

## Spectral intensity of electron cyclotron radiation coming out of plasma in various regimes of ITER operation

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**1. Introduction.** Electron cyclotron radiation (ECR) in ITER is expected to play an important role in power loss balance due to high electron temperature and strong magnetic field [1], [2]. This radiation is also a source of additional thermal and electromagnetic loads on microwave and optical diagnostics [3]. The ECR generated in plasma dominates over the stray radiation from electron cyclotron resonance heating (ECRH) and current drive (ECCD) microwave power sources in high performance discharges, and therefore its impact upon diagnostics must be investigated [3]. This is especially important for mm-wave diagnostics in ITER such as microwave reflectometers and Collective Thomson Scattering system, whose transmission lines allow, in principle, additional measurements of EC radiation spectra [4]. The transmission lines for HFS reflectometry are planned to be used as waveguides for X-mode observation in the frequency band 12-90 GHz and O-mode observations in the band 18-140 GHz. Although the working frequency range is significantly lower than the operational frequency for ITER ECRH system ( $>170$  GHz), the antennas and the waveguide can receive the entire emission spectrum at frequencies above 12 GHz. Thus, the absorption and heating in the primary and secondary vacuum windows and the residual power on the receiving mixers are determined both by the power density of the EC radiation from the plasma and by the transmission line losses, which increase strongly with increasing frequency.

Here we report on calculations, with the CYNEQ code [5], [2] of spectral intensity of the ECR coming out of plasma in various regimes of ITER operation in the view of its possible impact on in-vessel components and diagnostics.

**2. CYNEQ code.** CYNEQ code [5], [2] gives a semi-analytical solution of the EC radiation transport problem in tokamak-reactor conditions: high-temperature plasma with average electron temperature  $\langle T_e \rangle_v \geq 10$  keV, non-circular cross-section of torus, moderate values of the aspect ratio  $A \sim 3$ , multiple reflection of radiation from the wall of the vacuum chamber.

In [6], [7] it was shown that in tokamak-reactor conditions the results of the CYNEQ code are in good agreement with those of other ECR transport codes: (1) SNECTR code [8], [9], which is based on Monte-Carlo simulation of the EC wave emission and absorption in an axisymmetric toroidal plasma with specular or diffuse reflection of waves from the walls of a

vacuum chamber, and (2) RAYTEC code [10], which integrates the intensity along the trajectories of EC waves, taking into account reflection of radiation from the wall. In tokamak-reactor conditions, the transport of ECR turns out to be non-local (non-diffusive), i.e. most of energy of EC radiation is carried by waves, for which plasma is optically thin. CYNEQ code uses the assumption of the angular isotropy of the intensity of EC radiation, suggested by SNECTR calculations [8], [9]. In optically thin region, the intensity of the outgoing EC radiation,  $J$ , is a function of wave frequency and wave mode and depends on angle-averaged coefficients of absorption and emission of EC waves:

$$J(\omega, \zeta) = \frac{\int d\Omega_n \int dV q(\phi, \vec{r})}{\int_{(\vec{n}\vec{d}\vec{S}) > 0} d\Omega_n \int (\vec{n}\vec{d}\vec{S})(1 - R_w(\phi, \vec{r})) + \int d\Omega_n \int dV \kappa(\phi, \vec{r})}, \quad (1)$$

where  $\phi = \{\nu, \vec{n}, \zeta\}$  – wave parameters:  $\nu$  – frequency,  $\vec{n}$  – wave direction,  $\zeta$  – wave mode (polarization) (O – ordinary wave, X – extraordinary wave),  $q$  and  $\kappa$  – emission and absorption coefficients of EC waves,  $R_w$  – coefficient of reflection of radiation from the wall of vacuum chamber. Absorption and emission coefficients of EC waves are calculated using the Trubnikov formulas [11].

When solving the EC radiation transport problem, the phase space  $\Gamma = \{\vec{r}, \nu, \zeta\}$  is divided into two regions by the type of the transport. The first region is an optically thin outer plasma layer, defined by equation

$$\int_{\rho}^1 a \kappa(\rho, \nu, \zeta) d\rho \leq \tau_{\text{crit}} \approx 1, \quad (2)$$

where  $a$  is minor radius of toroidal plasma,  $\rho$  is magnetic surface label (square root of the normalized toroidal magnetic flux). In this region the intensity of the outgoing EC radiation is calculated by the equation (1). For steady-state regime of ITER operation [12] this region is dominant for high harmonics of EC wave frequency  $n \geq 3$  (figure 1). The second region is an optically thick inner region of plasma, where diffusive transport dominates.

For radiation of EC wave harmonics  $n=1$  and  $n=2$  the plasma is optically thick. Local EC radiation intensity is close to blackbody intensity with temperature equal to the local electron temperature. This allows to relate (in a reasonable approximation) spectral intensity of the outgoing EC radiation to spatial electron temperature profile  $T_e$  along the chord of observation. Therefore, to estimate the intensity of the outgoing EC radiation from this region, we can assume that the EC radiation temperature, which uniquely determines the spectral intensity of the blackbody radiation, is equal to the electron temperature in the resonance region of wave-particle interaction:  $T_{\text{rad}}(\nu) = T_e(\nu = n \nu_{\text{res}0})$  (see, for example, the calculations of EC radiation in ITER at low harmonics in [13]), where  $\nu_{\text{res}0}$  is the EC fundamental harmonic frequency for magnetic field on the torus axis,  $B_0$ ).

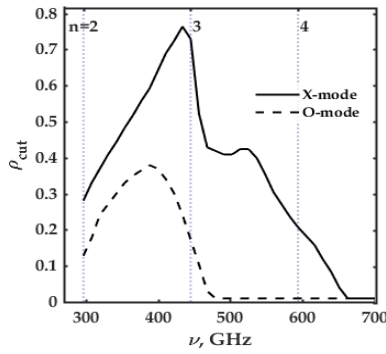


Figure 1. Dependence of the position of the inner boundary magnetic surface of the outer, optically thick region inside plasma (for  $\tau_{\text{crit}}=1.5$  in eq. (2)) on the frequency of EC radiation for ordinary (O-mode) and extraordinary waves (X-mode) for the steady-state regime of ITER operation [12].

The spectral intensity of the ECR, differential also in solid angles, is calculated by the equation:

$$I(\nu) = \frac{\nu^2}{c^2} T_{\text{rad}}(\nu), \quad (3)$$

Note that the ECR intensity at low harmonics coming out from optically thick region of plasma (for given frequency) is isotropic.

**3. Calculations of ECR intensity in ITER.** Calculations are carried out for the following ITER parameters: major radius of torus  $R_0=6.1$  m, minor radius of plasma torus  $a=2$  m, elongation  $k_{\text{elong}}=2.1$ , triangularity  $\delta=0.5$ , vacuum magnetic field on toroidal axis  $B_0=5.3$  T. Figure 2 shows the intensity of the ECR from plasma in steady-state regime of ITER operation [12] for two values of reflection coefficient of the EC radiation from the wall of the vacuum chamber (average over the surface):  $R_w=0.6$  and  $R_w=0.9$ . Figure 3 shows the contribution to the spectrum of ECR from high harmonics ( $n \geq 3$ ), calculated by the CYNEQ code, and the contribution from harmonics  $n=1, 2$ , which is estimated with the equation (3) with the radiation temperature equal to the electron temperature in the region of wave-particle EC resonance. Figure 4 presents calculations of ECR intensity for the hybrid scenario of ITER operation [14].

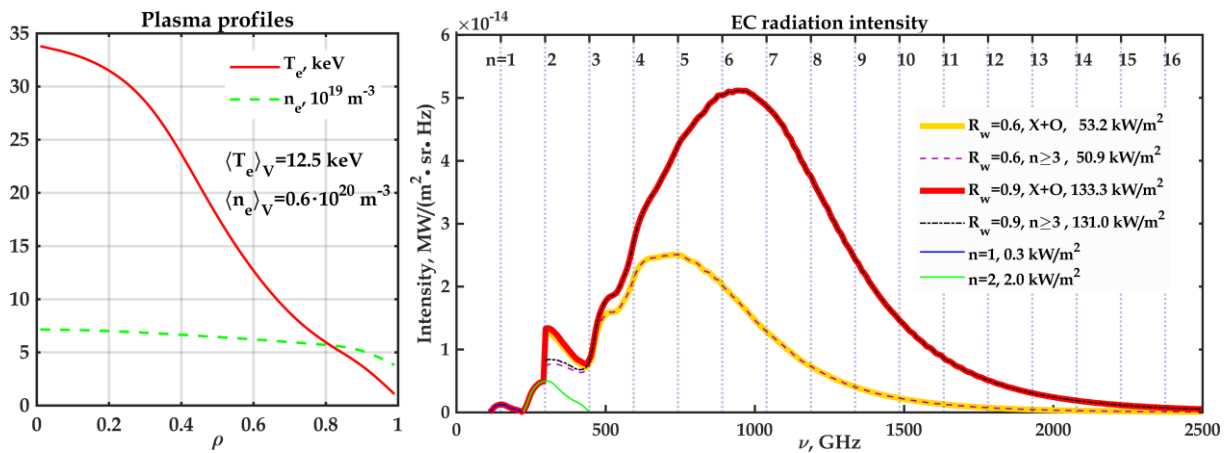


Figure 2. Electron density and temperature profiles in steady-state regime of ITER operation [12] predicted by the ASTRA code (left), and the intensity of ECR for  $R_w=0.6$  and  $R_w=0.9$  and mode conversion coefficients in reflections  $R_{\text{OX}}=R_{\text{XO}}=0.05$  (right). The angle-integrated ECR power per unit area of the vacuum chamber wall is shown in legend.

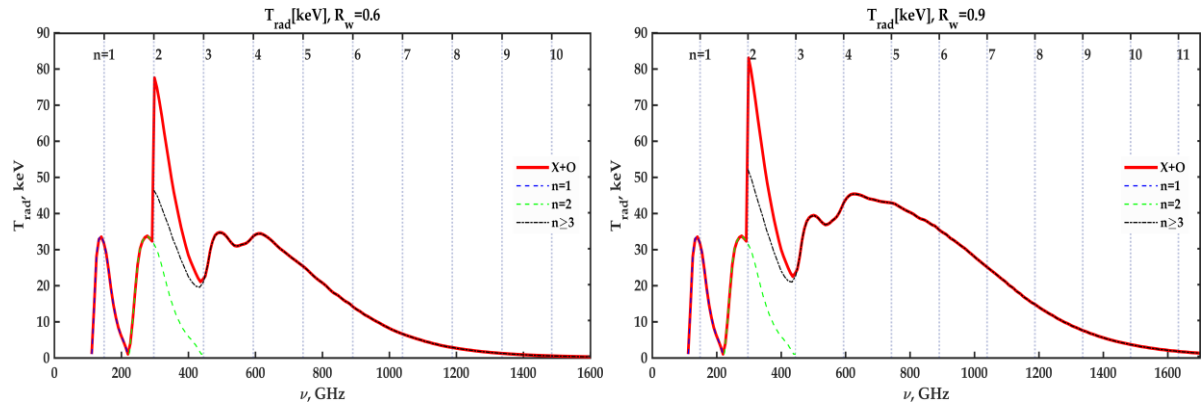


Figure 3. Radiation temperature of the ECR in the steady-state regime of ITER operation [12] for  $R_w=0.6$  (left) and  $R_w=0.9$  (right).

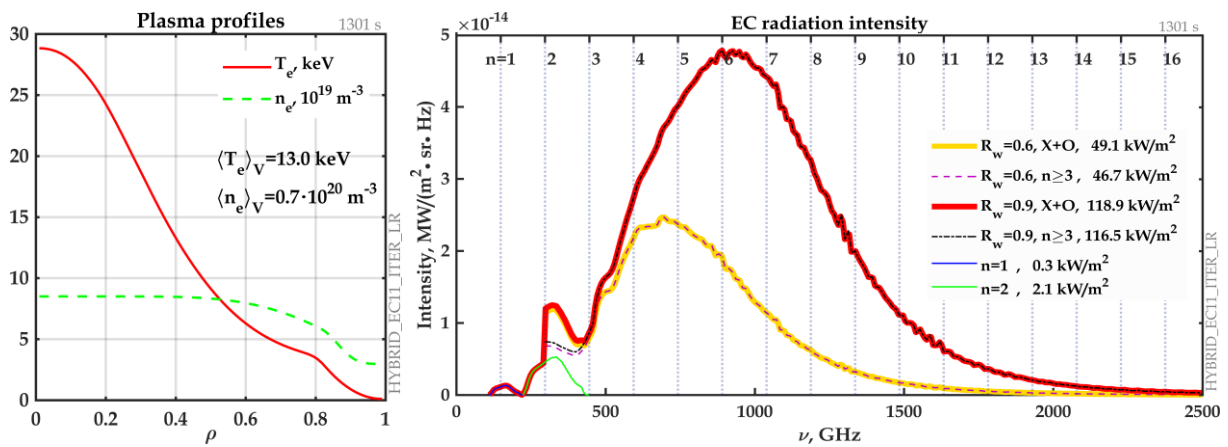


Figure 4. The same as in figure 2 but for the hybrid scenario of ITER operation [14].

**Conclusions.** Calculations of the spectral intensity of generated in plasma EC radiation coming out of plasma for various scenarios of ITER operation are carried out by the CYNEQ code. Additional calculations are needed to assess the possible impact of this ECR on the in-vessel components and diagnostics.

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