Fast Signal Modeling for Thomson Scattering Diagnostics and Effects on Electron Temperature Evaluation*)

Hisamichi FUNABA, Ichihiro YAMADA, Ryo YASUHARA, Hiyori UEHARA, Hiroshi TOJO[1], Eiichi YATSUKA[1], Jong-ha LEE[2] and Yuan HUANG[3]

National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu 509-5292, Japan

[1]*National Institutes for Quantum Science and Technology, Naka, Ibaraki 311-0193, Japan*

[2]*Korea Institute of Fusion Energy, Daejeon 34133, Korea*

[3]*Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China*

(Received 27 December 2021 / Accepted 21 February 2022)

As a signal processing method for fast digitizers of the switched-capacitor-type in Thomson scattering diagnostics, a “model fitting” method is proposed. An ideal shape of the signal is estimated by this method by averaging many Thomson scattering signals. After applying this method to a relatively low density LHD plasma, the scattering of electron temperature profiles becomes small. The magnitude of error is also reduced by about 60% at some spatial channels in the core plasma. Simulations of signals with some noises based on the JT-60SA Thomson scattering system enables a showing of the expected error in electron temperature. The error can be suppressed by the “model fitting” method.

Keywords: Thomson scattering, electron temperature, signal processing

DOI: 10.1585/pfr.17.2402032

1. Introduction

The Thomson scattering system requires a large number of measuring channels, which corresponds to a product of the number of the spectral channels and that of the spatial positions, in order to measure the electron temperature (T_e) and density (n_e) profiles. For example, the number of channels is 884 in the case of the Thomson scattering system for the Large Helical Device (LHD) [1, 2] and it is more than 600 in the JT-60SA case [3]. A laser pulse which has the energy of a few joules is injected into the plasma and the scattered light is detected and dispersed by spectrometers. Since the temporal width of a signal is almost a few tens of nanoseconds, a high speed multi-channel digitizer is suitable as analog-to-digital convertors (ADC) for recording output of the spectrometers in many channels. The acquisition of the signals with the temporal development has advantages in reduction of effects of stray light or noise components through the data processing [4, 5].

In order to obtain T_e and n_e from the signals of fast digitizers, time integration of the signals is required. One method of the integration is a simple summation. Another method is fitting by a mathematic function. For example, a function in Ref. [4], which is a convolution of the Gaussian part and a slow decay part due to the characteristics of an amplifier, is used in KSTAR [6], GAMMA 10/PDX [7], and so on. In the case of LHD, since the decay is not slow and an overshoot is found, the signal cannot be reproduced by this function. A third method, fitting with a modeled function which is derived by averaging of many Thomson scattering signals is used. This method is also used on TST-2 in the University of Tokyo [8] in order to distinguish the two pulses of the double-pass Thomson signal. In this paper, since this method assumes an ideal signal shape for a channel and a laser, it is called the “model fitting” method. Since this method can provide an ideal signal, it may be possible to use this signal shape as an input for machine learning, in order to identify noises, determine proper background level, and so on. Moreover, the time integration of the signal becomes quite fast if the integrated value is prepared in advance, since it depends on the magnitude only.

One of the high speed multi-channel digitizers, a switched-capacitor type digitizer, CAEN V1742, is used in LHD, KSTAR [6], HL-2A [9], and HL-2 M. Another type of switched-capacitor digitizer by TechnoAP is adopted in LHD and JT-60SA. The digitizer by TechnoAP can obtain the data with a time interval, which is needed for reading out data, lower than 50 μs, when the number of the data points is reduced by a fourth. This is the reason why it has been used in LHD since a new high-repetition-rate Nd:YAG laser [10, 11] was installed on LHD and its operation with a repetition frequency up to 20 kHz started. One digitizer board of this type includes four ADC chips of the switched-capacitor arrays, which are called DRS4 (Domino Ring Sampler) [12]. Some corrections are required for the signals acquired by DRS4, for example, a

author’s e-mail: funaba.hisamichi@nifs.ac.jp

*) This article is based on the presentation at the 30th International Toki Conference on Plasma and Fusion Research (ITC30).

cell amplitude calibration, which is needed to compensate for the amplitude differences in the capacitors [13]. However, a few noise components caused by DRS4 still remain in the data acquired by the digitizer of TechnoAP, even after applying such corrections. It is necessary to distinguish these noises from the data, even when they appear at the same timing of the Thomson scattering signal.

In this paper it is intended to establish fitting and integration by the "model fitting" methods for the signals of fast digitizers and improve the evaluation of T_e and n_e in LHD. Moreover, this method is applied to the estimated signals of JT-60SA, where the same switched-capacitor-type ADCs are adopted and the broader wavelength region will be observed, since a higher T_e range is predicted. Noises generated by the digitizers such as small spikes or by the spectrometers such as fluctuation of the light from the plasma or reflection from the wall, degrade correct T_e and n_e measurements. In order to estimate the errors in T_e by such noises, it is also intended to predict the signals of Thomson scattering in JT-60SA and estimate effects of the fitting and integration methods.

The method of "model fitting" is described in section 2. This method is applied for a relatively low density LHD plasma and improvement of T_e profiles is tried in section 3. In section 4, simulation results for JT-60SA are shown. Section 5 is a summary.

2. Exraction of Scattering Signal Using "Model Fitting" Method

The "model fitting" method is proposed and its process is shown in this section. This method is based on the following assumption. Although each channel has a unique characteristic shape of signals, the signal shape basically depends on only the laser pulses and the configuration in the electronic circuits for amplifying the signal of the avalanche photo diode (APD).

The number of spatial positions of the LHD Thomson scattering system is 144. The scattered light from each position is detected by a polychromator. In Fig. 1 (a), an example of Thomson scattering signals of channel No.3 in polychromator No.55, which is observed at $R = 3.54$ m, is shown. The stray light component was evaluated from the signals without plasmas and it is subtracted. No stray light was observed in this channel. The red broken lines show the time range where the signal is integrated by the simple summation. Figure 1 (b) shows many signals which are normalized and overplotted. The temporal jitter is almost a few nanoseconds and it is adjusted here. The red signal shows their average, which corresponds to the "model fitting" signal. A comparison between the raw signal (green) and the fitted curve (red) obtained from the "model fitting" by adjusting the magnitude of the signal is plotted in Fig. 1 (c) and it shows a good agreement. In the process of the time integration after using the "model fitting" method, only the amplitude of the signal pulse is required, because

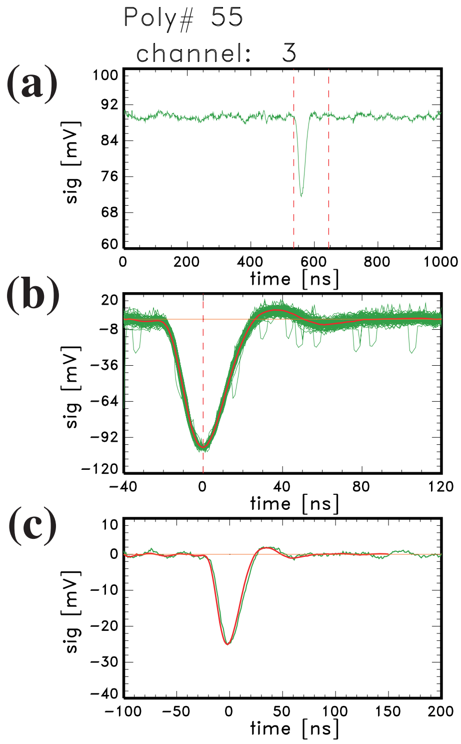

Fig. 1 Thomson scattering signals of channel No. 3 in polychromator No. 55. (a) One signal, (b) Many signals are normalized and overplotted. The red signal shows their averaging, which shows the "model fitting" signal. (c) One signal is approximated by the "model fitting" method.

it is possible to obtain the integration of the "model fitting" signals in advance. The data in the shot numbers of #171374, 171376, 171377, and 171379 are used here.

3. Application of "Model Fitting" for T_e Evaluation in LHD

In this section, T_e profiles which are evaluated by "simple summation" and "model fitting" are compared in LHD. T_e is evaluated by the χ^2-method which minimize the following χ^2,

$$\chi^2 = \sum_i w_i(x_i - \lambda s_i)^2, \tag{1}$$

where i, w_i, x_i, λ, and s_i are i-th spectral channel of a polychromator, weight, signal intensity, a constant, and expected intensity for a specific T_e, respectively. The error of T_e is evaluated from the T_e region which is provided under $\chi^2 + \Delta\chi^2$. When the weight, w_i, in Eq. (1) corresponds to the inverse of the magnitude of the signals, $\Delta\chi^2 = 1$ can be used.

Figure 2 (a) shows T_e (●) and n_e (●) profiles in an LHD plasma of #171376. For this measurement, a high-repetition-rate laser is used at 1 kHz. The time integration of the signals is made by the simple summation. The T_e data are scattered at the center region, where n_e is relatively low. In Fig. 2 (b), T_e and n_e profiles of the same shot

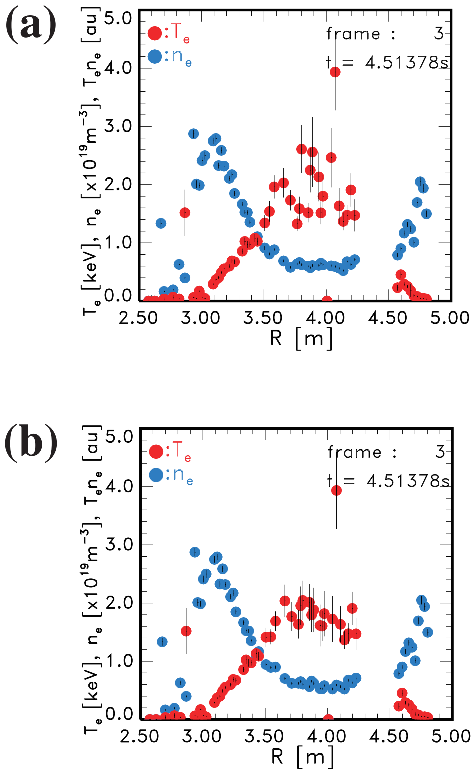

Fig. 2 T_e (●) and n_e (●) profiles in an LHD plasma of #171376. A high-repetition-rate laser is used. The time integration of the signals is made by (a) simple summation and (b) "model fitting" method for $R = 3.51 \sim 3.97$ m.

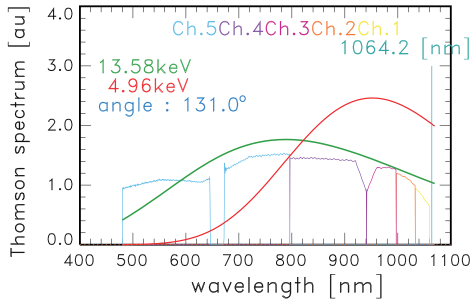

Fig. 3 Thomson scattering spectra of T_e = 13.58 and 4.96 keV with a scattering angle of 131° and wavelength ranges of the polychromator channels for the core Thomson scattering system of JT-60SA. 1064.2 nm is the wavelength of the Nd:YAG laser.

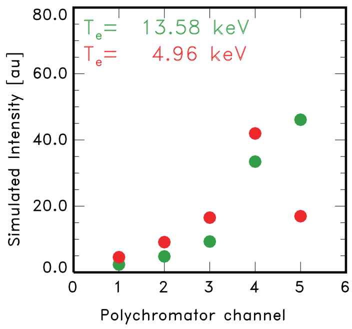

Fig. 4 Expected signal intensity in the polychromator channels for T_e = 13.58 (●) and 4.96 keV (●).

and timing are shown. Here, the time integration is made by the "model fitting" method for $R = 3.51 \sim 3.97$ m. The scattering of T_e values becomes small by this method. The magnitude of error is also reduced by about 60% at $R = 3.89$ m. The data in $R = 4.244 \sim 4.544$ m were not obtained due to some problems with the digitizer boards.

4. Simulation of Thomson Scattered Signals for JT-60SA

Simulations of Thomson scattering signals in JT-60SA were performed and T_e was evaluated by the integration with simple summation and the "model fitting" method in this section. The "model fitting" method excluded noises and revealed its effect quantitatively.

Figure 3 shows Thomson scattering spectra of T_e = 13.58 and 4.96 keV for a scattering angle of 131°. This T_e value, around 13.5 keV, was obtained from simulation results by some transport codes for JT-60SA [14]. The wavelength ranges of the polychromator channels and the scattering angle for the core system of JT-60SA were assumed [3]. The channels are numbered from the closest wavelength to that of the Nd:YAG laser, 1064.2 nm. Figure 4 shows the expected signal intensity in the polychromator channels for T_e = 13.58 (●) and 4.96 keV (●).

The "model fitting" signal was made based on the 500 test signals which were obtained by the actual fast digitizer system of JT-60SA, with pulses of almost 50 ns width, made by a function generator. Figure 5 (a) shows simulated signals of five channels of a polychromator with some noise pulses. The intensity in each channel without noises was determined from the ratio in Fig. 4 in order to simulate signals from a plasma of T_e = 13.58 keV. Small pulses of noise were added in channel Nos. 3 and 4. Since the simple summation was made between the red broken lines, T_e evaluated by the simple summation could be affected by these noises. Figures 5 (b) and (c) show the ratio of the signal intensity and T_e evaluation by the χ^2-method, respectively. The derived T_e = 12.48 keV is lower than the assumed value of 13.58 keV, due to the noises. In Fig. 6 (a), the same simulated signals with noise were approximated by the "model fitting" method (dark green curves). The effects of the noise were excluded. Figures 6 (b) and (c) also show the ratio and T_e evaluation, respectively. The evaluated T_e = 13.68 keV becomes close to the assumed value of 13.58 keV in the "model fitting" case. This example shows that the error can be suppressed by signal processing, even when some noise components affect the digitizer in JT-60SA.

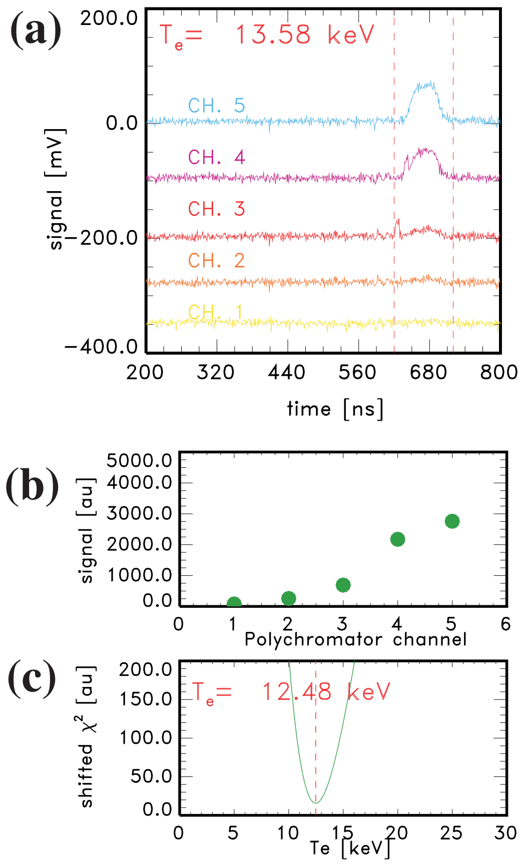

Fig. 5 Signals and T_e simulation for JT-60SA with the integration by the simple summation.
(a) Simulated signals with small noises, (b) Ratio of signal intensity and (c) T_e evaluation by χ^2-method.

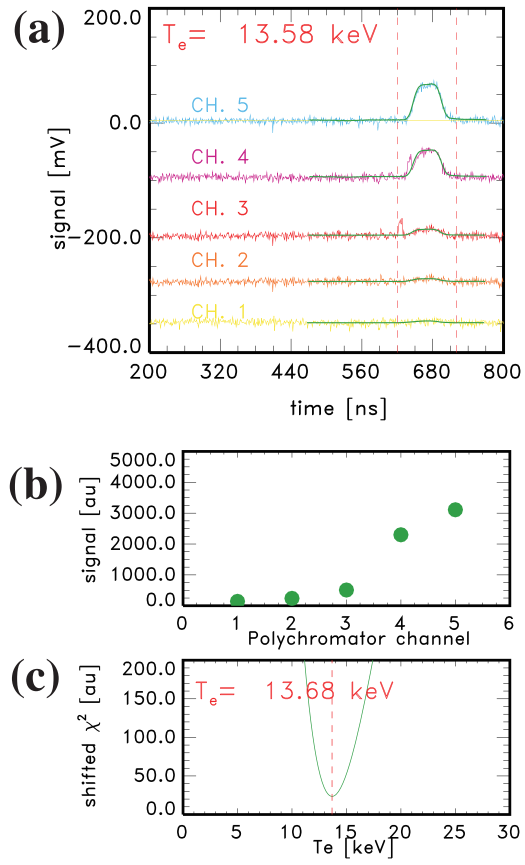

Fig. 6 Signals and T_e simulation for JT-60SA with integration by the "model fitting" method.
(a) Simulated signals with small noises and approximation by the "model fitting" (dark green curves), (b) Ratio of signal intensity and (c) T_e evaluation by χ^2-method.

5. Summary

As a signal processing method for fast digitizers, the "model fitting" method is proposed for switched-capacitor-type digitizers, such as CAEN V1742 and TechnoAP boards. The "model fitting" method was applied to a relatively low density LHD plasma. The scattering of T_e values and the magnitude of errors become small by this method. Simulating signals with some noises based on the JT-60SA Thomson scattering system enables the showing of expected error in T_e by conventional simple summation. The error can be suppressed by the "model fitting" method.

Acknowledgements

The authors thank the LHD experiment group. This work was supported by NIFS20ULHH005 and JSPS KAKENHI Grant Numbers JP15KK0245 and JP21K03518. This work was also accomplished under the Tokamak Fusion Plasma Collaborative Research "Signal processing for Thomson scattering diagnostics with fast digitizers" by QST. This work was in cooperation with "KSTAR Experimental Collaboration and Fusion Plasma Research (KFE-EN2101-12)" with Ministry of Science and ICT under KFE R&D Program.

[1] K. Narihara *et al.*, Rev. Sci. Instrum. **72**, 1122 (2001).
[2] I. Yamada *et al.*, Fusion Sci. Technol. **58**, 345 (2010).
[3] H. Tojo *et al.*, Rev. Sci. Instrum. **92**, 043556 (2021).
[4] B. Kurzan *et al.*, Plasma Phys. Control. Fusion **46**, 299 (2004).
[5] E. Yatsuka *et al.*, JINST **8**, C12001 (2013).
[6] J.H. Lee *et al.*, JINST **12**, C12035 (2017).
[7] K. Ohta *et al.*, Rev. Sci. Instrum. **87**, 11E730 (2016).
[8] J. Hiratsuka *et al.*, Plasma Fusion Res. **6**, 1202133 (2011).
[9] Y. Huang *et al.*, Rev. Sci. Instrum. **89**, 10C116 (2018).
[10] D.J. Den Hartog *et al.*, Rev. Sci. Instrum. **81**, 10D513 (2010).
[11] D.J. Den Hartog *et al.*, J. Phys. Conf. Ser. **227**, 012023 (2010).
[12] S. Ritt *et al.*, Nucl. Instrum. Methods **A 623**, 486 (2010).
[13] *UM4279-V1742/VX1742 User Manual rev. 8* (downloaded from https://www.caen.it/download/?filter=V1742) p.28.
[14] L. Garzotti *et al.*, Nucl. Fusion **58**, 026029 (2018).