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Particle loss signatures during sawtooth events at JET

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Introduction

The energetic component of the ion distribution function in the core of fusion plasmas is known to have a strong effect on sawtooth stability [1,2]. Stabilising effects can lead to the occurrence of long sawtooth periods where the crash may be triggered as a result of a sudden depletion of fast ions from the core due to other instabilities. For example, particle losses due to fishbone activity have been observed just prior to sawtooth crashes. The detailed time evolution of the fast particle distribution throughout the sawtooth cycle is therefore of considerable interest.

Diagnostic setup

The Joint European Torus (JET) was recently equipped with a new scintillator probe diagnostic [3] to measure fast ion losses with temporal and spatial (gyro radius, pitch angle) resolution. It operates as a magnetic spectrometer, routinely delivering data with a resolution of 5% in pitch angle and 20% in gyro radius at a sampling rate of 20 Hz (CCD camera). The image (example in figure 1) is generated by a scintillating plate (yellow outline) on particle impact. The same 2-dimensional image, albeit at reduced spatial resolution, is observed by a photomultiplier tube array with time resolution above the diagnostic's limit given by the scintillator decay time (~2.5 ms) by means of a beam-splitter. The phase-space mapping (cyan grid) between the 3D plate and gyro radius and pitch angle coordinates is field dependent and generated by applying a Monte-Carlo code package which calculates the centroids of particle impacts with identical starting parameters at the collimator using an accurate 3D model of the probe. Data analysis shows that peak signal identification is reliable and accurate due to the good spatial resolution of the diagnostic.

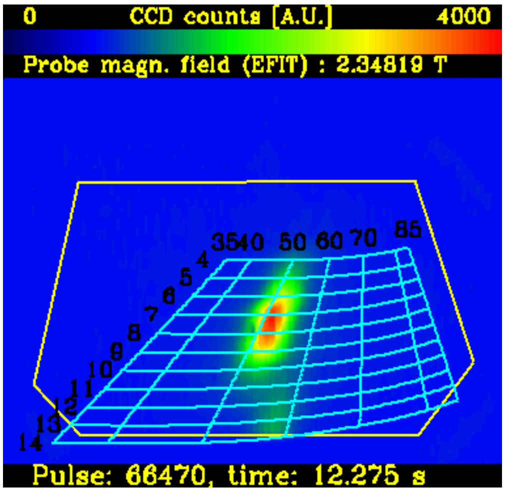

Figure 1: Scintillator plate contour with phase-space grid (gyro radius in cm and pitch angle in degrees) just after sawtooth reconnection event. Prompt losses (lower right) and purely sawtooth induced losses (upper left) 50 ms after crash

Experimental results

Many JET pulses with low frequency (typically fast particle stabilised) sawtooth activity show a strong correlation between the time when particle losses are detected by the scintillator probe and the onset time of the sawtooth crash as seen by the soft X-ray diagnostic. Since the time resolution of the detector is not sufficient to resolve the time-scale of the sawtooth crash itself as it happens (sub-ms), it is not fully clarified, whether the particle losses, well correlated in time with the crash, originate from a population which is stabilising the mode or whether those losses are caused by the sawtooth. However, particle losses of such nature, as seen in figure 1, usually show a footprint expected for a particle distribution with a pitch angle distribution nearly matching a delta function. The energy (or rather: gyro radius) distribution of those particles is wider than a delta response would be but it is limited in its extent so that maximum and minimum energy for an assumed species can be determined. The long axis of the elliptic footprint is always aligned with a line of constant pitch angle.

In JET pulse #66470 a current of 2.5 MA and a toroidal field of 3 T was used which results in a q_{95} of about 4. The discharge was heated by NBI (6 MW) and hydrogen minority ICRH (6 MW) with frequencies ranging from 51.1 MHz to 51.9 MHz, putting the resonance layer near 2.6 m, which is on the high field side, but still close to the plasma core. The combination of NBI with ICRH provides a large population of fast particles (fast protons from the hydrogen minority heating and energetic deuterium from 2nd harmonic heating of NBI ions) in the plasma. The weak loss signal in the lower part of the plate (figure 1) has a central pitch angle of 56° and corresponds to particles with a gyro radius of about 12 cm (±1.5 cm) or a proton energy of approximately 4 MeV, while the second, much more intense spot at a radius of 8 cm (±1.5 cm) resembles protons of about 1.5 MeV, deuterium of 800 keV or ^{3}He with 2 MeV. Gamma ray spectroscopy [4] indicates the presence of a population of fast hydrogen and deuterium ions, but the density of protons above 4.5 MeV is rather low. This suggests an interpretation of the weak signal, which is seen continuously throughout the high-power ICRH phase, as direct losses of protons above ~4 MeV, while the character of the losses at the pitch angle of 52° is unclear, especially since subsequent sawtooth crashes do not indicate further losses in that phase-space region, but only modulate the intensity of losses at the larger angle.

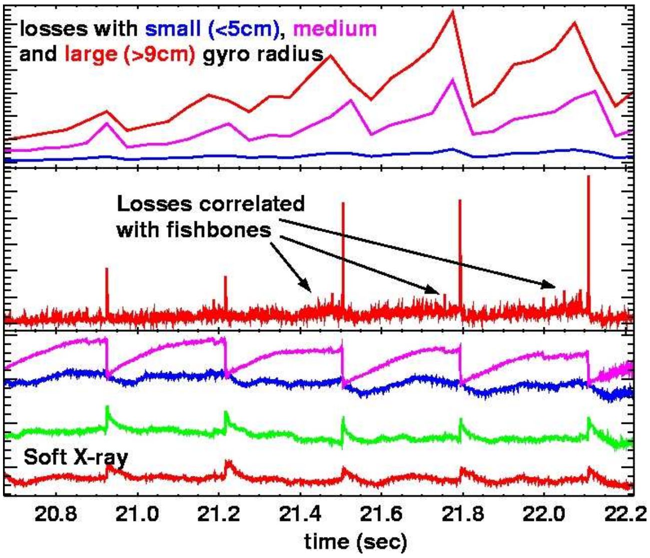

Figure 2:
Pulse #66486 with repetitive sawtooth activity. Top: CCD camera integral signal over different gyro radii, Middle: Photomultiplier total photon count, Lower: Soft-X-ray temperature traces

In a different plasma discharge (#66486), at a current of 1.2 MA and a field of 2.7 T (q_{95}=6), the pulse with the combined heating power of 9 MW NBI and 5.9 MW ICRH has a long time interval (several seconds, small slice shown in figure 2) with large repetitive sawteeth with a period of about 280 ms. Additionally, the sawtooth events in this discharge are preceded by intermittent fishbone activity. Both the fishbone bursts as well as the sawtooth crashes are seen to produce particle loss signals detectable by the scintillator probe. Again, two distinct regions can be identified which have different time behaviour relative to the sawtooth onset times. The exact onset time for the detected losses can be determined using the photomultiplier time resolution of 1 kHz. Due to the relatively large number of similar sawtooth events, we can pick one (at 22.12s) which takes place immediately after one CCD exposure ends so that particle losses from before the sawtooth to losses at or after the sawtooth can be resolved spatially with the full possible resolution. The highest contrast is gained by differencing the two relevant subsequent frames (figure 3), so that the result presents the change of signal for a full integration time (50 ms) of the CCD camera. The two identified phase-space locations are centred around (8 cm, 58°) and (10.5 cm, 60.5°).

Modelling

Since the detector measures gyro radius and pitch angle (ρ, θ), every plate location can be described by a (E, Λ) pair, where $\Lambda = \mu B_0 / E = B_0 / B\ (1 - \cos^2\theta)$ and B_0 is the magnetic field on axis. The energy is calculated from the gyro radius and depends on the particle type (H, D, ^{3}He, etc.). Each Λ describes a class of particles approximately equivalent to those arising from ICRH heating [5]. A population of such fast ions with trapped orbits increases when ICRH is applied as the wave energy primarily heats the perpendicular component of particle velocity and the particles assume orbits which have the tips of their bananas exactly in the region of ICRH resonance.

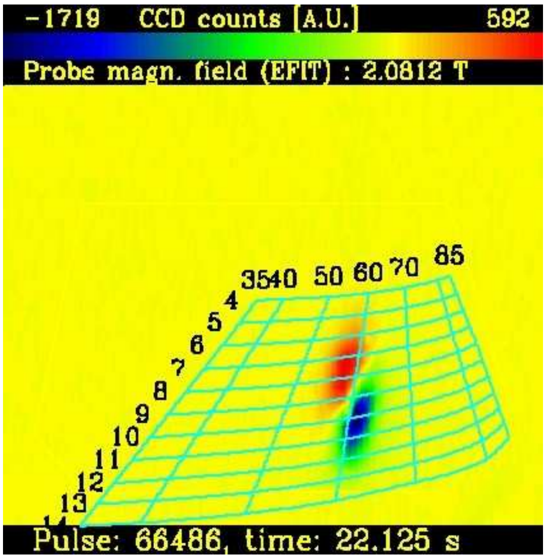

Figure 3: Difference plot at sawtooth time. Red spot indicates losses after sawtooth, blue spot shows maximum before the crash.

The clear alignment of particle losses with a fixed pitch angle also makes those particles likely to be originating from an ICRH generated fast particle population. In order to identify the particles the guiding-centre code HAGIS [6] was used. HAGIS is run with the magnetic equilibrium and particle characteristics (energy, pitch angle, starting location) and calculates the guiding centre orbits of the resulting motion in the plasma as well as the ion cyclotron frequency at the particles' high field side turning point (banana tip). The particle starting positions were chosen as close as possible to the last closed flux surface and distributed on the low field side of the plasma. Plotted are all possible solutions for guiding centre orbits started near the separatrix, while those directed towards the detector are highlighted in red.

Discussion

The calculation of particle orbits shows that only trapped particles are candidates for the losses for all cases. For #66470 the pronounced difference between the two identified pitch angles allows one to differentiate between ICRH heated and differently classified particles. The diagnostic resolution is not sufficient to do the same for #66486, where it is deemed possible that both loss channels tap into the same particle source: the large population of fast hydrogen minority.

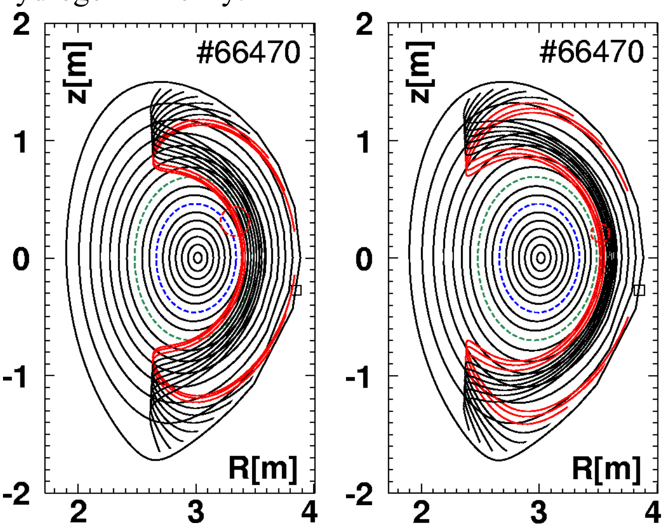

Figure 4:
Left: Loss orbits with 12cm, 56° signature at probe detector
Right: Loss orbits with 8 cm, 52° signature at probe detector
Guiding center orbits which may hit the probe are colored red, the small circle has the size of the gyro radius, the sawtooth inversion radius is blue, the q=1.5 surface green, IC resonance plane aligns with the banana tips in the left. Detector position is indicated by small rectangle (LFS).

In #66470, the ion cyclotron frequency of protons with an initial pitch angle of 56° near the plasma edge is determined as f_{ci} = 52.3 MHz at the turning points of the banana, which is within a few percent of the ICRH range of frequencies used and matches it within the diagnostic's accuracy. This allows to identify these losses as part of the ICRH generated fast particle population of either hydrogen heated by fundamental or deuterium by 2^{nd} harmonic, which have the same orbits when pitch angle and gyro radius are set. The other test ion cyclotron frequency calculated for the particles at (8 cm, 52°) is 57.9 MHz which disqualifies those particles as compatible with a population solely generated by ICRH. Furthermore, the loss orbits belonging to particles of this smaller pitch angle (figure 4b) are outside the sawtooth inversion radius and should not be affected by the sawtooth directly. It is probable that those particles were expelled from the plasma core at the crash time. By looking at their orbits, one sees that they originate near the q=1.5 surface, where a m=3, n=2 tearing mode is excited simultaneously with the sawtooth. The photomultiplier channel connected to this plate position shows that the signal quickly (<1 ms) grows to its maximum after which it decays with a time constant of about 200 ms. Subsequent sawteeth do cause particle losses only from the ICRH ion distribution and with considerably smaller amplitude than the first event. These particles move on guiding centre orbits within one gyro motion of the sawtooth inversion radius, hence the influence.

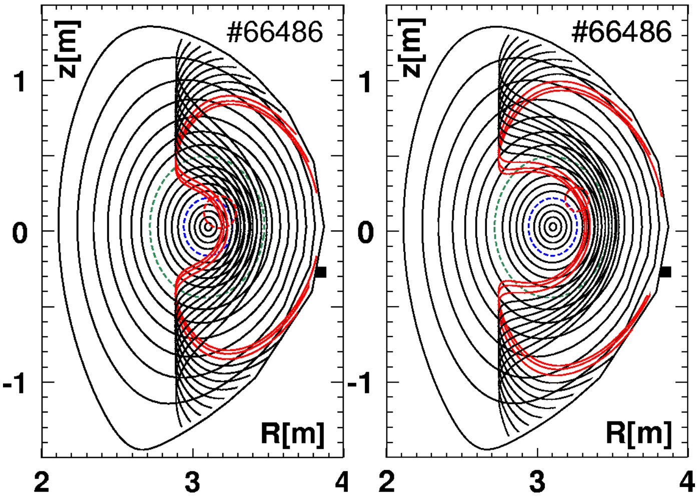

Figure 5:
Left: Orbits with (10.5 cm, 60.5°) at detector, guiding centre within sawtooth inversion. Right: Orbits with (8 cm, 58°), guiding centre always outside inversion radius, detector position indicated by small black rectangle.

In #66486, the loss orbits of both separated phase-space regions are such that they are within one gyro radius of the sawtooth inversion radius (figure 5), but while the guiding centre of the (8 cm, 58°)- particles is just outside the q=1, the guiding centre orbit of the (10.5 cm, 60.5°)-particles cuts through the q=1 surface. It is the particles on orbits outside the q=1 surface which are expelled at or after the sawtooth event, while losses before the sawtooth reach their maximum amplitude before the sawtooth onset and must mainly be caused by fishbones (compare also with figure 3).

Summary

The ICRH minority heating scheme generates particles which can be classified by their pitch angle outside the plasma (e.g. at the scintillator probe). The HAGIS code has been used to identify the part of the fast ion distribution function that is expelled from the plasma in relation with the destabilisation of sawteeth. The orbits of sawtooth related fast ion losses are found to originate near the sawtooth inversion radius for 2 exemplary cases. Strong additional losses are confirmed to originate from the q=1.5 surface at the same time when a m=3, n=2 tearing mode is excited which was seeded by the sawtooth crash. Fishbone and sawtooth instabilities were seen to redistribute particles onto loss orbits from within and outside the sawtooth inversion radius, respectively.

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