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Tangential System of Thomson Scattering for Tokamak T-15

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Abstract—Two systems of Thomson scattering diagnostics, with vertical and tangential probing, are used in the D-shaped plasma cross section in tokamak T-15. The tangential system allows measuring plasma temperature and density profiles along the major radius of the tokamak. This paper presents the tangential system project. The system is based on a Nd:YAG laser with wavelength of 1064 nm, pulse energy of 3 J, pulse duration of 10 ns, and repetition rate of 100 Hz. The chosen geometry allows collecting light from ten uniformly spaced points. Optimization of the registration system has been accomplished. The collected light will be transmitted through an optical fiber bundle with diameter of 3 mm and quartz fibers (numerical aperture is 0.22). Six-channel polychromators based on high-contrast interference filters have been chosen as spectral equipment. The radiation will be registered by avalanche photodiodes. The technique of electron temperature and density measurement is described, and estimation of its accuracy is carried out. The proposed system allows measuring the electron temperature with accuracy not worse than 10% within the range of 50 eV to 10 keV on the pinch edge over the internal contour, from 20 eV to 9 keV in the plasma central region, and from 2 eV to 400 eV on the pinch edge over the outer contour. The estimation is made for electron density of not less than 2.6×10^{13} cm^{-3}.

Keywords: tokamak T-15, laser diagnostics, Thomson scattering

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Thomson scattering diagnostics will be used in the upgraded tokamak T-15 as a tool for studying plasma temperature and density. The tokamak chamber will have a noncircular cross section, which raises interest in measuring the temperature and density profiles along both the vertical chord of observation and the major radius of plasma. Therefore, installation of two diagnostic Thomson scattering systems with vertical and tangential probing is planned.

Thomson scattering systems with tangential probing are rarely used in tokamaks. Use of this geometry is usually rather complicated because of the necessity to choose the optimum disposition for the light collecting unit and is due to the impossibility to use a simpler geometry with vertical probing and light collection through equatorial branch pipes because of the constructional features of the devices. Thomson scattering diagnostics in the Globus-M [1] and MAST [2] tokamaks are examples of systems with tangential probing. The geometry of collecting diffused light is similar to the system geometry for the T-15 and is applied in the LHD [3].

In this paper, the key parameters, calculations, and hardware components of the designed Thomson scattering tangential system for tokamak T-15 are reviewed, and the estimate of measurement accuracy is presented.

DISPOSITION OF DIAGNOSTIC EQUIPMENT

The basic advantage of the tangential system of probing is the possibility to consider the profile of plasma temperature on the major radius in the equatorial plane of the tokamak. In Fig. 1, an outline of the equatorial section of the tokamak is presented. The beam input will be arranged through the 15th branch pipe, and its output will be through the 9th branch pipe, which will ensure the capture of most of the plasma from the edge of the plasma pinch on the torus internal contour to the edge on the torus external contour.

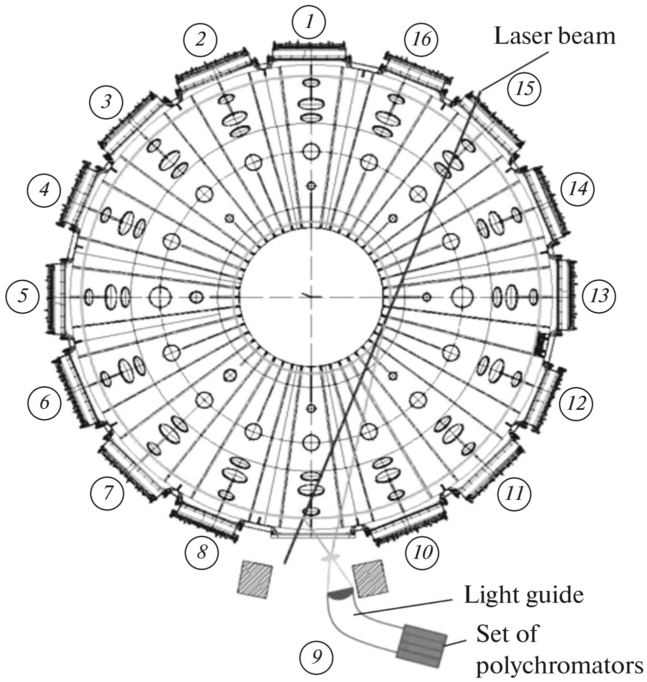

Fig. 1. The equatorial section of tokamak T-15 chamber. Laser beam input to the chamber. The zone of diffused light observation is limited to the green segments.

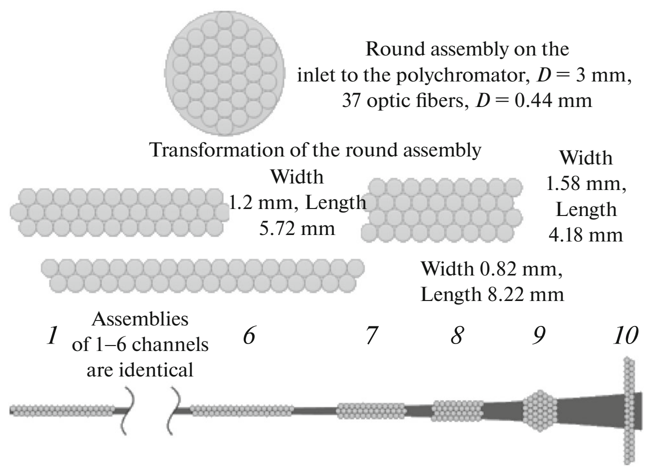

Fig. 2. Options of assemblies on the flank of fiber-optic channels and the outline of assembly positions along the beam image.

SYSTEMS OF LIGHT COLLECTION, TRANSPORT, AND REGISTRATION

Light collection will be carried out from ten spatial segments of the laser chord, whose projections onto the major radius are arranged uniformly. The arrangement of the light collection system is shown in Fig. 1; it provides the total overlapping of the plasma pinch from its internal to external edge and maximum collection of diffused light. For light transmission to the spectral device, optical quartz-quartz type fibers are chosen (numerical aperture NA = 0.22) with diameter $D = 440$ μm, which conform well with the inlet aperture of the spectral device [4].

At optimization of the light collecting system, modification of the laser beam diameter along the observation chord has been taken into account, as well as the geometry of the receiving flange of the fiber-optic guide. The inlet diameter of the filter polychromator to be used in the diagnostic system is 3 mm, which limits the assembly to 37 fibers with diameter of 440 μm. Since the collected light is projected onto the plane of the image by spots of different shapes, the inlet flanks of the fiber-optic assembly geometry should differ from the ones placed on the polychromator inlet in order to achieve the full capture of the beam over the entire width. Options of transformation of fiber-optic assemblies are presented in Fig. 2. Numbers *1–10* indicate images of the observation chord segments from which the collection is arranged.

At observation under a small angle in the plane of the image, light is collected from different points of the observation chord with various spatial angles. The amount of collected light varies depending on which spatial point output numerical aperture matches the fiber numerical aperture. The amount of registered scattered photons is described by the formula

$$N_0 = N\sigma_{TS} n_e L d\Omega K, \quad (1)$$

where N is the total number of photons in a laser pulse, σ_{TS} is the Thomson scattering cross section, n_e is the electron density, $d\Omega$ is the spatial angle of collection, L is the length of laser pulse, and K is the total transmission factor of the registration system. Here, $Ld\Omega$ is the geometrical factor determining the amount of collected light.

In Fig. 3, graphs for three different cases of matching point choice are shown: the innermost channel on the edge of the plasma pinch on the torus internal contour (internal edge), the central region of plasma, and the outermost channel on the torus external contour (external edge). In each of these variants, the optimum geometry of inlet flanks of the light guides was chosen. By results of comparison, the central point has been chosen, since it is the most favorable by the amount of collected light. The greatest objective aperture making it possible to ensure the complete trapping of the laser beam over the width to measure the plasma density is 117 mm. However, to avoid alignment errors, we choose the objective aperture diaphragm of 100 mm.

The objective will be placed close to the inlet window of the tokamak chamber at a distance of 1200 mm from its center. In Fig. 4, a more detailed outline of the flange and the objective disposition are shown. For the chosen geometry, the calculation of the collecting objective has shown the following parameters: focal

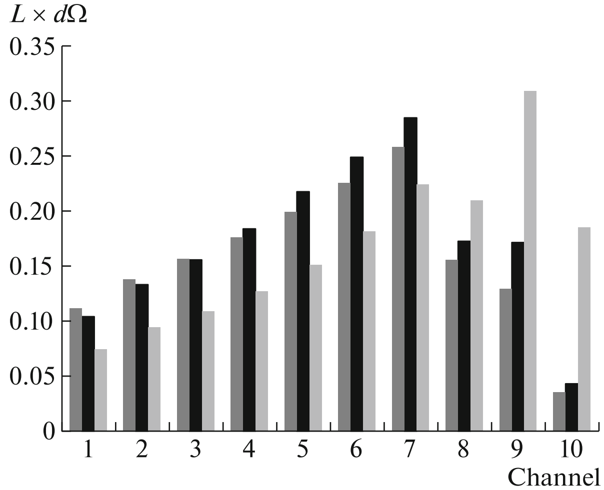

Fig. 3. Geometrical factor determining the amount of collected light for three cases of optimization of the collecting objective: (■) internal edge; (■) center; (■) external edge.

point is 182 mm, diaphragm opening is 1 : 1.8, and viewing angle is $\alpha = 47°$.

Registration of the collected light will be carried out by means of six-channel polychromators based on high-contrast interference filters and avalanche-type photodiodes [4]. The polychromator channel width is chosen on the basis of provision of the maximum dynamic range; signals in each spectral channel should not differ greatly, which will ensure the identical accuracy of measurements. In Fig. 5, reference spectra of Thomson scattering are presented for various temperatures and ranges of sensitivity of polychromator spectral channels optimized for the temperature of central zone of 1 keV, which will allow performing measurements both in the ohmic operating mode of the device and in modes with additional heating. For calculations, study [5] was used.

Below we present the estimated accuracy of electronic temperature measurement for the chosen parameters of the system.

LASER

Parameters of Nd:YAG laser which will be used in the system [6, 7]:

Operating wavelength, nm ...	1064
Pulse energy, J ...	3
Pulse operating frequency, Hz ...	100
Pulse duration, ns ...	10
Output beam diameter, mm ...	15
Divergence, mrad ...	0.1

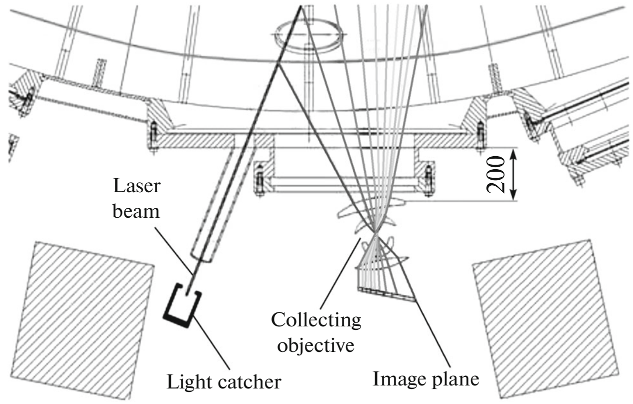

Fig. 4. Disposition of the collecting objective on the tokamak diagnostic flange.

The first trial of this laser will be carried out within the Thomson scattering diagnostics in the T-10 device.

To inject laser radiation into the chamber, it should be transported over a considerable distance of about 25 m. Diffraction effects appear at these distances. The estimation shows the Fresnel diffraction effect at this distance, and the laser spot is not homogeneous, but takes the form of ring. When the laser beam is used without size modification, the number of open Fresnel zones is

$$F = \frac{\rho^2}{z\lambda} \approx 2.11;$$

here, F is the number of open Fresnel zones; z is the required distance of the beam transport; λ is the wavelength of laser radiation; ρ is the minimum diameter of the laser beam in the tract. Two- to threefold expansion of the beam makes it possible to reduce the influ-

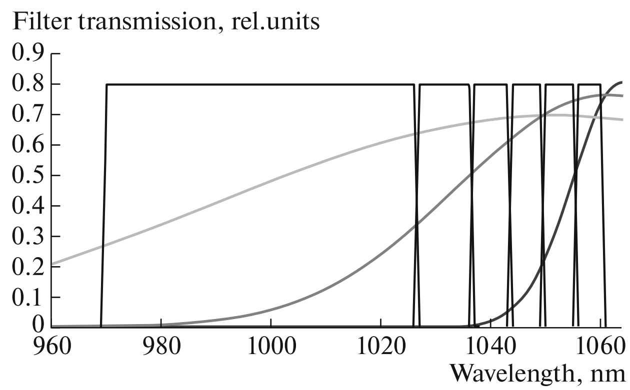

Fig. 5. Performance characteristics of the polychromator spectral channels (——) and profiles of Thomson scattering for different temperatures: (——) 100 eV; (——) 1 keV; (——) 5 keV.

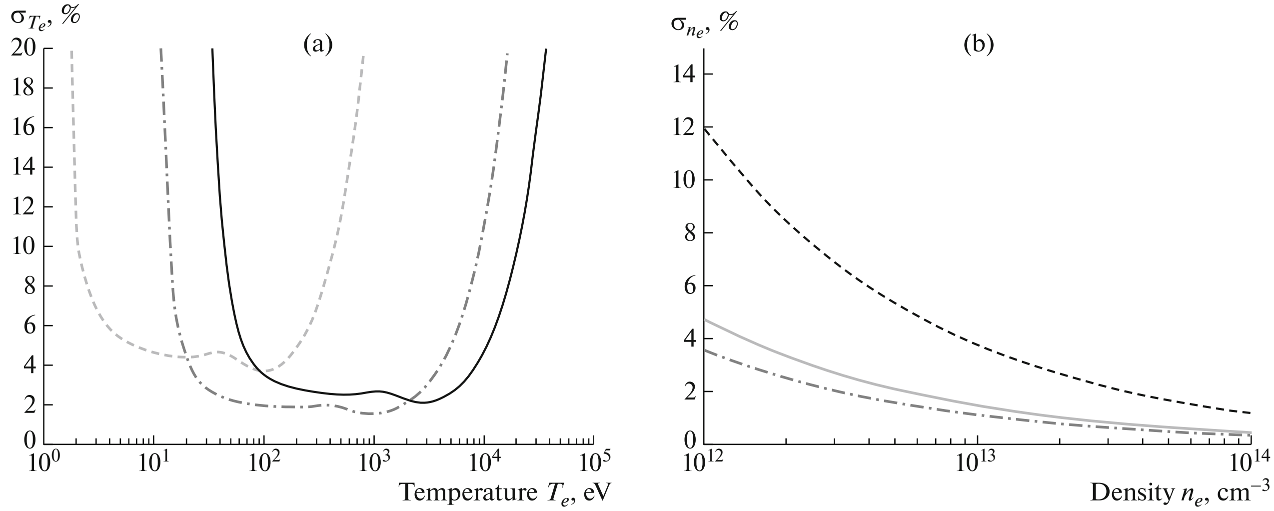

Fig. 6. Curves of errors at measurement of temperature: (- - - - - -) external edge; (– · – · –) center; (———) internal edge (a); density: (- - - - - -) 10 keV; (– · – · –) 1 keV; (———) 100 eV (b).

ence of diffraction and to obtain a homogeneous profile. For this purpose, an expanding telescope at the beginning of the tract and a focusing telescope at the chamber inlet will be used.

ESTIMATION OF MEASUREMENT ACCURACY

To evaluate the temperature measurement accuracy, the technique provided in [5] was used. In our case, the spectrum is divided into channels nonuniformly, and the number of photoelectrons in the set range of wavelengths will be determined as

$$N_k = \eta N_0 \int_{x_1}^{x_2} \frac{1}{\sqrt{2\pi}} \frac{c}{a} Y \exp\left(-\left(\frac{c}{a}\right)^2 Z\right) dx, \qquad (2)$$

where $x = \dfrac{\lambda_s - \lambda_0}{\lambda_0}$; c is the speed of light; λ_s is the diffused light wavelength over which the integration is performed; N_0 is the number of photons over the entire spectrum found from (1); η is the quantum yield of the detector; a is the presumed velocity of electrons; and Y and Z are determined by the expressions

$$Y = 2^{-1/2}(1 - 3.5x + 7.4x^2 - 12.5x^3);$$

$$Z = x^2(1 - x)/2; \; x = \lambda_k/\lambda_0,$$

where λ_k is the central wavelength of the kth channel, for which Y and Z are calculated, and λ_0 is the laser wavelength.

As formula (2) shows, the diffused light spectrum plotted on a semi-log scale looks like a straight line. The measurement accuracy is estimated by the least squares method.

In Fig. 6, curves of relative errors of temperature and plasma density measurements for the chosen set of polychromator spectral channels are shown. The calculation has been carried out for three regions: the plasma edge zone on the torus external contour, the central zone, and the edge zone on the torus internal contour. Note that only the statistical photoeffect error on avalanche-type photodiodes is considered in the calculation. The plasma density of 2.6×10^{13} cm^{-3} [8] has been used in the estimation.

As the graphs show, the proposed system makes it possible to carry out measurements with accuracy above 10% for electron temperature in the internal edge zone in the range from 50 eV to 10 keV, in the central zone in the range from 20 eV to 9 keV, and in the external edge zone in the range from 2 to 400 eV and for densities exceeding 2×10^{12} cm^{-3} over all the observation chord.

For comparison, we give the results of several diagnostics based on Nd:YAG lasers. The Japanese JT-60U device features measurement accuracy of 4–10% for temperatures in the range from 100 eV to 10 keV and 2–5% accuracy for density of 5×10^{13} cm^{-3} [9]. The measurement accuracy for the Globus-M device is 5–10% within the range from 10 eV to 2 keV [1]. We can make a conclusion that the tangential system designed for the T-15M device compares favorably with the measurement accuracy of other devices.

CONCLUSIONS

Hence, the key parameters are calculated and basic hardware components are selected for the future tangential Thomson scattering diagnostics of tokamak T-15. Presently, the laser is undergoing tests in the structure of the tokamak T-10 system.

The expected temperature range in various conditions of the upgraded T-15 device at a mean density 2.6×10^{13} cm^{-3} will be from 100 eV to 17 keV (radial variation) with 8-MW electron-cyclotron heating and 8-MW heating by a neutral beam [8]. Comparing these values with the estimates, we see that the expected measurement accuracy of diagnostics in the main region of T-15 operating parameters, both for temperature and for density, exceeds 10%. However, when the measured temperature is above 10 keV, the accuracy slightly decreases, but the error does not exceed 20%.

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