Hybrid Simulations of Alpha Particle Effects on Internal Kink Mode in ITER

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Outline

- Introduction
- M3D code: hybrid model
- Alpha Particle effects on Internal Kink
- Summary

Introduction

- We investigate alpha particle stabilization of internal kink mode in ITER by particle/MHD hybrid simulations;
- Our main tool, M3D, is a 3D global nonlinear extended MHD code.

M3D code

M3D project is part of SciDAC's CEMM: Center for Extended MHD Modeling

M3D is an extended-MHD (XMHD) code which has multi-level of physics:

Resistive MHD;
Two fluids;
Particle/MHD hybrid;

M3D XMHD Model

$$\rho\frac{d\mathbf{v}}{dt} + \rho(\mathbf{v}_{\mathbf{i}}^{\star}\cdot\nabla)\mathbf{v}_{\perp} = -\nabla P - \nabla\cdot\mathbf{P}_{h} + \mathbf{J}\times\mathbf{B} - \mathbf{b}\cdot\nabla\cdot\Pi_{i}$$

$$\mathbf{J} = \nabla\times\mathbf{B}, \qquad \frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$$

$$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{J} - \nabla_{\|}P_{e}/en - \mathbf{b}\cdot\nabla\cdot\Pi_{e}$$

$$\partial P/\partial t + \mathbf{v}\cdot P = -\gamma P\nabla\cdot\mathbf{v} + ...$$

$$\partial P_{e}/\partial t + \mathbf{v}\cdot P_{e} = -\gamma P_{e}\nabla\cdot\mathbf{v} + ...$$

- Pressure tensor

$$\mathbf{P}_h = P_\perp \mathbf{I} + (P_\parallel - P_\perp)\mathbf{bb}$$

$$f = \sum_i \delta(\mathbf{R} - \mathbf{R}_i)\delta(v_\parallel - v_{\parallel,i})\delta(\mu - \mu_i)$$

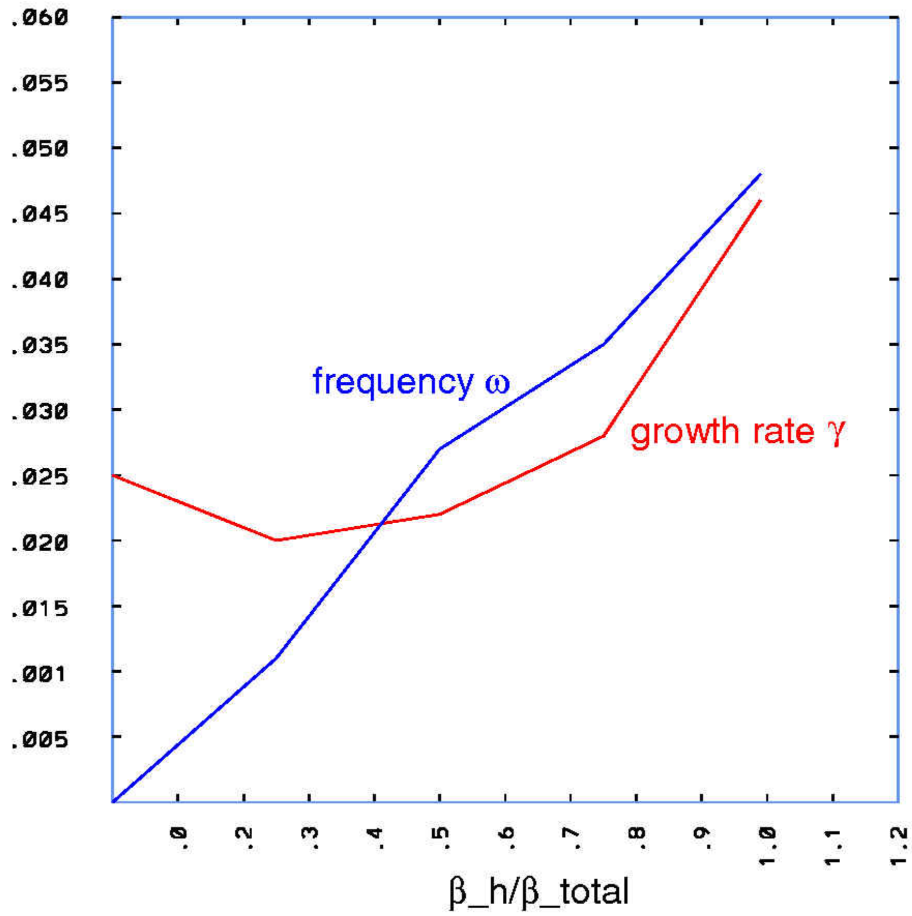
- Gyrokinetic Equations

$$\frac{d\mathbf{R}}{dt} = \frac{1}{B^{\star\star}}\left[v_\parallel(\mathbf{B}^\star - \mathbf{b_0} \times (< \mathbf{E} > -\frac{1}{q}\mu\nabla(B_0 + < \delta B >))\right]$$

$$m\frac{dv_\parallel}{dt} = \frac{q}{B^{\star\star}}\mathbf{B}^\star \cdot (< \mathbf{E} > -\frac{1}{q}\mu\nabla(B_0 + < \delta B >))$$

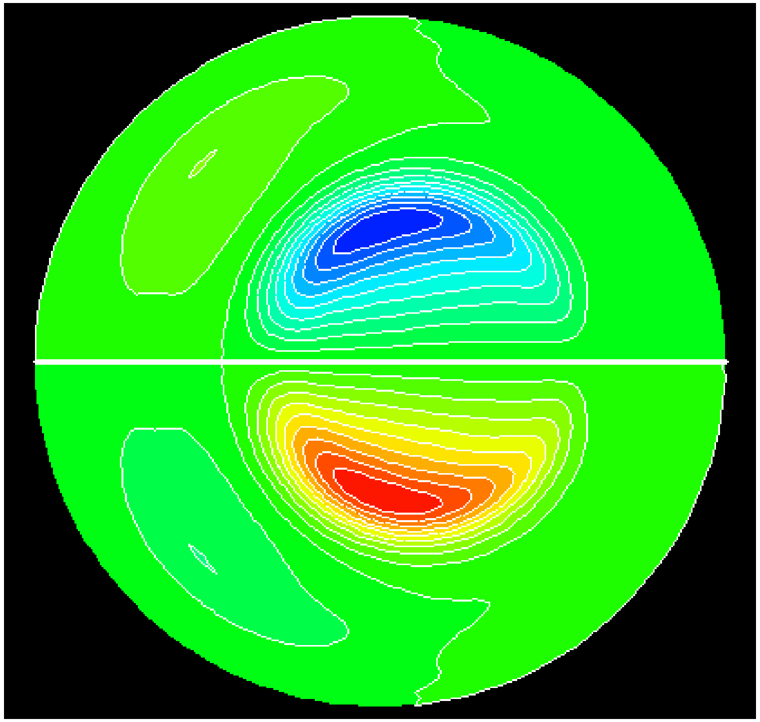
$$\mathbf{B}^\star = \mathbf{B_0} + < \delta\mathbf{B} > + \frac{mv_\parallel}{q}\nabla \times \mathbf{b_0}, \qquad B^{\star\star} = \mathbf{B}^\star \cdot \mathbf{b_0}$$

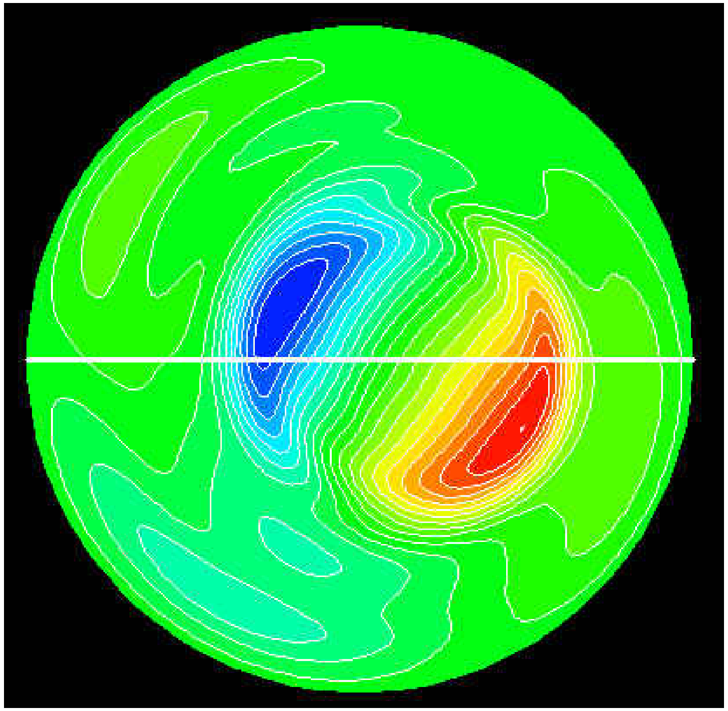
Stabilization of Internal Kink and Excitation of Fishbone Instability



circular tokamak R/a=2.76
q(0)=0.6, q(a)=2.4
β_total(0) = 8%
v_h/v_A = 1.0, ρ_h/a=0.05
Isotropic slowing-down
hot particle distribution

Mode Structure: Ideal Kink v.s. Fishbone





Alpha Particle Stabilization of Internal Kink Mode:
Analytic Model

$$\frac{\gamma}{\omega} = \frac{\gamma_{mhd}}{\omega} - \beta_\alpha(0)\delta W_\alpha$$

$$\delta W_\alpha = \frac{\sqrt{3}\pi}{8s_1}\sqrt{\frac{R}{r_1}}\int_0^{r_1} dr[(0.6+3.2(1-q-0.5s))(\frac{r}{r_1})^{1.5}\frac{d\hat{p}_\alpha}{dr}]$$

Alpha Particle Stabilization of Internal Kink:

Numerical Results for a Model Tokamak Equilibrium

Parameters and Profiles:

R/a=3.2, circular flux surfaces;

β_{total} (0) = 3.3%;

q(0)=0.85, q(a)=2.7;

constant density profile;

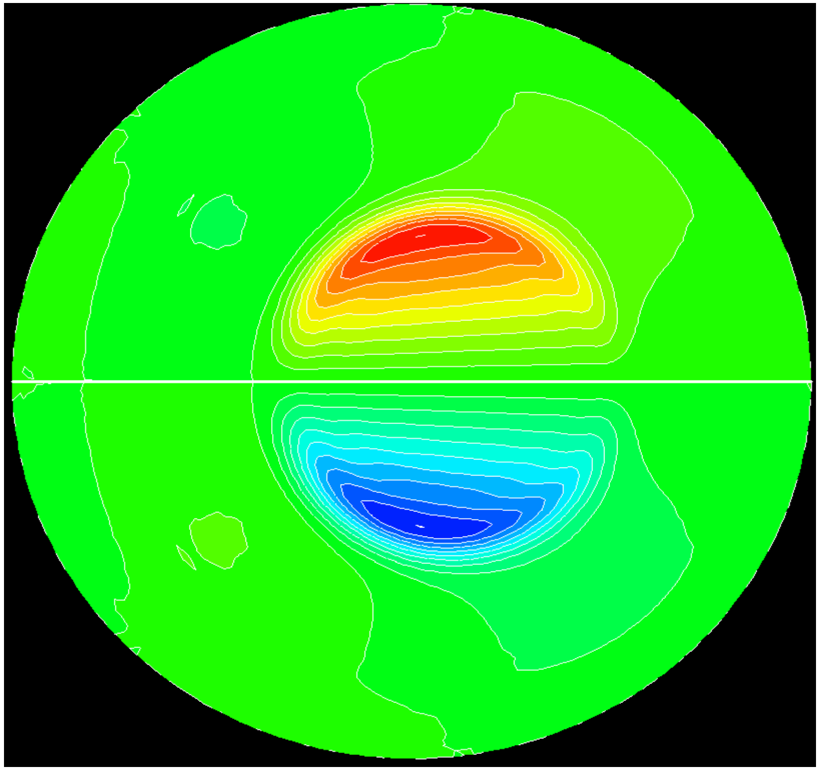
thermal and alpha pressure profiles:

$P(\psi) \sim \exp(-\psi/0.25)$;

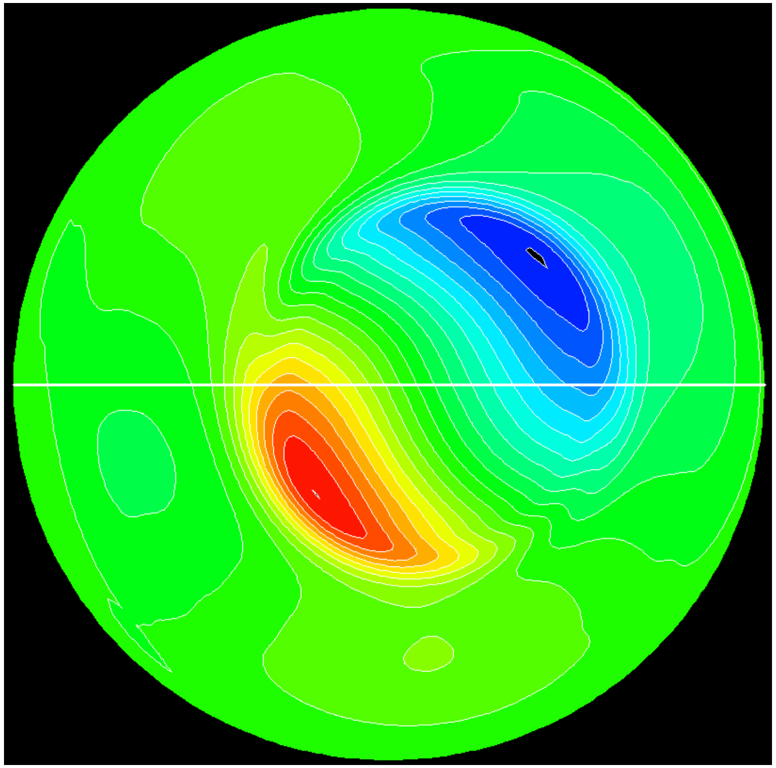
alpha particle beta is varied at fixed total beta.

Numerical Results for a Model Tokamak Equilibrium:
Internal Kink Mode Structure

β_α=0.0%

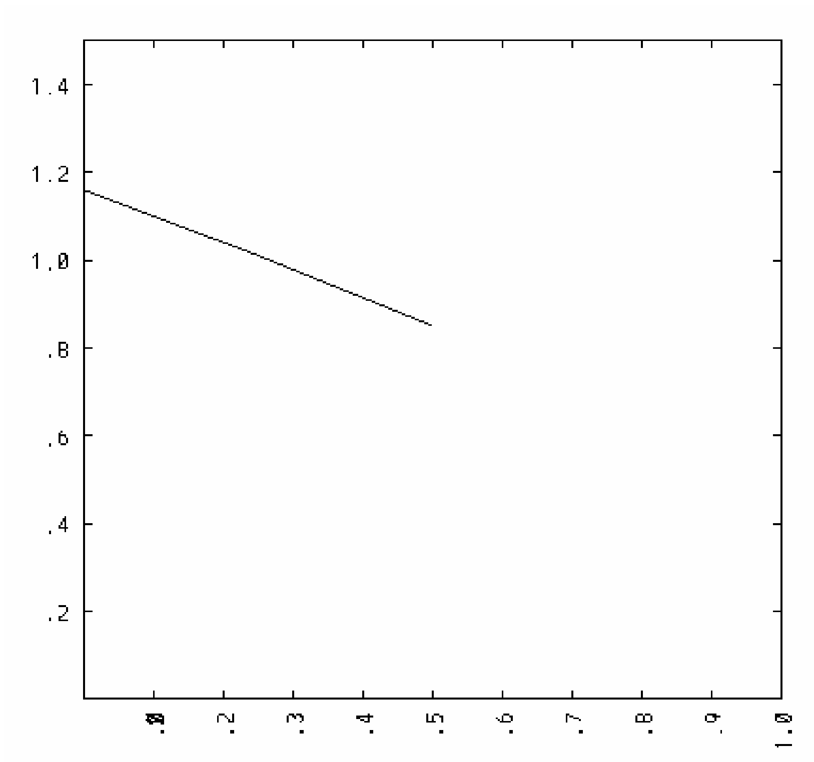


β_α=0.5%



Numerical Results for a Model Tokamak Equilibrium:
Growth Rates agree with Analytic Results

γ (%)



$\beta_\alpha(0)$

Alpha Particle Stabilization of Internal Kink Mode for ITER: Parameters and Profiles

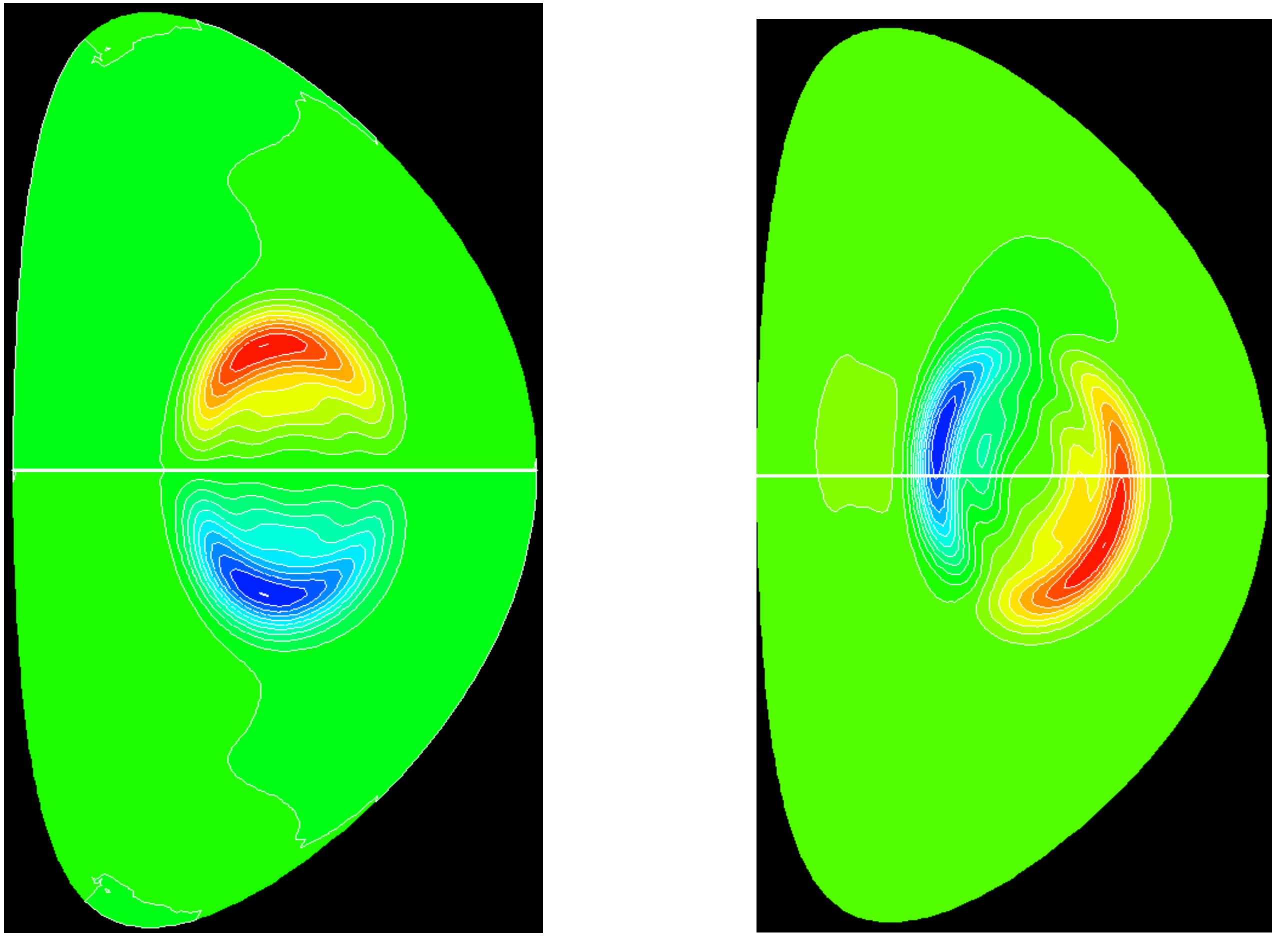
- R=620cm, a=200cm, B=5.05T, $n_e(0)$=1.0e15, Ti=19kev, Te=23kev;
- q(0) ~ 1, q(a)=3.83;

  $\beta(0)$=6.5%, $\beta_\alpha(0)$=1%;
- v_α/v_{Alfven} = 2.5, ρ_α/a =0.023

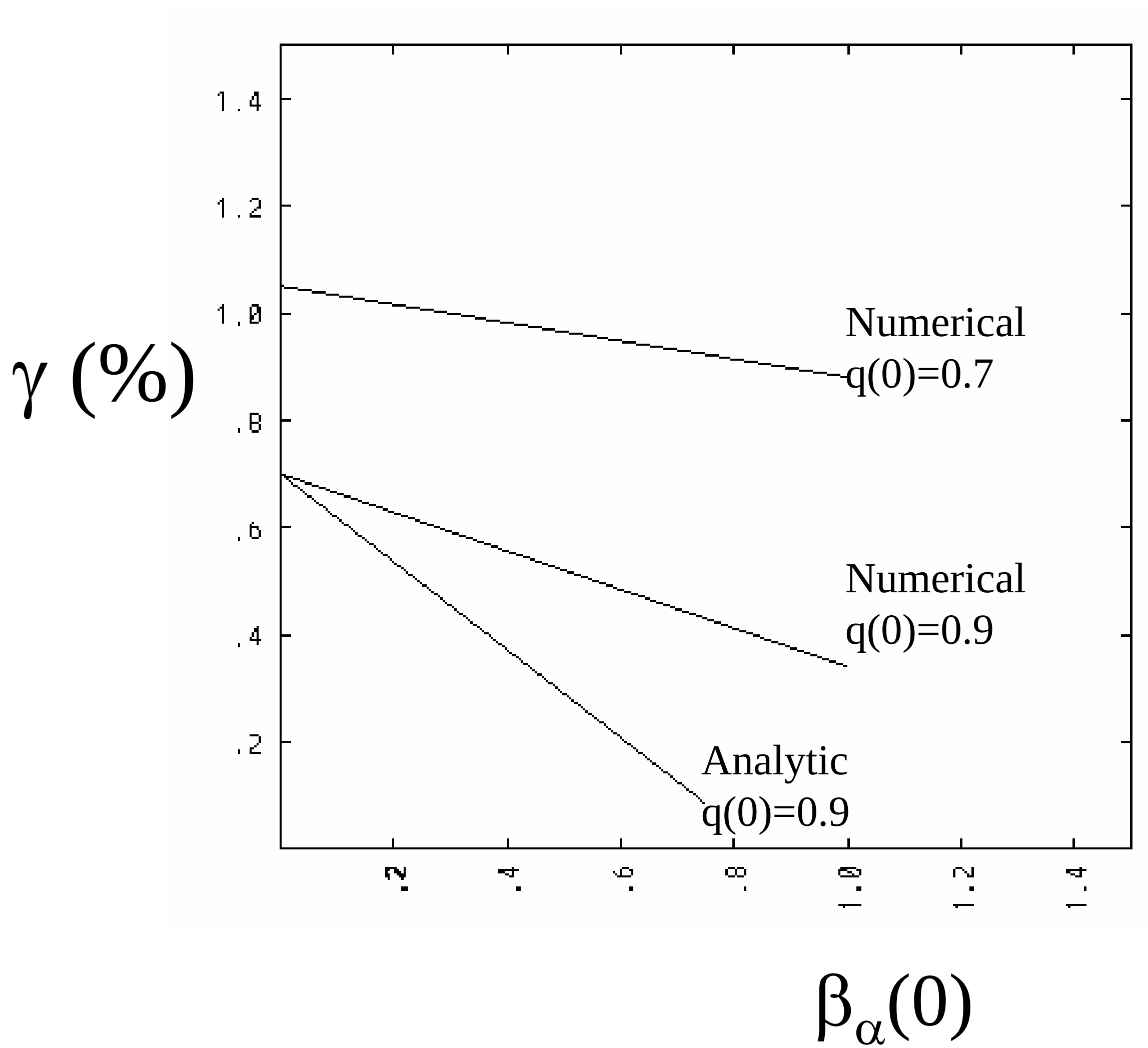
Alpha Particle Stabilization of Internal Kink Mode for ITER:

Internal Kink Mode Structure

β_α=0.0 β_α=1.0%



Alpha Particle Stabilization of Internal Kink Mode for ITER:
dependence on q(0)



Summary

- We have investigated alpha particle stabilization of internal kink mode in ITER via hybrid simulations;
- We have shown that alpha particles can be strongly stabilizing when q(0) is close to unity or when q profile is flat near the center;
- However, simple analytic results overestimate the alpha stabilization by a factor of two;
- Initial results indicate that finite orbit width and passing particle's non-adiabatic response are not significant for alpha stabilization, as usually assumed in analytic theory.