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Runaway Electron Behaviour during Auxiliary Heating in the FTU Tokamak

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Abstract The behaviour of high energy runaway electrons during Electron Cyclotron (EC) and Lower Hybrid (LH) heating has been investigated in the Frascati Tokamak Upgrade (FTU). During EC heating, the fall of the electric field associated with the temperature increase has been observed to yield a reduction of the runaway energy which frequently leads to runaway quenching. During LH heating, although quenching of the MeV-runaway electrons is observed due to the drop of the electric field via Lower Hybrid Current Drive, acceleration of the wave-resonant suprathermal tail (of several hundreds of keV) after the heating phase allows the runaway population to be restored.

1. Electron Cyclotron Resonance Heating The experiments were carried out in deuterium discharges with typical plasma parameters: plasma current $I_p = 0.3 - 0.5\,\mathrm{MA}$, toroidal magnetic field $B_0 = 4 - 6\,\mathrm{T}$ and central line averaged density $\overline{n}_e = (4 - 8) \times 10^{19}\,\mathrm{m}^{-3}$. The EC waves were injected during the current flat-top phase of the discharge and the input power was varied in a range from 0.3 to 1 MW.

Fig. 1 (left) shows the time evolution of the main plasma parameters for a typical ECRH discharge (maximum injected power $P_{EC} \sim 0.9\,\mathrm{MW}$). During heating, the electron temperature T_e increases ($\sim$ from 1 to 4 keV in the plasma center), which leads to a decrease of the plasma resistivity ($\eta \propto T_e^{-3/2}$) and, hence, of the plasma loop voltage V_l [loop voltage drop $\sim$ 40%, trace (c) in left Fig. 1]. Thus, the electric field is reduced and the runaway energy decreases which, if the energy fall is large enough, can yield the quenching of the runaway population. This is illustrated in Fig. 1 (right) which shows, for the same discharge, the time traces of the measurements of a set of BF_3 counters [1] for neutron detection, and a NE213 scintillator, sensitive both to neutrons and gamma-rays. During discharges with negligible runaway population, a perfect overlapping of the two traces occurs, while in runaway discharges, the NE213 signal is contaminated by an excess of gamma-ray events and the NE213 signal no longer equals the BF_3 measurements [2]. The large difference observed in right Fig. 1 (a) between the BF_3 and NE213 signals during the first 500 ms of the discharge is due to the runaway electrons created during the current ramp-up. During EC injection, the difference between the signals is reduced until they overlap, indicating the disappearance of the runaway population.

Right Fig. 1 (b) shows the time evolution of the photon counts (total number and in several energy intervals) detected by a gamma-ray spectrometer viewing the plasma on the equatorial plane. The system allows to collect gamma-ray spectra in the energy range 0.3-23 MeV with a time resolution of 0.1 s. The gamma-ray measurements are typically

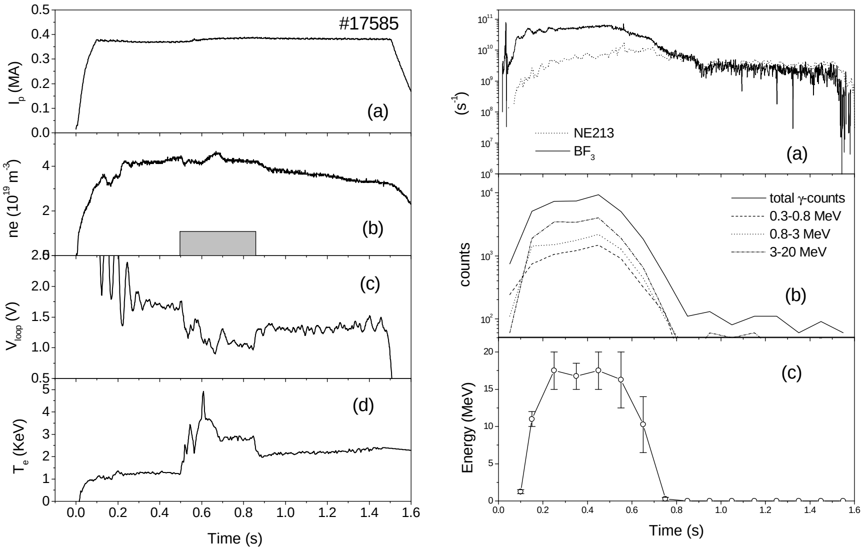


Figure 1: **Left:** Time evolution of plasma current, central line averaged density, loop voltage, and electron temperature at plasma axis for deuterium discharge 17585. The shaded area shows the time interval for ECRH heating; **Right:** For the same discharge: Time traces of BF_3 and NE213 scintillator, photon counts detected by the gamma-ray system (total and in several energy ranges), and maximum measured gamma energy.

thick target bremsstrahlung spectra produced by runaway electrons hitting the limiter and the vessel structures. The fall of the gamma-ray emission at $\sim 0.5\,\mathrm{s}$ is correlated to the reduction of the energy and number of runaway electrons following EC injection. The maximum gamma energy (as roughly determined from the end points of the pulse height distributions) can be used as an estimate of the maximum runaway energy [2], and it is plotted versus time in right Fig. 1 (c): the electron energy increases during the current ramp-up to $\sim 15\,\mathrm{MeV}$ and experiences a large drop after ECRH is applied, finally going to zero. No runaway electrons are observed anymore after ECRH, even when the pre-heating plasma conditions have been restored.

The efficiency of this mitigation scheme is determined to a great extent by the EC plasma heating efficiency as, the larger is the temperature increase, the larger will be the drop of the electric field ($E_{||} \propto T_e^{-3/2}$). For efficient enough runaway suppression, the temperature increase during ECRH should be high enough to drop the electric field close to the threshold field, E_{th}, for runaway generation (minimum electric field for runaway generation under the given plasma conditions). The analysis made for a selected set of ECRH FTU discharges has shown that this condition is reached in FTU for a temperature increase factor during the heating phase $> 1.3 - 1.5$ (loop voltage drop $> 35\%$).

2. Lower Hybrid Heating The behaviour of runaway electrons during Lower Hybrid Current Drive (LHCD) has been investigated for a set of deuterium FTU discharges [$I_p = 0.4 - 0.5\,\mathrm{MA}$, $B_0 = 5 - 7\,\mathrm{T}$, and $\overline{n}_e = (3 - 7) \times 10^{19}\,\mathrm{m}^{-3}$]. The frequency of the waves was $f = 8\,\mathrm{GHz}$ and the parallel refractive index $N_{||} = 1.5\,\mathrm{or}\,1.8$ (nominal energy

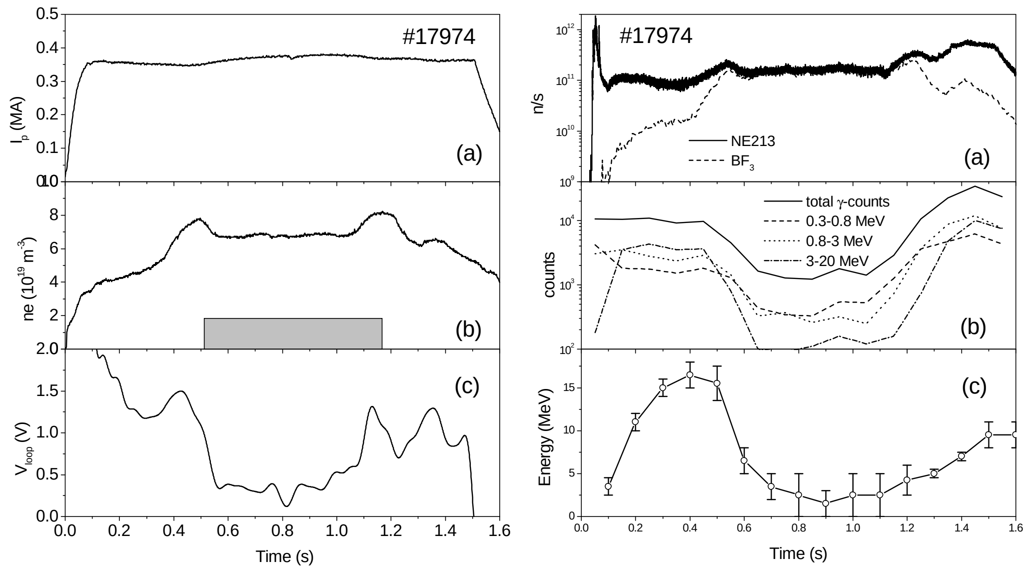
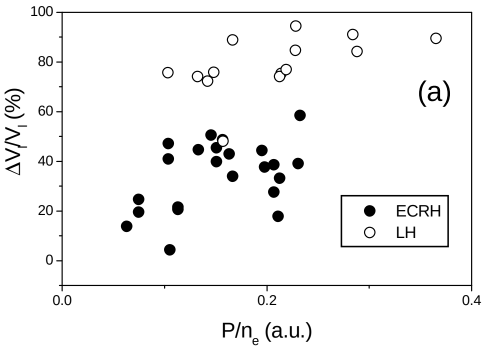


Figure 2: **Left:** Time evolution of plasma current, central line averaged density and loop voltage for deuterium discharge 17974. The shaded area shows the time interval for LH injection; **Right:** For the same pulse: Time traces of BF_3 and NE213 scintillator, photon counts detected by the gamma-ray system, and maximum measured gamma energy.

for the resonant electrons $\sim 100 - 175\,\mathrm{keV}$). The LH waves were injected during the current flat-top and the input power was varied between 0.3 and 1.2 MW.

Fig. 2 (left) shows the time evolution of some plasma parameters for the discharge 17974 ($N_{||} = 1.8$; $P_{LH} \simeq 1\,\mathrm{MW}$). It should be noticed the large drop of the loop voltage during the LH phase. The loop voltage drop is, in general, much larger for LH discharges than for ECRH discharges [see Fig. 3 (a)] and must be attributed to the replacement of the plasma current by the current carried by the suprathermal electrons resonant with the waves during LHCD. The resonant electrons ($\sim$ several hundreds of keV) can be detected by an FEB camera measuring, in the energy range 20 - 200 keV, the bremsstrahlung x-ray emission through a set of vertical and horizontal lines of sight. In Fig. 3 (b), the loop voltage drop is plotted versus the measured line integrated FEB emission (central vertical chord) during the LH phase for a set of LH discharges, illustrating the correlation between the fall of the electric field and the creation of the fast resonant electrons.

The runaway measurements for discharge 17974 are shown in right Fig. 2. It can be observed that the runaway population created during the current ramp-up is suppressed (the BF_3 and $NE213$ signals overlap) during the LH phase, when the loop voltage has dropped close to zero. The runaway energy during this phase is rapidly reduced, from $\sim 16\,\mathrm{MeV}$ to zero inside the experimental uncertainties. This behaviour is similar to the one discussed for ECRH discharges, except that the reason for the loop voltage fall is different in the two cases. However, meanwhile the runaway population disappears during ECRH and is never restored after the heating phase, the runaway signals recover their pre-heating level (see right Fig. 2) once LH injection stops, even when the drop of the



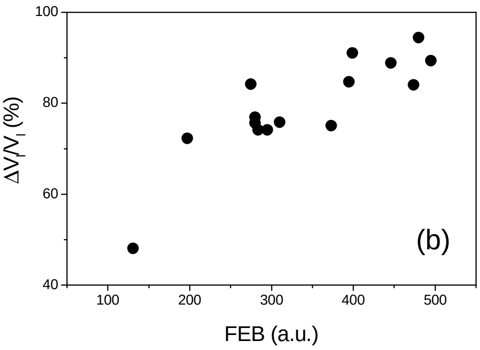


Figure 3: (a) Loop voltage drop versus input power per particle for ECRH (black circles) and LH (open circles) FTU discharges; (b) For LHCD discharges: Loop voltage drop versus line integrated x-ray emission (FEB central chord) during the LH phase.

electric field during LHCD is noticeable larger [Fig. 3 (a)]. This is due to the population of suprathermal electrons created via Landau damping during the LH phase. When the LH waves are injected, the drop of the electric field annihilates the MeV runaway electrons generated during the start-up of the discharge and, at the same time, a population of suprathermal electrons, resonant with the wave ($\sim$ 100 keV for $N_{||} = 1.8$), is created. After the heating phase, the LH resonant electrons, accelerated by the restored electric field, constitute the observed MeV runaway population. Simulations of the electron energy gain after LH injection confirm that suprathermal electrons $\sim$ hundreds of keV can be accelerated to the measured MeV energies after the LH phase.

It should be noticed that the observed runaway population after LH heating is completely independent of the runaway electrons previous to the heating phase, and is only determined by the reservoir of suprathermal electrons created during LHCD and the plasma conditions after heating. The plasma parameters after wave injection will "decide" if the suprathermal electrons can be converted into runaway electrons and their final energy. Hence, for LH discharges in which the plasma density is sufficiently increased after heating, no MeV electrons are observed following the LH phase; on the contrary, when the density is lowered, the runaway population and energy can significantly increase in comparison to the pre-heating phase of the discharge. This could be of importance if a disruption takes place during LH injection: the suprathermal electrons accelerated by the high electric field during the current quench could noticeably enlarge the generated runaway population during the fast disruptive event. In fact, FTU disruptions during LHCD usually show much larger neutron emission than normal disruptions, which could be associated to acceleration of the suprathermal electron tail created during LHCD.

References

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