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Runaway Electron Measurements in the FTU Tokamak

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Abstract Gamma-ray spectra produced by runaway electrons when they impinge on the limiter or the vessel structures are measured in the Frascati Tokamak Upgrade (FTU) by a NaI scintillator spectrometer system [1]. The system is used to follow the energy evolution of the runaway electrons since their appearance early in the discharge. Measurements of gamma-ray spectra during the ramp-up and flat-top phase of ohmic and auxiliary heated discharges in hydrogen and deuterium plasmas have been performed. Both the maximum gamma-ray measured energy and the spectrum shape show a strong sensitivity to the plasma density and the toroidal electric field. A comparison with the predictions of a test particle model for the runaway energy [2] has been made. The results indicate that the behaviour of high energy runaway electrons (up to $\sim 20\,\mathrm{MeV}$) during auxiliary heating is determined by the change in the plasma parameters induced by the heating scheme with no evidence for an efficient resonant wave-particle interaction at large electron energies ($> 3\,\mathrm{MeV}$).

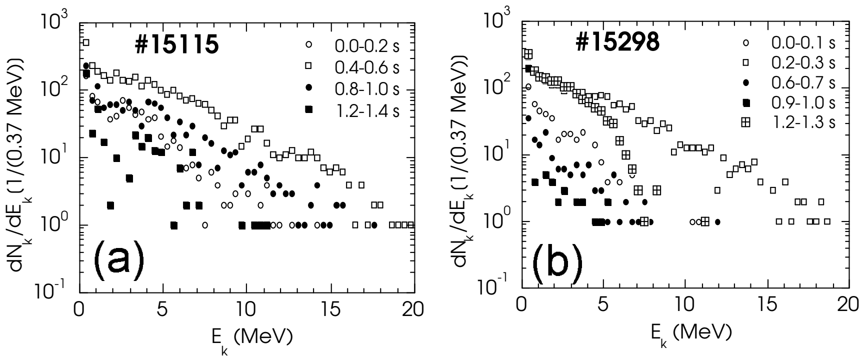
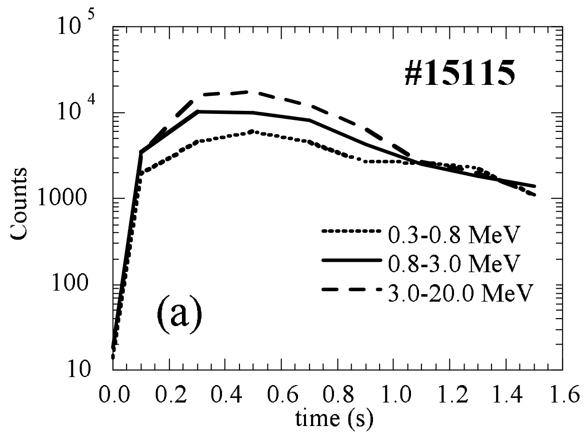


Figure 1: Bremsstrahlung gamma-ray spectra at selected time intervals for ohmic discharge # 15115 and Lower Hybrid current drive discharge # 15298 (dN_k/dE_k is the number of photon counts per energy interval and E_k the photon energy).

1. Experimental Set-up The measurement of gamma-ray spectra constitutes a useful tool to study the dynamics of runaway electrons in the FTU tokamak. The detection system is based on a 3" × 3" NaI scintillator, located $\sim 150°$ from the poloidal limiter, viewing at the plasma on the equatorial plane. The spectra are collected in the energy range (0.3-23) MeV with 1024 channel resolution and in 16 programmable time windows (0.1 s duration) during each plasma discharge. The measured gamma-rays are typically



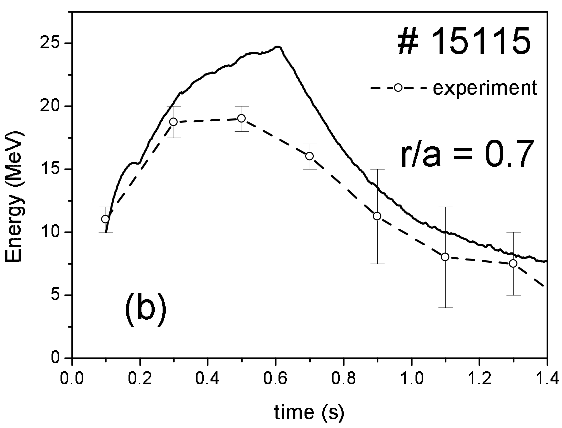


Figure 2: For ohmic discharge # 15115 (I_p = 700 kA; B_t = 5.4 T): (a) Time evolution of the photon counts detected by the gamma-ray spectrometer in several energy ranges; (b) Comparison between the maximum measured gamma energy (as roughly determined from the end points of the pulse height distributions) and the maximum runaway energy predicted by a test particle model of the runaway dynamics.

thick-target bremsstrahlung spectra produced by runaway electrons hitting the inconel limiter and the vessel structures. Fig. 1 shows typical gamma-ray spectra for FTU ohmic and auxiliary heated discharges.

2. Ohmic Discharges Runaway electrons have been observed during the current ramp-up and flat-top phase of ohmic discharges in hydrogen and deuterium plasmas. The plasma current during the flat-top phase ranges from 300 kA to 1 MA, $B_t \sim 6\,\mathrm{T}$, $R_0 \sim 0.94\,\mathrm{m}$, $a \sim 0.30\,\mathrm{m}$ and the line average density reaches up to $\sim 10^{20}\,\mathrm{m}^{-3}$. Fig. 2 (a) shows the time evolution of the photon counts measured by the gamma-ray spectrometer in different energy intervals for the ohmic discharge # 15115 ($I_p \sim 700\,\mathrm{kA}$). The figure suggests that the runaway electrons are created during the current ramp-up (up to $\sim 0.2\,\mathrm{s}$), when the electric field is high and the density low. This has been confirmed by calculations of Dreicer generation of runaway electrons. Nevertheless, runaway electrons of several MeVs are observed during all the discharge, suggesting that the runaways remain well confined in the plasma. The gamma-ray spectra at selected times for # 15115 are plotted in Fig. 1 (a). The gamma-ray spectrum builds up during the current ramp-up (up to $\sim 0.5\,\mathrm{s}$) and decays later on during the flat-top phase (up to $\sim 1.5\,\mathrm{s}$).

In Fig. 2 (b), the time evolution of the maximum measured gamma energy (dashed line) is compared with the predictions of a test particle model for the runaway dynamics [2] (full line). The model for the runaway dynamics includes acceleration in the electric field, collisions with the plasma particles and synchrotron radiation losses. As input data for the simulations are used the electric field inferred from the measured loop voltage, the effective charge Z_{eff} from visible bremsstrahlung measurements and the electron density at $r/a \simeq 0.7$ from Abel inverted DCN interferometer profiles (as the gamma ray spectra

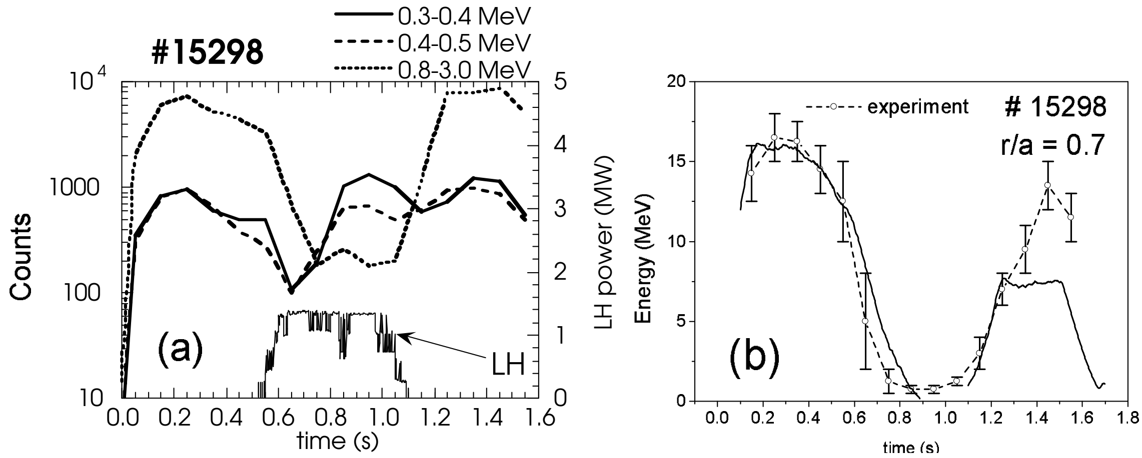


Figure 3: For Lower Hybrid current drive discharge # 15298 (I_p = 350 kA; P_{LH} = 1.4 MW): (a) Time evolution of the photon counts detected by the gamma-ray spectrometer in several energy ranges; (b) Comparison between maximum measured gamma energy and maximum predicted runaway energy.

should be mainly due to runaways hitting the limiter/vessel structures and therefore located in the plasma edge region). It can be seen that the model properly reproduces the main features of the experimental measurements. Application of the model to different discharges indicate that the runaway dynamics is strongly sensitive to the toroidal electric field and the plasma density and that no qualitative differences are observed in the runaway behaviour between hydrogen and deuterium plasmas.

3. Auxiliary Heated Discharges The effect of auxiliary heating on runaway electrons has been investigated. Lower Hybrid (LH) and Electron Cyclotron (ECRH) heated discharges have been analyzed. Fig. 3 (a) shows in different energy ranges the photon counts vs. time for the LH shot # 15298 ($I_p \simeq 350$ kA; LH frequency $f = 8$ GHz; $P_{LH} \simeq 1.4$ MW). During the LH phase, the number of counts at high energy (0.8-3 MeV in the figure) decreases. This is due to the reduction of the runaway energy associated with Lower Hybrid current drive which decreases the electric field during this phase as it is observed in the loop voltage signal. However, in the low energy range (up to 500 keV in the figure) the number of counts increases after a fast initial decay, probably because of the resonant interaction with the LH waves via Landau damping giving rise to the current drive. Nevertheless, as it is shown in Fig. 3, the increase in the gamma-ray emission is still observed for energies significantly larger than the nominal resonant energy ($\sim$ 100 keV, corresponding to a parallel refractive index $N_{||} = 1.8$). The gamma-ray spectra at different times are plotted in Fig. 1: the runaway population builds up during the plasma current ramp-up and, during the Lower Hybrid phase ($\sim 0.5 - 1.1$ s), a sharp steepening of the slope of the spectrum is observed together with a reduction of the maximum gamma ray energy. After LH injection, the pre-current drive situation (both the spectrum shape and the maximum measured gamma ray energy) is restored corresponding to a runaway

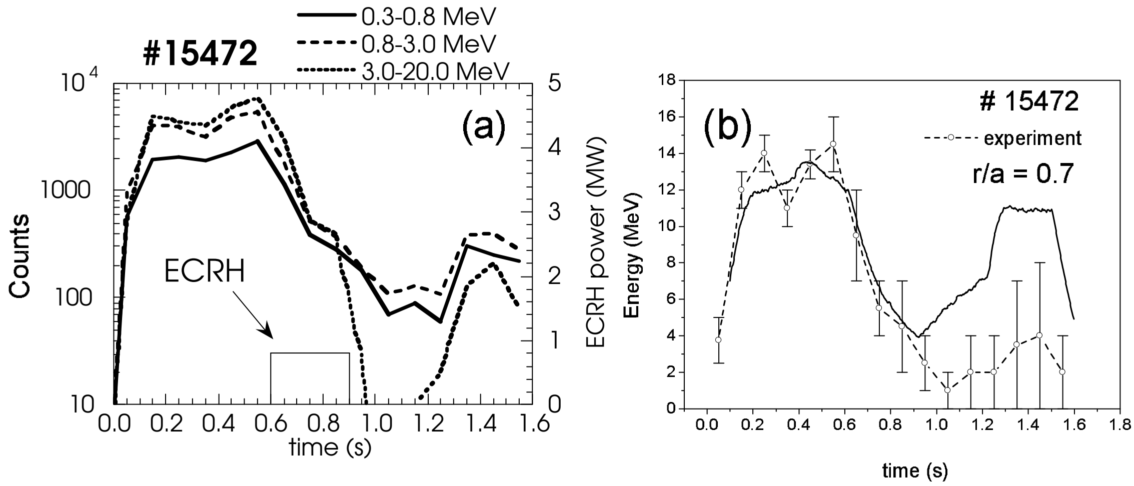


Figure 4: For ECRH discharge # 15472 (I_p = 400 kA; P_{ECRH} = 0.8 MW): (a) Time evolution of measured photon counts in several energy ranges; (b) Comparison between maximum measured gamma energy and maximum predicted runaway energy.

population rapidly building up again. The effect of the LH waves on the high energy electrons is better illustrated in Fig. 3 (b), in which the maximum measured gamma energy is compared with the predictions of the test particle model. The decrease of the maximum energy during the LH phase is determined by the reduction of the electric field. Once the LH power stops (at $\sim$ 1.1 s), the electric field goes up and the runaway energy increases again. No evidence has been found for an efficient resonant wave-particle interaction at large electron energies ($>$ 3 MeV), such as the interaction of runaway electrons with Lower Hybrid waves via anomalous Doppler broadening [3].

In Fig. 4, the results for the ECRH discharge # 15472 ($I_p \sim$ 400 kA; $P_{ECRH} \simeq$ 0.8 MW, f = 140 GHz, off-axis heating) are illustrated. During ECRH ($\sim 0.6 - 0.9$ s), the electron temperature increases and hence the plasma resistivity and the electric field decrease, resulting in the reduction of the runaway energy [see Fig. 4 (b)]. In this case, the reduction in the number of counts during the ECRH phase [shown in Fig. 4 (a)] is observed in all the energy intervals as there is not an efficient resonant interaction at low energy as it is seen during LH current drive. Later on, once the ECRH power is turned off, the electric field rises again and therefore the runaway energy and the gamma ray emission. The disagreement between the measurements and the simulation for $t > 0.9$ s could be due to local variations of T_e (and hence of the electric field) associated with the off-axis heating, not accounted for in the estimate of the electric field based on the loop voltage signal.

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