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Neoclassical Tearing Modes and Fast Ions Confinement in ASDEX Upgrade

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One of the critical issues for ITER relevant fusion research is fast particle physics. Fast particles can in fact drive MHD instabilities, but also their confinement is affected by MHD modes.

In this paper we present new results, coming from the present 2006 ASDEX Upgrade (AUG) [1] experimental campaign, on the role of Neoclassical Tearing Modes (NTM) in causing fast ion losses. A theoretical interpretation is proposed.

Neoclassical Tearing Modes are metastable modes driven by the missing bootstrap current within a preexisting seed magnetic island, provided that the plasma poloidal beta, β_{pol}, is larger than a treshold value [2]. When a NTM grows in the plasma, global confinement is severely affected, and NTMs set the limit to the maximum achievable β in conventional scenarios. It has been demonstrated that they can be actively stabilized via Electron Cyclotron Current Drive (ECCD) [3].

While the NTM impact on the global confinement is rather well established, less is known on how they influence energetic particles, like for example ICRH heated ions, or ions of NBI origin. The study of the effect of low frequency MHD modes, like NTMs, on confinement of fast ions it is important, for example, to fully asses the efficiency of NBI heating and current drive. In next generation devices, like ITER, this information is important also to predict the confinement of alpha particles and the impact of fast ion losses on the plasma facing components.

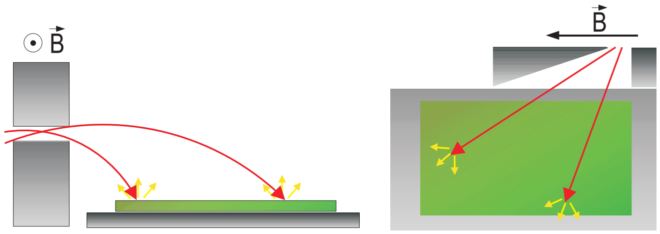

Figure 1

To this purpose, AUG has unique capabilities: its heating system, with 20 MW of NBI at 60/100 keV, 6 MW of ICRH and 2 MW of ECRH, allows for a variety of scenarios, where the behavior of fast ion population can be finely tuned and decoupled from the bulk plasma environment. A new diagnostic, the fast ion losses detector (FILD), provides energy and pitch-angle resolved measurements of fast ion losses, with a bandwidth of 1 MHz [4,5]. The active part of the diagnostic is a scintillator plate contained within a cylindrical cup, which can be inserted via the midplane manipulator up to a few mm behind the limiter. Fast ions enter the detector through a slit open in the cup and hit the scintillator. Their strike points depend on fast particles gyroradius (i.e. their energy) and on their pitch angle, defined as the angle between their velocity and the local magnetic field B (Fig. 1). The scintillator surface is observed via a CCD camera, which provides a slow but highly spatially resolved image, and by an array of 20 photomultipliers, which have a bandwidth of 1 MHz and provide therefore a very high time resolution.

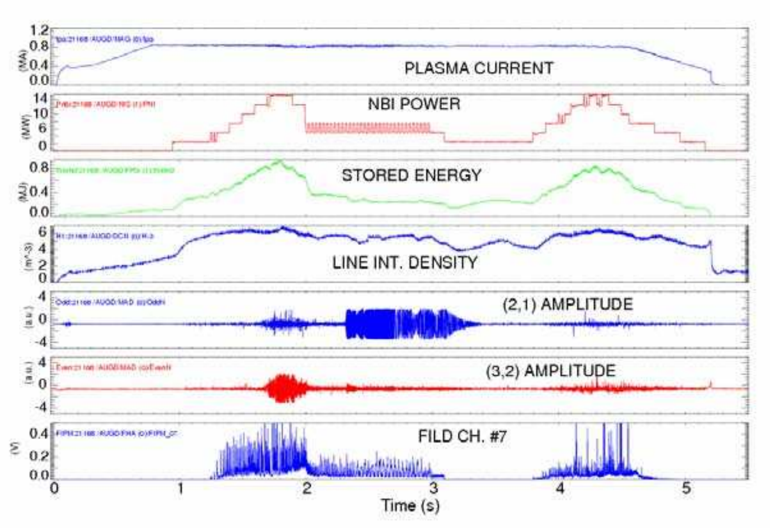

Figure 2

The experiments discussed in this paper have been mainly performed in plasmas with current I_p=0.8 MA, toroidal field B_t=2 T, q_{95}=4.5 and NBI as main heating and fast particle source [4].

ICRH has also been used to modify the fast particle population as well as in improved H-mode plasmas, but the results on these experiments have been reported elsewhere [4]. Waveforms of plasma current, NBI power, stored magnetic energy, line average density, magnetic fluctuation due to the (2,1) and (3,2) NTM, and of one FILD fast channel are shown in Fig. 2 for a typical discharge (#21168). In the time period [2.0,3.0]s, one of the NBI sources (one which is injecting tangentially deuterons at 100 keV) has been modulated with square pulses of 2.5 MW amplitude, superimposed to a constant background of 5 MW; this provides a periodically changing source of fast particles.

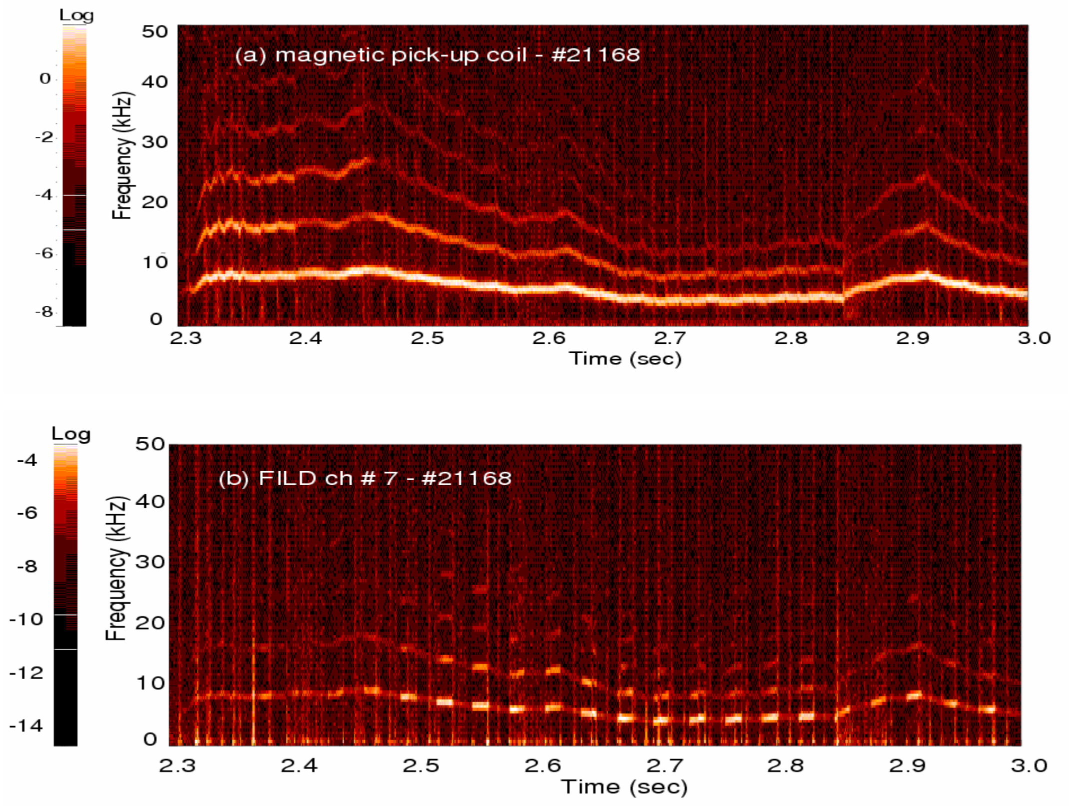

Figure 3 (power spectra in a.u.)

In general, fast particle losses are recorded in presence of both (2,1) and (3,2) NTMs. These particles – of NBI origin - are mostly passing, and they are lost basically with the energy that they had at their birthplace, i.e. the NBI energy. Their transit frequency (~ 200 kHz) is higher than the mode frequency (typically < 10 kHz for (2,1), <20 kHz for (3,2)). We observe a coincidence between the frequency and phase of the mode and those of the losses as well as a strong correlation between the NTM amplitude and the amount of particle losses. An example is shown in the Fig. 3, which reports the Fourier spectrograms vs. time for a magnetic pick-up probe and for one of the FILD channels (#7) for a time lag where a (2,1) NTM and its harmonics are present. This channel records passing deuterons with energy ~100 keV (i.e. that of the modulated NBI source) and pitch angle ~35°. The dynamics of these losses closely follows that of the NTM and that of the modulated NBI source. The modulation is in fact clearly visible also in Fig. 3-b. This indicates a strong correlation between fast ion losses, of NBI origin, and the presence of the NTM.

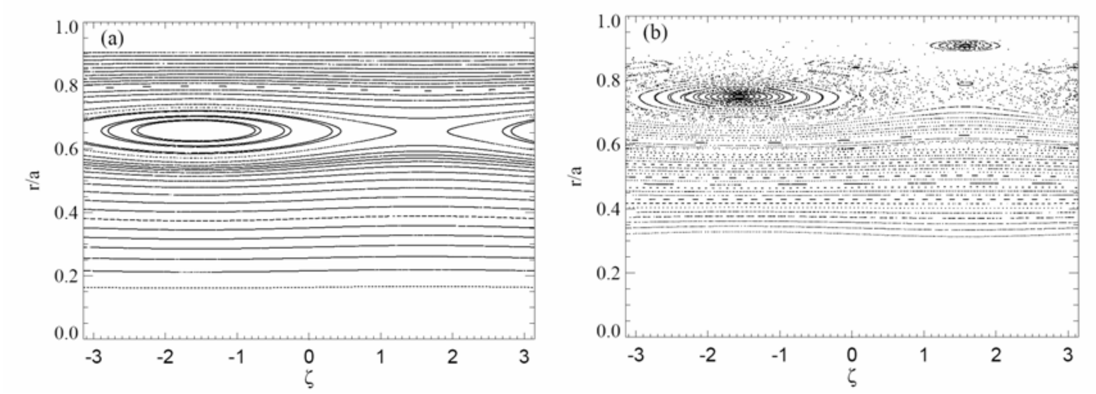

Figure 4

The NTM-induced fast ion losses are interpreted as a result of a mechanism called orbit stochasticity [6,7]: a magnetic perturbation, like that due to the (2,1) NTM, produces an island in the magnetic field. If only this island chain is present, this does not cause significant ergodicity of magnetic field lines (which are followed by the guiding centers of thermal particles). The situation for fast particles is different: the coupling between the fast particles guiding center motion in the perturbed magnetic field and the orbit shift due to the drifts (which has a (1,0) character) results in drift islands in the fast particle's phase space. These islands, in the orbit space, can overlap and originate there a stochastic region. Simulations of 100 keV deuterons motions in a tokamak magnetic equilibrium perturbed by a (2,1) mode, performed with the Hamiltonian guiding center code ORBIT [8] code, confirm the presence of this mechanism. Fig. 4 shows the toroidal Poincaré puncture plot for the magnetic field lines (Fig. 4-a, the (2,1) island is evident) and for the drift surfaces of 100 keV deuterons (Fig. 4-b). ζ is the Boozer toroidal coordinate. A

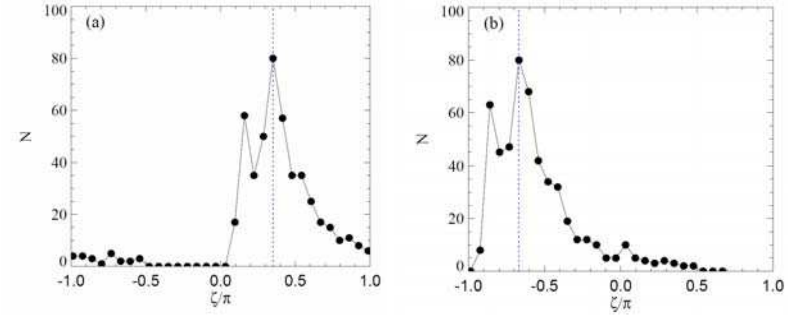

Figure 5

stochastic region is evident in Fig. 4-b. As an initial test case, the motion of a population of 1000 deuterons at 100 keV with pitch=1 (i.e. with velocity parallel to the magnetic field) has been studied in a collisionless plasma. A circular cross-section tokamak equilibrium (with the same AUG minor and major radii and B_t=2 T) with a superimposed (2,1) perturbation, has been considered. The particles have been deposited on the HFS, on the equatorial plane, distributed over a radial range defined by $0.57 < r/a < 0.81$, where a is the minor radius. Fig. 5 shows the distribution of the lost particles, recorded at the plasma edge, as a function of the toroidal angle, for two initial poloidal phases of the (2,1) mode, $\theta=0$ (Fig. 5-a) and $\theta=\pi$ (Fig. 5-b). A clear maximum as a function of the toroidal angle is evident. This is a signature of a dominant n=1 pattern. This is consistent with the experimental observation of the constant phase locking between the NTM and the losses signal. The cumulative probability distribution of the fast particles loss time is reported in Fig. 6: in the x-axis there are the loss times, τ_{loss}, i.e. the time a fast particle travels before being lost. For a given value of τ_{loss}, the curve gives the fraction (in %) of the initial fast deuterons, which are lost within that time. The plot shows that particles are lost in a broad range of time scales: while the first are promptly lost after a few tenths of μs (to be compared with the toroidal transit time for 100 keV deuterons equal to 5 μs) a fraction of the population takes a longer time before being lost, up to several ms.

In conclusion, the data presented in this paper indicate that NTMs are responsible for enhanced transport of 100 keV ions, and a mechanism, based on the overlapping of drift islands in the orbit space, has been identified which is a good candidate to explain these losses.

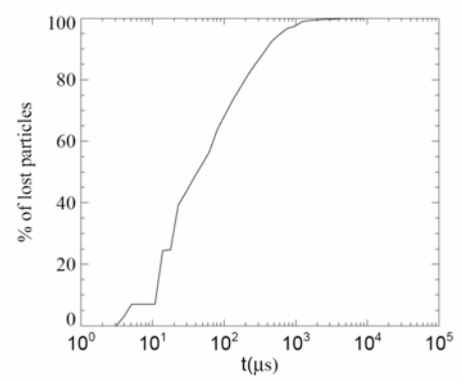

Figure 6

Further work will be devoted to a more quantitative evaluation of the losses, in particular as a function of NTM amplitude, and of its helicity. Preliminary analysis show that losses caused by the (3,2) NTM have some different features, which might be due to the different spatial localization of the mode. We will also optimize the numerical simulation, by taking into account a realistic AUG geometry, the experimental NBI deposition pattern (both in terms of particles location pitch) and the role of collisions. This should allow a more quantitative statement on the effect of NTMs on the whole population of injected NB ions.

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