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Electron temperature measurements at the Globus-M2 tokamak using multi-laser Thomson scattering

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Diagnostics of the plasma electron component by the method of Thomson scattering $T_e(R, t)$ of laser radiation makes it possible to reliably measure the spatial distributions of the electron temperature and density. One of the obstacles to the implementation of TS diagnostics in thermonuclear reactors is the distortion of the spectral characteristics of the optical system due to radiation-induced absorption and contamination of optical elements with erosion products of the first wall. As a consequence, the reliability of measurements by the TS method will decrease over time. The paper describes the method of multi-laser Thomson scattering, which will solve this problem. The results of the first experiments on the Globus-M2 tokamak are also presented.

Keywords: plasma diagnostic, tokamak, thomson scattering, laser diagnostic, spectroscopy.

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An essential requirement for diagnostic systems of Thomson scattering (TS) in reactor conditions is the ability to measure the temperature of electrons under the assumption that the spectral characteristic of the light collection system is unknown and may vary over time [1,2]. This problem is solved using the method of multi-wave laser sensing [3]. This approach is planned to be applied in all three diagnostic systems of the ITER reactor TS, including diagnostic systems for central, edge and divertor plasma [2,4]. The first preliminary experiments to test this approach were carried out on the RFX-mod [5] and Globus-M [6]. The method is based on the observation of Thomson scattering signals from probing lasers generating radiation at different wavelengths. The main assumption is the condition of the invariance of the electron temperature in the observation area, limited by the intersection of the probing laser beam and the projection of the detector image on it, in the time interval determined by the delay between the laser pulses. In the experiments carried out earlier on the Globus-M and RFX-mod installations, this condition was not fulfilled, since the time interval between laser pulses was comparable to the characteristic times of the development of magnetohydrodynamic instabilities. Another option of this approach involves observing the TS signal from a given volume of plasma measured at two different angles simultaneously. This approach, which makes it possible to estimate plasma parameters using differently broadened TS spectra, was experimentally tested on the TST-2 [7] installation. This option has a number of significant limitations in relation to a thermonuclear reactor, since it requires the use of either a complex geometry of collecting scattered radiation, or a multi-pass probing system (assuming at least twice the passage of laser radiation through the plasma region under study). To implement the considered approach, the time interval between laser pulses should be minimal, preferably on a time scale smaller than the characteristic times of electron temperature change.

This paper presents the results of experiments on measuring the electron temperature using a multi-wave laser technique implemented on a Globus-M2 tokamak [8,9]. In these experiments, two pulse-periodic laser sources on Nd:YAG and Nd:YLF crystals are used to probe the plasma, emitting at wavelengths of 1064 and 1047 nm respectively. Nd:YAG laser generates pulses with energy in each pulse $\leqslant 3$ J at pulse duration 10 ns with pulse repetition frequency up to 300 Hz. For an Nd:YLF laser, the pulse energy is up to 2 J with a pulse duration of 3 ns with a pulse repetition frequency of up to 50 Hz. A system of filter spectrometers equipped with a precision registration system [10,11] was used to register scattering signals. A feature of the diagnostic system is the ability to adjust the time delay between Nd:YAG and Nd:YLF laser pulses, which ensures synchronization of laser pulses with nanosecond accuracy.

Assuming that on the time scale < 100 ns local plasma parameters in a tokamak are a constant value, the electron temperature can be determined by minimizing the expression [3]:

$$\sum_{i=1}^{N} \frac{\left(S_i - \gamma F_i(T_e)\right)^2}{\sigma_{S_i}^2} \to \min. \quad (1)$$

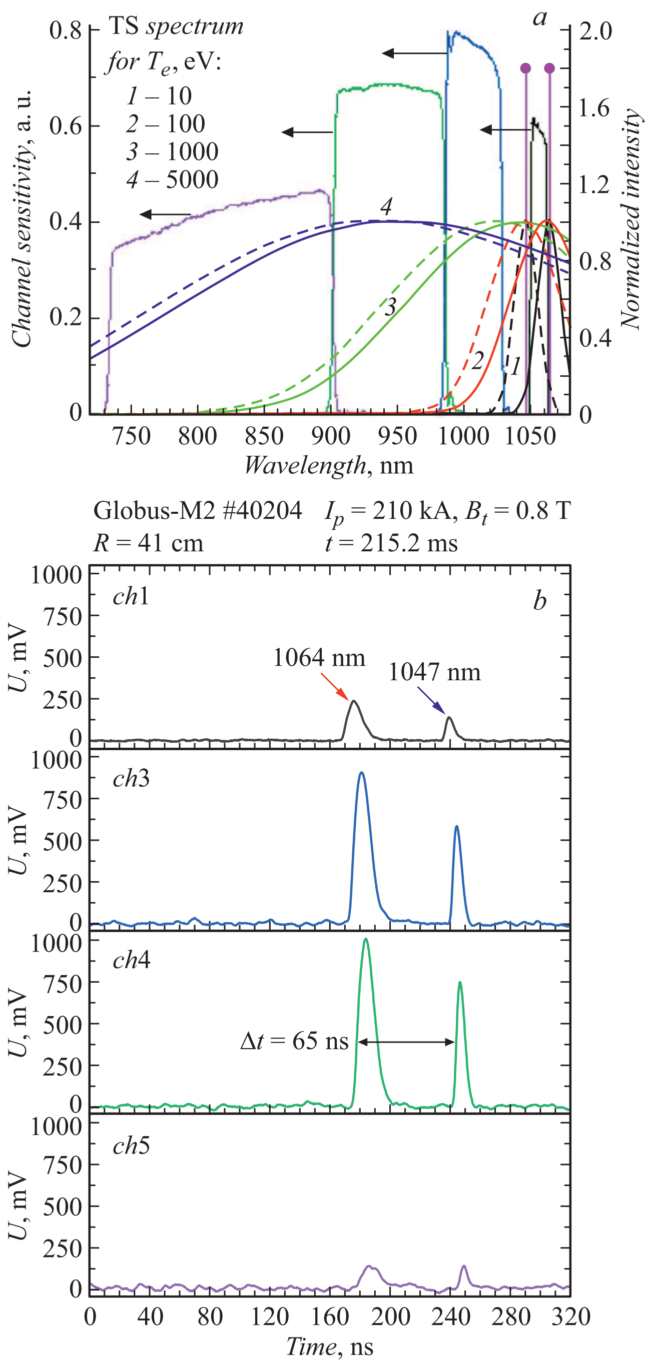

Figure 1. *a* — comparison of the spectral characteristics of a polychromator with scattered radiation contours for both values of probing wavelengths at different electron temperatures. Solid curves correspond to scattering contours for $\lambda_{01} = 1064$ nm, dashed — for $\lambda_{02} = 1047$ nm. The position of the probing wavelengths is indicated by vertical markers. *b* — oscillograms of synchronized Thomson scattering signals for $\lambda_{01} = 1064$ nm and $\lambda_{02} = 1047$ nm.

Here γ — the ratio of the laser pulse energy in the observed scattering volume, S_i — the ratio of the signals of the i channel of the spectrometer detecting the scattering of laser radiation at two wavelengths λ_{01} and λ_{02}: $S_i = U^{\mathrm{TS}}_{\lambda_{01_i}}/U^{\mathrm{TS}}_{\lambda_{02_i}}$, $\sigma^2_{S_i}$ — estimate of the variance of this ratio, and $F_i(T_e)$ — expected dependence of the ratio of scattering signals on electron temperature:

$$F_i(T_e) \approx \frac{\int_{\lambda_{\min_i}}^{\lambda_{\max_i}} \sigma_{\mathrm{TS}}(T_e, \lambda, \lambda_{01}) d\lambda}{\int_{\lambda_{\min_i}}^{\lambda_{\max_i}} \sigma_{\mathrm{TS}}(T_e, \lambda, \lambda_{02}) d\lambda}. \tag{2}$$

Here $\lambda_{\min_i}$ and $\lambda_{\max_i}$ are the boundaries of the corresponding spectral channel.

A demonstration of the application of this approach in a plasma experiment was performed on the upgraded Thomson scattering diagnostics system of the Globus-M2 tokamak. For this purpose, the existing sensing system was equipped with an additional Nd:YLF laser with generation at a wavelength of 1047 nm. This laser source was developed as a calibration laser for diagnostics of the divertor plasma of the tokamak reactor ITER. Its main task on ITER is the calibration of spectral equipment by TS signals in a narrow range of electron temperature < 200 eV [1]. The duration of the laser pulse at half the height in the experiment was 3ns with a repetition frequency of 50 Hz. The optical gates of the Nd:YAG and Nd:YLF laser sources were synchronized, every sixth pulse of the Nd:YAG laser operating at a frequency of 300 Hz was accompanied by an Nd:YLF pulse with a time delay of 60–70 ns. The use of high-bandwidth detectors and a high-speed recording system 3.2 GSamples/s made it possible to record scattering signals from both lasers within one page of the digitizer's memory.

A comparison of the spectral characteristics of the polychromator with the scattered radiation contours corresponding to different electron temperatures and measured at both probing wavelengths is shown in Fig. 1, *a*. Since the filter system of the tokamak Globus-M2 TS polychromators is not designed to measure TS signals from a laser emitting at a wavelength of 1047 nm, a high level of parasitic-scattered radiation in the second spectral channel led to the need to turn it off. It should be noted that the value of S_1 practically does not depend on the electron temperature, since the critical wavelength (see [3]) falls on the first spectral channel: $\lambda_{crit} = \sqrt{\lambda_{01}\lambda_{02}} = 1055$ nm. Due to the relatively close location of the probing wavelengths, measuring high temperatures using a multilaser technique requires high accuracy of measuring scattering signals in short-wave spectral channels.

Fig. 1, *b* shows examples of oscillograms of synchronized Thomson scattering signals. The first time pulse corresponds to the laser 1064 nm, the second — laser 1047 nm. The time delay between laser pulses is 60–70 ns. Fig. 2, *a* shows a comparison of the corresponding electron temperature profiles measured in the experiment. The calculation of T_e was carried out on the basis of spectral calibration data. It can be seen that at this time scale the discrepancy of the

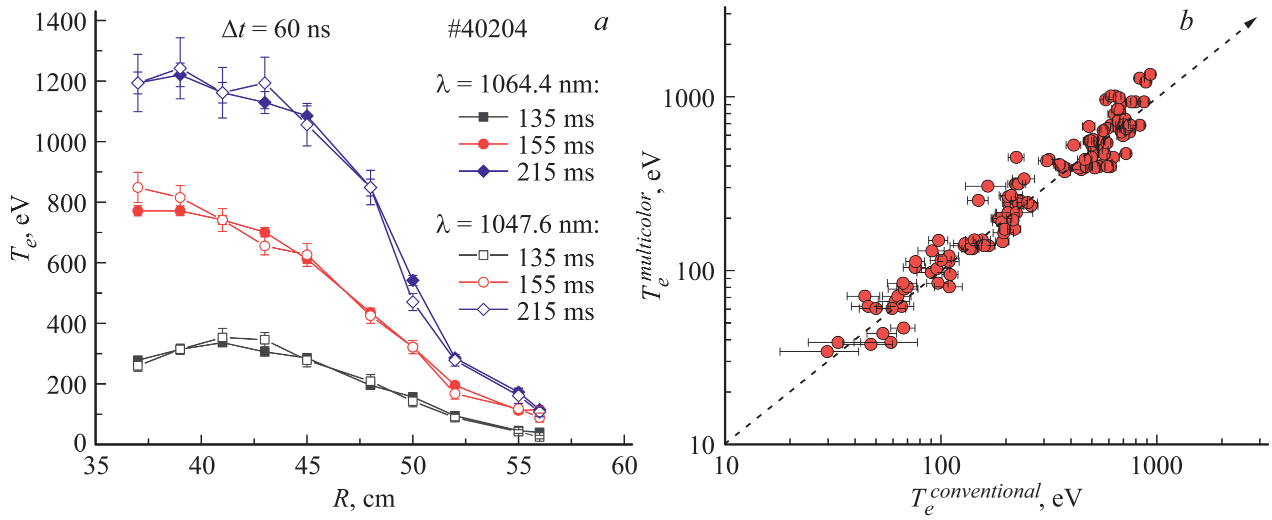

Figure 2. *a* — comparison of measured electron temperature profiles in various phases of the Globus-M2 tokamak discharge with a time delay of 60–70 ns. *b* — comparison of electron temperature calculated using a multilaser technique under the assumption unknown spectral calibration of the system (Y-axis), with values determined in the conventionall way (X-axis).

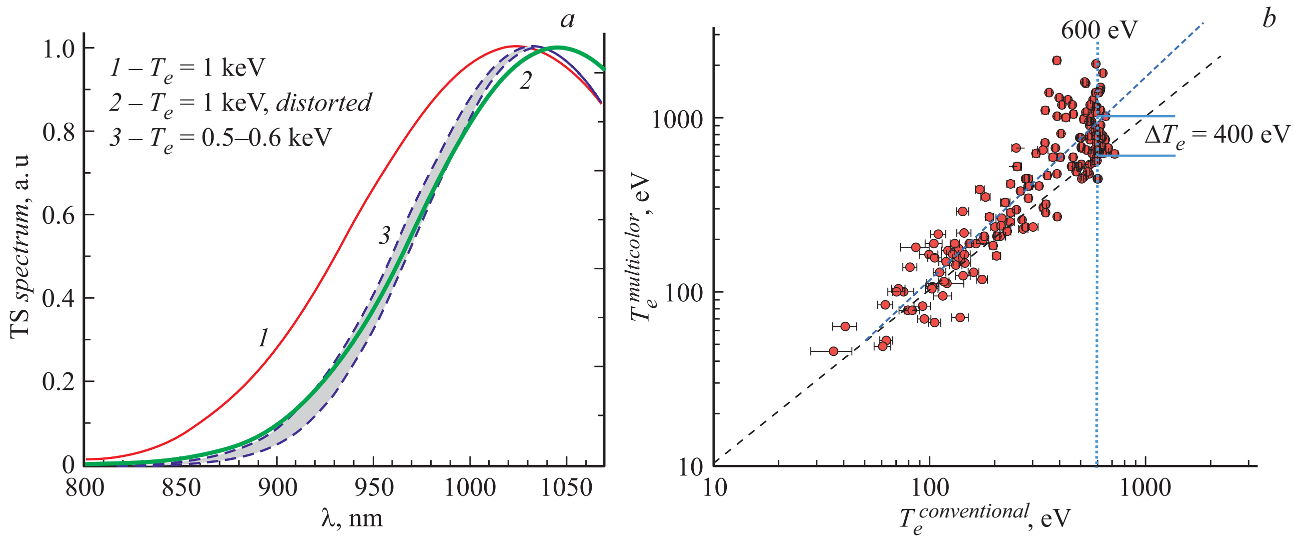

Figure 3. *a* — distortion of the spectral contour of the scattered laser for electron temperature 1 keV when introducing colored glass ZhS-20 into the optical scheme of the light collection system. *1* — undistorted contour for $T_e = 1$ keV, *2* — contour for $T_e = 1$ keV after passing through colored glass, *3* — undistorted contours of the scattered laser for $T_e = 0.5$ and 0.6 keV. *b* — electron temperature dependence (unknown spectral calibration of the system) from the values determined in the conventional way for undistorted spectral characteristics.

measured values T_e does not exceed the measurement error estimate.

Fig. 2, *b* illustrates a comparison of the electron temperature calculated using a multilaser technique under the assumption of an unknown spectral calibration of the system (Y-axis) with the values determined in the conventionall way (X-axis). It can be seen from the above dependence that multilaser sensing allows reliably determining the temperature of electrons. To answer the question of whether the proposed approach will allow tracking a possible change in the spectral characteristics of the light collection system, a special experiment was conducted. Distortion of the spectral characteristics of the optical light collection system both due to radiation-induced absorption of [2,4] and due to contamination of optical elements by products of erosion of the first wall [1] will manifest itself primarily in the form of a decrease in transmission in the shorter wavelength region of the spectrum. Such distortion can be simulated with the help of colored glass ZhS-20, installed in the optical path of diagnostics between the lens and fiber-optic bundles. The introduction of such a change led to a hardware distortion of the scattering contour caused by the transmission of colored glass. Fig. 3, *a* shows a comparison of undistorted and distorted scattering contours for electron temperature 1 keV. It can be seen that in the absence of information about the change in the spectral characteristics of the system, conventionall diagnostics mistakenly determines the electron temperature as 0.5–0.6 keV (contours shown by dashed lines in the figure) instead of 1 keV. Fig. 3, *b* shows a comparison of the electron temperature calculated using a multilaser technique under the assumption of an unknown spectral calibration of the system (Y-axis) with the values determined in the conventionall way (X-axis) for undistorted spectral characteristics. It can be seen from the figure that the main part of the points lies above the line $x = y$, which indicates a systematic underestimation of the value T_e calculated within the framework of the conventional approach, which was expected. Also, as expected, underestimating the value of T_e the greater the wider the spectral contour of the scattered radiation, i.e., the higher the values of the electron temperature itself. With the true value of $T_e = 1$ keV the measurements performed within the framework of the conventional approach turned out to be on average 0.4 keV lower according to calculations.

Thus, the temperature of electrons in the range of 30–1000 eV was measured on the Globe-M2 tokamak by the two-wave Thomson scattering method. The time delay between probing laser pulses at wavelengths 1047 and 1064 nm was several tens of nanoseconds. A Thomson scattering system is demonstrated that allows reliable measurements of the electron temperature under conditions of an unknown spectral characteristic of the scattered radiation collection system. The created multi-laser diagnostic system allows measurements to be carried out in the stationary mode of operation of the installation and can be used for use in a thermonuclear reactor and a source of thermonuclear neutrons.

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Conflict of interest

The authors declare that they have no conflict of interest.

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