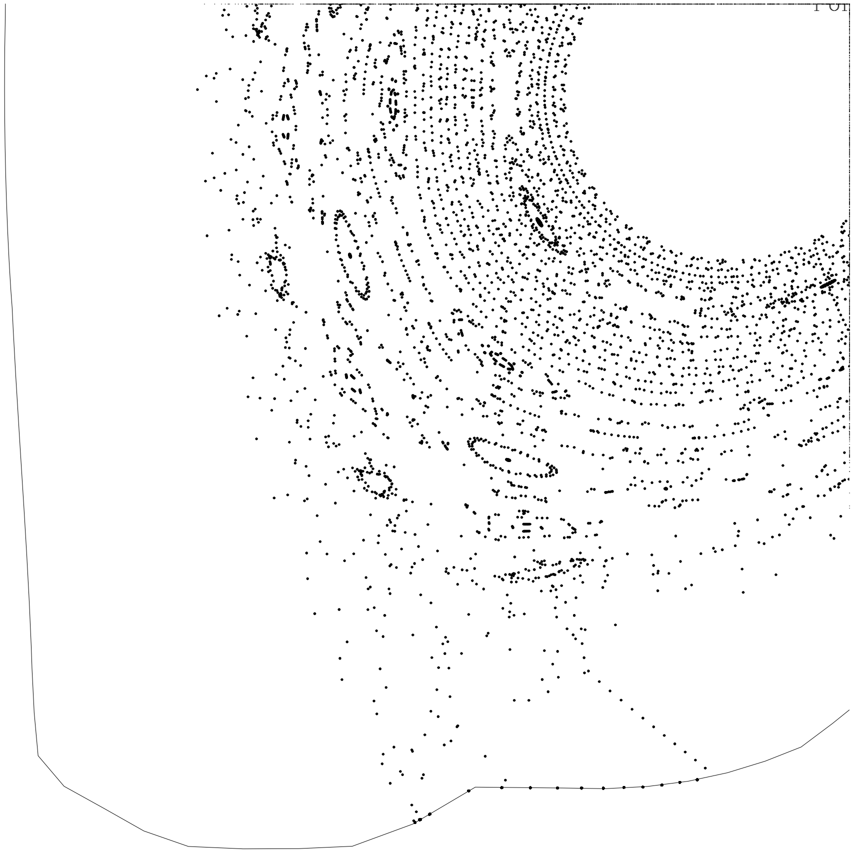
M3D Simulation of RMPs, ELMs, RWMs

H. R. Strauss

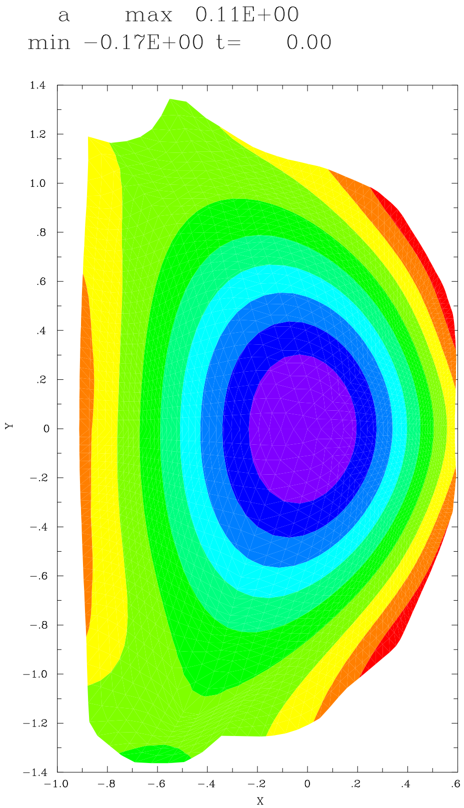
RMP – resonant magnetic perturbations

- RMP has suppressed ELMs in DIII-D
  - I coil produces n=3 magnetic perturbations
  - “vacuum” RMP produces stochastic magnetic field in outer 1/3 of plasma

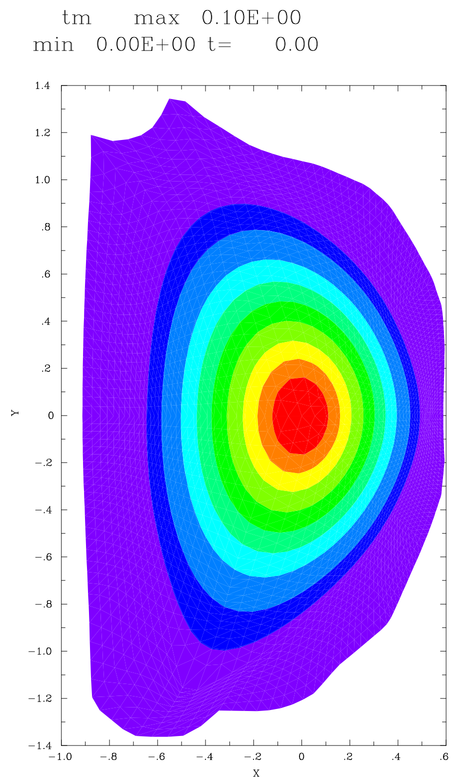


M3D MHD simulations – initial state

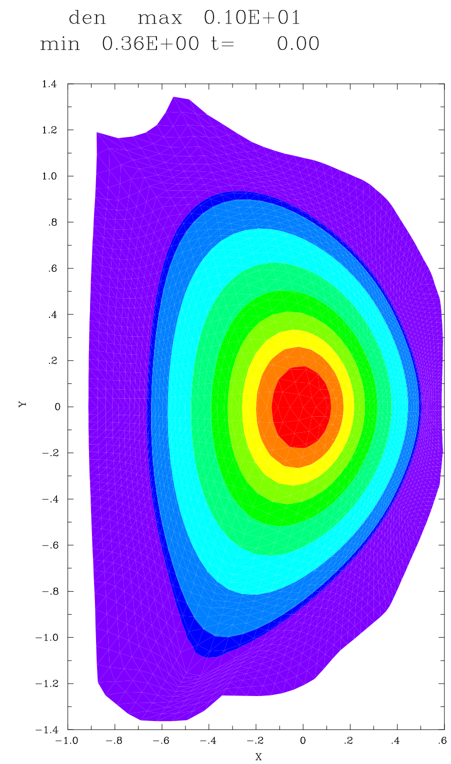
- M3D MHD simulations
  - Initialized from DIII-D eqdsk file of equilibrium reconstruction g126006



Magnetic flux



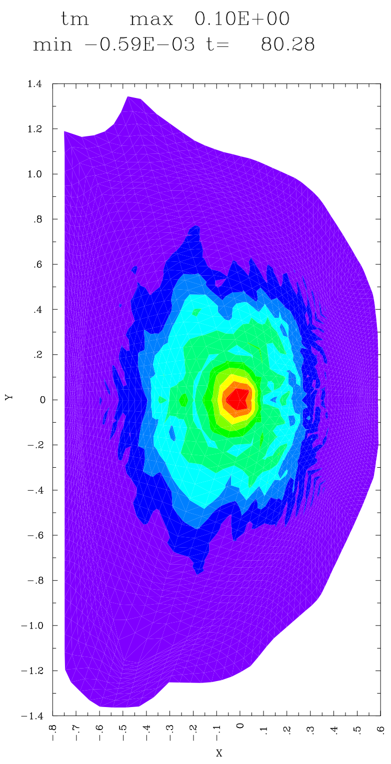
temperature



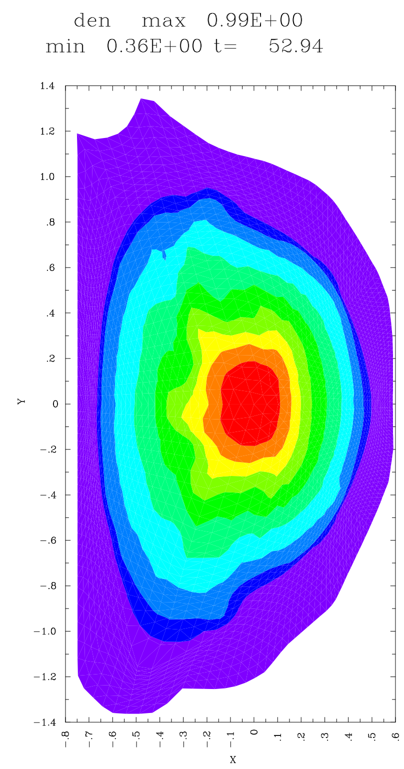
density

Effect of “vacuum” RMP

- “vacuum” RMP added to initial equilibrium
  - Initial state evolved until t=80 $\tau_A = R / v_A$
  - Rapid cooling due to large parallel thermal conduction
  - Slower density loss
- This is not what happens in DIII-D!



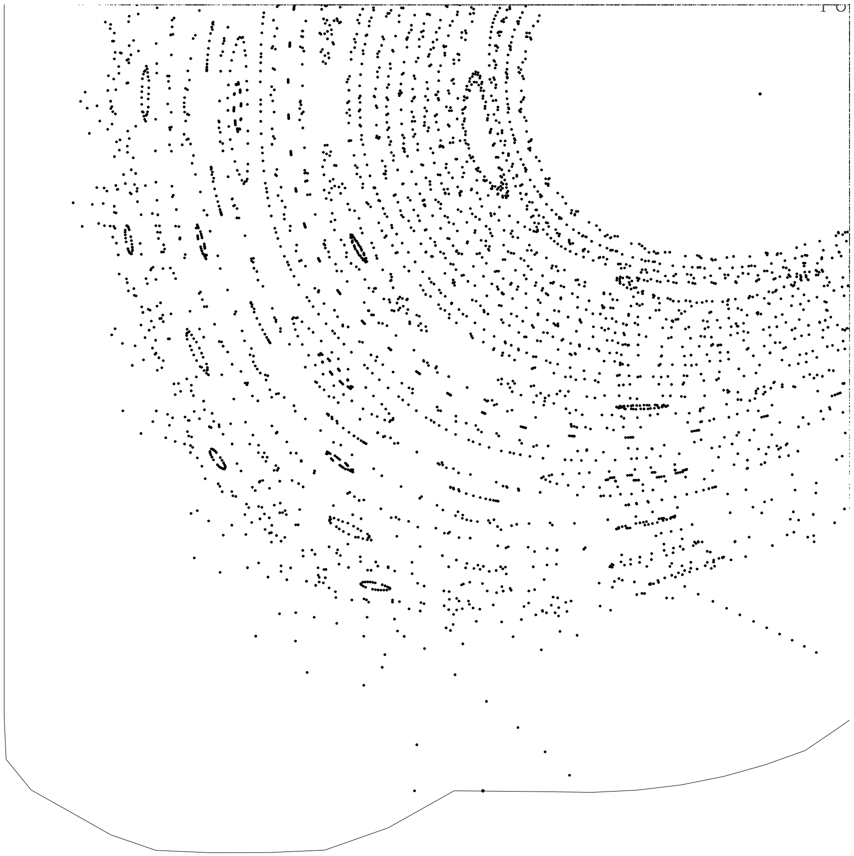
Temperature



density

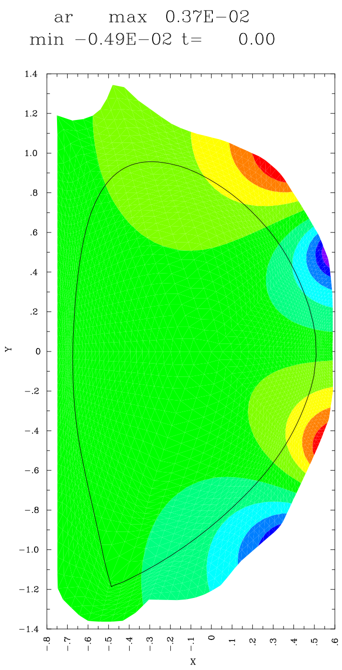
Rotational screening of RMP

- In RMP experiments (Evans et al., PoP 12, 2006, Moyer et al. PoP 11, 2005) have a different behavior
  - Temperature is hardly affected by RMP
  - Density gradient relaxes
  - Density is pumped out
- Effect of rotation in M3D
  - First, consider purely toroidal rotation
  - Magnetic islands shrink
  - Plot at t = 56

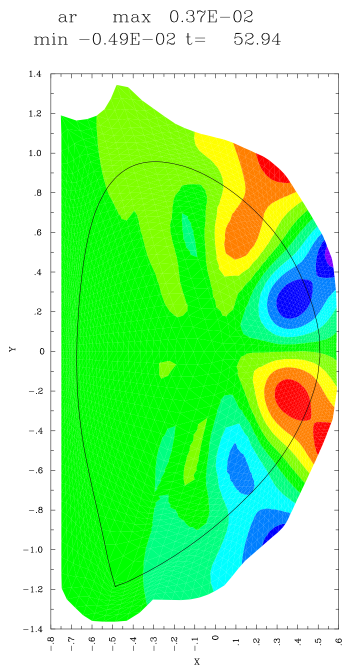


Effect of rotation on RMP flux

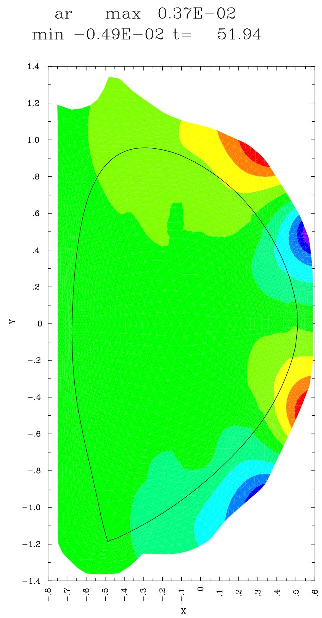
- In resistive MHD, the RMP appears to couple to a resistive mode
  - Magnetic perturbations exceed the “vacuum” RMP
  - Rotation suppresses this mode, as well as screening the RMP
  - Rotating and non rotating poloidal flux compared at t=52.



Vacuum RMP
N=3 Poloidal flux



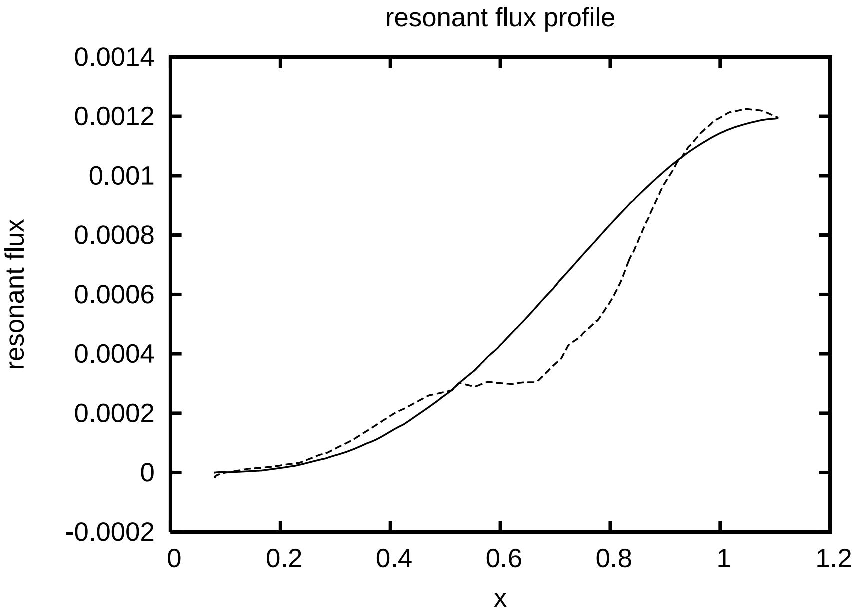
No rotation
Poloidal flux



Rotation suppresses
Mode and screens RMP

Effect of rotation on flux penetration profile

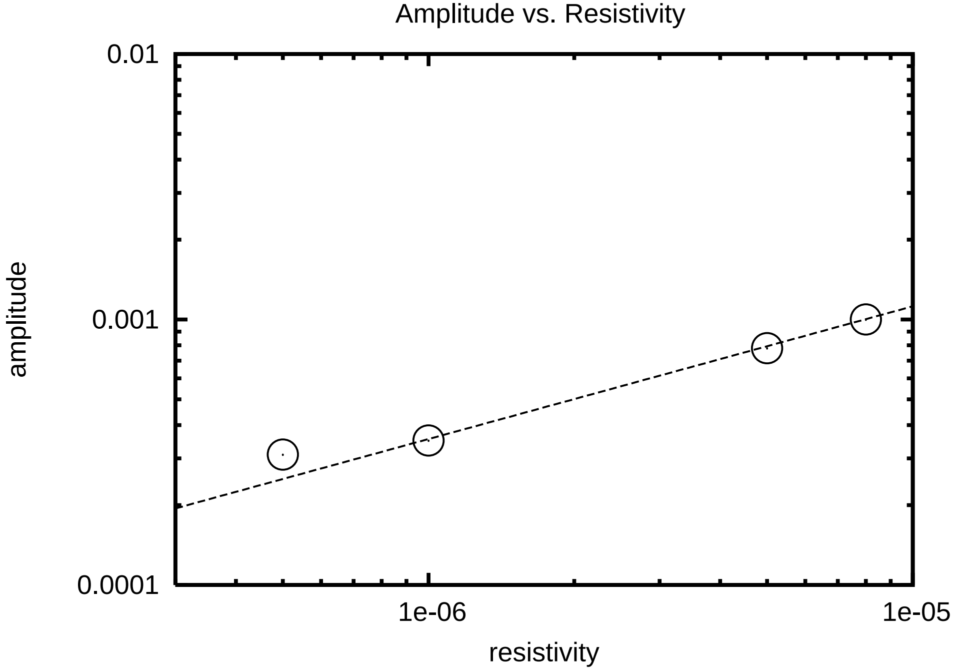
- Rotation excludes perturbed flux from the plasma
  - Profiles of perturbed flux along a ray from the magnetic axis to a point on the boundary where the flux is maximum
  - Solid curve: initial RMP flux, dashed curve: flux at t=52 with rotationl
- Flux penetration profile depends on rotation (especially poloidal rotation)



Perturbed poloidal n=3 flux along a ray – solid: initial flux

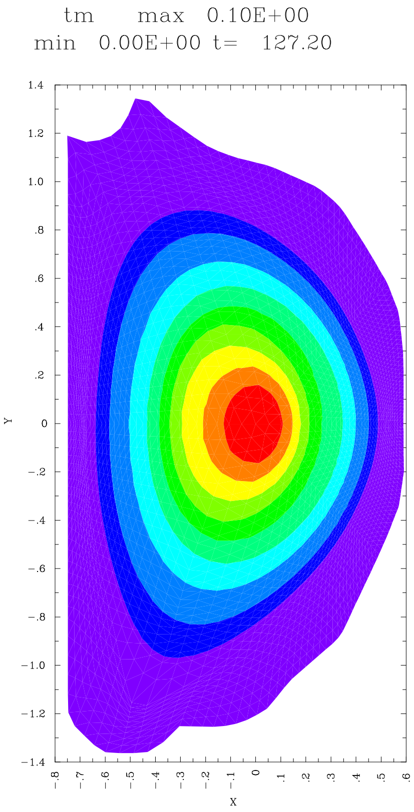
scaling of critical rotation

- The growth of the resistive mode appears to scale as the ½ power of resistivity
  - In the simulations a Spitzer – like self consistent resistivity is used which varies at temperature to the -3/2 power
  - Starting from the same initial state, the maximum amplitude of the n=3 perturbation out of phase with the vacuum RMP is measured at t=52
  - Critical rotation should have same scaling to shield RMP and suppress mode

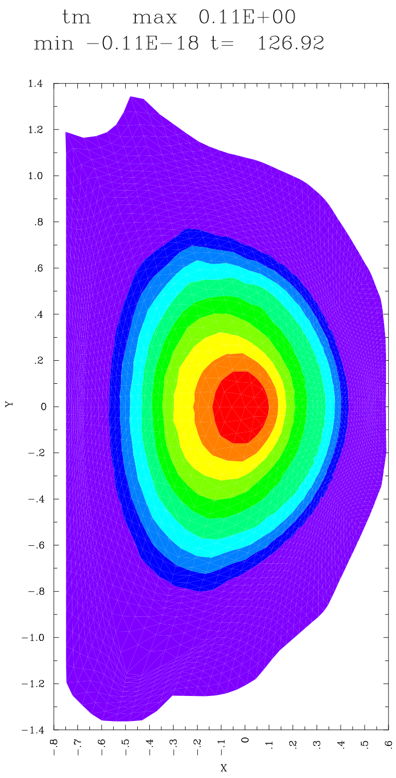


Effects of rotation on temperature

- Rotation shrinks magnetic islands so there is less island overlap
  - A relatively thin stochastic layer remains at the separatrix
  - This causes some cooling at the edge
- Two rotating cases are compared: with and without RMP
  - The rotation in this case is purely toroidal, but the rotation profile is taken from g126006 equilibrium reconstruction
  - The rotation amplitude is larger in order to produce enough screening numerically
  - Show at time t=126



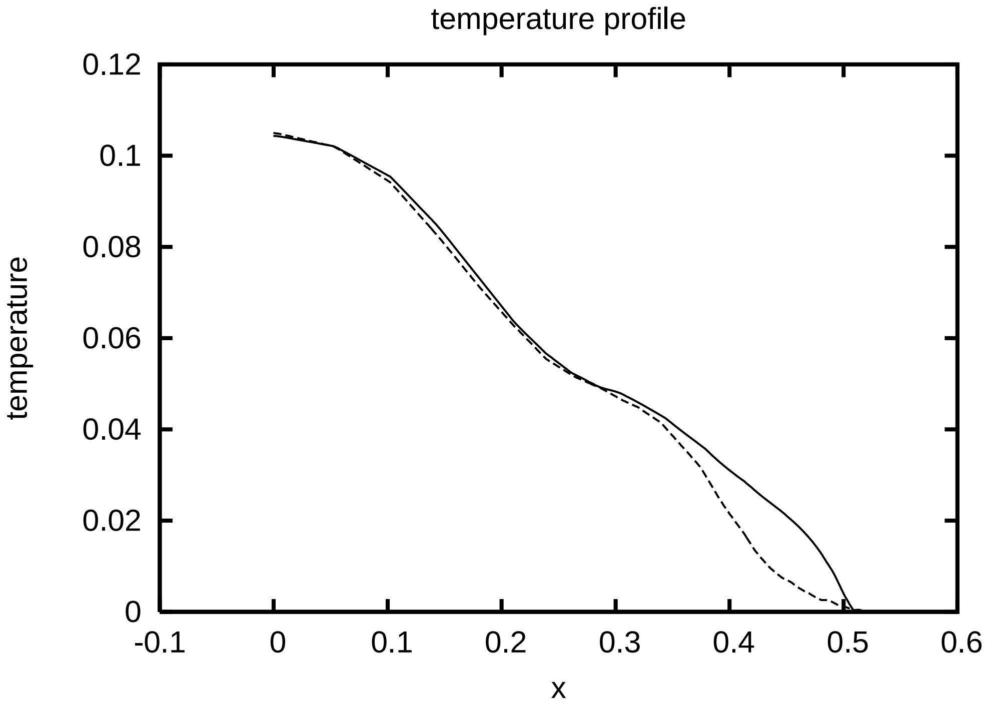
Temperature,
No RMP



Temperature
With RMP

Effect of RMP and rotation on temperature profile

- The cooling region penetrates into the plasma
  - Profiles of temperature along midplane as a function of $R – R_{axis}$
  - Solid line: no RMP, dashed line: with RMP
  - small effect on the plasma core

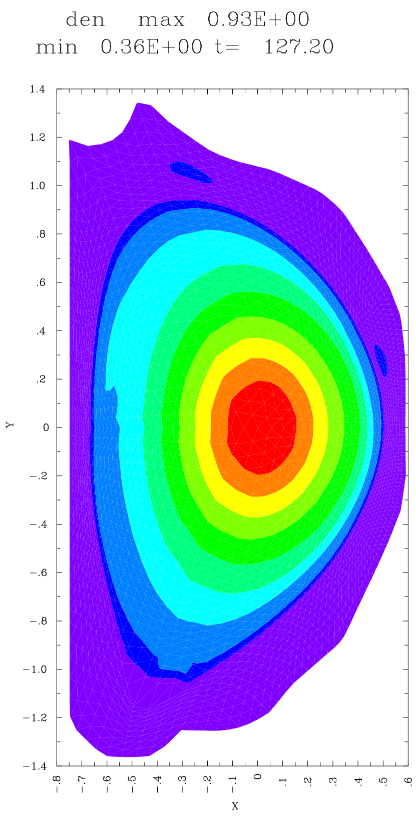


Effect of rotation on density

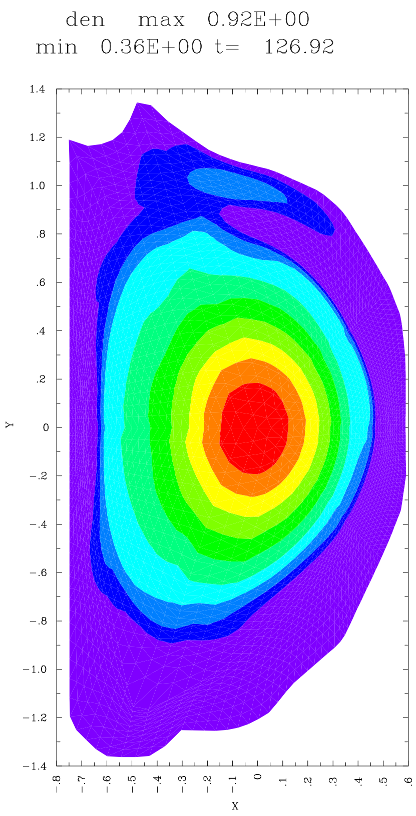
- The effect of rotation on the density is more complicated and more problematic numerically
  - Rotation causes density and pressure to deviate from magnetic flux surfaces
  - Temperature is a flux function because of high parallel thermal conduction
  - Toroidal rotation is more straightforward
  - Poloidal rotation can cause a density pedestal (MHD H mode) and shocks (Betti and Friedberg, PoP 2000)
    - Flux surface averaged sound speed vanishes at separatrix
    - Poloidal rotation at the separatrix is supersonic

Density with toroidal rotation and RMP

- With toroidal rotation there is density loss even without the RMP. With the RMP the loss is enhanced. Density perturbations on open field lines tend to flow to an x-point
  - In this case there is an x-point at the top, outside the boundary, as well as at the bottom



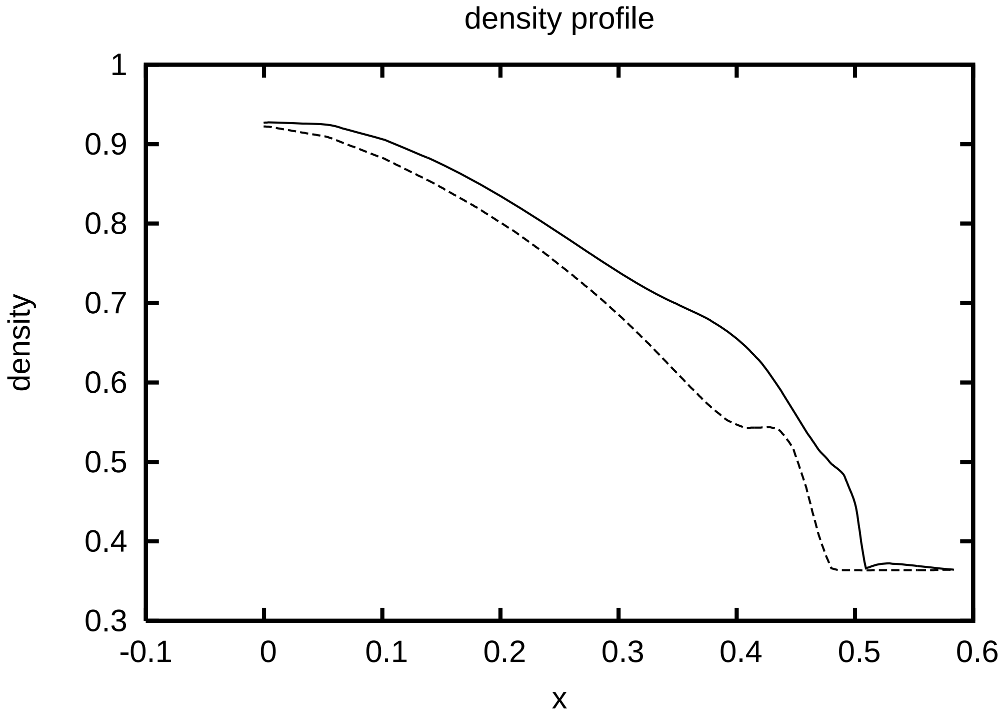
Density with No RMP



Density with RMP

Density profiles with toroidal rotation and RMP

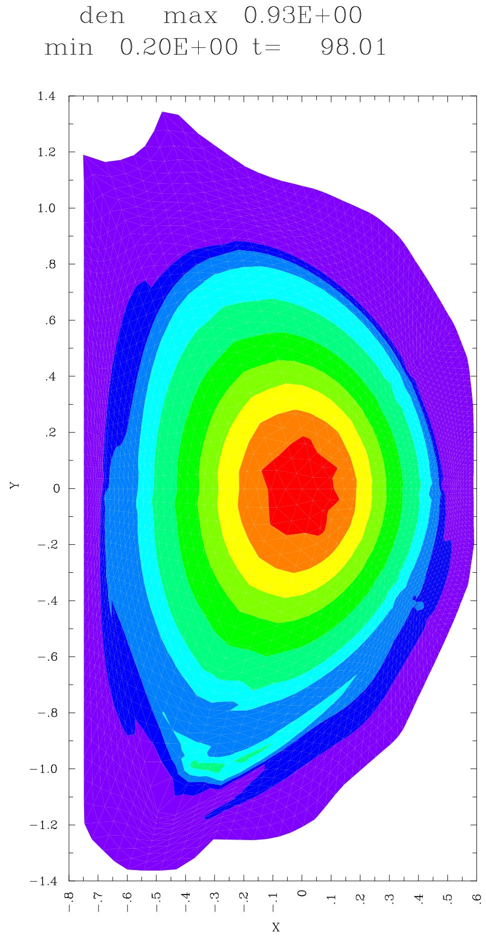
- Density profiles along the midplane are compared with toroidal rotation with and without the RMP. In comparison to the temperature perturbations, the density perturbations extend into the plasma core



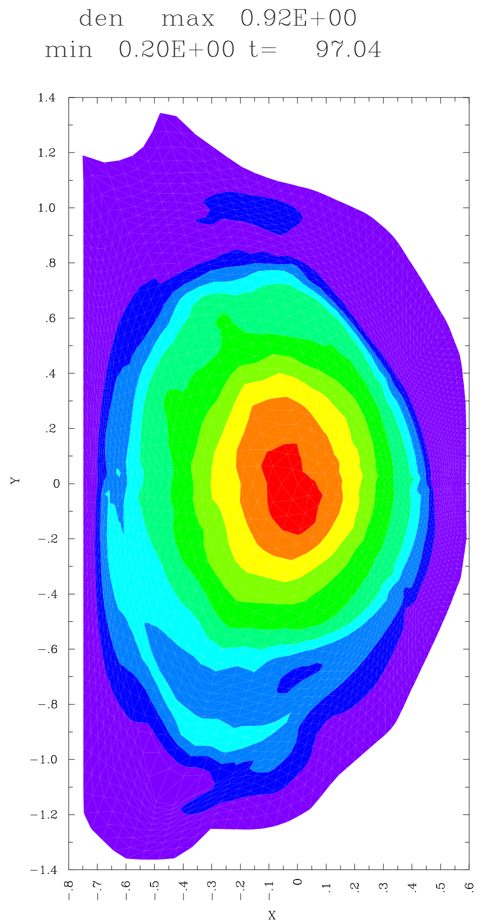
Poloidal and toroidal rotation

- Poloidal and toroidal rotation were combined. This is more problematic numerically. To get cleaner results, a free boundary Grad Shafranov solver with flow is being developed.
- The initial poloidal velocity is of the form

$$\vec{v}_{pol} \propto \nabla T \times \nabla \varphi$$



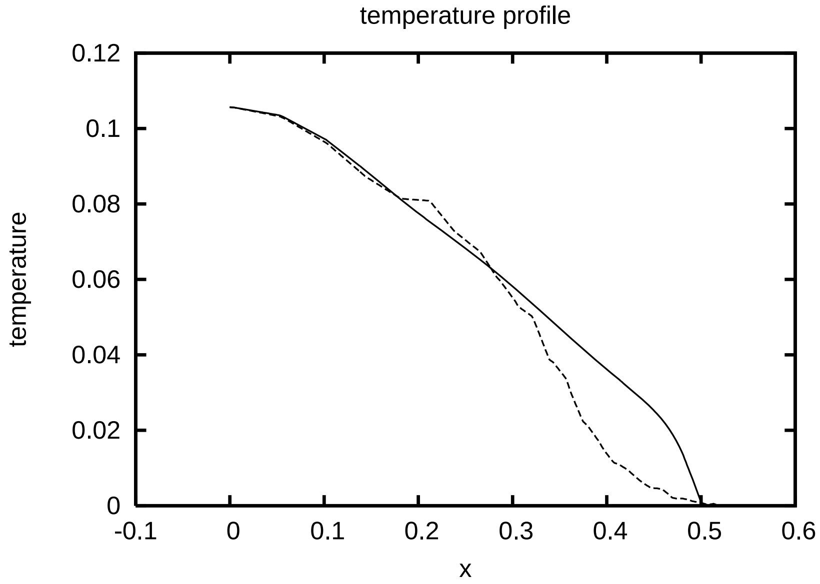
Density without RMP

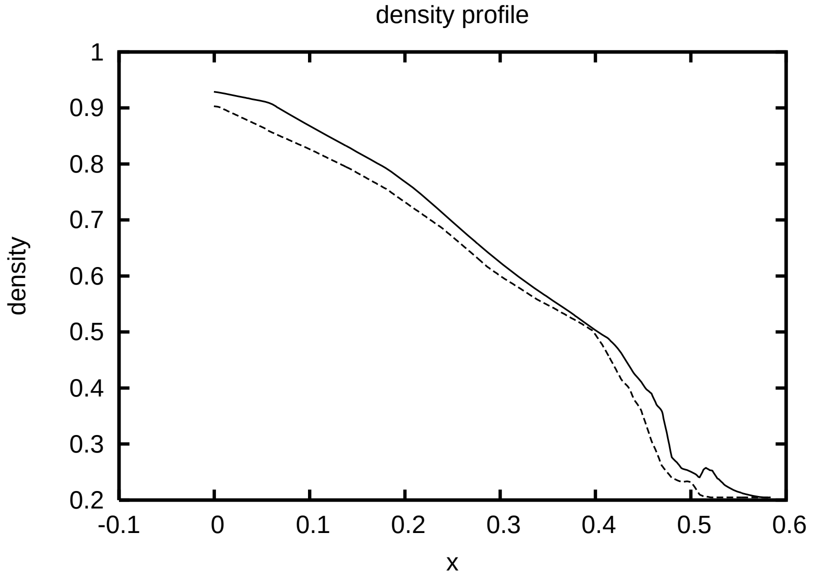


Density with RMP

profiles of temperature and density

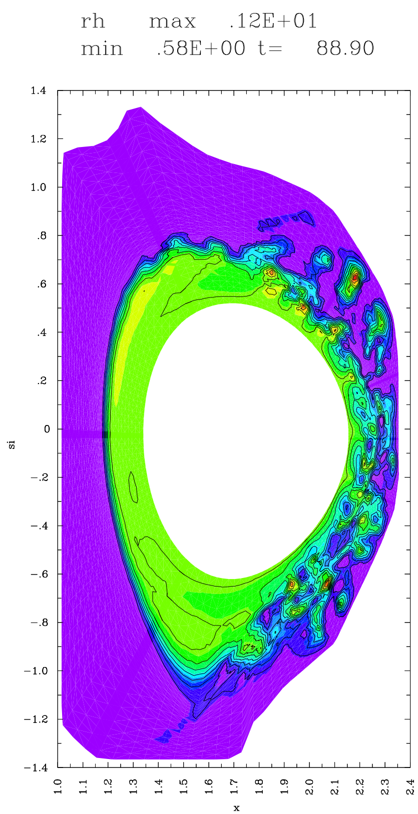
- In this case the flows are smaller and the temperature perturbations are larger, although they do not extend to the core, while the density perturbations do.
  - Solid lines: no RMP, dashed lines: with RMP

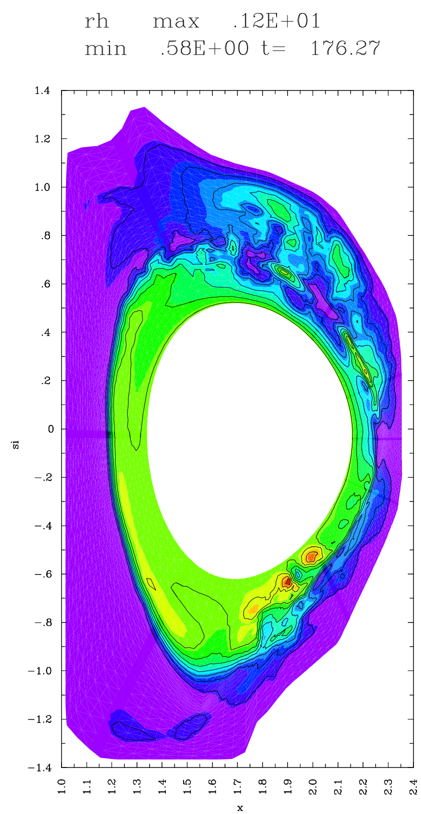


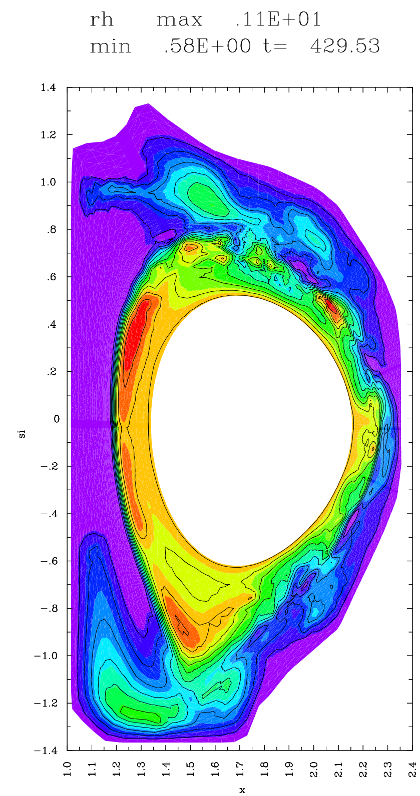


Long time ELM simulations

- ELM simulations have been extended in time well beyond saturation
  - Methods: upwinding, nonlinear smoothing, dealiasing
- Resemblance to RMP
- Convergence criterion for coupling to XGC (CPES)

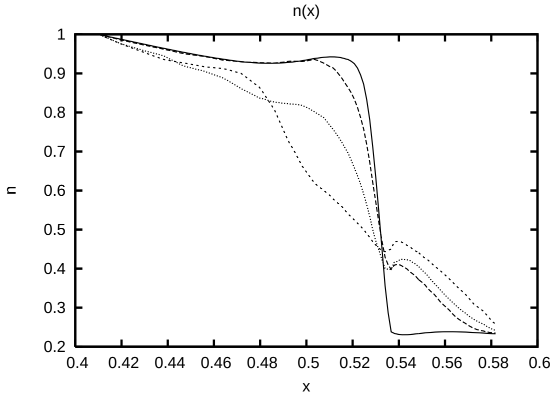


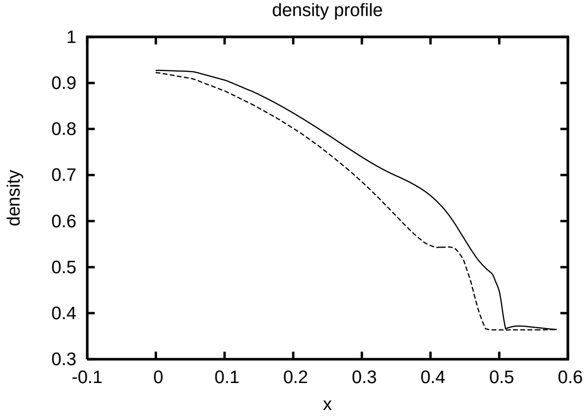


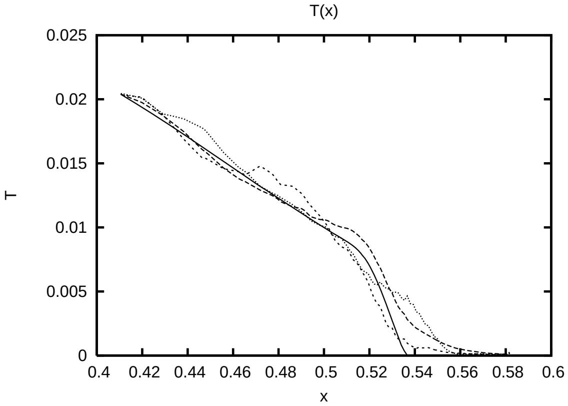


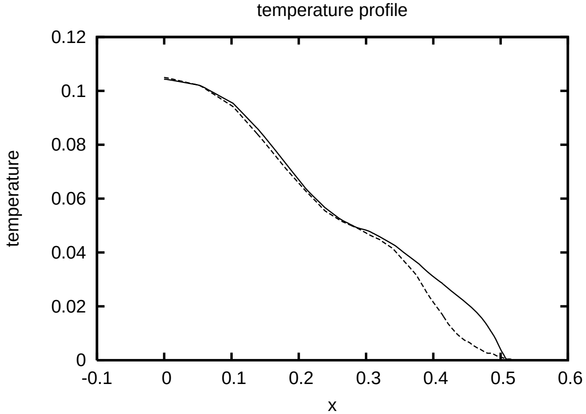
ELM - RMP

- Density perturbations are larger than temperature perturbations
  - Temperature perturbations are localized to stochastic layer









ELM

RMP

RMP summary

- RMP is affected by rotation
  - Plasma rotation screens the RMP from the plasma
    - Shrinks islands and reduces overlap to thin edge layer
    - stabilizes resistive mode excited by the RMP
  - RMP penetration profile depends on rotation profile
    - To get penetration as in GY Park model, need edge poloidal rotation
      - Free boundary G – S solver with flow will help
      - Need to stabilize resistive mode with less rotation
    - Present results like collisional RMP
- RMP resembles ELM
    - Temperature perturbations are local to edge
    - Density perturbations are non local
    - Density flows to x points

M3D – XGC coupling

- Long time ELM simulations could reach relaxation stage
  - Convergence criterion introduced in M3D-MPP
    - Relative density fluctuation level below criterion, after ELM saturation
    - Variables averaged in toroidal angle and written out
    - M3D-OMP flux surface averages to get profiles
    - M3D-OMP computes new Grad Shafranov equilibrium
    - XGC computes new profiles
- Add rotation to G-S solver in M3D-OMP
  - XGC calculates radial electric field
  - Need free boundary equilibria with flow
- RMP
  - XGC with 3D magnetic field calculates profiles and radial E field
  - M3D calculates 3D magnetic field and 3D motion

Resistive Wall Modes

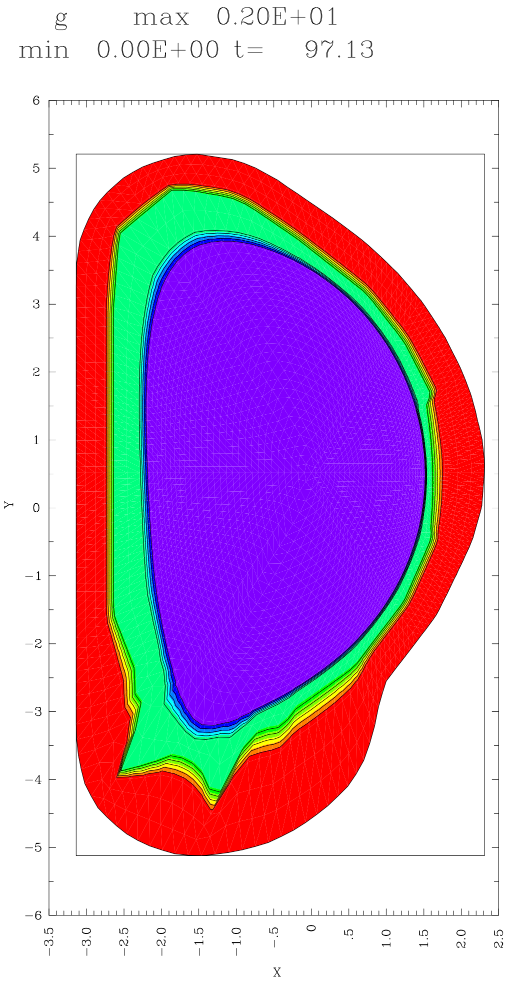
H. Strauss

R. Paccagnella

J. Breslau

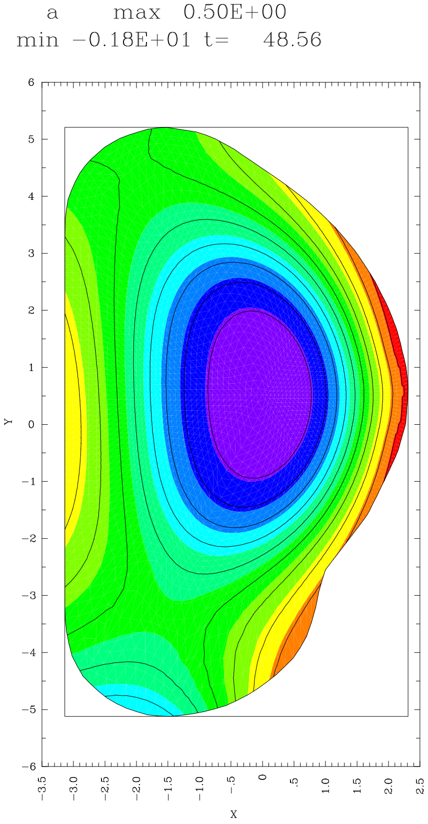
ITER resistive wall model

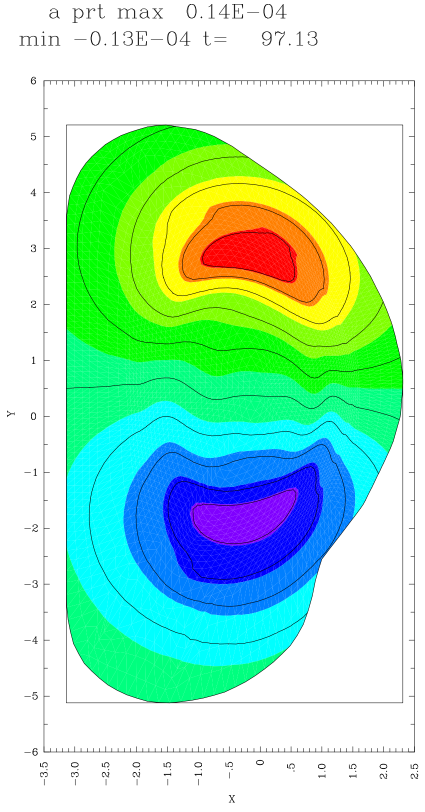
- ITER has 2 walls: 1st wall and vacuum vessel 2nd wall
- 2 models used in M3D
  - “no outer wall”: impenetrable resistive 1st wall
  - “outer resistive wall” : impenetrable 1st wall with continuous magnetic field, resistive 2nd wall, highly resistive region between 1st and 2nd walls



2 wall RWM

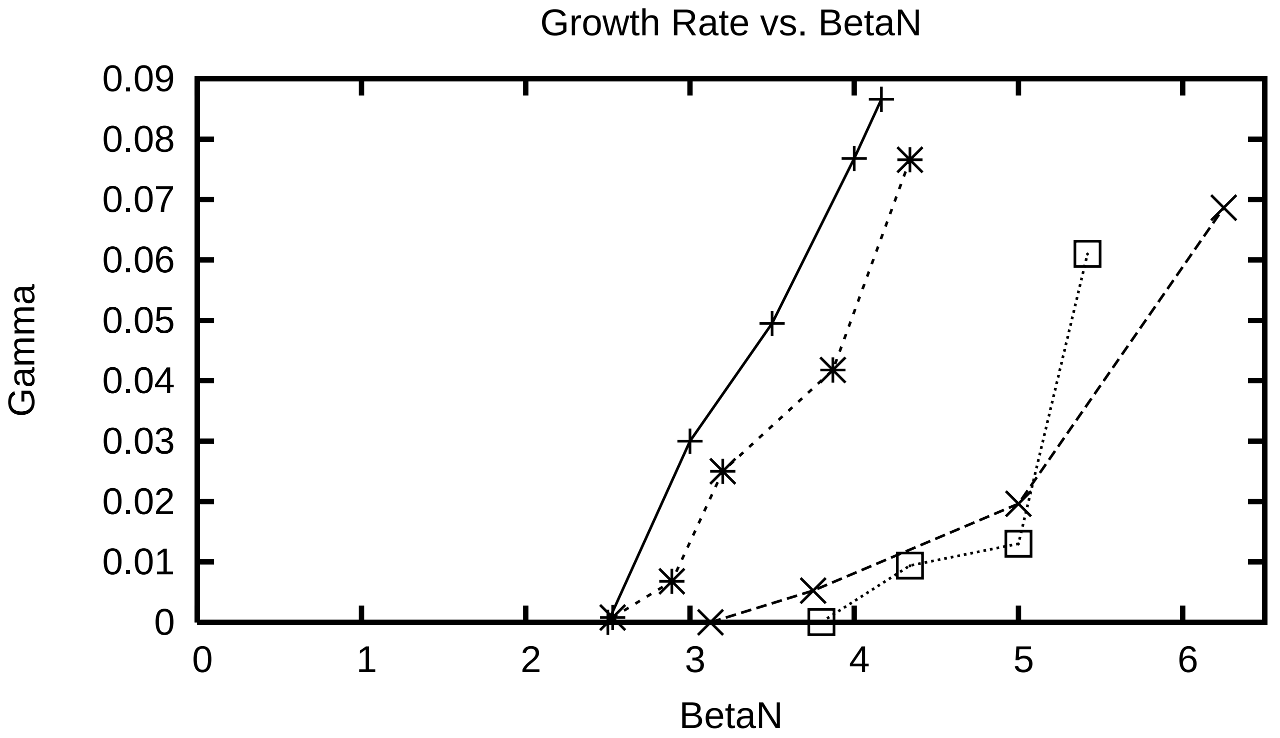
- Linear RWM calculated with 2 wall model
- AS Equilibrium and perturbed poloidal magnetic flux





M3D – MARS comparison

- “no outer wall” and 2 wall linear growth rates were compared
- MARS: curves marked with + and boxes
- M3D: curves marked with * and x



M3D RWM status

- M3D-MPP 1 wall model is implemented
  - Used for linear simulations in MARS comparison
- 2 wall model
  - Implemented in M3D-OMP
  - Also implemented in M3D-MPP, but has some problems
- Green’s function method for 2 walls is preferable