EUROPEAN FUSION DEVELOPMENT AGREEMENT

Task Force M

Influence of the relative position of ICRH resonant layer on the internal kink mode stability

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INTRODUCTION

The problem of the internal kink mode stabilisation by ion cyclotron resonance heating (ICRH) driven fast particles has been the subject of several studies over the last years. The internal kink mode is supposed to be responsible for the sawtooth instability, which play an important role on the central plasma stability. The control of sawtooth assumes then a crucial importance, with one of the most promising methods for sawtooth control being based on the use of ICRH. The effect of the ICRH driven fast particles on sawtooth stability was analysed using a hybrid kinetic-magnetohydrodynamics (MHD) model, the CASTOR-K code, for different JET experimental scenarios.

The mappings presented in ref. [1] are now extended for the case of higher frequency internal kink modes (20 kHz) that occurs when higher NBI power is used. Low density ICRH-only discharges with high fast-ion energy content are analysed. In this regime unlike the monster sawtooth normally associated with ICRH, small sawtooth crashes are observed [2]. JET experiments to study plasma rotation [3] allowed the analysis of the influence of the ICRH resonance position over the internal kink stability.

THE CASTOR-K CODE

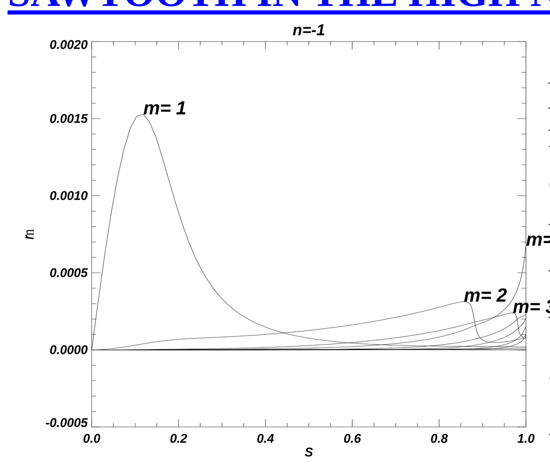
The CASTOR-K [4] code is a hybrid kinetic-magnetohydrodynamic model that calculates the transference of energy between the fast particles and the mode. Using the MHD equilibria reconstructed by EFIT and HELENA, the linear-normal mode analysis is performed by the CASTOR or MISHKA [5] codes. The required information about the fast particles population is calculated by the PION code [6]. The CASTOR-K code computes then the first order perturbation on the eigenvalue due to the interaction between the wave and the energetic ion population using a perturbative approach,

$$\delta W_{hot} = -\frac{2\pi^2}{\Omega m^2}\sum_{\sigma}\int dP_{\phi}dEd\mu \sum_{p=-\infty}^{\infty}\frac{\partial f}{\partial E}\frac{\tau_b\left|Y_p\right|^2(\omega - n_0\omega^*)}{\omega + n_0\omega_D + p\omega_b}\;,\quad Y_p = \oint \frac{d\tau}{\tau_b}L^{(1)}e^{ip\omega_b\tau}$$

P_ϕ represents the toroidal canonical momentum, μ the magnetic momentum, E the energy, L(1) the perturbed orbit Lagrangian, ω_* the diamagnetic frequency of the fast ions, ω the perturbation frequency, ω_d the toroidal precession drift frequency and ω_b the poloidal bounce frequency. The real part of dW_{HOT} is related to the growth rate of the internal kink mode due to the presence of the fast particles (γ_{HOT}) by ,where E_k is proportional to the mode energy and γ is the growth rate of the unperturbed mode. In this paper, the modes growth rates are normalised to the Alfven frequency.

$$\gamma_{HOT} = \frac{1}{2\gamma}\frac{\mathrm{Re}\,\delta W_{HOT}}{E_k}$$

SAWTOOTH IN THE HIGH NBI POWER SCENARIO

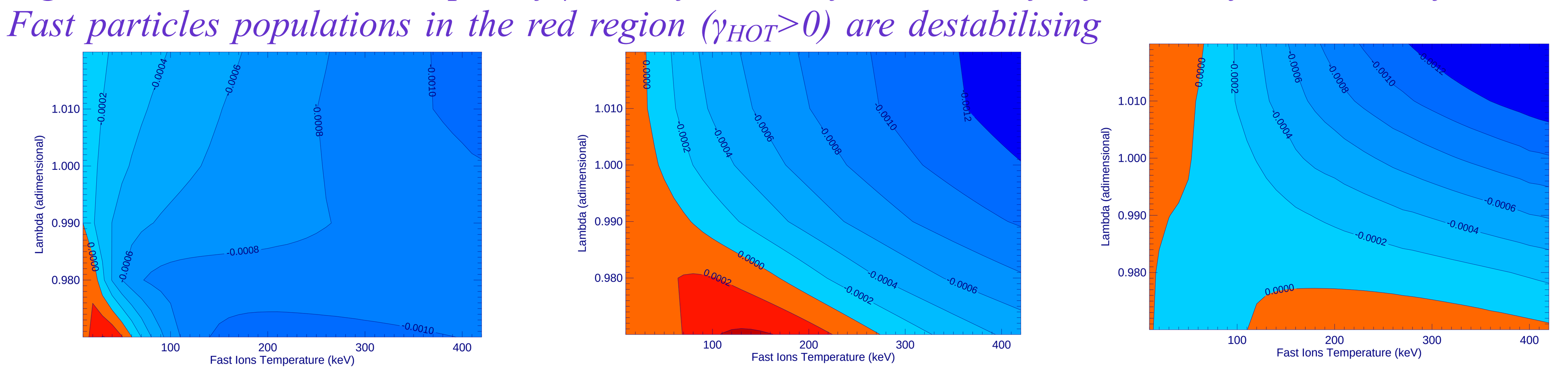


Sawtooth in the ICRH-only and combined heating with moderate NBI power scenarios were already treated in a previous paper [1]. The scenario of high NBI power will now be addressed. The exchange of energy between NBI driven fast particles and the internal kink mode will not be considered here. In the previous scenarios, typical frequencies of the internal kink mode of 1 kHz and 8 kHz were considered, consistent with observed sawtooth precursor frequencies. In this paper, the case of a 20 kHz internal kink mode is analysed. The equilibrium and the eigenfunction used in this paper are the same used in ref. [1].

Figure 1: Radial displacement of the n=1, m=1 internal kink mode used in the simulations (q_0= 0.95, b_p=0.51). The top hat m=1 structure is clearly visible but changed due the finite beta.

The distribution function of fast particles used by CASTOR-K is a function of E, $\lambda \equiv \mu B_0/E$ and P_Φ. The distribution function is assumed to be a Maxwellian on the energy, characterized by a temperature, T_{HOT}. For the majority of JET experiments λ take values close to one and the ICRH driven fast particles will be either mirror trapped (banana orbits) or co-passing (potato orbits). Since the transference of energy between the particles and the mode critically depends on the type of orbits, the position of the cyclotronic resonance (measured by λ) and the central temperature of the fast ions, T_{HOT}, are the crucial parameters on which δW_{HOT} depends. These parameters are related to the RF frequency and power respectively. Figures 2 to 4 show the mappings of the stabilising-destabilising regions for the three scenarios. The fast ions populations are destabilising mainly for low values of λ and T_{HOT}.

Figures 2, 3 and 4: Contour plot of γ_{HOT} as function of T_{HOT} and λ for f=1 kHz, f=8 kHz and f=20 kHz. Fast particles populations in the red region (γ_{HOT}>0) are destabilising



while in the blue region (γ_{HOT}<0) are stabilising. These mappings were built using $\gamma=\omega_A$ and $n_{HOT}=10^{18}m^{-3}$.

SAWTOOTH ACTIVITY IN LOW DENSITY ICRH-ONLY DISCHARGES

In some ICRH heating experiments carried out in JET a new domain of sawtooth behaviour was found in ICRH-only low density discharges with high fast ion energy content. During these experiments the plasma density was varied using deuterium gas puffs. It was observed that when the central electron density $n_e(0)$ decreases below $2x10^{19}$ m^{-3} a new domain of sawtooth behaviour appears [2]. This new type of sawtooth activity is characterized by a sawtooth period five times shorter than in the case of typical JET sawtooth in ICRF heating discharges.

The CASTOR-K code has been used to analyse two similar discharges (47575 and 47576, see more details in ref. [2]), with identical ICRH injected power, between 48.5 s and 50.0 s. The main difference between the two discharges was the electron density. In discharge 47575 the electron densities found were between $2.2\text{-}2.4x10^{-19}m^{-3}$ and long sawtooth free periods have been observed, while in discharge 47576 where the density was between $1.6\text{-}1.8x10^{-19}m^{-3}$ the new regime with short sawtooth free periods have been observed. The classical slowing down time of fast ions depends on the plasma density and becomes longer when the density decreases. So, the fast ions can achieve higher velocities in low density plasmas and its populations higher values of T_{HOT}. For the time interval analysed, the fast ions temperatures were close to 1200 keV the first discharge and close to 3400 keV in the second. According to the simulations, the ICRH driven fast particles have a strong stabilising effect in the range of fast ions temperatures observed in discharge 47575 that is lost when T_{HOT} is increased to the values observed in discharge 47576.

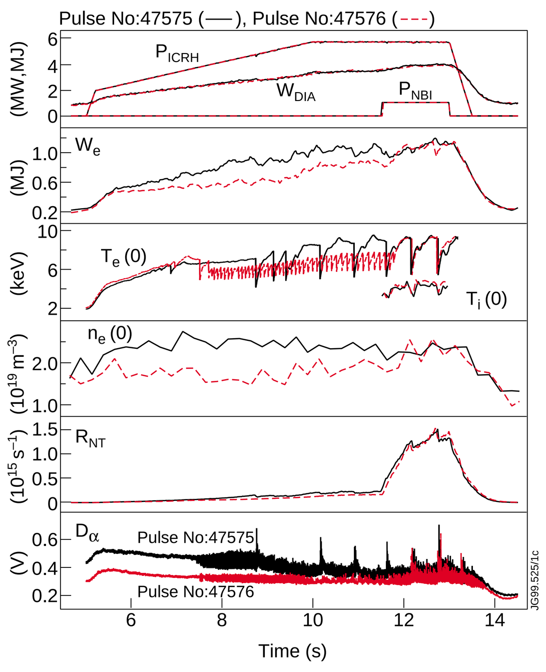


Figure 5: ICRH and NBI power, diamagnetic plasma energy content, electron energy content, central electron and ion temperatures, central electron density, D-D neutron rate and D_α signal for discharges 47575 and 47476, B_0= 2,7 T, I_0= 2.5 MA.

Besides, there is a clear correlation between T_{HOT} (and n_e) and the sawtooth period in discharge 47576. Between approximately t= 47.5 s and t= 49.5 s the electron density has it's lowest values, T_{HOT} is always higher than 3 MeV and the sawtooth period is short. Between t= 49.5 s and t= 51.5 s is clearly visible in fig. 5 an increase both in the electron density and sawtooth period. By this time, T_{HOT} decreases to less than 2 MeV. After this time, n_e increases to higher values and sawtooth monster appears. T_{HOT} was now close to 1200 keV, approximately the same value as in discharge 47575.

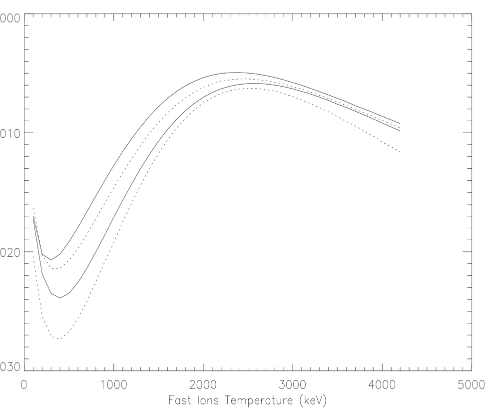
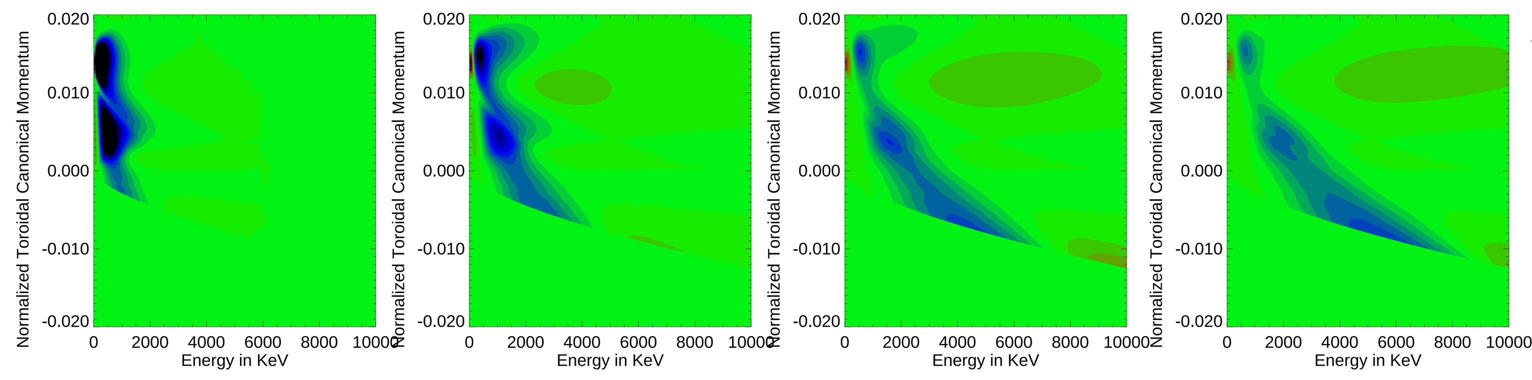


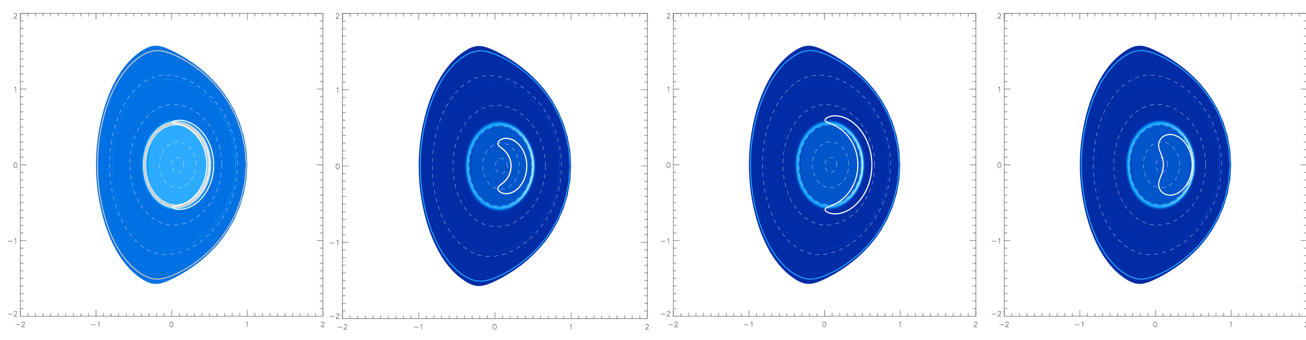
Figure 6: Contribution of the ICRH driven fast particles to the growth rate of the internal kink mode as function of the fast ions temperature. Solid lines: #47575 t=48,5 s (inferior) and t=50 s (superior), dotted lines: #47576 t=48,5 s (inferior) and t=50 s (superior).

ENERGY EXCHANGE AND ORBITS



Figures 7, 8, 9 and 10: The energy exchange between the internal kink mode (#47575, t=48.5 s) and the fast particles as function of P_ϕ and E, λ=0.99, for T_{HOT}=400 keV, T_{HOT}=1200 keV, T_{HOT}=2400 keV and T_{HOT}=3200 keV. In the red region particles are destabilising while in the blue region are stabilising.

Figures 7 to 10 show the energy exchange between the internal kink mode and fast particles populations characterized by different values of T_{HOT}. For low fast ions temperatures, there is a strong stabilising influence originated by particles with low width banana orbits located close the q=1 surface (fig. 11), and with large width banana orbits located inside the q=1 surface (fig. 12). For higher fast ions temperatures, the energy exchange becomes dominated by banana orbits close the q=1 surface but with larger width (fig. 13), by banana orbits with the size of the mode (fig. 14) and by small potato orbits. These orbits have a less efficient stabilising effect (see fig. 7 to 10).

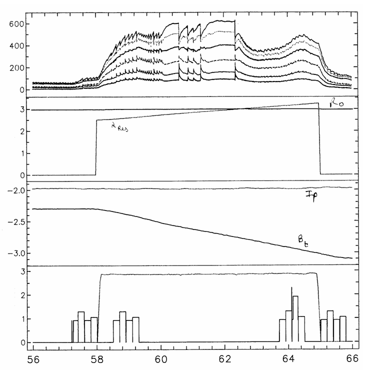


Figures 11, 12, 13, 14: Orbits that exchange more energy with the mode for T_{HOT}=400 keV (figs. 11, 12) and for T_{HOT}=3200 keV (figs. 13, 14),λ=0.99, β_p=0.23

VARIATION OF THE POSITION OF THE ICRH RESONANT LAYER

In JET experiments to study plasma rotation with ICRH [3], the toroidal magnetic field was varied throughout the heating phase. Consequently the ICRH resonance position, which depends on the magnetic field, was also varied throughout the heating phase. The influence of the position of the cyclotronic resonance on the internal kink stability was analysed with the CASTOR-K code for the discharge 51661.

Figure 15: Central electron temperature (eV), ICRH resonant layer radius (m), toroidal magnetic field (T) and ICRH and NBI power (MW) for discharge 51661.



In this discharge B_0 was increased during the heating phase, while the other parameters remained approximately constant q_0~0.83-0.88. In the beginning of the heating phase, when the magnetic field was low (B_0 between 2.3 and 2.5 T, λ between 0.85 and 0.90) and the resonance layer was well in the high field side outside the q=1 surface, sawtooth exhibited its usual behaviour with short sawtooth period. In this time interval the ICRH driven fast particles had a very strong destabilising effect, γ_{HOT}~0.07.Later in the discharge, when the cyclotronic resonant layer was yet on the high field side but close to the axis (λ~ 0.94 to 0.97), the called monster sawteeth appeared. By this time the ICRH driven fast particles had a stabilising effect, γ_{HOT}= -0.008 to -0.024, stronger than the ideal growth rate calculated by the MISHKA code γ= 0.0075.

Just before the cyclotronic resonant layer reached the axis, a major sawtooth crash occurred triggering other modes and ending the sawtooth regime. Just before this crash, the ICRH driven fast particles had a weak stabilising effect, γ_{HOT}= -0.002, not enough to compensate the ideal internal kink growth rate.

CONCLUSIONS

The effect of ICRH driven fast particles over the internal kink mode depends on the mode energy. In the range of parameters analysed, destabilising populations require low values of λ or low values of T_{HOT}. Higher energies ions have different orbits that in the case of #47576 (λ=0.99) have smaller stabilising effect. In this discharge a correlation between T_{HOT} (and n_e) and the sawtooth period was observed.

In discharge 51661, ICRH driven fast particles shown a very strong destabilising effect when the resonance layer was outside the q=1 surface. When the resonance layer was inside the q=1 surface and sawtooth monsters were observed, the fast particles were stabilising with | γ_{HOT} | > γ. Just before a major crash the effect of the fast particles was yet stabilising but weaker | γ_{HOT} | < γ.

References

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