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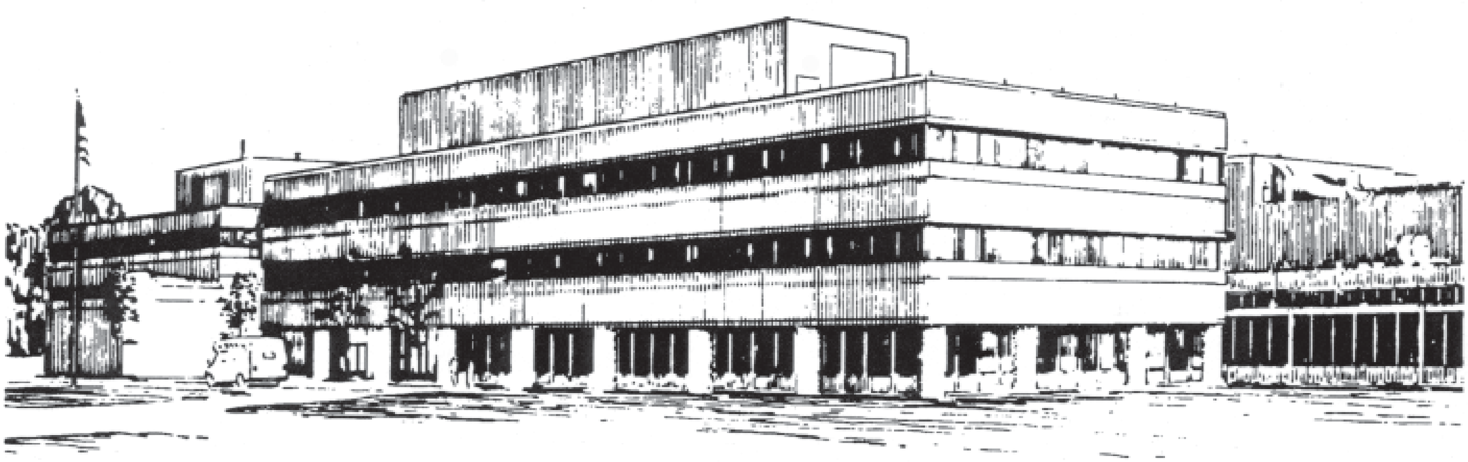

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Modeling of ICRH H-minority driven $n = 1$ resonant modes in JET*

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New types of low frequency $n = 1$ MHD activity were observed in JET discharges with high fast-ion energy content [1] exceeding the energy content of the background plasma. The frequency of such activity is between 50 and $80kHz$. The period of sawteeth in those discharges was changed by a factor of five by controlling the plasma density, which was attributed to the stabilization effect of fast hydrogen minority ions on the sawteeth. Note that fast H-minority beta was building up strongly in a low density plasma, because the slowing down time of fast ions is inversely proportional to the electron density.

In this paper we report on the development and application of NOVA-KN (Kinetic Non-perturbative) hybrid code, which uses ideal MHD approximation for the background plasma and includes kinetic fast particle response non-perturbatively. It is based on the ideal non-perturbative MHD code NOVA [2], and is modified to include finite orbit width (FOW) effects of fast ions. In its current version NOVA-KN has only trapped hot ions included. In general the mode frequencies of the resonant branches correspond to the combinations of characteristic trapped ion toroidal precession frequency, ω_d, and bounce frequency ω_b. We apply NOVA-KN to JET plasma conditions and show that $n = 1$ resonant and ideal branches can be unstable. Our results indicate that with the proper parameters of the hot ion population chosen obtained precession frequency branch has frequency, which match the one measured in experiments. This requires the energy of Maxwellian distributed H-minority ions to be $E_{H0} \simeq 0.8MeV$. This is above $E_{H0} = 0.5MeV$ typically found with NPA for similar discharges such as $\#47575$ and $\#47576$ reported in Ref. [1]. The mode structure and properties of such resonant branches are discussed.

1 Experimental observations

As an example we choose one of JET discharges $\#54305$, which had relatively low plasma density. This discharge revealed new types of MHD activity. The time evolution of electron temperature, plasma density and applied ICRH power are shown in Fig. 1 (a). Fig. 1 (b) clearly shows two types of plasma oscillations: $60 - 80kHz$ and $10 - 20kHz$ (around $t \simeq 52.5sec$) MHD activities with chirping frequencies. Fourier analysis of these instabilities shows that the toroidal mode number is $n = 1$.

2 Numerical procedure

The detailed description of the numerical procedure is given in Ref. [2] with the set of equations in which the effect of fast ions is included through the components of the perpendicular and parallel to the magnetic field perturbed pressure $\delta p_\perp = m_h \int d\mathbf{v} \mu B \hat{g}$, $\delta p_\parallel = m_h \int d\mathbf{v} 2 \left(\mathcal{E} - \mu B\right) \hat{g}$, where μ is the adiabatic invariant, B is the equilibrium magnetic field,

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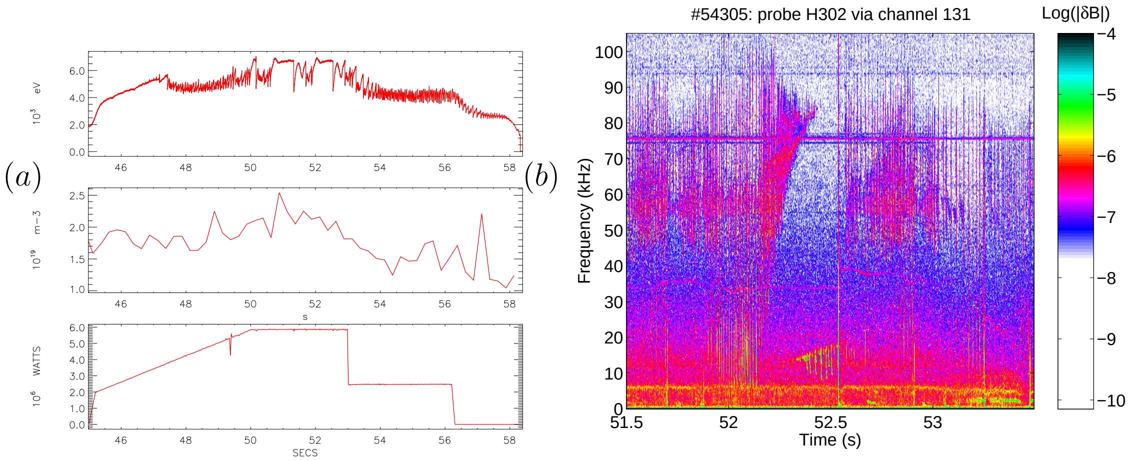

Figure 1: *On the figure (a), plasma electron temperature, density and ICRH power in JET* $\#54305$ *discharge are shown. On the figure (b), the magnetic coil signal spectrum is presented spanning within* $f = 0 - 100kHz$*.*

$\mathcal{E} = v^2/2$, $\mathbf{v}$ and v are the vector and the absolute value of the hot ion velocity, m_h is the hot ion (proton) mass, $\hat{g}$ is the nonadiabatic part of the perturbed distribution function. In this paper we will consider only trapped particle part of the nonadiabatic distribution function, while the adiabatic part includes both passing and trapped hot ions assuming isotropic equilibrium distribution function. For the function $\hat{g}$ we make use of the general expression from Ref. [3]

$$\hat{g} = \mathcal{E} \sum_{m,p} \frac{(\omega - \omega_*) G_{m,p}}{\omega - \overline{\omega_d} - p\omega_b} \frac{\partial F_h}{\partial \mathcal{E}} e^{-it\omega + im\theta - in\varphi}, \tag{1}$$

where ω_* is the H-minority drift frequency, $G_{m,p}$ is the matrix of wave-particle interaction (see Ref.[2]), F_h is the H-minority equilibrium distribution function, $\bar{\omega}_d$ is the bounce averaged toroidal precession frequency, ω_b is the bounce frequency of ion periodic motion in the poloidal cross section of the tokamak. In this paper we report on NOVA-KN development in which FOW effects are kept evaluating ion characteristic frequencies, whereas matrix G is calculated in zero orbit width (ZOW) limit. This allows to benchmark the code against ZOW version as well as clearly understand the effects due to the change in particle frequencies. In addition the equilibrium distribution function was assumed isotropic, which differs from peaked pitch angle distribution as expected for ICRH H-minority ions. However on average the characteristic frequencies of isotropic distribution are similar to the ones for H-minority ions as can be shown numerically. We note that typically the growth rate of resonant modes driven by hot ions with peaked pitch angle distribution is expected to be stronger, so that our results could underestimate the drive of resonant modes.

3 Simulations

To understand properties of resonant modes we show the spectrum of Alfvén continuum for chosen JET discharge $\#54305$ at $t = 51sec$ in Fig. 2 (a). $q = 1$ surface is approximately at $r/a \equiv \sqrt{\psi/\psi_0} = 0.6$, where ψ is the poloidal magnetic flux within a given surface and subscript 0 means that the value is taken at the edge. Without the bounce resonances NOVA-KN find two solutions. First mode is the continuation of the ideal $m = 1/n = 1$ mode (I-mode), which has zero real frequency without hot ions and is located within $q = 1$ surface.

The second solution is the resonant branch (R-mode) and has non-zero real frequency. R-mode interacts with the continuum and typically experiences the damping on the continuum. Provided that the drive is strong enough such mode can be driven unstable.

As expected the ideal kink mode is found unstable with NOVA in the absence of hot ions, but is strongly stabilized by the H-minority ions. It is shown in Fig. 2 (b), where I-mode is seen unstable at $\beta_{H0}/\beta_{pl} < 0.2$. It is plausible that the ideal branch is responsible for the low end of the spectrum oscillations shown in Fig. 1(b) at $f = 10 - 20kHz$. The frequency in NOVA-KN code is normalized to the Alfvén frequency, which for a given plasma discharge is around $f_A = 160kHz$, so that the I-mode solution should have mode frequency $f_{ideal} \sim 1kHz$ according to Fig. 2(b). Note, that this frequency is expected to increase when the radial coupling through FOW and realistic distribution function are introduced.

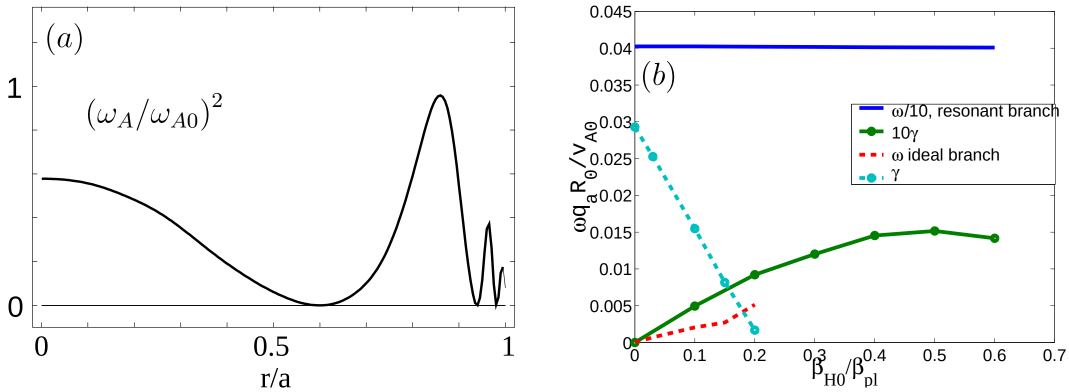

Figure 2: *Alfvén continuum for $n = 1$ (figure (a)) and real and imaginary parts of I- and R-mode frequencies of the resonant and ideal branches (figure (b)).*

The real part of the mode frequency of the resonant branches is determined by the characteristic particle frequencies. We plot the characteristic deeply trapped hot particle drift motion frequencies corresponding to ions with the bounce point at $r = a/3, \theta \simeq 0$ and with energies $E_{H0} = 0.8MeV$ in Fig. 3 (a). In the same figure we show the velocity weighting function in the integrand of the perturbed pressure, which gives the maximum contribution from particles with velocities $v/v_{H0} \simeq 1.7$. Such velocity corresponds to ions at the tail of Maxwellian energy distribution $E_H = 2.3MeV$. Thus it is those energetic tail ions which mostly determine the frequency of the R-mode. Note, that Fig. 3 (a) corresponds to the deeply trapped particles whereas on average over the phase space characteristic frequencies are similar to ones for the ions with the bounce tip at $\theta = \pi/2$ (i.e. such as ICRH H-minority ions). For trapped ions with bounce tip at $\theta = \pi/2$ the toroidal precession frequency is approximately two times smaller, i.e. if for the deeply trapped ions (as one can see from the figure) $\Omega_d \equiv \omega_d q_a R_0/v_{A0} \simeq 0.7$, than on average over the phase space $\langle\Omega_d\rangle \simeq 0.35$. This is a value of the resonant mode frequency to be expected in the code. One can see also from Fig. 3(a) that the finite orbit effects do not change the toroidal precession (and bounce frequency) significantly. On the other hand if the bounce resonance is included in the denominator of the perturbed pressure, the frequency of such resonant mode should have been $\Omega \sim 2$ (it is about the same for the H-minority ions), which is in the TAE frequency range.

Indeed NOVA-KN founds the mode with the frequency $\Omega = 0.4$, which is almost unchanged as the beta of hot ions is increased according to Fig. 2 (b). Since it has finite frequency the R-mode interacts with and reflects from the continuum. The R-mode structure shown in

Fig. 3 (b) has visible "drop" at $r/a = 0.4$ (at the Alfven continuum), which is in contrast with the ideal I-mode drop at $q = 1$ surface. The convergence of the code was checked by increasing the number of the radial points. Note, that we have chosen the temperature of the H-minority ions to be $E_{H0} = 0.8MeV$ to match the computed R-mode frequency to the measured one. It is also worthwhile to note, that recent analysis [4] of the gamma-spectrum (method described in Ref. [5]) shows that in the particular discharge of interest the temperature of the hot ions was about $1MeV$.

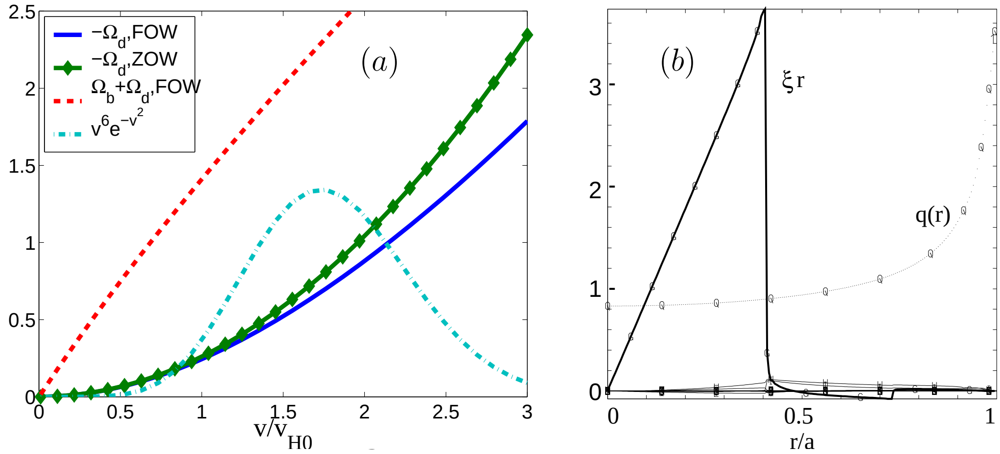

Figure 3: *On Figure (a), shown are the H-minority ion characteristic frequencies as they appear in the denominator of Eq.(1) and the weighting factor, which is the integrand in the expression for the perturbed pressure. On Figure (b), the mode poloidal harmonic radial structure (dominant harmonic has $m = 1$) and the safety factor profile are shown.*

4 Summary

A non-perturbative code NOVA-KN has been developed to account for FOW effects in non-perturbative resonant modes such as the low frequency MHD modes observed in JET. NOVA-KN code was used to show that the resonant modes with frequencies in the observed frequency range are ones having the characteristic toroidal precession frequency of H-minority ions. Results are similar to previous theoretical studies of fishbone instabilities, which were found to exist at characteristic precession frequencies of hot ions.

References

[1] M. J. Mantsinen, S. E. Sharapov, B. Alper, A. Gondhalekar and D. C. McDonald, Plasma Phys. Control. Fusion **42** (2000) 1291.

[2] C. Z. Cheng, Phys. Reports, **211**, 1 (1992).

[3] N. N. Gorelenkov, *et.al.*, Phys.Plasmas **6**, 2802 (1999).

[4] V. G. Kiptily, private communication.

[5] V. G. Kiptily, F. E. Cecil, O. N. Jarvis, *et. al.*, Nucl. Fusion, **42** (2002) 999.

[6] L. Chen, R. B. White, M. N. Rosenbluth, Phys. Rev. Lett., **52** (1984) 1122.

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