Observation and modeling of fast-ion losses due to high frequency MHD instabilities in the ASDEX Upgrade tokamak

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Introduction

The interplay between MHD instabilities and energetic ions is of crucial importance for a safe plasma performance in particular in next step fusion devices like ITER. A detailed knowledge of the underlying physics can be gained from direct measurements of fast particle losses. To this purpose, a scintillator based detector for MHD induced fast ion losses has been installed in ASDEX Upgrade [1]. Time resolved energy and pitch angle measurements of fast ion losses correlated in frequency and phase with Toroidal Alfven Eigenmodes (TAEs) have been obtained for the first time in a magnetic fusion device and are presented here [2]. A new core localised MHD instability, the Sierpes mode, has been identified by means of its deleterious influence on the energetic particle confinement. The internal structure of both, TAEs and Sierpes mode has been reconstructed by means of highly-resolved multichord soft X-ray measurements. The mechanisms responsible for the radial transport and loss of fast-ions are investigated using the HAGIS code [3].

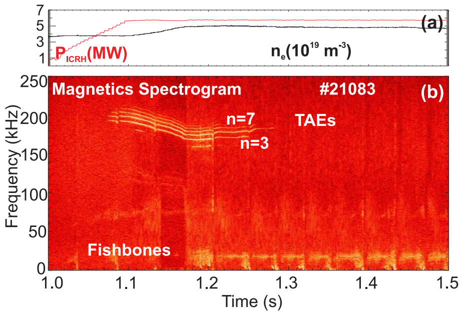

Figure 1: (a) Core line integrated electron density (n_e) and total ICRH power (P_{ICRH}). (b) Spectrogram of an in-vessel magnetic pick-up coil.

Experimental Results

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.1-a shows the typical core line averaged electron density, $\bar{n}_e$, together with ICRH power for a reference discharge, #21083. Fig.1-b shows the Fourier spectrogram of a magnetic fluctuation signal from a Mirnov coil. 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.

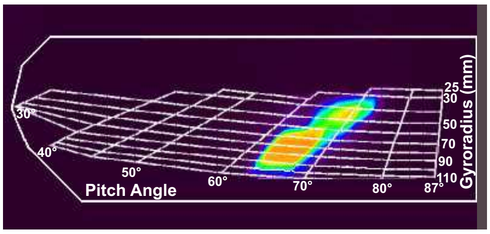

Figure 2: AUG discharge 21011: CCD view of the light pattern produced by the incident ions ejected from the plasma due to interactions with high frequency modes.

The energy and pitch angle of the fast-ion losses due to these MHD instabilities are shown in Fig. 2, 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°.

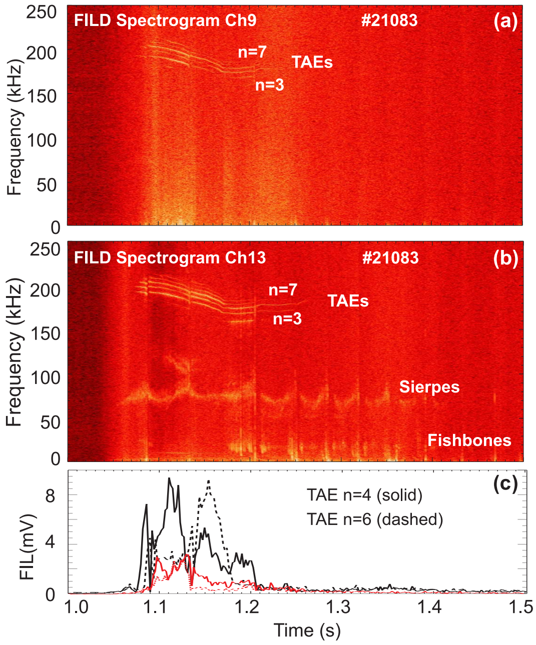

Figure 3: FIL-spectrograms of low (a) and high (b) energies. (c) FIL amplitudes at TAE n=4 and n=5 frequencies.

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. 3-a shows the spectrogram of a signal, which is measuring lost ions with a gyroradius $\approx 45mm$ (upper spot in Fig. 2). We observe a correlation between the frequency and phase of the individual TAEs ($n = 3,4,5,6,7$), see Fig. 1-b, and those of the losses. The spectrogram in Fig. 3-b refers to ion losses at larger gyroradii ($60 - 110mm$), i.e. the lower spot in Fig. 2. 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. 1-b. The frequencies of the Sierpes mode, at around 80 kHz, appear with a dominant character in the fast ion loss pattern, lasting for a longer time than the TAEs. 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 (Fig. 3-a and -b).

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.4. The maximum TAE displacement ranges from 0.1 to 0.4 mm and the inferred core magnetic perturbation amounts to $\delta b_r/B_t = 0.2 - 5\times10^{-4}$. The Sierpes mode has a more core-localized eigenfunction (Fig.4), 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.4 where the ICRF fast hydrogen ion pressure profile, as given by the PION code, has been superimposed.

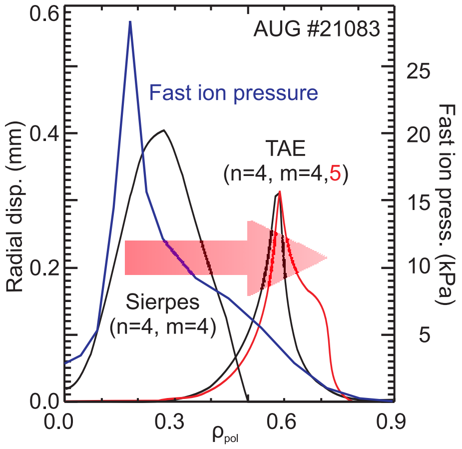

Figure 4: Schematic of the channeling loss mechanism due to a radial chain of multiple fast-ion driven MHD perturbations.

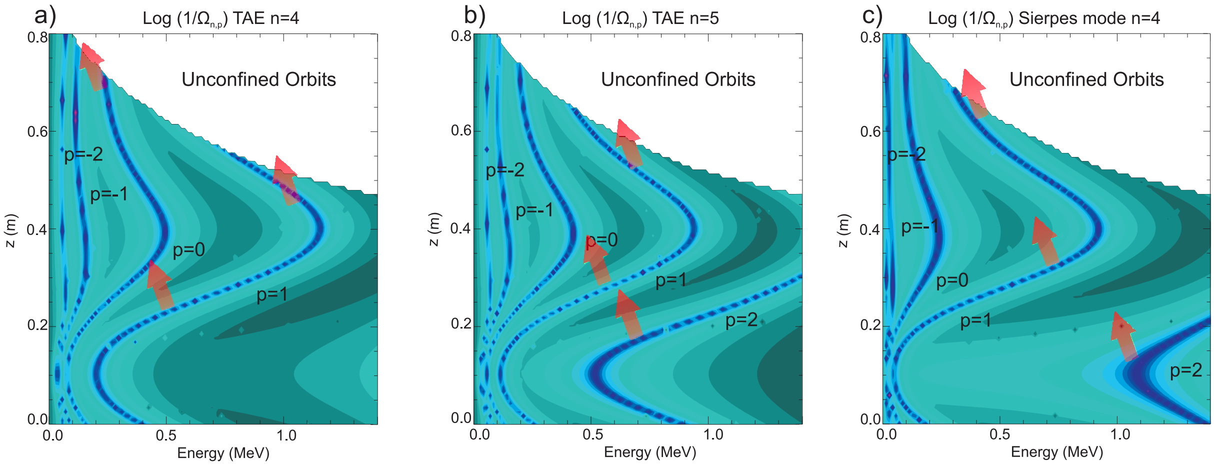

Figure 5: AUG discharge 21083: Phase-space resonance lines between on-axis ICRF heated hydrogen ions and the $n = 4$ TAE (a), $n = 5$ TAE (b) and the $n = 4$ Sierpes mode (c).

Numerical Results

The fast-ion loss mechanisms due to TAEs and Sierpes mode are investigated using the HAGIS code. 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 $\Omega_{n,p} = n\omega_\phi - p\omega_\theta - \omega \approx 0$ is fulfilled, where n is the toroidal mode number, p is the bounce harmonic, ω_ϕ, the fast-ion precession frequency, ω_θ, the fast-ion bounce frequency and ω the wave frequency. 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 Fig.5 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 discharge #21083. The wave-particle interaction results in an exchange of energy and toroidal angular momentum 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.

References

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