Cleaning of Thomson scattering window by a laser blow-off method

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Practicability of cleaning Thomson scattering windows by a laser blow-off method is demonstrated and discussed in terms of sweep speed and window damage probability. Optimum sweep speeds of ~ 6 cm^2/s are obtainable with a 30-Hz, 0.4-J/pulse Nd:YAG laser.

In magnetic confinement fusion experiments incoherent Thomson scattering (TS in brief henceforth) is the most reliable and therefore widely used diagnostic to measure electron temperature T_e and density n_e.[1] As other diagnostics, to obtain the accurate values of T_e and n_e from scattered data many efforts must be made to eliminate or correct all conceivable sources of systematic errors. Although most of the systematic errors are eliminated by calibrations after assembling components, some still arise from the gradual variations of instrument parameters, e.g., transmittance of the optical system or the gain of the detectors. Among them the most laborious one is caused by gradual growth of thin film on the inside of the TS view window, as is quantitatively described by McNeill[2] for TFTR TV Thomson. The lights passing through the thin film suffer absorption which depends on the wavelength, thereby its spectrum being distorted. Figure 1 shows, as an example, the wavelength dependence of the transmittance of the window (fused quartz) exposed to about 10 000 shots of the JIPPTII-U tokamak plasma with duration of 0.5 s and about 48-h carbonization discharge. This transmittance behavior causes the systematic errors $\Delta T_e/T_e$ and $\Delta n_e/n_e$ as shown in Fig. 2, which are calculated so that at 25 spectrum channels covering from 700 to 1100 nm the distorted relativistic TS spectrum with T_e and n_e is best fit with the TS spectrum with $T_e - \Delta T_e$ and $n_e - \Delta n_e$. Here we used the analytic formula for the relativistic TS spectrum given by Selden[3] and assumed that the incident laser of wavelength $= 1064$ nm is scattered off in 90° direction. The very small (less than 1%) chi-square per freedoms (23) shows that fitting itself is very good. Thus, in cases such as this, the quality of fit is not a good indicator of a transmission problem, and significant errors result in the determination of T_e and n_e at high T_e. Usual solutions to this problem are to manually clean windows occasionally by breaking vacuum, or as is adopted on TFTR,[4] to remove the top of a stacked cover glasses set at the inside of the window every, for example, three months. The latter method prolongs the interval between necessary vacuum breaks to about one year. This interval will get shorter as the discharge time becomes longer as expected in future machines. This occasional vacuum break will heavily burden the long-term operation of the future large machines. Thus it is highly desirable to develop methods to clean windows without breaking vacuum. An easily conceivable method which fulfills the above requirement is to use a laser to blow off the thin film. The concept stemmed from the observation that where a laser beam passes through the vacuum window no thin film forms. In developing this method for practical use, important issues are its sweep speed and the probability of window damage. In order to test these issues, we did experiments using a high repetition rate Nd:YAG laser (YH900S; LUMONICS). The laser parameters are: laser wavelength $= 1064$ nm, repetition rate ~ 100 Hz, energy per pulse ~ 0.4 J, pulse width ~ 30 ns, laser mode is TEM00 and linearly polarized. The energy density of laser are changed by focusing or defocusing the laser beam of 10 mm in diameter. The laser beams with different energy densities are irradiated at the window described above in the atmosphere. Phenomenologically the responses of the thin film to laser irradiation are categorized into three types according to the energy density ϵ:(1) for $\epsilon < 0.5$ J/cm^2 no blow off occurs even with irradiation of a train of 700 laser pulses; (2) for 0.5 J/cm$^2 < \epsilon < 2$ J/cm^2 the proportion of the blown off part in the laser spot gradually increases as the train of laser pulses proceeds; (3) for $\epsilon > 2$ J/cm^2 one shot laser blows off the thin film completely. In Fig. 3(a) these behaviors are summarized as the relation between ϵ and the necessary number of laser shots N_L to remove the thin film completely. Although details of this ϵ vs N_L relation will depend, for example, on the plasma parameters, on the spatial distribution of laser energy, and on the shot by shot fluctuation of laser energy, the general trend is thought to be the case. Once the brown thin film is visually confirmed to be removed, the transmittance over the wavelength 700–1100 nm was recovered to a nearly perfect level as shown in Fig. 1.

The sweeping speed is approximately given by

$$Sp = fA/N_L = fE_L/\epsilon N_L, \tag{1}$$

where f is the repetition rate of the laser, A is the area of the laser spot, and E_L is the laser energy per pulse. With

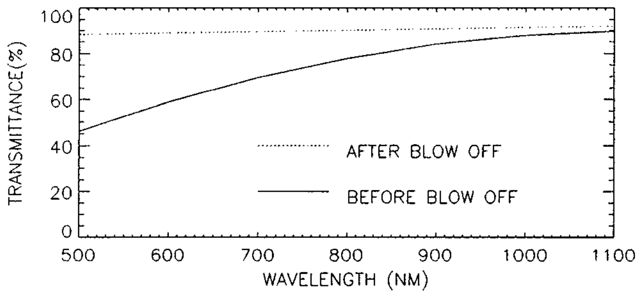

FIG. 1. Transmittance of the window before and after laser blow-off. Reflectance loss at both sides of the window is included.

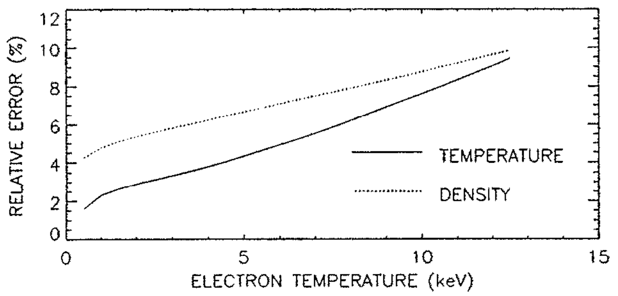

FIG. 2. The systematic errors $\Delta T_e/T_e$ and $\Delta n_e/n_e$ caused by absorption by the thin film deposited on the window.

the help of the ϵ vs N_L relation given in Fig. 3(a), ϵ dependence of *Sp* is shown in Fig. 3(b). Here we assumed a laser oscillator with $f=30$ Hz and $E_L=0.4$ J/pulse, which is commercially available at a reasonable cost. The highest sweep speed of ~ 6 cm^2/s is obtained at $\epsilon \sim 2$ J/cm^2

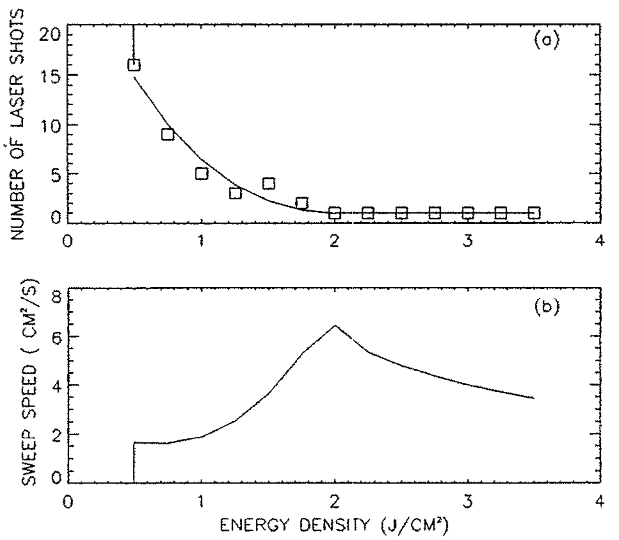

FIG. 3. (a) The relation between the laser energy density ϵ and the number of laser shots N_L required to blow off the thin film completely. (b) ϵ vs sweep speed *Sp*.

for the present case. With this speed the window of, for example, 2500 cm^2 in area is cleaned in about 7 min, which is practically short even for every day cleaning.

Another serious concern is the damage probability of window. In spite of extensive studies on the laser-induced damage[5] a unified quantitative data is not yet available. This is because in many cases the damage threshold is determined by physical and chemical imperfections such as cracks or pits.[6] Our concern is then whether there is any enhancement on the damage threshold due to plasma sputtering or the presence of thin film. To see this, the laser spot size on the window is progressively reduced to the level at which the window is damaged by a train of 500 laser shots. Damage begins to occur on the surface at the energy density ~ 50 J/cm^2. This value is not so different from the damage threshold, 35 J/cm^2 for a 3-ns pulse width, given by Lowdermilk and Milam.[6] This demonstrates, at least for the present case, that there is not so much deterioration in the strength of the window against the laser irradiation due to spattering of particles from plasma. In view of the fact that the damage probability drops very sharply with the decreasing laser energy density, the damage probability at $\epsilon = 2$ J/cm^2, at which the highest sweep speed is attained, will be extremely small. Indeed this energy density is well below the safe energy level of 5 J/cm^2 certified by lens makers.[7]

In conclusion, it is demonstrated that the thin film formed on the inside of a Thomson scattering window can be blown off by a commercially available high repetition rate laser with a practical sweep speed and negligibly small probability of window damage. The use of a two-dimensional computer-controlled laser scanner, which is commercially available, will facilitate the construction of a laser blow-off window cleaner.

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