Runaway electrons measurements by ECE on the GOLEM tokamak

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The GOLEM tokamak is a small machine (R = 40 cm, a = 8.5 cm). Due to the high loop voltage (U_{loop} > 5 V) during quasi-state phase the feature of this device is generating the significant amount of runaway electrons (RE) [1]. The 16 channels 26.5 – 40 GHz ECE radiometer provided by the team of the COMPASS tokamak [2] was installed radialy on LFS. The plasma parameters of GOLEM (low n_e and T_e) do not allow to use the radiometer for tempertature measurements, however it is sensetive to ECE from runaway electrons.

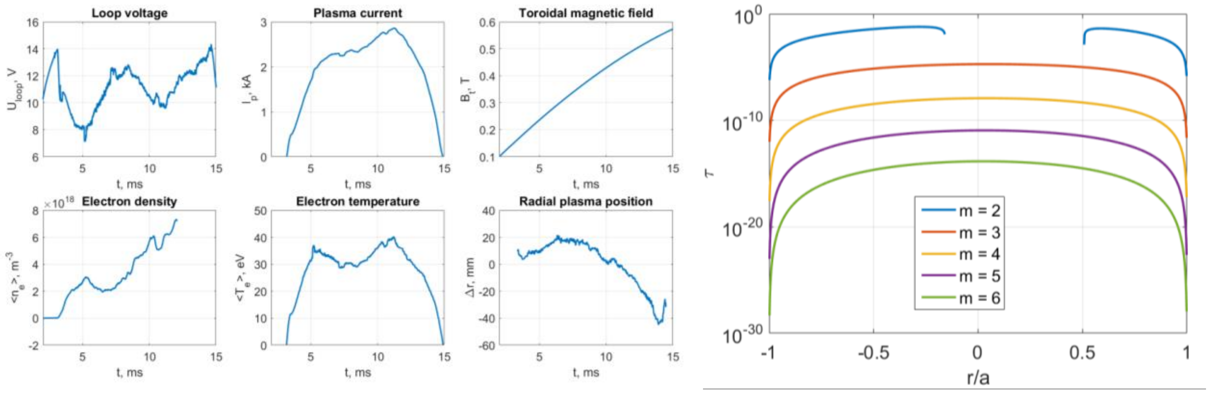

Figure 1: *Parameters of GOLEM plasma(left), opticall thickness for m-th ECE harmonic(right)*

The parameters of considered discharge are presented in figure 1. Low electron density and temperature create conditions when classical approach for temperature measurements by ECE cannot be used. Due to low optical thickness of GOLEM plasma ECE cannot be approximated by blackbody radiation model and at the same time under these conditions cyclotron radiation is dominated by emission from high energetic electrons. For modeling of this radiation the thin plasma model was suggested. In this model ECE is simulated as combination of single electrons emission. For the m-th harmonic of ECE electric field of a single electron can be presented in the next form:

$$\vec{E}_m = \frac{i\omega e}{4\pi\epsilon_0 cR}\left(\vec{x}\left(\frac{\cos\theta}{\sin\theta}\left(\cos\theta - \beta_{\|}\right)\right)J_m(\xi) + \ \vec{y}(-i\beta_{\perp})J'_m(\xi) + \vec{z}\left(\cos\theta - \beta_{\|}\right)J_m(\xi)\right)$$

$$\xi = \frac{\omega}{\omega_{ce}}\beta_{\perp}\sin\theta\,, \ \ \omega = \frac{m\omega_{ce}}{1-\beta_{\|}\cos\theta}, \ \ J - Bessel\ function$$

For the case of pure radial observation the equation can be simplified. $E_z/E_y \ \sim 10^{-4}$, so z-component of electric field also can be neglected:

$$E_m = \frac{m\omega_{ce}e}{4\pi\epsilon_0 cR}\left(\beta_\perp J'_m(m\beta_\perp)\right)$$

Assuming the rate of RE constant the signal measured by radiometer can be expressed next way:

$$P \sim n_e f_{RE} \sum_m |E_m|^2$$

Matching this model to experimental data via variation of the electron energy distribution function allows estimating the energy distribution. The shape of energy distribution was taken from hard x-ray measurements by scintillation detectors with CeBr3 crystals. The measurements presented in fig. 5 demonstrate exponential form of photon energy distribution $f \sim e^{-E/E_0}$. Assuming majority of photons being generated by bremstrahlung radiation from RE, such shape of distribution function was taken for the first estimation for RE energy distribution. In this case the task is to determine a coefficient E_0.

Simulation in accordance with this model (fig.2) demonstrates that the signal is mainly affected by harmonics with numbers m = 3 – 6.

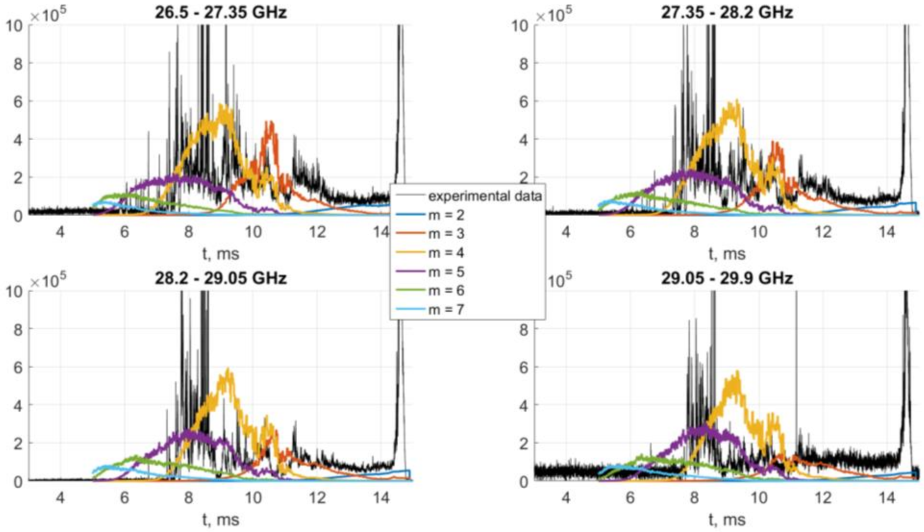

Figure 2: *Simulated signal from different harmonics for 1 – 4 channels of the radiometer*

This fact allows to estimate electron energy range available for observation by radiometer. The estimation was made by simple calculation on magnetic field, relativistic frequency shift, channel frequency and geometry of vacuum chamber. Energy range for harmonics 3 – 6 is presented in figure 3 (left). According to this energy range estimation and times of growth and decrease of different harmonics the main influence to signal is given by electrons with energies about 300-600 keV. Unfortunately the strong relativistic shift and harmonics overlapping also make impossible the accurate recovering of measurements localization.

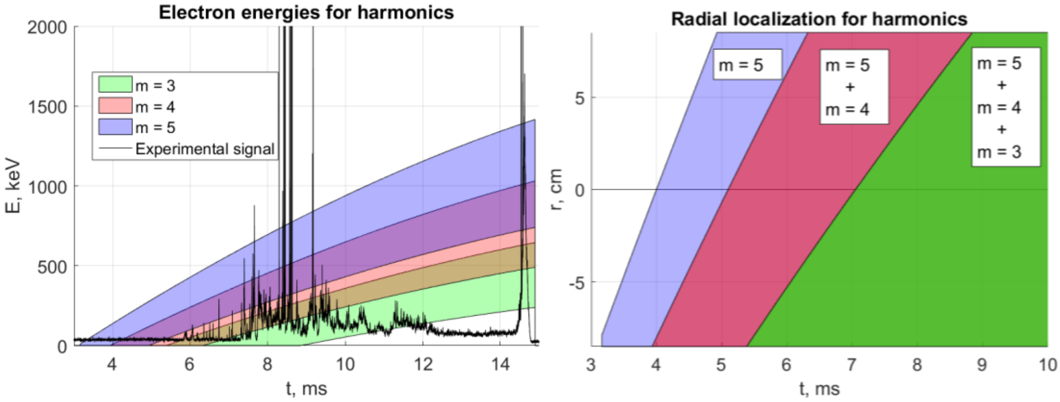

Figure 3: *Estimation of measured electron energies (left) and radial localisation(right)*

The full simulated signal for different parameters E_0 is shown in fig. 4. And a comparison of corresponded runaway energy distribution with photon distribution measured by scintillation detector is demonstrated in fig.5. The required E_0 for HXR data approximation is equal to 88 keV. However the simulation with using such coefficient is not able to explain ECE signal. Especially for times until 9.2 ms. Scanning of E_0 for matching the simulated and measured signals showed – there is no possibility to fit signals with using only one coefficient for the whole discharge. This fact demonstrates changing of RE energy distribution during the discharge. It was discovered that the ECE signal before 9.2 ms can be matched with $E_0 = 40\ keV$ and for the rest of signal the chosen coefficient is $E_0 = 180\ keV$. However it should be mentioned that changing of RE energy distribution in range 90 – 180 keV do not give significant change of shape of ECE signal. So, taking into account the measurements error it is not possible to recover the value accurately. Also the beginning of measured ECE signal (about 7.5 ms) is not fully matched with simulated data probably because of changing the RE distribution. E_0 should be equal to 30 keV or about this value for this part of signal but due to short length of signal there is no possibility to confirm it.

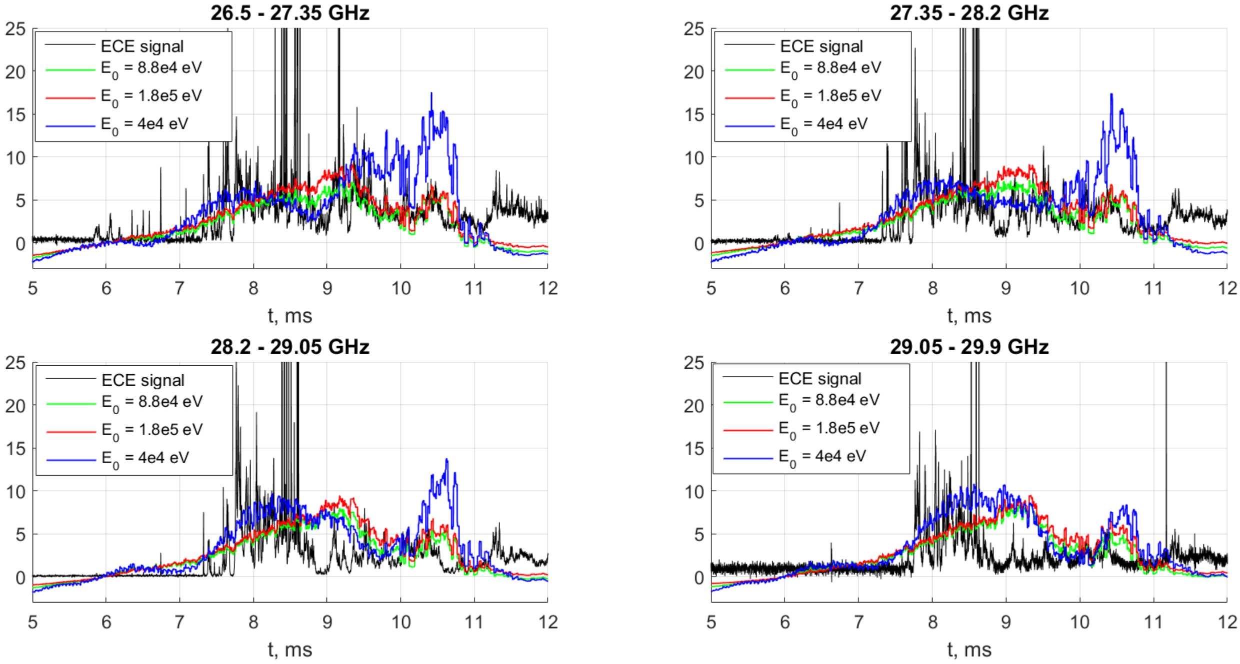

Figure 4. *Simpulations of ECE signal for different E_0*

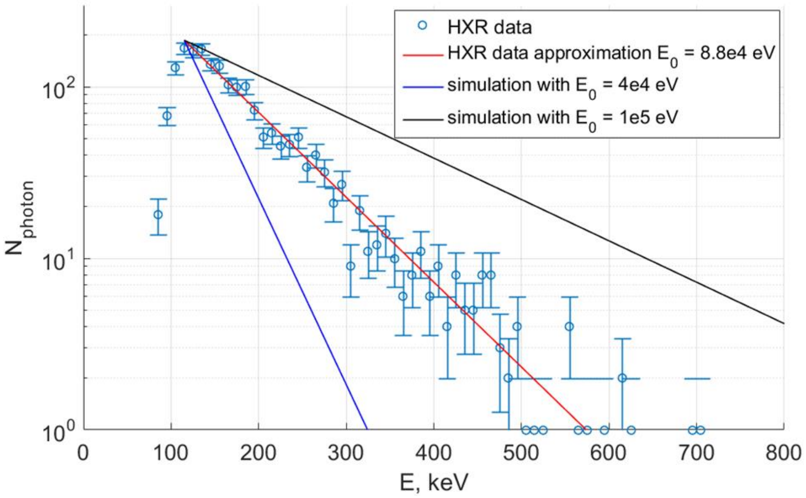

Figure 5: *Comparison of HXR energy distribution and electron energy distribution from ECE measurements*

As a result of the current the radiometer from the COMPASS tokamak was implemented to the GOLEM tokamak. First measurements revealed impossibility of using this radiometer for temperature measurements, but they demonstrated sensitivity of this diagnostic to runaway electrons radiation. During the joint experiment with using hard X-ray sensors, ECE radiometer and simulations of ECE in model of optically thin plasma the energy distribution function was estimated in form: $f \sim e^{-E/E_0}$, with coefficient E_0 = 40 keV before 9.2 ms of the discharge and with E_0 = 90-180 keV for the rest of discharge. One of significant disadvantages of the method suggested in the current work is necessity of assumption of electron energy distribution form from HXR measurement; however this assumption also can be made from theoretical modeling. The advantage of ECE diagnostic in comparison with HXR detectors is also possibility to separately estimate the electron distribution function for different parts of discharge and simplicity of measurements.

The measurements by HXR require an accurate position of sensors to have enough detected photons for analysis but the same time to do not have many of them to let overlapping of spikes of single photons at signal.

References:

[1] P. Dhyani, (2019) Journal of Instrumentation, **14**(09) (2019) C09029–C09029.
[2] J. Zajac, AIP Conference Proceedings **1187** (2009) 473