IAEA
INTERNATIONAL ATOMIC ENERGY AGENCY

22nd IAEA Fusion Energy Conference

Geneva, Switzerland, 13-18 October 2008

IAEA-CN-165/EX/6-1

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Abstract. The interplay between MHD instabilities and energetic ions is of crucial importance for a safe plasma performance in self-heated fusion experiments like ITER. A detailed knowledge of the underlying physics has been gained from direct measurements of MHD induced fast-ion losses (FIL). Time resolved energy and pitch angle measurements of FIL correlated in frequency and phase with Neoclassical Tearing Modes (NTMs) and Toroidicity-induced Alfven Eigenmodes (TAEs) have been obtained using a scintillator based FIL-detector. The investigation of FILs due to TAEs has revealed the existence of a new core localized MHD fluctuation, the Sierpes mode. The Sierpes mode is a non-Alfvenic instability which dominates the transport of fast-ions in ICRF heated discharges. The internal structure of both, TAEs and Sierpes mode has been reconstructed by means of highly-resolved multichord soft X-ray measurements. A spatial overlapping of their eigenfunctions leads to a fast-ion loss coupling, showing the strong influence that a core-localised fast-ion driven MHD instability may have on the fast-ion transport. On the modelling side, we have identified the FIL mechanisms due to NTMs as well as due to TAEs. The drift islands formed by fast-ions in particle phase space are responsible for the loss of NBI fast-ions due to NTMs. In ICRF heated plasmas, a resonance condition fulfilled by the characteristic trapped fast-ion orbit frequencies lead to a phase-matching between fast-ion orbit and NTM or TAE magnetic fluctuation. The banana tips of a resonant trapped fast-ion bounce radially due to an $E \times B$-drift in the TAE-case. The NTM radial bounce of the fast-ion banana tips is caused by the radial component of the perturbed magnetic field lines. At the end of each section, we will discuss the implications of these results for MHD induced fast-ion transport in ITER.

1. Introduction

As a burning plasma experiment, ITER will be mainly self-heated by fusion born α-particles e.g. fast-ions with an isotropic phase-space distribution. MHD instabilities can be driven by a population of fast-ions but they also can lead to an enhancement of the fast-ions radial transport. In ITER, an α-particle loss below 5% of their nominal power is envisaged to avoid grave consequences. Therefore, the interplay between MHD instabilities and fast-ions must be well understood [1]. A detailed knowledge of the underlying physics can be gained from direct measurements of MHD induced fast-ion losses (FIL). ASDEX Upgrade (AUG) is well equipped for such studies, due to its powerful and flexible heating system (up to 20 MW NBI at 60/93 keV; up to 6MW ICRH and up to 2 MW ECRH) and its well developed diagnostics. An array of magnetic pick-up coils (with 1 MHz bandwidth) together with a set of SXR cameras (with 500 kHz bandwidth) allow the study of the internal structure of the MHD instabilities while a recently installed scintillator based FIL-detector enables the identification of the MHD instabil-

ity responsible for the FIL. The FIL-detector design is based on the concept of the scintillator based α-particle detector used for the first time in TFTR [2]. Time-resolved energy and pitch angle ($\Lambda = arcos(v_{\parallel}/v)$) measurements of FIL correlated in frequency and phase with NTMs and fast-ion driven MHD instabilities have been obtained.
The theoretical investigation of the mechanisms leading to the expulsion of fast-ions (α-particles) is becoming more relevant as we need to benchmark the numerical tools for ITER predictions. Further efforts to simulate the loss of fast-ions due to MHD instabilities are needed, since the calculated MHD induced fast-ion transport, so far, is up to one order of magnitude smaller than the measured losses [3]. The FIL-detector, the improved set of fluctuation diagnostics like magnetics pick-up coils, SXR-cameras and doppler reflectometry, and the, to this purpose, developed numerical tools should clarify such discrepancy in the fast-ion loss levels.
In this paper, we present the observation and preliminary modeling of fast-ion losses due to NTMs and fast-ion driven MHD instabilities in AUG. The end of each section is devoted to discuss the implications of these results for ITER.

2. Fast-Ion Losses due to NTMs

It is well known that a significant fraction of plasma pressure in a magnetically confined fusion plasma is carried by fast-ions. While the NTM impact on the global confinement is rather well established, less is known on how they influence energetic particles, like for example ICRF heated ions, or ions of NBI origin. Experiments on this subject have been performed in TFTR [4] and DIII-D [5] using α-particles and NBI fast-ions respectively. A good understanding of the magnetic island effects on the fast-ion confinement is important, for example, to fully asses the efficiency of external heating systems and NBI current drive. In next generation devices, like ITER, this information is important also to predict the confinement of alpha particles and the impact of their losses on plasma facing components. The AUG heating system allows a rich variety of scenarios, where the behaviour of fast-ions can be finely tuned and decoupled from the bulk plasma environment. Dedicated studies to investigate the effect of NTMs on the fast-ions confinement of NBI and ICRF origin have been carried out separately.

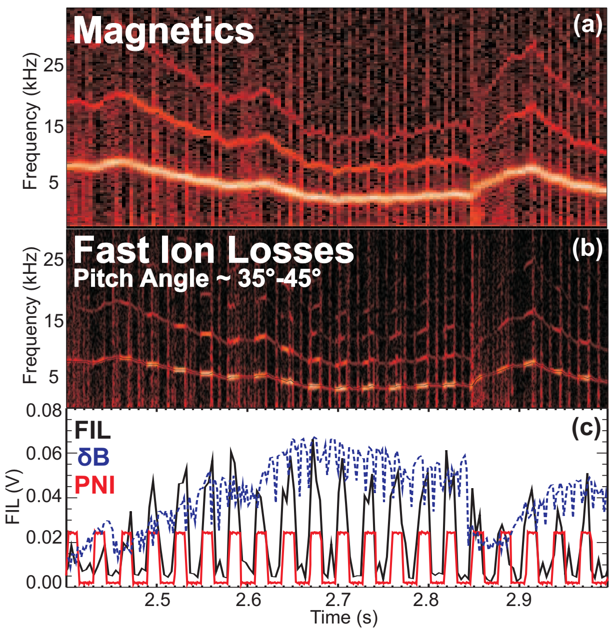

FIG. 1: AUG discharge #21168: (a) and (b): spectrograms of the magnetic island fluctuation and FILD signal corresponding to losses with pitch angle $\Lambda = (35, 45)^{\circ}$ respectively. (c): waveforms of the NBI modulated power (red curve; modulation amplitude of 2.5 MW), of the amplitude of the (2,1) mode (blue doted curve) and of the amplitude of the FILD signal at the frequency of the (2,1) magnetic fluctuation (black curve).

2.1. NTM Induced Fast-Ion Losses of NBI Origin

The loss of NBI fast-ions correlated in frequency and phase with a (2, 1) magnetic island fluctuation has been measured with the FIL-detector and interpreted by means of a numerical model [6]. The (2,1) NTM contribution

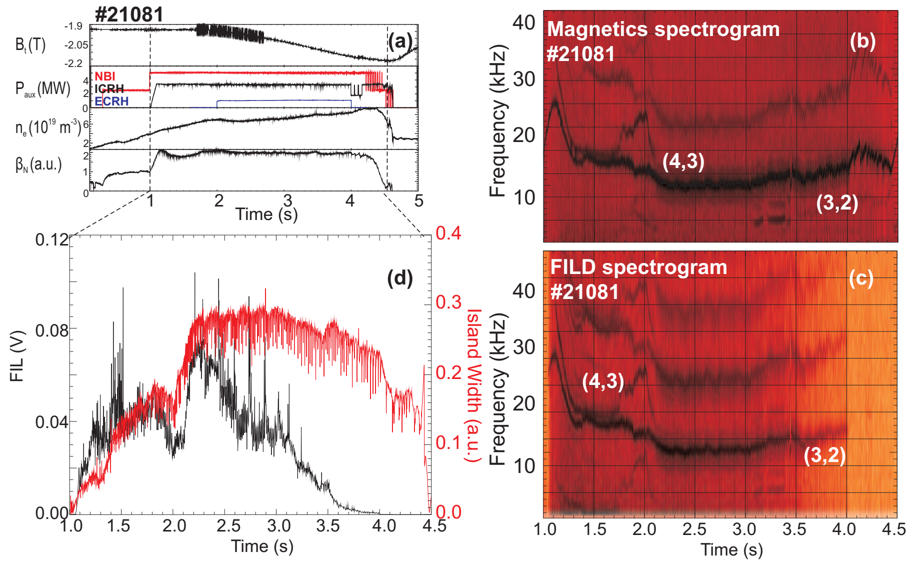

FIG. 2: AUG discharge #21081: (a) Overview of the discharge; from top to bottom, the evolution of the toroidal magnetic field, heating power, core electron density, and β_N *are presented. (b) magnetic spectrogram showing the MHD activity. (c) FILD spectrogram of lost ions with gyroradius* $\rho \approx 50mm$. *(d) Amplitude analysis of magnetic island and FILs at the fluctuation frequency.*

to the measured FIL pattern is twofold; an enhancement of the NBI prompt loss flux and a loss of passing fast-ions which are thought to be well confined in the absence of magnetic fluctuation. The experiments discussed in this section have been mainly performed in plasmas with toroidal current $Ip = 0.8\ MA$, toroidal field $B_t = 2\ T$, safety factor at the edge $q_{95} = 4.5$ and NBI as main heating and fast-ion source. The intermittent operation of a $2.5MW$ NBI source, with a switch-off time shorter than 50 μs, has been used to provide a periodically changing source of fast-ions which helps to study the loss time scales. The plasma density is kept at a relatively low value of $4.5 \times 10^{19} m^{-3}$ during the NBI modulation phase. An NBI heating ramp-up (up to $15MW$) was performed to trigger a (2,1) magnetic island. During the modulation of the NBI source a constant heating of 5 MW was kept. Fig.1(a) shows the magnetic activity due to the (2,1) magnetic island. A Fourier analysis of the FIL-flux with pitch angles ($\Lambda = (35,45)^\circ$) corresponding to passing orbits is shown in Fig.1(b). Besides the slow trend following the frequency evolution of the mode and of its harmonics, we note discrete spots corresponding to the NBI modulation. As shown in Fig.1(c), the amplitude of the losses at the dominant mode frequency (black curve) is modulated according to the NBI evolution (red curve) and its envelope follows the amplitude of the magnetic mode (blue curve). Two well distinguished FIL time scales, depending on the pitch angle of the lost ions, have been observed experimentally by modulation of the NBI source. Losses of fast-ions with rather parallel velocities ($\Lambda = (35,45)^\circ$) decay promptly as soon as the modulated NBI source is switched off, thus indicating a time scale for these losses not longer than a few tens of μs. In contrast, the loss of fast-ions with rather perpendicular velocity ($\Lambda = (70,75)^\circ$) needs to vanish $\approx 5ms$ after the NBI switching off. The typical lost ion flux varies from $4 \cdot 10^{13} \frac{Ions}{s \cdot cm^2}$ for the NTM prompt losses up to $10^{14} \frac{Ions}{s \cdot cm^2}$ for the lost ions with higher pitch angle. Both signals are of the same order as the maximal NBI prompt loss signal, $4 \cdot 10^{14} \frac{Ions}{s \cdot cm^2}$. The observed strong increase of fast-ion losses caused by magnetic islands is consistent with the observation of increased heat loads to the limiters found in experiments as soon as large magnetic islands appear.

Drift orbit calculations using the ORBIT [7] and the GOURDON [8, 9] codes have allowed

the identification of the loss mechanisms. The intersection of the drift islands formed by fast-ions in particle phase-space with plasma-facing components is responsible for the prompt NTM induced FIL (loss time of $\approx 10\mu s$). An overlap of these drift islands leads to an orbit stochastization and consequently to a loss of fast-ions on a diffusive time-scale (loss time $\approx ms$). This overlap depends on the shape of the q-profile, on the location of the $q = 2$ resonance surface, the amplitude of the original (2,1) mode and the fast-ion characteristics.
Dedicated experiments are foreseen in AUG to estimate the effect of magnetic islands with (2,1) helicity on α-particle-like fast-ions in ITER-like scenarios with a $q = 2$ surface rather close to the separatrix which could lead to a strong increase of the 3.5 MeV α-particle loss due to orbit stochasticity.

2.2. NTM Induced Fast-Ion Losses of ICRF Origin

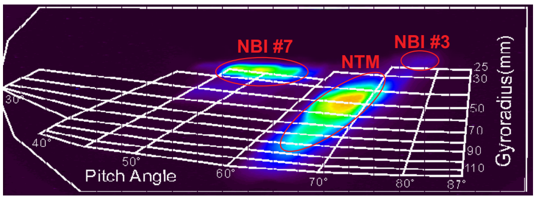

FIG. 3: AUG discharge #21081: CCD view of the light pattern produced by the incident ions ejected from the plasma due to interactions with high frequency modes.

Losses of ICRF generated trapped fast-ions caused by the presence of low-frequency (3, 2) NTMs have been observed and investigated numerically [10] with the HAGIS code [11]. The experiments discussed here were performed in plasmas with toroidal plasma current $I_p = 1.2$ MA, toroidal magnetic field ramp of $B_t = 1.95 - 2.15$ T, and safety factor at the edge $q_{95} = 3.2$. Auxiliary plasma heating was provided by means of two NBI sources delivering a total power of 5 MW, 1 MW of ECRH and 3 MW of on-axis ICRF minority heating in a deuterium plasma with a hydrogen to deuterium ratio of $n_H/n_D \approx 6\%$. Fig.2(a) shows the relevant plasma parameters for the reference discharge, #21083. The MHD activity during the discharge is shown in Fig.2(b) through a fast Fourier transform (FFT) applied to a magnetic fluctuation pick-up coil signal. The presence of a (3,2) NTM is clearly visible during the whole time window. EC waves were launched with the goal of stabilizing the NTM (in this shot, however, the correct matching of the EC resonance with the island position through the magnetic-field ramp did not succeed) . In order to identify the lost particles in phase-space we analyze the loss pattern recorded by the CCD camera of the FIL-detector during the MHD activity. Fig.3 shows a CCD frame for the discharge #21081 at $t = 1.43$ s, when the NTM is present; the NTM-induced fast-ion losses together with the prompt losses generated by both NBI sources are visible. The prompt losses from the more radially injected ions (source #3) appear in the region of higher pitch angle (70°75°) while a tangential source (#7) produces prompt losses in a lower pitch angle region (50°60°). The main (3, 2) NTM contribution to the FIL pattern shows a selective pitch angle character ($\Lambda = (60,70)^\circ$) at gyroradii corresponding to hydrogen ions with energy $E = 600$ keV. The ratio of FIL versus magnetic island width has been investigated by means of a Fourier analysis. Fig.2(c) shows an FFT analysis of the fast-ion loss signal presented in Fig.3. The similarity in the magnetics and FILD spectrograms are striking. The FILD spectrogram is not only revealing the loss of fast-ions due to the (4,3) and the (3,2) magnetic islands, but also due to their harmonics. The (3,2) island width is shown in Fig.2(d) together with the amplitude of the fast-ion loss signal at the (3,2) magnetic fluctuation frequency. The FIL-flux depends sensitively on the relative radial location of the fast-ion population with respect to the magnetic island radial position. A shift of the ICRH resonance layer by means of a B_t-ramp leads to a large FIL-flux change, as shown in Fig.2(d).

The fast-ion expulsion is explained in terms of the radial drift induced by the perturbed magnetic field, $\tilde{\mathbf{B}}$, when the resonance condition $\Omega_{n,p} = n\omega_\phi - p\omega_\theta - \omega \approx 0$ is fulfilled, where n is the toroidal mode number, p is the poloidal harmonic, ω_ϕ, the fast-ion precession frequency, ω_θ, the fast-ion poloidal frequency and ω the mode frequency. At the high energies we are considering, ω_ϕ and ω_θ become comparable, and since they are much larger than ω, the resonance condition can be satisfied if $n\omega_\phi \approx p\omega_\theta$. In general, the radial drift induced by a MHD mode is a combination of the $E \times B$-drift and the radial excursion following the magnetic field lines caused by the perturbed field, $\tilde{\mathbf{B}}$. In the presence of a quasistatic ($\omega \ll \omega_\phi, \omega_\theta$) magnetic-field fluctuation, the dynamics of the trapped particles is changed essentially in two ways: a radial component in the parallel velocity appears and the parallel gradient in the mirror force is modified. The role of the electric field associated to the mode, which scales proportionally to the mode frequency, ω, is negligible. In the experiments described above, where $n = 2$, the resonance condition $2\omega_\phi \approx \omega_\theta$ is satisfied. In other words, the particle has the same phase with respect to the island after each bounce time. This leads a secular radial drift motion, its direction, inwards or outwards, being determined by the relative alignment of the parallel velocity and of the magnetic-field perturbation. This explains the phase locking observed in the measurements, where the FILs are modulated at the mode rotation frequency and occur during half of the rotation period. In ITER, 3.5 MeV α-particles will have a poloidal motion frequency at about midradius of $\omega_\theta/2\pi \approx 460$ kHz and a toroidal precession frequency $\omega_\phi/2\pi \approx 115$ kHz, indicating a potential resonance with quasistatic n=4 magnetic islands.

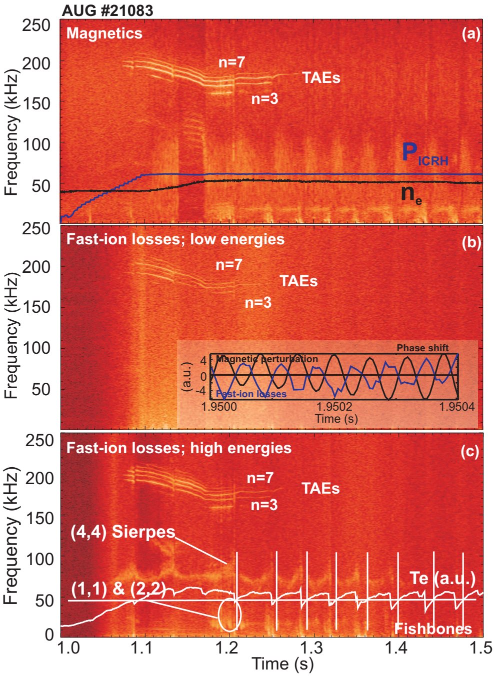

FIG. 4: AUG discharge #21083: Spectrograms of magnetic fluctuation (a) and FILs of low (b) and high (c) energies.

3. ICRH Fast-Ion Losses due to Fast-Ion Driven MHD Instabilities

Intense fast-ion populations drive MHD instabilities unstable in magnetically confined fusion plasmas. Two kinds of fast-ion driven MHD instabilities can be distinguished; Alfven instabilities which are part of the continuum spectrum and appear in toroidally confined plasmas because of the periodicity in the refraction index, and energetic particle modes (EPMs) which appear usually at a characteristic frequency of the fast-ion orbits when the energetic particle pressure is very large [3]. An exchange of energy between particle and wave takes place if an amount of free energy is available due to gradients in the fast-ion distribution function and a wave-particle resonance condition is fulfilled. The resonance condition between the wave phase velocity and the fast-ion orbital frequencies already has been introduced in the previous section to explain the expulsion of ICRF fast-ions due to NTMs. A bidirectional energy exchange between wave and particle takes place depending on the free energy of the system. On one hand, particles may transfer energy to the waves overcoming the continuum and background plasma damping and driving them unstable but on the other hand waves may transfer energy to the particles leading to a radial drift and a possible loss. The study of the fast-ion driven MHD stability (driving and damping rates) and the subsequent fast-ion transport has been extensively studied theoretically and experimentally in almost all major fusion devices [1].

In this section we present the observations and modeling of fast-ion losses due to fast-ion driven MHD instabilities in ICRF heated AUG plasmas. The nature of a recently discovered fast-ion driven MHD instability, the *Sierpes mode*, is briefly discussed [12].

The experiments discussed here have been mainly performed in plasmas with toroidal plasma current $I_p = 1.0 - 1.2\ MA$, toroidal field $B_t = 2.0 - 2.2\ T$, safety factor at the edge $q_{95} = 3.2 - 4.0$ and ICRH as main heating and fast particle source. 5 MW of on axis ICRH of hydrogen minority was applied in a deuterium plasma ($n_H/n_D \approx 6\%$). Fig.4(a) shows the typical core line averaged electron density, $\bar{n_e}$, together with ICRH power for a reference discharge, #21083, overploted on a Fourier spectrogram of a magnetic fluctuation signal. Several TAEs with frequencies between 150 and 225 kHz and toroidal mode numbers $n = 3, 4, 5, 6, 7$ are clearly visible at $t \approx (1.0 - 1.3)\ s$. At lower frequencies, up to 25 kHz, some bursting fishbone modes appear.

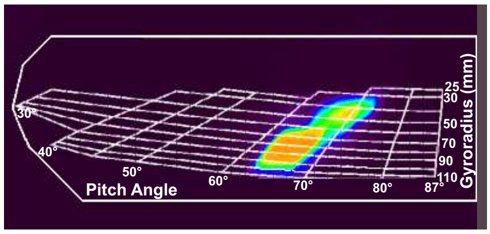

FIG. 5: AUG discharge #21011: CCD view of the light pattern produced by the incident ions ejected from the plasma due to interactions with high frequency modes.

The energy and pitch angle of the fast-ion losses due to these MHD instabilities are shown in Fig. 5, which shows a CCD frame for the discharge #21011 at $t = 1.43\ s$. When the TAEs are present, two different contributions to the fast-ion loss pattern are simultaneously visible at different gyroradii and almost the same pitch angle. For the magnetic field of $1.6\,T$ at the probe, the losses peak at a gyroradius of 45 mm, which correspond to hydrogen ions with $E_H \approx 250$ keV, and pitch angles between 68°-70°. The losses at higher energies appear with a much broader distribution in giroradii, between 60 and 110 mm which correspond to hydrogens with $E_H \approx 1 MeV$ and pitch angles between 62° and 68°.

In order to identify the MHD instabilities responsible for these losses, a Fast Fourier Transformation (FFT) was applied to the signal of the photomultipliers which observe the phase-space regions where losses are detected. Fig. 4(b) shows the spectrogram of a signal, which is measuring lost ions with a gyroradius $\approx 45mm$ (upper spot in Fig. 5). We observe a correlation between the frequency and phase of the individual TAEs ($n = 3, 4, 5, 6, 7$), see Fig. 4(a)-(b), and those of the losses. The spectrogram in Fig. 4(c) refers to ion losses at larger gyroradii ($60 - 110mm$), i.e. the lower spot in Fig. 5. A clear correlation between the TAE frequency pattern and the fast-ion loss frequencies is also observed. An interesting feature is present in the FILD spectrogram of high energies at intermediate frequencies, $\approx 80kHz$, where a dominant frequency emerges. We call this new MHD instability the *Sierpes* mode because of its footprints in the fast-ion loss spectrogram and the fact that it is hardly visible for the Mirnov pickup coils, see Fig. 4(a). Tracking the frequencies corresponding to the individual TAEs, we observe stronger losses (up to a factor of three higher) due to TAEs if the Sierpes mode is also ejecting fast-ions. This can be observed by comparing the losses due to individual TAEs in both FILD channels.

The stability of the Sierpes mode seems to be more weakly dependent on background plasma parameters than the TAEs, since it remains unstable usually for time periods much longer than the TAEs, eventually up to 1 sec, unaffected by changes in the q-profile. The Sierpes fluctuation always disappears at large sawtooth crashes and appears again within the next $\approx 10ms$, when the T_e, i.e. the collisionality (ν_e) has reached a certain threshold, T_e=1.9 keV, and the fast-ion population has been rebuilt. The frequency of the Sierpes mode, $f_{Sierpes}$, does not change with the toroidal magnetic field B_t or the core electron density n_e, see Fig. 4(c). A rapid change of the electron density, n_e, due to L-H mode confinement transition, $t \approx 1.15sec$ in Fig. 4(c), is followed by a change in the f_{TAE}, as expected, but not by a change in $f_{Sierpes}$. This hints that the Sierpes mode is not an Alfvénic mode. Furthermore, the rapid frequency rise before the sawtooth crashes can not be explained by the classical Alfvénic physics since no relevant background plasma parameter (i.e. n_e or B_t) can change so fast. In fact, the behavior before the sawtooth crash suggests some kinetic effects of the energetic particles as in the EPM case. Including background diamagnetic effects in the Beta-induced Alfven Eigenmode (BAE) dispersion relation, a reasonable agreement of the $f_{Sierpes}$ with the f_{BAE} has been found when the fast-ion pressure is not too large. However when the fast-ion pressure achieves values comparable to the plasma pressure, a $f_{Sierpes}$ chirp of up to $\Delta f \approx 40kHz$ occurs, indicating an EPM character, not explained by any BAE dispersion relation [13]. Further analysis using nonlinear codes are necessary to clarify whether a strong nonlinear interaction of fast-ions with Alfven waves can explain the $f_{Sierpes}$ behaviour.

To understand the combined effect of both MHD instabilities on the fast-ion transport, the TAE and Sierpes internal structure has been reconstructed by means of high time resolution SXR measurements, see Fig.6.

The maximum TAE displacement ranges from 0.1 to 0.4 mm and the inferred core magnetic fluctuation amounts to $\delta b_r/B_t = 0.2 - 5 \times 10^{-4}$. The Sierpes mode has a more core-localized eigenfunction (Fig.6), which is peaked around $\rho_{pol} \approx 0.25$ and it extends up to $\rho_{pol} \approx 0.5$, leading to a maximum displacement of the order of 0.5 mm in the plasmas analyzed so far. It is interesting to note that there is a radial region, $\rho_{overlap} \in (0.2, 0.5)$, where the $n = 4$ TAE and Sierpes eigenfunctions overlap with non-zero values. The overlapping of radial eigenfunctions might be the reason for the drastic increase in the fast-ion losses when both modes are present simultaneously, by channeling the ions which fulfill the loss conditions from the plasma core to the edge. This channeling process is illustrated in Fig.6 where the ICRF fast hydrogen ion pressure profile, calculated with the PION code, has been superimposed.

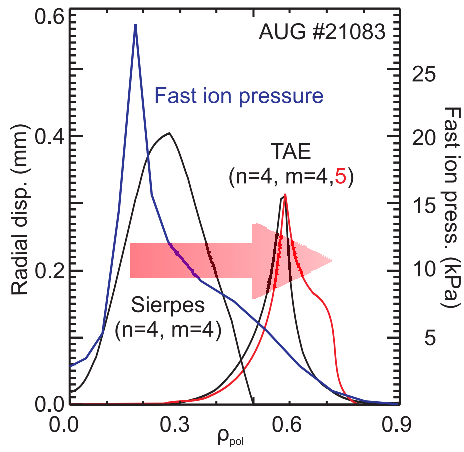

FIG. 6: Schematic of the channeling loss mechanism due to a radial chain of multiple fast-ion driven MHD fluctuations.

The fast-ion loss mechanisms due to TAEs and Sierpes mode are investigated using the HAGIS code [14]. The fast-ion orbits are usually described by their constant of motion; energy, pitch angle and toroidal canonical angular momentum (E, Λ, P_ϕ). A simplified ICRH particle distribution function has been simulated by taking pitch angle $\Lambda = 1$. This corresponds to trapped orbits with turning points at the on-axis ICRH resonance layer. A resonant wave-particle interaction takes place if the resonance condition introduced in the previous section, $\Omega_{n,p} = n\omega_\phi - p\omega_\theta - \omega \approx 0$, is fulfilled. By plotting, $\log(1/\Omega_{n,p})$ in the energy range of the fast-ions measured by FILD, we can identify the regions of phase-space where a resonant interaction could occur. The resonance condition fulfilled by the characteristic trapped fast-ion orbit frequencies and the mode rotation frequency leads to a phase matching between fast-ion orbit and TAE fluctuation. The banana tips of a resonant trapped fast-ion drift radially due to the $E \times B$-drift (with E the poloidal electric field induced by the high-frequency MHD fluctuation) with a net inwards or outwards drift depending on the relative phase between MHD fluctuation and particle movement. Fig.7 contour plot shows the on-axis ICRF heated hydrogen ions that are resonant with the $n = 4$ and $n = 5$ TAE and $n = 4$ Sierpes mode for the AUG plasma dis-

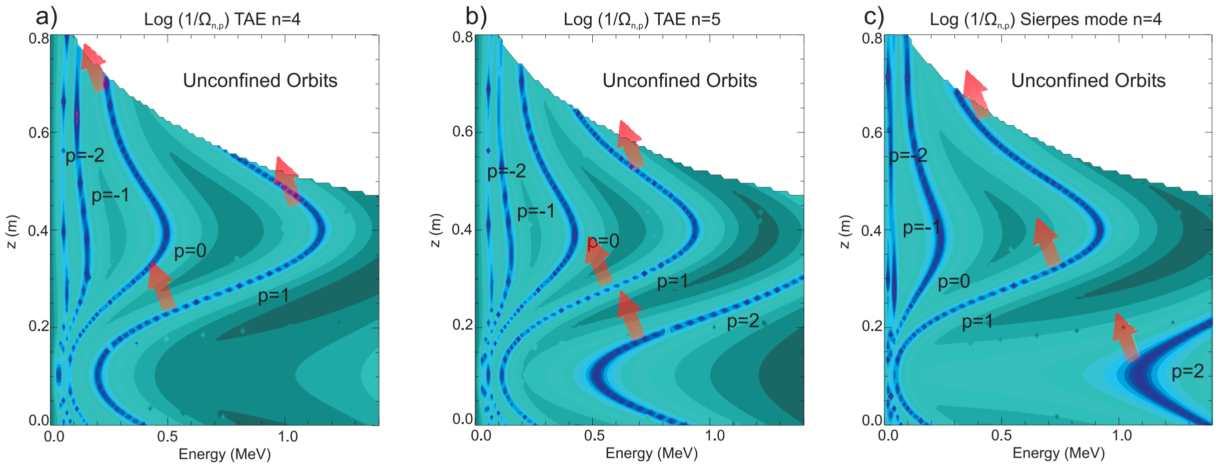

FIG. 7: AUG discharge #21083: Phase-space resonance lines between on-axis ICRF heated hydrogen ions and the $n = 4$ TAE (a), $n = 5$ TAE (b) and the $n = 4$ Sierpes mode (c).

charge #21083. The wave-particle interaction results in an exchange of energy, E, and toroidal canonical angular momentum, P_ϕ which at the tips of the bananas translates into a radial drift of the particle. This fast-particle channeling in phase-space may be the responsible not only for the high fluxes of fast-ion losses when both instabilities are present at the same time, but also for the driving of the instabilities due to the modification of fast-ion distribution function gradients. A quantitative analyses of the coupling between fast-ion loss mechanisms due to a radial chain of fast-ion driven MHD fluctuations is under way to benchmark numerical tools for ITER.

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