Effects of Plasma Radiation on the Thomson Scattering Diagnostic Installed on the Large Helical Device

Kazumichi NARIHARA, Ichihiro YAMADA, Hiroshi HAYASHI and Hisamichi FUNABA
National Institute for Fusion Science, Toki 509-5292, Japan

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Recently we modified the Thomson scattering diagnostic (TS) installed on LHD so that DC levels (V_{DC}) of all avalanche photodiodes (APD) used for detecting scattered light can be registered every 1 ms, which enabling us to make validity check on TS data taken under very intense plasma radiation. In the line of this task, we first examined how the pulse-performance of an APD degrades as the intensity of continuous light (J_{DC}) incident to the APD increases. We found two effects are involved in deteriorating the pulse-performance of the APD: (1) the responsivity of the APD to a pulsed light drops as J_{DC} increases, causing a systematic errors on the deduced electron temperature (T_e) and density (n_e); (2) the frequency response of the APD and the following circuit drops as J_{DC} increases, which deforms the pulse shape. The bias voltage applied to the APD (V_b) has large influence on these behaviors, showing the best overall performance for a high J_{DC} around $V_b \sim 0.5V_r$, where V_r is the recommended voltage giving responsivity of 675 kV/W at 1060 nm. Considering these effects together, we set a conservative validity criterion for the pulse APD performance in term of the V_{DC}: $V_{DC} < 0.5$ V. The $V_b = 0.5\,V_r$ setup gives much reliable T_e-profiles without a collapse in T_e-profile for a much wider range of plasma radiation intensity. With this criterion, we check the validity of T_e-and n_e-profiles of two example data.

Keywords: Thomson scattering diagnostic, high-density plasma, validity check, LHD, APD

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1. Introduction

Thomson scattering diagnostic (TS) is widely used for measuring electron temperature (T_e) and density (n_e) in fusion plasma experiments because of its high reliability. However, this 'reliability', is realized only in a limited ranges of plasma- and setting- parameters and through a careful calibration. We should make a severe validity check on TS data as the plasma to be measured enters a new regime such as the very high-density plasma which was recently observed [1]. In applying TS to very dense plasma, the first thing to be checked is the 'incoherence scattering' condition: the wavelength associated with the momentum transfer $\lambda = \lambda_L/2\sin(\theta/2)$ should be less than the Debye length. With $\lambda_L = 1.06\,\mu$m (Nd:YAG laser) and $\sin(\theta/2)\sim 1$ for the LHD-TS configuration this condition is expressed as $(n_e/10^{20}\mathrm{m}^{-3})/(T_e/\mathrm{keV})<10^5$, which is sufficiently met even in the low temperature edge region with $T_e \sim 20$ eV. Another concern is the effect of intense plasma radiation on the pulse-performance of avalanche photo diodes (APD) used for detecting scattered light, since as n_e goes up the plasma Bremsstrahlung increases in proportion to n_e^2 [2], while the scattered signal in proportional to n_e. To solve this problem to some extent by monitoring the DC-level of each APD output, which is supposed to be proportional to the intensity of plasma radiation, we modified the existing LHD-TS and implemented scanning ADCs. This paper treats this plasma radiation problem. The next section describes the LHD-TS and its modification, Section 3 shows the measured pulse-performance of an APD under an intense continuous light illumination, Section 4 examines validity of T_e and n_e profiles of two example shots, and Section 5 gives discussions.

author's e-mail: Narihara@nifs.ac.jp

2. LHD Thomson Scattering Diagnostic

We first give a very brief description on the LHD-TS [3,4] and the modification done recently. The LHD-TS is characterized by its heavily inclined backward scattering configuration, which enables measuring T_e and density n_e at 200 points along a major radius passing the magnetic axis, covering entire region from the inner- to outer-edges of the plasma. Three 2J-10 Hz Nd:YAG lasers give T_e and n_e profiles at 30 Hz repetition rate. The scattered light from each scattering volume is collected on a tip of 200 optical fibers of 2 mm in diameter and transported 45 m to a five-color filter polychromator, where it is resolved into five spectra, each of which is detected by an APD (EG&G C30950 CD-1161). A diagram of the APD circuit plus data acquisition system is shown in Fig. 1. To each APD the bias voltage (V_b) equal to 0.9 times the recommended voltage (V_r) which gives the responsivity $R = 675$ kV/W at 1060 nm is applied through a 100 kΩ resistor. This resistor is absolutely necessary for guarding the APD and

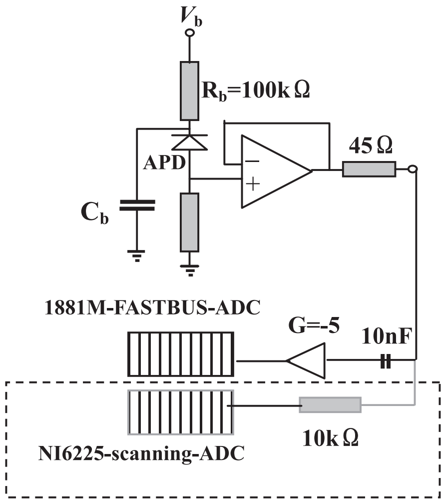

Fig. 1 Schematic drawing of the APD plus data acquisition system. The lower part enclosed by dashed line is newly installed.

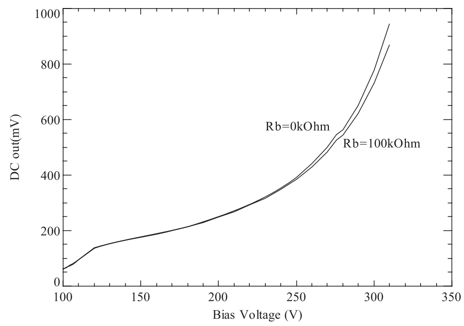

Fig. 2 DC output voltages as a function of V_b for $R_b = 0\,\mathrm{k\Omega}$ and $100\,\mathrm{k\Omega}$. Continuous light intensity was held at a constant.

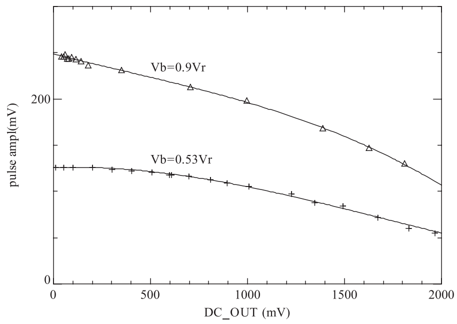

Fig. 3 Amplitude of 30ns-pulse-signal as a function of V_{DC} for $V_b = 0.9\,V_r$ and $V_b = 0.5\,V_r$ settings. Note that input light intensity is not exactly the same for the two measurements.

the following circuit against damage due to excess light illumination with a long duration. For a very short pulse light illumination such as TS light, the capacitor C_b will supply enough charge at a constant voltage. The output of APD is connected to an inverting wideband amplifier with gain g∼5 via a capacitor of 10nF and fed to charge-ADC (Lecroy FASTBUS 1881 M). This capacitor is used to block the low frequency ($f < 1$ MHz) fluctuating plasma light to enter into the signal, thus the information on the DC output of the APD (V_{DC}) being lost. Including laser monitor signals, total number of signals to be fed to ADCs is 1024. As the LHD experiment began to explore into a very high-density regime with central $n_e > 10^{20}\mathrm{m}^{-3}$, and hence, the data validity of the TS data being suspected, we modified the LHD-TS so that V_{DC} of all APDs can be monitored routinely. For this aim, we connected the output of each APD to the input of scanning ADC (NI 6225, maximum scanning rate is 1 ms) via 10 kΩ resistor, which is needed to keep the impedance matching for the short pulse propagation in cables.

3. Characteristics of APD under Intense Background Light Illumination

In considering the plasma radiation effects on the performance of an APD for detecting a very short pulse light, important issues are the responsivity (R) saturation and the change of frequency response, the latter of which has influence to the former for a pulse light detection. It is reported that an APD itself has a good linearity over many orders of magnitudes of incident light [5]. The R saturation mechanisms in the body of an APD, such as space-charge effect and heating effect were discussed in literatures [5]. Another sources of the R saturation come from an electric circuit used for an APD. Referring to Fig. 1, we guess two sources of R saturation: (1) one is the voltage drop across the resistor R_b and the consequent R drop; (2) the other is the saturation of output voltage of the amplifier due to a limited current driving capability of the output transistor. In order to examine these guessed effects, we tested a sample APD (EG&G C30950 CD-1161 S/N = C2087-D), whose specifications are: the recommended operating voltage (V_r) which gives the responsivity $R = 675$ kV/W is 307 V; dark current $I_d = 180$ nA, bandwidth $B = 25$ MHz, and the noise equivalent power $NEP = 60\,\mathrm{fW}/\sqrt{\mathrm{Hz}}$. We first measured the V_{DC} as a function of V_r for $R_b = 0\,\mathrm{k\Omega}$ and $R_b = 100\,\mathrm{k\Omega}$ settings under a fixed continuous light illumination from a tungsten lamp. The results are shown in Fig. 2. The curve for $R_b = 0\,\mathrm{k\Omega}$ can be regarded as the intrinsic R as a function of V_b apart from some constant: $R = R(V_b)$. The curve for the $R_b = 100\,\mathrm{k\Omega}$ setting shows up R-drop due to the voltage drop across R_b. In order to reduce the R-drop due to voltage drop across R_b, it is obviously favorable to operate at lower V_b, where the derivative of $R(V_b)$ is the smaller. However, lowering V_b leads to an increase of the capacity across the depression layer of the APD, loosing the fast response necessary for detecting short pulse TS light. The allowable minimum V_b for this APD is about $0.5\,V_r$.

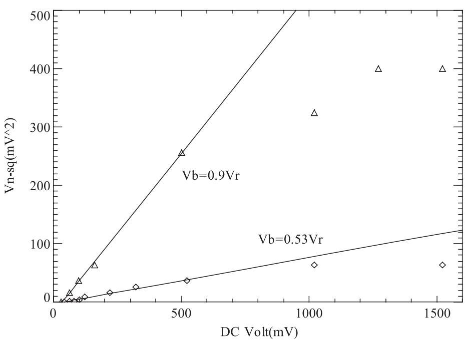

Fig. 4 Square of wide band noise p-p voltage as a function of V_{DC} for $V_b = 0.9V_r$ and $V_b = 0.53\,V_r$.

Secondly, we measured the pulse-output voltage in response to the pulse light as a function of the V_{DC}, which was changed by the current in the tungsten lamp, for the fixed bias voltages of $V_b = 0.9\,V_r$ and $V_b = 0.5V_r$, with the results show in Fig. 3. The output pulse height gradually decreases as V_{DC} rises, with the faster decay for the higher V_b, which is partly explained by the larger dR/dV_b for the higher V_b as seen in Fig. 2. The drop in pulse amplitude for $V_{DC} > 0.5$ V seems to result from the narrowing of the bandwidth (B) of the APD plus the following circuit, which is evidenced as a deformation of output pulse shape. To check this observation further, we measured the square of the peak-to-peak voltage (V_n) of wideband noise as a function of V_{DC} for $V_b = 0.5\,V_r$ and $0.9\,V_r$ settings. The results are shown in Fig. 4.

According to the noise theory [6], $< V_n^2 > \propto R^2 I_{pe} B \propto R^2 B V_{DC}$. Here I_{pe} is the diode current, which is proportional to V_{DC}. This relation holds up to $V_{DC} = 0.5$ V for both bias voltages. The departure from the theoretical curve implies that B becomes smaller than needed for pulse-light detection when V_{DC} exceeds 0.5 V.

Taking account of the above measured data together, we consider that the pulse-signal from the APD under intense light illumination is valid if $V_{DC} < 0.5$ V, irrespective of the V_b-setting. Under the $V_b = 0.9\,V_r$ setting, V_{DC} reaches 0.5 V with a lower intensity light illumination. Moreover, within this criterion, pulse signals suffer drop in magnitude up to 10 %, introducing the same magnitude errors in the deduced T_e and n_e. A correction scheme in a data deduction program using V_{DC} data may reduce these errors substantially. On the other hand, under the $V_b = 0.5\,V_r$ setting, the V_{DC} is below 0.5 V for much intense continuous light illumination without appreciable drop in R, thus being much favorable for measuring a very high density plasma, which inevitably accompanies intense plasma radiation.

4. Examination of T_e-and n_e-Profiles

Firstly, we examine the data that yields unnatural T_e- and n_e-profiles such as shown in Fig. 5 (A). The V_b was set at $0.9\,V_r$. The distribution of V_{DC} at the time when T_e-profile was taken is shown in Fig. 5 (B) for five color-channels. We can see that high V_{DC} exceeding 0.5 V localizes around 3.0 m $< R_o$ (major radius)$<$ 3.4 m, where the T_e-profile accompanies large error-bars. From our criterion described above, the raw data and hence the deduced T_e and n_e between 3.0 m $< R_o <$ 3.4 m are invalid.

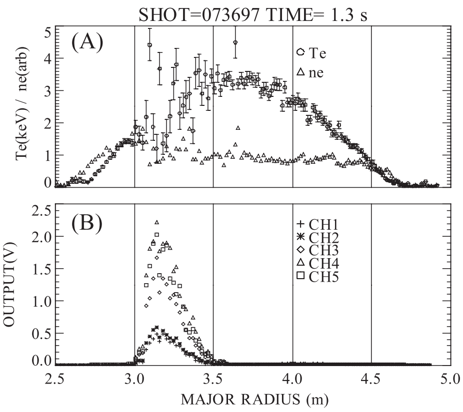

Fig. 5 (A) An example with unnatural T_e and n_e profiles. $V_b = 0.9\,V_r$. (B) Spatial V_{DC}-distributions. In order of the magnitude (from the top): ch5, ch4, ch3, ch2 and ch1. The ch1 collects light of the longest wavelength.

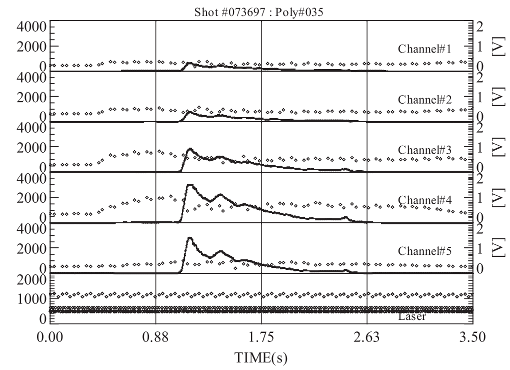

Fig. 6 Time evolutions of five-channel TS-signal and V_{DC} from the #35 polychromator, which 'sees' $R \sim 3.22$ m. The solid lines (right scale) are V_{DC}. The dotted lines are TS-signal (left scale).

Examining the TS optical configuration, we confirmed that the polychromators yielding the high V_{DC} 'see' the divertor plates behind.

Figure 6 shows the time evolutions of V_{DC} from the #35polychromator, which 'sees' around $R \sim 3.22$ m. The V_{DC} rise exceeding the criterion voltage of 0.5 V with 230 ms delay after NB injection (#1+#2+#3). This phenomenon depends on the LHD magnetic configuration and plasma parameters.

The second example is data that yields T_e- and n_e-profiles shown in Fig. 7 (A). The V_b was set to $0.5\,V_r$. Spatial distributions of V_{DC} are plotted in Fig. 7 (B).

All V_{DC} are small enough to guarantee the validity

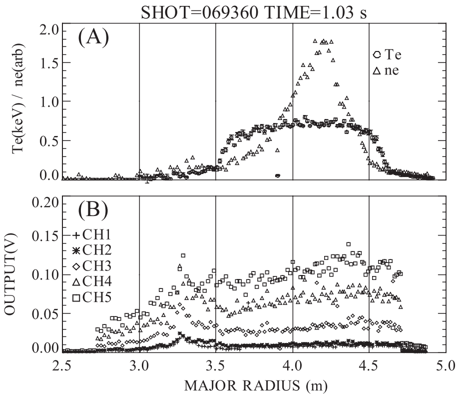

Fig. 7 (A) An example of T_e- and n_e- profiles. $V_b = 0.5V_r$. (B) Spatial distribution of 5-channel V_{DC}. In order of magnitude (from the top), ch5, ch4, ch3, ch2 and ch1.

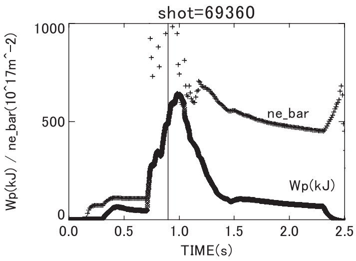

Fig. 8 Time evolutions of line integrated density (n_{e_bar}) and diamagnetic energy (W_p).

of the APD pulse-signals. The electron density integrated along the center cord (n_{e_bar}) and the diamagnetic energy (W_p) as function of time are shown in Fig. 8. Assuming that the n_e profile is correct and comparing $\int n_e \, dR_o$ with n_{e_bar} at 0.53 s, when the HCN interferometer data was still free from a fringe-jump, we give the scale for n_e shown in Fig. 8. If we succeed in developing an absolute n_e calibration method based on high-pressure Rayleigh scattering with a much reduced laser power, thus mitigating the severe stray light problem, we may get a more precise and probably smoother n_e profiles.

Under the $V_b = 0.5\,V_r$ setting, most, if not all, of the plasma with the magnetic axis position greater than 3.75 m show that $V_{DC} < 0.5$ V, thus proved to have valid TS-data. If plasma radiation intensity is low enough, the $V_b = 0.9\,V_r$ setting is more suitable to obtain better data quality.

5. Discussions

We examined the effect of continuous light illumination on the pulse-performance of an APD in terms of the pulse-amplitude and the bandwidth, and offered the validity criterion: $V_{DC} < 0.5$ V. In reality, however, the scattering signals that are converted to digital data and used for data deduction are the time integration of the signal (q-data) over a fixed gate interval (usually 60 ns-100 ns). If the effects are examined in term of the q-data, a somewhat different criterion may be obtained. Moreover, since characteristic of APDs differ appreciably from piece to piece, it is necessary to examine the effects of continuous light illumination on q-data of all 1000-APDs. For this purpose we are preparing a white reflector coated with $BaSO_4$ of 65 cm $\times$ 32 cm in area, which is set on the observation window and illuminated by both continuous and pulse light. The diffused light thus obtained will facilitate simultaneous examination of all 1000-APDs.

We adopted scanning ADCs to monitor the DC-levels of all APD for the economical reason, but much better is to use GHz-sampling digitizers that register all information including the shape of the scattered signals and the background plasma radiation as adopted on ASDEX-U [7].

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