Spectroscopic diagnostics of the T-15MD tokamak

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For the upgraded T-15MD tokamak [1] (R = 1.48 m, a = 0.67 m, k = 1.8, $I_{pl} \leq 2$ MA, $B \leq 2$ T, discharge duration ≤ 4 s (up to 400 s for 250 kA), additional heating power up to 20 MW) modern spectroscopic diagnostic systems have been developed. These are active CXRS-diagnostics and passive bremsstrahlung and line emission spectroscopy. CXRS-diagnostics can function on both the diagnostic injector of hydrogen atoms DINA-KI60 [2] with $E_{\rm H}$ = 60 keV ($P_{\rm DNB}$ = 0.15 MW), and heating injector with $E_{\rm H}$ = 60 keV ($P_{\rm NBI}$ is up to 2 MW). The T-15MD CXRS-diagnostics will make it possible to measure with high spatial (≈ 1 cm) and temporal (≈ 3 ms) resolutions the local values of the following plasma parameters: ion temperature, concentrations of protons, of carbon and of one selected light impurity (He, Li, N, O etc.) nuclei, cord toroidal and poloidal rotation velocities, the concentration and energy of fast ions, the profile of the radial electric field in the ETB region.

The light collecting systems are designed to achieve the maximum level of the useful signal at the best possible values of spectral, spatial, and temporal resolutions. Light collecting systems for the registration of CXRS radiation in toroidal and poloidal directions contain 30 lines of sight (LOS) each and will provide the measurements with high spatial resolution (up to 1 cm), scanning the entire diameter of the plasma column (Figure 1). At the same time, the LOS in the collecting systems are directed in a way that is safe from the negative influence of the radiation from the bumper limiter. On the later stages of work the divertor stray light might complicate the measurements. However, the beneficial DNB power and the viewing dump on the inner wall can provide us with good active signal contrast even in these harsh conditions.

Poloidal CXRS-pedestal diagnostics allows measuring $T_i(r)$, $n_p(r)$, $n_z(r)$, $V_{pol}(r)$ parameters in the area of the external transport barrier (ETB) with high spatial resolution up to 5-7 mm. For collecting optics will be used Edmund optics achromatic doublets: for poloidal and toroidal CXRS on DNB, passive spectroscopy – D = 50 mm, f = 150 mm, for toroidal CXRS on HNB – D = 50 mm, f = 150 mm.

To estimate the efficiency of the CXRS diagnostics and the level of the active signal that can be expected in an experiment, a simulation of the T-15MD discharge is performed. The distribution of plasma parameters for standard discharges in the ohmic mode without additional heating with a Z_{eff} level of ~3 and a circular cross section of the column is calculated. These parameters are expected at the first stage of the installation. Taking into account calculated beam stopping coefficients and the experimentally obtained profile of the diagnostic beam density distribution along its radius, a two-dimensional calculation of the intensity of the active radiation of the C^{5+} line (λ = 5291 Å) is made.

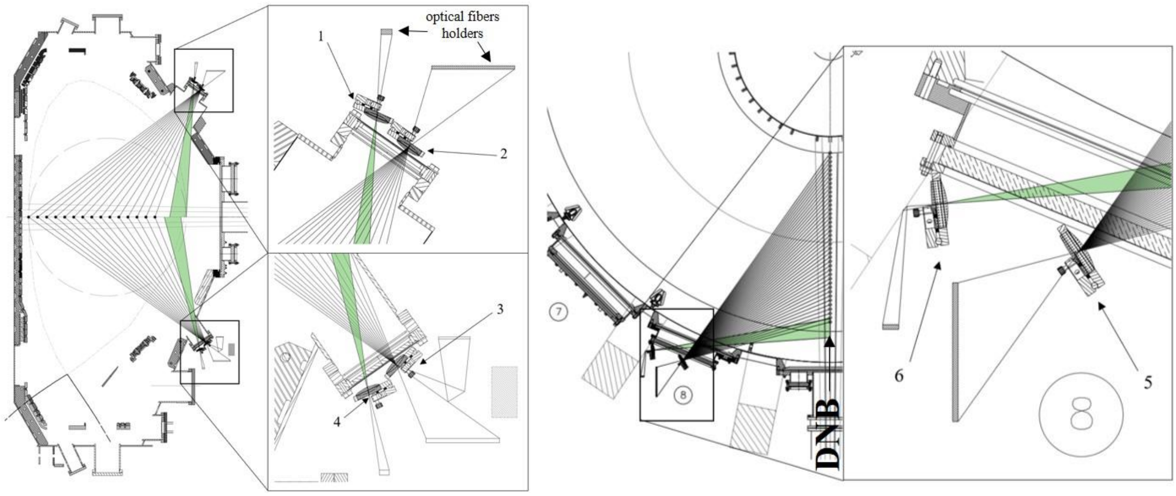

Figure 1. Scheme of the poloidal (left) and toroidal (right) CXRS-diagnostics light collecting systems: 1,4 – upper and lower poloidal CXRS-pedestal diagnostics collecting optics; 2,3 – upper and lower core CXRS diagnostics collecting optics; 5 – toroidal CXRS diagnostics collecting optics; 6 – toroidal CXRS-pedestal diagnostics collecting optics.

The total intensity (active + passive) of the emission of this line in the toroidal and poloidal planes is shown in the figure 2. It can be seen from the figures that the intensity of the active component is much higher than the intensity of the passive one. This allows us to achieve a high level of active CX-signal contrast of about 2 – 4 and significantly reduce the temporal resolution of the measurements without substantial rise of its statistical error, thereby increasing the reliability of measured values. Simulated spectra of the C^{5+} 5291 Å line from the synthetic T-15MD CXRS-diagnostics with its statistical noises are presented in the figure 3: (a) full and passive signal, (b) active component. Spectra were predicted from Doppler line broadening and additionally broadened by accounting line fine structure and Zeeman effect. The line shift due to the plasma rotation is not accounted since the estimations predict low line shift in T-15MD ohmic discharges against Doppler line broadening [3].

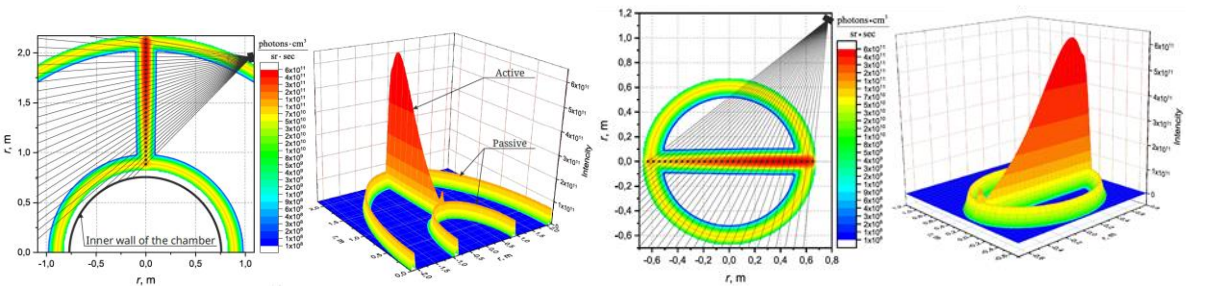

Figure 2. Calculated intensity of the emission of the C^{5+} 5291 Å line (active CX + passive) in the toroidal (left) and poloidal (right) planes.

Registration errors of CXRS-measurements are estimated with Monte-Carlo method (including the statistical errors of neutral beam density measurements): δT_i – 2,4%; δn_z – 1.5 % (without accounting errors of $n_e(r)$ measurements); ΔV_{tor}, ΔV_{pol} – ±(1.5 – 2.1) km/s.

Passive spectroscopic diagnostics allows determining the effective ion charge profiles via bremsstrahlung measurements, the main gas and impurities inflows, the peripheral values of the ion temperature and the rotation velocities of the plasma column.

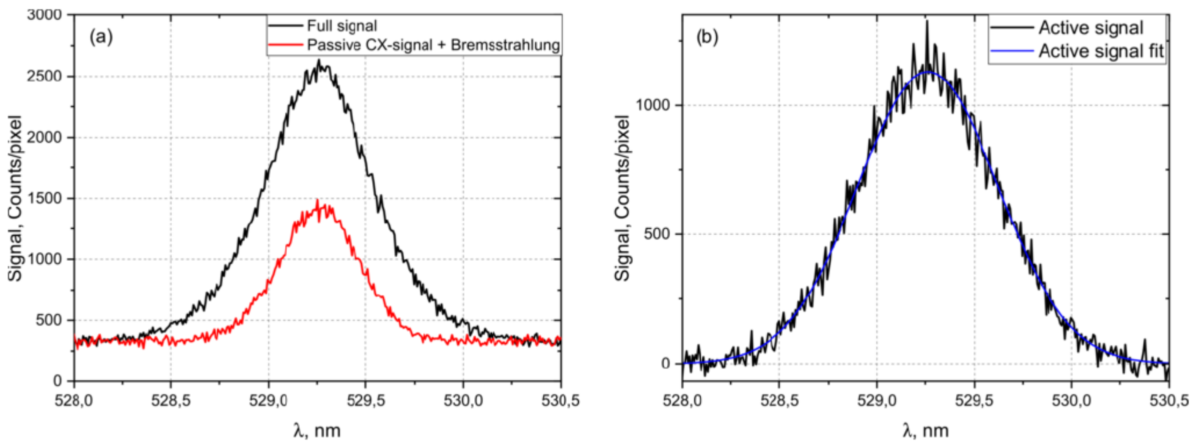

Figure 3. Simulated spectra of the C^{5+} 5291 Å from the synthetic T-15MD CXRS-diagnostics: (a) full and passive signal, (b) active component.

High spectral resolution visible bremsstrahlung profile diagnostics is going to be used to provide reliable measurements of the effective ion charge profiles $Z_{eff}(r)$. One toroidal and two poloidal (upper and lower) observation directions of this diagnostics are shown in the figure 4. It contains 20 lines of sight (LOS) each. Poloidal light collecting system and CXRS-pedestal diagnostics is going to use the same optics. Viewing dump mounted on the inner wall will reduce the reflection light from the divertor area. There is no possibility to use viewing dumps for toroidal system so perceptible level of reflection light from the divertor area is expected. To estimate the intensity of this parasitic component the model of T-15MD divertor emission intensity is developing and graphite tiles reflection coefficients are measured.

Two high-etendue spectrometers HES-370 are going to be used for poloidal visible bremsstrahlung and line emission profiles measurements with high spectral resolution. Spectrometers are made based on an Echelle reflection grating with 200 grooves/mm operating in the 11^{th}–16^{th} diffraction orders. Inverse linear dispersion of the spectrometers is 3.3–5.3 Å/mm depending on the wavelength, relative aperture is 1/3.2 and transmission factor is about 30%. EMCCD cameras PhotonMax-512B will be used as detectors in this system. The limiting spectral resolution achieved on this system is 0.17 Å. This is enough to resolve molecular line emission spectrum in the area of 5236 Å where the bremsstrahlung is usually measured. So, the system is able to provide reliable Z_{eff} measurements in low density regimes ($n_e \leq 1 \cdot 10^{19}$ m^{-3}) and in discharges with high level of additional heating when molecular line emission dominates the bremsstrahlung one.

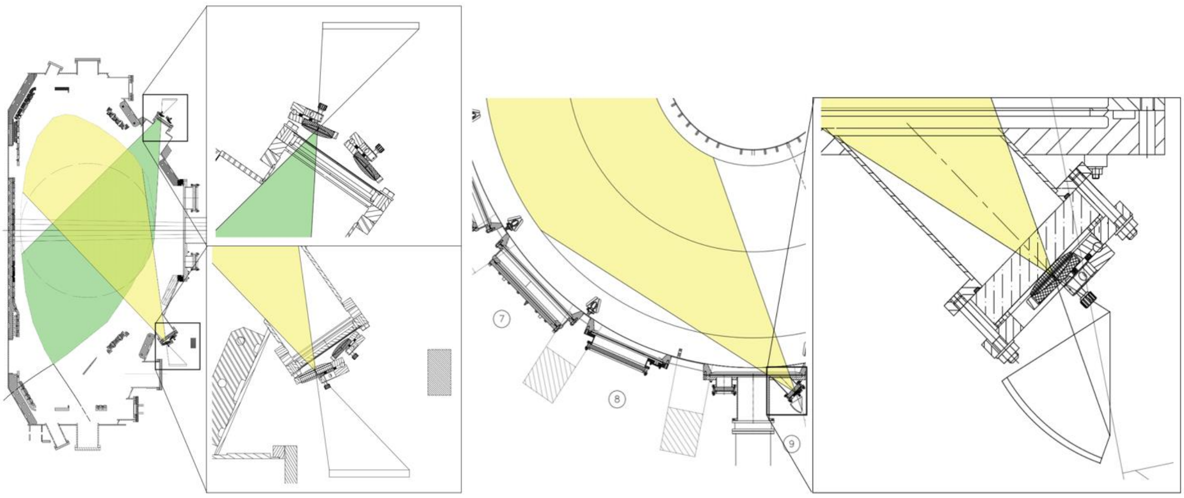

Figure 4. Scheme of the poloidal (left) and toroidal (right) light collecting systems of the high spectral resolution visible bremsstrahlung and line emission diagnostics.

Several fast systems (temporal resolution $\leq 10^{-4}$ s) based on the monochromator MDR-2 with PMT detector is going to be used for impurities spectral lines brightness behavior measurements. The BWTEK Exemplar LS survey spectrometer will be used to obtain the entire visible range spectrum for express estimation of impurity composition. More detailed spectra in the ranges of interest about 250 Å wide with spectral resolution ~1 Å will be measured using MDR-23 spectrometers and CCD cameras.

[1] Khvostenko P.P. et al. Current status of tokamak T-15MD // Fusion Engineering and Design Volume 164, March 2021, 112211

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[3] Krupin V.A. et al. The development of charge exchange recombination spectroscopy diagnostics for the T-15MD tokamak // J. Instrum. IOP Publishing, 2020. Vol. 15, #02. P. C02027

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