Studies of MHD Effects on Fast Ions: towards Burning Plasma with ITER-like Wall on JET

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Abstract. This work is carried out as continuation of fast ion research on JET due to its significance for the future JET operation with ITER-like Be wall and ITER. Fast ion studies on JET aiming at assessing the peak values of fast-ion losses caused by plasma disruptions, TAE, and NTM are performed. Gamma-ray diagnostics, NPA, neutron spectrometry, Faraday Cups and Scintillator Probe were used for simultaneous measurements of various species of confined and lost fast ions in the MeV energy range. The fast ion populations were generated in fusion reactions and were also produced by NBI and by accelerating with ICRH. Significant fast ion losses preceding disruptions were often detected by Scintillator Probe in discharges with high β_N. It was found that the losses are caused by the m=2/n=1 kink mode and these losses typically occur at the same time as the thermal quench before the current quench that follows. A set of experiments were carried out where interactions of core-localised TAE modes with fast ions in the MeV energy range were studied in plasmas with monster sawteeth. Energy and pitch angle resolved SP measurements of MeV-ions ejected from the plasma due to fishbone oscillations driven by NBI-ions are also studied. Experiments using RMP ELM control have exhibited a strong effect of EFCC on NTM and on NTM-induced losses of NBI ions.

1. Introduction

Fast ion studies on JET aiming at assessing the peak values of fast-ion losses caused by plasma disruptions, TAE, and NTM are performed. This work is carried out as continuation of fast ion research on JET [1] due to its significance for the future JET operation with ITER-like beryllium wall. Study of the MHD induced peak losses of fast ions play a crucial role for the plasma facing components (PFC) selection for DEMO.

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Gamma-ray diagnostics [2,3], neutral particle analyser (NPA) [4], neutron spectrometry (NS) [5], Faraday Cups (FC) [6] and Scintillator Probe (SP) [7] were used for simultaneous measurements of various species of confined and lost fast ions in the MeV energy range in D, D-^{3}He, and D-^{4}He plasmas. The high time resolution of diagnostics allowed studying both resonant and non-resonant MHD effects on redistribution and losses of energetic ions. The fast ion populations were generated in fusion reactions D+D→p(3MeV)+T(1MeV), D+^{3}He→α(3.7MeV)+p(15MeV), and were also produced by NBI and by accelerating minority- or NBI-ions with ICRH.

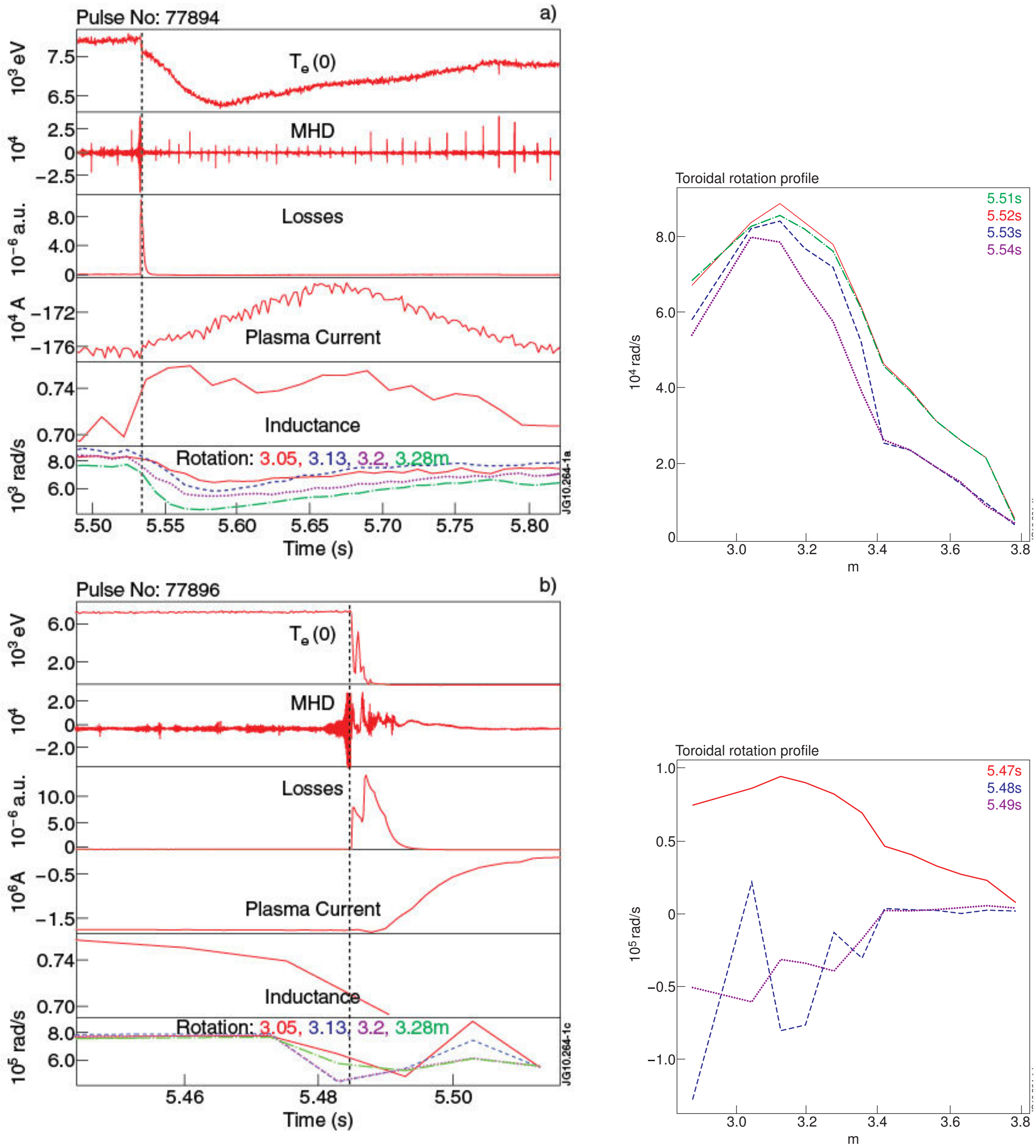

FIG. 1. Time-traces of plasma parameters, SP losses and toroidal rotation profiles measured in 2.7T/1.8MA discharges #77894 (a) and #77896 (b).

2. Fast ion losses and disruptions

Significant fast ion bursting losses preceding plasma crash or disruption were detected by SP in AT plasma discharges with high β_N and q(0)>1.5 [8]. MHD modes m=2/n=1 and m=3/n=2 were dominantly limiting plasma performance in these experiments. A most significant impact on the plasma was in the case of the m=2/n=1 modes with high amplitudes. Figure 1 shows time traces of electron temperature, the n=1 MHD signal, internal plasma inductance, plasma current, toroidal rotation and fast ion losses measured with SP for two discharges #77894 and #77896 with a weak ITB.

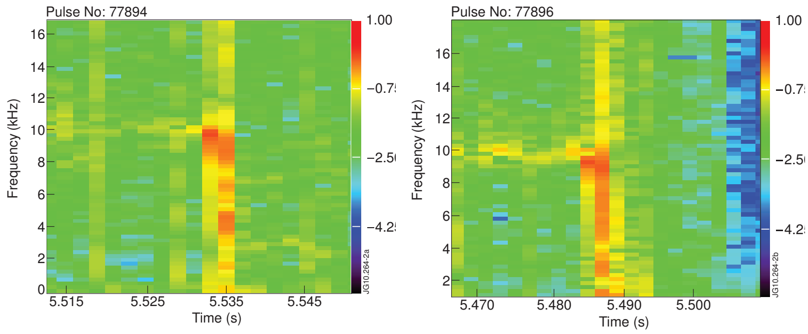

FIG.2. Magnetic spectrograms showing m=2/n=1 mode in #77894 and #77896.

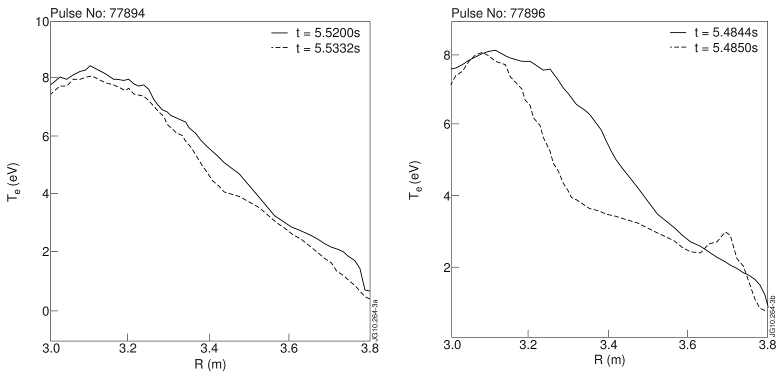

FIG. 3. Electron temperature profiles before (red line) and after the crash event (blue) in #77894 and #77896.

In this discharges rather similar MHD activities (magnetic spectrograms shown on Fig.2.) are leading to the different consequences. In the first discharge (#77984), one can see a fast drop of T_e. In the second one this MHD instability initiates a thermal quench with following disruption.

A theory of fast ion redistribution due to m=2/n=1 kink-mode instability has been developed in Ref.9, where the interaction mechanism of energetic trapped ions with the pressure driven MHD instability very similar to that shown in Fig.1 was studied. It was found that due to the mode, an internal magnetic reconnection takes place and a large size magnetic perturbation forms. The main indicator of the reconnection is an abrupt change of the internal inductance. In the case of discharge with disruption (#77896) the internal inductance and plasma rotation are dropping down similarly to [9] just before the thermal quench; in the discharge #77894 the plasma rotation also decreases though the inductance jump was observed. One notes that in the discharge #77894 the plasma rotation was significantly decreased at the R=3.4m during the crash (t_{cr}=5.533s), while the central plasma rotation drop was observed in the case on #77896 (t_{cr}=5.485s). Figure 3 demonstrates how the electron temperature profile reacts on the MHD events in these shots. Location of the mode at the q=2 is seen from the changes in the electron temperature profiles.

The magnetic reconnection may affect energetic trapped ions and direct evidence of that are losses observed with SP shown on Fig.4. Although the saturation of the MHD signal in Fig.1 prevents the investigation of the loss intensity as function of the mode amplitude, the temporal evolution of the losses detected by SP shows a significant change in the regions of the phase space, where energetic ions are lost from. Indeed, in both cases ions from the area which is close

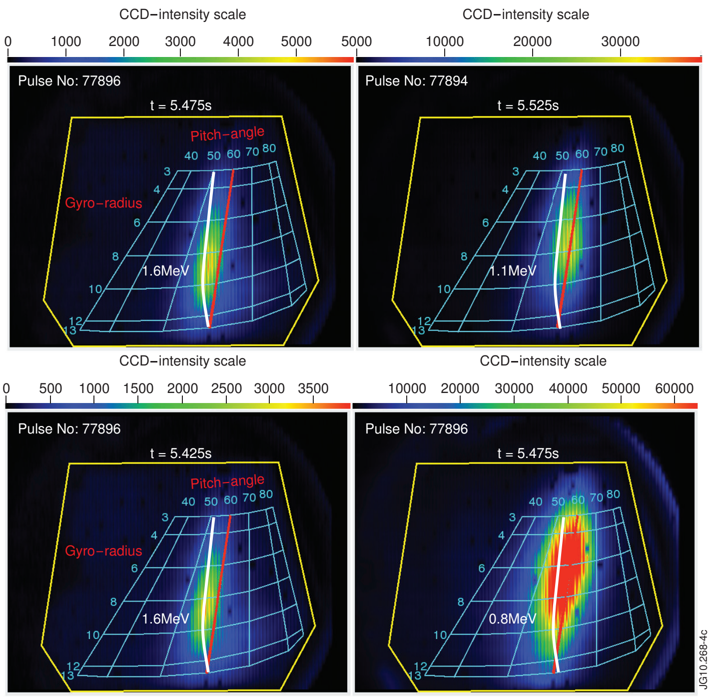

FIG. 4. Footprints of losses detected with SP probe; red line – pitch-angle of the ICRH resonant ions; white line – the trapped-passing boundary on the SP grid.

to the trapped-passing boundary (white line) are continuously lost before the crashes. During the crash, the trapped ions accelerated by ICRH are affected as the pitch-angle of the maximum loss is on the red line which is related to ICRF resonance position on the SP grid. The ion loss increases due to the high density of trapped ions near the resonance in the phase-space.

One can see from Fig.1 that the losses caused by the m=2/n=1 kink mode occur at the same time as the thermal quench i.e. about 5-30 ms before the current quench. Also, bursts of metal impurities influx following the losses were observed [10].

3. Fast ion interaction with tornado modes

A set of experiments were carried out where interactions of core-localised TAE modes [11,12], so-called 'tornado' modes localised inside the q=1 magnetic surface, with fast D-ions in the MeV energy range were studied in plasmas with monster sawteeth.

The tornado modes were identified as core-localized TAEs within the q = 1 radius [13]. The effect of tornado modes on fast particles has been first detected on JT-60U [11], where a

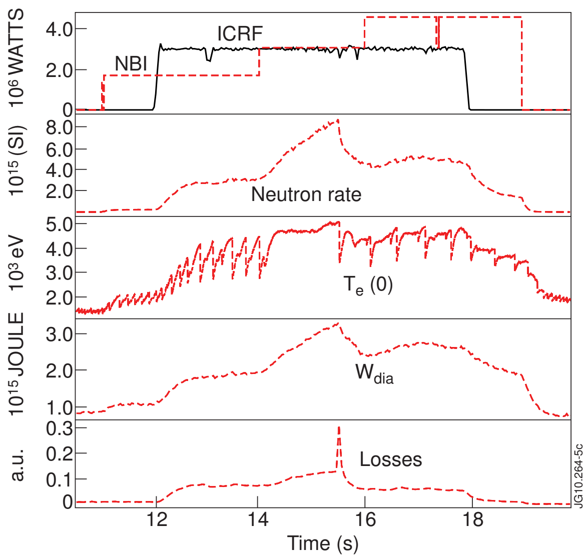

FIG.5. A typical JET D-plasma discharge 2.2T/ 2.2MA with 3rd harmonic ICRH (51MHz) of D beam-ions.

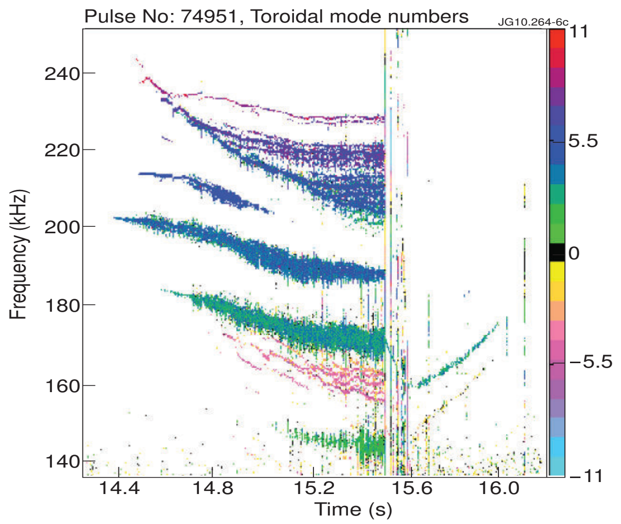

FIG.6. Magnetic spectrogram showing toroidal mode numbers of TAE and tornado modes before monster sawtooth crash in JPN 74951.

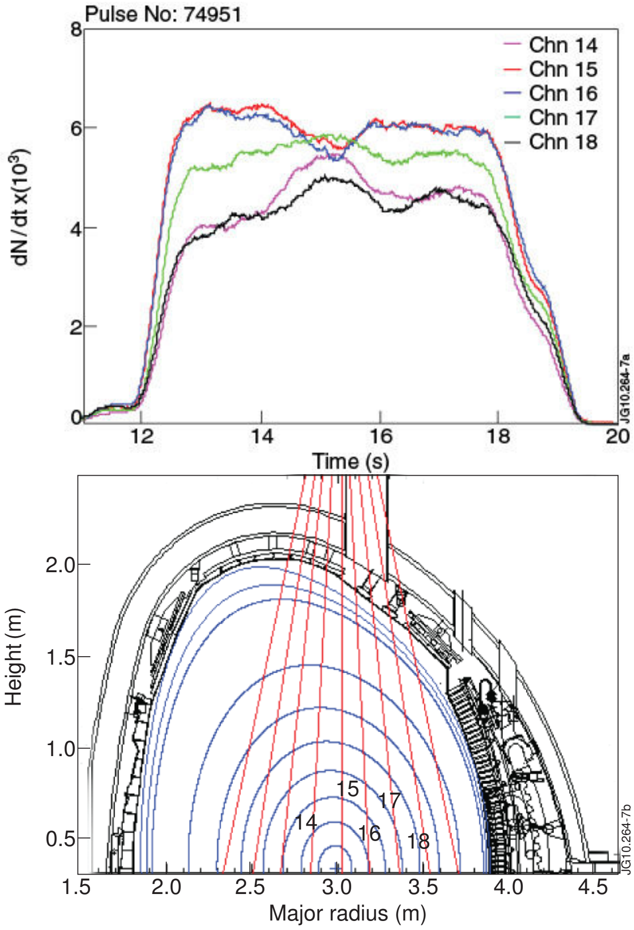

FIG.7. Top – 3.1-MeV γ-ray intensities vs. time recorded by vertical camera; bottom – the vertical camera lines of sight.

significant loss of the fast-ion confinement and degradation of total plasma energy content were observed. Also the TAE and tornado mode activities affecting fast ion power deposition profiles on DIII-D [14, 15] and on TFTR [16] were found. The fast particle redistribution/ losses similar to these observed on JT-60U were found on JET as a significant (by a factor of 2) decrease of γ-ray emission coming from the nuclear reaction $^{12}C(p,p'\gamma)^{12}C$ during the combined activity of tornado (inside the q = 1 radius) and TAE (outside the q = 1 radius) [17,18]. Also core-localized TAE modes were observed to cause significant fast ion redistribution in the plasma core and enhanced losses in AT plasma discharges [19].

Measurements of confined fast particles with 2D γ-ray camera allowed distinguishing the energy ranges of fast D-ions and observing their spatial redistribution during the core-localised TAE activity preceding monster sawtooth crashes. Information on energetic confined ions is provided by γ-ray technique [2,3] routinely used for the fast-ion study in JET [6,7], which is based on measurements of γ-rays due to nuclear reactions between fast ions and the main plasma intrinsic impurities in JET (C, Be). In these experiments the γ-ray emission from the $^{12}C(D,p\gamma)^{13}C$ reaction was observed. A peak at 3.1 MeV (transition 3.1 → 0 in ^{13}C) in γ-ray emission spectra reflects the presence in plasmas of the fast D-ions with energies $E_D>0.5$ MeV.

In the present JET experiments population of the fast particles was obtained during the D-plasma heating with 3rd harmonic ICRF of D beam-ions and ion cyclotron resonance, $\omega\approx3\omega_c(D)$, in the plasma centre. A similar scenario has been used in experiments, where ^4He beam ions were accelerated in ^4He-plasmas [3]. Figure 5 shows wave-forms of a typical plasma discharge with a monster sawtooth. The tornado modes, one sees from Fig.6, showing a spectrogram made with a fast magnetic probe, are presented by many discrete modes. Just before the crash, at t>15.1 sec the following toroidal mode numbers of TAE and bi-directional tornadoes are seen with toroidal mode numbers n = 3, ±4, ±5, 6, 7, 8. The existence of the n=3 mode, the lowest-n mode before the monster sawtooth crash, shows that q (0) at the time of the mode appearance, 15.1 sec, has to be below $q_{TAE}^{n=3} < 0.83$.

In all discharges with tornado modes an extensive re-distribution of fast D-ions in the energy range of 0.8MeV - 1.8MeV was observed with 2-D γ-camera. Indeed, line-integrated emissivities of 3.1-MeV γ-rays depicted on Fig.7 show that intensities of central channels of the vertical camera (#15 and #16) begin slowly decreasing with appearing tornado modes during the monster sawtooth period. At the same time, intensities of the high- and low-field side channels (#14, #17 and #18) are growing up. That means the energetic particles are leaving the plasma centre toward the periphery. Neutron and γ-ray spectrometry had also provided an evidence of the D-ion redistribution [5]. The lines of sight for neutron and γ-spectrometers are relatively narrow and are overlapping with γ-ray camera channels #14, #15 and ch#16. It was found that intensity of DD-neutrons with energy E_n>4.5 MeV produced by ions with E_D>1.3 MeV is decreasing in the period of the tornado mode development. The same tendency has been observed for 3.1-MeV gammas from the $^{12}C(D,p\gamma)^{13}C$ reaction.

One can see that at around t = 15.5 s the observed TAE activity is abruptly terminated by the occurrence of a monster sawtooth crash, which may have been triggered by the loss of fast ion stabilization [14-18]. The change in the equilibrium profiles as a result of the sawtooth crash, most notably the safety factor, q, then modifies the existence criterion for the tornado modes accounting for their abrupt disappearance. The modelling of D-ion orbits has been carries out using HELENA [20] equilibrium and TAE modes obtained with CASTOR code [21].

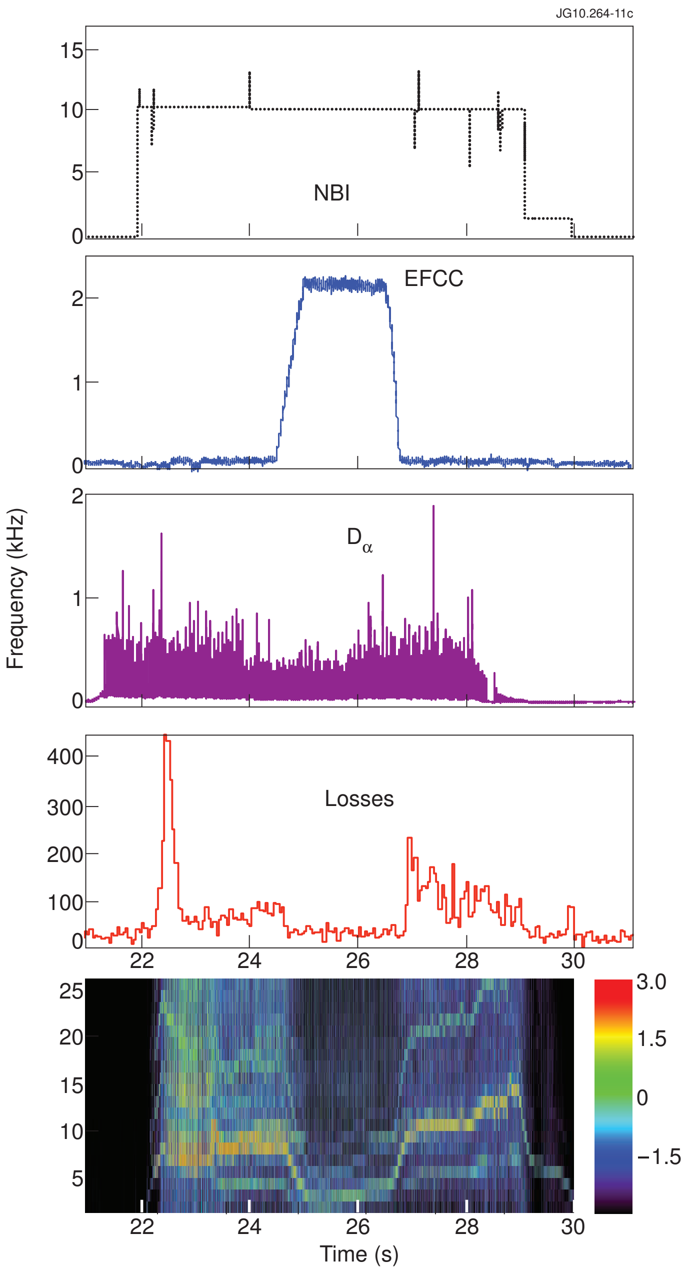

FIG.8. Waveforms and magnetic spectrogram (frequency, kHz vs time) showing 3/2 NTM mode evolution during EFCC (24.5 s– 26.8 s) in the discharge #75797 at B_T =1.0T, I_P=0.8MA and I_{EFCC}=2.2 kA; integral NBI losses (a.u.) were measured with SP.

4. Fishbone effect on fast ion losses

Interaction of fusion-born α-particles with fishbones is one of the important problems for burning plasma in ITER-type machine. Estimates show that fishbones may be driven by resonant interaction with relatively low-energy alphas, $E \cong 400$ keV. For this energy range, any radial transport of the almost thermalised alphas caused by the fishbones, may become beneficial since it helps solving the ash removal problem. However, the problem exists whether the low-frequency fishbone driven by thermalised alphas, may also deteriorate the confinement of alphas at much higher energies. This question was discussed in [22], and it was shown that the loss of toroidal symmetry caused by the n=1 perturbation may affect indeed the highly energetic non-resonant alphas strongly. In order to validate the theory of the non-resonant losses, JET experiments were performed for measuring losses of highly energetic ions in the MeV energy range in the presence of the fishbones driven by NBI ions with energy 80-100 keV. Namely, the energy and pitch angle resolved SP measurements of MeV-ions ejected from the plasma during to the non-resonant fishbone oscillations were studied [23]. The lost ions are identified as fast protons accelerated by ICRH (~0.5-4MeV). Losses arriving at the probe are enhanced by about a factor 10-20 with respect to MHD-quiescent levels, and are found to increase quadratically with the fishbone amplitude. Numerical simulations have been performed which combine the HAGIS, MISHKA and SELFO codes. The losses are found to originate from orbit stochastic diffusion of trapped protons near the plasma boundary or from counter-passing protons deep in the plasma core which transit under the influence of the fishbone into an unconfined trapped orbit. The simulations show that the losses are of non-resonant type indeed confirming the mechanism proposed in [22] for highly energetic α-particles.

5. Losses of NBI-produced ions caused by NTMs of varying amplitude and frequency

JET experiments with error field correction coils (EFCC) used for controlling ELMs have also exhibited a strong effect on NTM. It was found that amplitude of NTMs decreases (sometimes a complete suppression of NTM was observed) during EFCC while the frequency of NTM sweeps down. The decrease in the NTM amplitude and its frequency has a profound effect on NTM induced losses of fast NBI-produced ions measured by SP. An example of the beam-ion loss waveform and magnetic spectrogram showing 3/2 NTM are shown in Fig.8. Analysis of these experiments reveals that the EFCC reduce the gradient of plasma pressure, so that NTM driven by bootstrap current becomes weaker. It is remarkable that a relatively modest decrease in NTM amplitude (e.g. by a factor of three in Fig.8) cause a decrease in the losses by almost an order of magnitude.

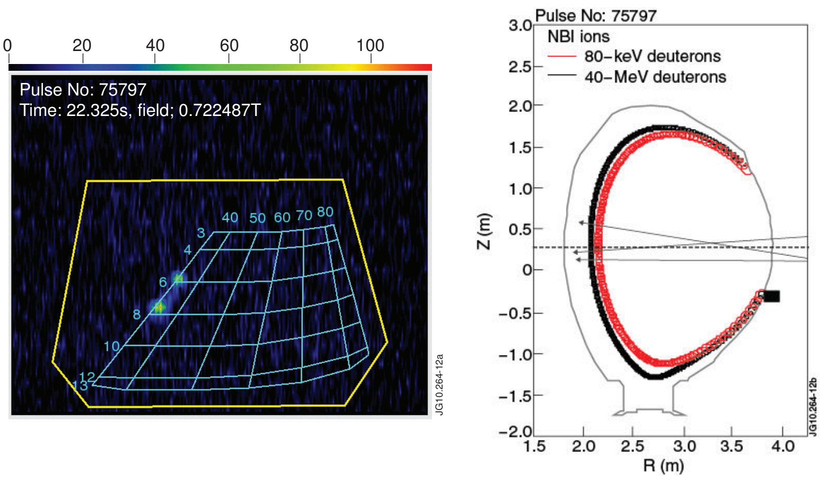

FIG.9. . Footprint of the NBI ion losses; right – orbit of injected D-ions calculated backward in time; arrows show the trajectories of NBI deuterons injected with normal PINI's.

Losses of E=80 keV and E/2 NBI ions were observed during the L-H transition and NTM appearance. It became only possible due to the low toroidal field experiments. The foot print of losses is shown on Fig.9 (left). The calculation of orbits performed backward in time from the two spots on the SP plate is indicated that losses are connected to the normal off-axes NBI ions. These ions are lost on the first orbit since the calculated orbits are terminated on limiters. Similar effects have been observed in all discharges of this experiment.

6. Conclusions

Results of this paper show the significance of MHD effects on fast ion confinement and losses for plasmas aiming at burning scenarios for JET and ITER. Further investigation of such effects has to be performed along several avenues. The losses observed during the m=2/n=1 kink mode, which constitute the highest peak loss mechanism in this paper, require both the MHD and SP re-calibration for measuring the amplitudes of the mode and the losses. Then, a scaling of the losses as function of the mode amplitude can be found and compared to modelling. In the case of the tornado modes, a conclusive modelling aiming at explaining the γ-ray intensity is required and such modelling is under way. The effect of non-resonant losses caused by low-frequency fishbones was explained and now a demonstration of similar effect for fusion α-particles in, e.g. hybrid scenario during future DT campaign on JET is of great interest. The effect of NTM on fast ions requires modelling and assessment of absolute value of the losses.

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