Non-perturbative Simulation of Resonant Modes*

N. N. Gorelenkov[1], C. Z. Cheng[1], M. J. Mantsinen[2], S. E. Sharapov[3]

6th October 2003

[1] *Princeton Plasma Physics Laboratory, Princeton, NJ, 08543, USA;*

[2]*Helsinki University of Technology, Finland*;

[3]*Euroatom/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK*

8th IAEA TCM on Energetic Particles

6-8 October 2003, San Diego, CA

This research was supported in part by the U.S. Department of Energy under the contract DE-AC02-76CH03073 and in part by the European Fusion Development Agreement.

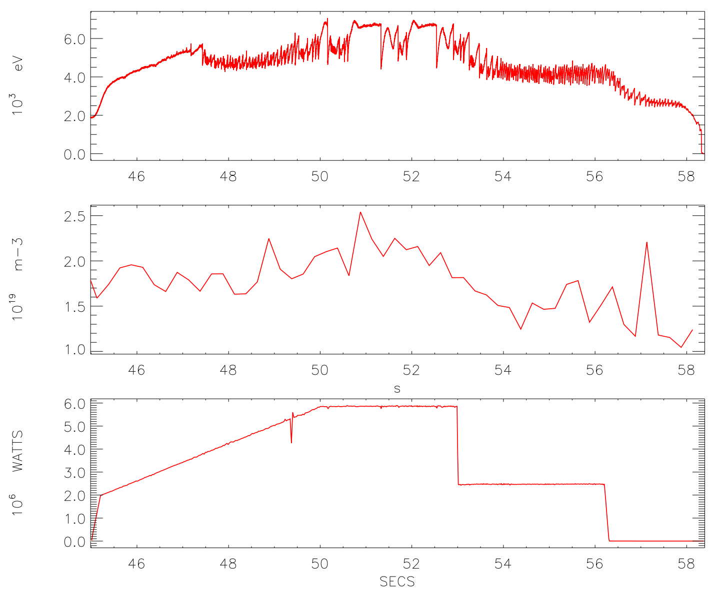
OUTLINE

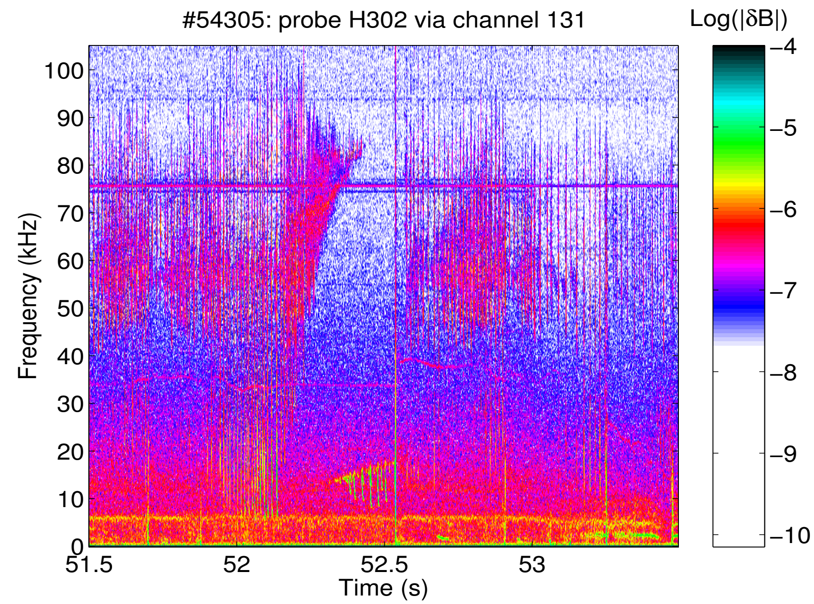
- Motivation to develop the nonperturbative numerical code
- Experimental motivation
- Numerical procedure
- Results and comparison with theory

Introduction

- Resonant (or Energetic Particle (EPM)) Modes are often observed in tokamak experiments in the presence of hot energetic ions (fishbones, BAEs, R-TAEs).
- New types of low frequency $n = 1$ MHD activity were observed in JET discharges with high fast-ion energy content (Mantsinen00).
- New realistic numerical tools are required to address resonant, non-perturbative modes:
  - such as NOVA-KN (Kinetic Non-perturbative) hybrid code we are developing and apply
  - Carefull phase space integration to evaluate effect of ω_d on the resonant mode drive is required.
  - Important to know linear dispersion relation for perturbative nonlinear theory application (such as Berk-Breizman TAE saturation theory).
  - Complex plasma geometries require numerical treatment of particle-wave interaction.
  - Continuum mechanism may play major role in damping of some modes.

Experimental Observations in JET discharge #54305





Two types of plasma oscillations are seen:

- $60 - 80kHz$ and $10 - 20kHz$ (around $t \simeq 52.5sec$) with $n = 1$.
- Hot ion (ICRH H-minority) beta is large $\beta_H \sim 2\% \sim \beta_{pl}$.
- Both are chirping frequency - “fishbones”?

Numerical procedure in NOVA-KN

NOVA-KN - hybrid code, integro-differential problem:

Second order ideal MHD $+$ hot ions, coupled through perturbed pressure (Cheng, '92, see also next talk by C.Z.Cheng):

$$\delta p_{\perp} = m_h \int d\mathbf{v} \mu B \hat{g}, \ \delta p_{\|} = m_h \int d\mathbf{v} 2\left(\mathcal{E} - \mu B\right)\hat{g}$$

$\hat{g}$ - nonadiabatic perturbed distribution function (Gorelenkov, '99):

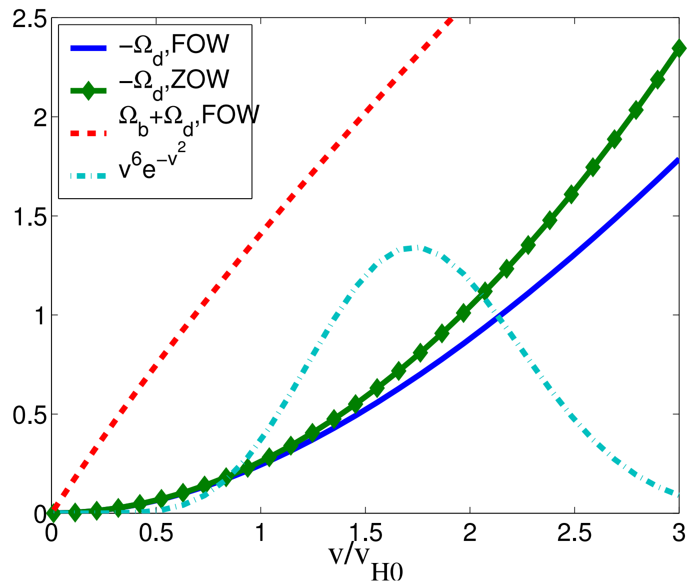
$$\hat{g} = \mathcal{E} \sum_{m,p} \frac{(\omega - \omega_*) G_{m,p}}{\omega - \overline{\omega_d} - p\omega_b} \frac{\partial F_h}{\partial \mathcal{E}} e^{-it\omega + im\theta - in\varphi}, \qquad (1)$$

$G_{m,p}$ is the matrix of wave-particle interaction (Cheng '92).

- Present version uses ZOW for G matrix.
- Accurate estimate of drift $\bar{\omega}_d$ and bounce ω_b hot ion frequencies in FOW.
- NOVA-KN solves integro-differential equations and finds mode frequency in complex plane.

Characteristic hot ion drift motion frequencies

Consider deeply trapped hot ions at $r/a = 1/3$ and $E_{H0} = 800keV$ (agrees with ORBIT).

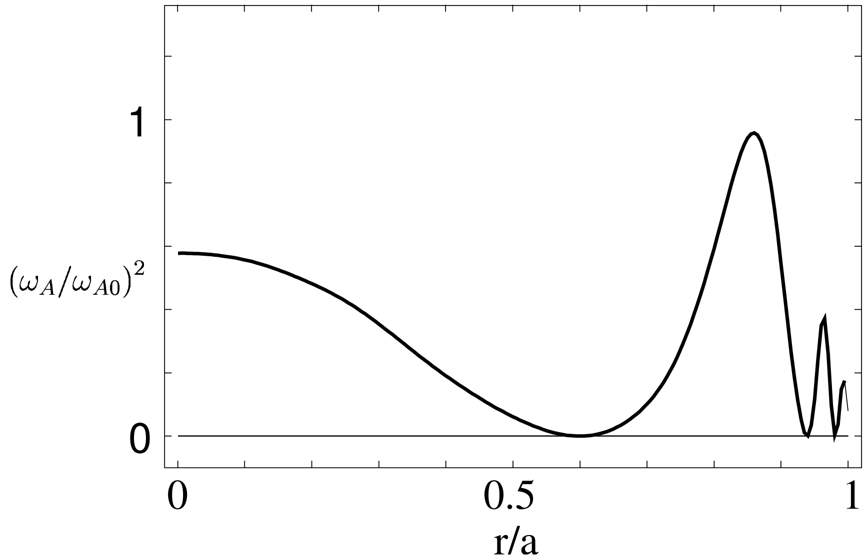


Characteristic frequencies are determined by the ions with $v/v_{H0} \simeq 1.7$ ($E_{H0} = 2.3MeV$), where the perturbed pressure integrand is peaked $v^6 e^{-v^2}$. $\Rightarrow$

1. $\Omega_d \equiv \omega_d/\omega_{A0} \sim 0.7$ (~ 0.35 for ICRH H-minority, $\sim 60kHz$) and
2. $\Omega_b \equiv \omega_b/\omega_{A0} \sim 2$, ($\omega_{A0}/2\pi = 160kHz$).

Alfvén continuum

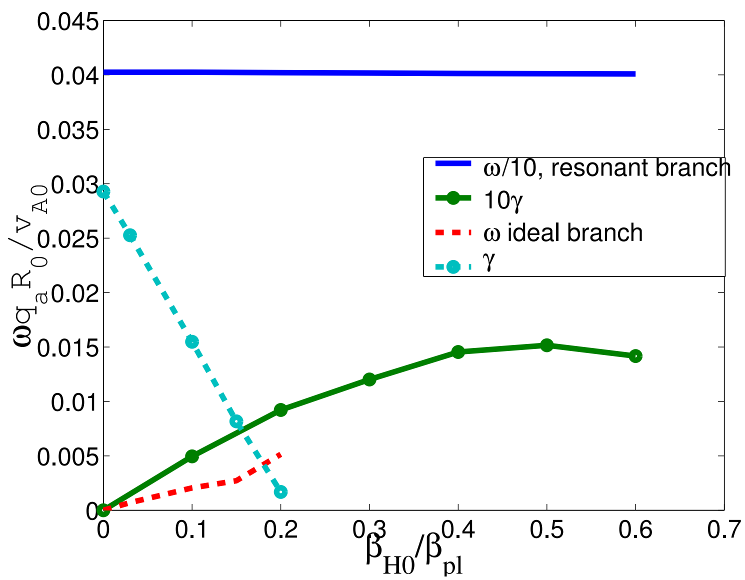
$q = 1$ surface is at $r/a \equiv \sqrt{\psi/\psi_0} = 0.6$.



- Any mode with non-zero frequency is reflected from the continuum.
- Drive should be strong enough to overcome the continuum damping.

Two branches are found with NOVA-KN

- Lower frequency mode is a continuation of the ideal mode.
  It is strongly stabilized by hot ions at $\beta_{H0}/\beta_{pl} > 0.2$.
- Higher frequency mode (higher frequency fishbone -resonant mode) has frequency comparable to the measured at H-minority temperature $800keV$.

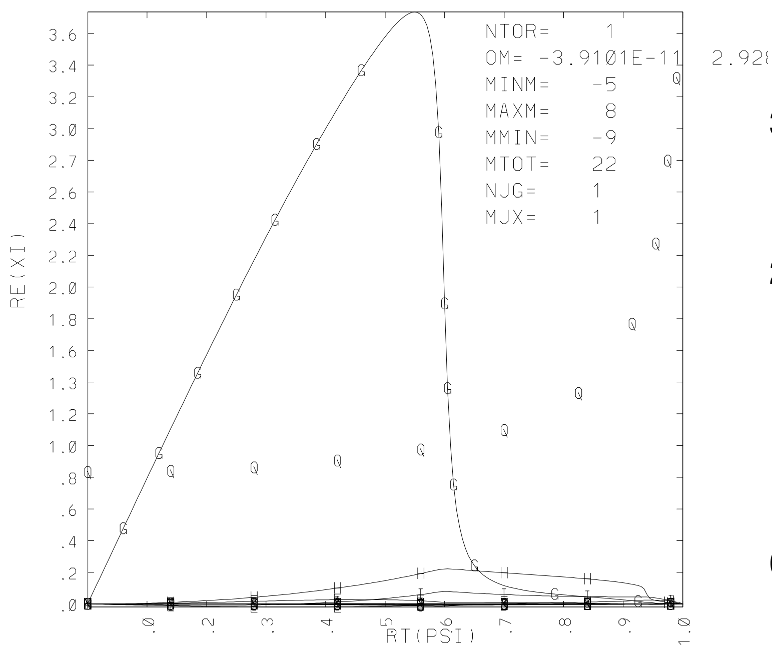


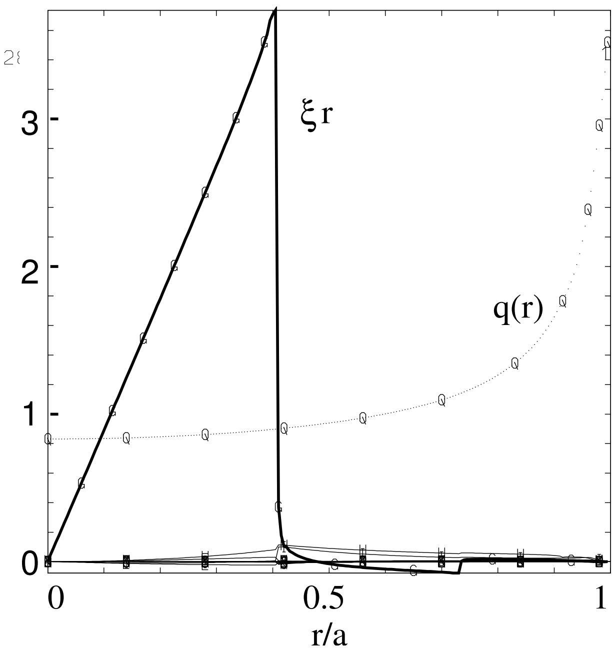
Ideal and Resonant mode radial structures

Shown are the radial structures of the dominant poloidal harmonics ($m = 1$).

Ideal mode

Resonant mode





- Ideal mode is strongly driven $\Rightarrow$ mode structure is effected.
- Resonant mode is reflected from the continuum due to finite frequency.
  - Predicted growth rate is probably too low for such nonperturbative mode.

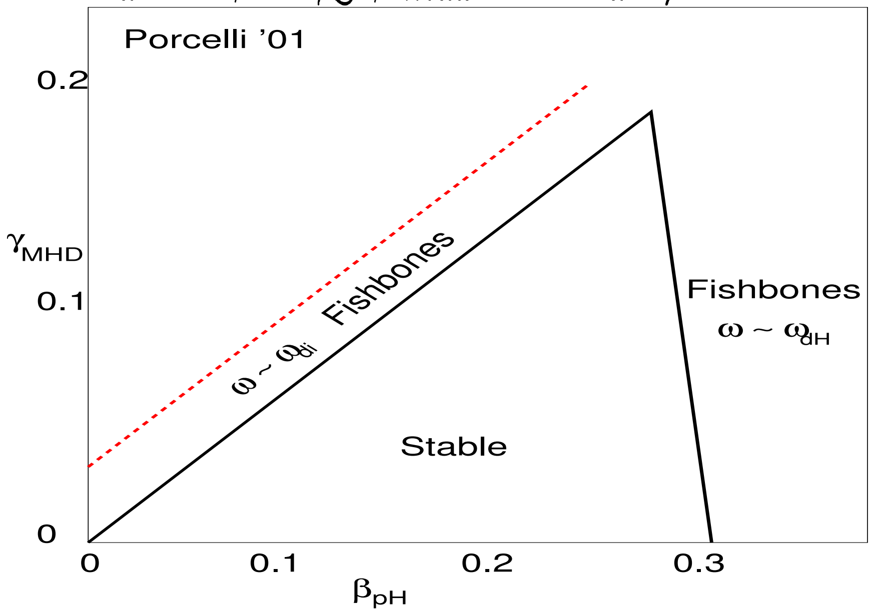
Comparison with theory

Two types (branches) of fishbones are known Chen, et.al. '84, Coppi, et.al. '86, '88, Porcelli '01: $i\left[\omega\left(\omega-\omega_{di}\right)\right]^{1/2}=\lambda_{mhd}+\lambda_{H}$.

- Low frequency $\omega\sim\omega_{di}$, if $\omega_{di}\ll\omega_{dH}$(∼1:250) and

$$\beta_{H}\lesssim\beta_{min}\simeq\pi\left[\beta^{2}-\left(\beta^{MHD}\right)^{2}\right]$$

- High frequency $\omega\simeq\omega_{dH}$, if $\beta_{H}\gtrsim\beta_{max}\simeq\epsilon\omega_{dH}/\omega_{A}\pi$.



NOVA-KN predicts $\omega/\omega_{dH}\sim 1/100$ for low frequency branch.

H-minority distribution function (factorizing?) may be a key factor for ω_{I}.

Summary

- A non-perturbative code NOVA-KN is being developed to account for realistic calculations of the non-perturbative resonant modes with FOW effects. It is fast and useful tool to study physics of particle-wave interaction.
- More new physics needs to be included in computations such as: nonisotropic distribution function of hot ions, nonisotropic plasma equilibrium, radial coupling due to FOW.
- Comparison with JET experiments shows that the possible explanation for the $10-70kHz$ frequency range MHD $n=1$ oscillations is the excitation of the two types of modes.
  - At low frequency $f = 10-20kHz$ the unstable mode is hot ion modified ideal MHD mode excited when beta of hot ions is not so strong, but frequency in experiment is higher.
  - At higher frequencies $f = 50-70kHz$ NOVA-KN predicts instability of the resonant modes having frequency equal to characteristic toroidal precession frequency of H-minority ions.

Summary (continued)

- Expected hot ion energy is $800keV$ in the discharge studied, which is slightly higher than typically observed $500keV$, but agrees with the preliminary results by V. Kiptily.