Runaway electrons in non-disruptive Tore Supra plasmas

E. Nilsson, Y. Peysson, J. Decker, J.F. Artaud, T. Aniel, M. Irishkin,
D. Mazon, F. Saint-Laurent and the Tore Supra team
CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France

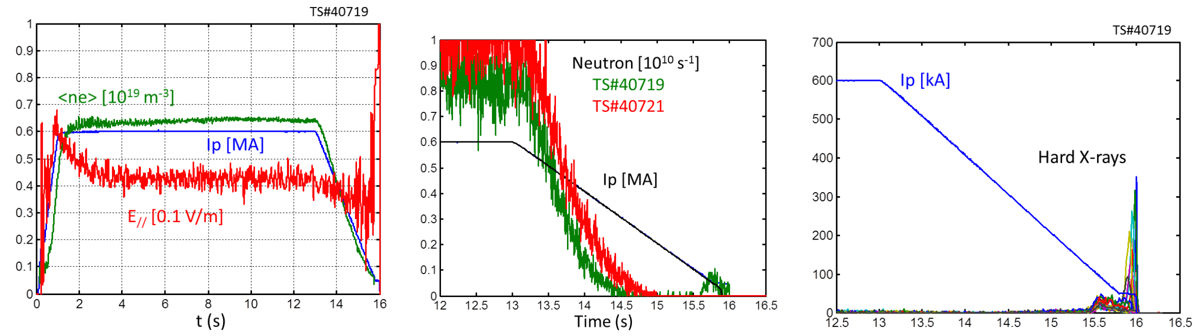
Runaway electrons can form in tokamak plasmas when the toroidal electric field exceeds some critical value (E_c) proportional to the electron density and may cause serious damage to plasma facing components in ITER [1]. These relativistic runaway electrons may appear during plasma disruptions [2], current ramp-up or ramp-down and even in the current flattop in quiescent low density plasmas as observed in several tokamaks [3]. In this work we perform interpretative kinetic modelling of the runaway formation in the current flattop of scenarios in the Tore Supra (TS) tokamak.

Runaway electrons are detected in the TS tokamak in low line averaged density discharges ($< n_e >< 10^{19}\ m^{-3}$) in the current ramp-down by hard X-ray (HXR), photo-neutron and electron cyclotron emission (ECE) measurements. Such signatures are found in discharge #40719 (Fig. 1), where the electron density in the current flattop is $< n_e >= 0.64 \cdot 10^{19} m^{-3}$, corresponding to $E/E_c \approx 8$, or $E/E_D \approx 0.06$, where $E_D = E_c m_e c^2/T_e$. However, in a similar discharge (#40721), with two times higher density, no runaways are observed even though the electric field exceeds the critical electric field ($E/E_c \approx 4$, or $E/E_D \approx 0.02$). This does not guarantee that no runaways or suprathermals are formed, it could simply be a consequence of that the population is too small to be detected by the diagnostics. Another signature of the runaway population is the remaining current (~ 50 kA) at the termination of the plasma as seen in Fig. 1(c) (t=$15.7-16$ s). This current plateau is believed to originate from a beam of well confined runaway electrons. Such a plateau is not seen in the higher density discharge (#40721).

The runaway electron formation is simulated using the LUKE code [4], a solver of the 3-D linearized bounce-averaged relativistic electron Fokker-Planck equation in a toroidal geometry. Global plasma parameters such as parallel electric field and plasma equilibrium are prescribed by the fast integrated modelling code METIS [6]. With this work we aim to contribute to understanding of runaway electron formation processes, and provide information beyond the experimental measurements.

Modelling of non-disruptive scenarios with LUKE/METIS

In order to understand the different outcome of the two non-disruptive TS scenarios, the formation of runaway electrons from the combined effect of Dreicer and avalanche is studied with the LUKE code. Temperature and density profiles are prescribed in METIS by fitting the



(a) (b) (c)

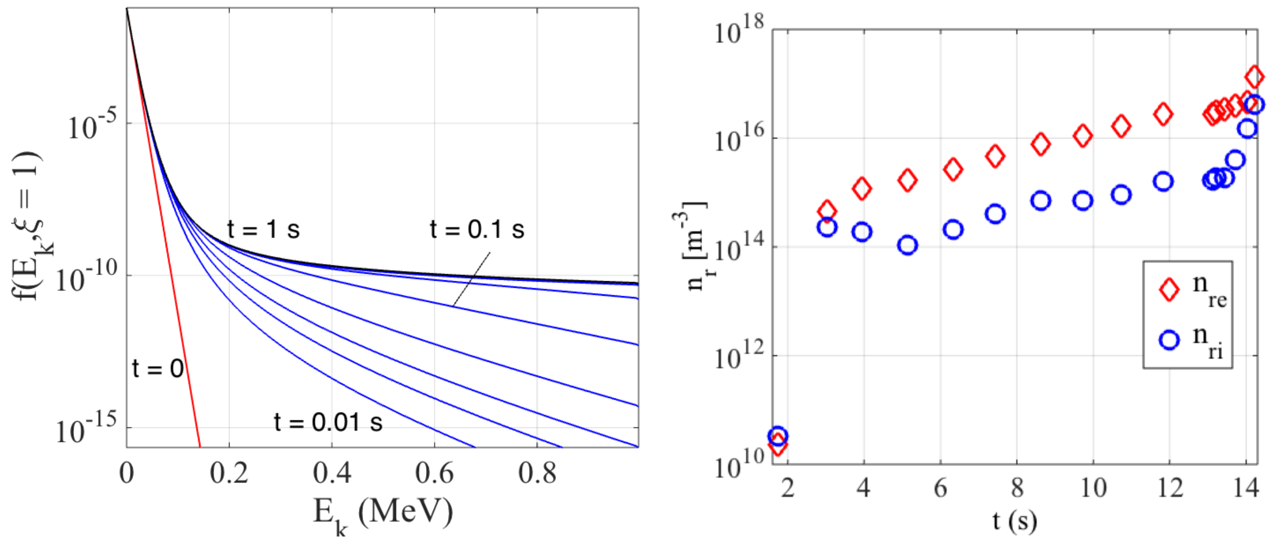
Figure 1: (a) Line averaged electron density, plasma current and parallel electric field strength in discharge #40719. (b) A peak in the neutron signal is observed at the plasma termination for the low density shot (40719) but none for the higher density shot (40721). (c) HXR data from the vertical camera (channels 1-21) in the energy range $E_{HXR} = 20-200\,\mathrm{keV}$ observed in the current ramp down in 40719.

combined results of several diagnostics including Thomson scattering, ECE, reflectometry and interferometry, weighted with Bayesian analysis. Given the METIS equilibria, the LUKE code calculates the effect on the electron distribution function of runaway processes including the Dreicer and avalanche effect through a recently implemented knock-on source term [5].

For #40719 the METIS/LUKE simulations show that runaways are progressively formed during the current flattop (Fig. 2), concentrated near the magnetic axis (Fig. 3(a)). Even though the density is lower off-axis and the E-field profile rather flat, E/E_D decreases with the radius due to the temperature profile. This would explain the slower Dreicer generation off the magnetic axis. Also, the increase of magnetic trapping effects off-axis contributes to a reduced runaway rate [5].

Figure 3(a) shows the calculated current density profile as carried by external runaways (with kinetic energy $E_k > 1\,\mathrm{MeV}$), when assuming that they move at the speed of light, compared to the current density profile of the bulk. The calculated Ohmic plasma current in the flattop at 13 s is 0.54 MA, compared to an experimental plasma current of 0.55 MA. To match the current, the effective charge had to be reduced from the predictions by METIS ($Z_{eff} = 3.9$) to $Z_{eff} = 2.6$. At the end of the current flattop the predicted current carried by external runaway electrons ($E_k > 1\,\mathrm{MeV}$) is 33 kA, which is the approximate level of remaining current ($I_p = 50\,\mathrm{kA}$) likely carried by a well confined beam of runaways, as seen in the termination of the plasma (Fig. 1(c)).

The simulations are compared to experimental measurements through reconstructed HXR

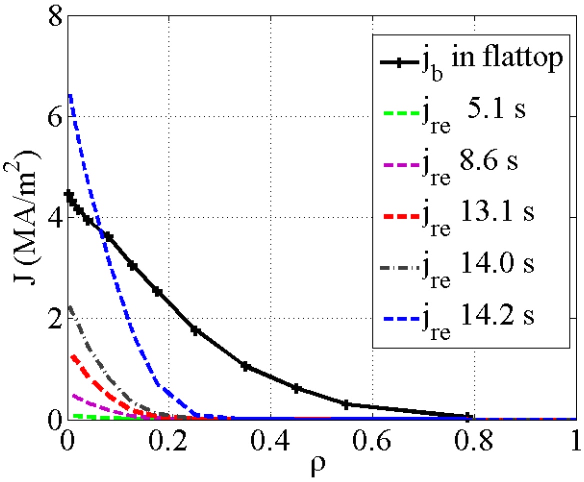


(a) (b)

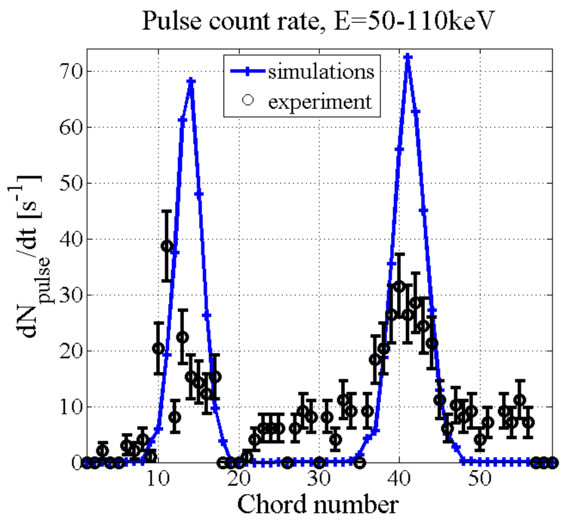
Figure 2: (a) Electron distribution function at $\xi = 1$ in TS discharge #40719 in current flat-top during 1 s. (b) Evolution of internal ($p_c < p < p(E_k = 1\,\text{MeV})$) and external ($p > p(E_k = 1\,\text{MeV})$) runaway electrons.

tomography emission based on the electron distribution function with the R5X2 code [7], that calculates the fast electron Bremsstrahlung (FEB) cross-section and integrates the emission along the lines of sight, accounting for the response function of the detectors. The HXR signals from a vertical (chords $1-21$) and horizontal (chords $22-59$) cameras provide information about the suprathermal electron population. The emission as measured by each detector is described by the count rate in the energy range $50-110\,\text{keV}$ (see Fig. 3(b)). LUKE simulations predict a runaway population concentrated near the magnetic axis. The shape and amplitude of reconstructed FEB emission agree fairly well with measurements.

With METIS/LUKE simulations we can investigate whether any suprathermals are formed also in the discharge without runaway signature (#40721), where $E > E_c$. The simulation of #40721 confirms the experimental observations; the runaway production is negligible as the simulations show the population of suprathermal electrons is formed during this pulse is negligible. The external runaway population, i.e. electrons with kinetic energy $E_k > 1\,\text{MeV}$, is so small that it would only carry a current of around 5 mA at the end of the 10 seconds long current flattop. These results are in line with the parametric study of runaway formation performed in Ref. [5], where it is found that 10 seconds of $E/E_c \approx 2.5$, which is the local central electric field strength, is not sufficient for a significant runaway population to form in a 3 keV plasma. Furthermore, these results support the experimental observations of Ref. [3] where at least $E/E_c \sim 3-12$ is required to generate a detectable population of runaway electrons in



(a)



(b)

Figure 3: (a) Current density profile of bulk (black) and current density carried by runaways ($E_k > 1\,\mathrm{MeV}$). (b) Reconstructed FEB profile, compared to measured FEB emission from HXR cameras.

various tokamaks.

Conclusion

The Fokker-Planck solver LUKE, is used to model runaway electron formation through Dreicer and avalanche mechanisms in non-disruptive Tore Supra scenarios in near-critical E-field. Simulations reveal progressive build-up of a suprathermal population during the flattop in the discharge where runaways are detected (#40719), but not in the higher density discharge (#40721) where $E/E_c \approx 4$. These results agree with experimental observations from various other tokamaks [3] where at least $E/E_c \approx 3-12$ is required for a detectable runaway population to form. The order of magnitude of the current carried by runaway correspond well to experimental indications. The magnitude of the reconstructed FEB emission from suprathermal electrons is well reproduced but the profile is more centrally peaked than experimental measurements.

References

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