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The Influence of ICRH-driven Energetic Ions on the Stability of Optimised Shear Discharges in JET

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1. Introduction

The optimised shear scenarios being developed at JET during the 1998-1999 experimental campaign require the use of high power auxiliary heating in low-density target plasmas. Under these conditions, Ion Cyclotron Resonant minority Heating (ICRH) with P_{ICRH}>6 MW generates a large tail of energetic ions (E>1 MeV). The super-thermal minority ions destabilise Alfvén Eigenmodes (AEs) in the frequency range of 100-200kHz, fishbone-like modes [1] in the frequency range of 20-40kHz, higher frequency chirping modes, and can influence the stability of the pressure driven n=1 infernal mode [2] found to be responsible for disruptions in some discharges. The hybrid kinetic-MagnetoHydroDynamic (MHD) model (CASTOR-K) has been extended in order to study the influence of energetic ICRH-driven minority ions on the stability of low frequency MHD modes. Using a perturbative approach, the modified version of the CASTOR-K [3] code calculates both the real part $Re(\delta W_{HOT})$ and the imaginary part $Im(\delta W_{HOT})$ of the quadratic form δW_{HOT}, which represents the energetic particle potential energy. In addition, finite temperature gradients and the effects of collisions of the fast ions are included, which are both relevant for the detailed analysis of the plasma stability in the presence of energetic ICRH-driven minority ions. Finite orbit width effects are retained, enabling the study of the influence of both potato and banana orbits.

2. Model

Using the MHD equilibria reconstructed by EFIT and HELENA, the linear-normal mode analysis is performed by the spectral code CASTOR. The contribution of the energetic ions is included perturbatively in the CASTOR-K code. The CASTOR-K code computes the first order perturbation on the eigenvalue due to the interaction between the eigenmodes and the energetic ion population using a gyro-kinetic model. CASTOR-K uses the linear eigenfunction obtained by CASTOR and decomposes the hot particle energy functional into poloidal bounce harmonics and integrates over the particle phase-space [4].

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

The resulting six-dimensional phase-space integration is performed (Table 1) without a major increase on the numerical computation requirements, given the particular characteristics of the ICRH distribution functions.

Table 1 Integration schemes used in the CASTOR-K code

Integration scheme	CASTOR-K Previous Version	CASTOR-K New Version (ICRH)
gyro-angle	analytical (average procedure)	analytical (average procedure)
poloidal angle	numerical (Fourier transforms)	numerical (Fourier transforms)
toroidal angle	analytical (Fourier decomposition)	analytical (Fourier decomposition)
energy	analytical (integration over the poles)	numerical (binary search algorithm)
magnetic moment	numerical (binary search algorithm)	analytical (ICRH distribution functions)
toroidal momentum	numerical (binary search algorithm)	numerical (binary search algorithm)

3. Plasma equilibrium and eigenmode structure

In optimised shear plasmas in JET, good confinement is obtained when the central value of the safety factor (q) is just below two ($1<q_0<2$) and the shear is either low or slightly reversed in some discharges. Under these conditions, the MHD model predicts the existence of: the diamagnetic branch of the infernal mode, believed to be associated with fishbone bursts; the infernal mode responsible for most disruptions; and Alfvén eigenmodes. The mode structures of the infernal mode and the fishbone mode are believed to be similar. This is confirmed by MHD modelling including diamagnetic effects and from experimental evidence by comparing the mode structure of fishbone bursts and disruption precursors using the soft x-rays cameras. The perturbed energy density of an n=3 toroidicity induced Alfvén eigenmode is shown Figure 2.

4. Energy exchange between particles and waves

The ICRH waves accelerate the energetic ions mainly in the perpendicular velocity direction. Therefore, in the region of the ICRH resonant layer, the fast ion perpendicular velocity is much larger than the fast ion parallel velocity. In terms of constants of motion, this corresponds to $\mu / E \approx 1$, where E is the particle energy and μ is magnetic moment. Thus, the ICRH produced ions become either mirror-trapped or co-passing, as shown in Figure 1.

In the optimised shear JET scenario, a few 100 ms after the high power ICRH with $P_{ICRH}>6$ MW has been switched on, the plasma stored energy is dominated by supra-thermal ions. It is during this phase that AE activity and fishbone bursts are most commonly observed. As the discharge progresses and the confinement is improved by the formation of a transport barrier, the thermal contribution increases up to 50% of the total plasma stored energy. The increase in the ion bulk temperature increases the ion Landau damping of the AE modes; consequently, the AE mode are stabilised during this phase in most discharges.

The energy exchange between the ICRH driven energetic ions and the AE is dominated by the side-band poloidal bounce resonances (p=-1,+1). A very small fraction of the ion population is responsible for the excitation of the AE, leading to a small saturation amplitude of the AE and a very small redistribution of the energetic ions. Both banana and potato orbits are involved, in particular at large energies as shown in Figures 1,2.

The excitation of the n=1 fishbone mode by ICRH ions is dominated by the toroidal precession drift resonance (p=0) and involves a larger fraction of energetic ions as shown in Figure 3. The energy exchange is maximised for ICRH driven ion energies in the 1-3 MeV range and for frequencies in the 15-25 kHz range (fast ion precession drift frequency), as shown in Figure 4, which is in agreement with the experimental observations.
The destabilising influence of the ICRH ions on the infernal mode is mainly due to the increase in the plasma pressure during the auxiliary heating. The stabilising influence is associated with the conservation of the third invariant of motion of the high energy ions. In the simulations, it is assumed a minority ion concentration of 1 % and a fast ion tail temperature of 3 MeV, corresponding to a fast ion stored energy of 2 MJ. For a magnetic fields of B_T=2.5,3.0,3.4 and 4.0 T the calculated values of the fast particle potential energy are $\delta\widehat{W}_{HOT} = 2.1\%, 1.7\%, 1.0\%, 0.2\%$,respectively , where $\delta\hat{W}_{HOT} = \delta W_{HOT} / \frac{1}{2}\rho\omega_A^2 \int \xi^2 dV$. In particular, for the magnetic of 3.4 T an energetic particle contribution of $\delta\widehat{W}_{HOT} = 1.0\%$ can increase the value of the pressure at marginal stability by 25%.

5. Conclusions

The hybrid kinetic-magnetohydrodynamic (MHD) model (CASTOR-K) has been extended in order to study the influence of energetic ICRH-driven minority ions on the stability of low frequency MHD modes. In ICRH heated discharges, the calculations show that the energetic particle stabilisation of the infernal mode can increase the pressure at marginal stability by up to 25%. It was shown that the excitation of the fishbone mode by ICRH ions is dominated by the toroidal precession drift resonance and that the energy exchange is maximised for frequencies in the 15-25 kHz range, which is in agreement with the experimental observations.

References

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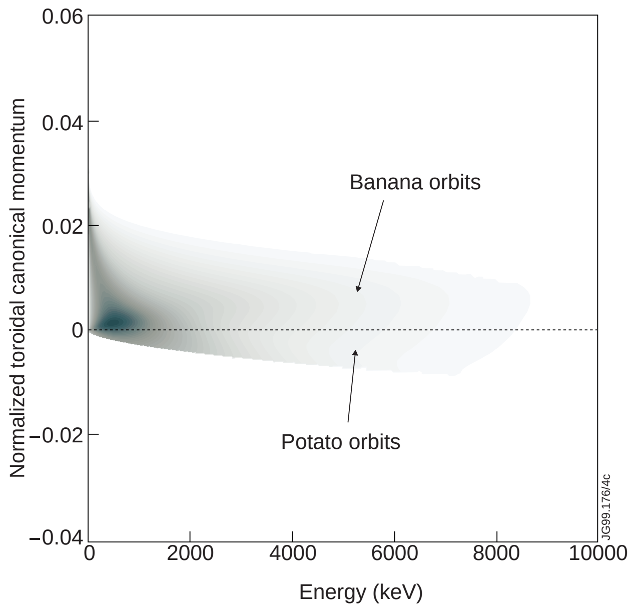

Fig.1: The particle density distribution in phase-space used in the CASTOR-K simulations as a function of the normalised toroidal canonical momentum and energy. For low energies the distribution is dominated by banana orbits, but for energies larger than 1 MeV there is a significant number of particles in the potato regime.

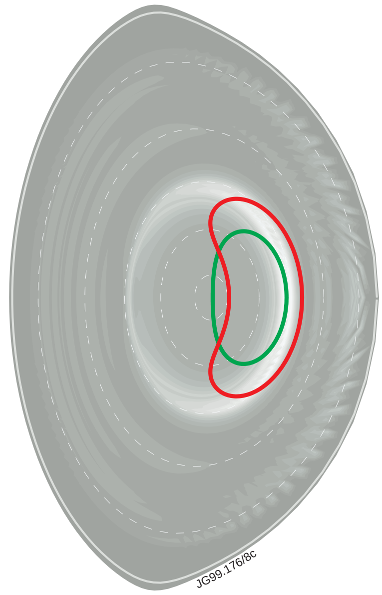

Fig.2: The energy density of a n=3 TAE mode in optimised shear discharges and the poloidal projection of the orbits that exchange most energy with the TAE mode. Both banana (red) orbits and potato (green) orbits are involved in the excitation of the TAE mode.

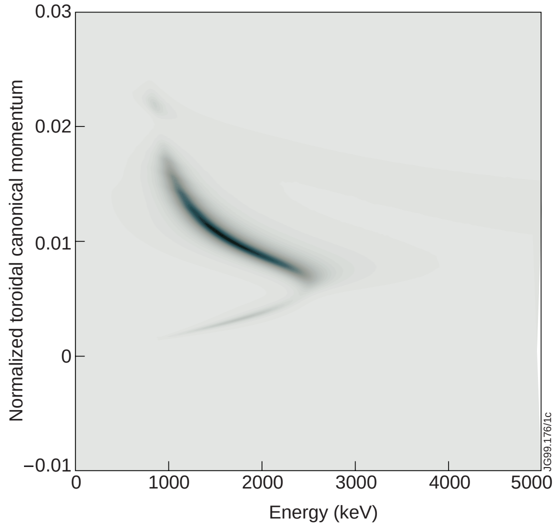

Fig.3: The energy exchange between the fishbone mode in optimised shear discharges and the ICRH energetic ions as a function of the normalised toroidal canonical momentum and energy.

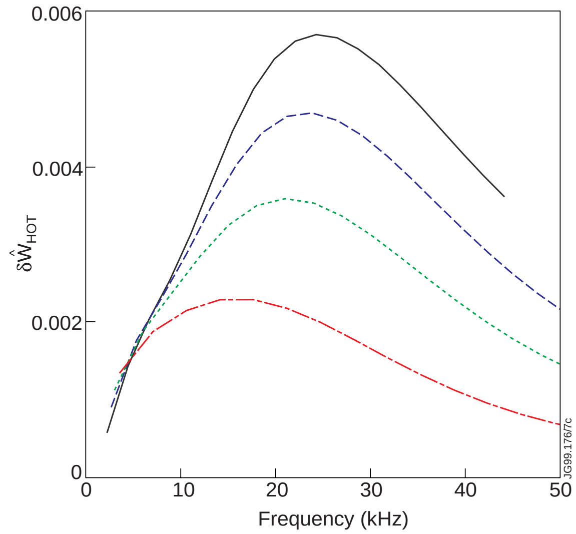

Fig.4: The energy exchange between the fishbone mode in optimised shear discharges and the ICRH energetic ions as a function of the mode frequency for values of the magnetic field of 2.5 T (black), 3.0 T (blue) , 3.4 T (green) , 4.0 T (red). The temperature of the fast ion tail of assumed to be T_{FAST}=1 MeV.