TOKAMAKI

VERTICAL DIAGNOSTICS OF THOMSON SCATTERING PROJECT FOR THE T-15MD TOKAMAK

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Abstract. To measure the parameters of the electronic component of the plasma of the T-15MD tokamak, a Thomson scattering diagnostics complex is being developed, which allows studying various zones of the plasma column. This work is devoted to the development of the T-15MD Thomson scattering system with vertical probing, which provides information on the plasma parameters along the vertical diameter of the plasma column. Plasma probing is performed by an Nd:YAG laser with a multi-pass system for inputting laser radiation into the tokamak chamber. The laser operates at the second harmonic $\lambda = 532$ nm. Scattered radiation is collected by one wide-angle lens. Light is transmitted to the registration system by a fiber-optic collector consisting of 159 fiber-optic assemblies measuring 2 × 1 mm. The registration system consists of three units, each of which includes a matching optics system and a polychromator with a detector. The scattering spectrum is recorded using an image intensifier tube and a CMOS camera. To achieve a high light transmittance of the optical diagnostic system, a detailed calculation of the parameters and design of each optical unit was performed: the collecting objective, the matching optics system, and the polychromator. In comparison with the T-10 Thomson scattering diagnostics, the system transmittance was significantly improved due to careful selection of optical materials, as well as a new design of the matching optics system, consisting mainly of mirrors. Using synthetic diagnostics, the accuracy of measuring the electron temperature and density was estimated. The plasma spectra from the T-15MD limiter region are used as the plasma background. The Thomson scattering diagnostics system in the T-15MD tokamak plasma with vertical probing will allow measuring the electron temperature with an error of less than 10% in the range from 80 eV to 6 keV at an electron density of more than 6×1018 m-3 in the central plasma region. At the periphery, the error is <10% for the Te range from 100 eV to 2 keV at ne>1×1019 m-3. The spatial resolution of diagnostics will be ~11 mm for the center of the plasma cord and ~22 mm for the peripheral region of the plasma.

Keywords: *Tokamak T-15MD, laser diagnostics, Thomson scattering*

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1. INTRODUCTION

Thomson scattering (TS) diagnostics, as one of the most informative tools for studying the electron component of plasma, will be used on the T-15MD tokamak. Due to the complex shape of the plasma column, it is planned to create a TS diagnostic complex that will include several systems. The first system is for measuring plasma parameters along the major radius of the device (tangential system) [1]; the second - along the vertical chord (vertical system [2]); the third - in the tokamak divertor (divertor system [3]). This article is devoted to the development of the vertical Thomson scattering system.

The vertical TS system is based on the use of the second harmonic of a Nd:YAG laser and light registration by an image intensifier (IIT) with a CMOS camera. A similar diagnostic scheme successfully operated on the T-10 tokamak [4], and the experience of developing and operating the system on T-10 has been transferred to the new vertical system of the T-15MD tokamak.

Currently, television diagnostics of Thomson scattering (TS) is used on modern facilities as a diagnostic tool that provides unique spatial resolution of plasma parameters along the laser beam, enabling the study of transport barriers in the plasma column [5 - 8]. The vertical TS diagnostics for T-15MD is being developed for tasks such as studying internal transport barriers, improving the reliability of magnetic configuration reconstruction, etc.

The following requirements are set for this diagnostic system on the T-15MD facility: measurement temperature range from 100 eV to 8 keV at electron density $10^{18} < n_e < 10^{20}$ m^{-3}, measurement errors should be less than 10%, spatial resolution should be from 1 to 2% of the tokamak minor radius [4,7,8].

The article presents the diagnostic design principle, a brief description of the main components, and the system alignment methodology. An assessment of the measurement accuracy of T_e and n_e based on synthetic diagnostics taking into account the background radiation of the T-15MD tokamak plasma is provided.

2. DIAGNOSTIC DESIGN PRINCIPLE

The cross-section of the T-15MD facility, where the vertical TS diagnostics with television registration of the scattering spectrum will be located, is shown in Figure 1. The probing laser beam is introduced into the tokamak chamber through the lower port. To increase the energy of the scattered light, it is proposed to use a multi-pass input-output laser radiation system [9,10]. The dimensions of the input and output ports allow for a 7-pass system. The light scattered by the plasma is collected by an objective lens and transmitted via a fiber optic collector to the spectral instrument(s), where it is registered by a detector (image intensifier with CMOS camera). To select the optimal parameters of the diagnostic optical components, a preliminary calculation of the system was performed.

The main parameter that characterizes the amount of collected light is the value $S_{det} d\Omega_{det}$ of the collection system - the product of the total area of photocathodes of the collection system and the solid angle in the image field in front of the detector. The value $d\Omega_{det}$ and the number of detectors determine the maximum possible amount of collected light, and consequently, the accuracy of plasma parameter determination. In a matched optical system, the parameter SdΩ remains invariant in any cross-section. The collection optics is designed so that the entire laser beam in cross-section is registered by the light collection system. The purpose of the collection lens is to transmit light from the laser chord, not the entire resulting image. Therefore, the collected scattered light is proportional to $Ld\Omega_{plasma}$, where L is the length of the laser chord segment. $Ld\Omega_{plasma}$ is not an invariant. This feature can be used to increase the collected scattered light in each spatial channel. Optical fiber is used to connect the collection lens and spectral instruments. When transforming the output end of the optical fiber with width b, relative to the input end with width a, it is possible to achieve an increase in collected light in one spatial channel by a factor of $1/m^2$, where m=a/b is the transformation coefficient of the fiber optic assembly.

The main parameters of the spectral instrument necessary for calculating the optical scheme of diagnostics are given in table 1.

Using the presented values, several variants of the vertical TS registration system with different transformations of the fiber optic collector and number of spectral instruments have been calculated.

The most optimal option is the one with the transformation of the fiber optic collector 1:2 and with three spectral instruments. In this case, we have the maximum amount of collected light ($Ld\Omega_{plasma}$ 5×10^{-5} m·sr) with spatial resolution meeting the diagnostic requirements (1-2%). Spatial resolution requirements are set taking into account the characteristic spatial resolution of TR television diagnostics. In the T-10 tokamak plasma, the resolution is 1.7% of the minor radius [4], MAST 1.1% [7], TEXTOR 0.9% [8].

During the development of the diagnostic optical units, a careful selection of optical materials in the working spectral range (400-700 nm) was carried out in order to obtain the maximum possible light transmission coefficient. The optical system was also required to provide optical resolution. When adjusting the position of the fiber optic collector relative to the laser beam, it is necessary to optically resolve the image of the laser beam on the collector. For this, it is necessary to resolve the image of an optical fiber with a diameter of 200 μm in each optical unit. The resolving power is determined using the frequency-contrast characteristic or MTF (modular transfer function), with a resolution criterion of MTF=0.15, which corresponds to the Rayleigh criterion [11].

3. PLACEMENT OF DIAGNOSTICS ON THE T-15MD TOKAMAK

The diagnostic is based on a Nd:YAG laser with a wavelength of 532 nm; pulse energy of 2.5 J with a duration of 10 ns and a pulse repetition rate of 100 Hz. Plasma probing is carried out in the vertical direction. The schematic diagram of the diagnostic is shown in Fig. 3.

Laser radiation is transported through a system of mirrors located in the basement of the facility. To adjust the input-output system of laser radiation into the plasma, the last two mirrors of the path are installed on motorized linear platforms, and the last mirror has a motorized mount for tilting. The lens provides focusing of laser radiation in the equatorial plane of the vacuum chamber.

The mirrors of the multi-pass system are installed in motorized mounts for remote adjustment of the system. The possibility of automatic adjustment of mirrors during the tokamak pulse is being considered, if necessary. The light collection unit is located in the equatorial port.

4. OPTICAL DIAGNOSTIC NODES

The developed collecting lens consists of three lenses bonded together. The front and rear surfaces of the lens have an aspherical shape to fulfill the optical resolution requirements. The distance from the front surface of the lens to the laser beam is 1150 mm. The lens characteristics are as follows: relative aperture 1:2.1, focal length 187 mm, field of view angle 90°. The average magnification factor is 1/8.2. The average light transmission coefficient for the working wavelength range is ~93%. The image surface has a spherical shape with principal rays running along the radii of this sphere. All image points have a numerical aperture of 0.202. The dimensions and MTF graph of the lens are shown in Fig. 4, 5.

The lens collects scattered light at the input end of the fiber optic collector. The end face has a spherical shape with a radius of R=202.4 mm and corresponds to the image surface of the lens. The collector consists of 159 separate fiber optic assemblies, 1×2 mm in size with an ordered arrangement of fibers. They consist of quartz optical fiber with a diameter of 200 μm, sheath thickness of 10 μm, and numerical aperture NA=0.22. Individual fiber optic assemblies are arranged radially, and their end faces are perpendicular to the principal rays of the collecting lens. An image of the input end of the fiber optic collector is shown in Figure 6.

The spatial resolution of the diagnostic is determined by the size of the image of an individual fiber optic assembly on the laser beam and is shown in Figure 7. It ranges from 11 mm in the central zone of the cord to 22 mm at the edge. The light collection system allows for registering the laser beam across its entire width, with the maximum width of the laser beam in the observation zone being 4.3 mm.

In the diagnostic room, the optical fiber is divided into three parts and connected to separate devices. The input end of the fiber optic bundle has a size of 318×1 mm, and the three output fiber optic ferrules are 53×2 mm each. Each consists of 53 fiber optic assemblies.

For coupling apertures of polychromators and fiber optic collectors, a matching optical system is used. Unlike the diagnostic system on the T-10 tokamak, on T-15MD it was possible to implement a matching system almost entirely based on mirrors. This significantly increased the light transmission coefficient (86%) and reduced chromatic aberrations. The design and MTF graph of the matching system are presented in Fig. 8, 9.

For registration of the collected light, polychromators based on a toroidal holographic diffraction grating were developed. Their design is shown in Fig. 10. The Littrow scheme, which was used on the T-10 installation [4], was taken as a basis. The new design uses a toroidal holographic diffraction grating, which allows eliminating the two-lens objective (Littrow doublet) in the instrument design. This makes it possible to increase the contrast of TS spectra and significantly reduce the effects of parasitic illumination from laser radiation. The central polychromator is planned to be manufactured with a diffraction grating of ~700 lines/mm. Two edge polychromators will register lower T_e compared to the plasma center, so they will be equipped with gratings with higher dispersion of ~900 lines/mm. The diameter of the diffraction gratings is 110 mm. Light from the entrance slit (200×8 mm) falls on the toroidal holographic grating and is decomposed into a spectrum. Then the light falls on a two-section spherical mirror (200 × 200 mm), with the entrance slit located between the sections. The cutout in the mirror has dimensions of 12 × 200 mm. The reciprocal linear dispersion D_{λ} on the two-section mirror is 1.67 nm/mm for the central and 1.1 nm/mm for the edge polychromators. The device is adjusted so that light with the laser wavelength falls into the gap between the mirror sections and is not recorded by the detector. The two-section mirror transmits light through a high-aperture lens (F#=0.85) to an sCMOS camera with an image intensifier. On the image intensifier, the dispersion D_{λ}=16 nm/mm for the central polychromator and D_{λ}=11 nm/mm for the edge ones. The MTF graph of the polychromator for the laser wavelength is shown in Fig. 11.

5. ALIGNMENT OF THE FIBER OPTIC COLLECTOR POSITION

To align the fiber optic collector relative to the laser beam, an optical diagnostic system is planned to be used. Individual fiber optic assemblies have an ordered arrangement of fibers, i.e., the image from the input end is transmitted to the output end. If the diffraction grating is rotated (~1°) so that the laser line hits the near edge of the two-section mirror of the spectral instrument, then the position of the laser beam on the input end of the optical fiber can be registered using Rayleigh scattering. Only the beam images will pass across the entrance slit in each assembly (Fig. 2.). For ease of perception, the image of each assembly can be rotated 90° using software to restore the real position of the laser beam image on the collector. Such an image allows evaluating the necessary correction of the position of the input end of the fiber optic collector for ideal centering of the laser beam image on it. To implement such adjustments, the input end of the fiber optic collector is intended to be mounted on a hexapod. Conducting such alignment requires optical resolution comparable to the image of the optical fiber. The necessary and calculated resolution for each optical unit is presented in Table 2.

6. MEASUREMENT ACCURACY ASSESSMENT

The assessment of the measurement accuracy of electron temperature and density was performed using synthetic diagnostics. This approach allows taking into account the combined influence of the diffraction grating dispersion, plasma background radiation, image intensifier noise, and the width of the entrance slit on the accuracy and range of plasma parameter measurements. The accuracy assessment algorithm is as follows. The vertical TS diagnostics of T-15MD operates in a two-frame mode. The first frame includes the scattering signal with plasma background radiation, the second frame contains only the plasma background. An array of frames with scattering signals is generated for a set of values n_e from 1×10^{18} m^{-3} to 1×10^{20} m^{-3} and T_e from 20 eV to 10 keV, taking into account the optical system transmission (21%) and the quantum efficiency of the image intensifier photocathode (GaAsP). It is assumed that the background radiation level does not depend on plasma parameters. The size of the spatial channels on the recording camera matrix is determined taking into account the magnification of the optical system and the size of the image intensifier. Then, the frames are made noisy using the Poisson distribution. To account for the influence of the image intensifier noise characteristics, the signal dispersion is increased by a factor of two. After adding noise, the background frame is subtracted from the useful frame, and the signals are summed vertically (across the area of one spatial channel). Next, the signal is summed horizontally (by wavelengths) to reduce the time for estimating plasma parameters. Then, the spectrum is approximated to determine n_e and T_e. The instrumental function of the spectral device introduces a significant systematic error in determining n_e and T_e. To reduce this contribution, the scattering spectrum obtained after approximation is deconvolved with the polychromator's instrumental function. The resulting scattering spectrum is approximated again to obtain the final values of plasma parameters. By repeatedly adding noise to the frames and processing them for the same values of electron temperature and density, the statistical and systematic measurement errors are determined. The algorithm of the synthetic diagnostics is shown in Fig. 12.

The calculation considers the main characteristics of the optical diagnostic scheme: the transmission of the lens, the matching optical system and polychromator, the transmission coefficient of the optical fiber, the solid angle of light collection, the width of the cutout in the two-section mirror, as well as the quantum yield of the GaAsP photocathode. The presence of a cutout in the mirror leads to a limitation on the minimum width of the scattering spectrum and, accordingly, the minimum measurable temperature. The assessment takes into account the superposition of scattering spectra that change shape during forward and backward passage of radiation in a multi-pass probing system. The length of the laser beam used in the accuracy calculation for each spatial point varies from 11 to 22 mm, the solid angle of light collection ranges from 5×10^{-3} to 2×10^{-3} sr.

To account for the plasma background radiation, spectroscopic data obtained during the experimental campaign of the T-15MD facility were used [12]. Figure 13 shows the main characteristics of discharge #890, which was used to estimate the background radiation.

When assessing accuracy, the emission spectrum from the limiter diaphragm region (Fig. 14) is used, which was installed 65 cm below the equatorial chamber of the facility. Due to the fact that the polychromator of the vertical Thomson scattering diagnostic of T-15MD operates with a wide input slit (~8 mm), it is necessary to convolve the original spectrum with its instrumental function – in our calculation, a Gaussian function with a full width at half maximum of 20 nm for the central polychromator and 13 nm for the edge one is used. The width of the instrumental function corresponds to the width of the cutout in the two-section mirror. It is assumed that the vertical Thomson scattering diagnostic of T-15MD will not operate under conditions of direct illumination from the limiter (divertor) region. Therefore, the spectrum was normalized to measurements of H_β and CIII lines along the central chord. Comparison of the intensity of line luminosity from the central plasma region and the limiter is given in Fig. 15.

The presented data shows that the luminosity differs by at least an order of magnitude. Therefore, in the synthetic diagnostic, the original spectrum from the T-15MD limiter was reduced by a factor of 10. Figure 16 shows examples of frames generated during the operation of the synthetic diagnostic for $n_e = 3\times10^{19}$ m^{-3} $T_e = 1$ keV.

Figures 17 and 18 show the results of accuracy assessment for temperature and electron density measurements for the central and edge channels. For the central channel at $n_e = 6\times10^{18}$ m^{-3}, the measurement error of $T_e < 10\%$ and $n_e < 10\%$ for the temperature range of 80 eV – 6 keV. In the case of the peripheral channel at $n_e = 1\times10^{19}$ m^{-3}, the measurement error of $T_e < 10\%$ and $n_e < 10\%$ for the temperature range of 100 eV – 2 keV. The difference in two-dimensional distributions of parameter measurement errors for the central and peripheral channels lies in the different scattering angle and the value of $Ld\Omega_{plasma}$.

7. CONCLUSION

A Thomson scattering system has been developed for the T-15MD tokamak with vertical probing of the plasma column. During the development, a mirror scheme of matching optics was designed, which made it possible to significantly increase the light transmission coefficient and reduce the level of chromatic aberrations. The optical scheme of the Littrow polychromator was also improved by using a toroidal holographic grating instead of a flat diffraction grating and a two-lens objective. This upgrade allows for a significant increase in the contrast of the spectral instrument.

The high optical resolution of the entire optical registration system – collecting lens, matching optics and polychromator – allows for controlling the adjustment of the optical fiber collector position relative to the laser beam.

An assessment of the accuracy of plasma parameter measurements was carried out. The estimation of temperature and density measurement errors was performed using synthetic diagnostics with a spectrum from the T-15MD experimental campaign from the limiter region. Taking into account the background illumination reduction by a factor of 10 in the central plasma region, the diagnostic allows measurements with 10% accuracy from 80 eV to 6 keV at $n_e > 6\times10^{18}$ m^{-3}. The central polychromator will be equipped with a 700 lines/mm diffraction grating, while the two peripheral polychromators will use 900 lines/mm gratings. In the peripheral region, an error of <10% is achieved in the T_e range from 100 eV to 2 keV at $n_e > 1\times10^{19}$ m^{-3}.

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Table 1. Main Parameters of the Spectral Device

Relative aperture of the MCP objective	1/0.85
MCP diameter, mm	25
Height of the entrance slit, mm	200
Numerical aperture of optical fiber	0.22

Table 2. Resolution of optical diagnostic units of TR T-15MD

Unit	Required optical resolution, line pairs/mm	Minimum calculated optical resolution, line pairs/mm
Collecting lens	>2.5	4.1
Matching system	>1	1.5
Spectral device for λ=532 nm	>7	12 (meridional plane)

FIGURE CAPTIONS

Рис. 1. Cross-section of the T-15MD tokamak with geometry of vertical TR diagnostics

Рис. 2. Transformation of the optical fiber collector

Рис. 3. Schematic diagram of the vertical TR diagnostics of T-15MD. *1laser;* laser; *2optical path control unit;* tract control unit; *3mirrors* of the optical path; *4focusing* lens; *5* -mirrors of the multi-pass system; *6* - vacuum windows; *7* - gate valves; *8* - laser beam; *9* - plasma; *10* - vacuum window; *11* - collecting lens; *12* - fiber optic collector; I, II, III) matching optics and spectral devices with recording cameras

Рис. 4. Design of the collecting lens: *1vacuum* window made of fused quartz; *2* - lens, front surface is aspherical; *3* - lens; *4* - lens, rear surface is aspherical; *5* - spherical image field

Рис. 5.MTF of the lens: C - sagittal plane; *M* - meridional plane; *1* - central image point; *2* - middle point; *3* - edge point. The horizontal black line corresponds to the Rayleigh criterion

Рис. 6. Input end of the fiber optic collector: a) side view; b) enlarged image of the assembly; c) fiber optic assembly. Dimensions in mm

Рис. 7. Spatial resolution of the TS diagnostics of the T-15MD tokamak

Рис. 8. Optical scheme of the mirror system of matching optics

Рис. 9.MTF of matching optics: C - sagittal plane; *M* - meridional plane; *1* - central image point; *2* - middle point; *3* - edge point. The horizontal black line corresponds to the Rayleigh criterion

Рис. 10. Optical scheme of the modernized Littrow polychromator

Рис. 11. MTF of the polychromator λ=532 nm: C - sagittal plane; M - meridional plane; *1* - central image point; *2* - middle point; *3* - edge point. The horizontal black line corresponds to the Rayleigh criterion

Рис. 12. Algorithm of the synthetic diagnostics operation

Рис. 13. Parameters of discharge #890 T-15MD B_t=1.2 T. a) I_p plasma current, P_{ECRH} 1 MW; b) Electron temperature; c) electron density; d) luminosity of H_β, CIII lines from the central chord

Рис. 14. Spectrum from the limiter region of the T-15MD tokamak. The red curve shows the spectrum taking into account the instrumental function of the polychromator of the vertical TS diagnostics of the T-15MD tokamak

Рис. 15. Intensity of spectral lines emission along the central chord and from the limiter region; a) H_β; b) CIII

Рис. 16. Frames generated by the synthetic TS diagnostics of T-15MD. a) Useful frame; b) background frame; c) useful and original signals

Рис. 17. Errors in determining plasma parameters for the central channel. Diffraction grating 700 lines/mm. a) Graph of electron temperature determination accuracy; b) graph of plasma density determination accuracy. Color shows accuracy in %

Рис. 18. Errors in determining plasma parameters for the peripheral channel. Diffraction grating 900 lines/mm. a) Graph of electron temperature determination accuracy; b) graph of plasma density determination accuracy. Color shows accuracy in %

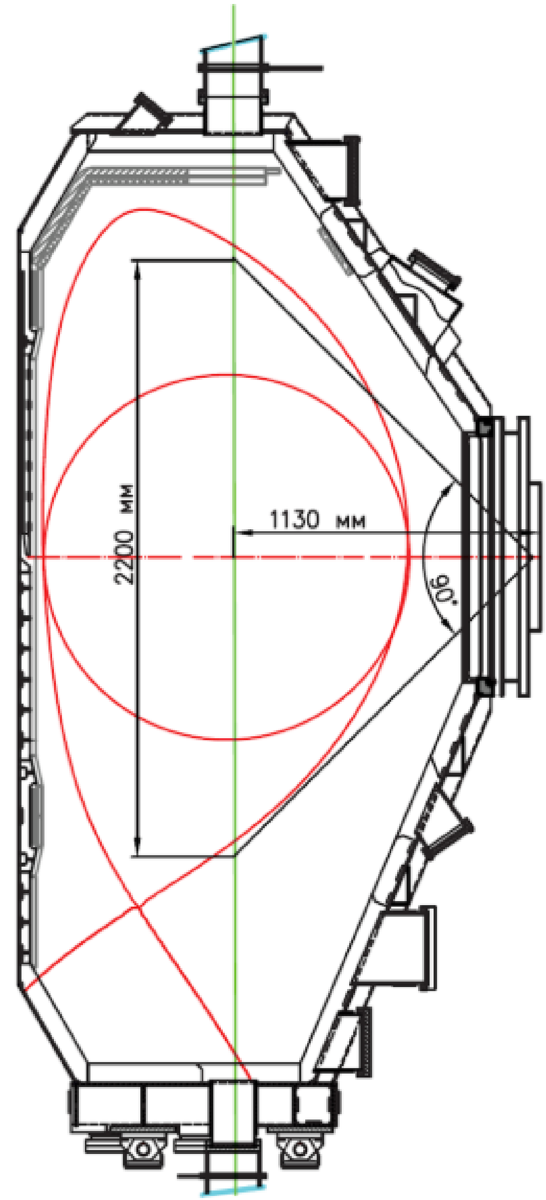


Figure 1.

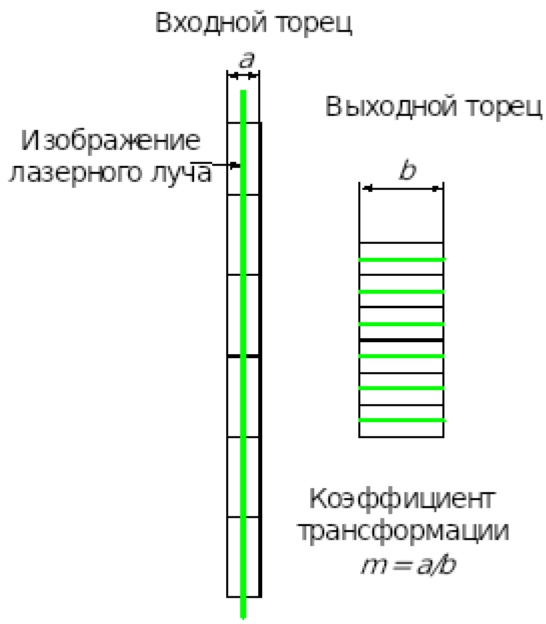
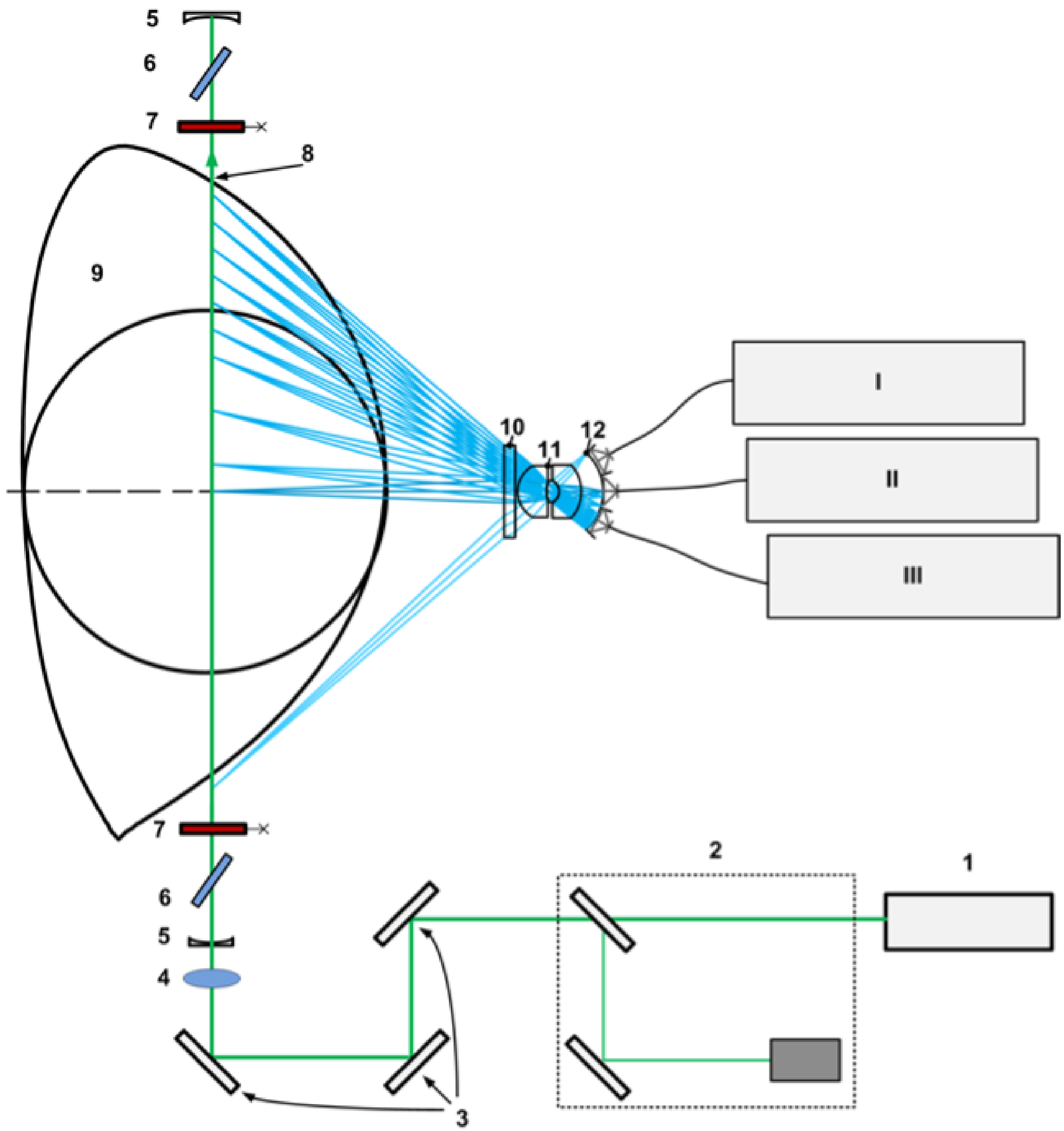

Входной торец
a
Выходной торец
Изображение
лазерного луча
b
Коэффициент
трансформации
m = a/b

Figure 2.



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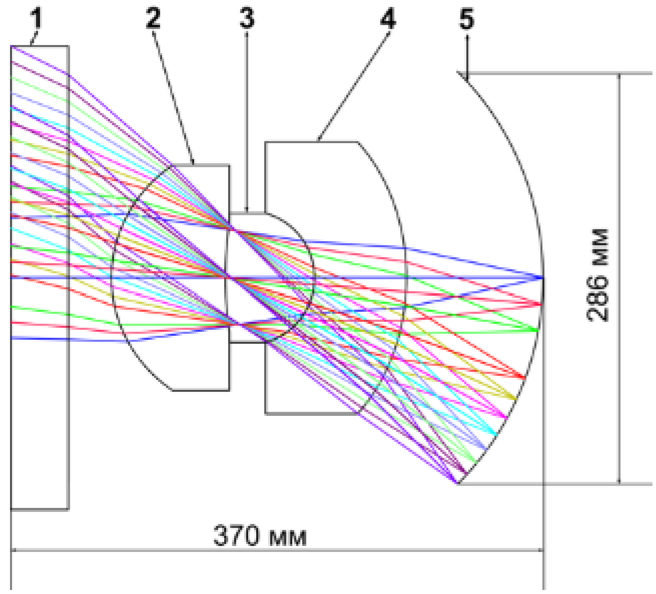

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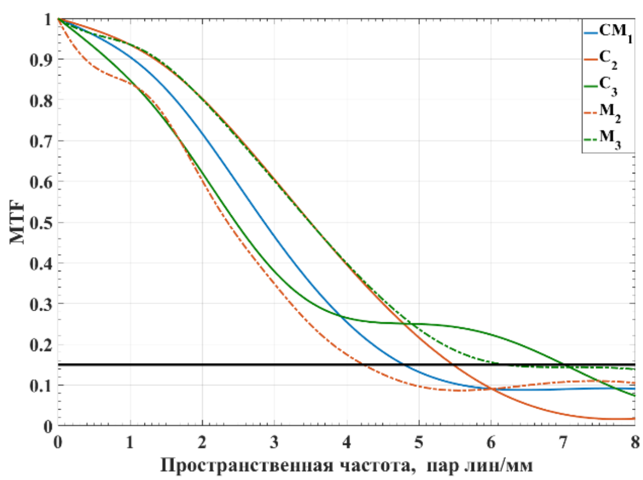

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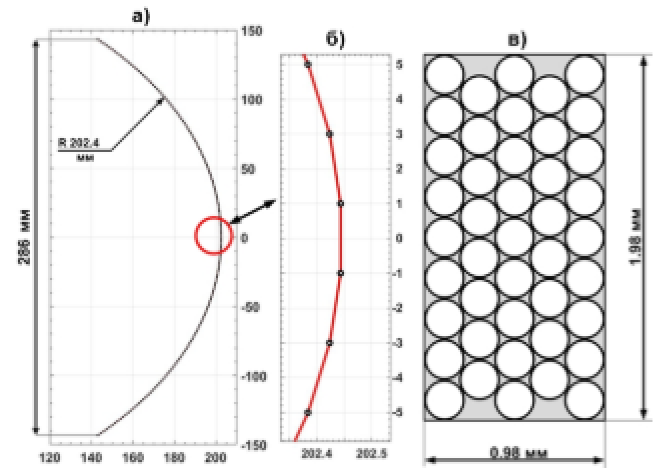


Figure 6.

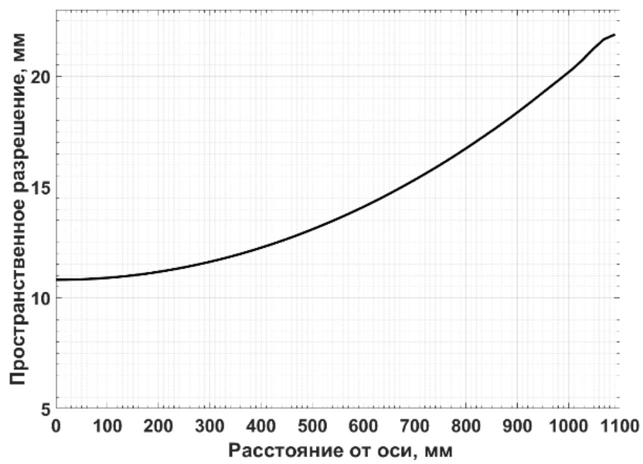


Figure 7.

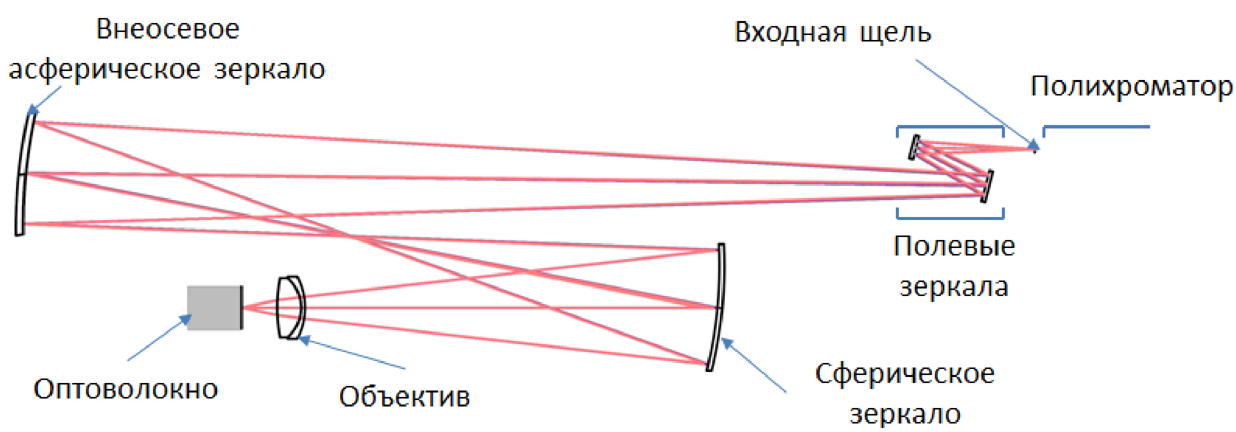
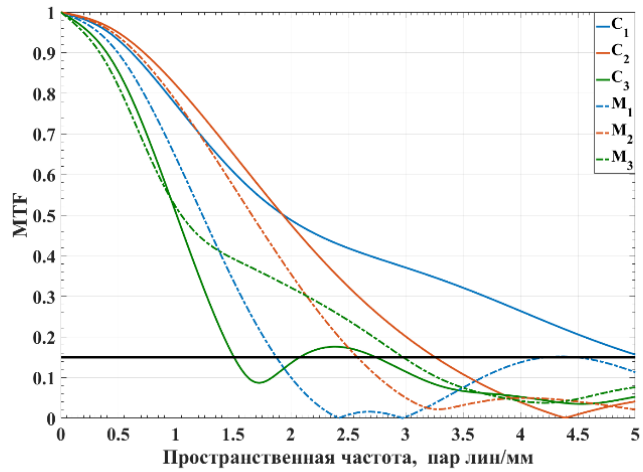


Figure 8.



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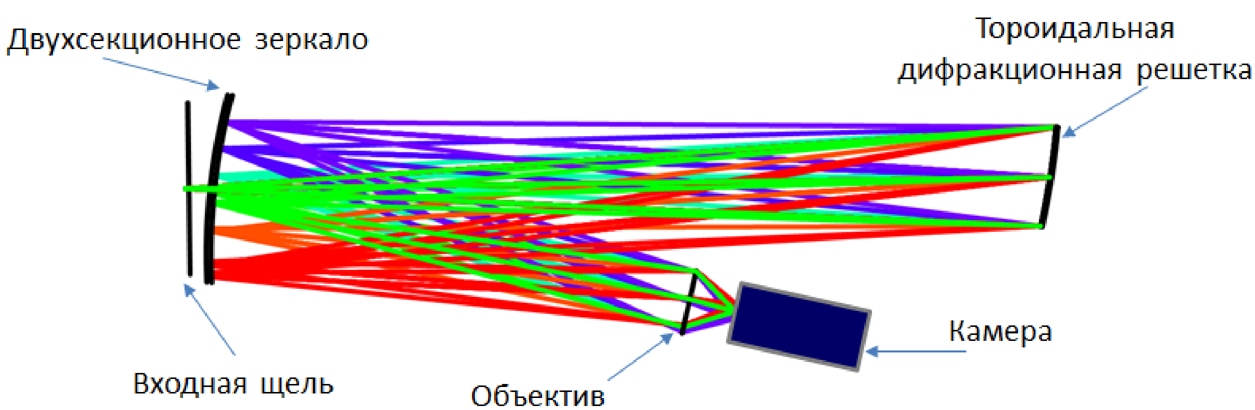

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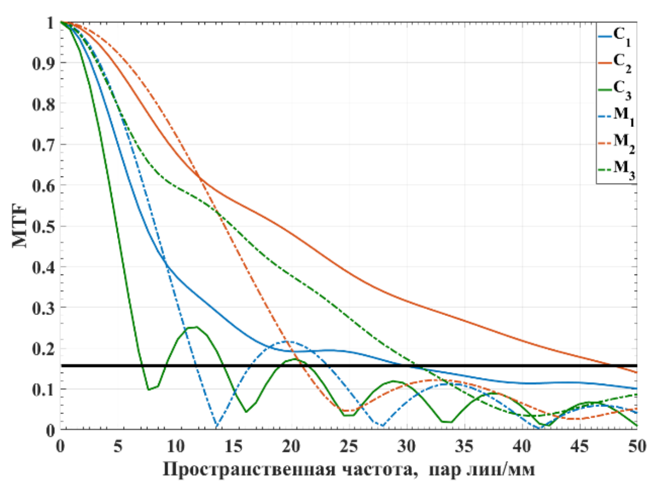

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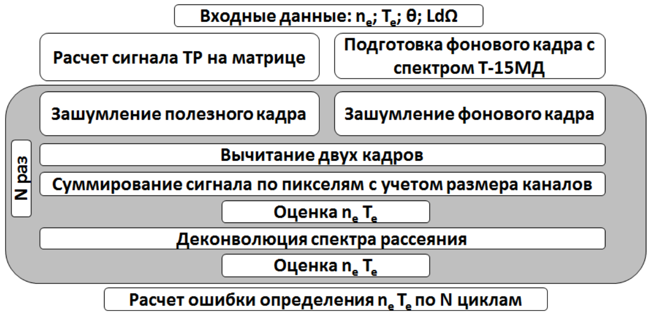

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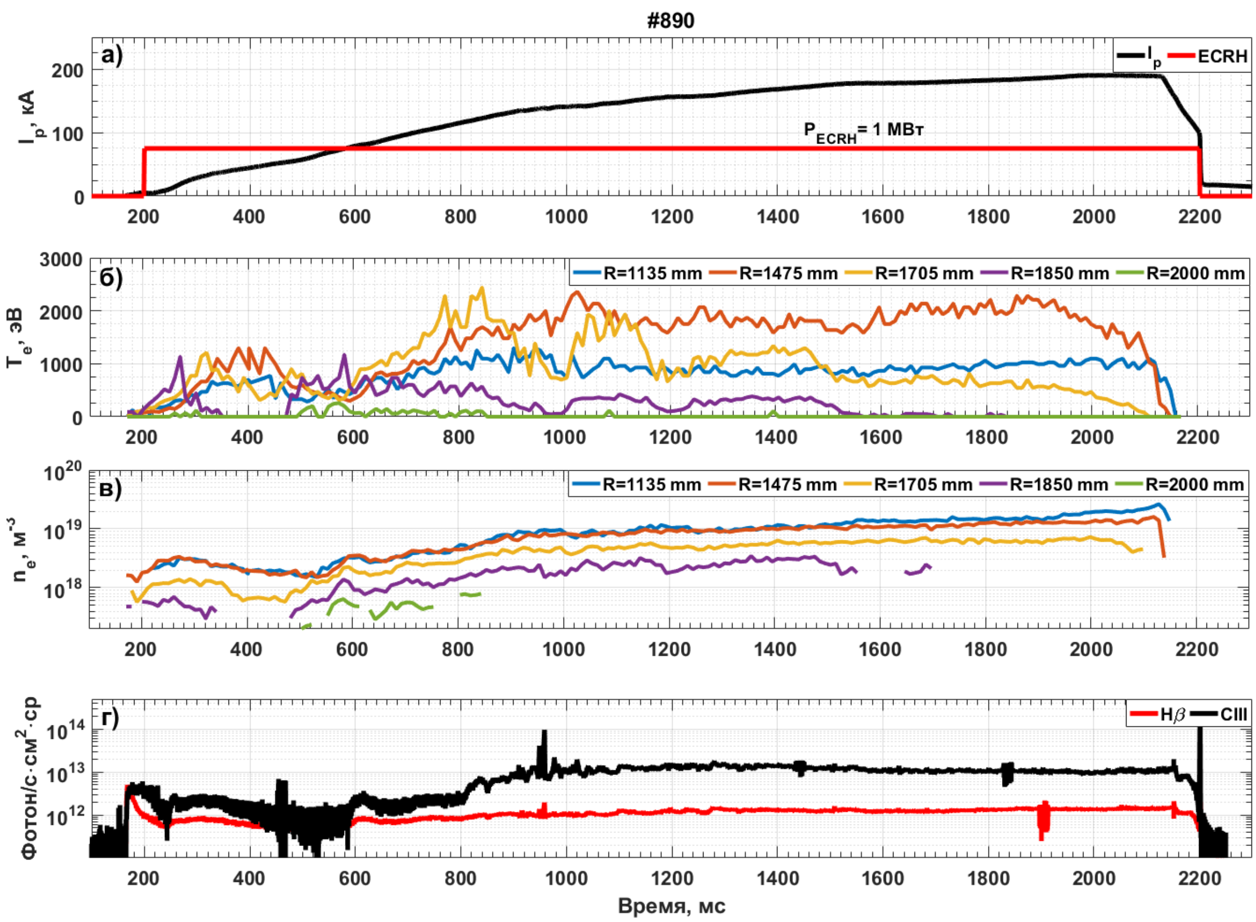

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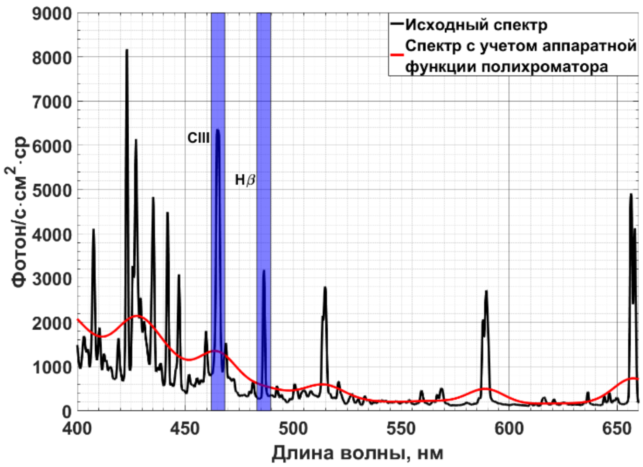

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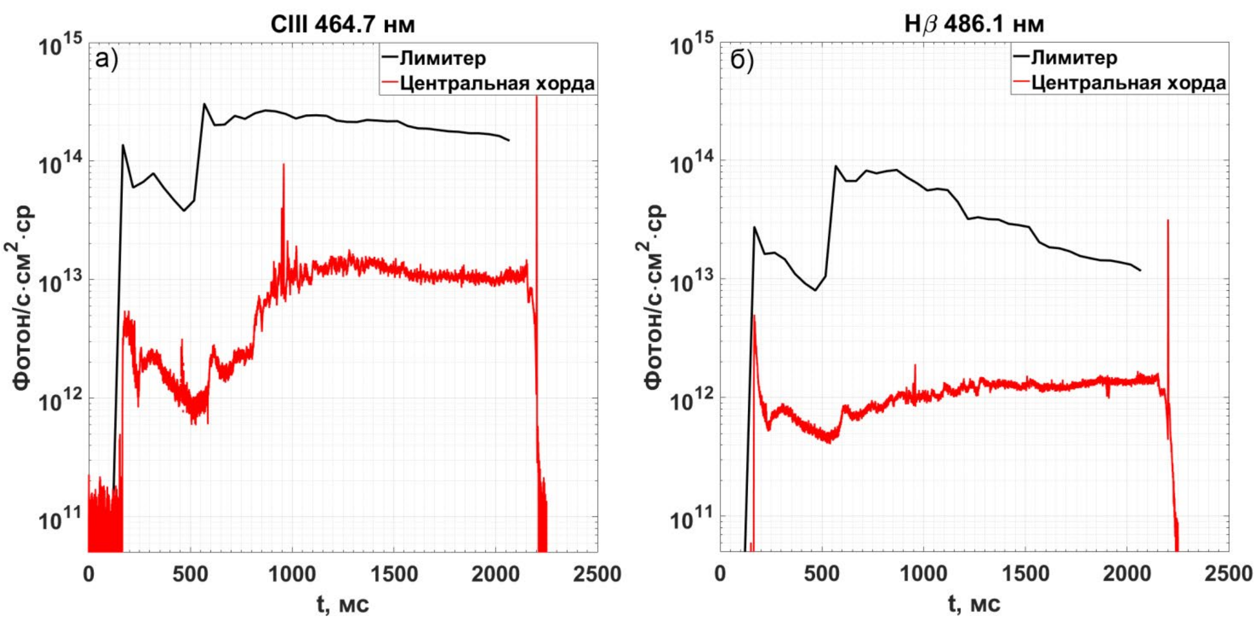

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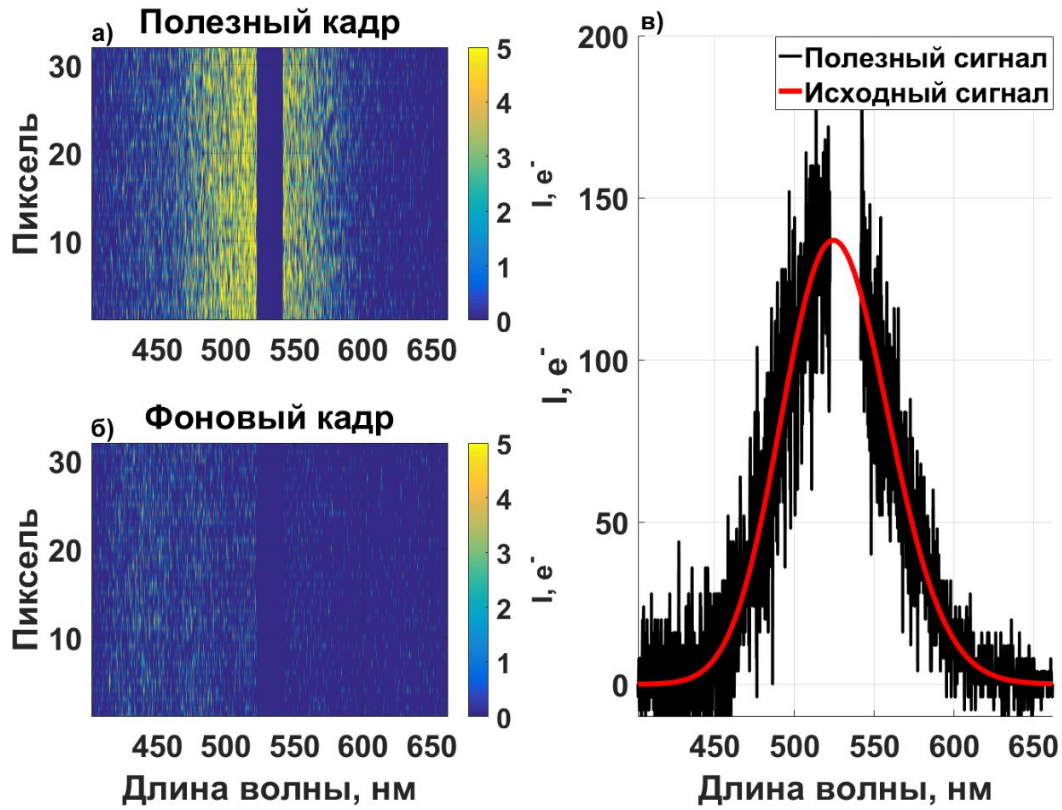

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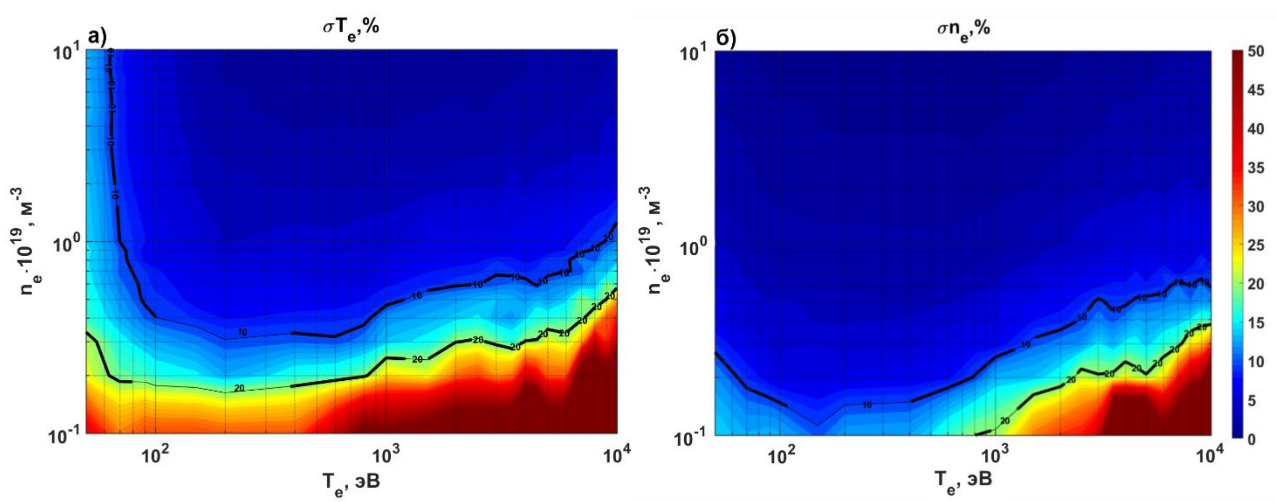

Figure 17.

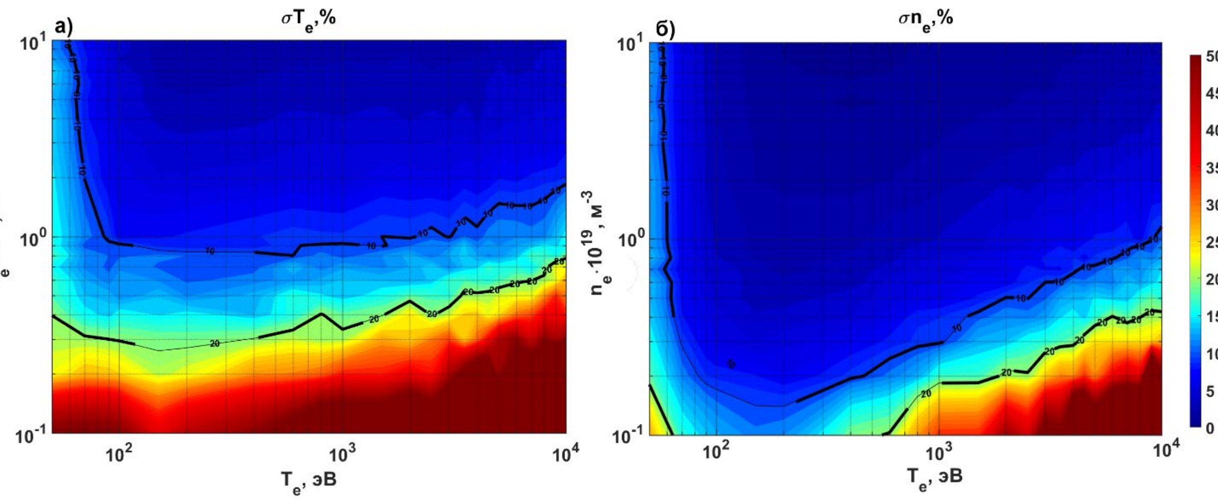

Figure 18.