Runaway electron expulsion during tokamak instabilities

F. Causa[1] and P. Buratti[2] and the FTU Team[3]

[1] Istituto per la Scienza e Tecnologia dei Plasmi, Consiglio Nazionale delle Ricerche, Milano, Italy

[2] ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Frascati (Roma), Italy

[3] see the Appendix of Pucella G. et al 2018 IAEA Fusion Energy Conf., Gandhinagar, India

Introduction

Runaway Electron (RE) beams with multi-MeV energies can develop within a tokamak plasma during instabilities. REs represent a major concern in tokamaks because when lost to the first wall they can cause significant local energy deposition, melting and damage to plasma-facing components. This work addresses two issues related to helical magnetic perturbations, first non-uniform distribution of RE loads and second RE propagation at significant distances beyond guard limiters into the Scrape Off Layer (SOL). Results are presented from the correlation of the Cherenkov signal with hard x-ray (hxr) counts and with amplitude and phase of magnetic perturbations.

Experimental apparatus

The Cherenkov probe consists of a single-crystal diamond (10 mm diameter, 1 mm thickness) radiator mounted on a TZM head inserted in the FTU vessel, [2]. The electron energy threshold of the diagnostics is 58 keV, when including both the diamond refractive index and the effect of the Ti/Pt/Au coating. The data acquisition rate was 2 MHz over the duration of the discharge (up to 2s). FTU is a compact, high field (up to B = 8 T) tokamak, with major radius R_0 = 0.935 m and wall radius a = 0.33 m, comprising toroidal and poloidal limiters; the former on the high field side, and the latter formed by an 86 deg segment placed at the low field side, at 29-30 cm from R_0 (the smaller distance used in pulses with large RE content in order to reinforce wall protection). The Cherenkov probe was positioned on the equatorial plane at ϕ = 150 deg from the poloidal limiter, at a radial position r = 0.310-0.320 m, in the limiter shadow. The scenarios presented in this paper have been analysed using data from the following diagnostics: neutron and hard x-ray detectors (ϕ = 240 deg), a single-channel Cherenkov probe (ϕ = 150 deg), Electron Cyclotron Emission (ECE) (ϕ = 90 deg), and a set of Mirnov pick-up coils to measure the poloidal field component (of interest here, the equatorial one at ϕ = 60 deg, that is 90 deg toroidal distance from the Cherenkov probe).

Experimental scenarios and results

Scenarios are analysed with different RE generation conditions and different instability dynamics. Density and toroidal field ranges are: 3-8 10^{19} m^{-3} and 2.8-5.3 T, respectively, Table 1. RE losses during tearing mode growth in the disruption precursor phase of the above scenarios occur on a time scale that is much shorter than the RE production timescale, but sufficiently long to resolve several rotation periods of the magnetic island (Figure 1). These conditions are particularly useful to study the dynamics and key interaction mechanisms of REs with magnetic perturbations. In both types of pulses, Cherenkov signal and hxr counts dramatically increase during mode growth, an evidence of enhanced RE expulsion. Furthermore, both signals are modulated at the island rotation frequency, showing that RE expulsion is non-axisymmetric, [1].

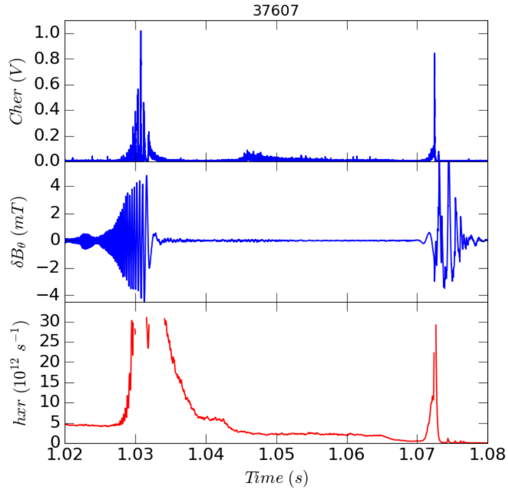

Figure 1: Time-evolution of plasma parameters for pulse #37607. From top panel: Cherenkov probe signal, 2/1 magnetic perturbation and hxr counts.

Table 1: Pulse characteristics for the scenarios of interest at time t, including toroidal field B, plasma current I_p; edge safety factor q; E, E_c and E_D inductive, critical and Dreicer electric field, respectively; hard x-ray count rate; average density; Cherenkov probe distance from the projected limiter position.

Pulse #	B (T)	Ip (MA)	t (s)	q_{edge}	E (V/m)	E_c (V/m)	E_D (V/m)	hxr counts (10^{12} s^{-1})	n_{AV} (10^{19} m^{-3})	dist (cm)
37606	5.3	0.5	**0.9**	5.7	0.31	0.1	26	0.45	8.4	1.5
37607	5.3	0.5	**1.0**	5.8	0.35	0.096	30	4.1	7.8	1.5
37608	5.3	0.5	**0.9**	5.7	0.32	0.1	27	0.28	8.3	1.5
37609	5.3	0.5	**0.8**	5.7	0.32	0.1	29	4.0	8.7	1.5
39555	2.8	0.35	**1.0**	4.0	0.39	0.046	18.5	10.0	4.0	2.0
39513	4.0	0.5	**1.1**	4.3	0.39	0.04	8	5.3	3.0	2.0
39593	4.0	0.5	**0.8**	4.2	0.4	0.05	12	3.2	4.2	2.0

When detecting fast electrons expulsions in the presence of magnetic islands, the waveforms obtained with the Cherenkov probe present 100% signal contrast during tearing mode growth and rotation, an indication of the non-axisymmetric RE flux forming a striped halo in the limiter shadow. Also hxr counts present a modulation, although much softer (< 25% contrast). It is noted that the magnetic perturbation amplitude considered here is typically smaller than that necessary to globally break magnetic surfaces and thus lead to disruption, for example, the analysis period in Figure 1 is around 1.03 s, while the instability becomes disruptive at 1.07 s.

A normalised time is defined as *phase* = $(t - t_X)/[2(t_O - t_X)]$ where t_X and t_O are the times of maximum and minimum magnetic perturbation amplitude, indicating the passage of the X and O points in front of the reference Mirnov coil.

The Cherenkov peaks vs *phase* plots of Figure 2 are used to visualise the alignment of the RE halo with island rotation. Pulses show leading edge in the vicinity of the O-point passage in front of the probe (phase=0.25), tail typically extending to X-point passage (phase=0.75) and signal at noise level after the X-point passage. These features indicate that an island internal to the plasma (located at around mid-radius in the cases shown here) produces a deep footprint in the SOL, in the form of a striped RE halo.

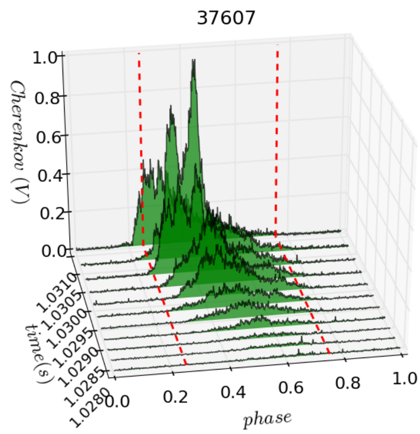

Figure 2: Time evolution of Cherenkov peaks profiles for FTU pulse 37607, as a function of *phase* (red dashed lines at 0.25 and 0.75 indicate O- and X-point passages at the Cherenkov probe port).

In the presence of a m/n magnetic island then, the RE density in the halo is affected by magnetic perturbation amplitude and phase ($m\theta$ - $n\varphi$ - $\omega_{m/n}t$), where θ and φ are the poloidal and toroidal angles, respectively, and $\omega_{m/n}$ is the island rotation frequency, as demonstrated by the trends obtained in Figure 3 (dependence on the amplitude) and in Figure 2 (dependence on the phase). The Cherenkov signal amplitude depends on both RE content and perturbation amplitude, but when plotting the ratio with hxr against magnetic perturbation amplitude, Figure 3, a neat nonlinear trajectory is found, for example, for a series of pulses characterised by similar macroscopic parameters, but different RE content.

Different shapes of the Cherenkov/hxr vs magnetic perturbation diagram are found for pulses with different macroscopic parameters, Figure 4. In particular, higher ratios are found at lower magnetic fields. This could be explained by the corresponding higher RE energy due to the correspondingly lower synchrotron losses.

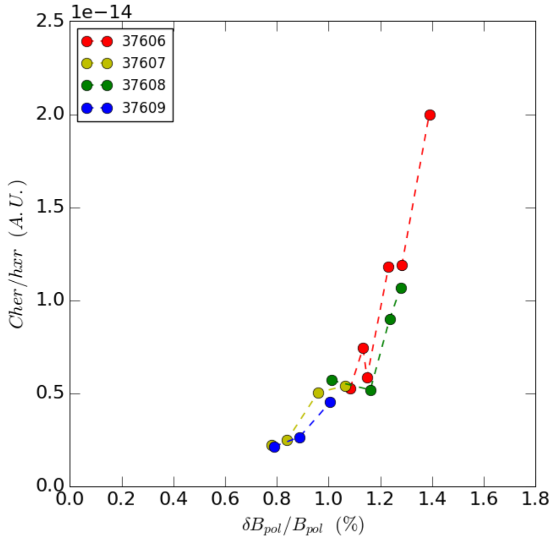

Figure 3: Cher/hrx ratio vs relative magnetic amplitude for pulses with similar macroscopic parameters, but different RE content.

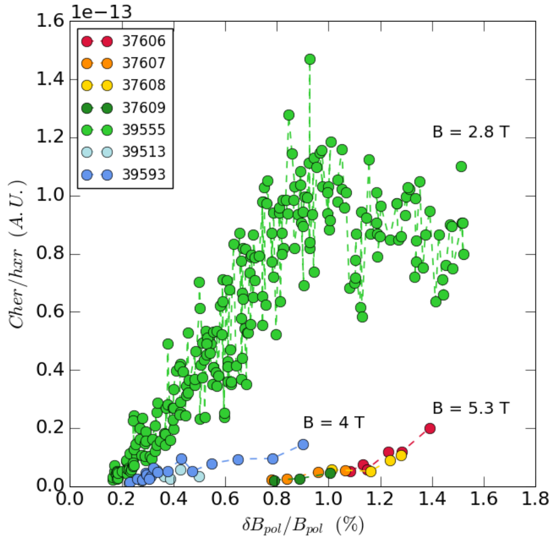

Figure 4: Cher/hrx ratio vs relative magnetic amplitude for pulses with different macroscopic parameters and RE content.

According to [2, 3], higher energy REs (>10 MeV) may indeed be lost even at lower perturbation levels, and this can be explained with the occurrence of side-band resonance due to the cross-field drift of REs.

Conclusion

There is experimental evidence of REs in the SOL, appearing as a striped structure aligned with the magnetic island, most likely due to orbit deformation resulting from broken axisymmetry. The Cherenkov signal presents 100% contrast with structured, non-symmetric peaks, implying strongly non-axisymmetric RE expulsion aligned with magnetic island perturbation. The Cherenkov/hrx signals ratio vs perturbation amplitude plot is indicative of the RE halo thickness in the SOL, which increases more than linearly with magnetic perturbation amplitude.

References

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