Halo Current and Resistive Wall Simulations of ITER

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Outline

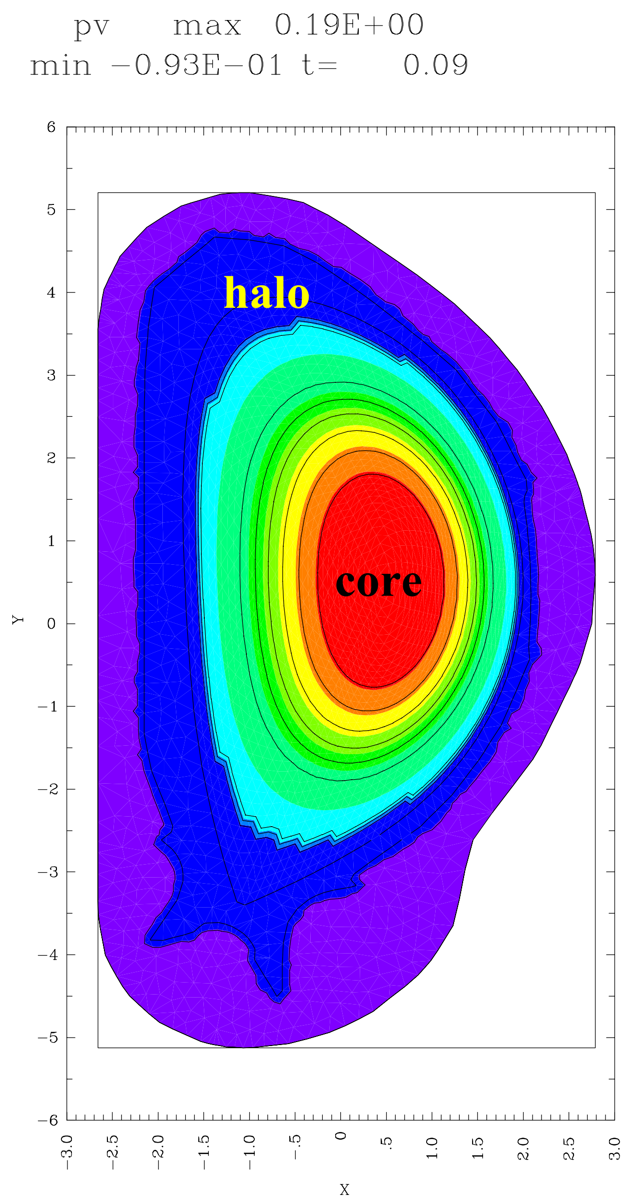
- **Resistive boundary in simulational problems**
- **Halo current – M3D : nonlinear, resistive MHD**
  - **VDE**
  - **Disruption**
  - **RWM (resistive wall mode)**
- **RWM – AEGIS : linear ideal MHD, resistive wall**
  - **Stabilization by rotation, Alfven resonance**
  - **Thick wall effect**

Halo Current

- **Halo current:**
  - current flowing on open field lines into wall
- **Causes stress on walls**
  - Toroidal asymmetry: TPF (toroidal peaking factor)
  - Halo current fraction
  - Want to confirm ITER database with simulation
- **Occurs during:**
  - VDE (vertical displacement event)
  - Major disruption
  - External kink / (RWM) Resistive wall mode

plasma – halo – vacuum model

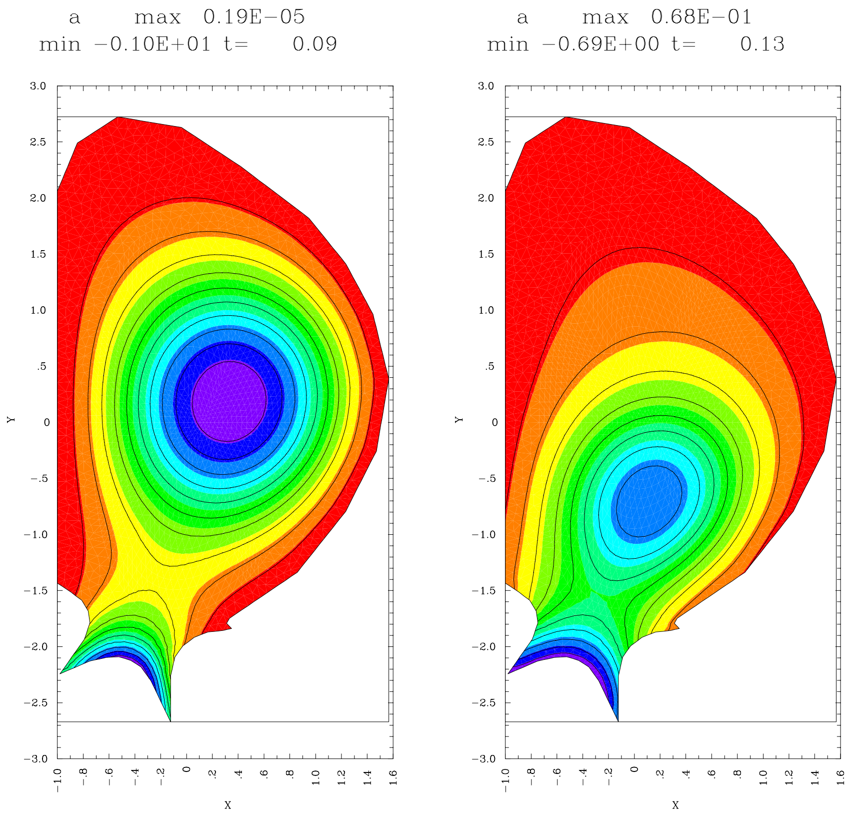
- Plasma regions
- Core
- separatrix
- halo
- 1st wall
- Outer wall
- Outer vacuum

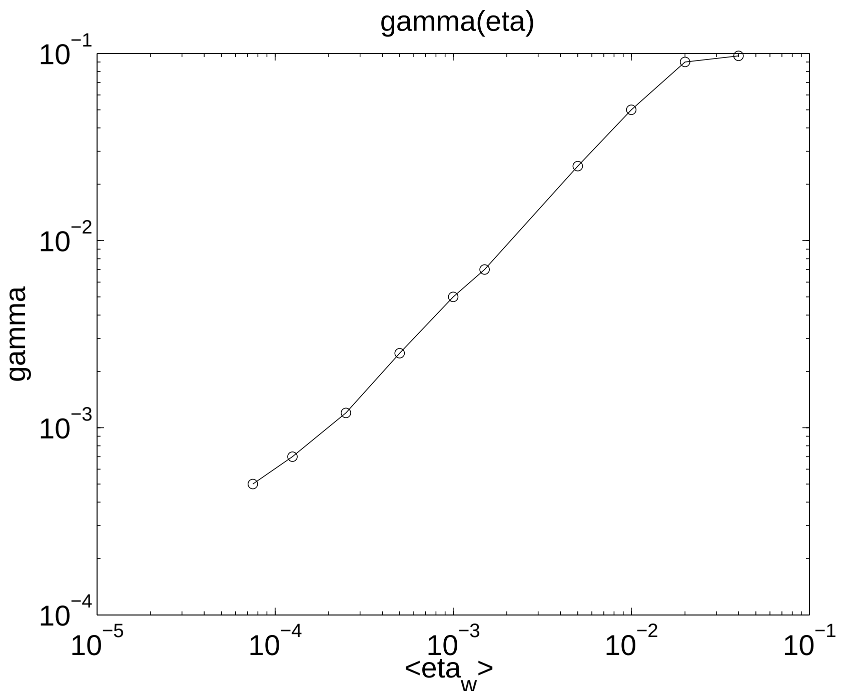


- **Resistive MHD with self consistent resistivity**
  - **proportional to temperature to -3/2 power**
- **Parallel thermal conduction**
  - **Separatrix thermally isolates hot core from cold halo**
  - **In 3D disruptions, stochastic magnetic field quenches core temperature, raising resistivity and quenching current**
- **Outer vacuum**
  - **Green's function method (GRIN)**
  - **Thin wall approximation**
  - **Continuity of normal magnetic field component**
  - **Calculate jump of tangential components, electric field**

VDE Instability

- **2D instability**
- **Growth rate proportional to wall resistivity**
- **Halo current flows when core near wall**





Poloidal flux function

Toroidal peaking factor and halo current fraction

Normal component of poloidal Current flowing out through the boundary as function of toroidal angle

$$I_h(\phi) = \pi \oint |n \cdot J| R dl$$

$$\approx \pi \oint \left| \frac{\partial R B_\phi}{\partial l} \right| dl$$

Toroidal peaking factor

$$TPF = \frac{I_h(\phi)_{\max}}{< I_h >}$$

Halo current fraction of Toroidal current

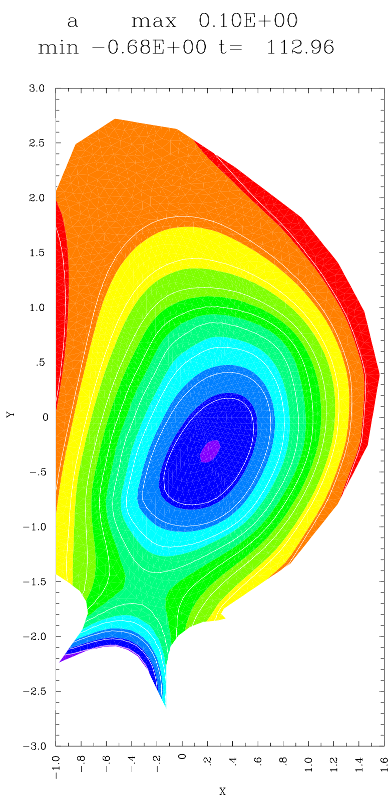
$$F_h = \frac{< I_h >}{I_\phi}$$

Inverse relation of TPF to Halo current fraction

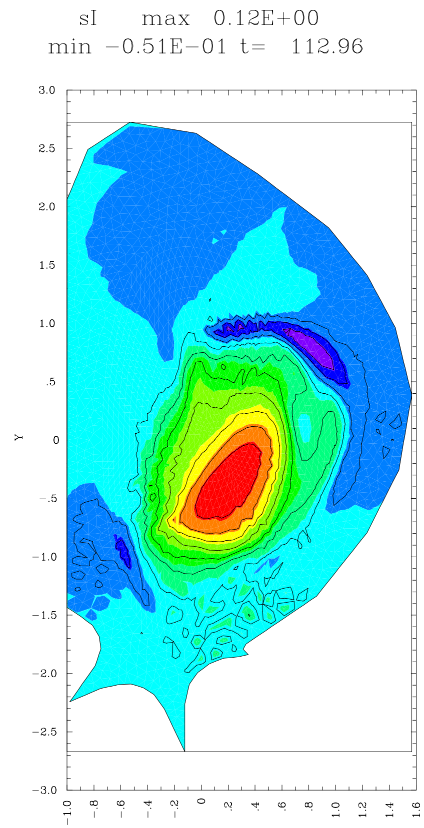
$$TPF \times F_h = \frac{I_h(\phi)_{\max}}{I_\phi}$$

3D disruptions

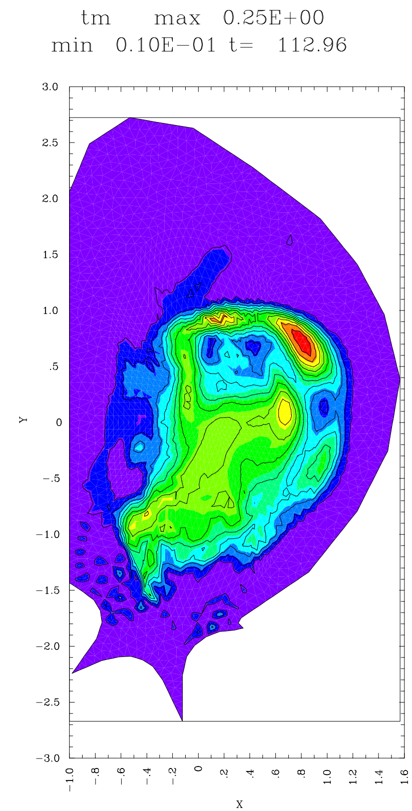
- TPF: Toroidal Peaking Factor - toroidal asymmetry of ITER halo currents
- Halo Current Fraction – measure of halo current
- Disruption can combine with VDE – increasing its growth rate
- Case of internal kink with large q=1 radius
- Halo current flows along contours of RB_t intersecting the wall



Poloidal flux(VDE)



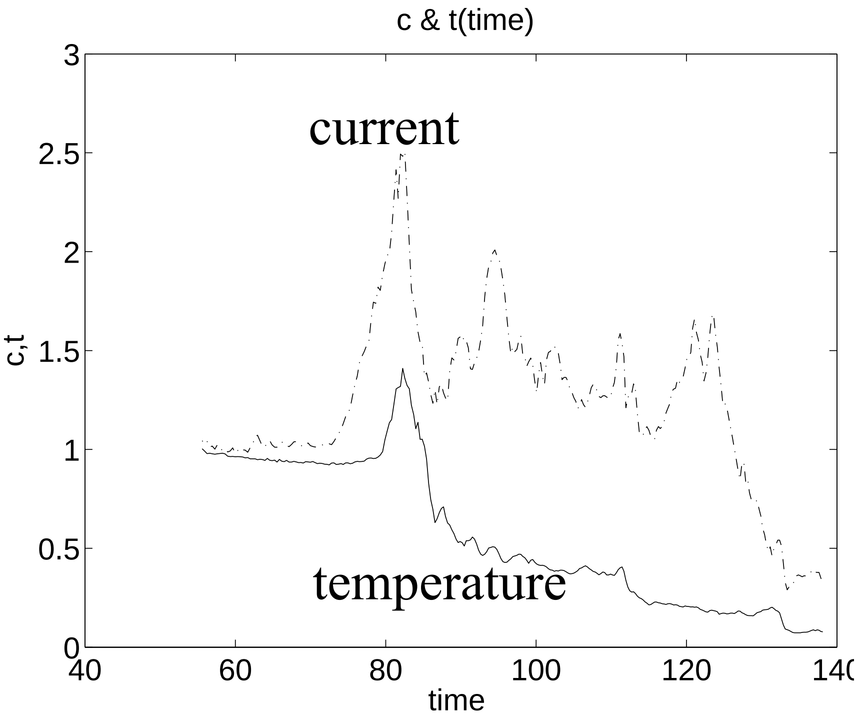
RB_t



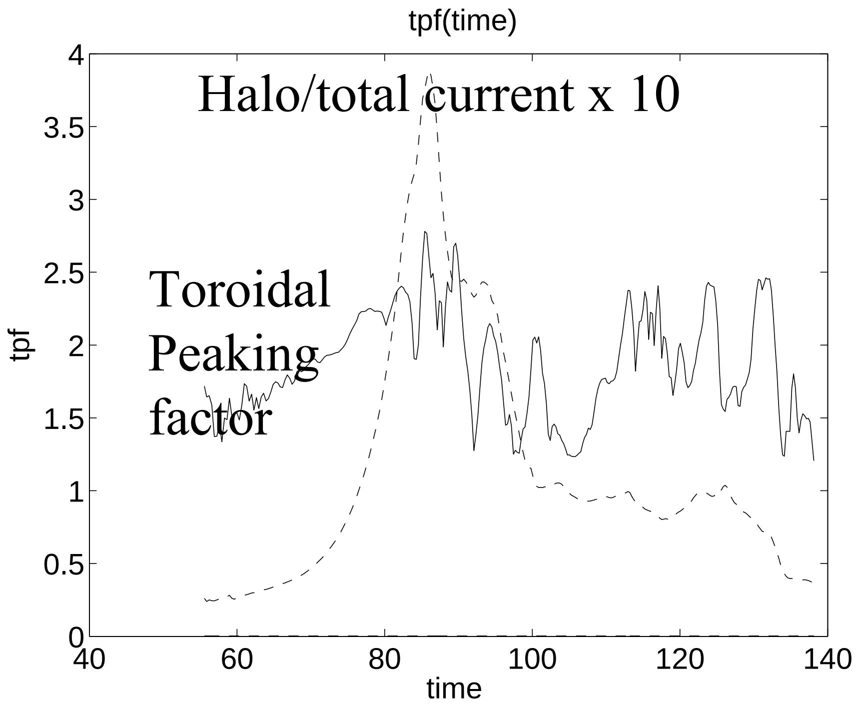
temperature

toroidal peaking factor and halo current fraction

TPF = 2, F_h= 0.35



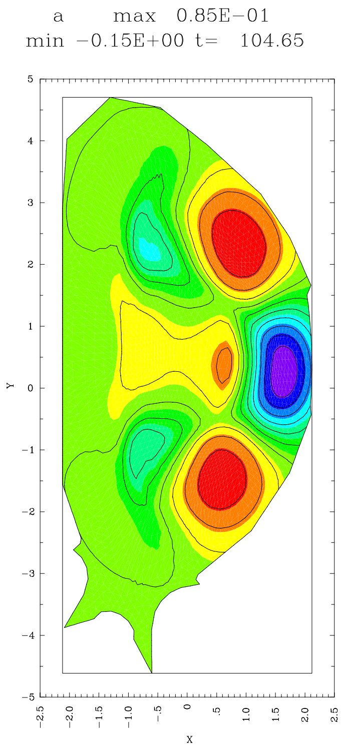
Temperature and current vs. time

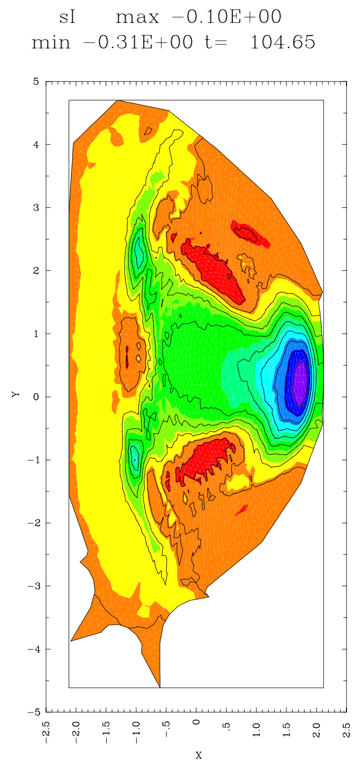


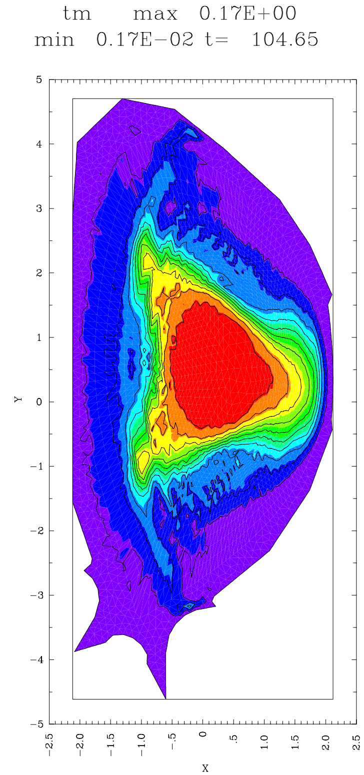
TPF and F_h vs. time

Nonlinear RW – external kink

TPF = 1.1, F_h = .2







Perturbed Poloidal flux **RB_t** **temperature**

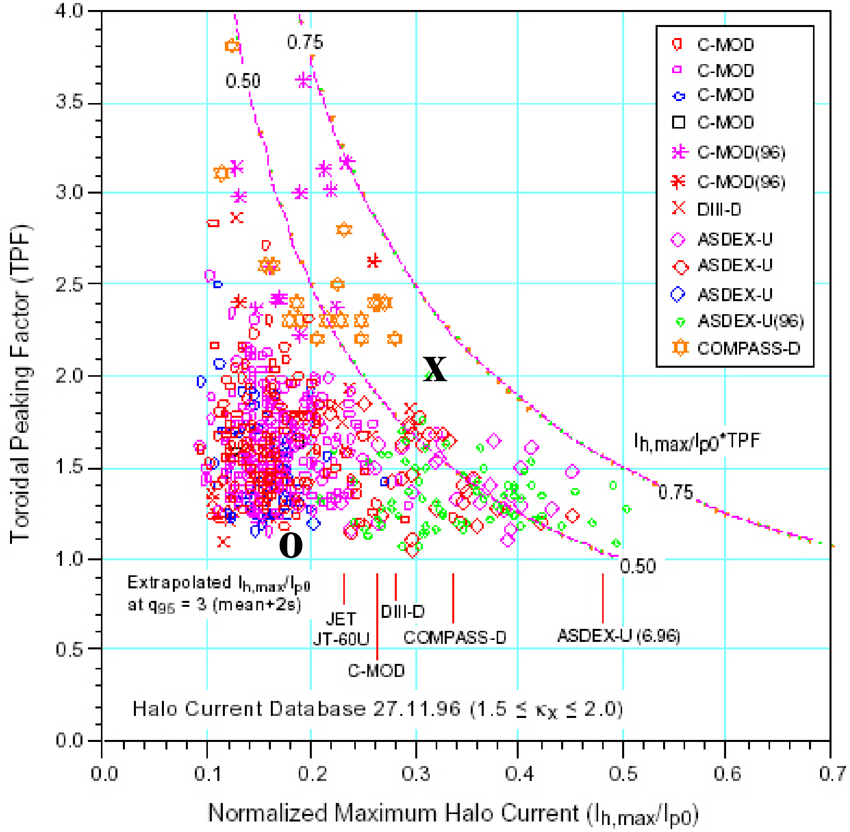
ITER AT:
m/n = 3/1

$$q_0 = 3.6, \beta_n = 2.4$$

Results are consistent with ITER database

X – kink instability
O – resistive wall mode

TPF

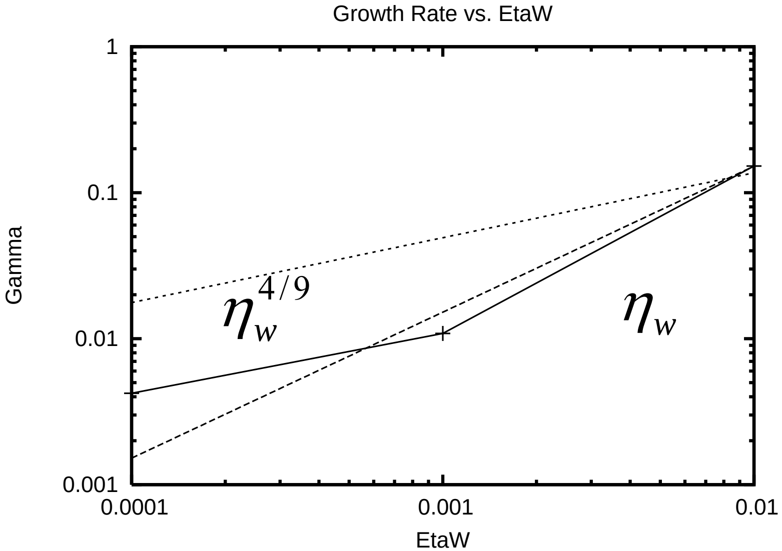


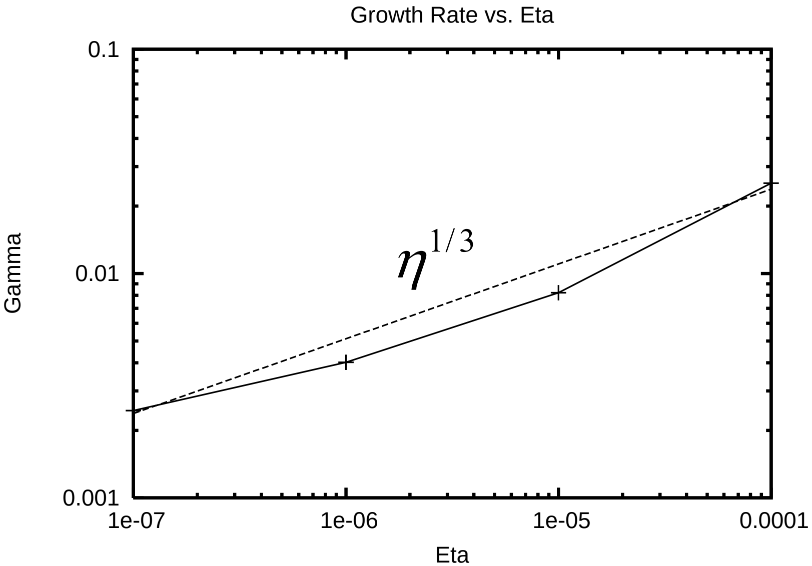
F_h

Scaling of RWRP mode

Simulation of RWM is complicated by plasma resistivity

Finn, 1995, Betti 1998





$\eta = 10^{-6}$ $\qquad$ $\eta_w = 10^{-3}$

$$\gamma_t > \gamma_{RWM} \qquad \gamma \sim \eta^{1/3}\eta_w^{4/9}$$

RWM interacts with tearing/electromagnetic resistive ballooning mode

New MHD code: AEGIS

Adaptive EiGenfunction Independent Solution

Features

- **Radial Adaptive mesh to resolve Alfven resonances**
- **Small matrix size formulation:**

  AEGIS: M, GATO or PEST: M x N (sparse)

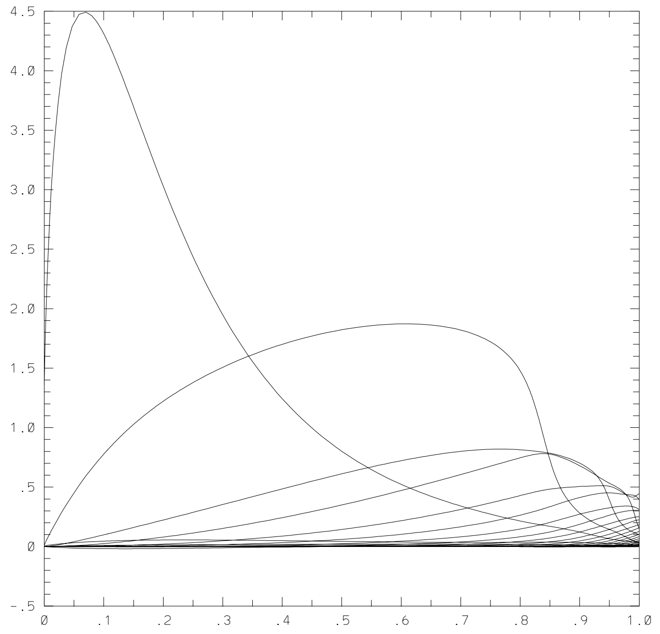
  M: no. of poloidal components, N: radial grids
- **Applicable both for low and high n modes**
- **Benchmark with GATO: good agreement in beta limit, growth rate, critical wall position, and mode shape**

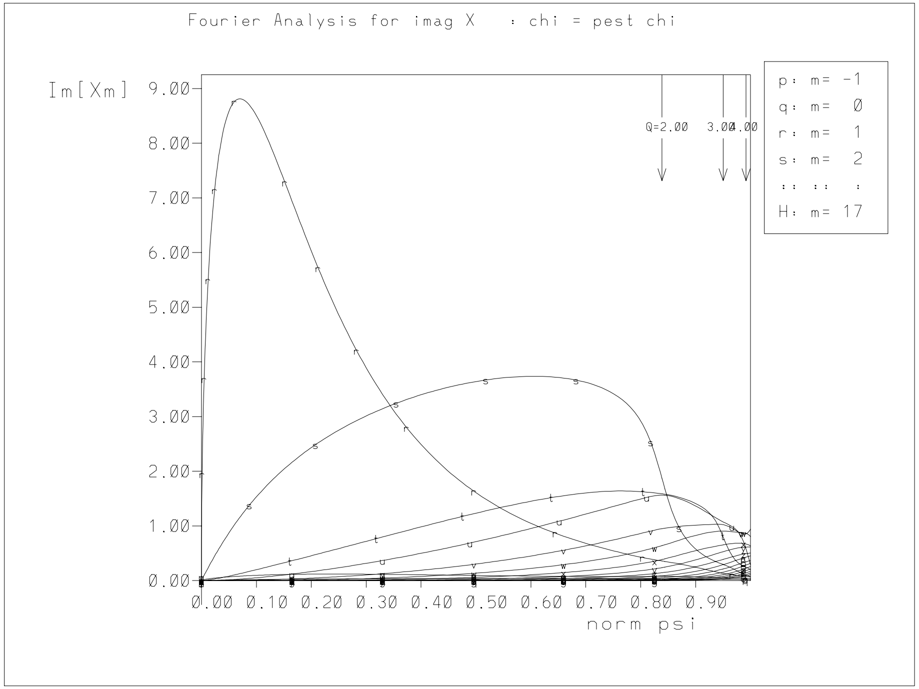
Benchmark with GATO

Good agreement in all aspects:

beta limit, growth rate, critical wall position, and mode shape…

- **AEGIS**
- **GATO**





Rotation effect on RWMs

- **Previous results:**

  Rotation stabilization results from sound wave resonance or generally particle wave resonance

- **Current results:**

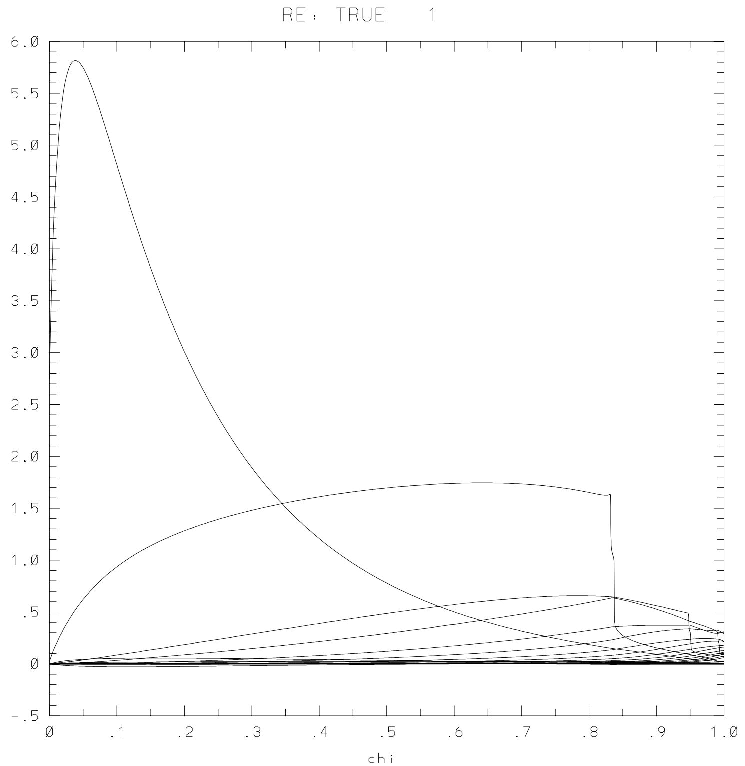
  Shear Alfven continuum damping can effectively stabilize RWMs.

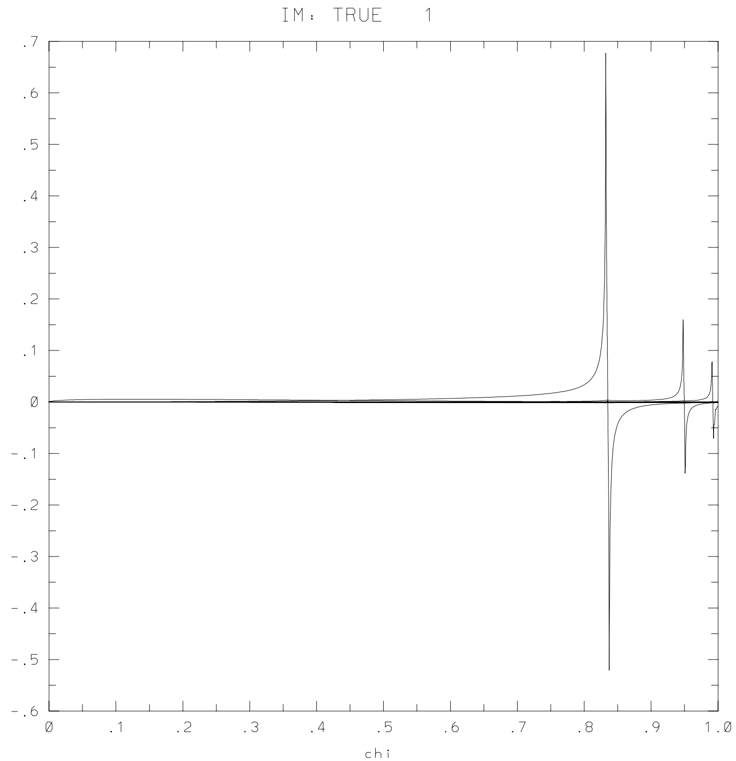
  --- this fine singular layer effect can be resolved by AEGIS due to its adaptive feature.

Parameters: $q(0) = 1.05$, $q(95) = 3$
volume average beta= 0.062, beta_n = 3.88.
no wall limit beta_n = 3.4

Grid adapts to resolve resonances

- **Eigenmode: Alfven resonances at q = 2, 3, 4**

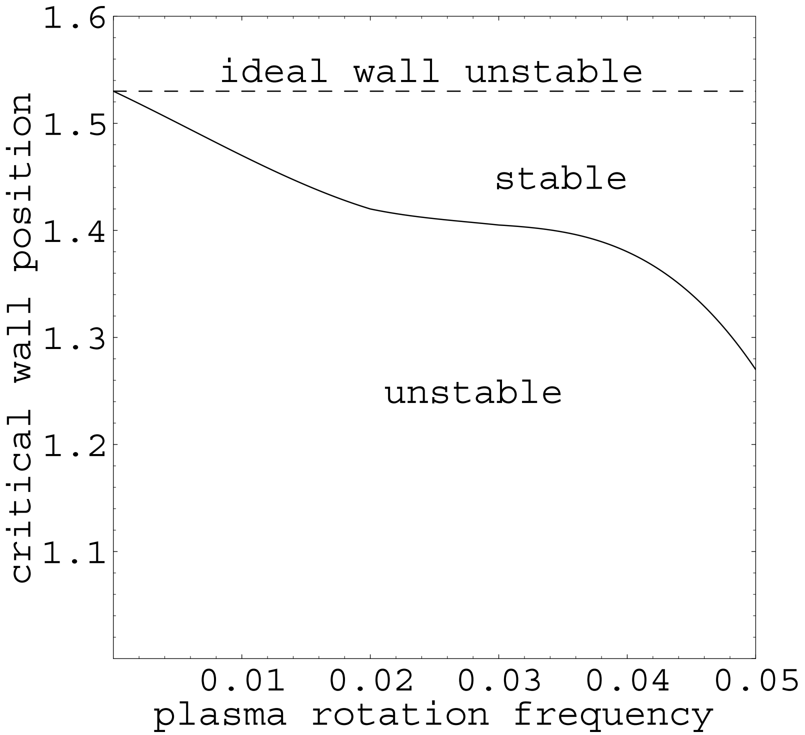




Resonances are singular in limit of zero growth rate

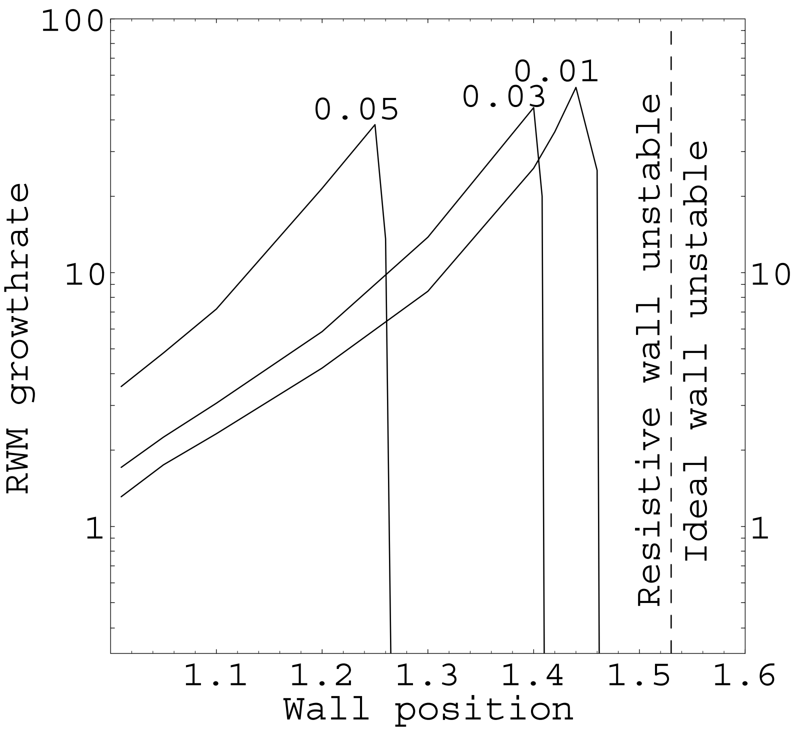
Low Mach number rotation stabilization for ITER configuration

Marginal wall position vs. rotation frequency



Stability window in wall position for nonzero rotation

RWM growth rate vs. wall position for different rotation frequencies



Growth rate drops sharply at stability boundary

Wall thickness effect on RWMs

- **Motivation:**

  ITER wall is 0.45 thick.
- **Method:**

  Adaptive shooting of the Euler-Lagrange equation in the wall region.
- **Results:**

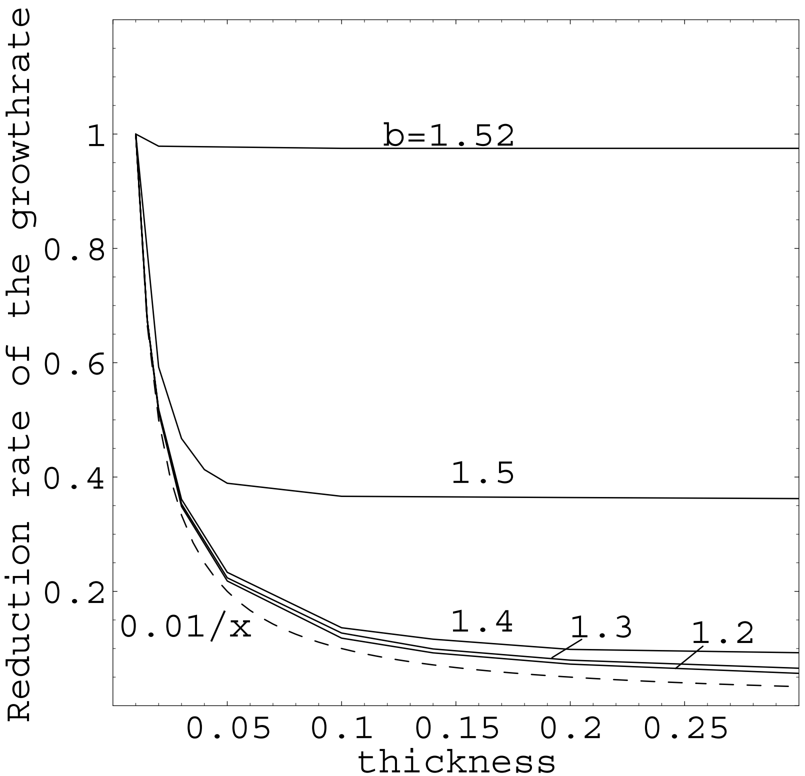
  The part of the wall located beyond the ideal-wall critical position gives no contribution for stability.

  Thick wall slows growth.

  Effects of rotation and thick wall to be studied later.

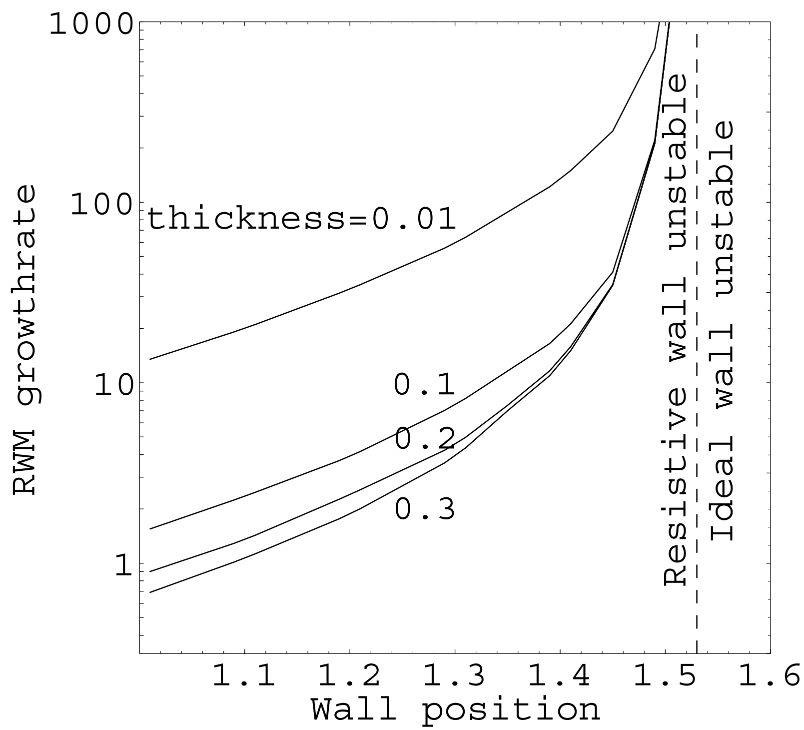
Effect of wall thickness on growth rate

- **Dashed curve represents the thin-wall-theory estimate and b is the wall position**



Thick wall has no effect outside the critical wall position

- **Growth rate vs wall position with different wall thickness**



For less than critical wall position, thickness slows mode

Summary

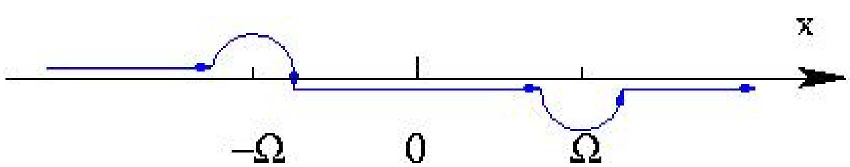
- Halo current calculated in nonlinear M3D simulations
- Model simulates VDE, disruption, thermal & current quench
- TPF and F_h consistent with ITER database
- Resistive plasma modifies RWM scaling

- AEGIS RWM simulations of rotation stabilization with self consistent Alfven damping, no model parameters
- Thick wall slows RWM growth rate, but has no effect outside critical wall position

Phase change across to the resonance

Integration orbit:

$\boldsymbol{\Omega = \Omega\_rot + i\,\omega + \gamma}$



- **Singular layer equation**

  d/dx (x^2-Ω^2) dξ /dx =0

- **Solution:**

$\xi \;= (b/2\Omega) \ln (x-\Omega)/(x+\Omega) + a$

At $-\infty$:

$$\xi = a - b/x$$

At $+\infty$:

$$\xi = a - b/x + i\, b\, \pi /\Omega$$