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

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MOTIVATION

- During plasma start-up in future fusion devices such as **ITER** [1], low prefill pressures may lead to low plasma densities and the generation of **runaway electrons (REs)**.
- Even relatively **small RE populations** may **damage plasma-facing components** or interfere with the build-up of the thermal plasma current.
- The classical Connor critical electric field [2], $E_R = n_e e^3 \ln\Lambda/4\pi\varepsilon_0^2 m_e c^2$, is often insufficient to determine RE generation because **synchrotron radiation losses increase the effective critical field**.
- This work uses a **runaway parameter phase space based on the radiation critical field** to identify runaway and non-runaway operating regimes and to analyse FTU start-up scenarios.

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 (E_R^{rad}) must be larger than the Connor critical field (E_R), later corroborated in the Frascati Tokamak Upgrade (FTU) [4,5]. A good empirical fitting to this increased critical field, E_R^{rad}, can be written [4]:

$$\boxed{\frac{E_R^{rad}}{E_R} \simeq 1 + C(Z)F_{gy}^{\alpha}} \qquad F_{gy} = \frac{2\varepsilon_0 B_0^2}{3n_e \ln\Lambda\, m_e} \qquad \alpha \simeq 0.5$$

Effect of radiation

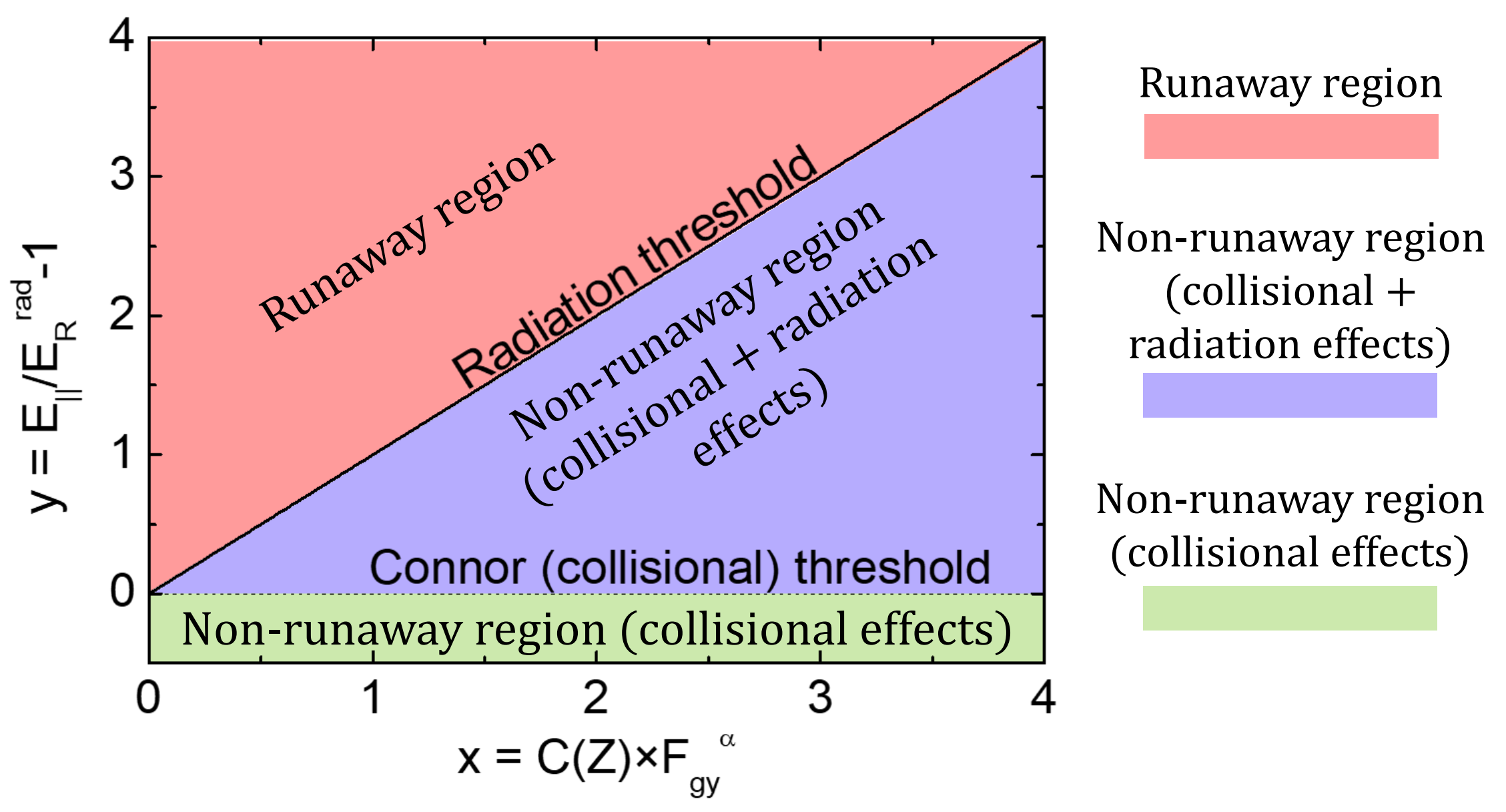
$$C(Z) \simeq 1.64 + 0.53Z - 0.015Z^2 \qquad Z\text{: effective ion charge}$$

Defining the dimensionless coordinates:

$$y = \frac{E_\parallel}{E_R} - 1$$

$$x = C(Z)F_{gy}^{\alpha}$$

A runaway parameter phase space can be defined, allowing identification of the non-runaway/runaway regions:



- $y = 0$ $(E_\parallel = E_R) \Longrightarrow$ Connor critical field (collisional threshold)
- $y = x$ $(E_\parallel = E_R^{rad}) \Longrightarrow$ Radiation threshold
- $y < x$ $(E_\parallel < E_R^{rad}) \Longrightarrow$ Non−runaway region
- $y > x$ $(E_\parallel > E_R^{rad}) \Longrightarrow$ Runaway region

Limiting runaway energy

The RE energy is determined by the balance between the gain in the electric field, and the losses due to collisions and synchrotron radiation. During start-up, it is expected that the electron radiation is dominated by the electron gyromotion around the magnetic field lines. In such a case, a good approximation to the steady state limiting RE energy is given by [3]:

$$\boxed{\gamma \simeq \frac{D(D-1)}{(1+Z)F_{gy}}}$$

Relativistic gamma factor $E = (\gamma - 1)m_e c^2$

Normalised electric field $D \equiv \frac{E_\parallel}{E_R}$

Regions of constant steady state limiting RE energy in the (x, y) phase space:

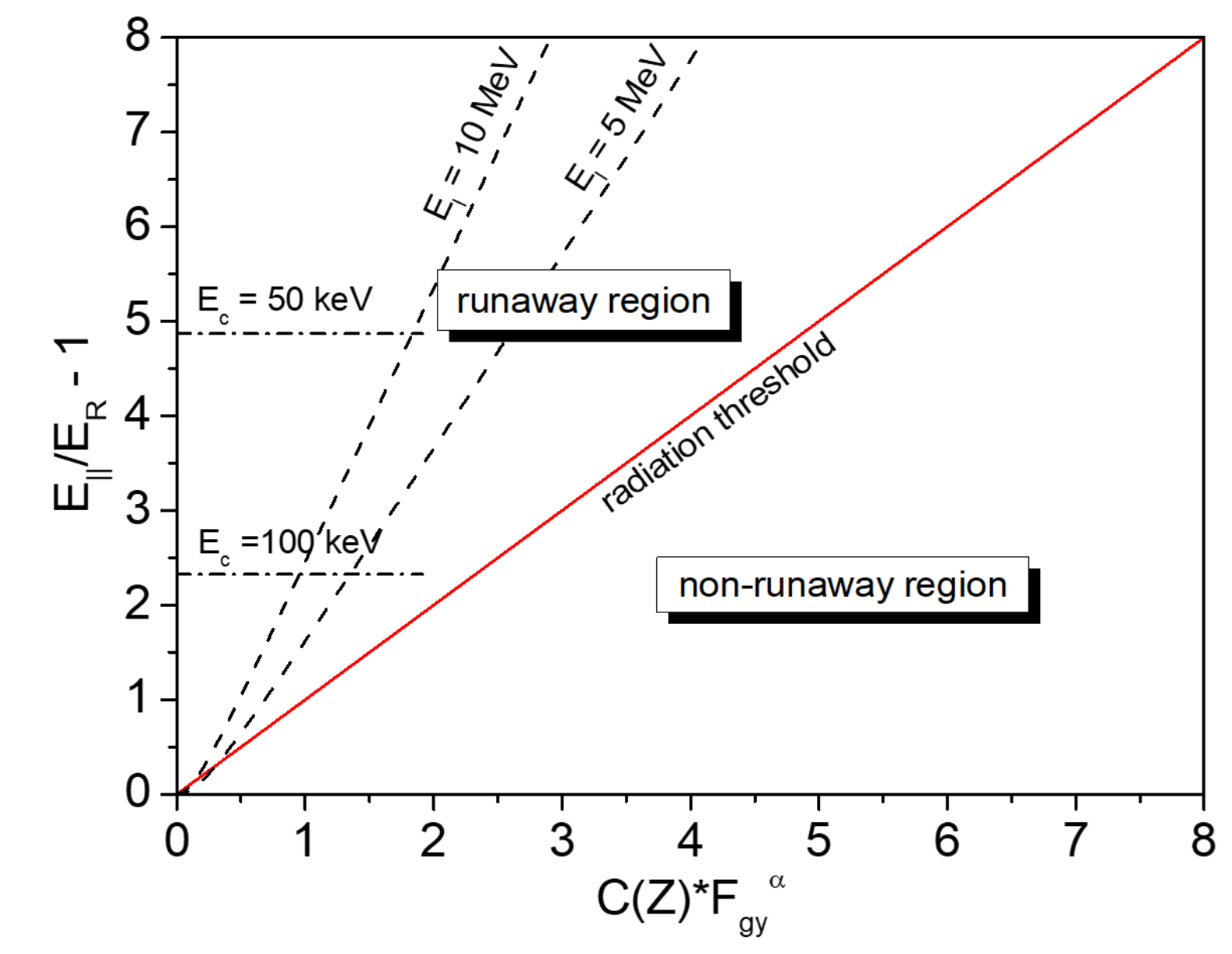
$$D = \frac{1}{2} + \left(\frac{1}{4} + (1+Z)\gamma F_{gy}\right)^{\frac{1}{2}} \Longrightarrow \begin{pmatrix} D = y - 1 \\ x \equiv C(Z)F_{gy}^{\alpha} \\ \alpha = 0.5 \end{pmatrix} \Longrightarrow \boxed{y \approx \left(\frac{1}{4} + \frac{(1+Z)\gamma}{C(Z)^2}x^2\right)^{\frac{1}{2}} - \frac{1}{2}}$$

Critical runaway energy

The normalized (to $m_e c$) critical momentum for RE generation can be estimated as $q_c \simeq 1/\sqrt{(E_\parallel/E_R) - 1}$ [2], so that the region of constant critical energy E_c $(\equiv (1 + q_c^2)^{1/2})$, in the (x, y) phase space corresponds to the line:

$$\boxed{y \equiv \frac{E_\parallel}{E_R} - 1 \approx \frac{1}{q_c^2} = \left[\left(1 + \frac{E_c}{m_e c^2}\right)^2 - 1\right]^{-1}}$$

$$q_c = (\gamma_c^2 - 1)^{1/2} \qquad E_c = (\gamma_c - 1)m_e c^2$$



Dreicer generation

The RE generation by the Dreicer process can be estimated in terms of the Dreicer generation parameter [6]:

$$\varepsilon = \frac{E_\parallel}{E_c} = \frac{E_\parallel}{E_R}\frac{kT_e}{m_e c^2} \Longrightarrow \boxed{y = \frac{m_e c^2}{kT_e}\varepsilon - 1} \qquad (T_e = 3\ \text{keV})$$

Generally, works, i.e., RE Dreicer generation becomes appreciable, when $\varepsilon \gtrsim 0.02$.

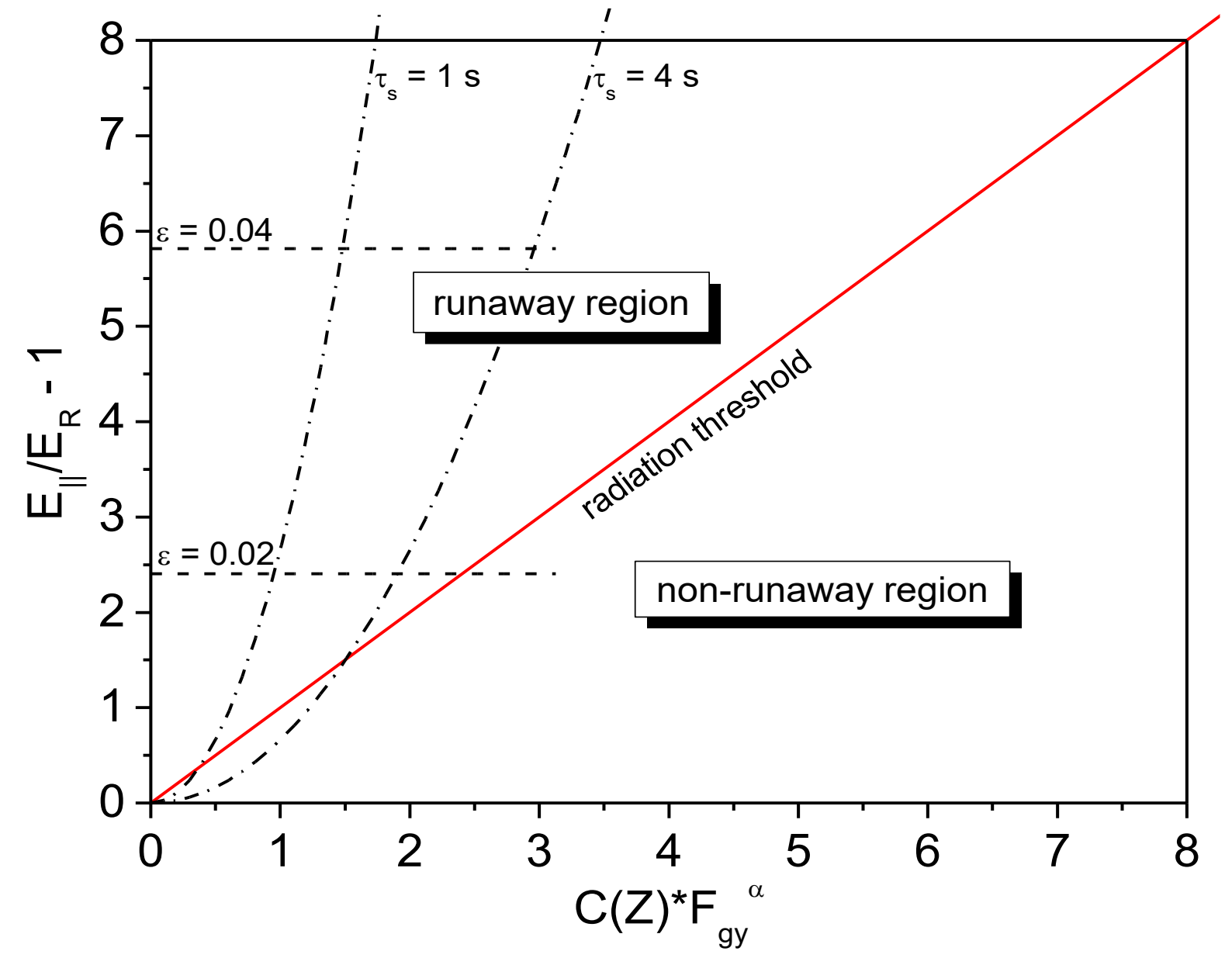
Secondary generation

The avalanching time, τ_s, determines the generation of REs by avalanche, and provides information about the secondary generation [7]:

$$\tau_s \approx \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e}\sqrt{\frac{3(5 + Z_{eff})}{\pi}}\left(\frac{E_\parallel}{E_R} - 1\right)^{-1} \Longrightarrow$$

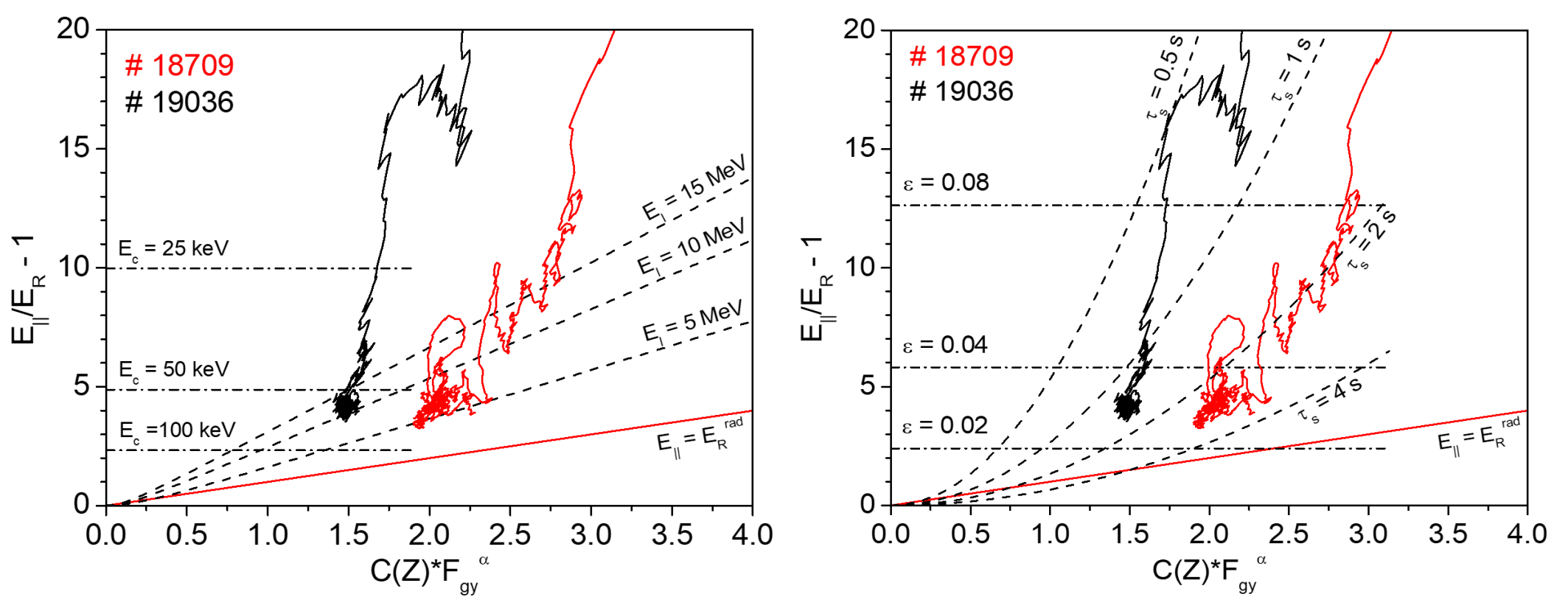
$$\boxed{y = \frac{m_e c \ln\Lambda\, a(Z)}{eE_R\tau_s} = \frac{6\pi\varepsilon_0 m_e^3 c^3 \ln\Lambda\, a(Z)}{e^4 B_0^2 C(Z)\tau_s}x^2}$$

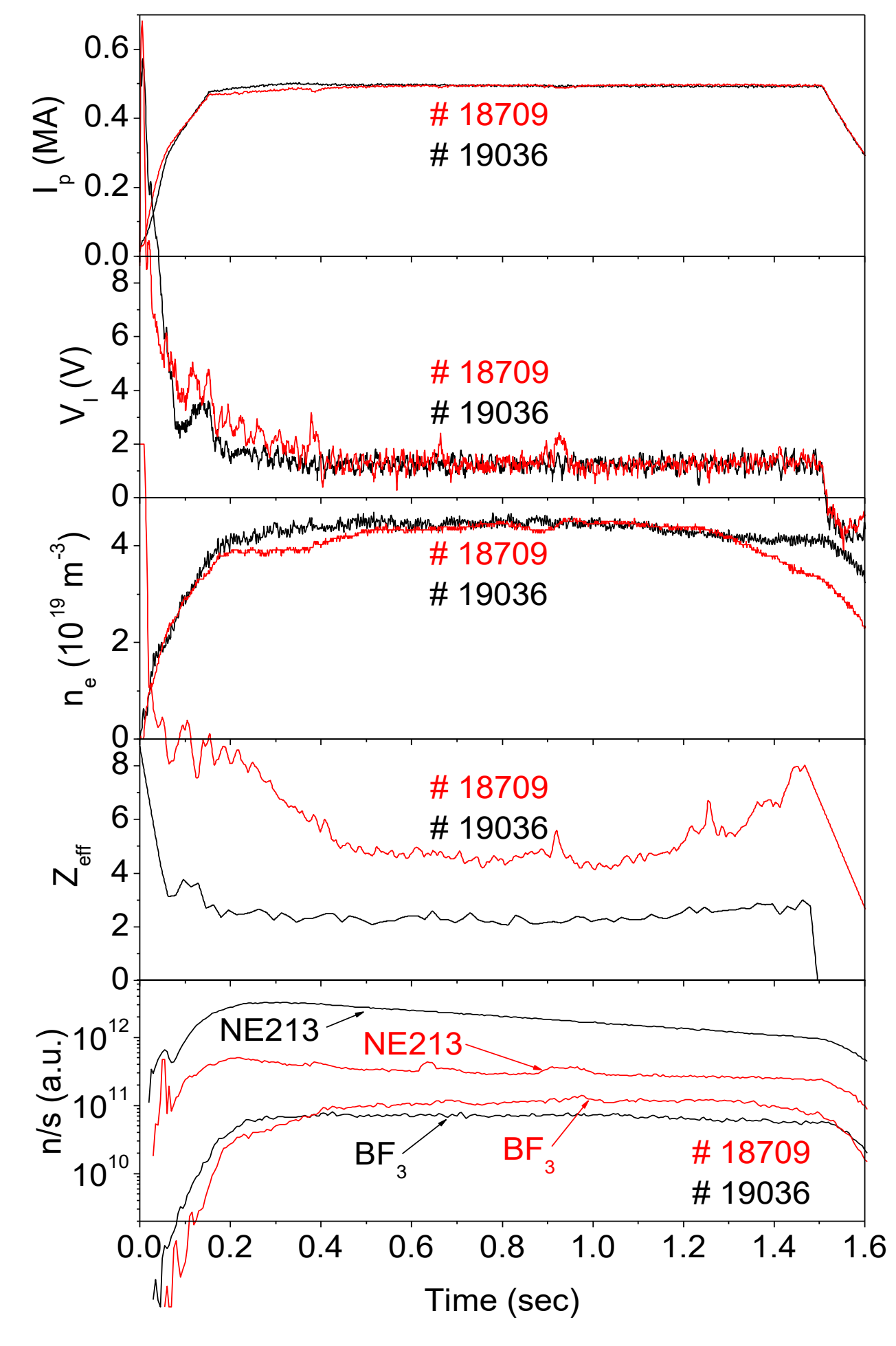
$$a(Z) \equiv \sqrt{3(5 + Z_{eff})/\pi}$$



ANALYSIS OF FTU DISCHARGES

General behaviour





REs have been routinely observed in FTU tokamak (circular cross-section tokamak with major radius $R_0 = 0.935$ m, minor radius $a = 0.3$ m, toroidal magnetic field up to $B_0 = 8$ T, and central line averaged density up to $\bar{n}_e \sim 3 \times 10^{20}$ m^{-3}) [8].

The plasma trajectory in parameter space in FTU shows that:

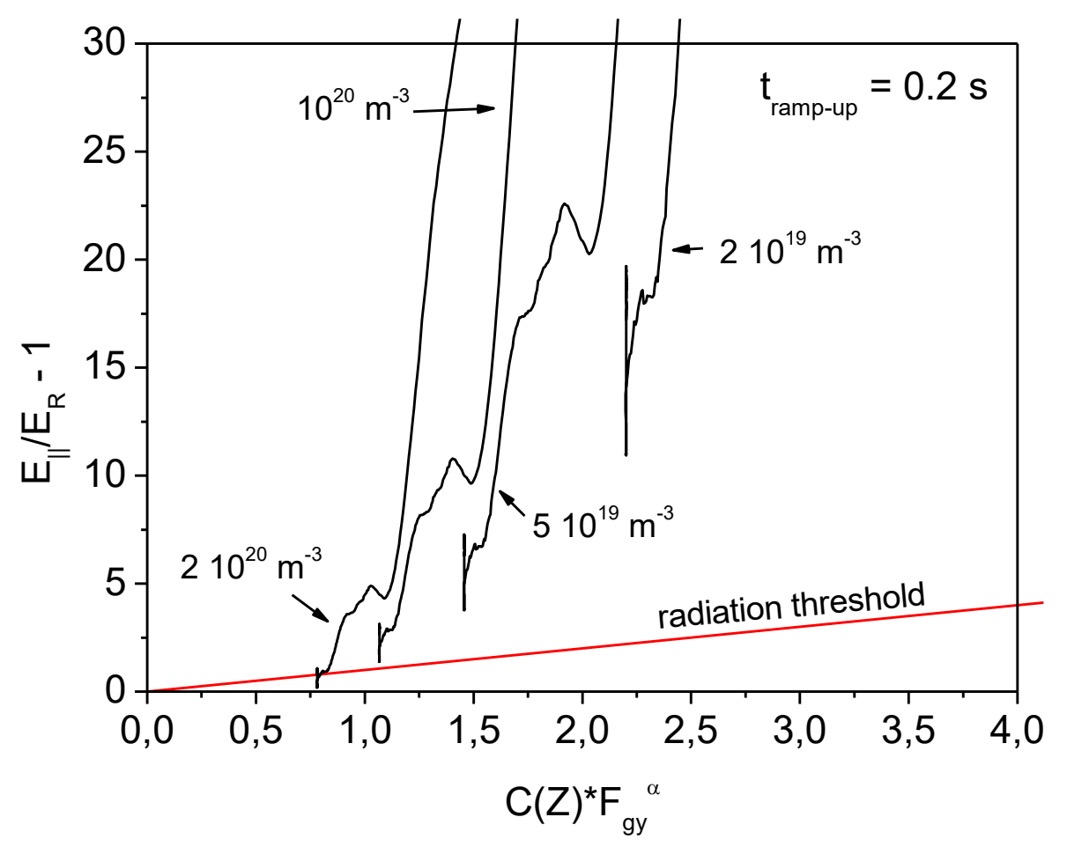
- The discharge remains inside the runaway region during current ramp-up and flat-top, in consistency with the RE measurements [8].
- Early in the discharge the plasma is located far from the radiation boundary, favouring RE production.
- During the evolution the operating point approaches the threshold while the limiting RE energy reaches the MeV range.
- The Dreicer mechanism is significant during start-up ($\varepsilon > 0.02$), whereas avalanche multiplication remains comparatively slow.

RE avoidance

The parameter-space representation provides a direct visualization of RE suppression strategies.

Density increase

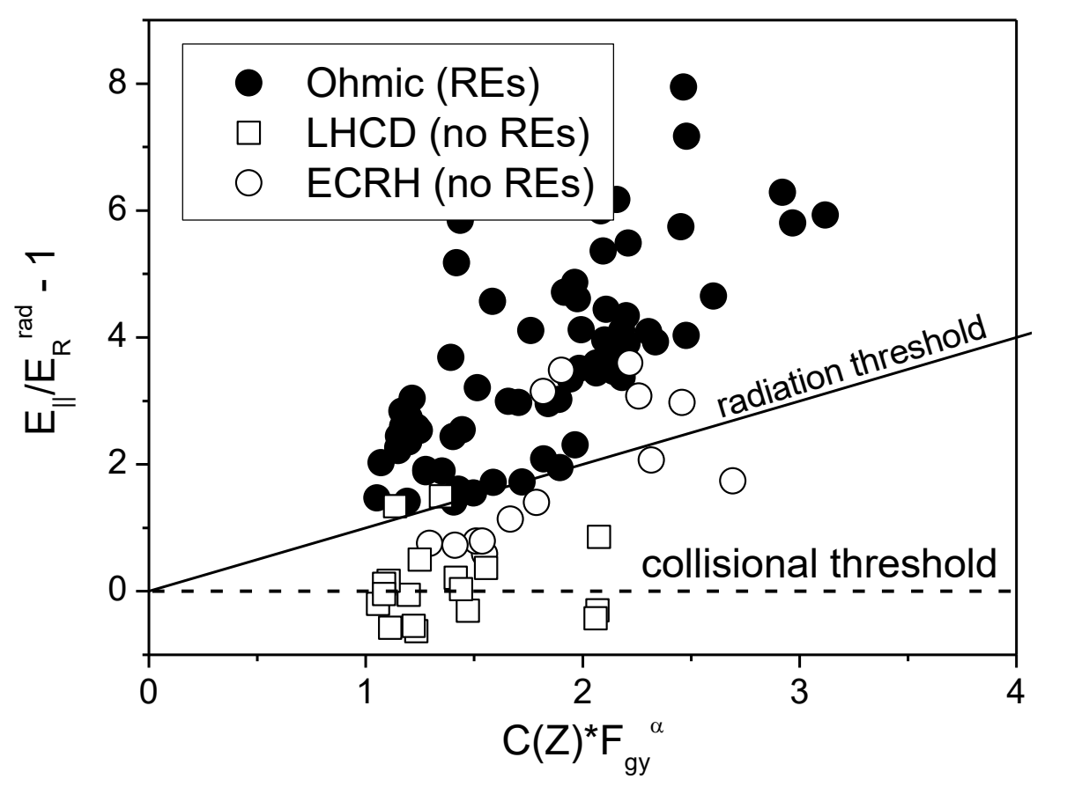
Calculations show that RE avoidance in purely ohmic FTU operation requires densities approaching $n_e \gtrsim 10^{20}$ m^{-3}, allowing the plasma trajectory to cross into the non-runaway region.



Trajectory of the plasma in the runaway parameter phase space for a typical waveform of the plasma loop voltage in FTU and different values of the flat-top density, assuming a linear increase of the density during the current ramp-up (up to 0.2 s).

Auxiliary heating

At lower densities, RE suppression can also be achieved through **ECRH** or **LHCD**, which reduce the normalized electric field below the radiation threshold.



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]).

MAIN RESULTS

- A parameter space analysis based on E_R^{rad}, allowing the identification of the non-RE and RE regions, is used to track the plasma during start-up in FTU.
- The analysis also provides information on the RE energy and generation.
- FTU start-up trajectories remain inside the runaway region during both ramp-up and current flat-top.
- The largest primary RE generation occurs at the beginning of start-up, where (E_c) is low and the Dreicer parameter (ε) is largest.
- Runaway avoidance requires either sufficiently high plasma density or effective electric field reduction through auxiliary heating.

CONCLUSIONS

- The proposed parameter-space analysis offers a compact tool for interpreting runaway electron dynamics during tokamak start-up.
- Tracking plasma trajectories in the (x, y) plane allows immediate identification of RE and non-RE operating regimes.
- Application to FTU demonstrates consistency with observed runaway behaviour and MeV electron energies.
- The methodology can be used to optimise future start-up scenarios aimed at minimising runaway electron production in ITER-like devices.

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