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# Recent Progress in Fast-Ion Physics on JET

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# Recent Progress in Fast-Ion Physics on JET

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## ABSTRACT.

This paper presents recent results on fast-ion studies on JET. A set of diagnostics for both confined and lost fast ions was employed for investigating the response of fast ions to MHD modes and for studying their behaviour in plasmas with toroidal field ripple and in shear-reversed plasmas. A dependence of the losses on MHD mode amplitude was deduced from the experimental data. A study of various plasma scenarios has shown that a significant redistribution of the fast ions happens during changes in the profile of the safety factor from shear-reversed to monotonic. Significant changes in the losses of ICRH accelerated protons were found to be associated with L-H confinement transitions in plasmas. After an L-H transition, an abrupt decrease in the ICRH proton losses was observed. In plasmas with an internal transport barrier, the loss of ICRH-accelerated ions was found to increase as the barrier forms. Further results concerning fast ion losses were obtained during JET experiments in which the magnitude of the TF ripple was varied. The ripple losses of fusion products appear similar to classical losses, and are in agreement with modelling.

## 1. INTRODUCTION

Future burning plasma devices such as ITER can only tolerate very low levels of fast ion classical and anomalous losses [1]. Even a re-distribution of fast ions is of serious concern for its effect upon the plasma heating profile. In the ITER burning plasma there will be several different groups of fast ions:  $\alpha$ -particles and other fusion products, deuterium NBI in the MeV range and ICRH-accelerated ions. It is therefore important to measure and separate the temporal and spatial evolution of these quite different fast ion populations. JET is exceptionally well equipped now for studying fast ion confinement and losses since it is capable of simultaneously measuring different species of confined fast ions using the  $\gamma$ -ray diagnostics [2, 3], and has recently been equipped with new lost ion diagnostics: a thin foil Faraday Cup (FC) array and a Scintillator Probe (SP) [4, 5].

Gamma-rays are emitted in JET plasmas due to nuclear reactions between fast ions and thermal plasma and Be and C impurities. The  $\gamma$ -ray energy spectra uniquely identify the presence of a particular type of fast ions, and such spectra are measured on JET with three independent devices [2], one with a quasi-tangential, and two with vertical lines of sight, through the plasma centre. The  $\gamma$ -ray spectra are continuously recorded during all JET discharges over the energy range 1-28MeV using modern Data Acquisition system (DAQ) based on transient recorder [6]. This DAQ allows avoidance of the pile-up effect and gain instability, which lead to a distortion of  $\gamma$ -ray spectra at high-count rates (up to 1 MHz) with fast rate variations.

For identification of the fast ions, which exist in the plasma and produce the observed  $\gamma$ -ray emission, and in order to assess the effective tail temperatures of these fast ions, the  $\gamma$ -ray spectrum modelling code, GAMMOD [2] is used. In addition the GAMMOD analysis gives the fast ion density and the contribution to the neutron yield from the fast particle-induced reactions.

Spatial profiles of the  $\gamma$ -ray emission in the energy range  $E_\gamma > 1$  MeV are tomographically reconstructed on JET by using the  $\gamma$ -cameras, which have ten horizontal and nine vertical collimated

lines of sight [3]. The data acquisition system accommodates the line-integrated  $\gamma$ -ray count-rate measurements in up to 4 independently adjustable energy windows with time resolution less than 100ms depending on the count-rates. Each window is set to correspond to the  $\gamma$ -ray peak(s) from a given fast ion population, thus up to four different groups of fast ions giving rise  $\gamma$ -rays of different energies are simultaneously measured with the  $\gamma$ -cameras providing 2D images of these ions [3]. In addition to the diagnostics of confined fast ions, the newly installed Faraday Cup array [4] detects lost fast ions at multiple poloidal locations. The array consists of nine detectors spread over five poloidal locations below the mid-plane just outside the plasma at low magnetic field side of the torus. Along the major radius, the detectors are equally spaced in three locations. A detection of the temporal evolution of the fast ion current signals in the radially and poloidally distributed detectors provides a map of lost particle fluxes at different locations with time resolution of about 1ms.

Another newly installed lost ion diagnostic detector, the Scintillator Probe (SP) [5] allows the detection of lost ions at a single position outside the plasma, and provides information on the lost ion pitch angle between  $35^\circ$  and  $85^\circ$  (5% resolution) and its gyro-radius between 30 and 140mm (15% resolution) with a time resolution of 10ms. The scintillator probe is located just below the mid-plane of the torus. The underlying principle of scintillator measurements is the emission of light by a scintillating material after a fast ion strikes this material. Selection criteria for the particles that hit the scintillator are introduced by using a collimator matched to the equilibrium magnetic field of JET. An optical arrangement within the scintillator probe is used to transfer the light emitted by the scintillator towards a charge-coupled device CCD camera and a photomultiplier array through a coherent fibre bundle.

## 2. MEASUREMENTS OF SPATIAL REDISTRIBUTION OF CONFINED FAST IONS IN D- $^3\text{He}$ FUSION PLASMAS

In order to detect spatial re-distribution of confined fast ions due to equilibrium changes and due to excitation of MHD modes, such as fishbones, Toroidal Alfvén Eigenmodes (TAEs) and Alfvén Cascades (ACs) by ICRH accelerated fast ions, time-resolved measurements of  $^3\text{He}$ -minority ions were performed using the  $\gamma$ -ray diagnostics. Previously reported studies on JET [7] have demonstrated that ICRH acceleration of  $^3\text{He}$  minority ions in deuterium plasmas provides a significant rate of D- $^3\text{He}$  fusion. Hence this scenario may be used for investigating highly energetic 3.6MeV alpha-particles and 15MeV protons born in these fusion reactions, without activating the machine as in deuterium-tritium plasma experiments. Nuclear reactions with the main impurities,  $^{12}\text{C}(^3\text{He},p\gamma)^{14}\text{N}$ ,  $^9\text{Be}(^3\text{He},n\gamma)^{11}\text{C}$ ,  $^9\text{Be}(^3\text{He},p\gamma)^{11}\text{B}$  gave rise to intense  $\gamma$ -ray emission, which may be used for the fast  $^3\text{He}$ -ion studies ( $E_{^3\text{He}} > 0.9\text{MeV}$ ). Gamma-ray spectra show that the energetic  $^3\text{He}$ -tail with an effective temperature 200-450keV was driven by ICRF heating in these discharges.

First, it was found that a significant change in the spatial profile of the gamma-rays from the fast  $^3\text{He}$  ions occurs when the profile of the safety factor ( $q$ ) changes from strongly shear-reversed to monotonic. Figure 1 shows two  $\gamma$ -ray emission profiles in the mid-plane, obtained during  $^3\text{He}$ -

minority heating in the same JET discharge, in which a monotonic  $q$ -profile was evolving into a shear-reversed  $q$ -profile so that Alfvén cascades were observed [8]. Gamma-ray images of energetic  $^3\text{He}$ -ions were recorded with 2-D  $\gamma$ -ray cameras. The figure demonstrates that the MeV  $^3\text{He}$ -ion profile in the non-monotonic phase of the discharge is  $\sim 25\%$  broader than the profile in the monotonic phase due to the change of the orbit topology.

Second, evidence of MeV range  $^3\text{He}$ -ion redistribution during sawtooth crashes has been also obtained with the 2-D  $\gamma$ -ray camera. The upper two figures in Fig.2 show the tomographic reconstructions of the  $\gamma$ -ray emission produced by  $^3\text{He}$ -ions in  $^{12}\text{C}+^3\text{He}$ ,  $^9\text{Be}+^3\text{He}$  nuclear reactions. The left profile was recorded during a fishbone preceding a sawtooth crash; the right one was after the sawtooth crash (see magnetic spectrogram in Fig.2, bottom).

### 3. FAST ION LOSSES INDUCED BY TOROIDAL ALFVÈN EIGENMODES AND ALFVÈN CASCADES

The measured 17MeV  $\gamma$ -rays of the  $\text{D}(^3\text{He},\gamma)^5\text{Li}$  reaction indicate the rate of the  $\text{D}(^3\text{He},\text{p})^4\text{He}$  fusion reaction, which produces  $\alpha$ -particles at 3.6MeV and protons at 15MeV and in most of the discharges this rate was rather high. During these discharges, the fast-ion loss scintillator probe shows that the fusion  $\alpha$ -particles more intensively escape from the plasma during Alfvén cascade and tornado mode activity [9]. It is expected that losses of 15MeV fusion protons, having Larmor radii outside the SP measurement range of 140mm, take place as well. There are two possible reasons for the observed effect of the loss dependence on the Alfvénic activity. First, ICRH-accelerated  $^3\text{He}$  ions with tail temperature of few hundred keV, which are the source for  $\text{D}(^3\text{He},\text{p})^4\text{He}$  fusion reaction, may be so strongly re-distributed by a resonant interaction with the Alfvénic modes, that the re-distribution of  $^3\text{He}$  affects the profiles of  $\alpha$ -particles born in  $\text{D}(^3\text{He},\text{p})^4\text{He}$  fusion reactions. Second, the perturbed magnetic field associated with the Alfvénic modes, may directly affect the fusion-born  $\alpha$ -particles in the region of the phase-space close to the boundary between confined and unconfined particles.

Dedicated discharges with  $^3\text{He}$  ICRF minority heating (no NBI) in deuterium plasmas were examined in detail to study the influence of TAEs and Alfvén Cascades ACs on fast ion losses [10]. In the MHD-free reference discharges two main types of losses were observed on the scintillator plate – denoted here as type **A** and type **B** (Fig.3a). From the orbit reconstructions (Fig.3b) it is found that the detected type **A** losses correspond to trapped particles whose banana tips are close to the ICRH resonance layer at an intermediate minor radii. It is also found that the temporal evolution of the light emission for the type **A** losses follows the 17 MeV  $\gamma$ -ray emission ( $\text{D}-^3\text{He}$  fusion rate indicator) from the  $\gamma$ -ray detectors. From this and the observed range of lost particle energies, which turn out to be consistent with kinematical calculations, the type **A** losses are identified as alpha particles on banana orbits, which are born from  $\text{D}-^3\text{He}$  reactions near the ICRH resonance layer and then lost promptly. The red symbols in Fig.4 show the light yield for type **A** losses for the MHD-free reference discharges. It can be seen that the light yield increases linearly with the achieved

D-<sup>3</sup>He fusion yield. It is noted that the particles responsible for the type **B** losses are born closer to the plasma centre, and that their identity is still under investigation. A likely candidate are protons born from reactions of <sup>3</sup>He with impurities (Be and/or C).

In the presence of TAEs/ACs, a linear scaling of type **A** losses on the D-<sup>3</sup>He fusion yield does not apply (Fig.4, blue symbols). For a given D-<sup>3</sup>He fusion yield, the type **A** intensity of the light increases by a factor ranging from 2 to 40. Hence, not only can the factor be very high but it also varies considerably. To quantify the losses on the intensity of Alfvénic perturbations that has been excited, the following method has been applied: a digital band-pass filter is applied to a signal from a magnetic pick-up coil through a time-windowed FFT and selection of the desired frequencies (in this case 100-255kHz). Before back-transforming, the amplitude at each frequency  $\omega$  is divided by  $\omega$  to account for the increasing sensitivity of pick-up coils with frequency. Finally, the resulting envelope for that signal is integrated over the relevant time-interval. Figure 5 shows the same loss data as in Fig.4, plotted against the obtained MHD amplitude. This yields the important conclusion that the MHD-induced  $\alpha$ -losses amplification is directly determined by the MHD amplitude, on which it depends linearly [10]. This linear dependence indicates that the increase of lost particles is most likely to be associated with the effect of Alfvénic perturbations on the boundary between confined and unconfined particles in phase space [11].

#### 4. MHD-INDUCED RESONANT LOSS

Alfvénic instabilities causing resonant fast ion redistribution and losses were found in a sawtoothed H-minority ICRH plasma with a safety factor profile  $q(0)<1$  [9, 12, 13]. The temporal evolution of fast ion losses with resolution on energy and pitch angle was measured using the SP, which allowed the determination of the orbits of fast ions that reached the detector. The fast ions in resonance with the different instabilities present in the plasma were identified using the CASTOR-K code [14]. It was then possible to identify which instabilities were responsible for the losses collected in the detector. Two different phases of losses, with different characteristics, were identified. The first phase occurs after a sawtooth crash (Fig.6, upper), when TAE and high frequency fishbones are unstable. In this phase, TAE are responsible for most of the measured losses. Losses caused by precessional drift fishbones, if any, are not significant. The second phase initiates when the core-localized TAE modes, so-called “tornado modes” [9] become unstable: the intensity of losses increases by a factor from 2 to 5, the average energy of the ions that reach the detector decreases and its pitch angle increases (Fig.6, lower). In this phase, the losses are mostly triggered by resonant interaction with the tornado modes. When fast ions interact with tornado modes, they are transported from the plasma core to a more peripheral region of the plasma while their orbits suffer a topological transition from potato to banana orbits. In this region, tornado and TAE eigenfunctions overlap and the fast ions will start interacting with TAE, which have around the same frequency and same toroidal  $n$  number as tornado modes. TAE will eventually end up by expelling these fast ions from the plasma [12, 13].



## 5. FAST-ION LOSS IN SAWTOOTH CRASH

The dynamics of the fast ion losses was studied in the H-minority ICRH scheme as well. Figure 7 shows the temporal evolution of pitch-angles and gyro-radii of lost ions measured with SP during a sawtooth crash. Gamma-ray spectrometry indicates the presence of fast protons and deuterons accelerated with 2<sup>nd</sup> harmonic ICRH in this discharge. It is seen that before the crash, losses of ions with very large Larmor radii, >12cm, and in a narrow pitch-angle, are dominant. These lost ions are identified as ICRH-accelerated protons. During the crash, the majority of the lost ions identified as deuterons have a much lower energy and are close to the trapped-passing boundary. After the crash, both types of losses co-exist for some time before a relaxation to the initial pre-crash state is observed. The ICRH minority heating scheme generates particles which can be classified by their pitch angle outside the plasma (e.g. at SP). The HAGIS code [15] 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. 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 [16].

## 6. FAST-ION LOSSES DURING L-H TRANSITION AND ITB FORMATION

A significant change in fast ion losses has been detected during L-H transition in JET plasmas with combined NBI and H-minority ICRF heating. Gamma-ray diagnostics indicated that both fast protons and deuterons accelerated with 2<sup>nd</sup> harmonic ICRF heating are present in the plasmas. Two types of losses were observed on the scintillator plate which was identified as First Orbit (FO) losses of fusion products (Fig.8, blue) and losses of ICRF accelerated ions (Fig.8, red). Significant changes in the losses of ICRH accelerated protons and deuterons happen after the confinement transition (L-H transition) as Figure 8 shows.

Another essential effect of plasma confinement regime on the fast ion losses has been found in the Advanced Tokamak (AT) scenario discharges. In plasmas with an Internal Transport Barrier (ITB), the loss of ICRF accelerated ions increases by an order of magnitude (Fig.9, red) as the barrier forms. During both the L-H transitions and ITB formation ( $t \sim 5$ s), no anomaly in the expected FO loss rate of fusion products (Fig.9, black) is observed (it follows the neutron rate, Fig.9, blue), in contrast to that for the ICRF accelerated ions. The very significant difference between the losses of fusion products (which don't change) and the losses of ICRF accelerated fast ions (which change significantly) remains to be explained. It is likely that the large difference in the fast ion energy between the species mentioned above makes a strong impact on the efficiency of fast ion interaction with turbulence associated with the confinement transitions, such as the experimentally observed magnetic turbulence in the range up to 250kHz on JET [17].

## 7. FUSION PRODUCT LOSSES IN THE RIPPLE EXPERIMENTS

In JET, which has a set of 32 coils, the Toroidal magnetic Field (TF) ripple is rather small,  $\delta \approx 0.08\%$  at the separatrix. However, JET TF can be configured to run different currents in odd & even numbered coils, to increase TF ripple at the plasma boundary up to  $\delta \approx 3.0\%$  to give a much closer representation of ITER ripple. Here, results of observations of the fusion products (p, T) losses induced by an N=16 TF ripple harmonic are presented. In a series of experiments [18], the TF ripple was varied from the standard JET TF ripple, 0.08%, to an intermediate high level of 1.0% at around  $B_T(0) = 2.2$  T.

The fusion product losses were measured with the SP. The ripple effects on fusion product losses in Low (LT) and High Triangularity (HT) H-mode plasmas were observed. There is evidence of MeV-ion redistribution due to the ripple. Modelling of 3MeV fusion reaction protons has been done with a guiding centre following Monte Carlo code ASCOT [19]. Protons have been sampled from an experimentally reconstructed 2-D fusion reactivity distribution and followed in an EFIT magnetic equilibrium together with toroidal magnetic field ripple and collisions. Collected guiding centre distribution has been corrected with the device transmission function to get the final SP response. A comparison of pitch-angle loss profiles for the 3MeV fusion protons measured in the HT H-mode discharges with normal and 1% TF ripples are presented in Fig.10 (upper). The modelling results placed below are qualitatively consistent with the experimental data that demonstrate a ripple effect on the fusion product first orbit losses. In the modelling it was observed that the extra protons measured by SP at high pitch angles in the case of 1% ripple operation were due to collisionless stochastic ripple banana diffusion pushing the protons born with low parallel velocity in the strong ripple region into the loss cone. Note, however, that the modelled pitch-angle distribution of ripple losses is quantitatively different from the measured one.

A similar loss effect was observed in discharges with Advanced Tokamak heating scenario (AT). Differences in the heating scheme, 4 MW of ICRH power at the hydrogen fundamental frequency on top of 8MW NBI, leads to generation of fast H- and D-ions (parasitic absorption of ICRH power by D-beam ions) in addition to the DD-fusion products (protons, tritons and  $^3\text{He}$ ). The existence of the RF-accelerated ions was confirmed by  $\gamma$ -ray spectrometry. The  $\gamma$ -ray lines from  $^{12}\text{C}(d,p\gamma)^{13}\text{C}$  and  $^{12}\text{C}(p,p'\gamma)^{12}\text{C}$  reactions [2] were found in spectra. Figure 11 shows the SP light emission recorded with CCD camera in two AT discharges. The left figure demonstrate the footprint of lost ions in the discharge with normal JET TF ripple, 0.08%. The right figure related to the discharge with 1%-ripple. Both images have the similar spots, **A** and **B**, which can be identified as ICRF-accelerated ion and fusion product losses, correspondently. The average energy of ICRF-accelerated ions is about of 1.7MeV for H-ions and 0.9 MeV for D-ions. Prompt losses of fusion products, tritons (1MeV) and protons (3 MeV), look like as in the H-mode discharges analysed above. In the discharge with 1% ripple (Fig.11, right), one could find an additional spot (**C**), which lies in the  $70^\circ - 75^\circ$  pitch-angle area. The time-trace for this spot is similar to the spot **B** trace and neutron rate. Hence, one can conclude that this is a footprint of the fusion product losses due to the collisionless stochastic ripple banana diffusion. The spot **A** trace is rather different from the spots **B** and **C** during these

shots. It reflects the ITB creation with sharp increasing of losses in the passing-trapped loss cone around of  $55^\circ$  as it was discussed in the section 6.

## SUMMARY

Recent JET results on fast-ion studies with a set of both confined and lost ion diagnostics show that the key phenomena, such as the loss dependence on plasma equilibrium, ripples and MHD modes, are in a broad agreement with the expectations. In particular, a linear dependence of the losses on the MHD mode amplitude has been observed in the experiments as well as a significant redistribution of the fast ions was detected during the change in the  $q$ -profile. In the ripple experiments, losses of the fusion products were determined to be in qualitative agreement with classical loss mechanisms. These expected phenomena in the loss evolution were accompanied by a surprising finding that the intensity of the losses changes after confinement transitions (L-H transition, ITB) in thermal plasmas.

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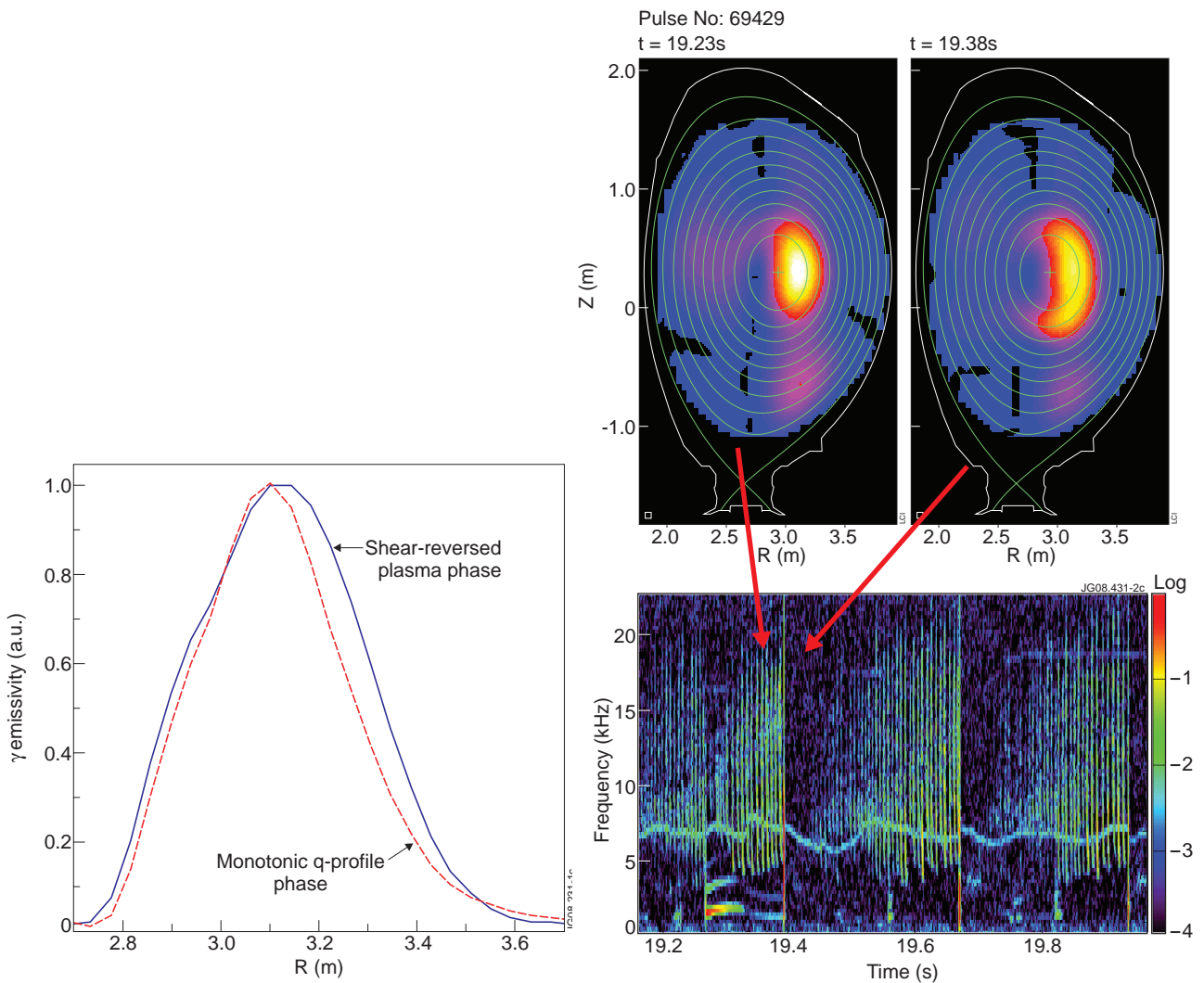


Figure 1: Mid-plane profiles of  $\gamma$ -ray emissivity obtained by tomographic reconstruction of the 2D  $\gamma$ -camera data of the  $^3\text{He}$ -minority ICRH Pulse No: 69436 ( $I_p=2.3\text{MA}$ ,  $B_T=3.1\text{T}$ ): blue - shear-reversed plasma phase,  $t=5.25\text{s}$ ; red - monotonic  $q$ -profile phase,  $t=6.75\text{s}$ .

Figure 2: Tomographic reconstructions of  $\gamma$ -ray emission profiles obtained with the 2D  $\gamma$ -camera [3] in the  $^3\text{He}$ -minority ICRH Pulse No: 69429 ( $I_p=3\text{MA}$ ,  $B_T=3.1\text{T}$ ): left - before a sawtooth crash; right - after the crash; bottom - magnetic spectrogram.

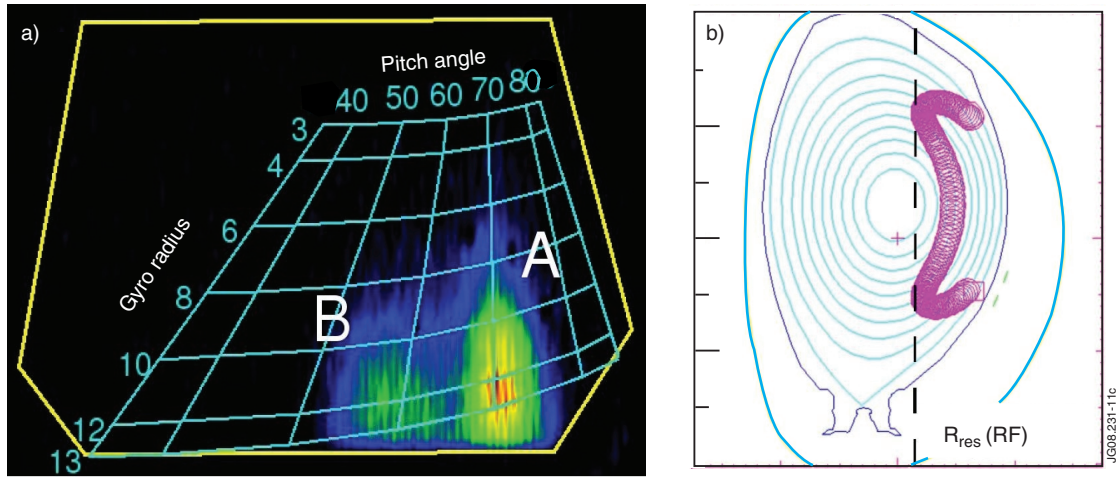


Figure 3: a) Loss spots observed on the scintillator plate;  
 b) ORBIT code reconstructions for detected losses of type A (see text).

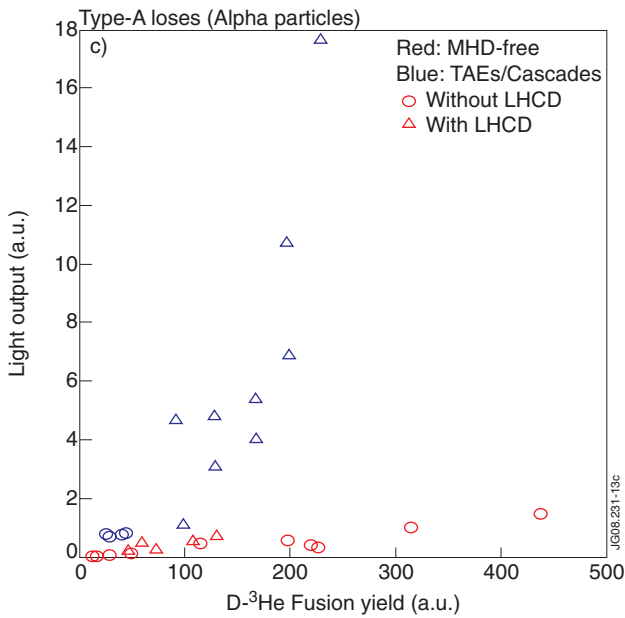


Figure 4: Light output on the scintillator plate for losses of type A (the light emission is integrated over the relevant spot area of the CCD chip for each time frame, and then time-integrated) versus D-<sup>3</sup>He fusion yield (from BGO  $\gamma$ -ray detector).

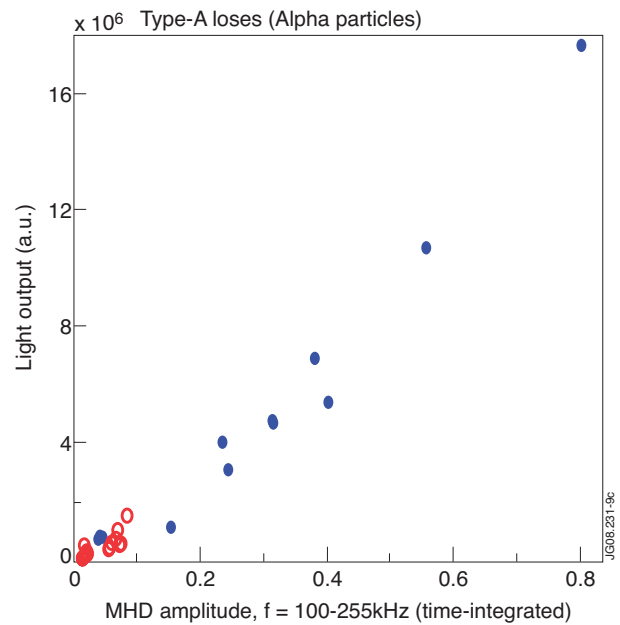


Figure 5: Same loss data as in Fig.4, but plotted against the amplitude of the Alfvénic MHD.

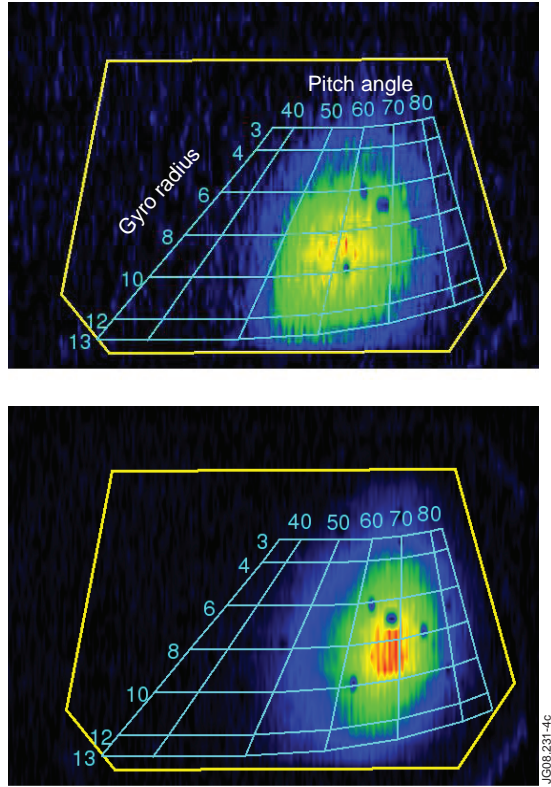


Figure 6: JET Pulse No:66380,  $I_p=2.5MA$ ,  $B_T=2.7T$  Footprints of fast protons lost at the SP during periods when: TAE and precessional fishbones are unstable (upper); tornado and TAE modes are unstable (bottom).

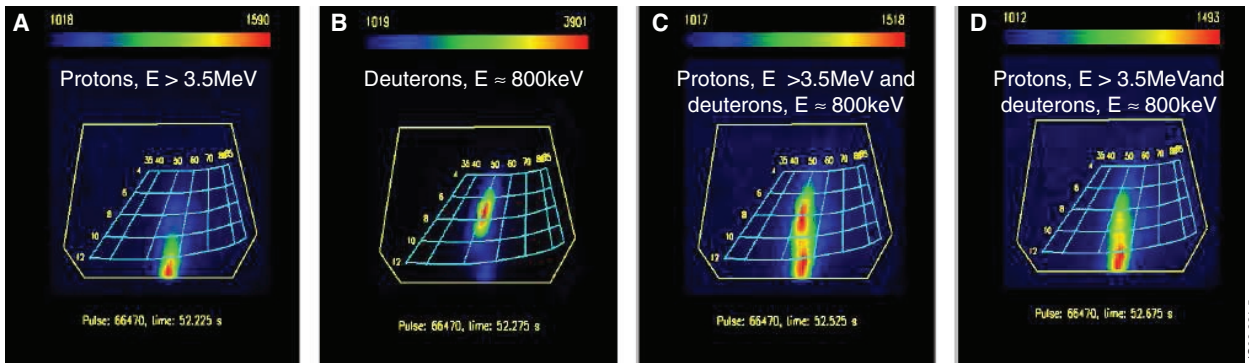
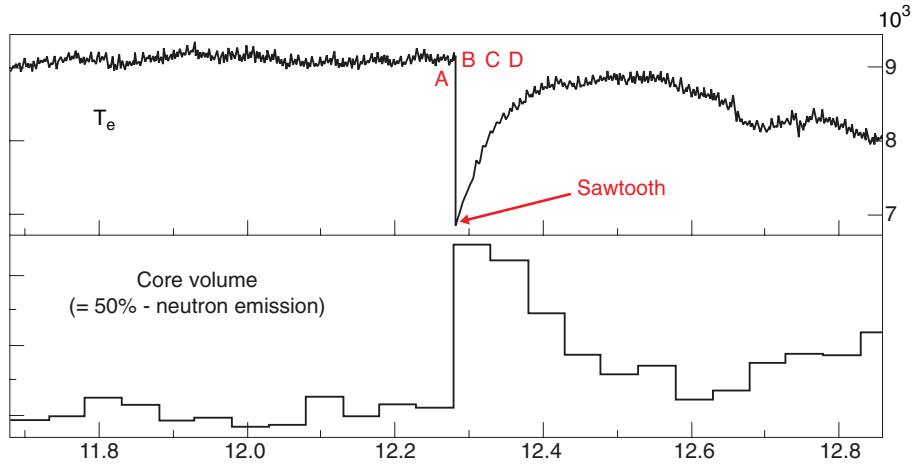


Figure 7: JET Pulse No: 66470,  $I_p=2.5MA$ ,  $B_T=3T$ . Top: central electron temperature vs. time; middle: plasma core volume changes during the sawtooth crash period; bottom: footprints of fast protons/ deuterons lost in SP during sawtooth periods A(12.225s), B(12.275s), C(12.575s) and D(12.675s).

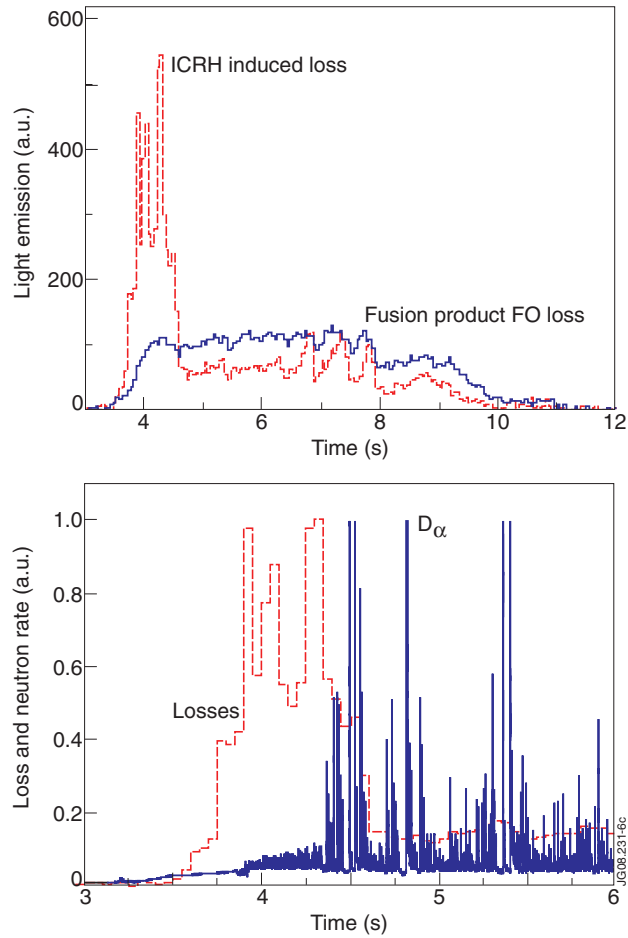


Figure 8: H-mode discharge: top - time traces of light emission at SP, related to ICRF-induced and FO fusion-product losses; bottom - ICRF-induced losses and  $D_{\alpha}$ -emission.

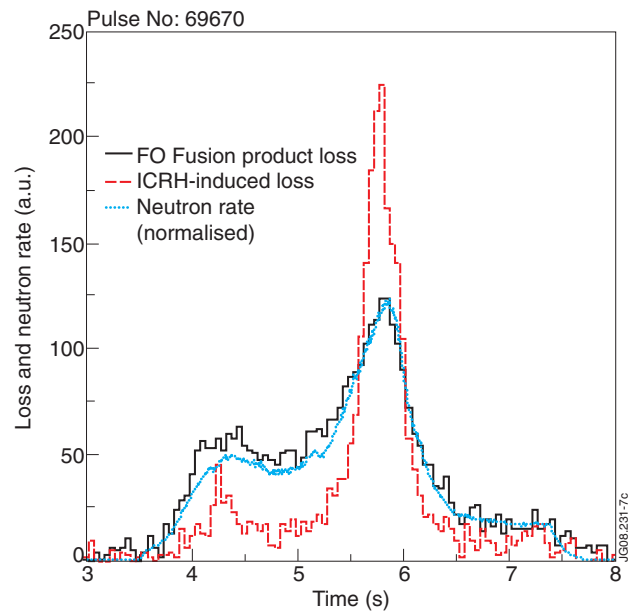


Figure 9: Time traces of light emission at SP, related to ICRF-induced and FO fusion-product losses and neutron rate in the discharge with ITB

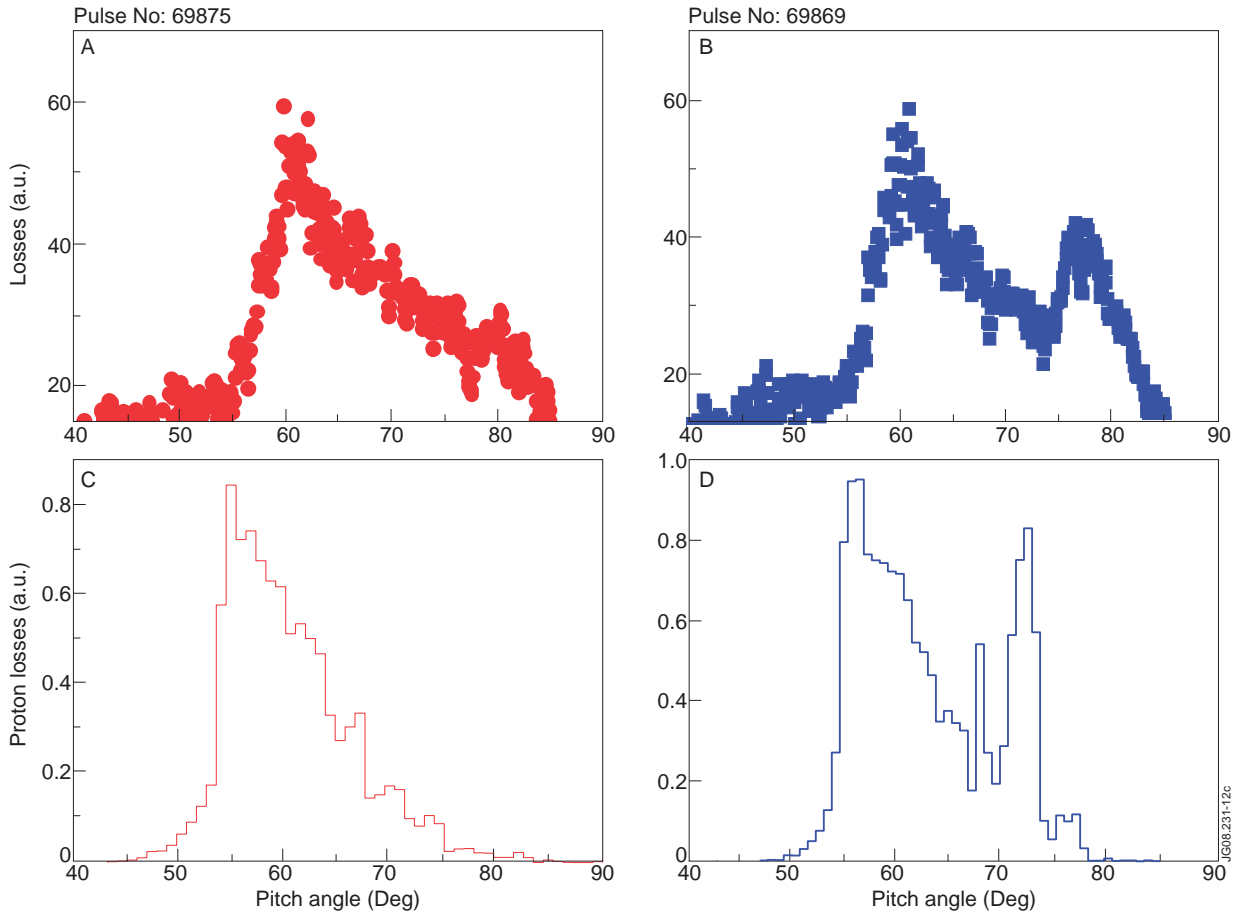


Figure 10: Top: pitch-angle distributions of fusion product losses relevant to 13cm gyro-radius, detected by SP during high triangularity H-mode plasmas, and related to: **left** – discharge with a normal TF ripple, 0.08%; **right** – discharge with 1% ripple. Bottom: **left** and **right** – results of the ASCOT modelling for the cases 0.08% (JET Pulse No: 69875) and 1%, (JET Pulse No: 69869) respectively.

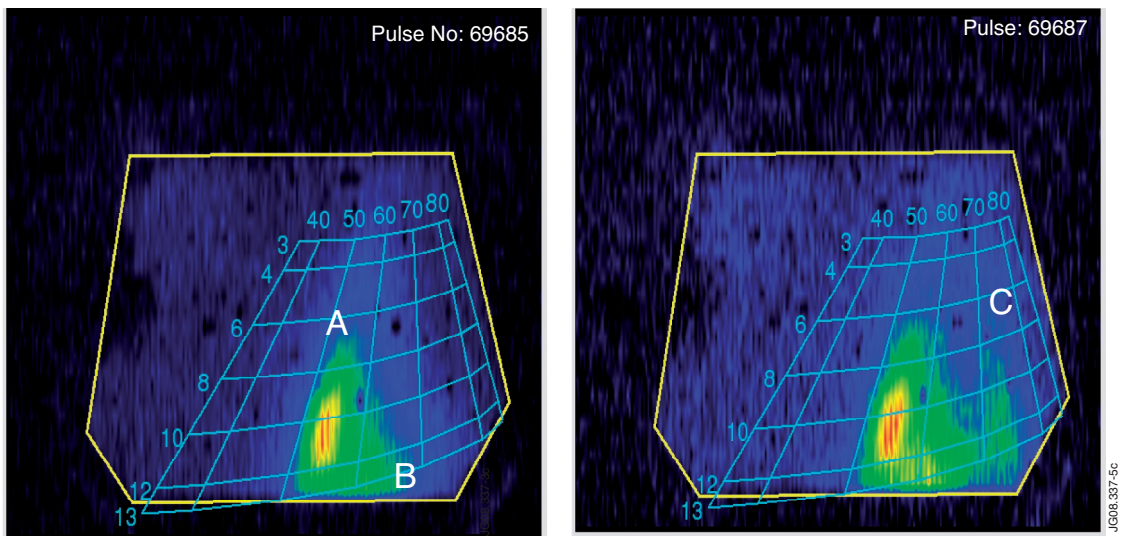


Figure 11: Footprints of fast ion lost on the SP in the AT scenario discharges,  $I_p=1.9MA$ ,  $B_T=2.2T$ : left – normal JET TF ripple (0.08%); right – 1% TF ripple. Spots **A**, **D** and **C** are related to different groups of the detected fast ions.