Fast ion losses in JET hybrid scenarios - MHD sources overview

*C Perez von Thun[1], V G Kiptily[2], S Popovichev[2], V Yavorskij[1,3], V Goloborod'ko[1,3], P Buratti[4], M Baruzzo[5], G Pucella[4], and JET EFDA Contributors**

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK

[1] University of Innsbruck, Association EURATOM-Österreichische Akademie der Wissenschaften (ÖAW), Austria
[2] Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[3] Institute for Nuclear Research of Ukrainian Academy of Sciences, Kyiv, Ukraine
[4] Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Roma, Italy
[5] Associazione EURATOM-ENEA sulla Fusione, Consorzio RFX Padova, Italy

Introduction Plasmas in hybrid scenario tend to exhibit a complex mix of low frequency MHD activity (notably fishbone oscillations, occasional sawteeth, continuous $n = 1$ modes, and often several pressure driven tearing modes with toroidal mode number $1 \leq n \leq 7$), whose impact on the fast ion confinement may differ significantly from the impact on the thermal confinement. The main aim of this work is to document and characterise the main MHD sources of fast ion losses and quantify their relative importance in hybrid operating scenarios with view to their future use in a JET DT campaign. The main tool for these studies are a fast ion losses detector (FILD) probe [1] yielding localised time-resolved velocity space information about the escaping energetic ions (fig. 1a), and a set of activation-foil calibrated Si diodes for volume-integrated 14 MeV neutron rates. A total of 92 NBI-heated hybrid pulses from the 2013 experiment campaigns were analysed. It is important to note that the FILD setup allows for the measurement of lost fusion products and ICRH accelerated ions ($E > 0.25$MeV), whereas neutral beam ions ($E \leq 125$ keV) cannot be currently measured.

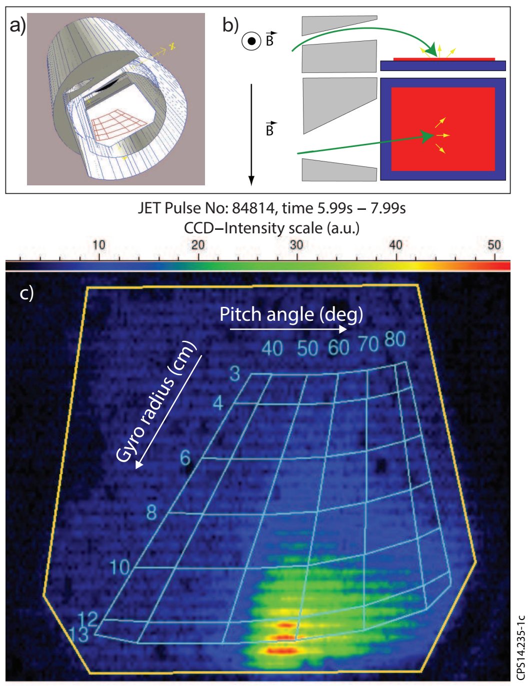

Figure 1: (a),(b): Scintillator probe measuring principle. (c) Typical snapshot for an NBI-heated D hybrid plasma, showing DD charged fusion product prompt losses (p,T).

Results In NBI heated discharges the escaping ion flux at the probe (fig. 1c) originates mainly from promptly lost 1 MeV tritons and 3 MeV protons (which have the same orbits as the 1

*See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US

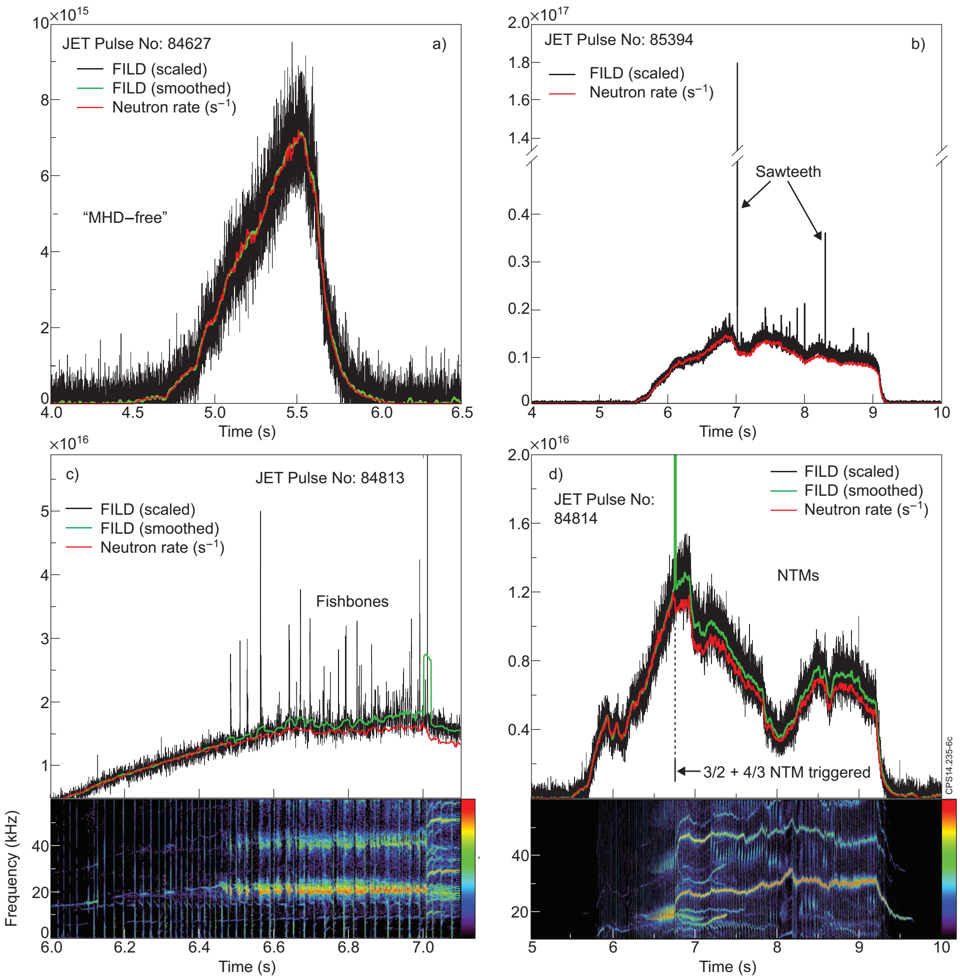

Figure 2: Examples showing typical lost tritons behaviour under the influence of various instabilities (black=raw signal, green=smoothed). Departures of FILD signals (excl. noise) from the scaled triton source (in red) indicate additional losses due to MHD activity. For the last two examples the corresponding magnetic spectrograms are also included.

MeV tritons). Stopping power calculations for the scintillator material show the tritons induce 56% of the measured light, and protons the remaining 44% [2]. In the absence of MHD and as long as certain conditions are satisfied (e.g. no changes in magnetic configuration), the phase space integrated FILD signal is proportional to the triton source signal (the 2.5 MeV neutrons), fig. 2a.

Sawtooth crashes (much less frequently triggered in hybrid than in baseline) give rise to the largest additional losses, with up to 15-fold increase in triton losses compared to the MHD-quiescent case (fig. 2b). This effect is however only short-lived, with duration comparable to the sampling rate of the diagnostic, and both the neutron rate and the fast ion losses are seen recover quickly their unperturbed values. Hence, no major impact on the overall (time-averaged) DT fusion performance is anticipated. Fishbone oscillations in hybrids can also yield transient losses (fig. 2c), but these are found to be much smaller than the sawteeth and often not detectable at all. Detailed analysis of the fast ion losses phase space reveals that during the sawtooth crash the fusion source spatial distribution is modified (consistent with [3]),

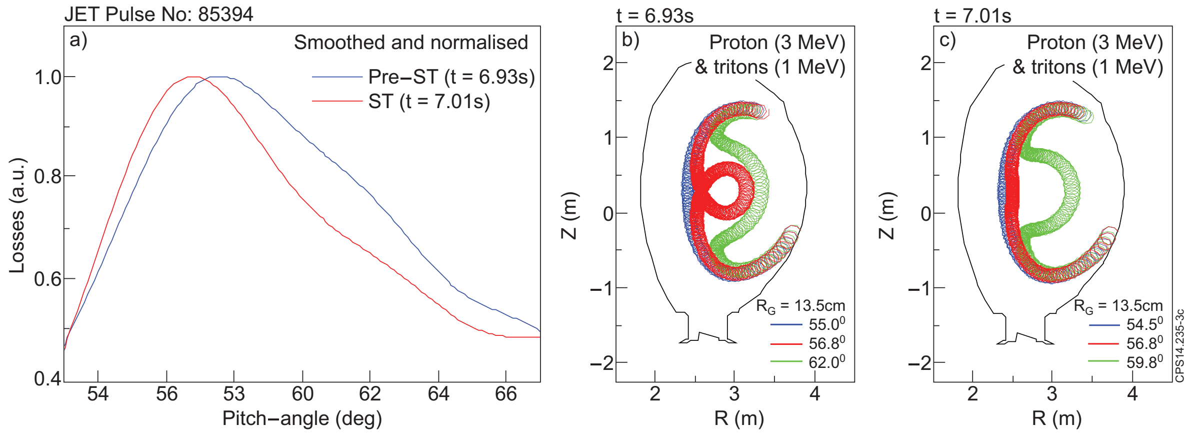

Figure 3: (a) Pitch angle distribution of DD-fusion product prompt losses before and during the sawtooth crash, showing a shift of the fusion source towards lower pitch angles, i.e. the high field side. Representative orbits of fast ions arriving at scintillator probe (with pitch angle at peak and half maximum values of losses distribution) before (b) and during (c) sawtooth crash.

generally shifting slightly towards the high field side (lower pitch angles). A similar (more pronounced) shift was previously reported also for ICRH minority ion losses [4].

For all the other MHD modes (tearing modes, fishbone oscillations, internal kinks) no modifications to the fast ion losses phase space have been encountered. However, the presence of tearing modes with $n \geq 2$ correlates with an anomalous increase in prompt DD-fusion product losses relative to the MHD-free case, by up to 25% (fig. 2d). The additional losses scale linearly with mode amplitude, which would be consistent with a model proposed by Poli *et al* [5] to explain 3/2 NTM induced fast ion losses on ASDEX-U in terms of a spatial rather than a temporal resonance condition. Another clear hint pointing towards a resonance mechanism is the observation that, in the presence of several tearing modes with $n \geq 2$, losses may not always correlate with the highest amplitude mode (usually the $n = 2$) but often correlate better with the smaller (higher n) modes.

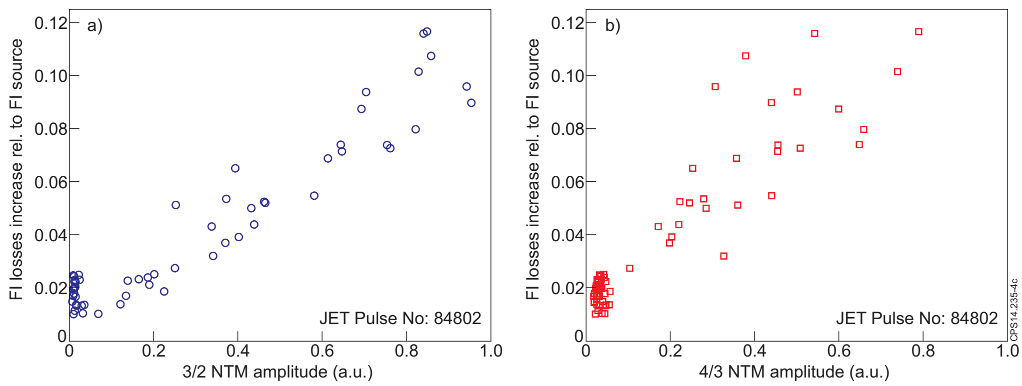

Figure 4: Additional triton losses vs NTM amplitude for a pulse with destabilised 4/3 and 3/2 modes, showing linear dependence. The amplitude evolution has been obtained through time-windowed Fourier tracking.

Notably, neither 2/1 NTMs nor the 1/1 continuous mode were observed to trigger additional fast ion losses despite their much larger mode amplitudes. This might seem to be in contradiction with the 2/1 NTM-induced losses observations on DIII-D [6] and ASDEX-U [7–9]. However, those were neutral beam ion losses, which, as noted above, our instrumentation doesn't measure at present.

For completeness, we also mention that Alfven Eigenmodes were only encountered briefly during the very early heating phase in these discharges (with low frequency, $f \sim 60 - 100$ kHz) and caused no measurable additional fast ion losses.

Triton burn-up fractions Due to its localised nature, the scintillator probe only samples a subset of the lost fast ion population. To assess whether the observed additional fast ion losses constitute a significant fraction on a global scale, the triton burnup fraction -defined as the ratio of 14.1 MeV n yield to the measured 2.5 MeV n source- was determined for a subset of 41 pulses with comparable plasma current (2.0-2.1 MA). For Z=1 plasmas with no additional losses, the burn-up fraction is expected to depend primarily only upon central electron temperature (electron drag) [10]. Premature loss of tritons e.g. due to MHD should lead to a reduced triton burnup. As shown in fig. 5, even for the discharges with largest additional losses the triton burnup fraction is not seen to depart from the MHD-free cases, which is also consistent with earlier results on TFTR [11]. Hence, the measured MHD-induced losses should overall represent a very small fraction of the total fusion product population and hence are not anticipated to have a lasting noticeable impact on the alpha heating efficiency on JET.

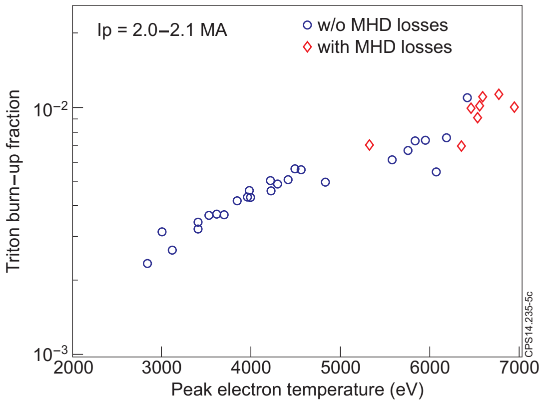

Figure 5: Shot-integrated triton burnup fraction vs central Te. Discharges with MHD-induced losses show no visible reduction in burn-up.

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