RWM Control Code Maturity

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RWM Control Code Maturity

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Ricerca Formazione Innovazione

DIII-D
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CREATE

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Outline

- **Introduction**
- **Formulations behind advanced RWM control code**
  - Passive stabilisation: drift-kinetic-MHD hybrid
  - Active control: 3D conductors + damping physics
- **Examples of recent results**
  - Kinetic effects from fast ions (DIII-D)
  - New CarMa implementation: 3D walls + kinetic effects
  - Simulation of RWM feedback in RFX
- **Summary**

Introduction: RWM code maturity issues

- **Significant progress has been made in recent years towards realistic modelling of the RWM**
- **Two major issues have been attacked in developing RWM control codes**
  - Passive control: mode damping physics (plasma rotation, drift-kinetic mode-particle resonances)
  - Active control: 3D structure of walls and feedback coils, realistic (and advanced) control logics
- **Eventual goal is to have a code capable of solving above issues simultanously and consistently**
- **CarMa code is ready to perform this task.**
- **There are a few other RWM codes, with one or another advanced features. (AEGIS-K, LIGKA, MISK, MISHKA+HAGIS, VALEN, STARWALL, NMA,KINX,...)**

Introduction: MARS-F/K & CarMa codes

- **MARS-F is single fluid, full MHD, full toroidal eigenvalue code with feedback options, including**
  - Toroidal shear flow of plasma
  - Complete thin wall model (2D wall)
  - Continous description of control coils along toroidal angle
- **MARS-K adds drift-kinetic terms into MHD in a self-consistent manner, including kinetic contributions from**
  - Trapped and passing thermal particles [Liu PoP08]
  - Trapped fast ions (reported here)
- **CarMa couples MARS-F/K with a 3D eddy current code CARIDDI**
  - Coupling strategy is a key issue

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Self-consistent formulation couples drift kinetic effects with fluid MHD via perturbed kinetic pressure tensors

- **MHD-kinetic hybrid formulation**

$$(\gamma + in\Omega)\xi = \mathbf{v} + (\xi \cdot \nabla\Omega)R^2\nabla\phi,$$

$$\rho(\gamma + in\Omega)\mathbf{v} = -\nabla \cdot \mathbf{p} + \mathbf{j} \times \mathbf{B} + \mathbf{J} \times \mathbf{Q} - \rho\left[2\Omega\hat{\mathbf{Z}} \times \mathbf{v} + (\mathbf{v} \cdot \nabla\Omega)R^2\nabla\phi\right],$$

$$(\gamma + in\Omega)\mathbf{Q} = \nabla \times (\mathbf{v} \times \mathbf{B}) + (\mathbf{Q} \cdot \nabla\Omega)R^2\nabla\phi,$$

$$(\gamma + in\Omega)p = -\mathbf{v} \cdot \nabla P,$$

$$\mathbf{j} = \nabla \times \mathbf{Q},$$

$$\mathbf{p} = p\mathbf{I} + p_\parallel\hat{\mathbf{b}}\hat{\mathbf{b}} + p_\perp(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}),$$

thermal **fast ion**

$$p_\parallel e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma M v_\parallel^2 f_{th}^1(\xi_\perp) + \int d\Gamma M v_\parallel^2 f_h^1(\xi_\perp),$$

$$p_\perp e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma \frac{1}{2} M v_\perp^2 f_{th}^1(\xi_\perp) + \int d\Gamma \frac{1}{2} M v_\perp^2 f_h^1(\xi_\perp)$$

Equilibrium distribution functions of particles

- **Assume Maxwellian distribution for thermal particles** →

$$f_{th}^0 = N\left(\frac{M}{2\pi T}\right)^{3/2} e^{-\varepsilon_k/T}$$

- **And slowing-down distribution for fast ions** →

$$f_h^0 = \begin{cases} \frac{C}{\varepsilon_k^{3/2}+\varepsilon_c^{3/2}} & 0 < \varepsilon_k < \varepsilon_0 \\ 0 & \varepsilon_k > \varepsilon_0 \end{cases}$$

- **Same assumptions made in MISK code**

- **Radial profile of hot ion's energy distribution determined given hot ion's density and pressure profiles** →

$$\varepsilon_0 = \begin{cases} 3.5\mathrm{MeV} & \alpha-\mathrm{particles} \\ \varepsilon_h(\psi) & \mathrm{hot\ \ ions} \end{cases}$$

Perturbed distribution functions of particles

- **Perturbed distribution functions for thermal and fast ions derived by solving linear perturbed drift kinetic equation, following [Antonsen PF82] and [Porcelli PoP94].**

- **Neglected finite drift orbit width and FLR**

- **Consider various resonances between mode and particles**

- **Thermal particles:**
  - Bounce resonance of ions
  - Precession drift of ion&electron
  - Trapped and passing particles
- **Fast ions:**
  - Precession drift of trapped ions

$$f^1_{th} \propto \frac{n[\omega^{th}_{*N} + (\hat{\varepsilon}_k - 3/2)\omega^{th}_{*T} + \omega_E] - \omega}{n\omega^{th}_d + (\alpha nq + l)\omega^{th}_b - i\nu_{\text{eff}} - \omega}$$

$$f^1_h \propto \frac{n(f^0_{h,\psi}/Zef^0_{h,\varepsilon}) - \omega}{n\omega^h_d - \omega}$$

MARS-K includes both perturbative & self-consistent approach

- **Drift kinetic energy perturbation** **[Antonsen82, Porcelli94]**

$$\delta W_K = \sum_{e,i} \frac{1}{2} \int d^3x \int d\Gamma(-f_\epsilon^0) \sum_l \hat{\lambda}_l \left| \left\langle e^{-il\omega_b t} \tilde{H}(t) \right\rangle \right|^2$$

$$\hat{\lambda}_l = \frac{n[\omega_{*N} + (\hat{\epsilon}_k - 3/2)\omega_{*T} + \omega_E] - \omega}{n\omega_d + (\alpha n q + l)\omega_b - i\nu_{\mathrm{eff}} - \omega}$$

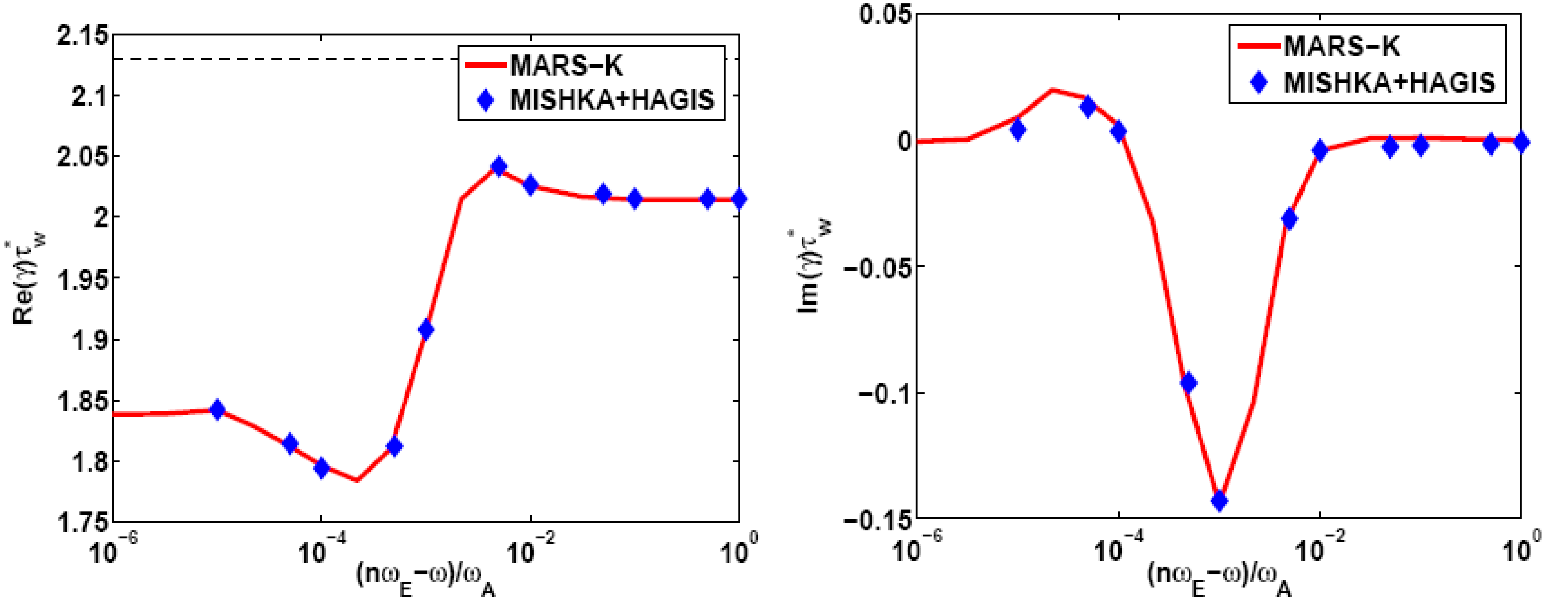
$$\tilde{H}(t) \propto \xi_\perp$$

precession ($n\omega_d$)   bounce (ω_b)   mode frequency (ω)

	perturbative	**self-consistent**
eigen-function $\xi_\perp$	**ideal-kink or fluid RWM**	**modified by kinetic effects self-consistently**
eigen-frequency ω	$\omega = 0$ **or** $i\gamma_f$	$\omega = i\gamma$ ⇨ **nonlinear eigenvalue formulation**
other damping	**shear Alfven damping included a-posteriori**	**continuum damping included via MHD terms**

MARS-K perturbative approach benchmarked against MISHKA+HAGIS code

- Choose a Soloviev equilibrium with circular-like shape
- Both codes run with perturbative approach



Liu, PoP08

- Validates approximation of neglecting banana width for kinetic RWM

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Formulations behind CarMa code

- **CarMa couples MARS-F/K to 3D eddy current code CARIDDI, via two coupling schemes**
  - ”Forward” coupling scheme
  - ”Backward” coupling scheme

- **Key ideas of forward coupling** **[Portone PPCF08]**
  - Introduce a coupling surface just outside plasma surface
  - Replace plasma magnetic response by a virtual surface current response at coupling surface
  - Effectively ”condense” MHD equations into eddy current equations

- **Forward coupling resembles in some aspects VALEN multimode approach. Like VALEN and STARWALL, consider static plasma response, hence no plasma inertia, (fast) rotation, kinetic effects**

Formulations behind CarMa code

- **Backward coupling scheme ”condenses” conductors’ (dynamic) response into MHD equations**
  - as a non-trival boundary condition at coupling surface just outside plasma.
- **Key idea is to transform conductors’ dynamic response into a linear BC [Smith PoP08, Guazzotto PoP08, Liu PoP08]**
  - Hugely beneficial for linear MHD eigenvalue formulation
  - Allows easy inclusion of all effects beyond ideal MHD in CarMa

$$\left(\overleftrightarrow{\mathrm{A}}_{0N} + \gamma\overleftrightarrow{\mathrm{A}}_{1N}\right)\mathrm{b}_N + \left(\overleftrightarrow{\mathrm{A}}_{0T} + \gamma\overleftrightarrow{\mathrm{A}}_{1T}\right)\mathrm{b}_T + \left(\overleftrightarrow{\mathrm{A}}_{0f} + \gamma\overleftrightarrow{\mathrm{A}}_{1f}\right)\mathrm{I}_f = 0,$$

CARIDDI

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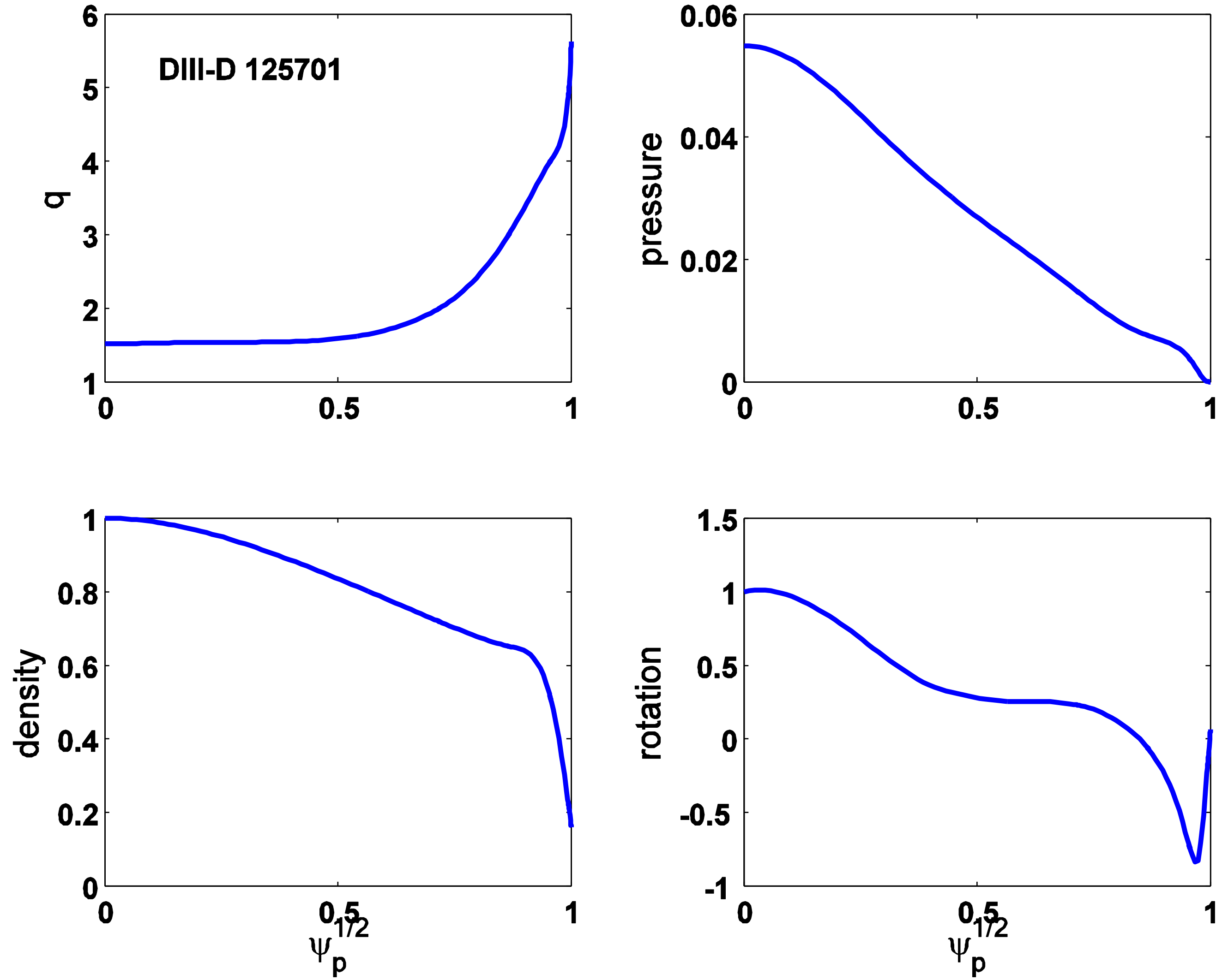
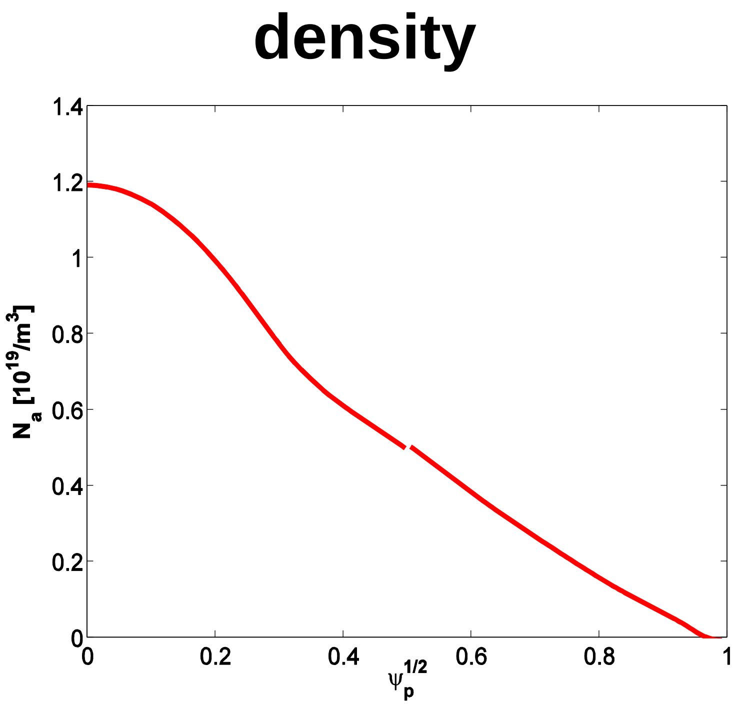
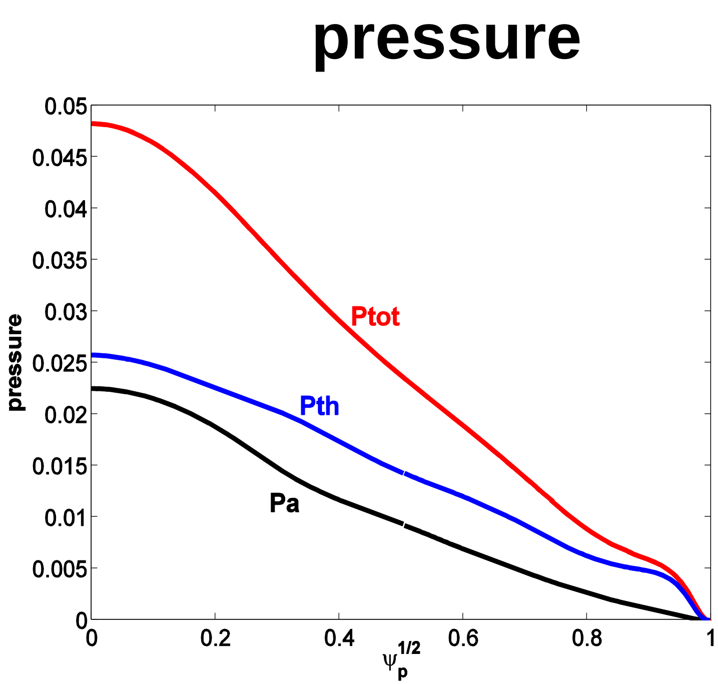
Equilibrium profiles from DIII-D 125701



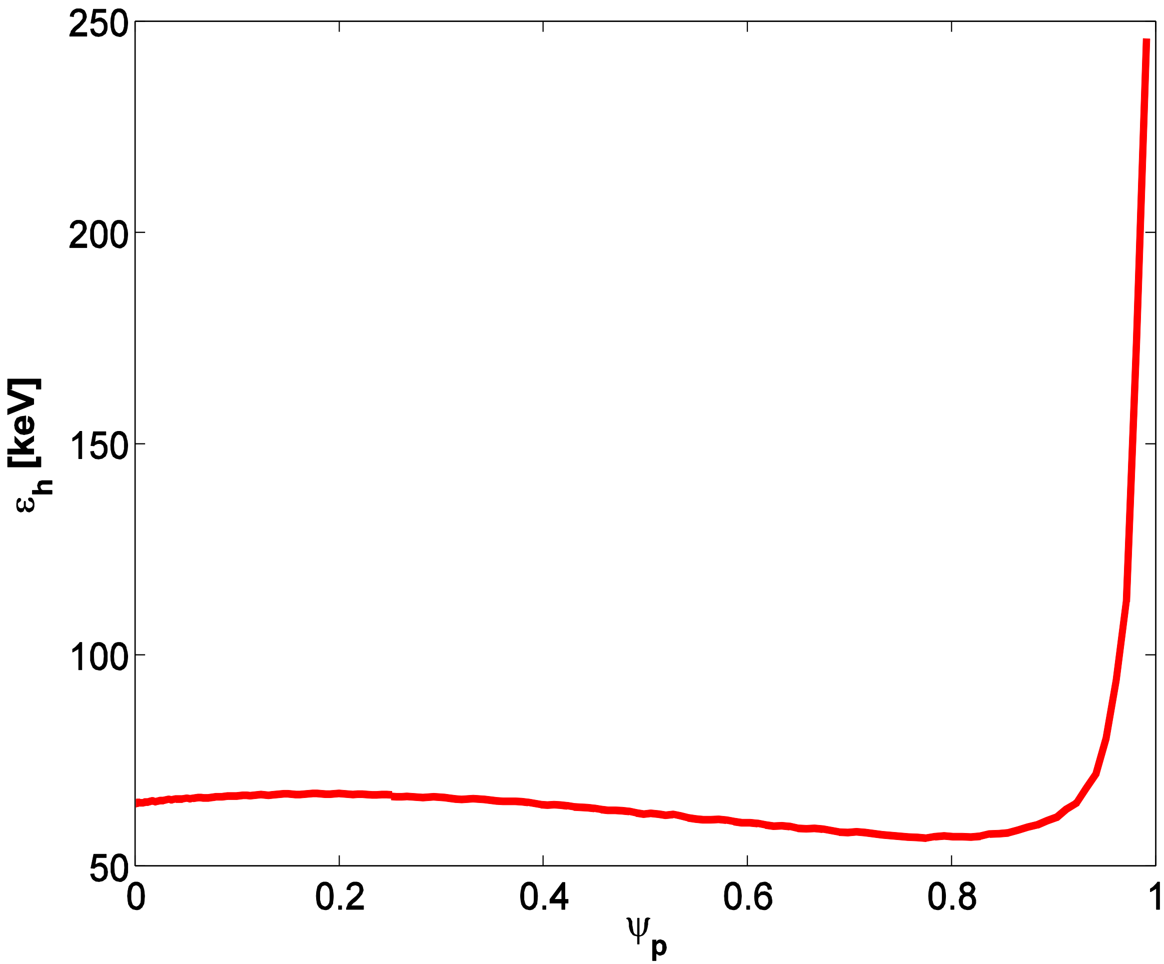
Fast ion density and pressure profiles



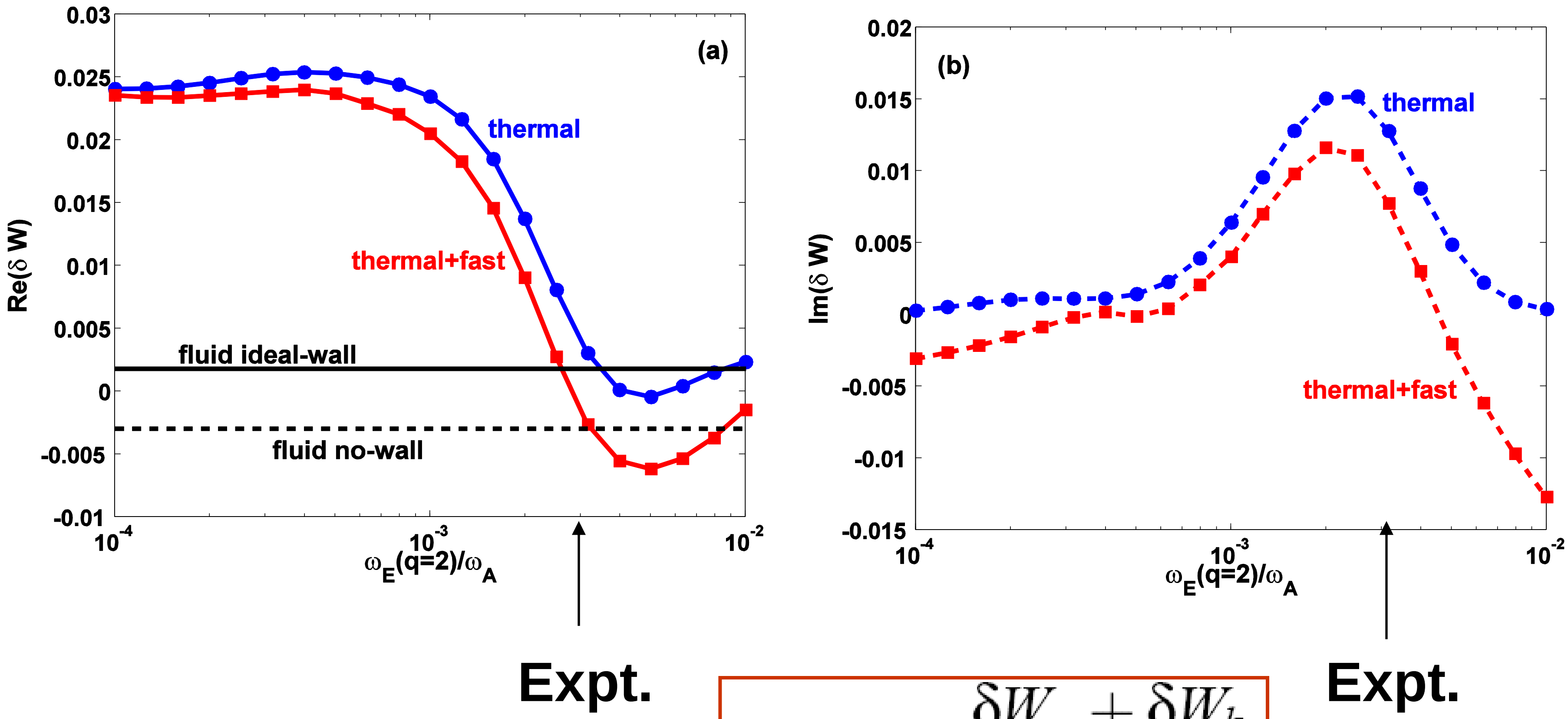


- **Fast ion contributes nearly half of total pressure**

Computed radial distribution of fast ion energy



Perturbative approach: energy



$$\gamma\tau_w^* = -\frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k}$$

- **Fast ions give minor contribution at slow rotation**

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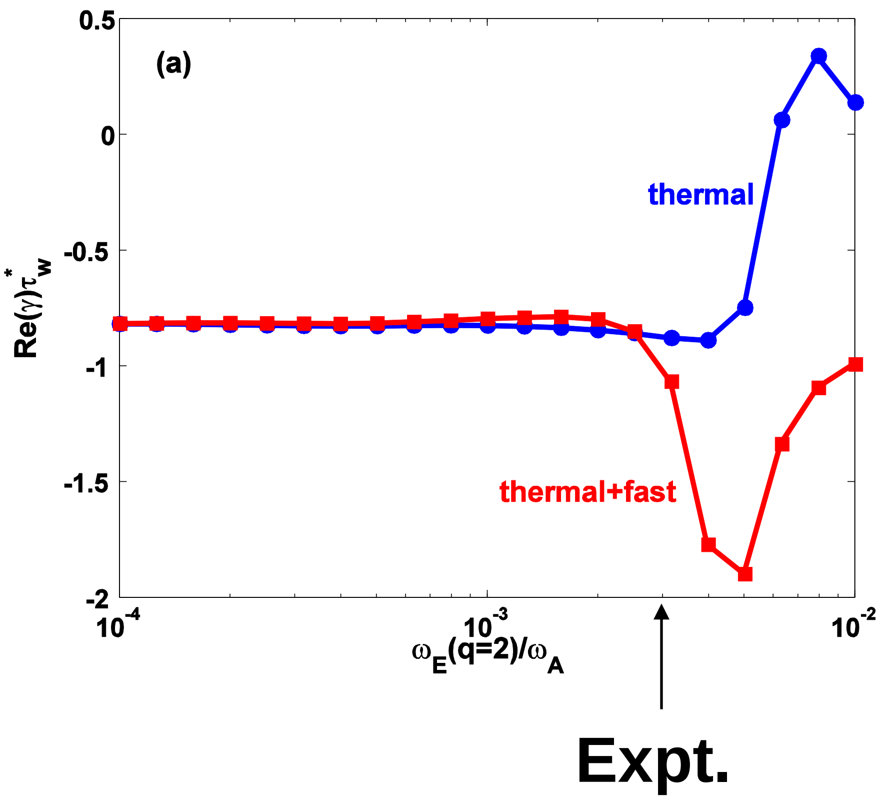
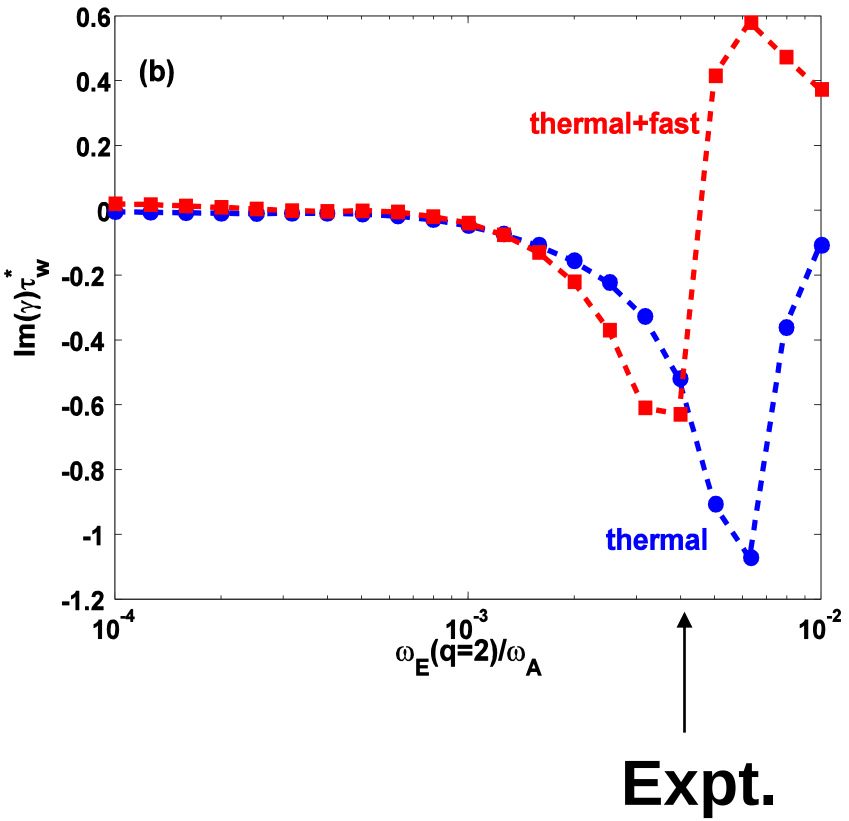
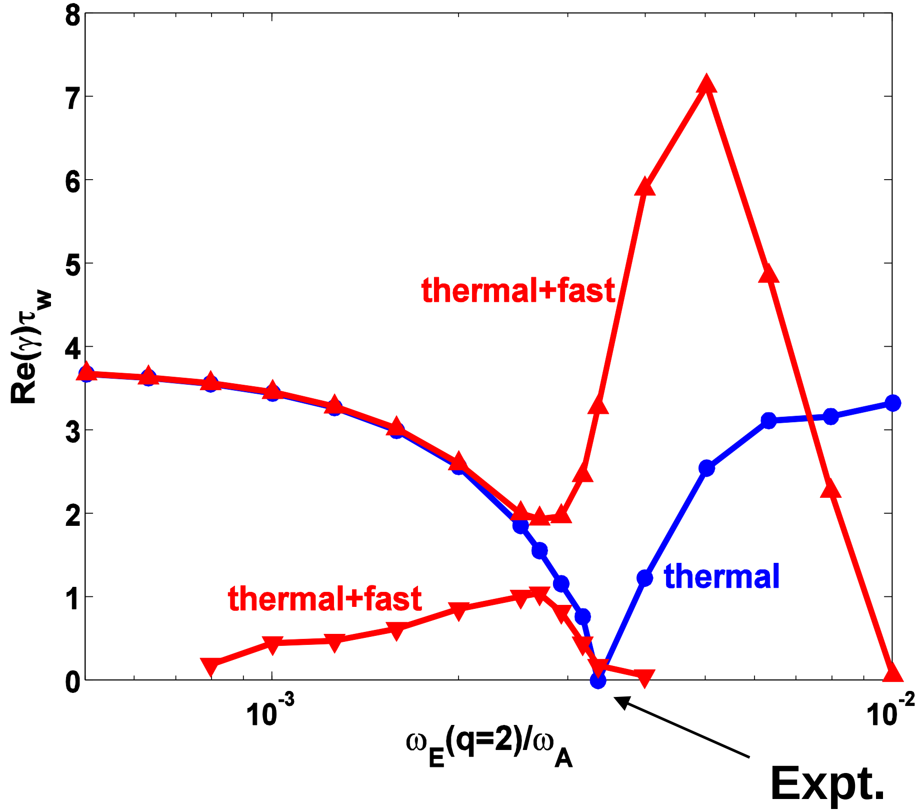
Perturbative approach: eigenvalue





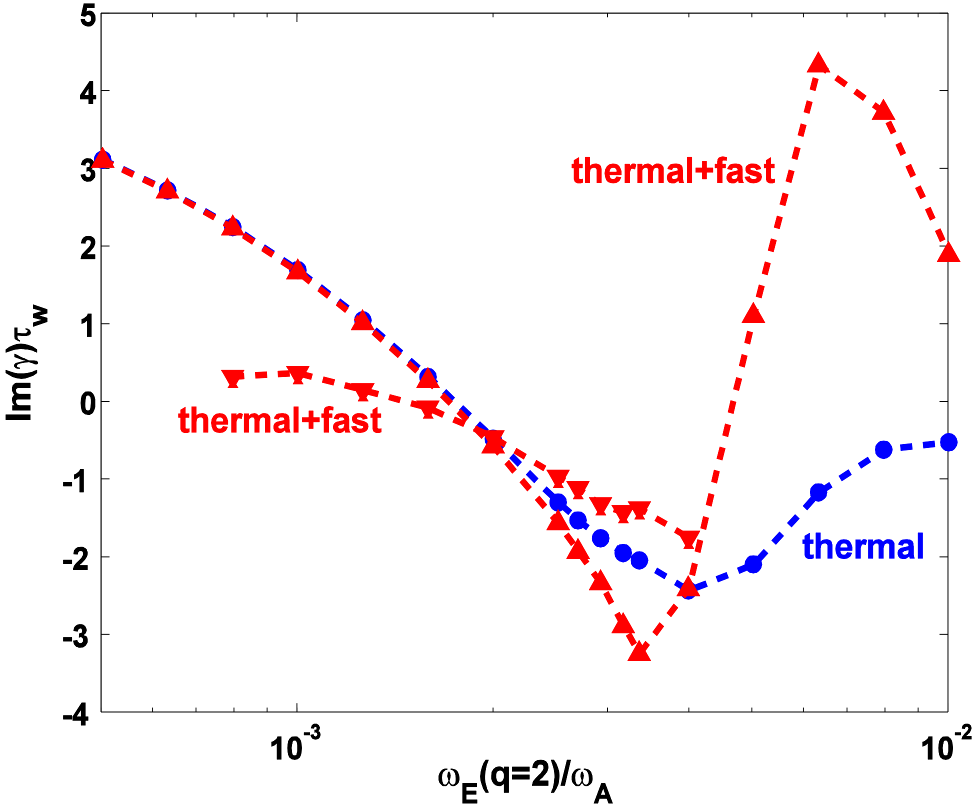
- **Fast ions are slightly destabilising at slow rotation, stabilising at faster rotation**
- **RWM at expt. rotation is stable w/ or w/o fast ions**

Self-consistent approach: growth rate



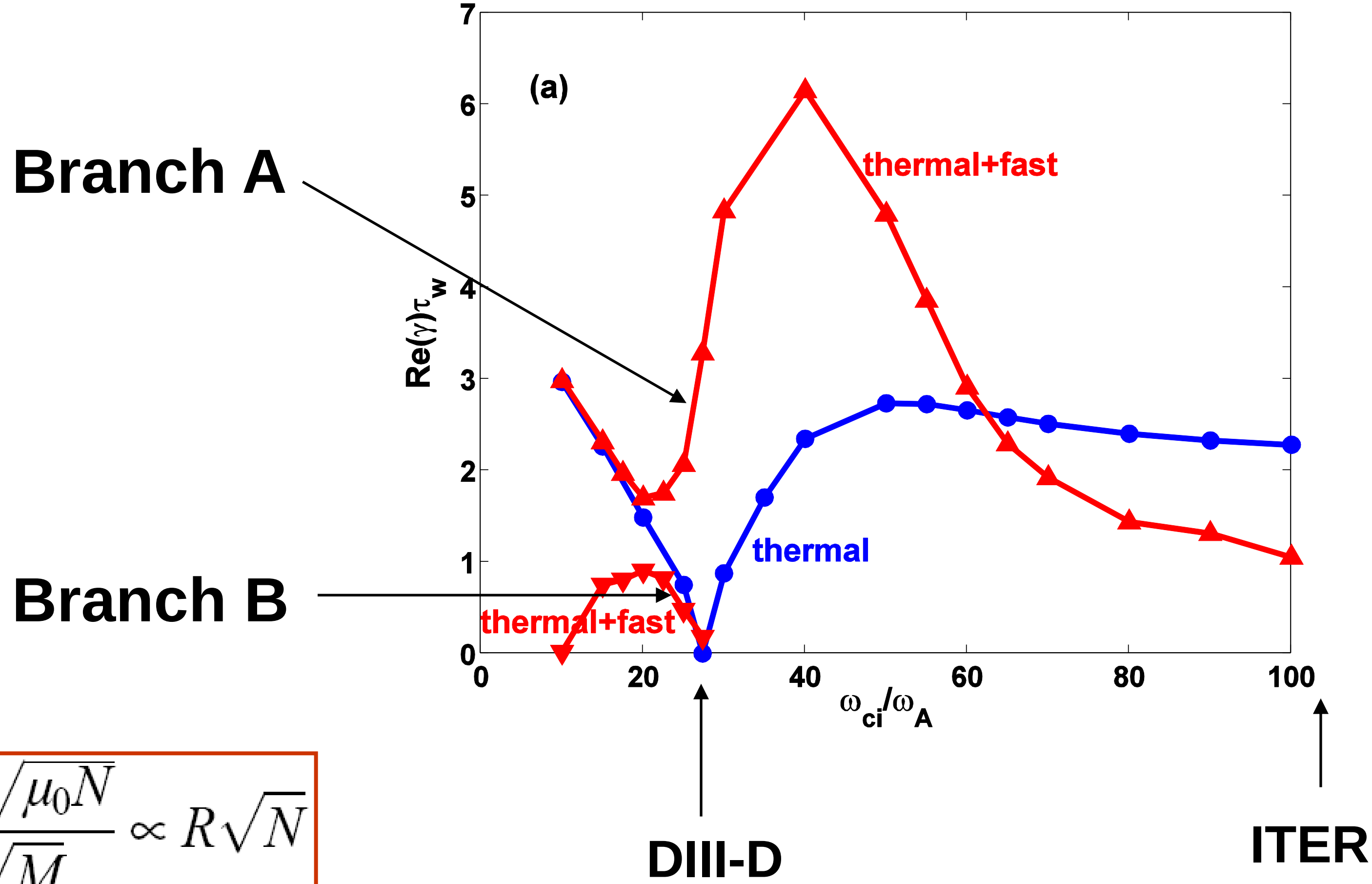
- **w/o fast ions, SC approach predicts a narrow window of stabilisation**
- **w/ fast ions, a second unstable branch appears**

Self-consistent approach: mode frequency



- **Fast ion driven (unstable) branch can have different direction of mode rotation**

Self-consistent approach: sensitivity on ion gyroradius

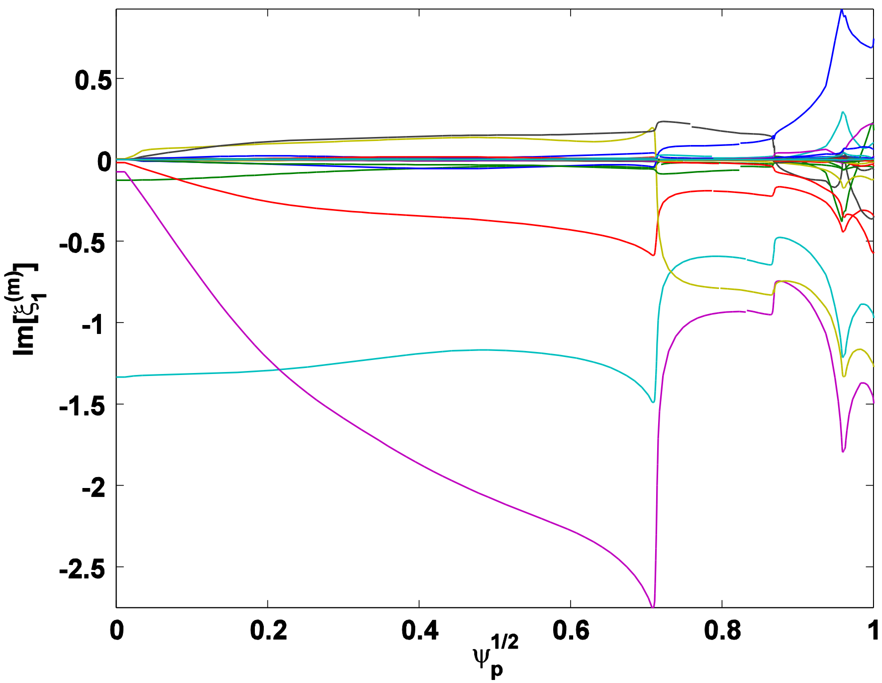


$$\frac{\omega_{ci}}{\omega_A} = \frac{eR\sqrt{\mu_0 N}}{\sqrt{M}} \propto R\sqrt{N}$$

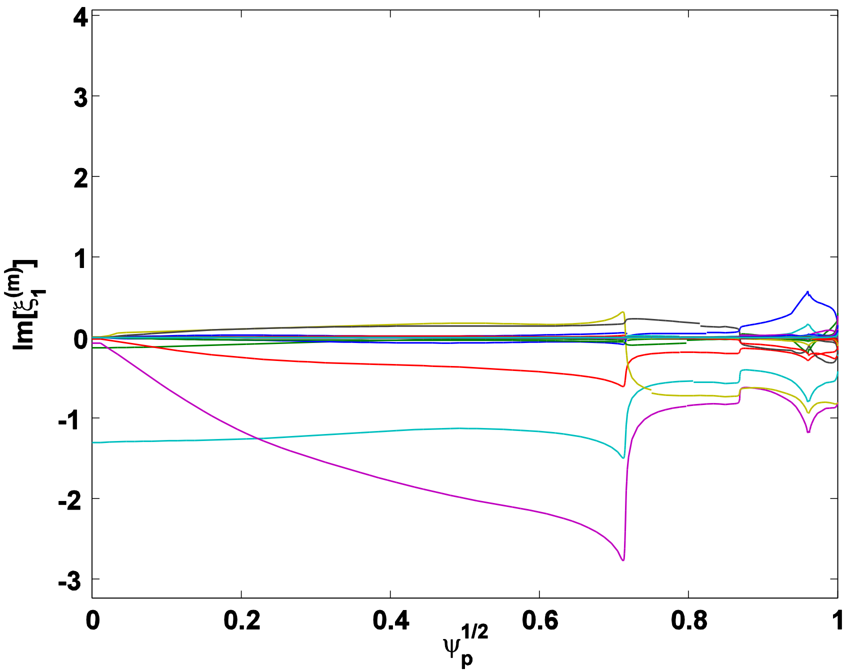
- **Fast ions can be stabilising in ITER**

Self-consistent approach: compare eigenmode structure

Branch A



Branch B



- **Less unstable mode (branch B) more peaked at last rational surface**

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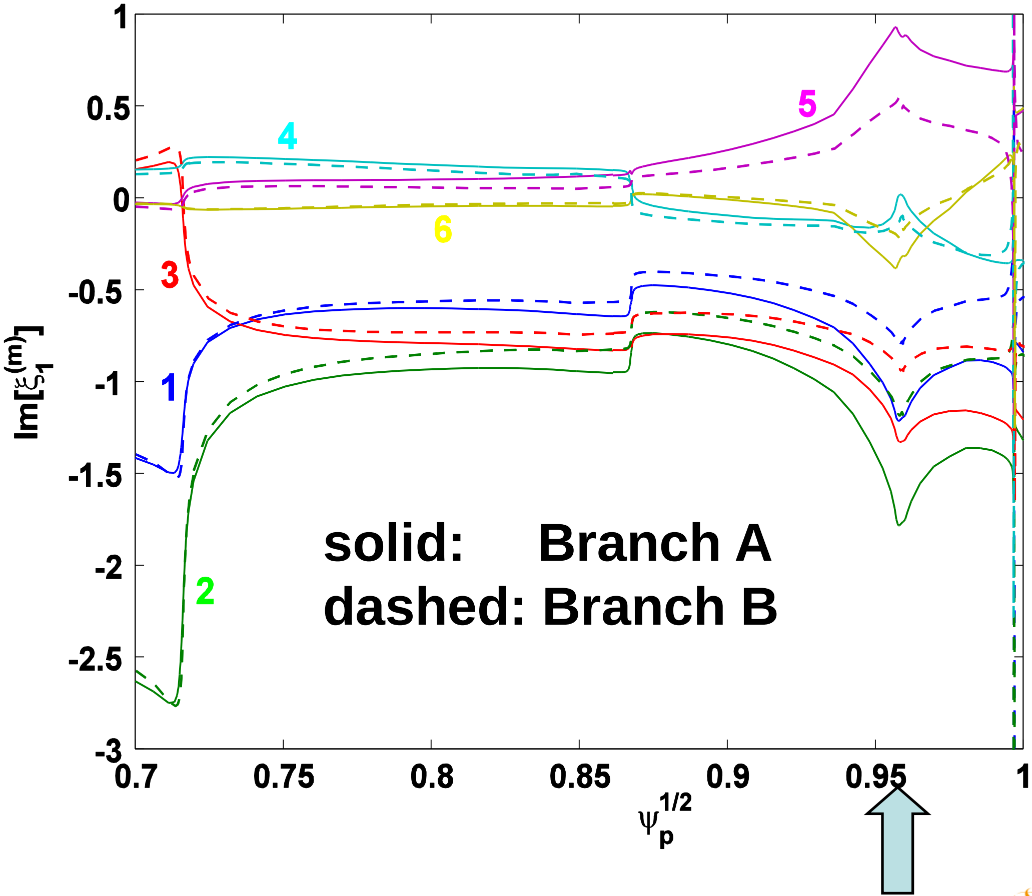
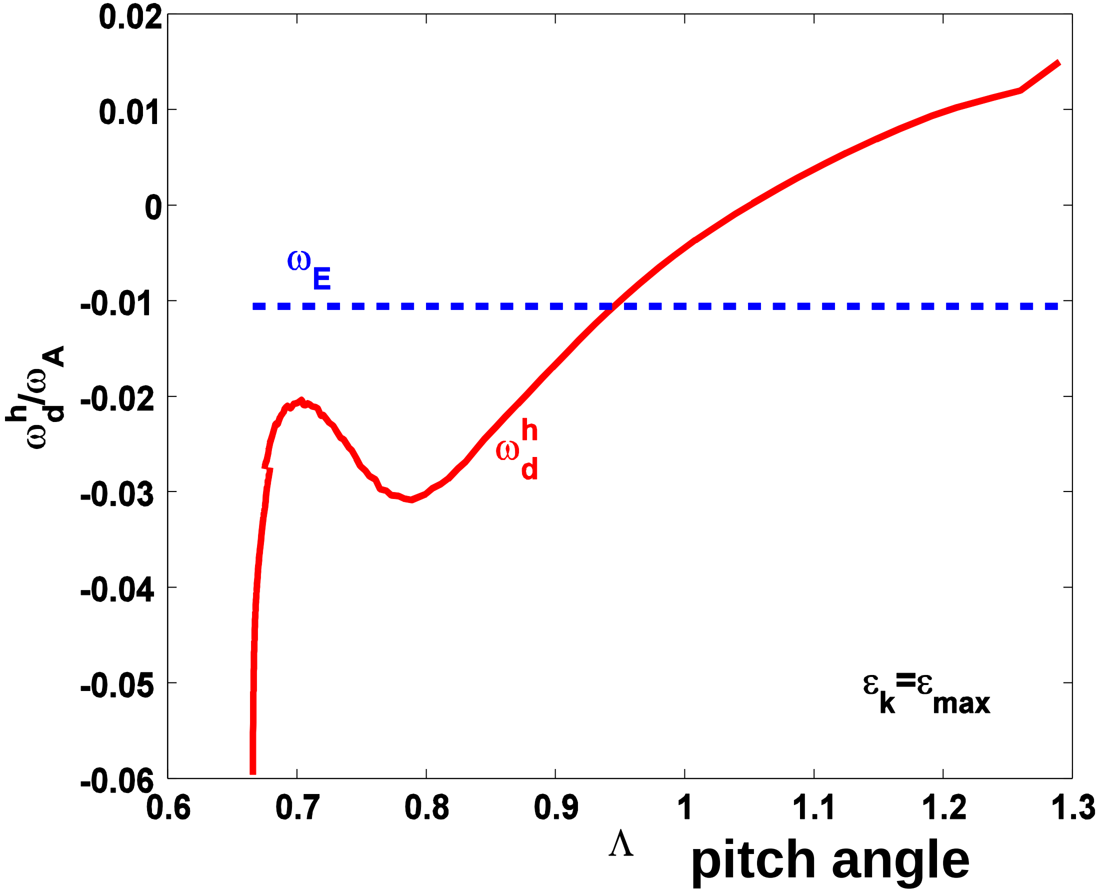
Self-consistent approach: compare eigenmode structure

- **Eigenmodes differ mostly in the outer region of the plasma, outside the q=2 surface**



Resonance condition for fast ions?

- **Fast ion precession drift frequency comparable to experimental rotation frequency**



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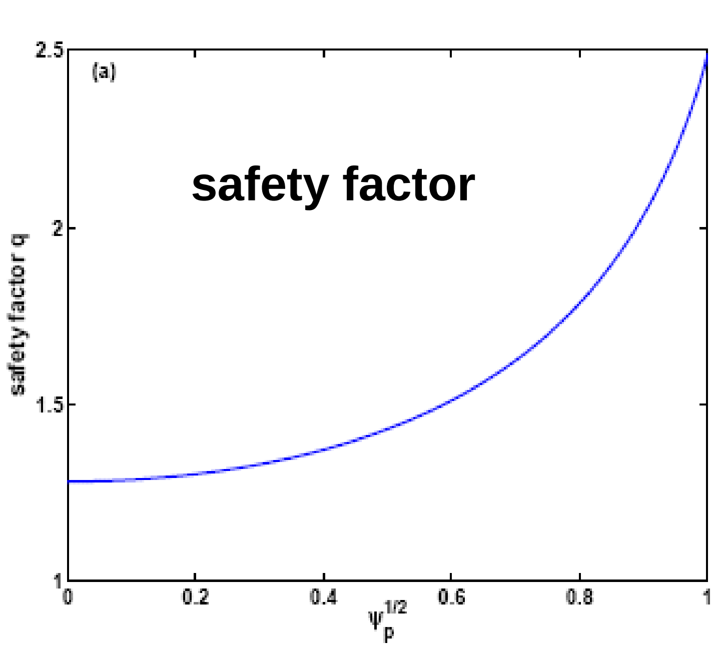
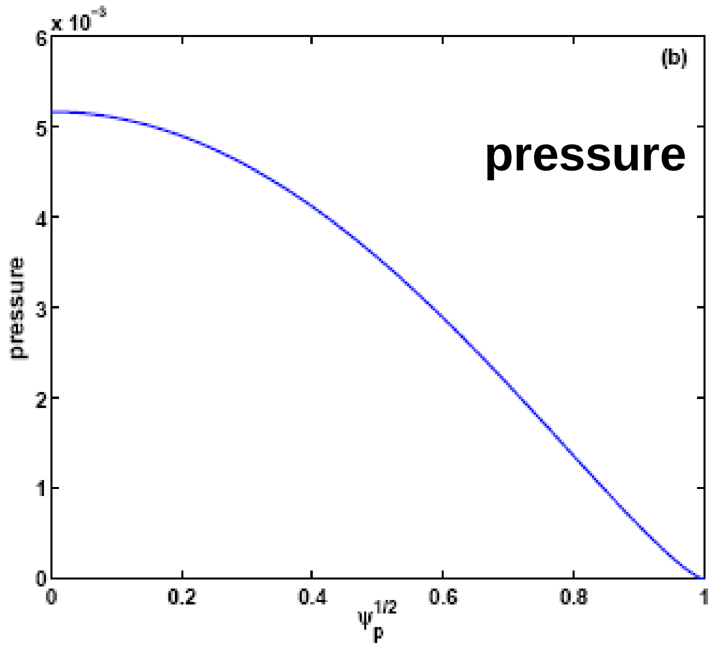
CarMa capable of solving RWM problems with damping + 3D wall + feedback

- Choose a test equilibrium with circular cross section, and R/a=5





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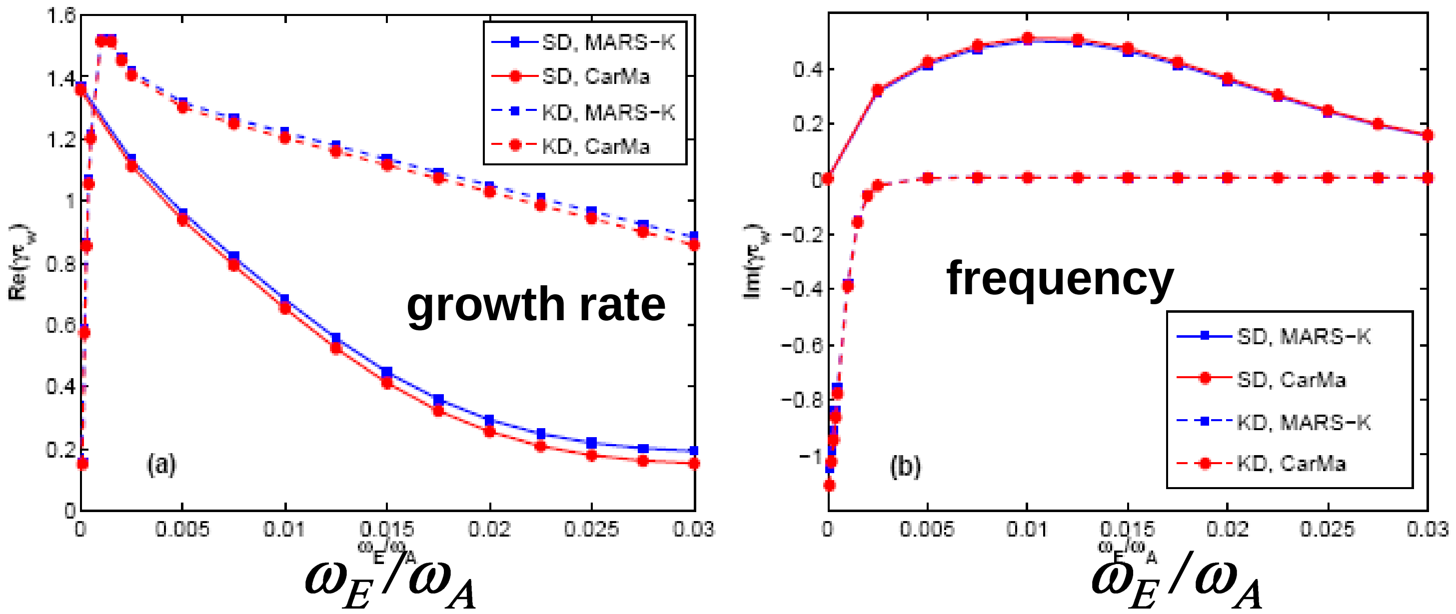
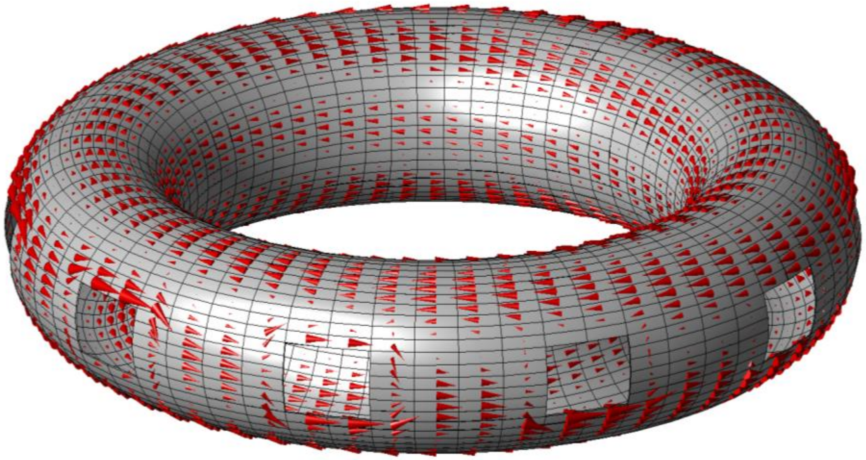
CarMa benchmarked for damping models

- **Compute passive stability versus plasma rotation**
  - Parallel sound wave damping
  - kinetic damping
- **With 2D wall, CarMa results almost identical to MARS-K**

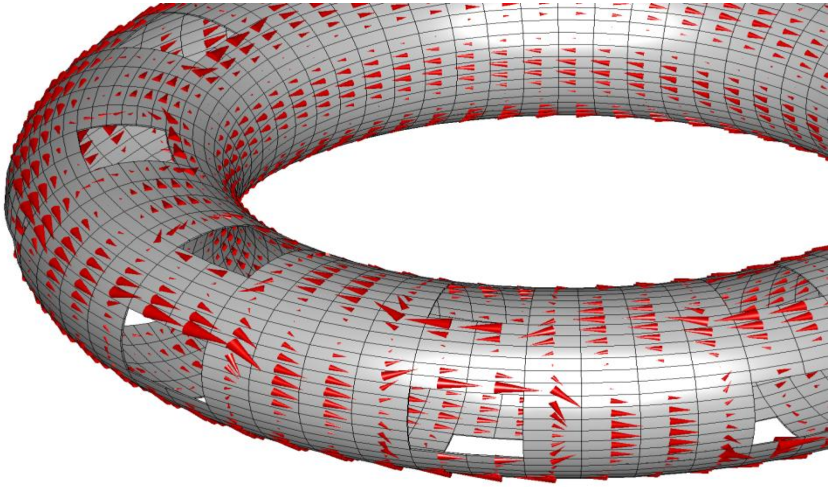


Models of 3D wall with holes



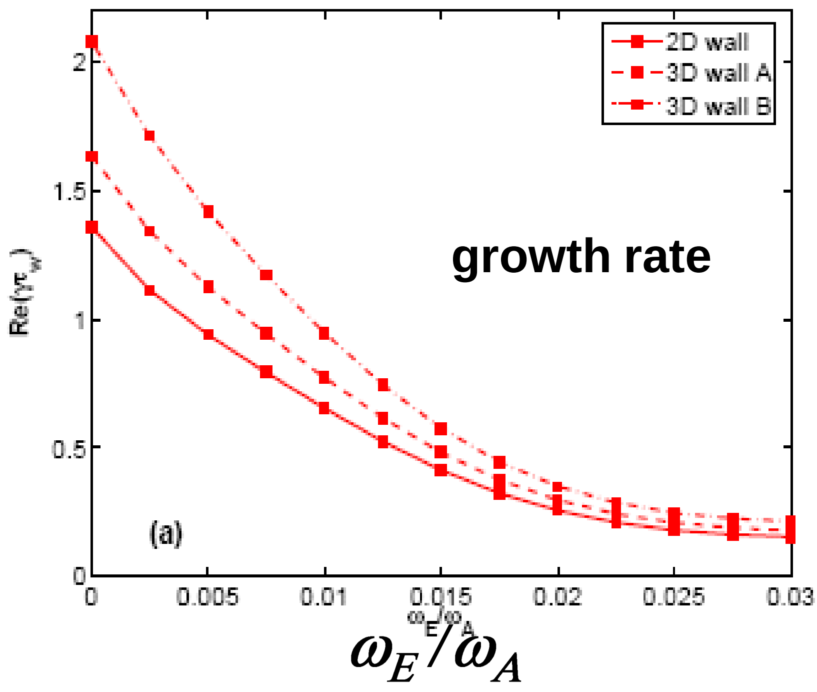
Model A

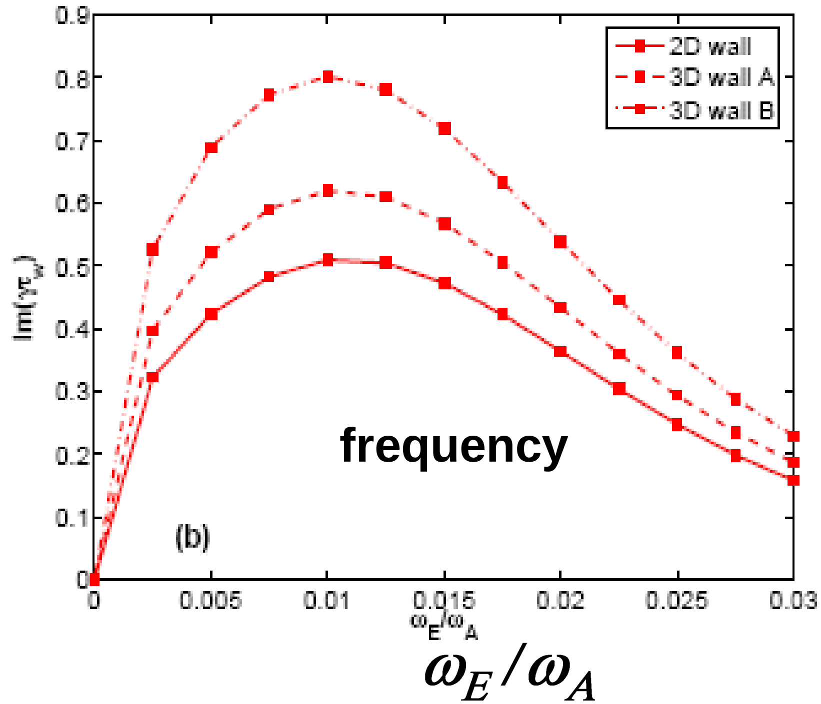
Model B



Wall holes increase both mode growth rate and frequency

- **Effect of 3D wall on RWM passive stability, with plasma rotation and strong sound wave damping**

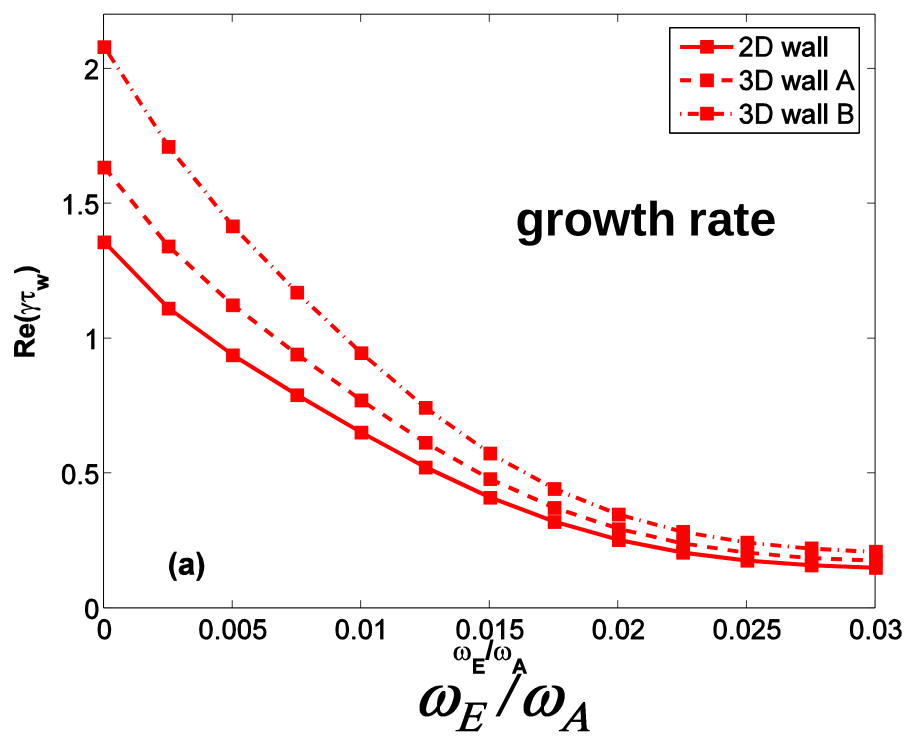


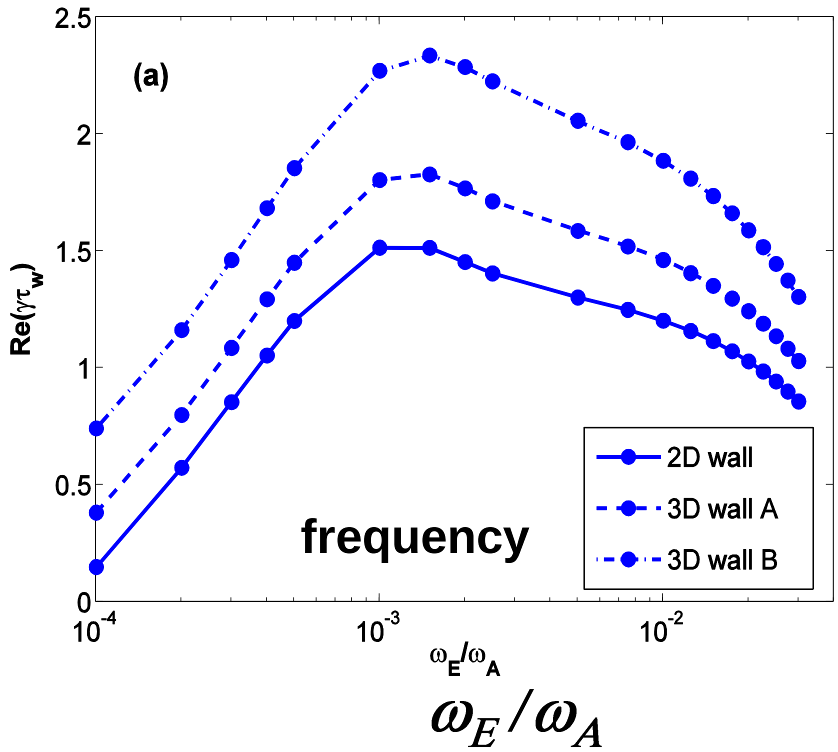


Liu PPCF09

Wall holes increase both mode growth rate and frequency

- **Effect of 3D wall on the RWM passive stability with plasma rotation and drift-kinetic damping model**

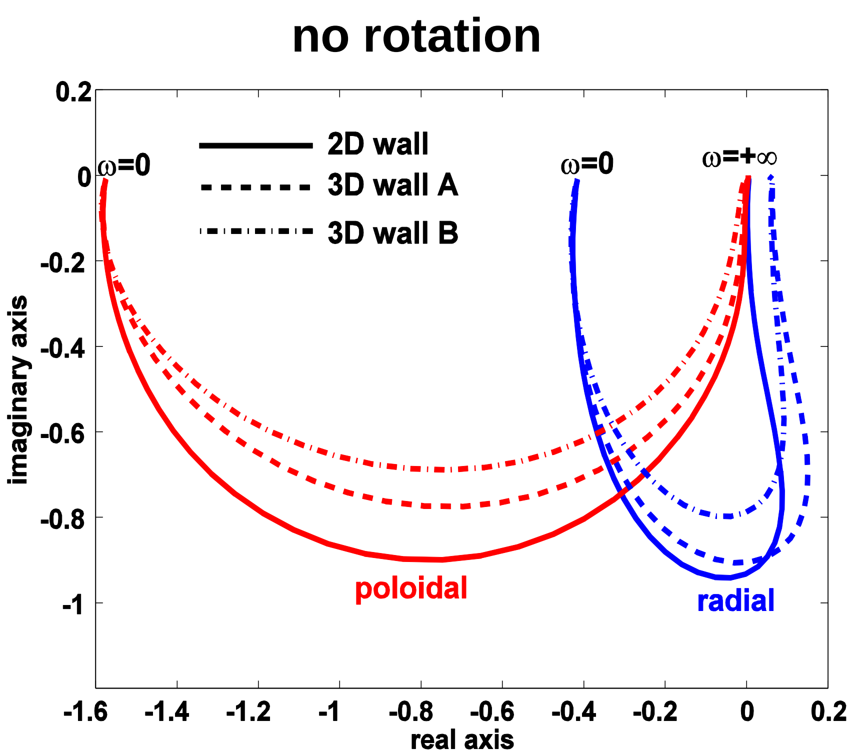


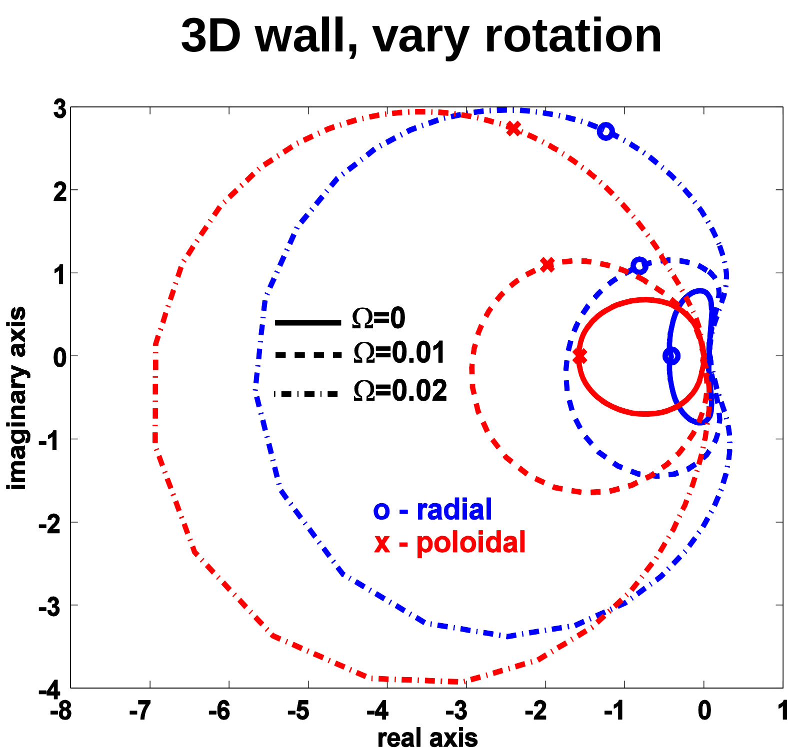


YQ Liu et al., 14th MHD Workshop, Nov 9-11, 2009, PPPL

Nyquist diagrams show effects of 3D wall on feedback performance

- 3D wall reduces closed loop stability margin
- Synergy between rotation and feedback, in presence of 3D wall





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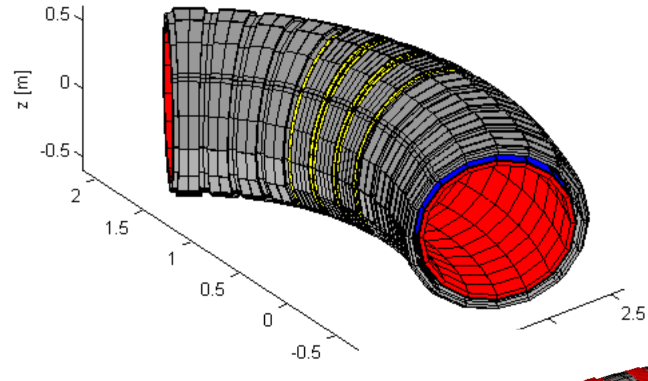
CarMa used for realistic modelling of RFX feedback experiments

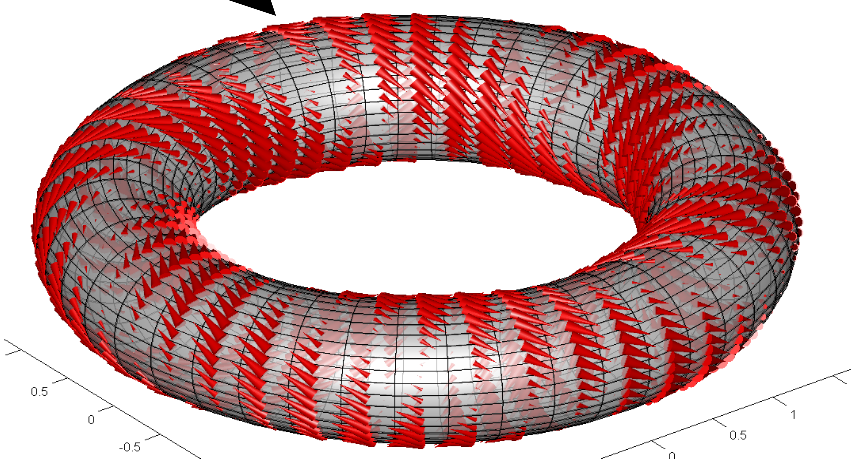
- **CarMa computed wall eddy current pattern**
- **For an unstable mode with n=3,m=1**

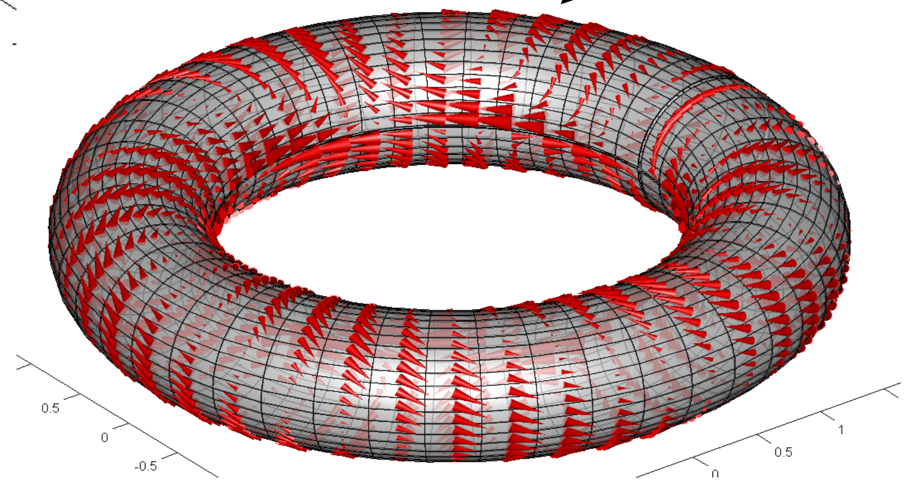
Villone PRL08



2D wall

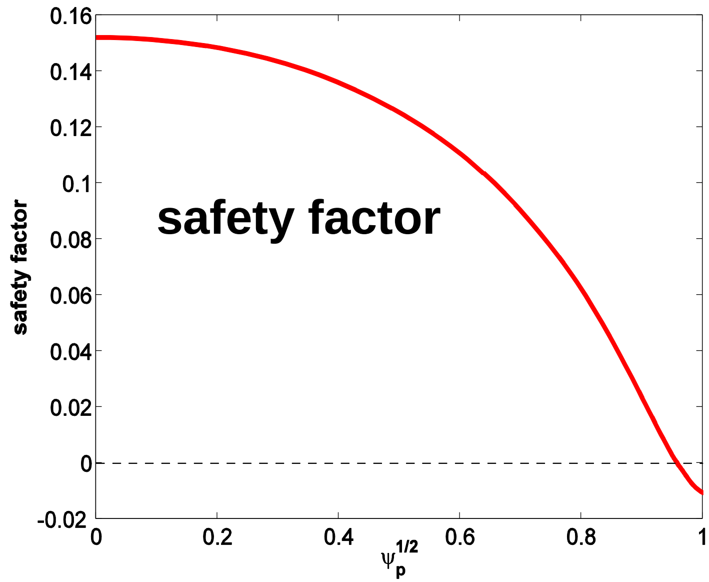
3D wall with gaps

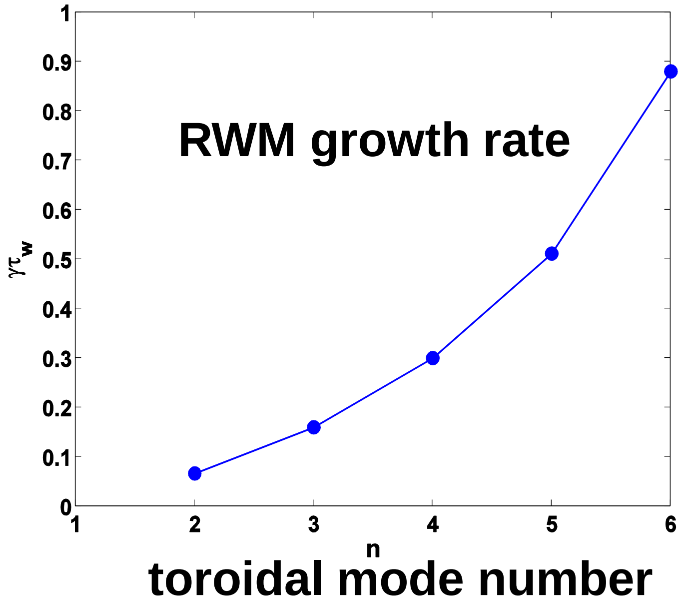




CarMa used for realistic modelling of RFX feedback experiments

- **A typical RFX plasma equilibrium with shallow field reversal: THETA=1.426, F=-0.060**

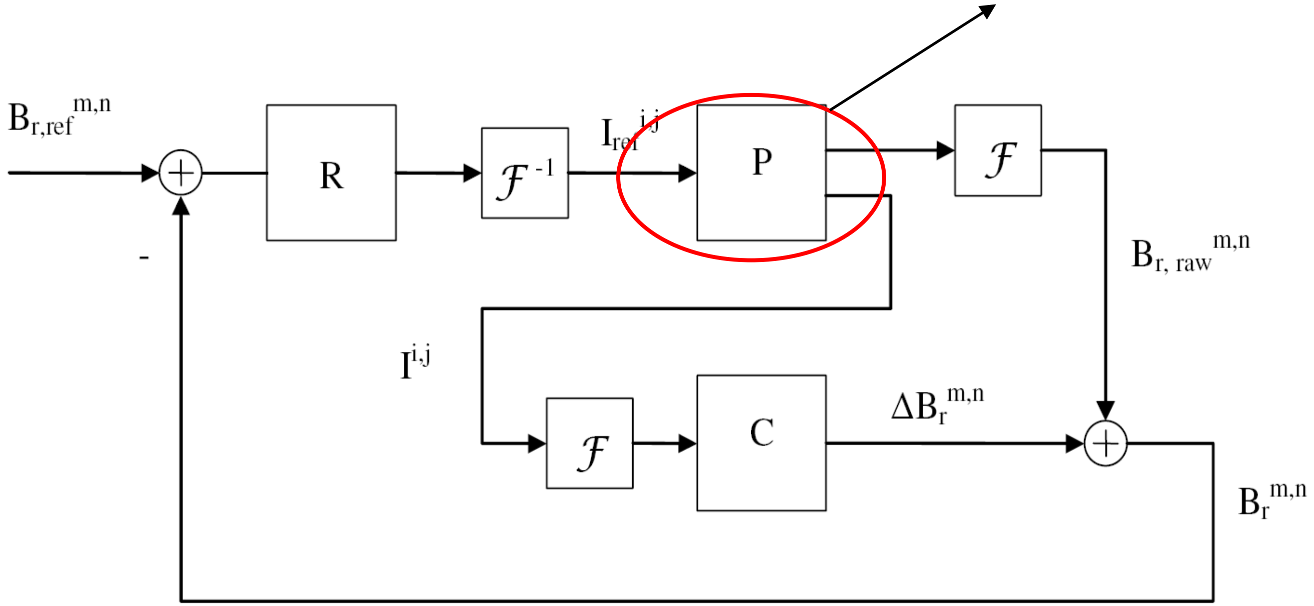




Feedback loop in RFX experiments

- **CarMa has been used to represent the plant in a full closed loop simulation of the RWM control system, yielding closed loop growth rates, that are directly compared with experiments**

CarMa Model

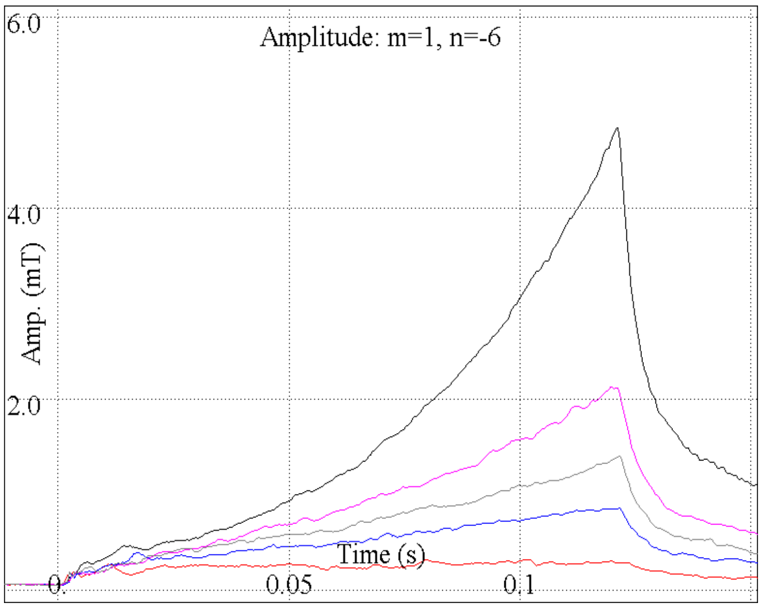


Marchiori EPS09

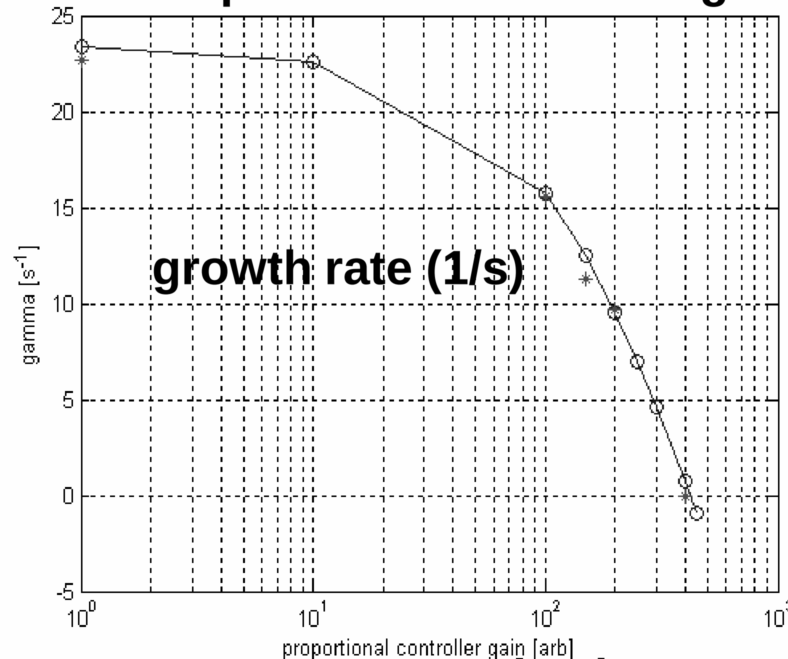
RWM feedback modelling in RFX

- **Comparing experimental vs. CarMa simulated closed-loop growth rates of RWM**

expriment



experiment vs. modeling

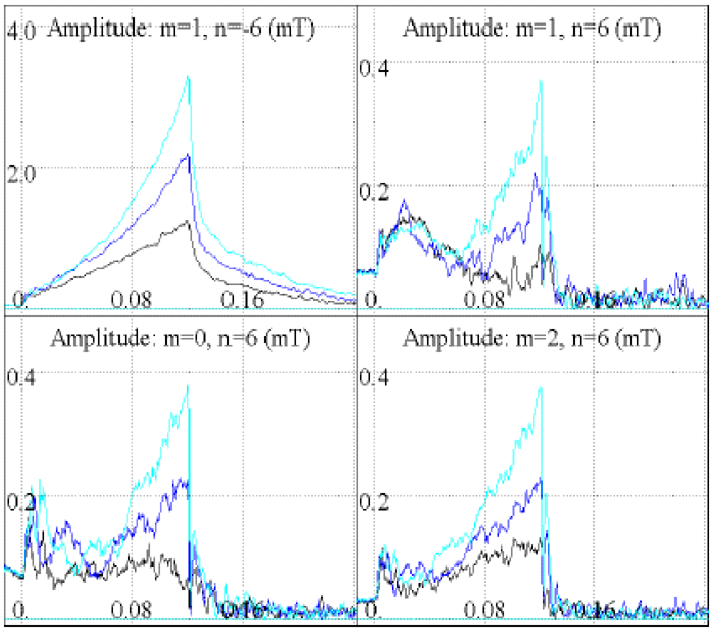


Marchiori EPS09

Eigenmode structure can also be compared between modeling and expt.

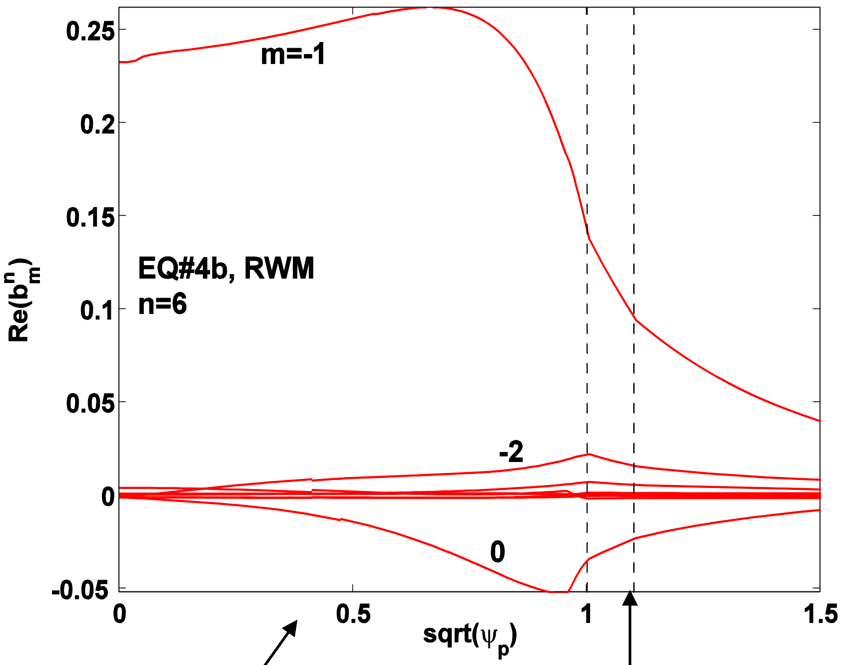
- **MARS-F computed amplitude ratio between poloidal harmonics (due to toroidicity) match reasonably well experiments**

expriment



Bolzonella EPS09

modeling



wall

n=6

Summary

- **Self-consistent approach generally predicts less kinetic stabilisation on RWM compared to perturbative approaches**
- **Fast ions contribution, whilst can give additional stabilisation in perturbative approach, can also drive an extra unstable branch in self-consistent approach**
- **A new version of CarMa code allows consistent modelling of 3D conductors, kinetic effects and feedback stabilisation all together**
- **The RFX feedback experiments well modelled by CarMa**
- **Other aspects of RWM code maturity, not discussed here**
  - Capability of treating thick walls and ferromagnetic materials
  - Multimodal analysis (e.g. n=0+1, n=1+2+3, etc.) …

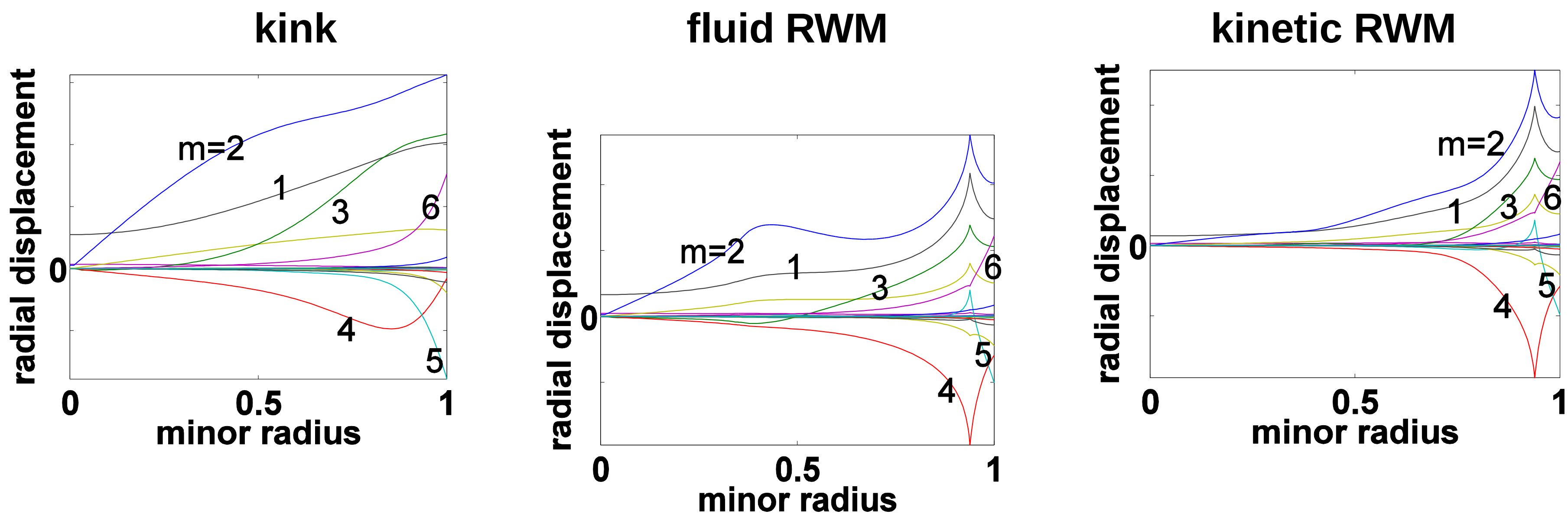
Discussions

- **Are RWM codes mature enough? (No)**
  - MARS-K: finite banana orbit effects, FLR, collision?
  - AEGIS-K, LIGKA more advanced in kinetic physics
  - Nonlinear physics (RWM couple to other modes)?
  - CarMa: iron saturation (nonlinear) ?
- **MARS-K results vs. DIII-D experiment?**
  - Finite banana effects? FLR?
  - Collision?
  - Fast particle distribution function? Profiles?
  - Evidence of fast ion driven RWM in other experiments?
- **What about prediction for ITER?**
  - Seems no complete stabilisation with thermal particles
  - MARS-K modelling with alpha particles in progress
  - Waiting for new reference plasma for steady state scenario…

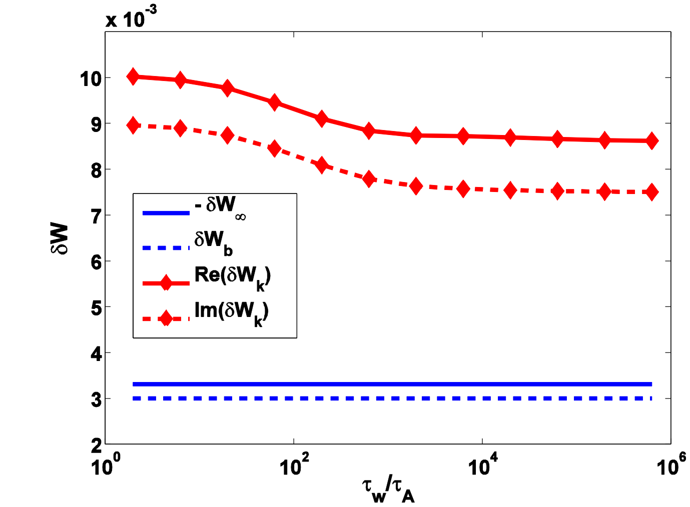
Backup slides …

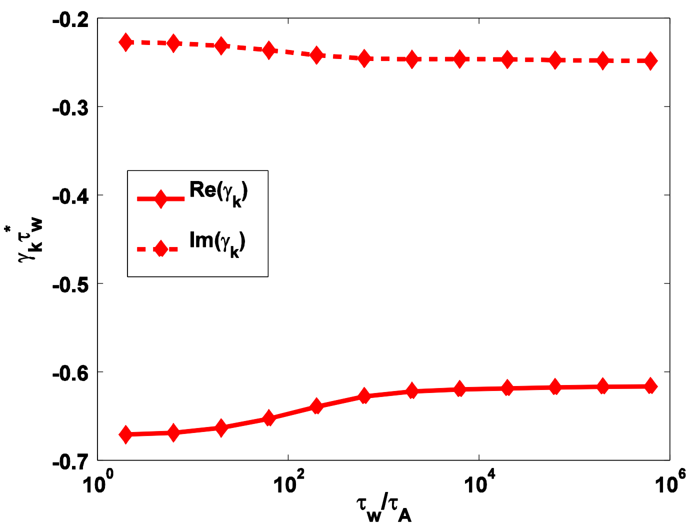
Kinetic effects do modify mode eigenfunction for a test toroidal equilibrium

- **Test toroidal Soloviev equilibrium: R/a=3, = 1.6 κ**

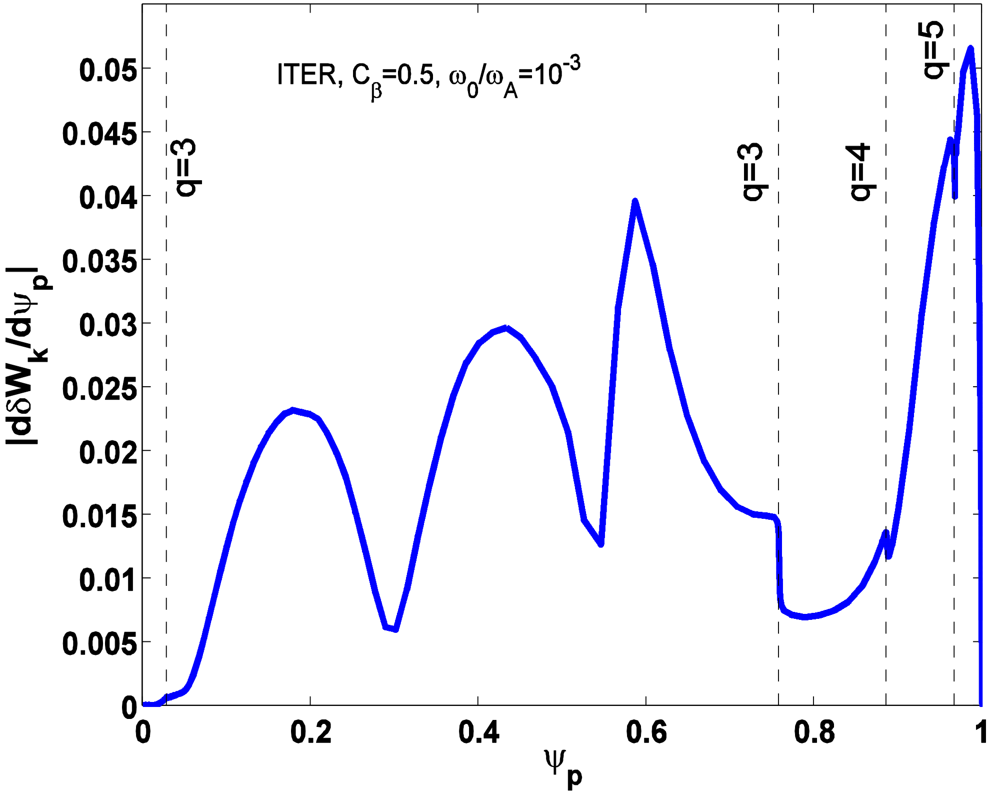


ITER: perturbative





- **Radial distribution of drift kinetic energy perturbation with precessional resonances**



YQ Liu et al., 14th MHD Workshop, Nov 9-11, 2009, PPPL

CCFE CULHAM CENTRE FOR FUSION ENERGY

CarMa allows multimodal analysis

Multimodal ITER results /2

- **Combined n=0 (VDE) + n=1 (external kink) plasma evolution**

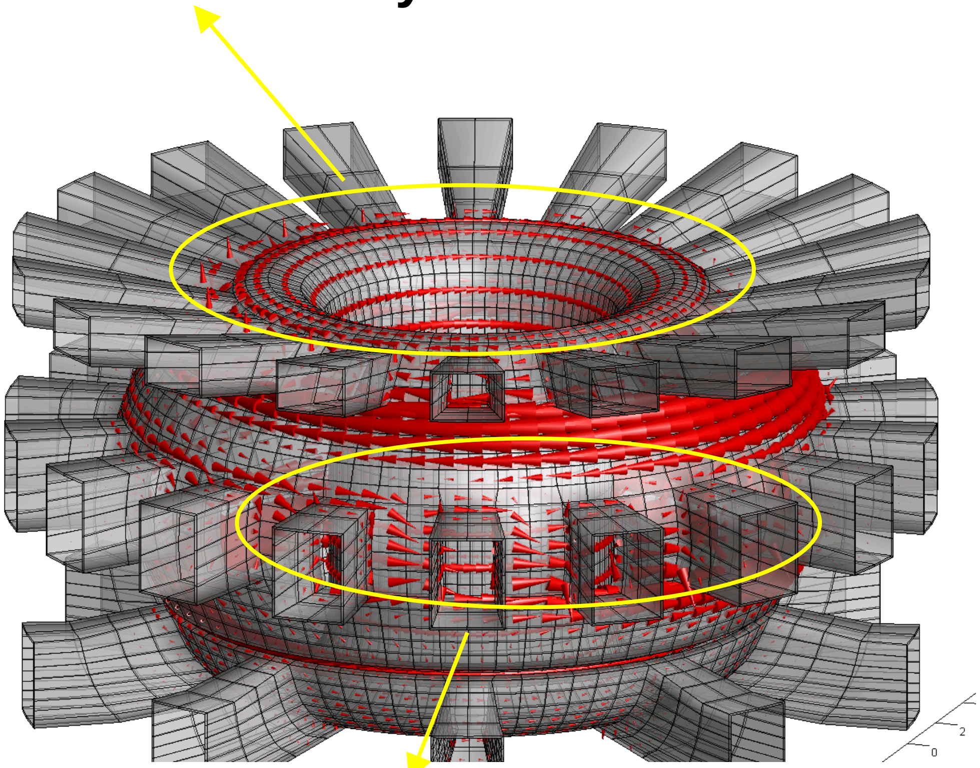
ITER Scenario 4 (β_N=2.7).
Three unstable eigenvalues:

• $\gamma_{1,2}$ = 10.4 s^{-1}, eigenvectors with a n=1 spatial behaviour, shifted of $\pi/2$ toroidally

• γ_3 = 7.66 s^{-1}, eigenvector with a n=0 spatial behaviour

Almost identical to those computed with monomodal models: little (open-loop) coupling of n=0 and n=1 modes due to 3D structures.

Predominantly n=0



Predominantly n=1