Changes of optical properties of retroreflector installed in LHD

journal or publication title	Review of Scientific Instruments
volume	Vol.78
page range	103501-1 - 103501-7
year	2007-10-01
URL	http://hdl.handle.net/10655/3924

doi: 10.1063/1.2786938

Changes of optical properties of retroreflector installed in LHD

T. Akiyama,^{a)} K. Kawahata, N. Ashikawa, and M. Tokitani

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-shi, Gifu 509-5292, Japan

S. Okajima and K. Nakayama

Chubu University, Matsumoto-cho, Kasugai-shi, Aichi 487-8501, Japan

N. Yoshida, A. Ebihara, K. Tokunaga, and Y. Ohtawa

Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan

S. Tsuji-lio

Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

(Received 24 May 2007; accepted 30 August 2007; published online 3 October 2007)

This article describes changes of optical properties of retroreflectors installed on the inner wall of the vacuum vessel of the Large Helical Device. They were made of stainless steel and were used for a CO₂ laser polarimeter. The reflectivity for a CO₂ laser beam dropped up to 40% after the start of glow discharge cleanings and main plasma experiments. Then it decreased gradually. The reflectivity in a wavelength range shorter than 10 μm decreased significantly through one experimental campaign (about 4 months). On the other hand the reflectivity in a wavelength range longer than 50 μm was larger than 70%. Decrease in the reflectivity in the central region of mirrors was more significant (the reflectivity for visible beams became almost zero) than that in the edge. The distribution of the reflectivity along the radial direction is expected to be related to the shape of the retroreflector. The parallelism of the reflected beam to an incident one also deteriorated. The changes in the polarization angle and in the ellipticity of reflected light polarization were not observed from the visible to the far infrared range. © 2007 American Institute of Physics. [DOI: 10.1063/1.2786938]

I. INTRODUCTION

Because of limitations of port access, diagnostic mirrors often have to be installed inside a vacuum vessel. These days, degradations of optical properties due to interactions between plasmas and mirror surfaces are becoming a serious problem. For first mirrors in ITER, dependences of the degradations on mirror materials,¹⁻⁵ plasma species,⁶ and so on have been investigated. Since inner mirrors in ITER cannot be replaced frequently, it is indispensable to understand how much the reflectivity deteriorates, the mechanism, and the dependence of the degradation on the wavelength.

Michelson-type interferometers and polarimeters often utilize retroreflectors^{5,7-9} for a double pass of a laser beam in plasmas. It consists of three reflecting surfaces which are mutually orthogonal like a corner of a cube. It is so useful because the reflected beam is parallel to an incident beam regardless of the incident angle. The retroreflector tends to be installed near a plasma⁹⁻¹¹ and the serious degradations of the optical properties are expected. In addition, several lasers with different wavelengths are used in the interferometer and polarimeter systems: from far infrared (for example, CH₃OH laser, 119 μm) to infrared lasers (CO₂ laser, 10.6 μm) for plasma measurement and from near infrared [yttrium aluminum garnet (YAG) laser, 1.06 μm] to visible lasers (He-Ne laser, 0.633 μm) for vibration compensation and beam alignment. Hence changes in optical properties in a wide wave-

length range have to be addressed. In large fusion devices such as ITER, the wavelength range of about 50 μm (Refs. 12-14) is attractive to a poloidal polari-interferometer because of the small beam refractive bending effect (the refractive bending angle is proportional to the squared wavelength) and a moderate phase shift and the Faraday rotation angle. However, as mentioned in Ref. 5, changes of optical properties in 50 μm range have not been analyzed so far, while those at 119 μm and at 10.6 μm have already been done.^{4,5} Since the levels of degradation of the optical properties are considerably different between at 119 μm and at 10.6 μm ,⁴ it is difficult to estimate properties in 50 μm range by interpolation. Hence, such experimental analyses are indispensable to develop the polari-interferometer with the 50 μm range source.

In this article, changes of optical properties of inner vessel retroreflectors installed in the Large Helical Device (LHD) are reported. The analyzed reflectors were originally used for the CO₂ laser polarimeter.⁹ The measurements were done in a wavelength range from the infrared to the visible range. A CH₃OD laser¹² operating at 57.2 μm was also used. This article is devoted to analyses of properties of retroreflector long-term operated in large fusion experimental devices in wide wavelength range and discussion of the relevance between the shape of the reflector and degradation, which have not been reported in detailed so far. In Sec. II, details of the reflectors and the experimental conditions when they were used for the polarimeter are described. The

^{a)}Electronic mail: takiyama@nifs.ac.jp

FIG. 1. (Color online) (a) A photograph of a capsulated retroreflector and (b) reflectors installed on the inner wall of the vacuum vessel of LHD (only ch 1 and ch 2 are shown). (c) Positions of three retroreflectors in LHD.

changes of the optical properties (reflectivity, polarization, and parallelism) and the dependence on the wavelength are reported in Sec. III. Secs. IV and V give discussion and summary.

II. RETROREFLECTOR INSTALLED IN LHD

Figure 1(a) shows a retroreflector used for the CO₂ laser polarimeter on LHD. Three reflecting surfaces are separated into three parts and they are fastened by screws without adhesive because they are installed inside the vacuum vessel. The reason of the separation is to raise machining accuracy. The retroreflectors are made of stainless steel 316 with mirror surfaces coated with gold. The gold film is to increase the reflectivity for a CO₂ laser beam. They are encapsulated in a cylinder made of stainless steel 303 to reduce direct bom-

bardment of plasma particles. The diameter and the effective aperture are 85 and 70 mm, respectively, and its weight is about 1.8 kg. The accuracy of parallelism before the installation was less than 0.36 mrad. This corresponds to a displacement of about 3.6 mm after traveling along the return path of about 10 m. The displacement is much smaller than the diameter of the window and the port.

The support structures of the reflectors were welded to the inner wall of the vacuum vessel without insulation. Figure 1(b) is a photograph of retroreflectors installed in LHD (only two reflectors, ch 1 and ch 2, are shown). Figure 1(c) shows a plan view of the vacuum vessel, a plasma with the magnetic axis at a major radius of 3.75 m, three probe beams, and retroreflectors. The reflectors are located on the equatorial plane. The reflector of ch 1 is the nearest to the plasma surface and the distance is about 30 cm. While that of ch 3 is the most away from the main plasma surface, it is surrounded by the vacuum vessel wall and is the closest reflector to a divertor leg. As the thickness of the divertor leg is about several centimeters and the distance between the leg and the reflector was more than about 20 cm, the flux did not strike the reflector. The CO₂ laser beams were injected above the center axis of the reflector by 20 mm so that the reflected beam can be separated by 40 mm from the incident one.

The retroreflectors were used in the fourth LHD experimental campaign, which lasted for about 4 months. The materials of the first wall and the divertor plate were stainless steel and graphite, respectively. Working gases were mainly hydrogen and helium. Heating powers of electron cyclotron heating (ECH), ion cyclotron range of frequency (ICRF) heating, and neutral beam injection (NBI) were 1, 2.7, and 5.2 MW, respectively, in the campaign. The maxima of the line averaged electron density and the electron temperature were $1.5 \times 10^{20} \text{ m}^{-3}$ and 4.4 keV (not simultaneous achievement). As wall conditioning, titanium gettering, and glow discharge cleaning, whose electrodes are near reflectors [shown in Fig. 1(c)] and at the opposite side of the torus, with hydrogen or helium were performed after plasma experiments almost every day. The total times of the glow discharge with hydrogen and helium were about 128 and 1612 h, respectively. The vacuum vessel during plasma experiments and the glow discharge cleanings were at room temperature. Wall baking at a temperature lower than 100 °C was performed in weekends.

III. CHANGES OF OPTICAL PROPERTIES

A. Reflectivity

Probe beams of the polarimeter were superposition of right- and left-handed circularly polarized beams with slight difference in frequencies for heterodyne detection of the polarization angles.⁹ During the experimental campaign, the power of incident and returned beams had been measured. Figure 2 shows the changes in the ratio. The origin of the horizontal axis corresponds to the day when the power monitor was started. The ratio includes the reflectivity of the retroreflectors and the transmissivity of the ZnSe window, through which beams passed twice. During each glow discharge cleaning, the window was shuttered. Since the win-

FIG. 2. Change in the ratio of returned power of the probe beam to the incident one before and during the fourth experimental campaign (Ref. 9).

dow was not coated for antireflection, the transmissivity changes according to the incident angle of the beam. Differences in the initial reflectivity were expected to arise from slight differences in the incident angles. Glow discharge cleaning before main plasma experiments started from a day of 35 and the reflectivities in all channels decreased by about 10%. Ratios of ch 2 and ch 3 dropped by 40% and 25%, respectively, just after the start of the main plasma experiment, while that of ch 1 kept almost constant. All the ratios decreased gradually during plasma experiments and the decrease of ch 1 was more significant than the others. At the end of the fourth experimental campaign, the spot of the returned He-Ne laser beam of ch 1 became too weak to be recognized by eyes. Due to the reduction in the returned power of the CO₂ laser beam, the beat signals for the heterodyne detection of the polarization angle became noisy. Generally to say, surface condition is determined by competing processes between sputtering and deposition. Since their speeds depend on the particle flux and positions of particle sources during glow discharge cleanings and main plasma experiments, the differences in temporal behaviors of the reflectivity might be related to locations of the reflectors.

A photograph of one of the reflectors after the experimental campaign is shown in Fig. 3(a). The gold film cannot be recognized visually on the surface. The degradation of the reflectivity strongly depends on the position on the mirror surface. Although the edge region still keeps specularly, the middle region is clouded. At the central region it appears to be gray and specularly is almost lost for visible light. White splotches whose dimension is less than about 2 mm are seen especially near the mirror edge. Because the density of the splotches is not high and the size is small, their contribution to the decrease in the reflectivity is small at present. However, increasing the density due to longer exposure may lead to decrease in the reflectivity. Figure 3(b) is an enlarged figure of the splotch with scanning electron microscopy (SEM). The area is scabrous with a crater circled with black broken line. Metals seem to melt locally and splash on the surface. Some reasons for these damages are speculated. One is an arcing since the mirrors were not insulated from the vacuum vessel. The fact that damages do not form scratches, which is explained to be caused by $\mathbf{B} \times \mathbf{J}$ force,¹⁵ may suggest that

FIG. 3. (Color online) (a) A photograph of one of the retroreflectors after the experimental campaign. (b) Enlarged photograph of white splotches with SEM and (c) the distribution of gold around the splotch with EDS (see Sec. IV).

these occur during glow discharge cleanings. The other is attachment of melted flakes or dust of metal since the scabrous area around the crater seems to be larger than arcing damages reported previously.^{16–18} After the attachment, the arcing may be induced due to the scabrous surface and then crater is thought to be formed.

Figure 4(a) illustrates the optical setup to measure the reflectivity of the retroreflector after exposure in LHD. The incident power was measured without the reflector at the same distance from the reflector, where the beam spot size was the same. Figure 5 shows the distribution of the reflectivity of the retroreflector for the CO₂ and YAG laser beams along the radial direction. The $1/e^2$ diameters of CO₂ and YAG laser beams are about 5 and 3 mm, respectively, and they both are horizontally linear polarization. The reasons why the CO₂ and YAG laser were selected are as follows: sensitive to surface condition because of short wavelengths and a good signal to noise ratio due to high power (CO₂: cw of 7.8 W; YAG: cw of 300 mW) and high output power stability. The reflectivity decreased, approaching the central region for both CO₂ and YAG laser beams. At the central region, the reflectivity in a wavelength range shorter than near

FIG. 4. (Color online) Experimental setups to measure the reflectivity (a) and the change in the polarization angle after reflection (b) after exposure to LHD plasmas. The radius r is defined as the distance between the beam and the central axis of the reflector. By changing the position of the reflector, r is scanned. Two optical path lengths after the reflector are the same in order to make two beam diameters equal.

infrared, which is often used for beam alignment and vibration compensation, is almost zero.

Figure 6 shows the dependence of the reflectivity on the wavelength from the visible to the far infrared range. The sources are a He-Ne laser, a YAG laser, a CO₂ laser, a CH₃OD laser, and a CH₃OH laser. All the polarizations except the He-Ne laser, which was randomly polarized, were horizontally linear polarization. The radius r of the position of the beam spots is 20 mm and the diameters of measured areas are less than 5 mm. The measured areas of the He-Ne laser, the YAG laser, and the CO₂ laser are determined by the beam diameters. In the cases of the CH₃OD laser and the CH₃OH laser, they are determined by the effective radius of a piezoelectric detector. The reflectivity of the reflector before exposure to LHD plasmas was measured at only 10.6 μm and was 87%. The reflectivity for longer wavelength was expected larger. In the cases of YAG and He-Ne lasers, for example, the reflectivities of a nonexposed and gold-coated aluminum mirror with the same dimensions, whose reflectivity at 10.6 μm is 93%, are 89% and 74%, respectively. While the reflectivities at wavelengths of 57.2 μm and at 119 μm are almost the same after exposure; it decreases gradually for shorter wavelength than infrared range. The reflectivity for the CO₂ laser beam decreases from 87% to 40%. Since the retroreflector reflects light three times, the reflectivity of the single reflection changes from 95% to 74%. Although Bennett's formula,¹⁹

$$R/R_0 = \exp[-(4\pi d/\lambda)^2], \quad (1)$$

where R is the reflectivity with a roughened surface, R_0 the reflectivity with an ideal surface, d the mean surface roughness, and λ the wavelength, describes the change in the reflectivity due to the surface roughness in the case of the normal incidence not oblique like retroreflectors, the estimated mean roughness of this retroreflector is about 0.4 μm . A SEM photograph of the mirror surface on the central re-

FIG. 5. (Color online) Distributions of the reflectivity for CO₂ and YAG laser beams as a function of the radius of the retroreflector r . The radius r is defined in Fig. 4(a).

gion, where the reflectivity deteriorated most [the position is circled in Fig. 3(a)], is presented in Fig. 7.^{20,21} From a stereoscopic observation, the roughness is found to be about 0.1–0.5 μm . There are also relatively larger “hills,” whose heights are about 2.5 μm , in places. Though the mean roughness estimated from Eq. (1) approximately corresponds to observation results with SEM, the estimated value seems to be slightly larger than observation.

B. Dependence on the polarization angle

The dependences of the reflectivity on the polarization angle are measured with the CO₂ laser and the CH₃OD laser beam. The results are shown in Table I. Polarization angles of the incident beams are 0° (horizontally linear polarization), 45°, and 90° (vertically linear polarization). The dependence on the polarization angle is not strong for both wavelengths. Table I also shows the changes in the polarization angle after reflection which was measured with the optical setup illustrated in Fig. 4(b). The polarization angle af-

FIG. 6. (Color online) Dependence of the reflectivity on the wavelength from far infrared (FIR) to visible region. The radius of the measured position is 20 mm.

FIG. 7. (Color online) SEM photograph of the mirror surface in the central region [the position is circled in Fig. 3(a)].

ter reflection was measured with a polarizer; the transmission axis of the polarizer is rotated to find the angle where detected power becomes zero. This measurement also checks the change in ellipticity of the reflected beam polarization. The measurement error in the angle was about $\pm 2^\circ$, which is not small. This is because the change in the transmission power is small when the transmission axis is almost perpendicular or parallel to the polarization angle ($P \propto 1 + \cos[2(\theta_r - \theta_i)]$, P is the detected power, θ_i the polarization angle of an incident light, and θ_r the transmission angle of a polarizer). The polarization angles were measured three times, and the averaged angle is shown in Table I. In the case of retroreflectors installed in LHD, the change in the polarization angle by the reflector which is larger than the measurement angle error was not observed even in the case of the CO_2 laser light whose reflectivity decreased to half. The changes in ellipticity of the laser beam were not also observed for both wavelengths.

C. Parallelism

The parallelism of the reflector degrades to 0.64 mrad at worst. This is caused by slack of screws which are used to fasten three reflection parts. Slight gaps can be seen between mirrors in Fig. 3. Since all magnetic coils of LHD are superconducting, amplitudes of mechanical vibrations during plasma discharge are much smaller than those in tokamak. The slack is expected to be mainly caused by expansion and contraction due to change in the temperature by the wall baking. Vibrations from vacuum pump and water cooling, which are so small but last for whole experimental campaign, may also be candidates. To reduce the lowering of the parallelism, the screws should be welded after assembly and the adjustment.

IV. DISCUSSIONS

After the exposure to LHD plasmas for 4 months, the reflectivity of the retroreflectors decreased and the degradation in the central region was significant. A laser beam falls on the center of a retroreflector in a usual usage unlike the polarimeter system on LHD. Since power is peaked at the

TABLE I. The dependences of the reflectivity and change in the polarization angle after reflection on the polarization angle.

Wavelength (μm)	Polarization angle (deg)	Reflectivity (%)	Change in the polarization angle (deg)
10.6	0	40	0
	45	42	-1
	90	44	0
57.2	0	73	0
	45	75	-1
	90	70	-1

beam axis in the case of the Gaussian beam, the small reflectivity in the central region of the reflector leads to a significant power loss.

The surface analyses with SEM and with energy dispersive spectroscopy (EDS) indicate the existence of a roughened layer of the deposition of Fe and Cr, which is expected to originate from the vacuum vessel wall, ICRF antenna, or own mirror materials. The thickness of the layer on the central region is found to be about several micrometers, and it is thicker than that on the edge region. The roughness on the surface also increases with the thickness of the deposition layer. This causes the distribution of the reflectivity along the surface of the reflector. On the outmost edge region, there are no deposition layer and the original mirror surface is eroded. These imply that the dominant process changes from sputtering to deposition, approaching to the central region.^{20,21} EDS also indicates that the gold film on the outmost edge of reflector was sputtered and lost, while that on the central region was covered with deposited materials.^{20,21} EDS also shows that the covered gold was exposed in the white splotches which locate on the deposition layer as shown in Fig. 3(c), while the gold is not observed in splotches on the outmost edge region. Detailed results of surface analyses will be published elsewhere.

Since the shape of the retroreflector is hollow, the particles sputtered from the mirror surface or the deposition layer are expected to tend to accumulate in the central region during the main and the glow discharges. Also, each mirror of the retroreflector largely tilts to the incident direction of high-energy particles (for example, charge exchange particles); it is possible that deposited particles on surfaces are sputtered (transported) mainly to the direction of the central region. If these accumulations of the deposition in the central region attribute to the shape of a retroreflector as speculated by above mechanism, the number of particles which hit the reflector directly has to be reduced. One method is to use a shutter, which is closed during the discharge cleaning. However, it cannot prevent the high-energy particles during main plasma experiments and such a mechanical system is not so reliable that the application will not be permitted in large fusion devices. The other is to bend a beam path by 90° with the use of a usual flat mirror just in front of the retroreflector. In this case high-energy particles do not hit the reflector directly, while the flat mirror will be damaged. Although the

FIG. 8. (Color online) Reflectivity of the retroreflector (triple reflection) with roughened surface calculated with Benett's formula [Eq. (1)]. $0.4 \mu\text{m}$ is the estimated mean roughness of the retroreflector installed in LHD.

reflectivity of the flat mirror will be degraded, the total loss of the beam power is expected to be smaller due to no accumulation of the deposition.

In order to reduce the incident particles during glow discharge cleanings, the reflector should be floated. Insulating materials usually have the low heat conductivity, and they cause local rise in temperature and thermal strain in the reflector. Aluminum nitride, which is a kind of ceramics, has high heat conductivity comparable to that of aluminum. Hence it is a candidate of insulation material of the reflector.

Figure 8 shows the dependence of the change in the reflectivity of the retroreflector (triple reflection) on the surface roughness and the wavelength calculated with Eq. (1). This figure indicates that the difference between the reflectivities at $57.2 \mu\text{m}$ and at $119 \mu\text{m}$ is less than 10% when the surface roughness is less than $1 \mu\text{m}$. Actually, in the case of retroreflector in LHD, the reflectivities at $57.2 \mu\text{m}$ and at $119 \mu\text{m}$ are almost the same. Considering the energy and the flux of charge exchange particles to the wall in ITER, the thicknesses of the eroded layer on molybdenum and tungsten mirrors are less than 5 and $1 \mu\text{m}$, respectively, during the full ITER lifetime.⁴ The effective roughnesses of CuCr and oxygen-free Cu mirror after $5 \mu\text{m}$ sputtering with deuterium ions are evaluated with Eq. (1) to be 0.77 and $0.28 \mu\text{m}$, respectively.⁴ Although the surface roughness by erosion strongly depends on the material, there are almost no differences between above two wavelengths as for degradation of the reflectivity if the surface roughness is almost equal level to the exposure experiments in Ref. 4. However, the surface roughness is determined by competing processes between sputtering and deposition, and the processes also depend on surrounding structural objects, which become sources of deposited particles. Hence, the experimental studies on the deposition on the mirror surface in actual fusion plasma experimental devices, test facilities, and modeling studies should be continued. In addition, the way to align and maintain the beam path after start of ITER operation should be addressed because the reflectivity for visible and near IR range will be expected to drop easily.

Reference 4 reports that the roughened mirror surface

causes the significant changes in the reflectivity and the polarization angle of the laser beam at $10.6 \mu\text{m}$ and the effects have the dependence on the incident polarization angle. On contrary to that, the reflector installed in LHD does not show the changes in the polarization angle even at $10.6 \mu\text{m}$. The material of the tested mirror, configuration of three mirrors, exposure conditions, and effective roughness of the surface are different between two mirrors. The mirror in Ref. 4 is made of polycrystalline CuCr alloy. They were exposed to deuterium ions and the surfaces were sputtered down to a depth of about $5 \mu\text{m}$ (with a roughness of $0.77 \mu\text{m}$). In the case of retroreflectors in LHD, the deposition is dominant except the edge region. The effective roughness evaluated from Eq. (1) is about half of that in Ref. 4 and the reflectivity at $10.6 \mu\text{m}$ is about four times larger. The difference in the polarization effect between two exposed mirrors might be related to the difference in the material, the surface condition, and the polarization angle of an incident beam due to the difference in the configuration of the mirrors.

V. SUMMARY

The optical properties of retroreflectors made of stainless steel 316 were studied. They were installed inside the vacuum vessel of LHD and used for 4 month experimental campaign. The reflectivity decreased significantly in a wavelength range shorter than $10 \mu\text{m}$, while that in a wavelength range longer than $50 \mu\text{m}$ was still larger than 70%. The decrease in the reflectivity was larger in the central region of the reflector than that in the edge region. This might be caused by the shape of a retroreflector. The parallelism also deteriorated due to the slack of screws, which is expected to be caused by the repetition of heat expansion and contraction by baking of the vacuum vessel. Changes in the polarization state were not observed even for the CO_2 laser beam, whose reflectivity decreased to about half.

ACKNOWLEDGMENTS

The authors thank Dr. N. Noda and Dr. S. Masuzaki of National Institute for Fusion Science for fruitful discussions. This work is supported by funds of NIFS06KCHH007, NIFS06KCHH010, and Grant-in-Aid for Scientific Research on Priority Areas "Advanced Diagnostics for Burning Plasmas" (16082208).

¹ V. S. Voitsenya, V. G. Konovalov, A. F. Shtan', S. I. Solodovchenko, M. F. Becker, A. F. Bardamid, K. I. Yakimov, V. T. Gritsyna, and D. V. Orlinskij, *Rev. Sci. Instrum.* **70**, 790 (1999).

² V. S. Voitsenya, A. E. Costley, V. Bandourko, A. Bardamid, V. Bondarenko, Y. Hirooka, S. Kasai, N. Klassen, V. Konovalov *et al.*, *Rev. Sci. Instrum.* **72**, 475 (2001).

³ V. S. Voitsenya, A. F. Bardamid, V. N. Bondarenko, W. Jacob, V. G. Konovalov, S. Masuzaki, O. Motojima, D. V. Orlinskij, V. L. Popereenko *et al.*, *J. Nucl. Mater.* **290–293**, 336 (2001).

⁴ V. S. Voitsenya, A. J. H. Donné, A. F. Bardamid, A. I. Belyaeva, V. L. Berezhnyj, A. A. Galuza, Ch. Gil, V. G. Konovalov, M. Lipa *et al.*, *Rev. Sci. Instrum.* **76**, 083502 (2005).

⁵ L. Giudicotti, M. Brombin, S. L. Prunty, L. De Pasqual, and E. Zilli, *Rev. Sci. Instrum.* **77**, 123504 (2006).

⁶ N. Yoshida, H. Iwakiri, K. Tokunaga, and T. Baba, *J. Nucl. Mater.* **337–339**, 946 (2005).

⁷ K. Kawahata, K. Tanaka, Y. Ito, A. Ejiri, and S. Okajima, *Rev. Sci. Instrum.* **70**, 707 (1999).

- ⁸H. K. Park C. W. Domier, W. R. Geck, and N. C. Luhmann, Jr., *Rev. Sci. Instrum.* **70**, 710 (1999).
- ⁹T. Akiyama, S. Tsuji-Iio, R. Shimada, K. Nakayama, S. Okajima, M. Takahashi, K. Terai, K. Tanaka, T. Tokuzawa *et al.*, *Rev. Sci. Instrum.* **74**, 2695 (2003).
- ¹⁰A. J. H. Donne, T. Edlington, E. Joffrin, H. R. Koslowski, C. Nieswand, S. E. Segre, P. E. Stott, and C. Walker, *Rev. Sci. Instrum.* **70**, 726 (1999).
- ¹¹P. Kornejew M. Hirsch, T. Bindemann, A. Dinklage, H. Dreier, and H.-J. Hartfuß, *Rev. Sci. Instrum.* **77**, 10F128 (2006).
- ¹²K. Nakayama H. Tazawa, S. Okajima, K. Kawahata, K. Tanaka, T. Tokuzawa, and Y. Ito, *Rev. Sci. Instrum.* **75**, 329 (2004).
- ¹³K. Kawahata K. Tanaka, T. Tokuzawa, T. Akiyama, Y. Ito, S. Okajima, K. Nakayama, and R. J. Wylde, *Rev. Sci. Instrum.* **75**, 3508 (2004).
- ¹⁴K. Kawahata T. Akiyama, R. Pavlichenko, K. Tanaka, T. Tokuzawa, Y. Ito, S. Okajima, K. Nakayama, and K. Wood, *Rev. Sci. Instrum.* **77**, 10F132 (2004).
- ¹⁵G. Federici, C. H. Skinner, J. N. Brooks, J. P. Coad, C. Grisolia, A. A. Haasz, A. Hassanein, V. Philipps, C. S. Pitcher *et al.*, *Nucl. Fusion* **41**, 1967 (2001).
- ¹⁶W. Duan J. Chen, and S. Yang, *J. Nucl. Mater.* **111&112**, 502 (1982).
- ¹⁷R. E. Clausing L. C. Emerson, and L. Heatherly, *J. Nucl. Mater.* **93&94**, 150 (1980).
- ¹⁸G. M. McCracken, *J. Nucl. Mater.* **93&94**, 3 (1980).
- ¹⁹H. E. Bennet, *J. Opt. Soc. Am.* **53**, 123 (1961).
- ²⁰N. Yoshida A. Ebihara, Y. Ohtawa, M. Tokitani, K. Tokunaga, K. Kawahata, and T. Akiyama, 23rd Annual Meeting of The Japan Society of Plasma and Nuclear Fusion Research, Tsukuba, 2006 (unpublished), Paper No. 30aB05.
- ²¹Y. Ohtawa A. Ebihara, M. Tokitani, K. Tokunaga, T. Fujiwara, N. Yoshida, K. Kawahata, and T. Akiyama, 2007 Spring Meeting of Atomic Energy of Society Japan, Nagoya, 2007 (unpublished), Paper No. M32.