

RUNAWAY ELECTRONS : FROM TORE-SUPRA TO ITER

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1. Introduction

Runaway electrons are a major concern for ITER [1]. Produced in large amounts during disruptions, either spontaneous or provoked by killer pellets, they can heavily damage the first wall. Considerable study is still needed to understand the underlying physics for their creation, acceleration and confinement.

Runaway electrons are routinely observed on Tore-Supra, during almost all disruptions. Although they usually cause little harm to the Tokamak, they have been involved in two water leaks, and several broken tiles on the first wall. They have been observed with several diagnostics : hard X-rays and neutrons monitors, synchrotron radiation and wall heating with IR cameras and induced radioactivity. Some characteristics of these electrons can be inferred from these observations.

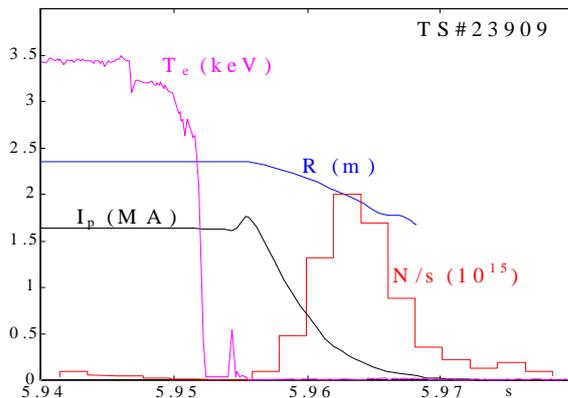


Fig. 1a : Typical disruption signal

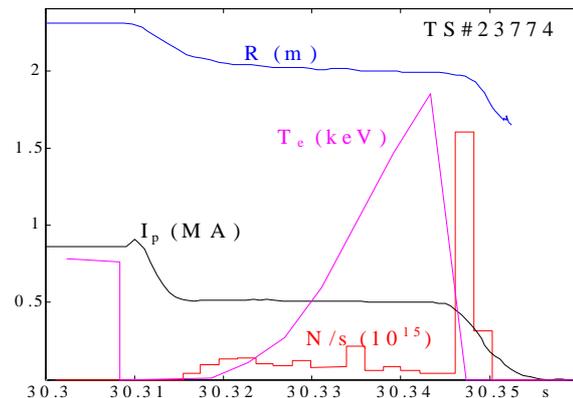


Fig. 1b : Disruption exhibiting a runaway plateau

A typical time trace of a disruption is plotted in Figure 1a. The central electron temperature, measured by ECE radiation, drops in less than a millisecond. After a short positive spike, the current starts to decrease, and the plasma is pushed toward the inner wall by the vertical field (no vertical instability is observed, due to the absence of elongation). During the ramp down, a large signal is observed on the neutron monitors : up to 10^{16} N/s, i.e. a hundred times more than during the plasma phase. These neutrons are the signature of the acceleration of runaway electrons at energies well above 10 MeV. During some disruptions, the current fall and the horizontal movement of the plasma stops transiently. This is interpreted as a stabilisation of a runaway current in the vertical field. A large level of non thermal ECE radiation is observed in this phase, as well as infrared synchrotron radiation. The duration of this plateau can vary from a simple hesitation in the current ramp down, up to more than one second of stable confinement.

2. Runaway Electron Energy Measurements

The energy of these electrons can be determined with the correlation of two measurements : photo-nuclear activation with high threshold and neutron/electron ratio. This energy determination is particularly useful to check the runaway creation and acceleration models. Two mechanisms have been proposed :

- i) with a « Dreicer » dominated creation [2], a large number of runaway electrons are created at the very beginning of the current quench, and then accelerated continuously with an energy gain of about 60 MeV/MA. The distribution is expected to be close to mono-energetic.
- ii) with an « avalanche » dominated creation [3], a small population is exponentially multiplied by head-on collisions with the cold plasma electrons. The model predicts in this case a maxwellian distribution with a temperature around 10 to 15 MeV.

The first energy measurement is based on spallation reactions on bismuth, with thresholds between 30 and 50 MeV. The corresponding cross sections are plotted on Figure 2a. A sample of bismuth is located outside the vacuum vessel, in the hard X-ray beam produced by the electrons, as they impinge the inner wall. The geometry of the irradiation is too complex to have access to absolute values, and only relative production of the various isotopes are used. Figure 2b represents two examples of radioactive spectra with different ratios of $\text{Bi}^{204}/\text{Bi}^{206}$. Nine disruptions have been studied, with I_p from 1 to 1.6 MA.

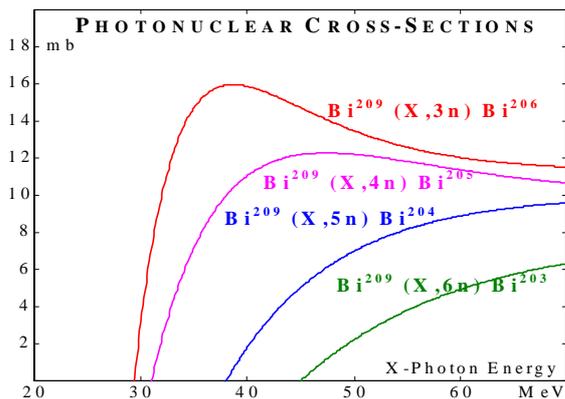


Fig. 2a : Bismuth spallation cross-sections

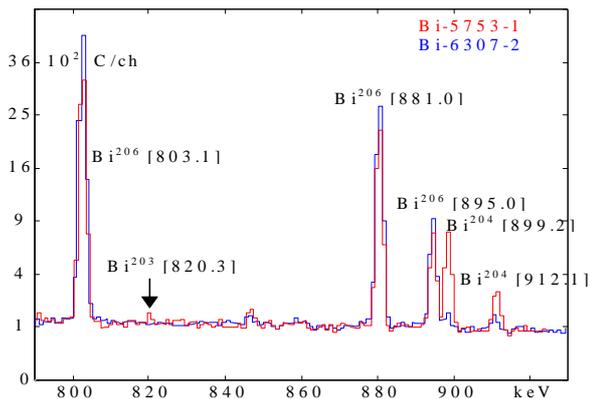


Fig. 2b : Typical γ spectrum from Bi samples

Theoretical ratios for the bismuth isotopes have been calculated with the assumption of a full slowing down of the electrons in graphite. The results are plotted in Figures 3a and 3b, for mono-energetic and maxwellian distribution respectively.

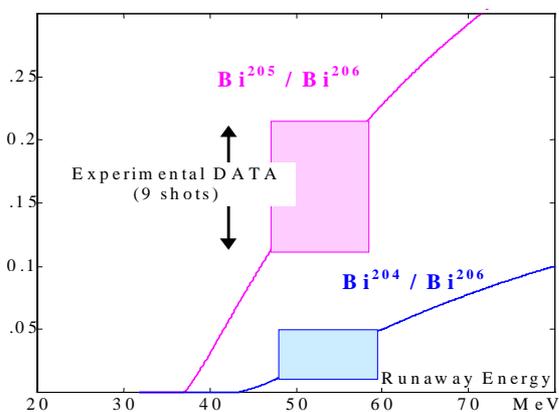


Fig. 3a : Bismuth isotope ratios produced by mono-energetic runaway electrons

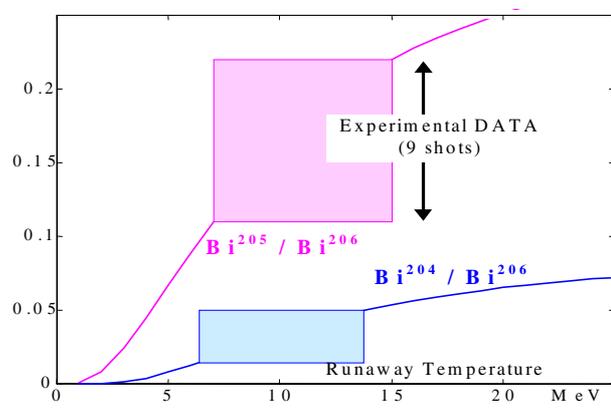


Fig. 3b : Bismuth isotope ratios produced by maxwellian distributions of runaway electrons

The low dispersion of the experimental results is more coherent with the second model (« avalanche ») for which only a small variation of the temperature is expected. If the « Dreicer » production were dominant, a proportional scaling between the electron energy and the plasma current would be expected, providing a larger scattering of the experimental points.

A second way to measure the electron energy uses an estimate of the number of neutrons produced by each electron. In this simulation also, electrons are supposed to stop in graphite, but the photo-nuclear process occurs mainly in the stainless steel of the vessel. The two hypotheses (« Dreicer » and « Avalanche ») for the electron distribution function give the curves plotted in Figures 4a and 4b respectively. During actual shots, the number of photo-neutrons is measured with fission chambers, and the number of electrons is known when a plateau is clearly seen in the current decay (Fig. 1b), assuming that this intermediate current is fully carried by the runaway. The results shown in Figures 4a and 4b clearly confirm that the « avalanching » process dominates runaway production during disruptions.

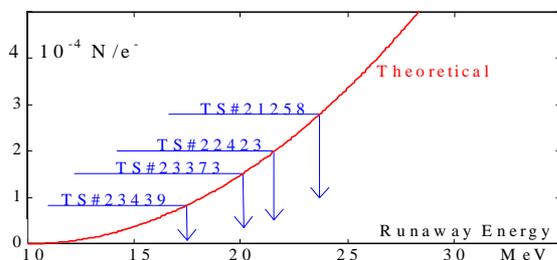


Fig. 4a : Neutrons produced per electrons for a mono-energetic distribution function

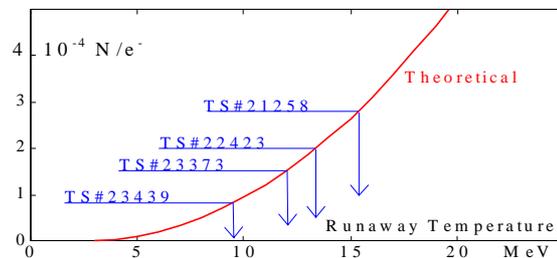


Fig. 4b : Neutrons produced per electrons for a maxwellian distribution function

3. Runaway Electron Diffusion Coefficient

Most of these electrons are lost in the equatorial plane, on the high field side toroidal belt limiter. The residual radioactivity is plotted in Figure 5 versus the toroidal direction. 18 peaks can be seen, correlated with the 18 coils ripple. The peak to peak variations in intensity are due to a slight misalignment of the 36 modules of the limiter. This has been confirmed in 1993 after a complete change in the relative position of these modules: the maximum of the radioactivity switched from 80 to 240°, as this position became more prominent. A shadowing of retracted modules by protracting ones is observed.

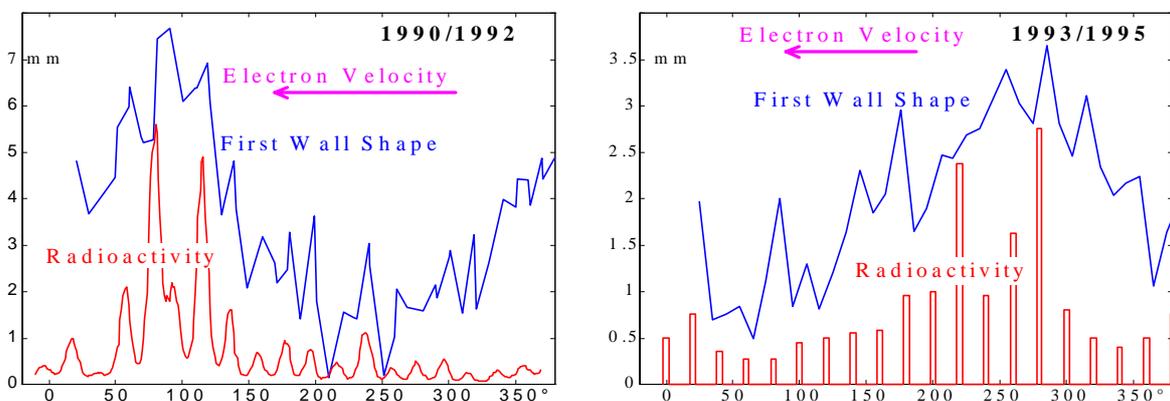


Fig. 5 : Radioactivity along the inner toroidal belt limiter and its toroidal shape, before and after the 1993 realignment of the modules.

The e-fold depth is around 1 mm. With the assumption of a random-walk mechanism with a typical time step of 0.3 μ s (one poloidal turn), it is possible to calculate the radial diffusion coefficient: $\approx 3 \text{ m}^2/\text{s}$. Similar values are obtained with the global confinement time of these electrons, which are confined for several tens of milliseconds when a plateau is observed. This low diffusion implies a strong peaking of the energy deposition on the first wall, which can worsen their potential damage to ITER.

4. Runaway Electron Production Mechanism

The production rate depends strongly on the toroidal field [4], as in JT60U [5], and only weakly on the plasma density [4]. This suggests both a relative importance of the magnetic turbulence on their confinement, and a non-Dreicer origin for their initial acceleration. A new model, based on the capture of a « ghost » hot tail from the pre-disruptive plasma by the increasing electric field, seems to explain most of the experimental scaling laws.

In this model, the tail of the electron maxwellian does not cool down during the thermal quench, which lasts less than its collision time. The loss of these fast electrons is instead controlled by their diffusion through the ergodised magnetic field. If their confinement time is large enough, a few of them are still there at the end of the quench, when the magnetic topology is restored. Supra-thermal electron confinement has been observed to depend strongly on the magnetic field strength [6] : the residual population scales exponentially with the toroidal field. Its mean energy is well above the after-quench runaway threshold. This small population is then multiplied by a factor around 50 for each lost mega-ampere by the avalanching mechanism. This process stops only when the current carried by the runaways equals the total plasma current.

5. Summary and References

Runaway electrons observations on Tore-Supra provide information to extrapolate these phenomena to ITER. Three points in particular are discussed :

- ➔ A small quantity of initial electrons will be multiplied by the so called avalanching mechanism , already dominating disruptions in existing Tokamaks. The electron distribution function is maxwellian, with typical temperatures of 10-15 MeV.
- ➔ Runaway electrons are lost to the wall with a very small diffusion coefficient, and their strike point is very sensitive to the relative alignment of the various modules of the first wall. A factor 1/e in energy deposition has been observed for a 1 mm misalignment.
- ➔ Runaway creation rates are only weakly sensitive to the plasma density, and vary mainly with the toroidal field. Commonly used Dreicer creation rates are not applicable during plasma disruption, where the global parameters evolve too rapidly.

References

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