol}^3 f_{bol}}{A_f^2}+\frac{N_{bol}f_{bol}^3}{5\kappa^2}}. \quad (1)$$

Here, k, κ, and t_f are the thermal conductivity, the thermal diffusivity, and the thickness of the foil absorber, respectively. A_f is the utilized area of the absorber. σ_{IR} and f_{IR} are the noise equivalent temperature difference and frame rate of an IR camera, respectively. N_{IR} is the number of available pixels of the IR camera that observes the absorber. f_{bol} is the frame rate of the IRVB. N_{bol} is the number of bolometer pixels, i.e., the number of detectors into which the foil absorber is divided.

An IRVB has been installed on GAMMA10/PDX. The IR camera is FLIR/Tau 2 336 (336 pixel × 256 pixel, noise equivalent temperature difference <50 mK, and frame rate = 60 Hz). The foil absorber coated by graphite on both sides consists of Pt with 2.5 μm thickness, which is the same as the absorber in the LHD. As a result of the preliminary measurement in GAMMA10/PDX, the temperature rise on the foil absorber was up to 1/5 of LHD. In the LHD,[11] σ_{IRVB} is 1200 μW/cm^2 without time averaging and the signal-to-noise ratio, SNR_{bolo} in Table II of Ref. 12, is 3.4. In GAMMA10/PDX, while σ_{IRVB} in the preliminary setting is 280 μW/cm^2, the SNR_{bolo} remains 2.8 using 1/5 P_{IRdet}[12] of the LHD. Therefore, further σ_{IRVB} improvement is required in GAMMA10/PDX to realize the comparable SNR_{bolo} to that in the LHD for the measurement even in

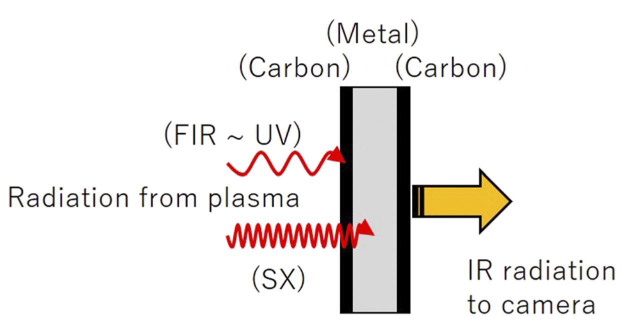

FIG. 1. Schematic of a foil absorber of the IRVB.

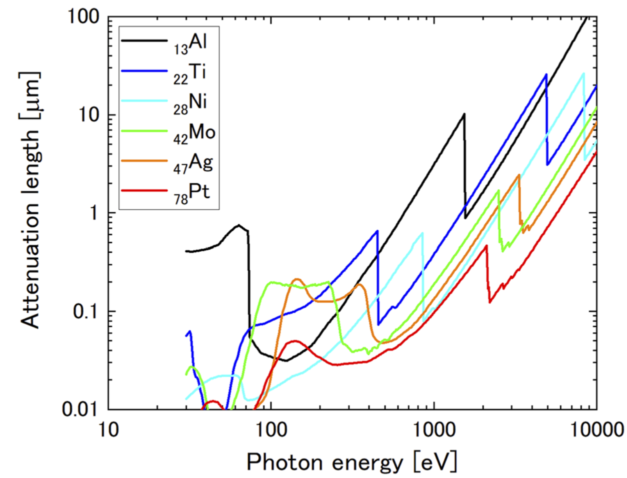

FIG. 2. Relation between the photon energy and the attenuation length in various materials.

TABLE I. Material dependence of the absorber thickness to detect the radiation with photon energies up to 1 keV, t_f^{1keV}, and "practical" minimum thickness, t_f^{min}, considering the mechanical strength.

Material	t_f^{1keV} (μm)	t_f^{min} (μm)
$_{13}$Al	3.0	3
$_{22}$Ti	0.7	1
$_{23}$V	0.6	1
$_{24}$Cr	0.5	1
$_{25}$Mn	0.6	1
$_{26}$Fe	0.6	1
$_{27}$Co	0.6	1
$_{28}$Ni	0.7	1
$_{29}$Cu	0.8	1
$_{30}$Zn	0.9	1
$_{40}$Zr	0.4	1
$_{41}$Nb	0.3	1
$_{42}$Mo	0.2	1
$_{45}$Rh	0.2	6
$_{46}$Pd	0.2	0.5
$_{47}$Ag	0.2	1
$_{48}$Cd	0.3	1
$_{49}$In	0.4	2
$_{50}$Sn	0.4	3
$_{72}$Hf	0.3	4
$_{73}$Ta	0.16	5
$_{74}$W	0.13	5
$_{75}$Re	0.2	12.5
$_{77}$Ir	0.1	10
$_{78}$Pt	0.1	2.5
$_{79}$Au	0.1	2

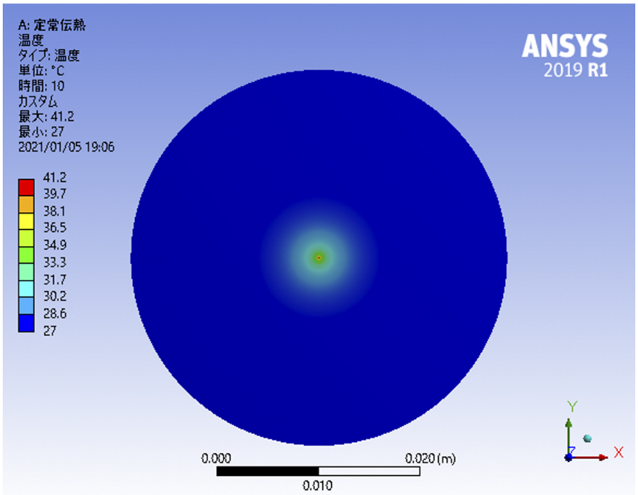

FIG. 3. Two-dimensional temperature profile simulated by the heat-transfer calculation, ANSYS.

lower radiation plasmas using various impurity gases for the plasma detachment.

Sensitivity improvement of an IRVB is equivalent to a decrease of σ_{IRVB}. From the viewpoint of the foil absorber, the product of k and t_f should be decreased. σ_{IRVB} can also decrease with the increase of κ. However, κ is proportional to k ($\kappa = k/(\rho c_p)$). Therefore, the decrease in κ is basically incompatible with the decrease of kt_f. Here, ρ and c_p are the density and specific heat capacity, respectively. Basically, reduction of kt_f by changing the material of the metal layer of the absorber is the most effective way to reduce σ_{IRVB}.

σ_{IRVB} can also be decreased from the viewpoint of the IR camera and its field of view.[12–14] However, in this paper, sensitivity improvement was considered by focusing on the foil absorber material.

III. MATERIAL DEPENDENCE OF FOIL ABSORBER THICKNESS

If a thinner foil is used, a higher sensitivity can be obtained as mentioned above. On the other hand, in order to absorb the photon with a certain energy, the foil absorber needs a thickness, which is determined by the attenuation length of photons in the material. The material dependence of the foil absorber thickness was investigated for the measurement including high-energy radiation from core plasmas.[10] According to the comparison among Ta, W, Pt, and Au, Pt with 2.5 μm thickness was optimal. The relation between the photon energy and the attenuation length in various materials[15] is shown in Fig. 2. Drastic changes of the attenuation length are due to the absorption end. The absorber thickness for the measurement with lower photon energy up to 1 keV was estimated as $t_f^{1\text{keV}}$ by the relation. The material dependence of $t_f^{1\text{keV}}$ is shown in Table I. In the case of Pt, 0.1 μm is sufficient for the absorber thickness. However, such a thin foil is easy to tear. Therefore, by considering the mechanical strength, a "practical" minimum thickness was evaluated as t_f^{min}. The criterion was that foil with the size of 50 × 50 mm^2 or larger is commercially available without support like an acrylic plate. The material dependence of t_f^{min} is also shown in Table I. $t_f^{1\text{keV}}$ decreases with the increase in the atomic number. On the other hand, due to the mechanical strength, t_f^{min} tends to increase with the increase in the atomic number.

IV. MATERIAL DEPENDENCE OF TEMPERATURE RISE ON FOIL ABSORBER

A. Temperature rise evaluation using heat-transfer calculation

A steady-state heat-transfer calculation was performed to investigate the material dependence of the temperature rise. The maximum temperature rise, ΔT_{max}, due to a certain heat flux was evaluated using ANSYS. The calculation model was a simple cylinder with a diameter of 37 mm. The cylinder consisted of three layers: carbon, metal, and carbon. The thickness of the metal layer was t_f^{min}, as shown in Table I. The thickness of the carbon layers was assumed

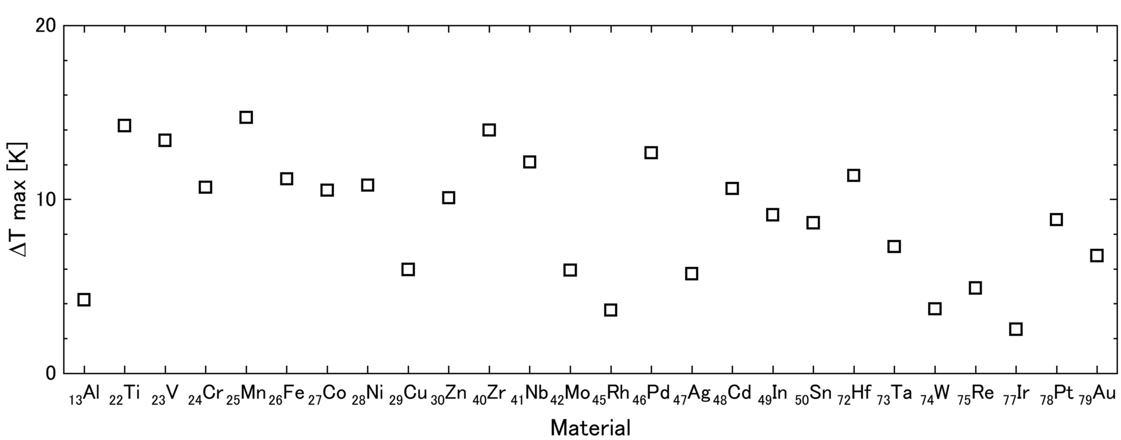

FIG. 4. Material dependence of ΔT_{max} evaluated using the heat-transfer calculation. The thickness of the metal layer was t_f^{min}, as shown in Table I.

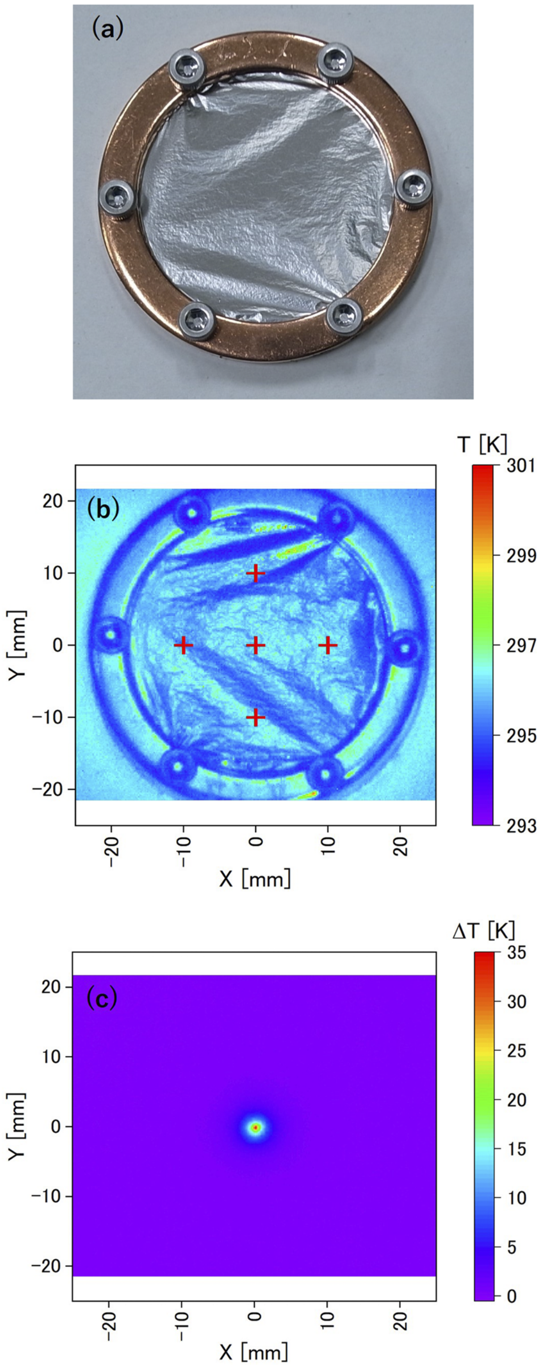

FIG. 5. (a) Sample of the foil absorber before carbon coating. (b) IR image of the sample without laser irradiation. "+" indicates the irradiation points. (c) Temperature rise, ΔT, profile due to the laser irradiation.

to be 5 μm, which was evaluated in a previous study.[16] The boundary temperature on the edge of the cylinder was fixed at 300 K. Gaussian heat flux was applied at the center on the carbon layer of the plasma side. The heat flux simulated He–Ne laser irradiation as described below. Blackbody radiation from the surface of the carbon layers was applied with the assumption that the emissivity is 1. The environmental temperature for blackbody radiation was also fixed at 300 K.

A temperature profile simulated by the heat-transfer calculation is shown in Fig. 3. The material dependence of ΔT_{max} is shown in Fig. 4. ΔT_{max} tends to increase above that of conventional Pt with the decrease in the atomic number, while Al had lower ΔT_{max} due to its higher t_f^{min}. Mn had the highest ΔT_{max}. However, since Mn is a magnetic substance, Mn is not appropriate to use for the measurement on magnetically confined plasma devices. Therefore, Ti is considered the best material, which had the second highest ΔT_{max}.

B. Temperature rise evaluation using He–Ne laser irradiation experiment

ΔT_{max} in the steady state was also evaluated experimentally using He–Ne laser irradiation. Figure 5(a) shows a foil absorber sample before carbon coating. A metal foil was held by two oxygen-free copper ring frames with inner diameters of 37 mm. Al, Ti, Ni, Mo, Ag, and Pt were used for the samples with the thickness of t_f^{min}, as shown in Table I. Both sides of the foil are coated by graphite spray (Henkel AG & Co. KGaA/BONDERITE S-AD AERODAG G AN). A He–Ne laser with the wavelength of 632.8 nm is irradiated onto the foil sample in vacuum. The $1/e^2$ width was 0.2 mm and the power was 5.8 mW. The temperature profile is observed from the backside using an IR camera (FLIR/A655sc). ΔT_{max} was evaluated as the average of the irradiations to five points (center and the 10 mm away in four directions), as shown in Fig. 5(b). The ΔT profile due to the laser irradiation is shown in Fig. 5(c). The influence of the foil wrinkles could be subtracted as a background.

Figure 6 shows the material dependence of ΔT_{max} as a comparison between the laser irradiation experiment and the heat-transfer calculation. ΔT_{max} of Ti with 1 μm thickness doubled that of Pt with 2.5 μm thickness. The tendency of the material

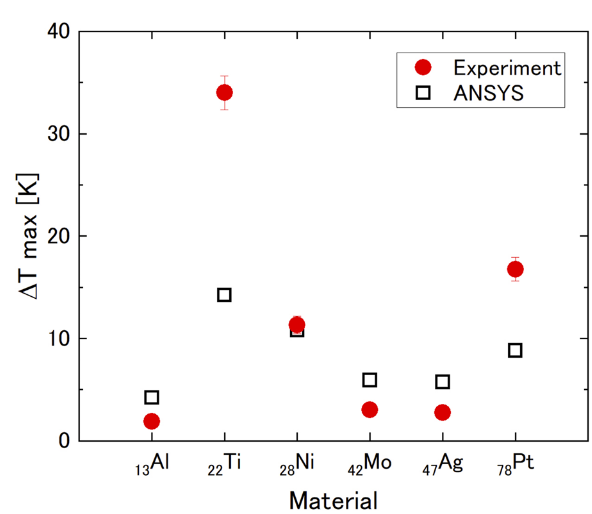

FIG. 6. Material dependence of ΔT_{max} as a comparison between the laser irradiation experiment and the heat-transfer calculation from ANSYS. The thickness of the metal layer was t_f^{min}, as shown in Table I.

dependence of ΔT_{max} is similar between the experiment and the calculation. One of the reasons for the difference between the experiment and the calculation can be considered as the error in the thickness of the metal and carbon layers. Cross-sectional observation using a scanning electron microscope and/or a transmission electron microscope is required for detailed analysis. A possible reason for the difference of experimental values of k from its literature values is the plastic deformation in the foil caused by the rolling method used in the manufacturing process.

σ_{IRVB} estimated using typical thermal characteristics of Ti and using current IR camera settings in GAMMA10/PDX is 90 μW/cm^2. Consequently, SNR_{bolo} is improved from 2.8 to 9.1. Here, it should be noted that σ_{IRVB} and SNR_{bolo} do not change significantly when k is halved. Since k is proportional to κ and the term related to κ is dominant in the root term of Eq. (1), the halved k is countered by $\sqrt{1/\kappa^2}$.

V. SUMMARY

The sensitivity of the IRVB was improved for the measurement of relatively low energy plasma radiation from the viewpoint of a metal foil absorber material. The photon energy of the radiation was considered up to 1 keV for the divertor plasma measurement. The thickness of a foil absorber was evaluated not only for conventional heavy elements, e.g., Pt, but also for light elements by the relation between the photon energy and attenuation length and by mechanical strength. A heat-transfer calculation using ANSYS suggested that light elements with practical foil thickness provide a higher temperature rise compared with heavy elements with practical foil thickness. The maximum of the temperature rise was evaluated using He–Ne laser irradiation onto absorber samples. The material dependence of the temperature rise has a similar tendency between the calculations and the experiments. The sensitivity of the IRVB could improve from 280 to 90 μW/cm^2 using Ti with 1 μm thickness instead of conventional Pt with 2.5 μm thickness. Consequently, SNR_{bolo} could be improved from 2.8 to 9.1.

In this paper, a graphite spray was used for the blackening of the foil absorber. However, the heat-transfer calculation suggested that a thinner carbon coating can improve the sensitivity further. A vapor deposition technique is a candidate for further sensitivity improvement. The improved foil absorber will be applied to plasma radiation measurements not only on GAMMA10/PDX but also on a medium-sized helical-axis heliotron device, Heliotron J. The foil absorber with high sensitivity is also available for divertor plasma measurements in large devices. IRVBs can increase the channels by finely dividing the foil absorber in analysis. Therefore, the higher-sensitivity foil absorber can provide higher spatial resolution measurement with the same signal-to-noise ratio.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Nos. JP17K14900 and JP19K14689; by NIFS/NINS Grant Nos. NIFS18ULHH038, NIFS14KUGM086, and IFS19KUHL089; and by the grant of Future Energy Research Association.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] N. Asakura, K. Hoshino, H. Utoh, Y. Someya, S. Suzuki, C. Bachmann, H. Reimerdes, R. Wenninger, H. Kudo, S. Tokunaga *et al.*, Fusion Eng. Des. **136**, 1214 (2018).

[2] M. Sakamoto, K. Oki, Y. Nakashima, Y. Akabane, Y. Nagatsuka, M. Yoshikawa, R. Nohara, K. Hosoi, H. Takeda, K. Ichimura *et al.*, Trans. Fusion Sci. Technol. **63**, 188 (2013).

[3] Y. Nakashima, K. Ichimura, M. S. Islam, M. Sakamoto, N. Ezumi, M. Hirata, M. Ichimura, R. Ikezoe, T. Imai, T. Kariya *et al.*, Nucl. Fusion **57**, 116033 (2017).

[4] K. F. Mast, J. C. Vallet, C. Andelfinger, P. Betzler, H. Kraus, and G. Schramm, Rev. Sci. Instrum. **62**, 744 (1991).

[5] B. J. Peterson, Rev. Sci. Instrum. **71**, 3696 (2000).

[6] B. J. Peterson, H. Parchamy, N. Ashikawa, H. Kawashima, S. Konoshima, A. Y. Kostryukov, I. V. Miroshnikov, D. C. Seo, and T. Omori, Rev. Sci. Instrum. **79**, 10E301 (2008).

[7] K. Mukai, S. Masuzaki, B. J. Peterson, T. Akiyama, M. Kobayashi, C. Suzuki, H. Tanaka, S. N. Pandya, R. Sano, G. Motojima *et al.*, Nucl. Fusion **55**, 083016 (2017).

[8] K. Mukai, B. J. Peterson, S. Takayama, and R. Sano, Rev. Sci. Instrum. **87**, 11E124 (2016).

[9] K. Mukai, R. Abe, B. J. Peterson, and S. Takayama, Rev. Sci. Instrum. **89**, 10E114 (2018).

[10] R. Sano, B. J. Peterson, E. A. Drapiko, Y. Watanabe, Y. Yamauchi, and T. Hino, Plasma Fusion Res. **6**, 2406076 (2011).

[11] K. Mukai, T. Nishitani, K. Ogawa, and B. J. Peterson, IEEE Trans. Plasma Sci. **47**(1), 18 (2019).

[12] S. N. Pandya, B. J. Peterson, K. Mukai, R. Sano, A. Enokuchi, and N. Takeyama, Rev. Sci. Instrum. **85**, 073107 (2014).

[13] B. J. Peterson, S. Konoshima, A. Y. Kostryukov, D. C. Seo, Y. Liu, I. V. Miroshnikov, N. Ashikawa, H. Parchamy, H. Kawashima, N. Iwama *et al.*, Plasma Fusion Res. **2**, S1018 (2007).

[14] K. Mukai, B. J. Peterson, S. N. Pandya, R. Sano, and M. Itomi, Plasma Fusion Res. **9**, 3402037 (2014).

[15] The Center for X-Ray Optics, Lawrence Berkeley National Laboratory, X-Ray Attenuation Length, http://henke.lbl.gov/optical_constants/atten2.html.

[16] S. N. Pandya, B. J. Peterson, R. Sano, K. Mukai, E. A. Drapiko, A. G. Alekseyev, T. Akiyama, M. Itomi, and T. Watanabe, Rev. Sci. Instrum. **85**, 054902 (2014).