

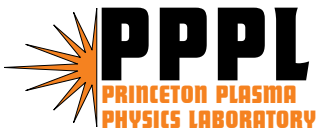
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## Fast Ion Effects on Fishbones and $n=1$ Kinks in JET Simulated by a Non-perturbative NOVA-KN Code

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**Fast ion effects on fishbones and  $n=1$  kinks in JET simulated by a non-perturbative NOVA-KN code\***

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# Fast ion effects on fishbones and $n=1$ kinks in JET simulated by a non-perturbative NOVA-KN code<sup>1</sup>

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**Abstract.** New global nonperturbative hybrid code, NOVA-KN, and simulations of resonant type modes in JET plasmas driven by energetic H-minority ions are presented. The NOVA-KN code employs the ideal MHD description for the background plasma and treats non-perturbatively the fast particle kinetic response, which includes the fast ion finite orbit width (FOW) effect. In particular, the  $n = 1$  fishbone mode, which is in precession drift resonance with fast ions, is studied. The NOVA-KN code is applied to model an  $n = 1$  ( $f = 50 - 80kHz$ ) MHD activity observed recently in JET low density plasma discharges with high fast ion (H-minority) energy content generated during the ICRH. This  $n = 1$  MHD activity is interpreted as the instability of the  $n = 1$  precession drift frequency fishbone modes.

Low frequency  $n = 1$  MHD activity was observed in JET discharges with high fast-ion energy content comparable to or exceeding the energy content of the background plasma [1]. 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. The energetic H-minority beta builds 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 the NOVA-KN (Kinetic Non-perturbative) hybrid code, which is an extension of the previously developed non-perturbative NOVA code in which fast ions were treated with zero orbit width (ZOW) [2–4].

It uses an ideal MHD approximation for the background plasma and includes kinetic fast particle response non-perturbatively. The new version of NOVA-KN includes realistic approximation for fast ions, as it can treat fast ions including the finite (arbitrary) orbit width (FOW). In its current

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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 fast ion toroidal precession drift frequency,  $\omega_d$ , and the bounce frequency  $\omega_b$ . We apply NOVA-KN to JET plasmas 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 the precession drift frequency branch has frequency close to the one measured in experiments as was suggested in Ref.[5]. This requires the energy of Maxwellian distributed H-minority ions to be  $E_{H0} \simeq 1MeV$ . The mode structure and properties of such resonant branches are discussed.

## 1. Experimental observations

For the analysis we choose one of JET discharges, #54305, which had relatively low plasma density  $n_e \simeq 2 \times 10^{13} cm^{-3}$ . Other plasma parameters in this shot were the equilibrium magnetic field in the geometrical center  $B_0 = 2.75T$ , geometrical center at  $R_0 = 2.91m$ , plasma minor radius  $a = 0.95m$ . The time evolution of electron temperature, density and applied ICRH power is shown in Fig. 1(a). This discharge revealed MHD activity in a new frequency range. Fig. 1 (b) clearly shows two types of plasma oscillations:  $50 - 80kHz$  and  $10 - 20kHz$  (around  $t \simeq 52.5sec$ ) MHD activities, both with chirping frequencies on a millisecond time scale. Fast frequency chirping of the former is different from the typical fishbone, whereas the latter has the downchirping more fishbone-like frequency evolution. Fourier analysis of these instabilities shows that the toroidal mode number is  $n = 1$ . For the interpretation of these observations it is critical to use realistic fast ion parameters such as the fast ion temperature measured by the diagnostic of the gamma ray emission due to fast proton interaction with different plasma species [6]. In Fig. 2(a) measured gamma spectrum shows an emission peak at  $4.4MeV$ , which is generated by minority ions at energies above  $5MeV$ , whereas the time evolution of this peak amplitude is plotted in Fig. 2(b). It reflects the correlation of the high energetic particle component density with the soft x-ray signal and is proportional to the density of high energy tail  $E_H > 5MeV$  ions. Detailed numerical analysis of this spectrum gives the effective temperature for the H-minority  $T_H = 1 (\pm 0.2) MeV$ .

## 2. Numerical procedure

The detailed description of the numerical procedure will be published elsewhere while the basic set of equations is derived in Ref. [3]. The effect of fast ions is included through the perpendicular and parallel to the magnetic field perturbed pressure components, which non-adiabatic parts are  $\delta p_{\perp} = m_h \int d^3v \mu B \hat{g}$ ,  $\delta p_{\parallel} = m_h \int d^3v 2(\mathcal{E} - \mu B) \hat{g}$ , where  $\mu$  is the adiabatic invariant,  $B$  is the equilibrium magnetic field,  $\mathcal{E} = v^2/2$ ,  $v$  is the absolute value of the hot ion velocity,  $m_h$  is the hot ion (H-minority, proton) mass,  $\hat{g}$  is the nonadiabatic part of the perturbed distribution function. In this paper we will include only the trapped particle part of the nonadiabatic distribution function. For

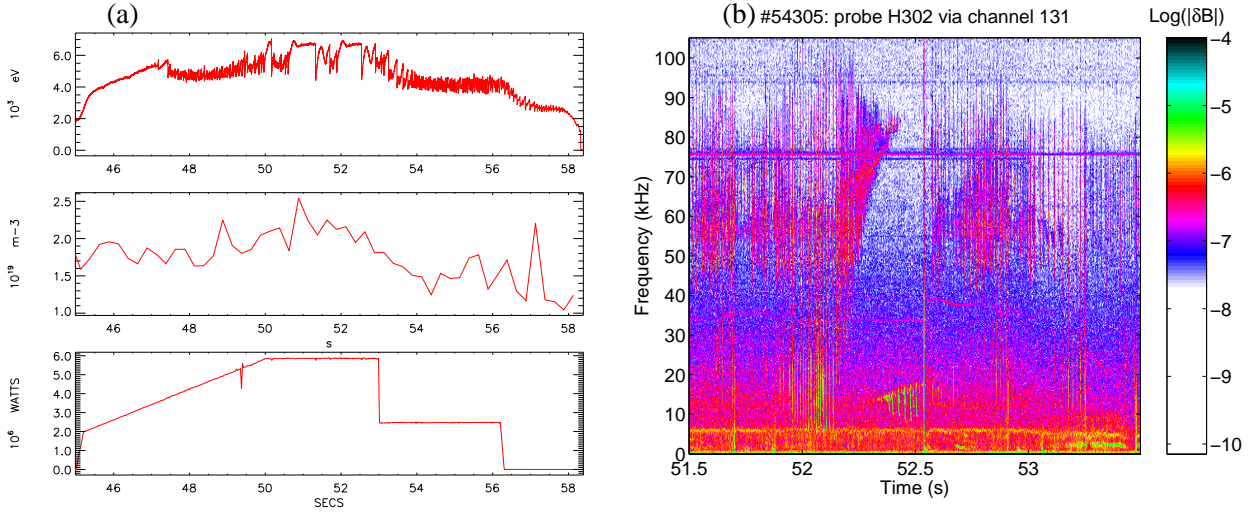


FIG. 1: Plasma electron temperature, density and ICRH power in JET #54305 discharge are shown on the figure (a). On the figure (b), the evolution of the spectrum of the magnetic coil signal is presented for the frequency range  $f = 0 - 100\text{kHz}$ .

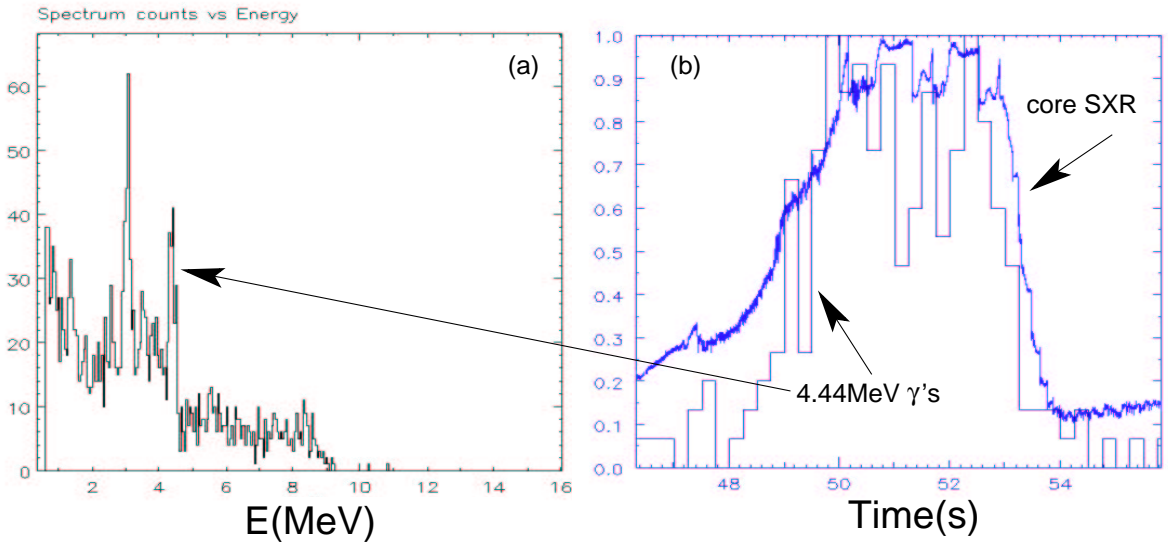


FIG. 2: Gamma spectrum for JET shot #54305 (figure (a)) and the time evolution of its 4.4 MeV peak amplitude (figure (b)). Also shown in figure (b) is the evolution of the soft x-ray signal.

the function  $\hat{g}$  we make use of the general expression from Ref. [7]

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

where  $\omega_*$  is the H-minority drift frequency,  $G_{m,p}$  is the matrix of wave-particle interaction (see Ref.[3]),  $F_h$  is the H-minority equilibrium distribution function,  $\bar{\omega}_d$  is the bounce averaged toroidal precession drift frequency,  $\omega_b$  is the bounce frequency of ion periodic motion. In our previous work [5] FOW effects were kept via the ion drift motion characteristic frequencies, whereas ma-

trix  $G$  was calculated in the ZOW limit. In addition the distribution function,  $F_h$ , was assumed isotropic. In this paper we compute the wave-particle interaction matrix  $G$  with FOW effects and with the following distribution function,

$$F_h = C e^{-E/T_H} e^{-(\lambda-\lambda_0)^2/\Delta\lambda^2} (1-\psi^2)^{2.2},$$

where  $C$  is the normalization constant,  $T_H$  is H-minority temperature, Gaussian pitch angle distribution is centered at the magnetic axis, i.e. at  $\lambda = \lambda_0 = 1$ ,  $\lambda = \mu B_{ax}/E$ ,  $B_{ax}$  is the magnetic field at the magnetic axis,  $\psi$  is the poloidal magnetic flux within a given surface, normalized to its edge value. The pitch angle width is taken as  $\Delta\lambda = 0.05$ .

### 3. Simulations

To understand properties of resonant modes it is useful to show the spectrum of the Alfvén continuum as given in Fig. 3(a) for the JET discharge #54305 at  $t = 51\text{sec}$  in which the total beta was  $\beta_{tot} = 3.6\%$ . The surface of  $q = 1$  is approximately at  $r/a \equiv \sqrt{\Psi} = 0.6$ . Note, that the minor radius of  $q = 1$  surface calculated with the respect to the normalized toroidal magnetic field,  $\phi$ , flux is  $\sqrt{\Phi} \sim 0.5$ . With the precession drift resonance, NOVA-KN finds two solutions. First mode is the continuation of the ideal  $m = 1/n = 1$  mode (we call it I-mode), which has zero real frequency without hot ions and is located within the  $q = 1$  surface. The second solution is the resonant branch (called here R-mode) and has non-zero real frequency. R-mode interacts with the continuum and typically experiences damping on it. Provided that the drive is strong enough such mode can be driven unstable by energetic ions due to the universal pressure gradient drive.

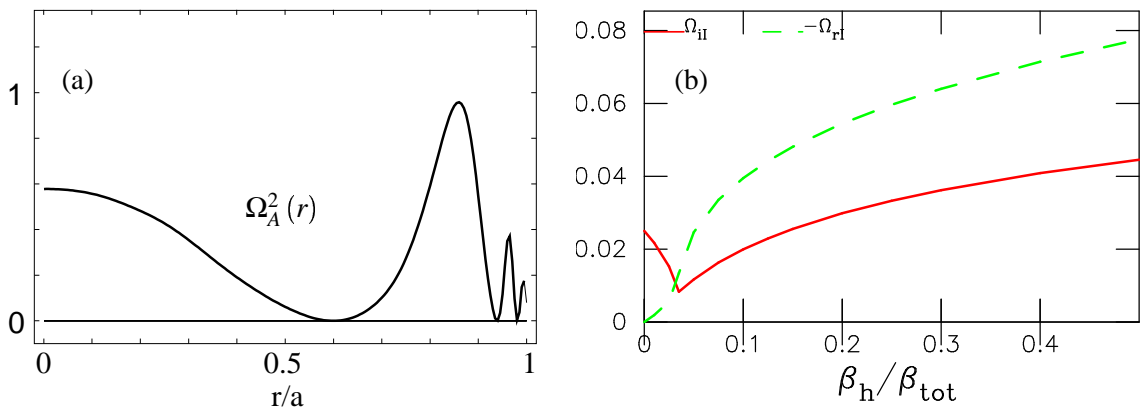


FIG. 3: Alfvén continuum for  $n = 1$  (figure (a)) and ideal mode (I-mode) frequency (imaginary and real parts, subscripts  $i$  and  $r$ ) for the H-minority temperature  $T_H/(T_i + T_e) = 6$  (figure (b)). All the frequencies are normalized to the Alfvén frequency  $\Omega \equiv \omega q_a R_0 / v_{A0}$ .

As expected the ideal kink mode is found unstable with NOVA-KN in the absence of hot ions, but is stabilized by the H-minority ions provided their temperature is high enough. At low tempera-

ture there is only one solution, I-mode. It stays unstable as the fast ion pressure is increased as shown in Fig. 3(b), where the ratio of the H-minority temperature to the plasma ion plus electron temperature  $T_H/(T_i + T_e) = 6$ . All the frequencies here are normalized  $\Omega \equiv \omega q_a R_0 / v_{A0}$ , where  $q_a$  is the edge safety factor,  $v_{A0}$  is the central Alfvén velocity. The real I-mode frequency increases with the fast ion beta. At  $\beta_{h0}/\beta_{tot0} > 0.05$  this solution shows the same properties as the fishbone branch (R-mode): its frequency is close to the averaged precession drift frequency.

At higher temperature these two branches appear as separate solutions as shown in Fig. 4(a) for  $T_H/(T_i + T_e) = 32$ . The R-mode frequency is an increasing function of H-minority temperature as shown in Fig. 4(b). In fact it is almost proportional to the precession drift frequency of the H-minority population. It follows from Fig. 4(a) that the I-mode is unstable at  $\beta_{H0}/\beta_{tot0} < 0.1$ . 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  $f_A = 130kHz$ , so that the I-mode solution should have mode frequency  $f_{ideal} \sim 1kHz$  according to Fig. 4(a). Note that the plasma rotation frequency is about  $f_{rot} \simeq 2kHz$ . Also we do not include the thermal ion diamagnetic frequency, which should increase the real frequency of the I-mode [8, 11]. If these effects are included, the I-mode frequency should account for the observed frequency of  $10 - 20kHz$ .

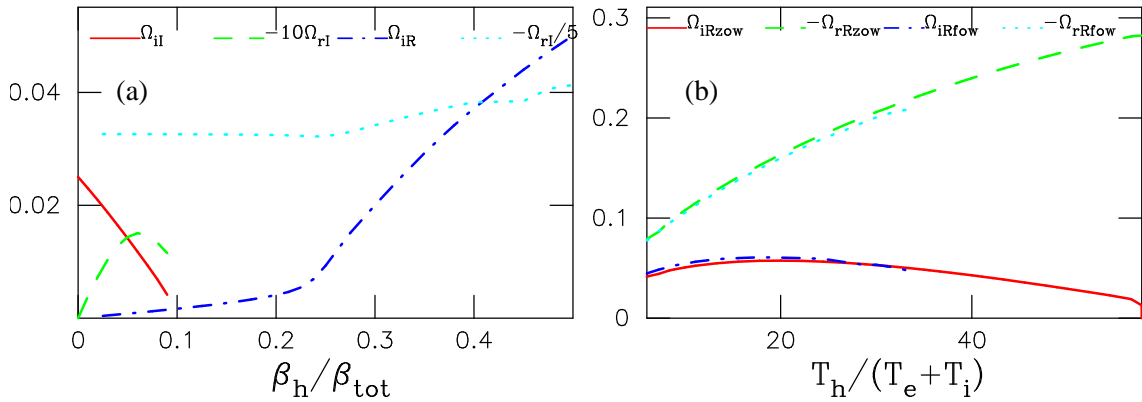


FIG. 4: The ideal and fishbone (I- and R-) mode frequencies (subscripts I and R) at  $T_H/(T_i + T_e) = 32$  (figure (a)). Real and imaginary parts of R- mode frequency as functions of H-minority temperature (figure (b)).

The real part of the frequency of the resonant branch is determined by the characteristic particle frequencies. We plot the characteristic trapped hot particle drift motion frequencies corresponding to ions with the bounce point at the plasma axis,  $\theta = \pi/2$ , and  $r = a/3$ , versus velocity normalized to particle velocity at  $E_H = 0.54MeV$  ( $T_H/(T_i + T_e) = 32$ ) in Fig. 5. 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, which have energy  $E_H = 1.56MeV$ . Thus it is those energetic tail ions which determine the frequency of the R-mode. One can see that for trapped ions with bounce tip at  $\theta = \pi/2$  the toroidal precession drift frequency is  $\Omega_d = 0.25$ . This is a value of the resonant mode frequency to be expected in the code, which we find to be close,  $\Omega_{rR} = 0.21$  (see Fig.4(a)). One can see also from Fig. 5 that the FOW effects do not change the toroidal precession 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  $\Omega \sim 1.1$ , which is in the TAE frequency range.

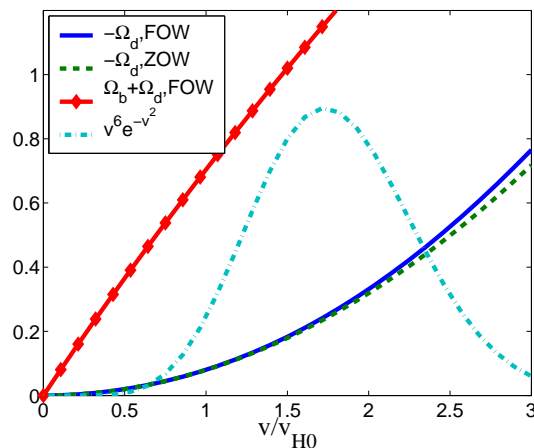


FIG. 5: The H-minority ion characteristic frequencies as they appear in the denominator of Eq.(1) and the weighting factor, which is the integrand in the expression for the perturbed pressure. Velocity is normalized to the velocity of  $E_H \simeq 0.54MeV$  H-minority ions.

Calculated real part of R-mode frequency  $\Omega_{rR} = 0.21$  (see Fig.4(a)) at  $T_H/(T_i + T_e) = 32$  corresponds to the measured value in the lab frame  $f = 27kHz + f_{rot} = 29kHz$ , i.e.  $T_H \simeq 0.54MeV$ , which is the achieved computational limit for the FOW calculations. Fig.4(a) shows, as expected, that the R-mode frequencies in ZOW are very similar to the FOW results. This is due to, first, the toroidal precession drift frequencies are about the same, and, second, the minor radius of  $q = 1$  surface is large in the case we analyzed, so that the majority of fast ions are localized inside  $q = 1$  surface where FOW effects are not important. Thus if  $q = 1$  surface is near the magnetic axis we would expect the FOW effects to be significant as only part of particle orbit will be interacting with the mode.

In the case of ZOW we obtained  $\Omega_{rR} = 0.3$  for  $T_H/(T_i + T_e) = 60$  (or  $f \simeq 40kHz + f_{rot} = 42kHz$ ), which is close to observations and the temperature of the H-minority to be  $T_H = 1MeV$ . One

notes that the R-mode is stabilized at high particle energy  $T_H/(T_i + T_e) > 60$ . This is due to the mode frequency increase, which results in stronger continuum damping. Indeed the results of NOVA-KN can be used to find the continuum damping of the R-mode (see Fig.4(a)) by assuming that at each value of  $\beta_h/\beta_{tot}$  the imaginary part is given by  $\Omega_{iR} = \Omega_{icont} + \Omega_{iH}$ , where  $\Omega_{iH} \sim \beta_h$  is the H-minority driving contribution to the growth rate of the R-mode. With this we find that  $\Omega_{icont} = -0.043$  at  $\beta_h/\beta_{tot} = 0.2$  and is about 40% of the mode real frequency (for that one needs to extrapolate  $\Omega_{iR}(\beta_h/\beta_{tot})$  curve on figure 4(a) from  $\beta_h/\beta_{tot} > 0.24$  to  $\beta_h/\beta_{tot} = 0.2$  as the numerical solution at  $\beta_h/\beta_{tot} < 0.24$  should be discarded). It is also seen from Fig.4(a) that the critical pressure of H-minority to excite the R-mode is  $\beta_{hcrit}/\beta_{tot} = 0.2$ . Theory prediction for the precession drift frequency fishbone instability [2, 3, 9–11] is  $\beta_{hcrit} = \Omega_d/\pi q_a \simeq 0.68\%$  for  $\Omega_d$  taken at  $E_H = T_H = 0.54 MeV$ . This is close to our result that  $\beta_h = 0.2\beta_{tot} = 0.72\%$  obtained for the same H-minority temperature. Theory predicts that the continuum damping is proportional to the real mode frequency  $\Omega_{icont} \simeq -\Omega_{rR}/q_a = -0.05$  (to be compared with obtained in NOVA-KN calculations  $\Omega_{icont} = -0.043$ ).

The observation that the continuum damping is proportional to the mode frequency is important and agrees with both numerical and experimental results. In Fig.1(b) at  $t \simeq 52.3 sec$  the observed MHD activity frequency rises from  $50 kHz$  to  $80 kHz$  and results in R-mode stabilization. The gamma spectrum peak signal increases at about that time (see Fig.2(b)), which may indicate the increase of the H-minority ion temperature.

Note that the increase in the mode frequency can be explained within the framework of the theory of the sawtooth effects on fast ions [12–14]. In that theory only low energetic fraction among the trapped fast ions is redistributed within the  $q = 1$  surface. The threshold ion energy is determined by the energy of fast ion whose precession drift frequency equal to the inversed sawtooth crash time and typically reaches several hundreds  $keV$  in JET. It seems plausible that after the sawtooth crash the low energy part of the fast ion distribution function is depleted so that the velocity space average of Eq.(1) results in higher mode frequency.

It is also important to note that the distribution function plays a major role in the R-mode frequency, which is supported by the numerical analysis. Broader pitch angle distribution and/or the higher value of the  $\lambda_0$  (this is equivalent to changing the cyclotron resonance layer since  $\lambda_0 \sim R_{res}$ ) increases the frequency by up to 50%.

Radial mode structures we analyzed are shown in Fig. 6. The I-mode has a step like eigenmode structure at  $q = 1$  surface. On the other hand the R-mode has double step structure around  $q = 1$  surface with the width of the non-ideal layer proportional to the frequency of the mode. It is also seen that the mode structure changes significantly as the fast ion parameters evolve.

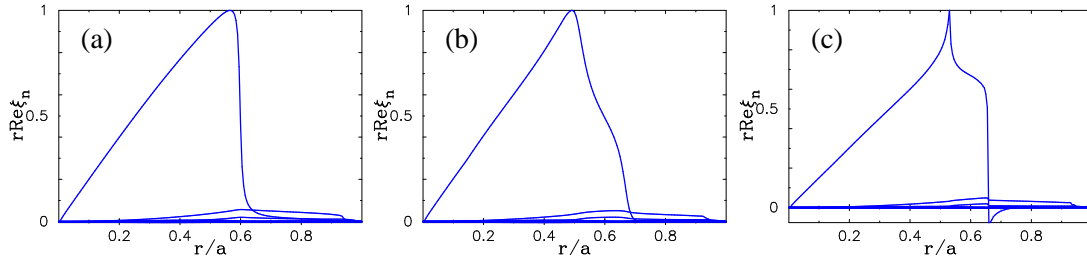


FIG. 6: Radial structures of the resonant mode poloidal harmonics (dominant harmonic has  $m = 1$  for all modes). On figure (a) the I-mode structure is given for  $\beta_h/\beta_{tot} = 0.002$  and  $T_H/(T_i + T_e) = 6$ . Figures (b) and (c) corresponds to  $T_H/(T_i + T_e) = 32$  and  $\beta_h/\beta_{tot} = 0.5$  and  $\beta_h/\beta_{tot} = 0.075$ , respectively.

#### 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. The NOVA-KN code was used to identify the observed activity of the resonant frequency fishbone modes having the characteristic toroidal precession drift frequency of H-minority ions, which is in agreement with our initial studies [5]. Plasma rotation and thermal ion drift frequencies need to be included to match the calculated frequencies to the observations. Numerical simulations are able to find the continuum damping of the R-mode and the critical pressure sufficient to excite these modes. The R-mode continuum damping has been confirmed to be proportional to the mode frequency explaining the observed stabilization of such instability as its frequency increases.

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