Cherenkov diagnostic observations of fast electron losses in FTU and interpretation with gyrokinetic simulations

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Introduction

Runaway electrons (REs) in tokamaks can reach energies in the range of tens of mega-electron-volts, [1], especially during plasma disruptions, representing a major concern for the safety of large tokamaks, [2]. Uncontrolled rapid loss of runaway current is detrimental, severely damaging plasma-facing components. Understanding how spontaneous or applied magnetic perturbations affect RE transport is crucial to evaluate the possibility of controlling and mitigating the RE current, [3]. Recently, an optical diagnostic system based on the Cherenkov effect, [4], was sucessfully installed and tested on the FTU tokamak, [5] to study the dynamics of non-thermal electrons. Emphasys is given here to results of the diagnostics in scenarios involving magnetic islands because they are more readily controllable than disruptions and, therefore, can be useful to identify key mechanisms of REs interacting with magnetic perturbations. The detailed analysis of the experimental scenarios is completemented by simulations obtained using the HMGC code, [6], in which a given RE distribution is evolved in an electormagnetic field representing the island perturbation to a FTU-like equilibrium.

Relevant diagnostics

The Cherenkov probe, [4], [5], consists of a diamond detector mounted on a TZM (99% Mo, 0.5% Ti, 0.1% Zr) head inserted in the FTU vessel at a variable radial position in the limiter shadow, on the equatorial plane of FTU, at ϕ = 150 deg, Figure 1. Data acquisition rate was 2.5 MHz over the duration of the discharge (up to 2 s), thus resulting in a high temporal resolution comparable to or better than that of other relevant existing FTU diagnostics. The probe is not sensitive to visible radiation, as verified experimentally by the lack of signal from the Cherenkov probe in the presence of a plasma with strong visible emission but no REs.

In FTU, a liquid organic proton recoil scintillator (NE213) and a proportional counter (BF3) are used to monitor, respectively, gamma and neutron emissions, [1]. The NE213 scintillator is located outside the cryostat on the equatorial plane, at $\phi = 210$ deg, and is sensitive to both neutron and gamma rays. Six BF3 proportional counters are used, positioned above the tokamak, insensitive to gamma rays. NE213 and BF3 have been cross-calibrated such that their outputs are identical in the absence of gamma rays. The gamma ray contribution due to the presence of REs is obtained by subtracting the neutron baseline (BF3) from the neutron and gamma rays integrated signal (NE213). The plasma magnetic activity is monitored by means of a set of poloidal field pick-up (Mirnov) coils. In particular, the poloidal (m) and toroidal (n) periodicity numbers of helical magnetic islands chains generated by tearing instabilities are determined by cross-phase measurements. Further information on the internal island structure is given by temperature profile oscillations, as measured by a twelve-channel Electron Cyclotron Emission (ECE) diagnostics. The ECE sightline is on the equatorial plane, at 90 deg toroidal distance from the poloidal limiter and 60 deg from the Cherenkov probe, Figure 1.

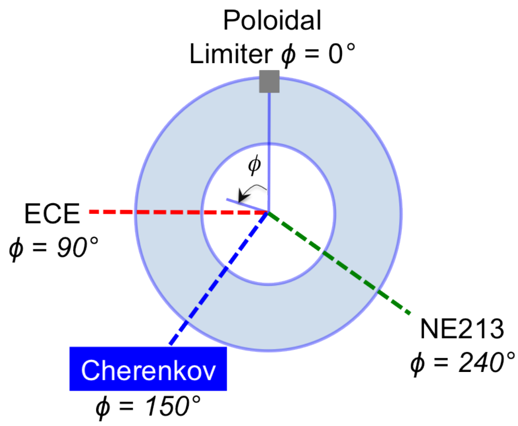

Figure 1: *Top view, simplified schematic of the FTU equatorial section with positions of relevant diagnostics.*

Results

The interest here is in scenarios with tearing modes developing magnetic islands where enhanced RE losses can be observed, in correlation with the island O-point transit in front of the probe, to study the dynamics of REs in the presence of magnetic islands. In the presence of MHD activity consisting in the growth and locking of a magnetic island with poloidal and toroidal periodicity numbers $(m, n) = (2, 1)$, a clear phase-relation was identified between Cherenkov, ECE and NE213 signals, showing that the modulation of the Cherenkov signal is due to the rotation of the magnetic island, Figure 2. The phase lags correspond to the toroidal separations between diagnostics. The scenario was simulated by evolving a model distribution of REs in a given electromagnetic field representing the island perturbation to a FTU-like equilibrium, using a particle-in-cell module of the HMGC code, [6]. The particle distribution satisfies the non-linear Vlasov equation in the low-β drift-kinetic limit: perpendicular components of the vector potential and finite Larmor radius effect are neglected, while magnetic

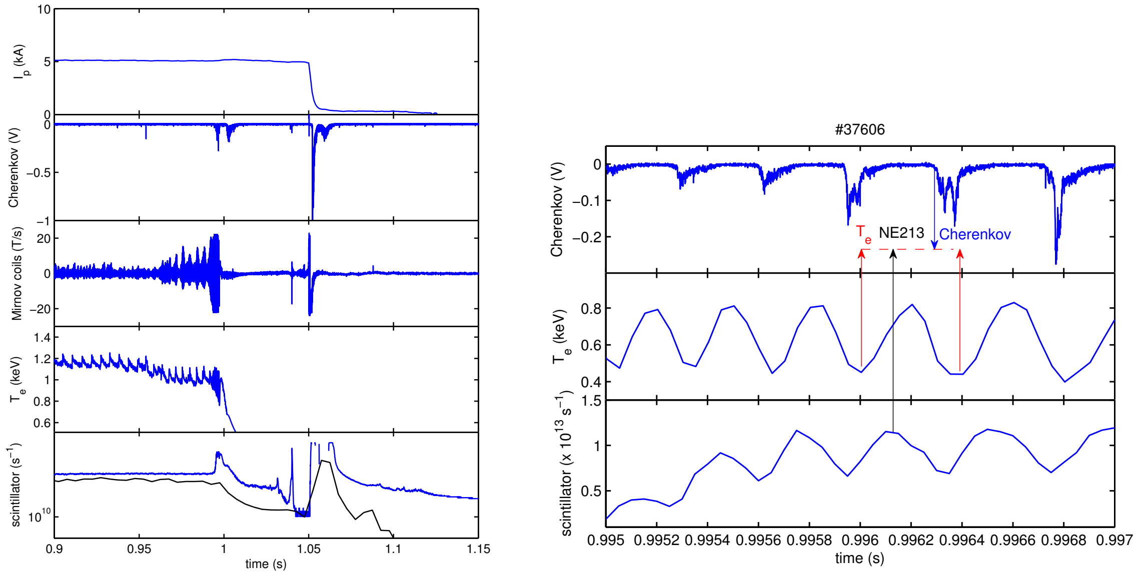

Figure 2: *Time traces of (Left) relevant quantities, note mode locking at t = 1 s and disruption at 1.05 s and (Right) zoom-in of Cherenkov, ECE (channel 10) and gamma-ray signals during island rotation in FTU pulse 37606 (B = 5.3 T, I = 520 kA).*

drift orbit widths are fully retained. The initial RE distribution function was assumed to be anisotropic Maxwellian with different parallel and perpendicular widths corresponding to temperatures $T_{||} = 1Mev$ and $T_{\perp} = 50keV$. The RE density profile was assumed to be vanishing outside magnetic surface $\psi_{out}/\psi_{edge} = 0.76$, here assumed to be the limiter position, near the plasma edge. The effect of a static (zero frequency and fixed amplitude) perturbation to the poloidal flux, with poloidal and toroidal periodicity numbers $(m, n) = (2, 1)$, on the RE distribution was calculated to investigate whether a detectable particle flux is produced in the outer region, where the initial RE density vanishes. The simulations show that in the outer region, the particle density perturbation exhibits the same poloidal and toroidal periodicity of the magnetic island, Figure 3 (Left), consistently with the experimentally observed correlation of enhanced RE losses and the passage of the island O-point in front of the Cherenkov probe. Further, the outward flux is almost exclusively due to trapped particles. In addition, the simulation results yield a quadratic scaling of the number of particles displaced in the outer region with respect to the amplitude of the perturbed poloidal magnetic field $\delta B_\theta / B_\theta$ in the outer region ($\psi/\psi_{edge} = 0.8$), Figure 3 (Right). The non-linear scaling obtained with the HMGC simulations is consistent with the experimental results, although the latter show that the scaling is nearly quadratic for small perturbations, becoming higher-order in the presence of larger perturbations.

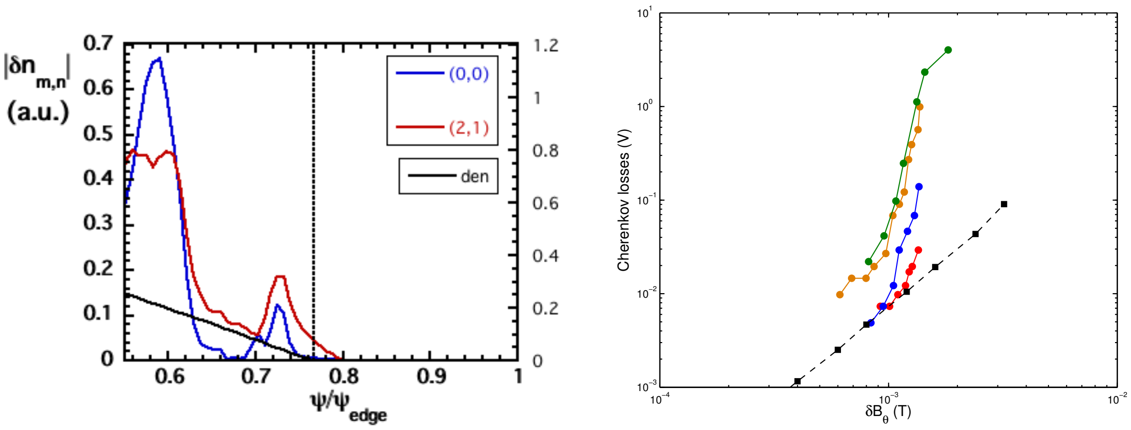

Figure 3: *(Left) HMGC simulated results showing the modulus of Fourier harmonics* $\delta n_{(2,1)}$ *(red) and* $\delta n_{(0,0)}$ *(blue) vs* ψ/ψ_{edge}*. The density perturbation outside the* ψ_{out} *surface (indicated by the dashed line) is dominated by the (2,1) component. [Initial density profile for reference (black)]. (Right) Simulated (black, square markers) and experimental (coloured curves) losses vs magnetic perturbation amplitude. (Experimental curves: series of four discharges at B = 5.3 T and I = 520 kA).*

Conclusions

Scenarios involving RE losses driven by magnetic islands were analysed in detail to gain a deeper insight into the mechanisms governing RE transport from plasma core to plasma edge. The experimental results show that the Cherenkov signal modulation is due to the island rotation and growth, and that the phase lags are due to the toroidal separations between diagnostics. The HMGC-PIC simulations provide a useful insight into RE dynamics in the presence of magnetic islands, showing that the outward flux is due to displaced trapped particles. Importantly, although simplified, the HMGC-PIC captures the non-linear scaling of the outward flux of particles with respect to the amplitude of the perturbed magnetic field representing the island.

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