Digital filter polychromator for Thomson scattering applications

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Abstract. Incoherent Thomson scattering diagnostics (TS) is a proven technique capable of reliable and robust instantaneous measurement of electron temperature ($T_e$) and density ($n_e$) local values in wide area of plasma physics experiments: from hall-effect thrusters to tokamaks and stellarators. The TS cross section is very low ($\sim 6.7 \times 10^{-30} \text{ m}^2$), and the corresponding TS signals, measured in fusion experiments, are usually of $\sim 10^{-15}$ of incident power. This paper represents 6 (7) channel filter polychromator equipped with avalanche photodiodes and low-noise preamplifiers. The incorporated ADC system (5 GS/s, 12 bit) provides digital optical output preventing acquisition system from electromagnetic interferences. The calibration techniques and $T_e$, $n_e$ with corresponding errors measured in Globus-M plasma are given for the digital polychromator test-bench.

1. Introduction

Incoherent Thomson scattering (TS) is one of the key diagnostics for measurements of electron temperature and density profiles in modern tokamaks. Study of such processes as L-H transitions, Internal Transport Barriers, Edge Localized Modes instability together with ability to use the diagnostic as a sensor for real-time plasma control require reliable multiple laser and spectral analytical systems. There are several approaches to TS spectrum analyses. These are diagnostic techniques based on matrix detector (CCD camera, Image Intensifier) on the output of filter [1] and grating polychromators [2] and avalanche photodiodes (APD), which can also be used with both filter [3] and grating [4] devices. The Globus-M TS system based on multiple pulsed Nd:Glass laser (1055 nm, 2 J, 30 ns, up to 20 pulses in burst mode with repetition rate up to 3 kHz) and Divertor system based on Nd:YAG laser (1064 nm, 2 J, 3 ns, 100 Hz). The laser wavelength choice prohibits the use of matrices sensors due to low quantum efficiency in the vicinity of 1000 nm and causes the choice of silicon APDs. Interference-filter-based polychromators with the APDs [3] have a high throughput and are routinely used for TS diagnostics in fusion devices. Laser pulse of 3 ns (FWHM) and high-speed electronics developed for Divertor TS system are chosen to resolve in time TS signals and stray light reflected from the closely spaced first wall as well as for minimizing signals of plasma background and heated surface radiation. Filter polychromator described in this paper, will be used for both the Equatorial Edge and Divertor TS systems on Globus-M tokamak [5] with the following parameters:
major radius $R = 36$ cm and minor radius $a = 24$ cm, toroidal magnetic field $B_T = 0.4$ T, core $n_e \sim 5 \times 10^{12}$ to $2 \times 10^{14}$ cm$^{-3}$ and core $T_e$ from 20 eV to 1.5 keV (see figure 1). The equatorial edge and divertor TS systems, to be launched next year, should provide measurements in 9 spatial points for divertor region and 5 at the edge – near the pedestal region. The edge $T_e$ are much lower than core ones [6] and require to use more narrow spectral channels.

![Figure 1. Globus-M typical $T_e$ and $n_e$ values](image)

![Figure 2. Spectral channels of edge TS polychromator, APD quantum efficiency and TS spectrum for $T_e = 100$ eV](image)

### 2. Data handling

#### 2.1. Signal processing

Principles of $T_e$ and $n_e$ measurements that underlie the TS diagnostics are quite simple: $n_e$ is determined from overall scattered light intensity and temperature comes from Doppler broadening of TS spectra (figure 2). Laser beam propagates through the plasma and scattered by free electrons. The scattered radiation is collected by fiber bundle and delivered to the high-transmission polychromators [7]. The 1.5 mm APD’s are equipped with low-noise transimpedance preamplifiers and the output signal are digitized in oscilloscope mode. Such approach looks the most flexible to distinguish TS signal against stray light; to record signal prehistory for background noise estimation and to process signal with the assistance of required tools of mathematics.

The number of scattered photons in spectral channels were calculated in accordance with:

$$N_{pe} = \frac{\int U_{signal} dt}{M \cdot G \cdot R_f \cdot e \cdot R_{out} / (R_{in} + R_{out})},$$

where $U_{signal}$ – amplified signal, $\tau$ – laser pulse duration, $M$ – APD gain, $G$ – multiplication factor of amplifier, $R_f$ – feedback resistances of transimpedance preamplifier, $e$ – electron charge, $R_{out}$ and $R_{in}$ – amplifier output and ADC input resistances.

#### 2.2. Temperature and density estimation

The number of photoelectrons in $i^{th}$ channel can be written as:

$$N_{fe_1} = n_e \cdot L \cdot \Omega \cdot E_L \cdot \frac{\lambda_0}{hc} \int_{\lambda_{MIN}}^{\lambda_{MAX}} \sigma_{TS} \cdot T_{over}^i \cdot QE^i \cdot K^i d\lambda,$$

where $n_e$ – electron density, $L$ – scattering length, $\Omega$ – solid angle, $E_L$ – laser pulse energy, $\lambda_0$ – incident light wavelength, $h$ – Planck constant, $c$ – speed of light, $\lambda_{MIN}$ and $\lambda_{MAX}$ – spectral channel edges, $\sigma_{TS}$ TS cross section, $T_{over}$ – overall transmission, $QE$ – APD quantum efficiency, $K$ – filter
spectral characteristics. The incoherent TS spectra for the expected in Globus-M $T_e$ values (see figure 1) can be found in a number of papers [8]. Temperature estimation is obtained from minimization of $\chi^2$ function.

$$\chi^2 = \sum_i \frac{1}{\sigma_{N_{TS}}} (N^i_{\text{EXP}} - N^i_{\text{NUM}})^2$$

(3)

where $N^i_{\text{EXP}}$ – measured number of photoelectrons, $N^i_{\text{NUM}}$ – number of photoelectrons for the expected $T_e$ and $n_e$. Iterative minimization of $\chi^2$ function gives the most probable values of the measured $T_e$ and $n_e$.

2.3. Accuracy of estimation

Random errors in $T_e$ and $n_e$ measurement were estimated using the following equations [9]:

$$\sigma_{T_e} \approx \left[ \sum \left( \frac{N_{fe_i}}{\sigma_{N_{fe_i}}} \right)^2 \cdot \left( \sum \left( \frac{\partial N_{fe_i}}{\partial T_e}, \frac{1}{\sigma_{N_{fe_i}}} \right)^2 - \left( \sum \frac{\partial N_{fe_i}}{\partial T_e} \frac{1}{\sigma_{N_{fe_i}}} \right)^2 \right) \right]^{-0.5}$$

(4)

$$\sigma_{n_e} \approx n_e \left[ \sum \left( \frac{\partial N_{fe_i}}{\partial n_e}, \frac{1}{\sigma_{N_{fe_i}}} \right)^2 \cdot \left( \sum \left( \frac{\partial N_{fe_i}}{\partial n_e}, \frac{1}{\sigma_{N_{fe_i}}} \right)^2 - \left( \sum \frac{\partial N_{fe_i}}{\partial n_e} \frac{1}{\sigma_{N_{fe_i}}} \right)^2 \right) \right]^{-0.5}$$

(5)

Here $\sigma_{N_{fe_i}}$ is the dispersion of the photoelectrons detected in $i$-th spectral channel:

$$\sigma_{N_{fe_i}} = \sqrt{F^i_{\text{APD}} (N_{fe_i} + 2N_{\text{bg_i}}) + 2N_{\text{AMP_i}}}$$

(6)

where $F^i_{\text{APD}}$ is APD excess noise factor in $i$-th channel, $N_{fe_i}$ and $N_{\text{bg_i}}$ – the TS and background photoelectrons before amplification in $i$-th channel, $N_{\text{AMP_i}}$ – the amplifier noise given also as the photoelectrons before amplification.

The equation (6) can be simplified to:

$$\sigma_{N_{fe_i}}^2 = F^i_{\text{APD}} N_{fe_i} + \sigma_0^2$$

(7)

where $\sigma_0^2$ – the total background noise including noise of electronics – is estimated from the noise analysis of the signal prehistory (see figure 3). For estimation of the effective excess noise factor $F$ we used dispersion of the signal intensity shown in figure 4. The linear fitting of the measured signals gives $F \sim 4.7$ exceeding by $\sim 17\%$ the value provided by Hamamatsu S11519 data sheet for APD gain $M = 100$.

2.4. Electronics

Specially designed PHEMT-based transimpedance preamplifier provides wideband, low noise amplification of APD signal. The integration time 3-5 ns were optimized for the detected TS signal duration 3-5 ns FWHM. The acquisition system based on DRS4 chip [10] provides 12-bit (4096 steps) digitizing with a $\sim 0.25$ mV amplitude resolution and $\sim 5$ GHz sampling rate. Designed option to compensate slowly variable signal (background radiation) provides the use of full ADC dynamic range for digitizing of pulsed TS signal. For 5 ns integration time the measured level of intrinsic noise is of $\sim 0.5$ mV or $\sim 16$ noise photoelectrons given to the detector input for $M = 100$. 
3. Polychromator performance

It is well known that a non-uniform distribution of the spectral channel widths [3] may cover a wide spectral range by relatively small number of the channels. The current design provides $T_e$ measurements in the range of 3–600 eV by four spectral channels (see figures 5–8). These estimations were carried out for actual design of the edge and divertor Globus-M TS systems with corresponding parameters presented at the figure 1 and including background from bremsstrahlung for typical Globus-M plasma.

The relative calibration was performed using the scanning light source. It includes the tungsten band lamp and monochromator with instrumental function (FWHM) $\sim 0.5$ nm that is much narrower than interference filter bandwidths. Nevertheless, we have found that deconvolution may be quite important for the absolute calibration with the use of Raman scattering. Even small shift of a spectral channel edge shown by dashed curve in figure 9 may lead to a marked change in rotational Raman scattering (RRS) signal intensity if the shift includes or excludes separate spectral lines. The differences between RRS signals with and without deconvolution are presented in Table 1 for first and second spectral channels.
Figure 5. Normalized error curve of $n_e$ estimation for typical divertor plasma.

Figure 6. Normalized error curve of $T_e$ estimation for typical divertor plasma.

Figure 7. Normalized error curve of $n_e$ estimation for typical edge plasma.

Figure 8. Normalized error curve of $T_e$ estimation for typical edge plasma.

Table 1. Calculated RRS signals at $p = 30$ Torr.

| Channel | RRS Signal, phe | RRS Signal, phe | Difference |
|---------|----------------|----------------|------------|
| Without deconvolution | 939 | 934 | 0.54% |
| With deconvolution | 258 | 250 | 3.20% |

The absolute or density calibration relies on Raman scattering for $0.03 – 10$ Torr of Nitrogen. Figure 10 represents scattering signal intensity versus $N_2$ pressure. Signal for each pressure was measured 100 times that are shown by grey points. The mean values (red cross in figure 10) demonstrates good linear dependence in overall pressure range. The dispersion of the Raman scattering signals (see figure 10) gives information about overall detection accuracy for different signal values, which includes superposition of statistical signal noise, amplifier noise and other disturbing influences on the signal. The results are in good agreement with predictions made for the existing experimental layout and Raman cross section data given from [11].
4. First $T_e$, $n_e$ measurements in plasma experiment

The developed digital filter polychromator was tested during 2016 summer campaign on Globus-M. The scattered light was collected from the plasma equatorial edge ($R = 0.21$ m), characterized by moderate electron densities $<n_e> \sim 2\times10^{19}$ m$^{-3}$ and temperatures $<T_e> \sim 150$ eV. To test polychromators the laser 1054 nm 30 ns was used.

Figure 11 represents an example of TS signals of 1$^{st}$, 2$^{nd}$, 3$^{rd}$ and 4$^{th}$ spectral channels, corresponding to $n_e = 3\times10^{19}$ m$^{-3}$ and $T_e = 160$ eV. The most intensive stray light manifested in the nearest to the laser wavelength – 1$^{st}$ channel (red mark on figure 11) and delayed by ~15 ns can be separated thanks to oscilloscopic operational mode and high sampling rate (5 GHz).

5. Summary

The paper presents first results obtained by the digital filter polychromator, which was developed for application in Thomson scattering plasma diagnostics. The polychromator is equipped with APDs of ~1.5 mm and specially designed PHEMT-based transimpedance preamplifiers. This fast and low-noise detector unit combined with build-in ADC (12 bit, 5 GS/s) provides ~16 photoelectrons own noise level of the entire detection system recalculated on the detector input (before APD amplification) for integration time of ~5 ns. The polychromator was calibrated and tested with the use of Raman scattering (RRS) in gas Nitrogen. The
dispersion of multiple RRS measurement allows performing the absolute measurement of overall system noise for different signals. This experiments shows that for signals of 100 photoelectrons and above, the noise of the RRS signal is defined mainly by statistical noise and constant excess noise factor. The measured excess noise \( F \approx 4.7 \) exceeding by \( \sim 17\% \) \( F = 4 \) provided by Hamamatsu S11519 data sheet for APD gain \( M = 100 \). The estimations carried out for RRS relative calibration demonstrates the necessity to measure spectral channel characteristics with quite high spectral resolution because even small shift of a spectral channel edge may lead to a significant change in RRS signal intensity. The extremely compact size and low energy consumption of the ADC based on DRS4 chip allow combining the filter polychromator, digitizer and CPU for data processing in one stand-alone device, providing digital optical output preventing electromagnetic interferences. The first TS measurements in Globus-M demonstrate that operation in oscilloscope mode and high sampling rate (5 GHz) helps to separate in time the TS and stray light delayed by \( \sim 15 \) ns.

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