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Redistribution of ICRH Fast Ions in the Presence of Fishbones and Alfvén Eigenmodes

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**See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)*

Abstract
A set of experiments on fast ion redistribution was carried out in recent JET campaigns, in which the new fast ion loss detectors were used for the first time [1]. This paper reports on the experiments carried out with low density plasmas and high ICRH power, a scenario that allow large populations of highly energetic fast ions to be built up and a variety of instabilities to be destabilized. Fast ion losses were successfully measured and it could be confirmed they were effectively associated to MHD activity. Losses occurred at considerably high energies (of the order of few MeV) and two types of fast ions were identified by the gamma-ray diagnostics [2]: fast protons with an energetic tail in excess of 4.5 MeV due to ICRH tuned to a fundamental H-resonance in the centre of the plasmas and D-ions accelerated with second harmonic heating whose energies exceeded 0.5 MeV. Three types of losses were identified, one associated with sawtooth crashes, one associated with TAE and high frequency fishbones and a third group that seems to correlate with tornado modes. When tornado modes became unstable, a significant increase in the number of losses was measured and a change in both the energy and pitch angle of the lost ions was observed. In addition, it was also observed that the number of losses increased significantly with the ICRH power.

Introduction
Fast ion losses are of concern for ITER since the first wall can only tolerate losses at a very low level before suffering damage. In addition, fast ion losses may cause the heating to be inefficient or, in case of alpha particles, fusion burn may not be sustained. To explore the physics of fast ion loss, JET has installed new fast ion loss detectors [1] and is now able to undertake dedicated fast ion redistribution experiments which allow predictions for ITER to be made. This paper reports on the experiments carried out in the scenario with low plasma densities and high ICRH power (I_p=2.5 MA, B_t=2.7 T and 3.5 MW $\le P_{ICRH} \le$ 7.5 MW) with on axis minority heating. When the plasma density exceeds the threshold for grassy sawteeth, long sawtooth periods occur [3] and a large population of highly energetic ions is built up, which constitutes a strong drive for many instabilities [4]. In particular, these experiments aimed to destabilize diamagnetic, hybrid and precessional drift fishbones, as well as TAE and core-localised TAE (tornado modes). The main objective was to measure the fast ion losses throughout the period between two consecutive giant sawtooth crashes and try to associate the measured losses with the observed instabilities. Of particular interest were the losses that precede the sawtooth crash, since it is thought that the occurrence of giant crashes may be related to the redistribution (depletion) of fast ions in the plasma centre [5].

Typical monster sawteeth

Monster sawteeth are composed of a ramp phase, a “saturated” phase and a crash phase. In the low density, high ICRH power scenario, monster sawteeth are more complex presenting “several phases” as shown in fig. 1(a). The electron temperature evolution starts as usual with a ramp-up phase but it is soon followed by a small ramp down. After this, the ramp-up phase resumes until the electron temperature reaches a maximum, which is also a characteristic feature of this scenario. After a small decrease in T_e, the steady-state phase is reached though a slight decrease in the electron temperature is sometimes observed before the sawtooth crash.

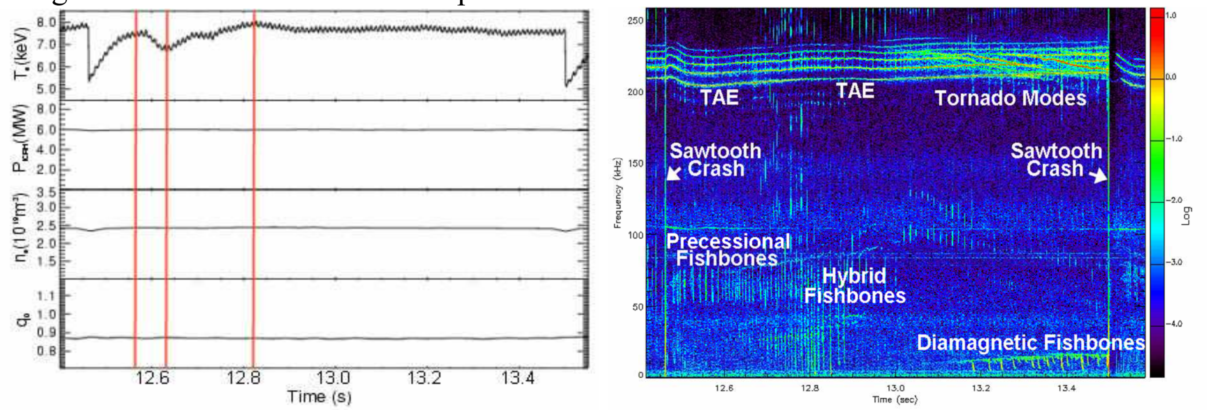

Figure 1(a): Electron temperature, ICRH power, central plasma density and safety factor on axis for a typical monster sawtooth in this scenario (pulse #66378). The different monster sawtooth phases are separated by red lines. Figure 1(b): Spectrogram of MHD activity for the same period of time.

MHD activity

All the targeted instabilities were normally observed during the period between two giant sawtooth crashes (fig. 1(b)). Toroidal Alfvén Eigenmodes (TAE) were usually observed throughout the whole period (except when the ICRH power was too low). Tornado modes occur above a P_{ICRH} threshold [6] and were always observed before the sawtooth crash but their behaviour changed significantly depending on the ICRH power: they could be observed for quite a long period or just shortly before the sawtooth crash. Fishbones were also always observed and always followed the same order of appearance: Precessional fishbones occurred first and appeared immediately after a sawtooth crash. They were later replaced by hybrid fishbones whose maximum amplitude coincided with the maximum in electron temperature. Finally, diamagnetic fishbones were observed before the sawtooth crash. Sometimes a gap without fishbones was observed after the hybrid fishbones are stabilized and before diamagnetic fishbones are destabilized.

Fast ion losses

When the ICRH power was high enough ($P_{ICRH} \geq \sim 4.0$ MW), fast ion losses were measured whenever MHD activity was observed. However, in periods where no MHD activity occurred, no losses were measured above the noise level. This allowed us to conclude that the measured losses were effectively caused by MHD activity. Throughout the period of a monster sawtooth, three types of fast ion losses were identified, exhibiting a clear correlation with the type of instabilities present in the plasma at that moment. The first type of losses was observed in the early phases of monster sawteeth, when TAE and precessional or hybrid fishbones were observed. The distribution of these losses is broad and typically (fig. 2(a)) pitch angle ranges from 50 deg. to 75 deg. while energy ranges from 0.7 MeV to 3.7 MeV in the case of protons (0.44 MeV to 1.9 MeV in the case of deuterons). When tornado modes and diamagnetic fishbones become unstable there is a change in the measured losses (fig. 2(b)). The distribution becomes narrower and the maximum number of counts increases typically by a factor of 2 to 4. Pitch angle ranges from 60 deg. to 75 deg. while energy ranges from 0.9 MeV to 2.2 MeV in the case of protons (0.54 MeV to 1.2 MeV in the case of deuterons). The instant at which changes in the distribution occur seem to correlate better with the destabilization of tornado modes than diamagnetic fishbones. The third type of losses is associated with giant sawtooth crashes (fig. 2(c)). In this case the loss distribution is narrower and energies are lower. Typically, pitch angle ranges from 45 deg. to 55 deg. while energy ranges from 0.5 MeV to 1.5 MeV in the case of protons (0.35 MeV to 0.8 MeV in the case of deuterons). Both tornado and crash associated losses may be observed simultaneously during the giant sawtooth crash. Finally, it should be pointed out that the number of losses increase significantly with ICRH power (from P_{ICRH} = 4.5 MW to P_{ICRH} = 7.5 MW may increase by a factor of 2 to 5) but the characteristics of the distributions do not.

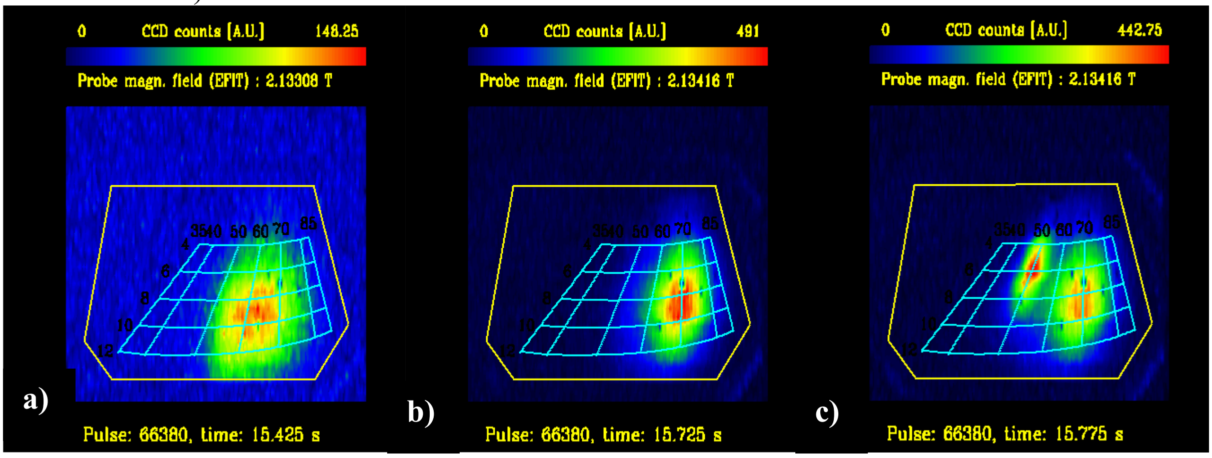

Figure 2 : The three types of measured fast ion losses as function of the pitch angle and gyro radius: before tornado modes are destabilized (left), after tornado modes are destabilized (middle) and during a giant sawtooth crash (right) (pulse #66380).

Analysis and discussion

One of the possible explanations for the occurrence of giant sawtooth crashes is that tornado modes may expel the fast ions responsible for sawtooth stabilization from the plasma centre [5]. These experiments tried to address this issue, but experimental results were not conclusive. There are a number of experimental observations that seems to support this explanation, but on the other hand there are also results difficult to explain. In support of it, there is the fact that tornado modes were always observed before giant sawtooth crashes, though it maybe a consequence of the changes in magnetic field line topology that occur in the plasma prior to the crashes and not the cause of the crashes itself. A stronger argument seems to be the significant increase in the number of measured fast ion losses that occur when tornado modes are destabilized. This indicates that tornado modes effectively provide an efficient mechanism for expelling fast ions from the plasma. Nevertheless, there are also observations difficult to explain in the light of this explanation. In pulses with lower ICRH power, such as pulse #66318 (P_{ICRH} ~3.5 MW), only very few losses were measured before giant sawtooth crashes. Besides, tornado modes were observed only for a very short time before the sawtooth crash. For tornado modes being the cause of the crash, it would be necessary that they had expelled the fast ion population responsible for sawtooth stabilization from the plasma centre in the very short time they were unstable. This contrasts with discharges with higher ICRH power, such as pulse #66378 (P_{ICRH}~6.0 MW), where strong signals from tornado modes are visible in the MHD spectrogram for around half a second before a giant crash occurs. In this case, even if the generation rate of fast ions is higher, it would be necessary to explain why it took so long for tornado modes to expel the fast ions from the plasma centre. Numerical simulations with the HAGIS code [7] have shown that the orbits of lost ions correspond typically to large banana orbits. This is not surprising since particles with this type of orbits travel nearer to the plasma edge along its trajectory. Fig. 3 shows a typical ICRH accelerated ion trajectory on a banana orbit with its banana tips inside the resonance layer and simultaneously close from any core localized MHD perturbation. It is important to remark that ions on these orbits due to the high *w/a* ratio (with *w* the banana width and *a* the minor plasma radius) are easily expelled during the crossing along the outer leg of the banana orbit even if the interaction with MHD instabilities is weak. Simulations with the CASTOR-K code [8] show there is an interaction between particles with this type of orbits and the MHD modes. A more detailed numerical analysis is still being carried out.

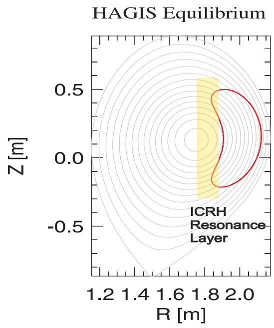

Figure 3: Hagis simulation: Typical banana orbit of an ICRH accelerated ion with its banana tips inside the ICRH resonance layer (yellow strip).

Conclusions

The experiments on fast ion redistribution in the low density, high ICRH power scenario were successfully carried out: all targeted instabilities (TAE, tornado modes, precessional, hybrid and diamagnetic fishbones) were destabilized and fast ion losses were measured. Besides, losses could unequivocally be associated with these instabilities and with sawtooth crashes. Regarding the risks of first wall damage in future tokamaks, these experiments have shown that fast ions are lost at very high energies, of the order of few MeV and that the number of losses increases significantly with the ICRH power. Three types of fast ions losses were measured throughout the period of a monster sawtooth. In the early phases, when TAEs were observed along with precessional and hybrid fishbones, a broad distribution of lost ions is observed. In the “saturated” phase of monster sawteeth, when tornado modes and diamagnetic fishbones become unstable, a second type of losses is observed. The distribution becomes narrower, there are clear changes both in the energies and pitch angle of the lost ions, and a significant increase (factor 2 to 4) in the number of losses is observed. This increase in the number of losses seems to correlate better with the appearance of tornado modes than with the appearance of diamagnetic fishbones. Finally, when a giant sawtooth crash occurs, a third type of losses is observed. These losses are observed for a short time, occur at lower energies, and are clearly associated with the giant sawtooth crash. Concerning the influence of tornado modes on giant sawtooth crashes, experimental results were not conclusive, however a numerical analysis is still being carried out in order to interpret the changes in the fast ion loss distribution when tornado modes become unstable.

Acknowledgments

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