

Parameter Space Analysis for Runaway Electrons during Start-up in the FTU Tokamak

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1. Introduction There is concern about the initiation phase in future large devices like ITER [1], which will require low prefill pressures, leading to low densities during the breakdown and burn-through phases, which can result in the generation of runaway electrons (REs). Hence, it is important to design the start-up of the tokamak so that no REs can be generated, or at least in a number that they do not damage the plasma facing components or interfere with the build-up of the thermal plasma current. The Connor critical electric field [2], $E_R = n_e e^3 \ln \Lambda / 4\pi \varepsilon_0^2 m_e c^2$, has been often used as the parameter determining the existence of REs, although due to energy losses other than collisions, as the electron synchrotron radiation, the critical field can be larger. In this work, a parameter space analysis, based on the critical electric field due to radiation, allowing the identification of the non-runaway/runaway regions, also providing information on the RE energy and generation, is used to track the plasma during start-up in the FTU tokamak.

2. Parameter phase space map for runaway electrons It has been predicted [3] that, due the synchrotron radiation losses, the critical electric field for RE generation must be larger than the Connor critical field, later corroborated in the FTU tokamak [4,5]. A good empirical fitting to this increased critical field, E_R^{rad} , can be written [4]:

$$\frac{E_R^{rad}}{E_R} \simeq 1 + C(Z) F_{gy}^\alpha \quad (1)$$

where $F_{gy} = 2\varepsilon_0 B_0^2 / 3n_e \ln \Lambda m_e$ is a parameter describing the effect of radiation [3], $C(Z) \simeq 1.64 + 0.53 Z - 0.015 Z^2$ (Z is the effective ion charge), and $\alpha \approx 0.5$.

Based on E_R^{rad} , a runaway parameter phase space can be defined in which $y \equiv (E_{||}/E_R) - 1$ and $x \equiv C(Z) F_{gy}^\alpha$ (Fig. 1), allowing a simple identification of the non-runaway/runaway regions: $y = x$ corresponds to the RE threshold due to radiation ($E_{||} = E_R^{rad}$), while $y = 0$ is the Connor threshold ($E_{||} = E_R$). Thus, $y > x$ represents the RE region ($E_{||} > E_R^{rad}$), $y < x$ corresponding to the non-RE region.

It is possible to include in this (x, y) space some additional information, such as the critical energy for RE generation, E_c , or the limiting RE energy, E_l . The normalized (to $m_e c$) critical momentum for RE generation is $q_c \simeq 1/\sqrt{(E_{||}/E_R) - 1}$ [2], so that the region of constant E_c ($\equiv (1 + q_c^2)^{1/2} - 1$), in the (x, y) phase space corresponds to the line

$$y \equiv \frac{E_{||}}{E_R} - 1 \approx \frac{1}{q_c^2} = \left\{ \left(1 + \frac{E_c}{m_e c^2} \right)^2 - 1 \right\}^{-1/2}. \quad (2)$$

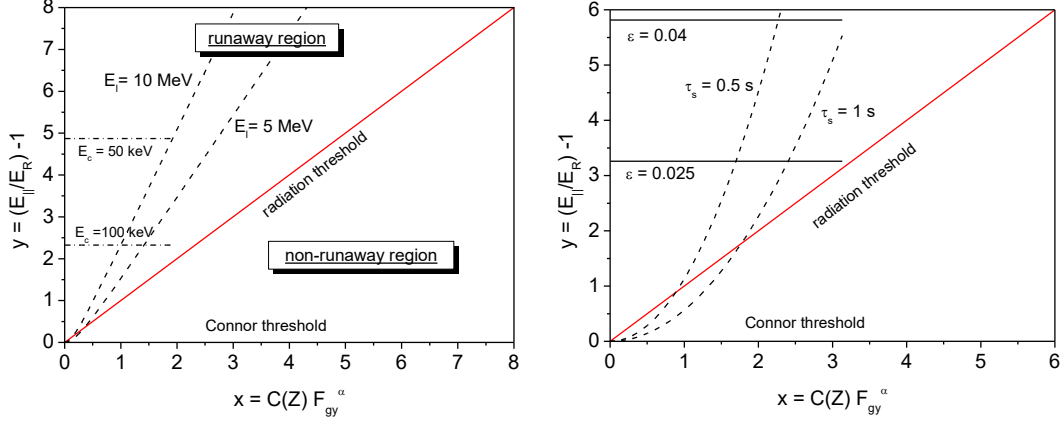


Figure 1: Runaway parameter space map, $y \equiv (E_{||}/E_R) - 1$ versus $x \equiv C(Z) F_{gy}^\alpha$. The red line ($y = x$) corresponds to the radiation threshold, and $y = 0$ to the Connor critical field. Left: The dashed black lines correspond to $E_l = 5$ and 10 MeV, and the dash-dotted lines to $E_c = 50$ and 100 keV; Right figure: The horizontal black lines correspond to $\varepsilon = 0.025$ and 0.04 , and the black dashed lines to constant values of τ_s .

During start-up, it is expected that the electron radiation is dominated by the electron gyromotion and, in such a case, the steady state limiting RE energy [3], $\gamma \simeq D(D-1)/(1+Z)F_{gy}$ (γ is the electron relativistic gamma factor, and $D \equiv E_{||}/E_R$). Thus, the regions of constant (limiting) energy (γ) in the (x, y) parameter phase space are given by:

$$D = \frac{1}{2} + \left(\frac{1}{4} + (1+Z)\gamma F_{gy} \right)^{1/2} \implies y \approx \left(\frac{1}{4} + \frac{(1+Z)\gamma x^2}{C(Z)^2} \right)^{1/2} - \frac{1}{2}. \quad (3)$$

Fig. 1 (left) shows, as example, the resulting lines of constant critical energy for $E_c = 50$ and 100 keV, and limiting RE energy ($E_l = (\gamma - 1)m_e c^2$) for 5 and 10 MeV in the RE parameter phase space ($Z = 3$ has been assumed).

Also, some information can be provided about the RE generation mechanisms. Thus, Fig. 1 (right) shows in the (x, y) space lines of constant values for the Dreicer parameter, $\varepsilon = (E_{||}/E_R) \cdot (m_e c^2/kT_e)$ ($\varepsilon = 0.02, 0.04$ in the figure), corresponding to $y = (m_e c^2/kT_e)\varepsilon - 1$, which determines the RE generation by the Dreicer process, and generally works for $\varepsilon > 0.02$. In addition, information about the RE avalanche mechanism (also in Fig. 1 (right)) can be provided by lines of constant avalanching time [6],

$$\tau_s \approx \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e} \sqrt{\frac{3(5+Z)}{\pi}} \left(\frac{E_{||}}{E_R} - 1 \right)^{-1} \implies y = \frac{m_e c \ln \Lambda a(Z)}{e E_R \tau_s} \quad (4)$$

$$(a(Z) \equiv \sqrt{3(5+Z)/\pi}).$$

3. FTU discharges REs have been routinely observed in the FTU tokamak. A typical example is shown in Fig. 2, corresponding to the FTU deuterium ohmic discharge # 18709 ($B_0 = 5.6$ T). The trajectory of the plasma in the runaway parameter phase space (middle and right figures), y vs. x , is illustrated in the figure. The arrows correspond to times close to the end of the ramp-up (0.3 s) and well within the flat-top phase (1.25 s), respectively. The plasma stays in the RE region, not only during the start-up but during

the flat-top phase too in consistency with the RE measurements (left Fig. 2 (d)) (the NE213 scintillator signal is larger than the BF_3 measurements, indication of the presence of REs [7]).

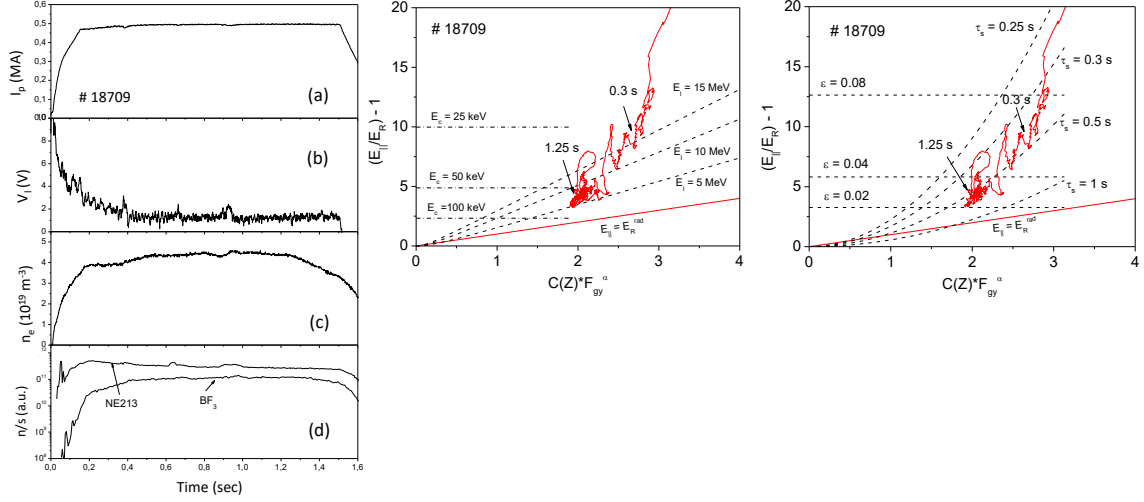


Figure 2: For FTU discharge 18709: Left: Time traces of I_p , V_t , line averaged n_e , and (BF_3 , NE213) measurements; Middle and Right: Trajectory of the plasma in the RE parameter phase space, indicating lines of constant limiting RE energy ($E_l = 5, 10, 15$ MeV), and E_c (25, 50, 100 keV) (middle), and Dreicer parameter ($\varepsilon = 0.02, 0.04, 0.08$) and $\tau_s = 0.25 - 1$ s (right).

Fig. 2 (middle) also shows in the (x, y) space the lines of constant steady state limiting RE energy for 5, 10 and 15 MeV, indicating that the REs reach energies during the flat-top in the range of a few MeVs, as observed in FTU¹ [7]. The lines of constant critical energy (25, 50 and 100 keV) are also plotted, and E_c is found to increase during ramp-up until ~ 75 keV during steady state. In Right Fig. 2, lines of constant Dreicer parameter ($\varepsilon = 0.02, 0.04$ and 0.08) and constant avalanching time ($\tau_s = 0.25 - 1$ s) are also included in the (x, y) space. The Dreicer process is large in the beginning (large ε) and remains operative during the start-up phase ($\varepsilon > 0.02$), ending close to $\varepsilon \approx 0.02$ during the flat-top, whereas τ_s increases during start-up from ~ 0.25 to 0.5 s, always larger than the characteristic ramp-up time ($t_{ramp-up} \sim 0.2$ s) suggesting that the avalanche process is not playing an important role during ramp-up.

4. RE avoidance In standard FTU ohmic (OH) discharges, the plasma always stays within the RE region both during start-up and during the flat-top phase, even in situations in which no RE electrons are detected under conditions in which the number of generated REs is too low to yield a measurable signal. RE avoidance demands that the plasma is in the non-RE region, below the line $E_{||} = E_R^{rad}$. An estimate can be made of the density required for RE avoidance in FTU. This is illustrated in Fig. 3 (Left) which, for a typical waveform of the plasma loop voltage in FTU (like in Fig. 3), shows the calculated plasma trajectory in the $y - x$ space, assuming a linear increase of the density during ramp-up (up to 0.2 s) to values during the flat-top ranging from $2 \times 10^{19} \text{ m}^{-3}$ to $2 \times 10^{20} \text{ m}^{-3}$, indicating that quite large densities ($> 10^{20} \text{ m}^{-3}$) are needed in FTU for RE

¹In the beginning of the ramp-up phase, the RE energy is lower than the steady state limiting RE energy which, in FTU, is typically reached during the flat-top phase.

avoidance. Instead, more often, RE avoidance can be reached in FTU at lower densities due to the drop of the electric field below E_R^{rad} by heating of the plasma during ECRH or by LHCD as illustrated in Fig. 3 (right).

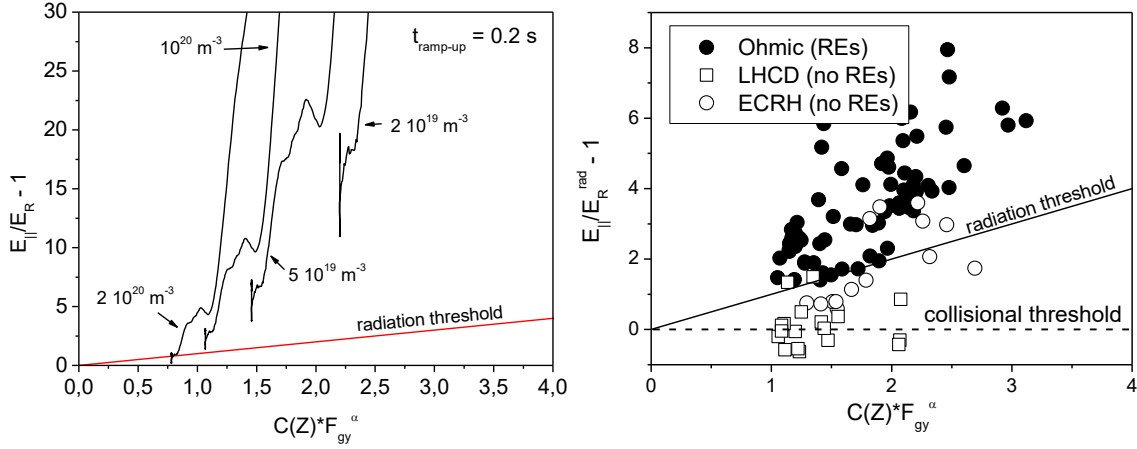


Figure 3: Left: Trajectory of the plasma in the RE parameter phase space for a typical waveform of the plasma loop voltage in FTU and different values of the flat-top density ($2 \times 10^{19} \text{ m}^{-3} - 2 \times 10^{20} \text{ m}^{-3}$), assuming a linear increase of the density during current ramp-up; Right: Experimental points on the RE phase space for steady state FTU OH discharges (with REs) and during RE avoidance for ECRH and LHCD discharges (Fig. taken from [4]).

5. Conclusions The trajectory of the plasma in the runaway parameter phase space based on the critical electric field E_R^{rad} has been followed during the start-up phase of FTU discharges. The analysis allows to identify the RE and non-RE regions, and provides information on the RE limiting and critical energies, and the RE generation mechanisms. The plasma is typically observed to stay inside the RE region, not only during the start-up but during the current flat-top too, starting far from the RE boundary ($E_{||} = E_R^{rad}$), when the REs are mostly generated (large ε , low E_c), approaching to the non-RE region along the start-up and flat-top phase, and reaching MeV energies. Runaway avoidance can be reached in FTU when the plasma crosses the radiation boundary, due to a large density ($> 10^{20} \text{ m}^{-3}$) or, at lower densities, due to the drop of the electric field during ECRH or LHCD.

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