Runaway Electron Synchrotron Spectra in FTU

Z. Popovic [1], B. Esposito [2], P. Buratti [2], F. Causa [2], M. Gospodarczyk [3], D. Carnevale [4], R. de Angelis [2], J. R. Martin-Solis [1], V. Piergotti [2], G. Rocchi [2] and FTU team

[1] *Universidad Carlos III de Madrid, Avda.Universidad 30, 28911-Madrid, Spain.*
[2] *ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Frascati, Rome, Italy.*
[3] *Dip. di Ingegneria Civile ed Informatica DICII, Universita di Roma, Tor Vergata, Via del Politecnico 1, 00133 Roma, Italy.*

1. Introduction Understanding the main mechanisms that dominate the behaviour of high-energy runaway electrons (RE) is an important issue for the safe operation of tokamaks, particularly during disruptions. The synchrotron radiation emitted by runaways provides information about the energy and pitch angle of in-flight RE in different stages of the discharge. The recently developed Runaway Electron Imaging and Spectroscopy (REIS) system [1] was designed for the detection of runaway electron synchrotron spectra during plasma discharges in MST (Medium Size Tokamaks) devices and has been tested in the FTU tokamak. In this paper, we present synchrotron radiation spectra for typical runaway experiments during plasma current flat-top in FTU. The measured synchrotron emission spectra are compared with calculated spectra, a) using actual calculated runaway distribution functions and b) assuming monoenergetic RE beams with an energy equal to the maximum electron energy.

2. The REIS System The REIS system in FTU [1] is a wide-angle optical diagnostic collecting the RE synchrotron radiation along two lines of sight (corresponding to plasma cross sections in the RE backward and forward views) and transmitting it to visible/infrared spectrometers through an incoherent bundle of fibres (Fig. 1). The system is portable and characterised by the spectral range spanning from 370 to 2100 nm and configurable sampling time of (10-100) ms.

3. Synchrotron Emission Spectra An example is shown in Fig. 2, corresponding to an 0.5 MA ohmic FTU discharge for which runaway electrons can be detected since the beginning of the discharge as evidenced by the difference between the BF_3 neutron detector and the NE213 neutron/gamma scintillator signals [2] (left plot). The synchrotron emission spectra measured by the REIS system at several time slices are shown in the right plot of the figure.

The simulated runaway dynamics is illustrated in Fig. 3. The runaway production [trace (b) in the left plot] has been calculated assuming to be dominated by the Dreicer mechanism, as typically observed in FTU OH discharges [2]. REs are generated in the beginning of the discharge (due to the large electric field and low density) and the runaway production stops soon at $\sim 0.15\,\mathrm{s}$ [trace (b)]. The runaway energy distribution function, $f_r(E)$, has been estimated calculating the energy evolution of the generated runaway

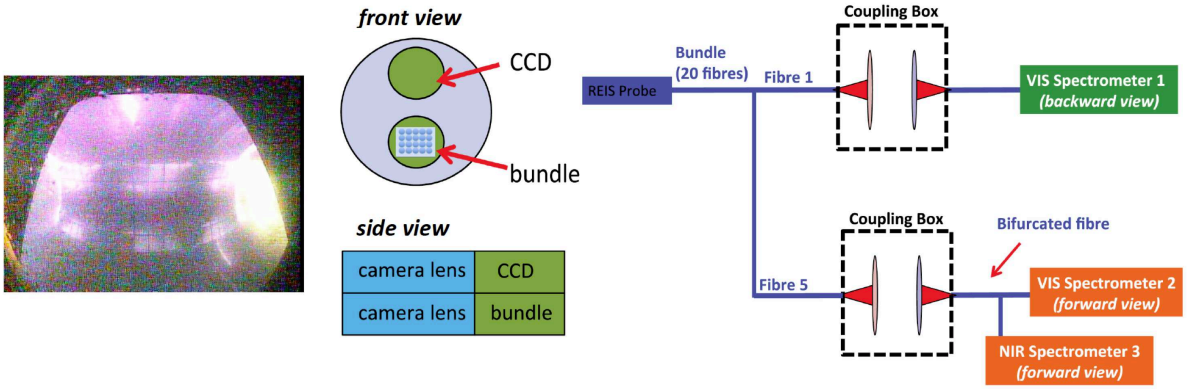

Figure 1: *Layout of the runaway electron imaging and spectroscopy (REIS) system. The REIS probe is composed by a wide-angle lens coupled to a CCD camera for the recording of video images and a wide-angle lens coupled, through an incoherent bundle of fibres, to visible (VIS) and near-infrared (NIR) spectrometers.*

electrons by means of a simple test particle model for the runaway dynamics [3] including the electric field acceleration, collisions with the plasma particles and deceleration due to synchrotron radiation losses. Then, the runaway distribution function is formally given by:

$$f_r(E,t) = \int_0^t \frac{dn_r}{dt'}(E_0,t')\,dt', \tag{1}$$

where $t = 0$ denotes the start of the runaway generation and the integration is carried out over the times t' for which an electron generated with energy E_0 would have gained, according to the test particle equations, an energy E at time t. The resulting distribution function at different times during the discharge is shown in Fig. 3 (right), whereas the time evolution of the maximum and average electron energies (E_{max} and E_{av}) is plotted in panel (c) of Fig. 3, left. The distribution function is initially broad, extending up to the maximum runaway energy at each time step, and showing a trend along the discharge to accumulate close to a steady state energy $\sim 19\,\mathrm{MeV}$.

The numerical tool PySYRUP (Python translation of SYRUP [4]) has been used to calculate the synchrotron emission spectra using the simulated runaway distribution functions (right Fig. 3) and are compared in Fig. 4 with the measurements at four different times during the discharge. The figure also shows at each time step the calculated spectra for the case of a monoenergetic beam with an energy and pitch angle best fitting the measurements at each time slice. The figure illustrates the difference between the calculations of the spectra using the full electron distribution and the monoenergetic case when the distribution function is broad. Only when the electron distribution becomes approximately monoenergetic (at 750 ms in the figure) the two calculations are closer. This suggests the need, for a correct interpretation of the synchrotron emission measurements, of taking into account the full electron distribution function [4]. Nevertheless, the monoenergetic case still yields sensible estimates of the maximum electron energy [green crosses in Fig. 3, panel (c)]. The figure also indicates a reasonable agreement between the calculations using the full electron distribution and the measurements until

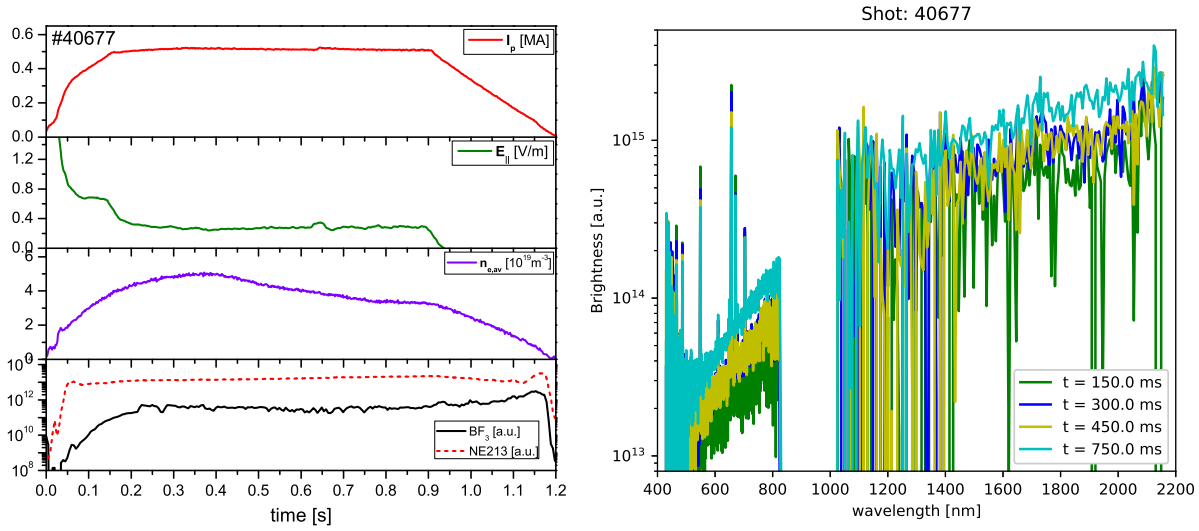

Figure 2: *For discharge 40677:* ***Left:*** *Time traces of the plasma current (I_p), electric field ($E_{||}$), line-averaged central density and NE213 ($\gamma + n$), BF_3 (n) signals:* ***Right:*** *Measured synchrotron radiation spectra at several time slices.*

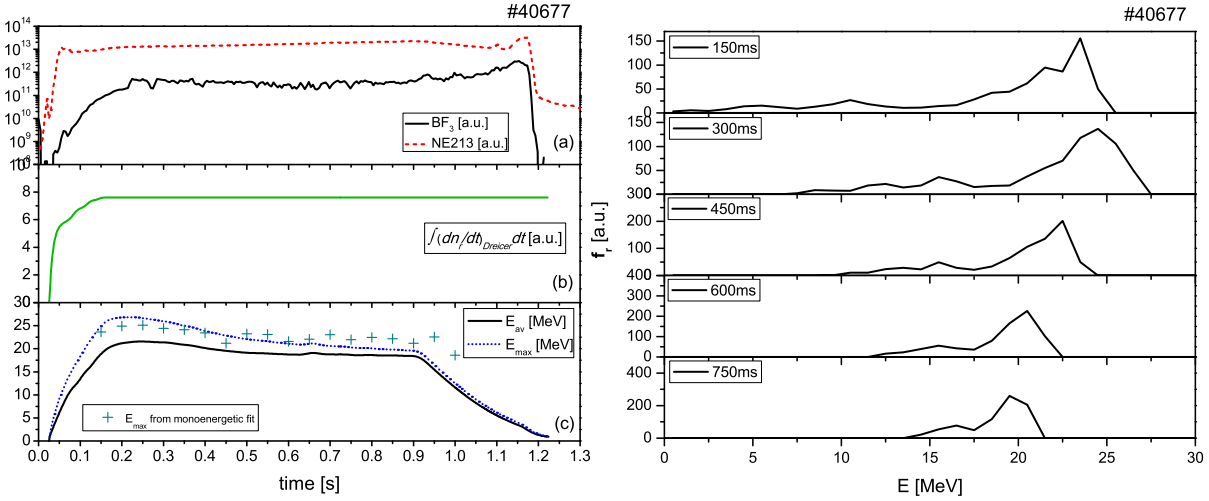

Figure 3: *For discharge # 40677:* ***Left:*** *Time evolution of BF_3 and NE213 scintillator signals (a),estimated runaway production (b), maximum and average runaway energies. The green crosses correspond to estimates of the maximum electron energy using a monoenergetic fitting to the measured spectra (c);* ***Right:*** *Calculated runaway distribution function at different times.*

~ 500 ms. The discrepancy between the calculated and measured spectra at later times, mainly in the visible region of the spectra, is still unclear and is the subject of ongoing investigations. For example, underestimates in the calculated pitch angle could partially explain such a difference.

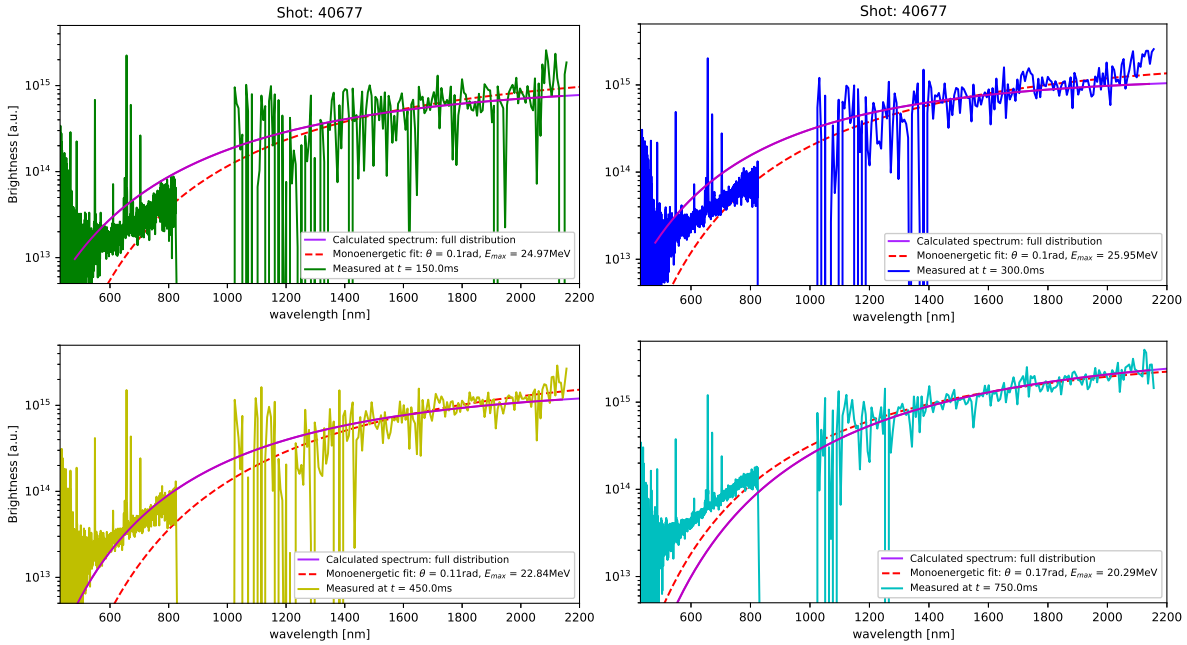

Figure 4: *Comparison between the measured and the calculated, using the full distribution function, synchrotron emission spectra for discharge # 40677 at four different times. The calculated spectra for a monoenergetic beam with an energy equal to the predicted maximum electron energy are also shown for comparison.*

Acknowledgements

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References

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