Wave-Particle Resonances and Redistribution/Losses of Fast Ions in Tokamaks

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Abstract

Enhanced fast ion losses, mostly in the range of energies from around 1.2 MeV to 2.4 MeV, were measured during the activity of tornado modes in the JET tokamak. In this paper, a mechanism that explains the loss of fast ions triggered by core-localized tornado modes is proposed. This mechanism is based on the combined effect of the tornado modes and TAE (Toroidal Alfvén Eigenmodes) over the fast ions, with the tornado modes transporting the fast ions from the centre of the plasma to a region where tornado modes and TAE coexist and the TAE transporting then convectively the fast ions, most efficiently through the first bounce resonances (p=1), all the way to the plasma edge. This mechanism of loss is in consonance with the experimental observations and it allows predicting accurately the energies at which most losses occur.

1. Introduction

Experiments using on-axis monopole Ion Cyclotron Resonance Heating (ICRH) in the monotonic scenario have been carried out in several tokamaks. The presence of the highly energetic ICRH accelerated fast ion population inside the $q=1$ surface (q representing the safety factor) has been observed to stabilize the sawteeth. However, sawtooth crashes occurred after the onset of tornado modes (core-localized TAE inside the $q=1$ surface) [1]. The occurrence of these crashes has then been attributed to the effect of tornado modes, which would remove the fast ions from the plasma centre [2]. Aside from internal redistribution of fast ions, direct measurements of the number of fast ions lost from the plasma in JET [3] have shown that tornado modes also cause significantly enhanced fast ion losses. Since the tornado modes are core-localized modes, a satisfactory explanation on how such modes can lead to the loss of fast ions is necessary. The experiments in JET were carried out using high power ICRH hydrogen minority heating ($P_{ICRH} \approx$ 6-7 MW) applied on axis in a low density deuterium plasma ($n_e \approx 2.4 \times 10^{19} m^{-3}$). Two distinct groups of modes in the Alfvén range of frequencies, each of them composed by several modes with different mode numbers, were present in the plasma (see figure 1).

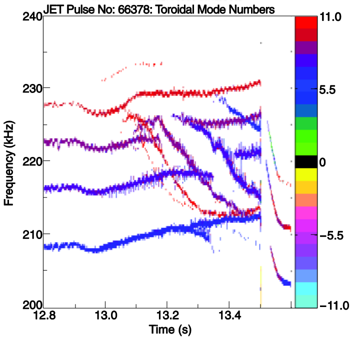

Figure 1: Frequencies and toroidal mode numbers of the TAE and tornado modes during a period in which enhanced losses were measured in pulse #66378.

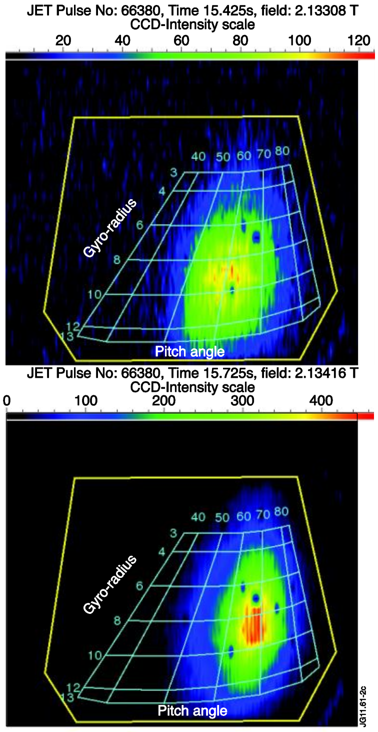

Figure 2: Footprint of the fast ion losses measured by the scintillator probe before the onset of the tornado modes (top) and after the onset of the tornado modes (bottom). Correspondence Gyro-radius to Energy: 4 cm = 0.535 MeV, 6 cm = 0.925 MeV, 8 cm = 1.499 MeV, 10 cm = 2.25 MeV, 12 cm = 3.18 MeV.

Modes belonging to one of the groups had nearly constant frequencies and were identified as global TAE [4], while the modes exhibiting chirping frequencies were identified as tornado modes. The scintillator probe installed in the JET tokamak allowed measuring the energy and the pitch angle of the lost ions. These measurements indicated that the fast ion losses do not only increase in number when the tornado modes become unstable but the average energy of the lost ions decreases and its average pitch angle increases (see figure 2). A relevant conclusion that can be drawn from these experimental results is that the majority of the losses triggered by tornado modes belong to a well defined range of energies, between 1.2 MeV and 2.4 MeV approximately. Aside from it, the footprints of losses triggered by the tornado modes (subtracting the losses triggered by the TAE from the total losses) during an equal period of time in two pulses in which different ICRH power was used (pulses #66378 and #66380) show that the effect of increasing the ICRH power was to increase significantly the number of losses but not the energies at which the losses occurred.

2. Mechanism for radial transport through the p=1 resonances

The orbits of ICRH accelerated fast ions are usually defined by the energy E, the normalized magnetic momentum $\mu B_0/E \equiv \Lambda$ and the toroidal canonical momentum P_φ. When a resonant interaction between a mode and a fast ion takes place, μ is conserved but E and P_φ both change during the process, with the change in energy being proportional to $(\omega/n)\Delta P_\varphi$, where n is the toroidal mode number, ω is the mode frequency, and ΔP_φ is the change in the toroidal canonical momentum of the ion. This interaction results predominantly in a change of P_φ, so, the condition that allows a large radial displacement of the ion to take place is the ion to keep exchanging energy with the mode as its toroidal canonical momentum changes. To calculate the transference of energy between the fast ions and the modes present in the plasma, the CASTOR-K code [5] was used. The calculation is done for each orbit separately so it allows identifying in which regions of the phase-space (E, Λ, P_φ) the resonant interaction results in an efficient exchange of energy. In the case of ions driving the modes, the radial movement of the ions is outward which with the definition of P_φ used by the CASTOR-K code corresponds to an increase in P_φ. The calculation was done for pulse #66378 at t=13.4 s, in which eight Alfvénic modes with significant amplitudes were present in the plasma; four TAE with and four tornado modes both with toroidal mode numbers from n=7 to n=10 (see fig. 1). In these calculations, the CASTOR-K code used the plasma equilibrium and mode eigenfunctions calculated by the usual JET chain of codes and a fast ion population peaked in the plasma centre characterized by Λ=1 (on-axis heating) and by T_{HOT} =1 MeV. Since a constant value of Λ was used (Λ=1), the results from the CASTOR-K code are presented graphically, for each mode, in a 2-dimensional contour plot in the space (E, P_φ). The numerical results show that the tornado modes interact with fast ions moving in orbits localized close from the plasma centre with energies between 1.0 and 3.5 MeV. The regions of significant exchange of energy between the ICRH driven fast ion population and the TAE calculated by the CASTOR-K code are shown in figure 3 (left) for the case of the n=8 TAE. Figure 3 (right) shows schematically the areas of the phase-space (E, Λ=1, P_φ) in which the resonant interaction between the ICRH-driven fast ion population and each TAE occurs through the p=1 resonances (shadowed light blue areas). For comparison, the range of energies at which significantly enhanced losses were measured experimentally is indicated by the red box on the top of the figure and the energy at which a maximum number of losses was measured is indicated by the vertical red line. From these figures it is clear that the range of energies at which the majority of the fast ions reach the scintillator probe agrees with the range of energies at which they are predicted to interact with the TAE through the p=1 resonances.

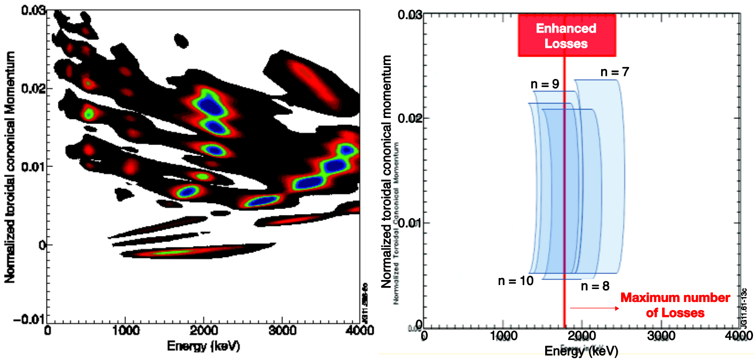

Figure 4: Location of the resonances p=1 of each TAE in the phase-space (E, Λ=1, P_φ), (shadowed blue areas) and energies at which the loss of fast ions was more significant (red box).

3. Discussion and conclusions

It was shown that the transport of fast ions through the first bounce resonances (p=1) of the TAE verifies the condition that allows a large radial displacement of the fast ions to take place. Calculations with the CASTOR-K code have also shown that the energy range of the ions which can be transported through the p=1 resonances of the TAE agrees with the energy range at which enhanced losses were measured experimentally. The fact that increasing the ICRH power increases the number of losses but not the energy of the lost ions is also an indication that the losses must occur as result of the transport of the ions through resonances at specific energy ranges. The numerical calculations also indicate that the transport of the ions through these resonances is essentially due to resonant interaction with the TAE. This analysis uses a combination of measurements and modeling, that complement each other delivering new insight in the interaction between fast ions and MHD instabilities.

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