Runaway electron diagnostics for the COMPASS tokamak using EC emission

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Electron cyclotron emission measured vertically along the line of a constant magnetic field can yield information about the electron velocity distribution function and its evolution during a discharge [1]. This could be used for the direct detection of the runaway electron (RE) presence during runaway experiments performed in the COMPASS tokamak [2]. Vertical ECE (V-ECE) diagnostic was installed on COMPASS, a compact-sized tokamak operated at IPP Prague. In the following text brief characteristics of the diagnostics will be provided together with results of V-ECE measurements in low-density flattop discharges and in discharges with massive gas injections (MGI) of high-Z elements.

1 Experimental Setup. COMPASS [3] is a device with a D-shape plasmas capable of the high confinement mode operation. The dimensions correspond to one tenth of ITER ones. Main parameters are: magnetic field $0.9-1.5$ T, plasma current $80-400$ kA, electron density $10^{19}-10^{20}$ m^{-3} and discharge length under 400 ms. During RE experiments the line-average electron density does not exceed $3\cdot 10^{19}$ m^{-3}.

An ECE/EBW heterodyne radiometer was used for V-ECE measurements. It consists of a 16-channel intermediate frequency receiver. The E2-band with a $76.5-88.3$ GHz frequency range was used as a front-end. Horn antenna with a teflon lens is placed behind a quartz viewport oriented in a perpendicular direction. [4]

Hard X-rays (HXR) NaI(Tl) and HXR/Photoneutron shielded composit scintillators are used for measurements of runaway electrons loses.

2 Energy Spectrum and Simulations. The electron cyclotron resonance condition

$$\omega = n\cdot\omega_{\text{ce}}/\gamma + k_{||}v_{||}.$$

gives us a relationship between the measured frequency and the electron energy. EC emission originates from a certain velocity phase space, which fulfils this condition. The value of the cyclotron frequency in COMPASS in the standard magnetic field scenario ($B_{\text{T}} = 1.15$ T) is 32.2

GHz on the axis. Thus, it is possible to detect the down-shifted radiation from $n \geq 3$ harmonics using the E2-band frequencies. The emission from the 4^{th} and 5^{th} harmonic is substantially weaker. The resonant energies for the 3^{rd} harmonic are in the $50 - 140$ keV range. It is possible to investigate low-energy REs with parallel velocities above 0.4 c (assuming $v_\perp < 0.1$ c). We can consider the electrons in this phase space being "*runaway*" because the maximum critical (parallel) velocity v_c for COMPASS runaway experiments is 0.37 c. The maximum critical velocity corresponds to 36 keV of kinetic energy.

Simulations using the SPECE ray-tracing code [5] have aided the final diagnostic design and are employed for experimental data interpretation. SPECE can use a bi-Maxwellian plasma. The non-thermal Maxwellian represents the RE population. The values of the optical depth (τ) were obtained together with ray trajectories. The optical depth is rather low for both ordinary and extraordinary polarizations. Hence there exists a possibility of detecting reflected emission from the tokamak wall, which complicates data interpretation. Measurement of X-mode was chosen as $\tau_X/\tau_O = 20$, although O-mode measurements were performed as well.

3 Measurements We have found no spurious signal or unwanted detection of the thermal emission. Experiments have proven that low-energy runaways are the source of the detected electron cyclotron signal. Comparison of the V-ECE diagnostics with the HXR detection was done and it is shown in Figure 1. The figure shows the comparison of three low-density shots #14468, #14469 and #14471. Each shot contains a different RE presence, which is apparent from the shielded HXR signal. The HXR signal (third diagram) is similar due to the saturation of the detector in the shots #14469 and #14471. The results from this amplitude collation are in a good agreement with other measurements of the International Tokamak Physics Activity (ITPA) joint experiment group [7]. There were measurements of the RE threshold condition, where a significant number of REs occurs, as a function of the electron density. The same threshold also occurs in COMPASS and it can be estimated as $\overline{n}_e \approx 1.6 \cdot 10^{19}$ m^{-3}. This density threshold is related to the ratio of the electric field in tokamak and the theoretical value of the critical field [8]. Based on measurements of V-ECE, REs occur in COMPASS when $E > 15 \cdot E_c$.

Generation of the so called runaway seed was measured. The generation of the runaway seed occurs primarily during the ramp-up phase of the discharge where there is a low density and a high U_{loop} i. ,e. the electric field E. In Figure 3, the density ramp-down experimental scenario with generation of the RE seed (#14574) is presented. The low-energy runaway population is to some extent terminated as shown by the 24ms delayed detection of the HXRs. The REs are accelerated and after 24 ms collide with the tokamak first wall. By normalising and shifting the HXR signal, we get the confinement time circa 24 ms for this particular discharge scenario. The

REEs generated later, also created by the a primary generation mechanism, i. e. by decreasing E_c, are confined for the same period of time.

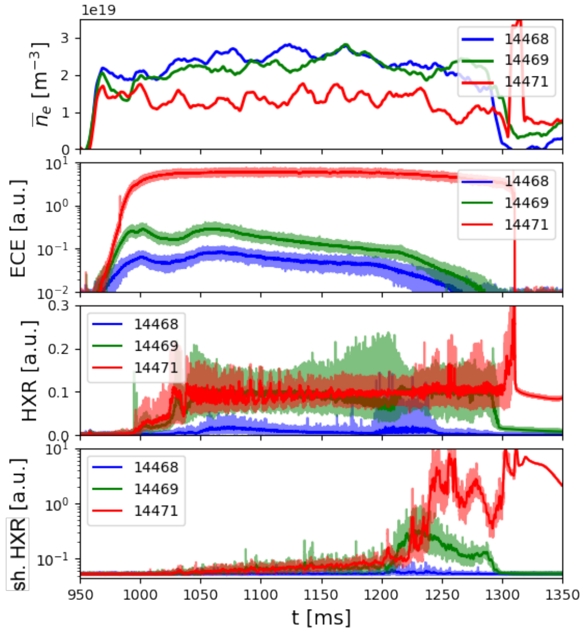

Figure 1: Comparison of the electron density, V-ECE and (shielded) HXR measurement from the shots 14468, 14469 and 14471.

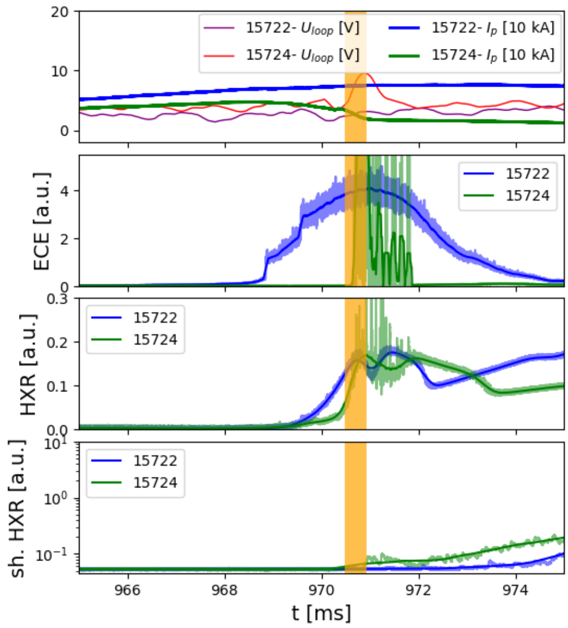

Figure 2: Comparison shots with the slow beam generation (#15722) and the strong beam generation (#15724). Orange denotes the current quench.

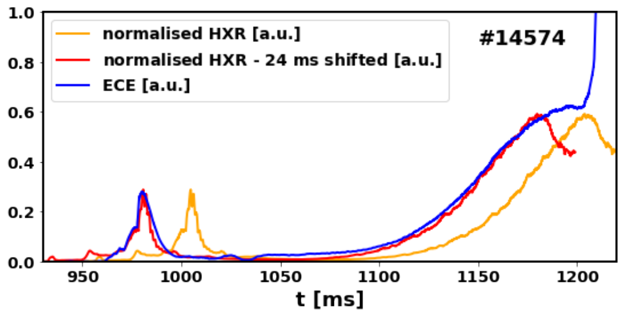

Figure 3: Smoothed HXR and V-ECE signals for the shot #14574.

Massive gas injection (MGI) experiments use high-Z gas puffs, for example argon, into the ramp-up phase of a discharge. It causes the radiative disruption during which the fastest electrons are subject to the Dreicer and the hot-tail generation mechanism and a RE beam is created.

Two scenarios of the RE beam generation were observed as it can be seen in Figure 2. The argon gas puff reaches the vacuum vessel at 969 ms and a milisecond after that in the shot #15724 the current quench (CQ) occurs. From the V-ECE diagnostics we can estimate that before the CQ in this shot there was no initial RE population. At the CQ, magnetic surfaces gradually collapse and filamentary structures are visible by the RIS camera. The filaments are captured also by the V-ECE in a form of frequent peaks. In the Vlainic classification [9] we talk about the strong beam. The RE beam has a minimum time to form itself and the generation is rather turbulent.

The second type of the RE beam generation is observed in the discharge #15722. The formation of the REs started slightly before the argon puff has reached the vessel. The RE generation is not so turbulent, there are no collapsing magnetic surfaces. Due to the initial RE presence, the entire plasma current is carried by the RE beam. There is no current quench. The RIS camera sees a wide non-filamentary RE beam column. In the Vlainic classification we talk about the slow beam. The RE beam has a sufficient time to form itself and the generation is rather calm. The RE beam, which is generated in this way, is sustained in the tokamak for much longer. There are only high-energy runaways, which cause the lack of the V-ECE signal in a later stage of the beam from 970 ms till the end of the discharge.

Conclusion

The V-ECE measurement provides information about the low-energy runaway electron presence. It can be used as a routine diagnostic, particulary in RE experiments. The RE threshold measurements agree with the results obtained on other tokamak devices. V-ECE is also useful diagnostic for MGI experiments due to its direct measurement of RE presence in a plasma during RE beam generation.

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