Bifurcated Helical Core Equilibrium States in Tokamaks

W. A. Cooper[1], J. P. Graves[1], H. Reimerdes[1], O. Sauter[1], M. Albergante[1], D. Brunetti[1], F. Halpern[1], D. Pfefferlé[1], T. M. Tran[1], J. Rossel [1], S. Coda[1], B. P. Duval[1], A. Pochelon [1], B. Labit[1], O. Schmitz[2], I. T. Chapman[3], A. D. Turnbull[4], T. E. Evans[4], L. Lao[4], R. Buttery[4], J. R. Ferron[4], E. Hollman[4], C. Petty[4], M. van Zeeland[4], E. A. Lazarus[5], F. Turco[6], J. Hanson[6] M. E. Fenstermacher[7], M. J. Lanctot[7], A. J. Cole[8], S. C. Jardin[9], B. J. Tobias[9]

[1]Ecole Polytechnique Fédérale de Lausanne, Association EURATOM-Confédération Suisse, Centre de Recherches en Physique des Plasmas, CH1015 Lausanne, Switzerland

[2]Forschungzentrum Jülich, Jülich, Germany

[3]CCFE, Abingdon, UK

[4]General Atomics, San Diego, USA

[5]Oak Ridge National Laboratory, Oak Ridge, USA

[6]Columbia University, New York, USA

[7]Lawrence Livermore National Laboratory, Livermore, USA

[8]University of Wisconsin, Madison, USA

[9]Princeton Plasma Physics Laboratory, Princeton, USA

Principal 3D Effects in Tokamaks

- Toroidal Magnetic Field Ripple
  Periodicity $\propto$ Number of toroidal coils

- Test Blanket Modules, Ferritic Inserts, Toroidal Coil Quench
  Periodicity typically $n = 1$

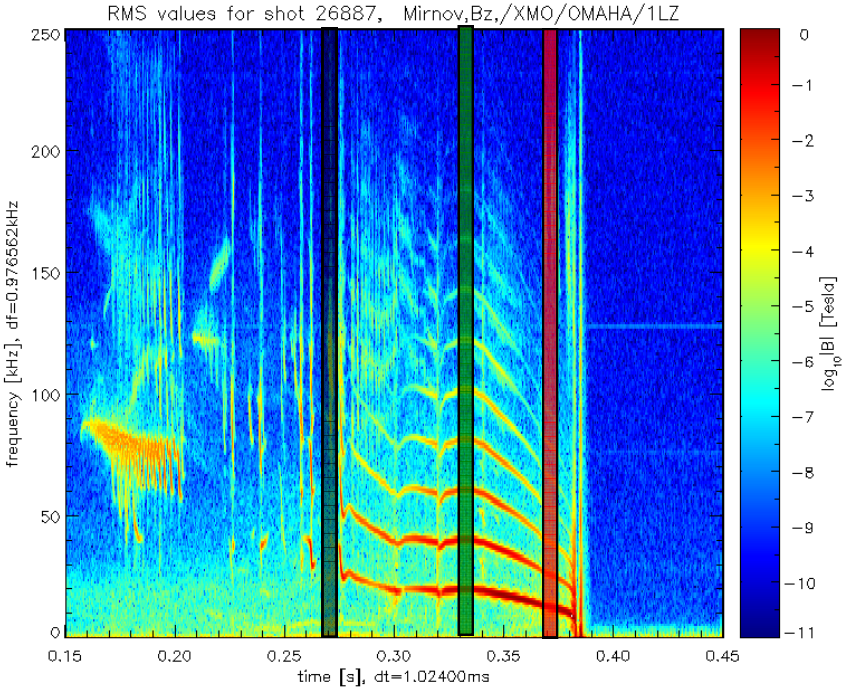
- ELM Control – RMP Coils
  Periodicity typically $n = 3 - 4$

- Spontaneous Internal Helical Structure Formation — typically 'Snakes'
  Periodicity $n = 1$

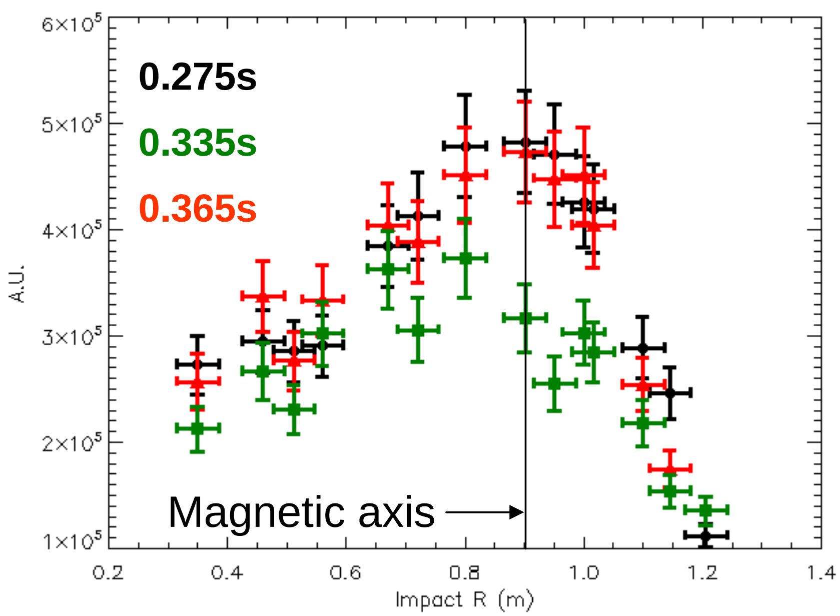
MOTIVATION

- MAST Long Lived Mode resembles n=m=1 saturated helical mode
  - As q_{min} approaches unity, LLM appears and fast ions are expelled from the plasma core (fast ions distribution represented by neutron emissivity)

•MAST frequency spectrum



•MAST neutron emissivity



IT Chapman et al, Nucl Fusion, 2010

Introduction

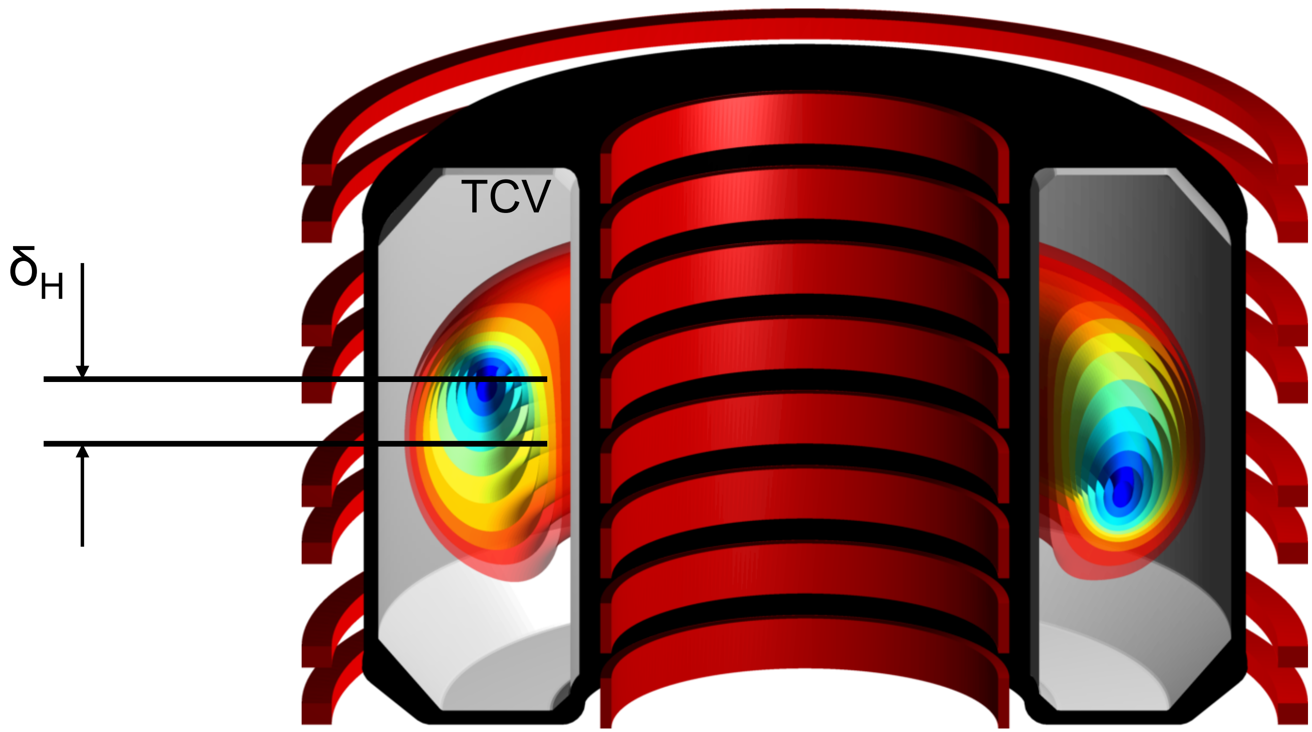
- Investigate 3D helical distortions.
- Long-Lived Modes in hybrid scenarios.
- Use MHD equilibrium approach. Compare with standard initial value nonlinear stability.
- Free boundary calculations to include RMP and ripple effects.
- Fast particle confinement in static 3D equilibrium fields.
- 3D distortion in tokamak similar to SHAx in RFP.

Equilibrium Description

(1) Assume standard tokamak coils (almost axisymmetric boundary)

(2) Solve for internal flux surfaces in equilibrium: $\rho \cancelto{0}{\frac{dV}{dt}} = \underline{J} \times \underline{B} - \underline{\nabla} P$

- Relax axisymmetry constraint in the vacuum and plasma



• Two solutions possible. One axisymmetric, the other is helical, with displacement amplitude $\delta_H = \sqrt{R_{01}^2(s=0) + Z_{01}^2(s=0)}/a$

- Impose nested magnetic surfaces and single magnetic axis
- Minimise energy of the system

$$W = \int\int\int d^3x \Big(\frac{B^2}{2\mu_0} + \frac{p_\parallel(s,B)}{\Gamma - 1} \Big)$$

- Solve inverse equilibrium problem : $R = R(s,u,v)$, $Z = Z(s,u,v)$.
- Variation of the energy

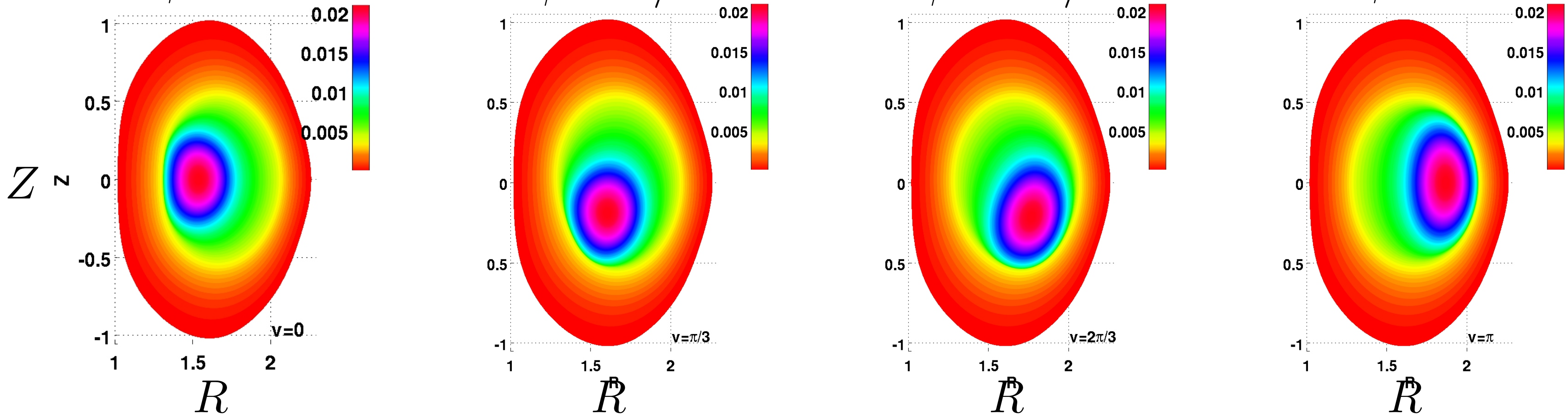
$$\begin{aligned} \frac{dW}{dt} = & - \int\int\int dsdudv \Big[F_R \frac{\partial R}{\partial t} + F_Z \frac{\partial Z}{\partial t} + F_\lambda \frac{\partial \lambda}{\partial t} \Big] \\ & - \int\int_{s=1} dudv \Big[R \Big(p_\perp + \frac{B^2}{2\mu_0} \Big) \Big(\frac{\partial R}{\partial u} \frac{\partial Z}{\partial t} - \frac{\partial Z}{\partial u} \frac{\partial R}{\partial t} \Big) \Big] \end{aligned}$$

- Use Fourier decomposition in the periodic angular variables u and v and a special finite difference scheme for the radial discretisation. Implemented in the VMEC/ANIMEC codes.

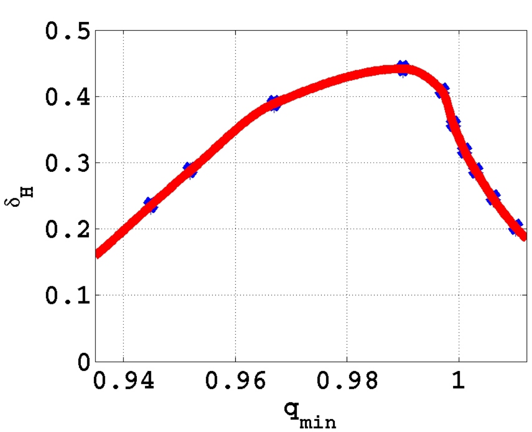
Fixed Boundary DIII-D Computations

- $\langle\beta\rangle \simeq 0.89\%$; $I_p = 1.43MA$; $q_{min} \sim 1$ near half radius

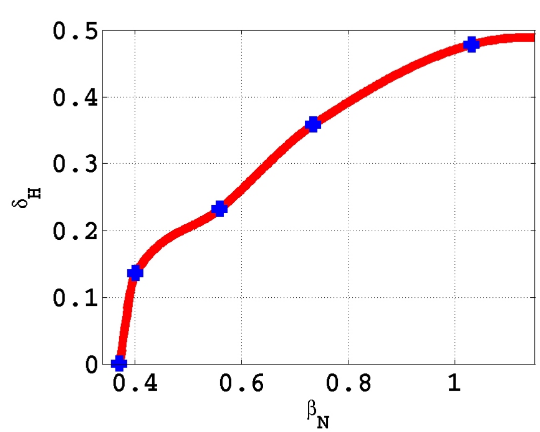
$\phi = 0$ $\phi = \pi/3$ $\phi = 2\pi/3$ $\phi = \pi$



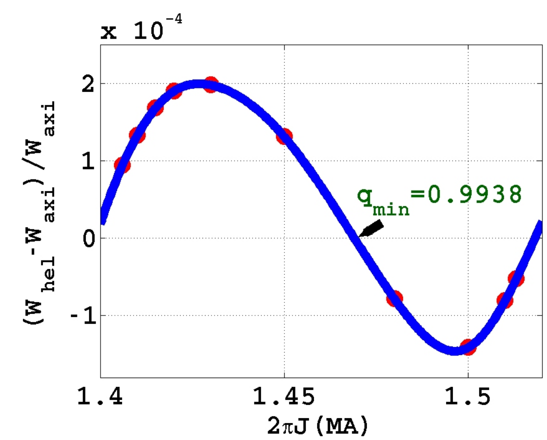
δ_H vs q_{min}



δ_H vs β_N

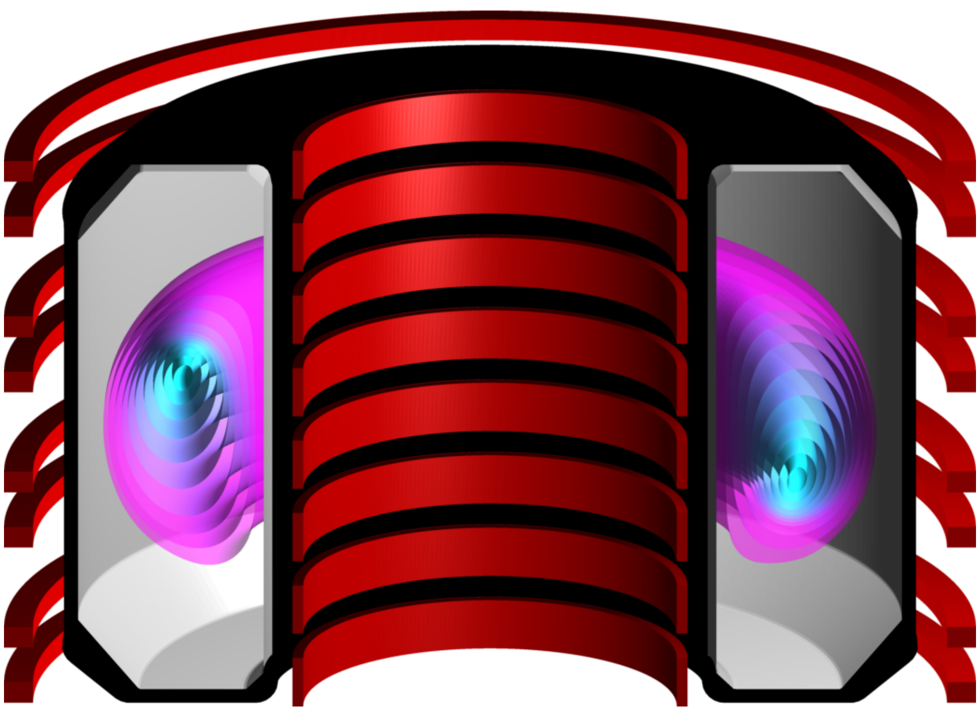


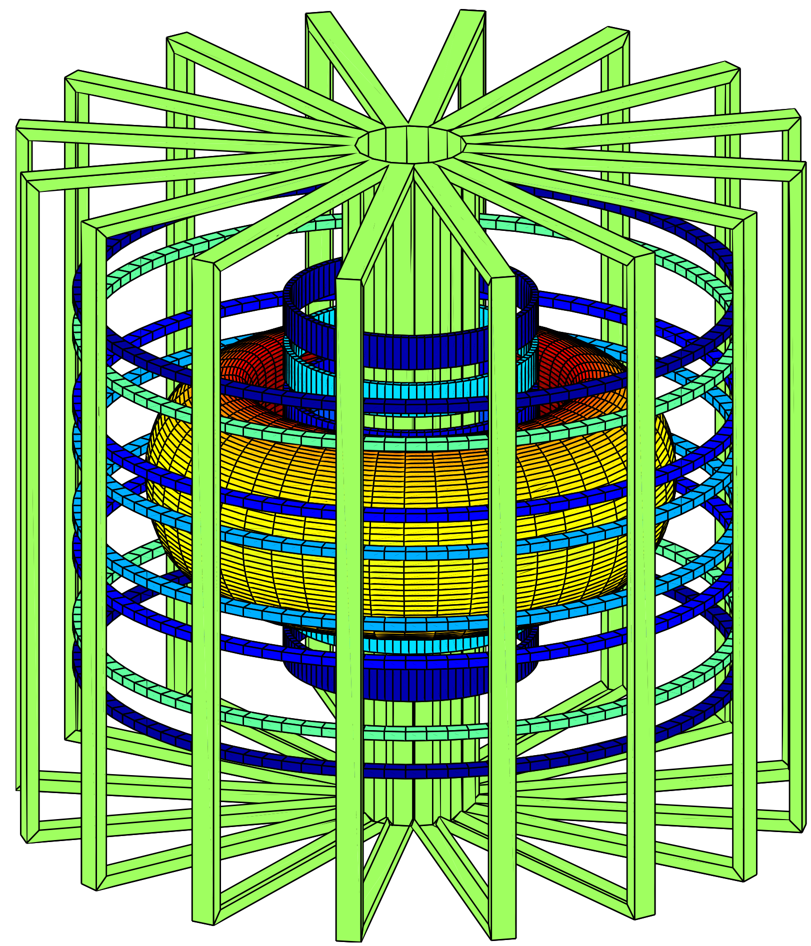
$\delta W/W$ vs I_p



Free Boundary TCV Computations

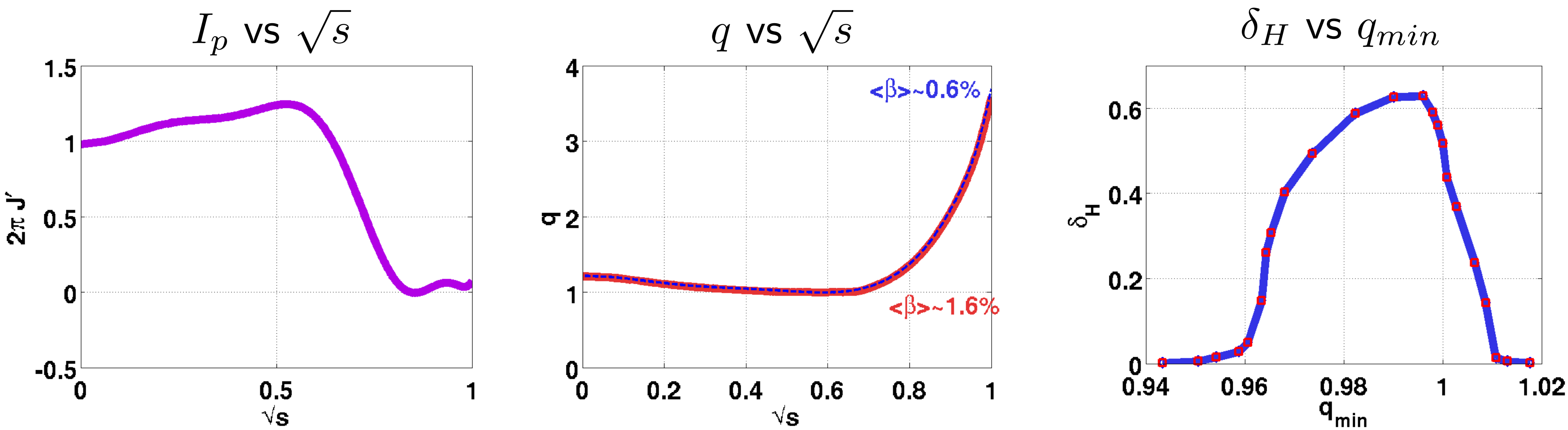
- TCV coil system
- Toroidal coils modelled with 4 filaments carrying a total of $358kA$
- There are 16 poloidal field coils that typically allow up to $238kA$





TCV Profiles and Axis Excursion versus q_{min}

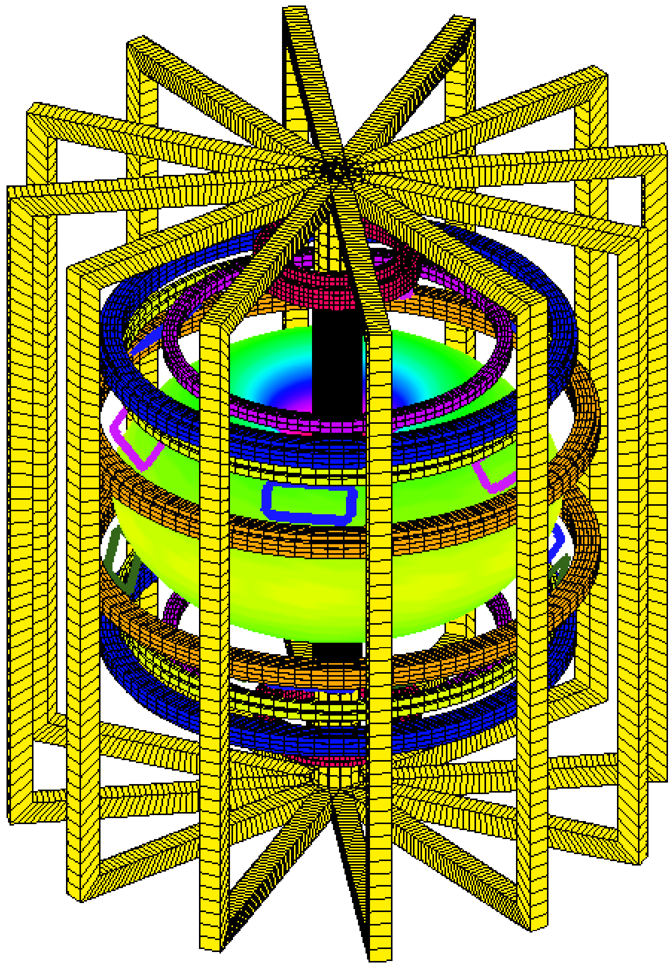
- Pressure profile prescribed as $p(s) = p(0)(1 - s)(1 - s^4)$



- Large helical core for $0.96 < q_{min} < 1.01$ for $\langle\beta\rangle > 0.6\%$

Free Boundary MAST Computations

- MAST coil system — 4 filaments per coil



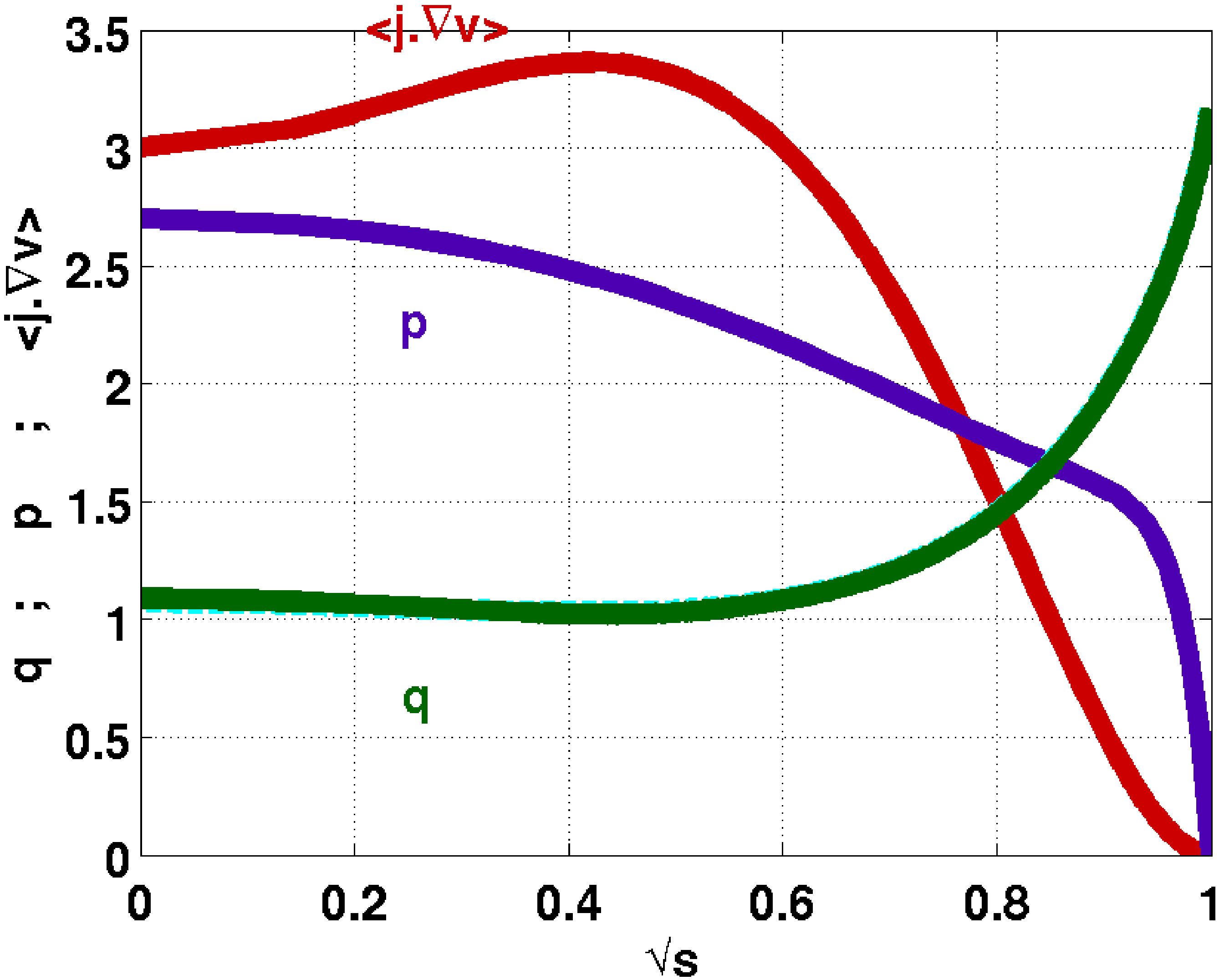
TF coils

+PF coils

+ $n = 3$ RMP coils

MAST profiles

- MAST profiles: pressure (p), toroidal current ($\langle j \cdot \nabla v \rangle$) and q versus $\sqrt{s}$.

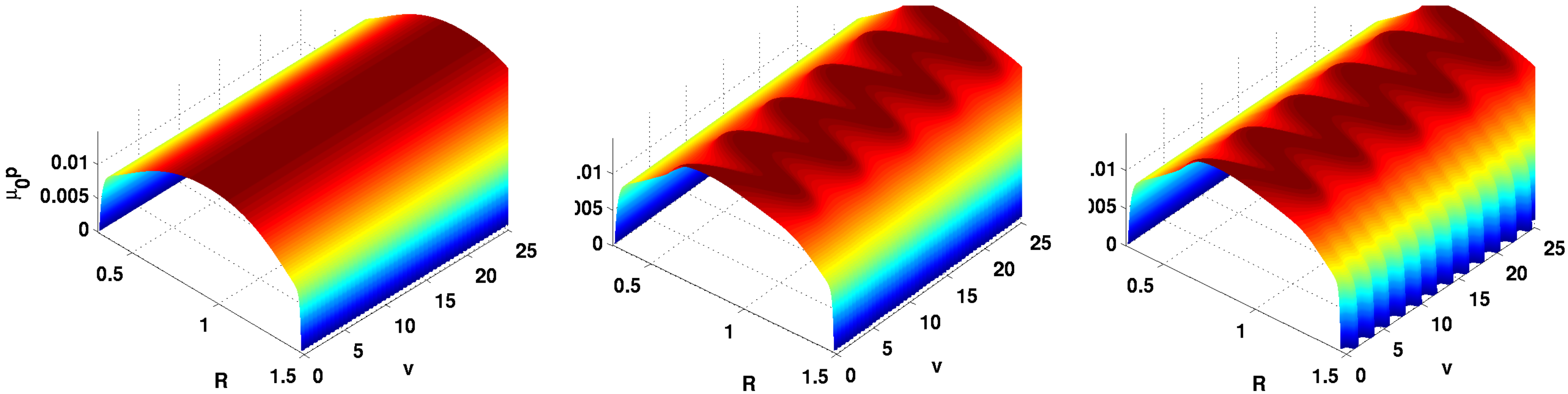


MAST pressure distribution at the midplane

- “Axisymmetric” Branch
- ripple

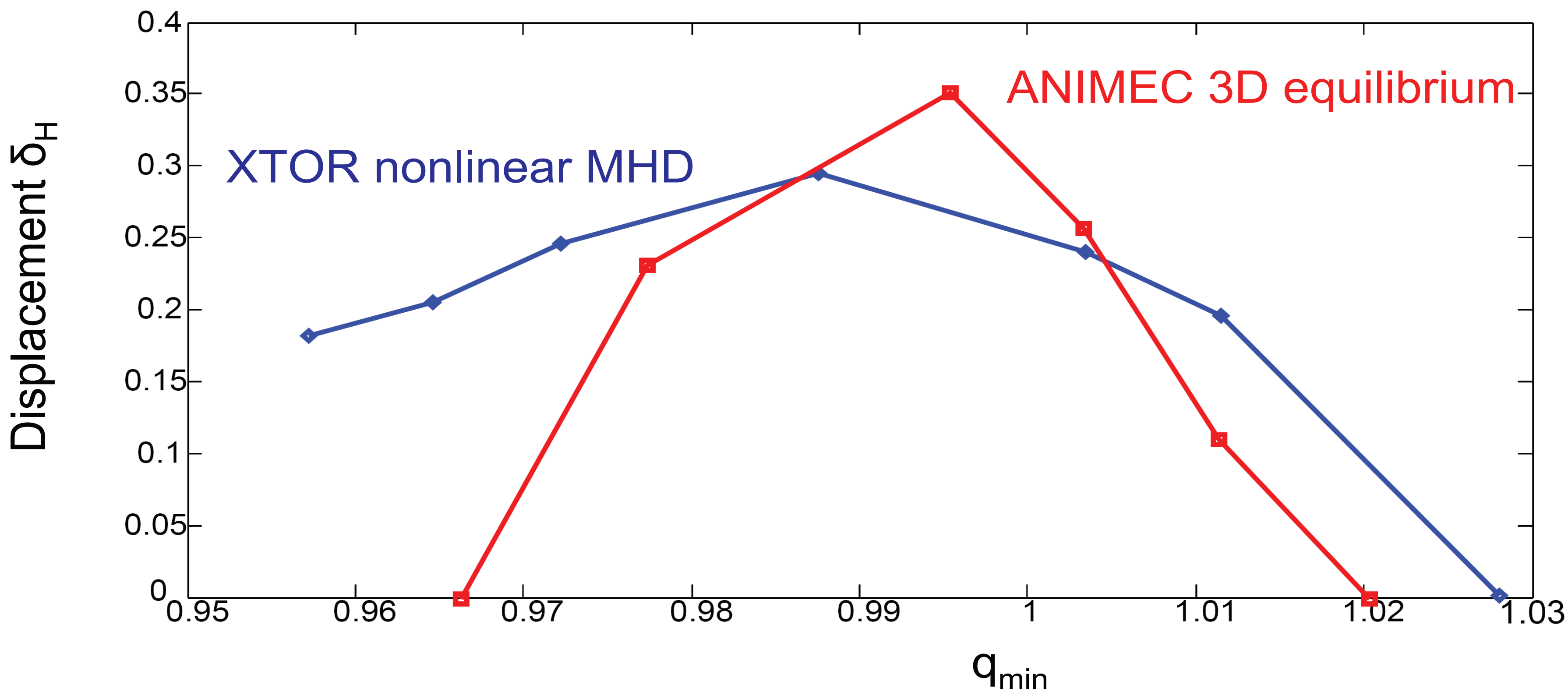
Helical Branch
no RMP

Helical Branch
+ RMP



- Boundary modulation due to core snake structure is weak.
- External perturbation does not disturb helical core.

- Comparison of the magnetic axis displacement between the ANIMEC 3D helical branch equilibrium solution and the nonlinear saturated state evolved with the XTOR initial value stability code (H. Lütjens and J. F. Luciani, J. Comput. Phys. 227 (2008) 6944) of the axisymmetric branch equilibrium solution in a fixed boundary ITER simulation.

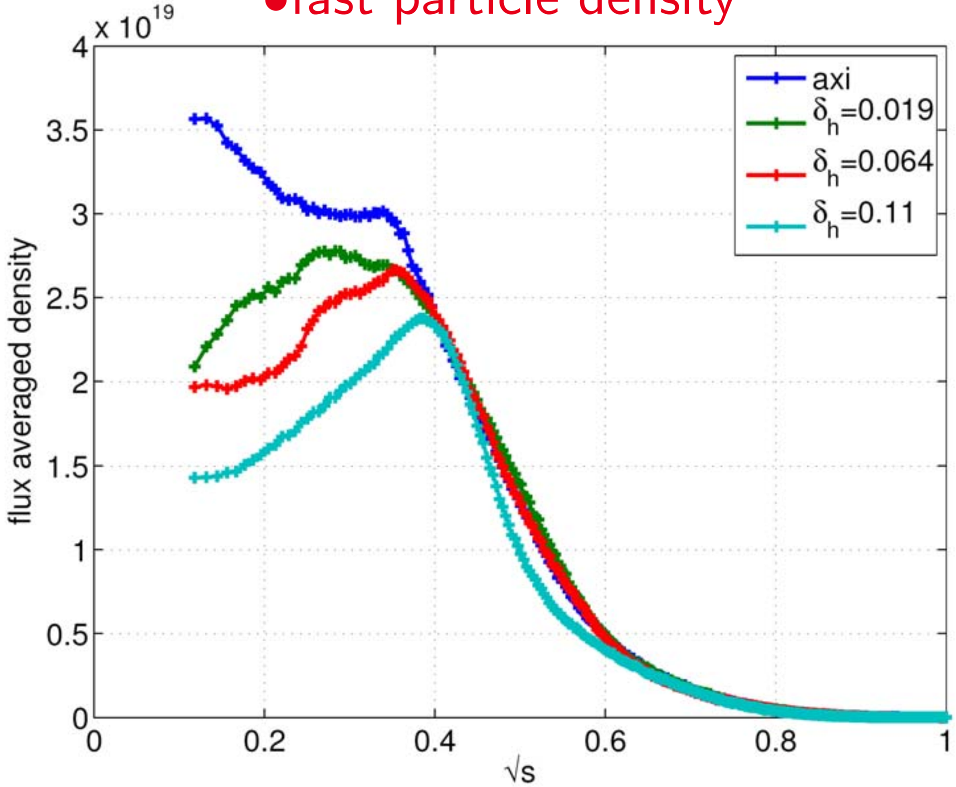


D. Brunetti *et al.*, 2012 Varenna-Lausanne Theory of Fusion Plasmas Workshop

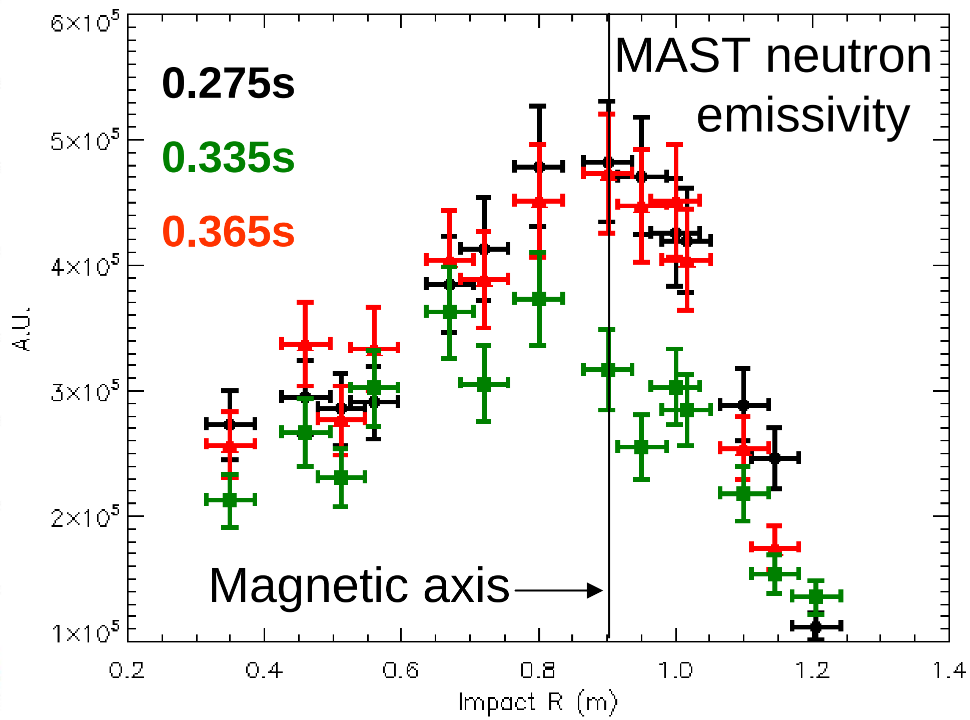
MAST Fast Particle Guiding Centre Orbits

- Coordinate independent noncanonical phase space Lagrangian formulation of guiding centre orbit theory (Littlejohn, J. Plasma Phys. **29** (1983) 111) implemented in the VENUS-LEVIS code.

•fast particle density



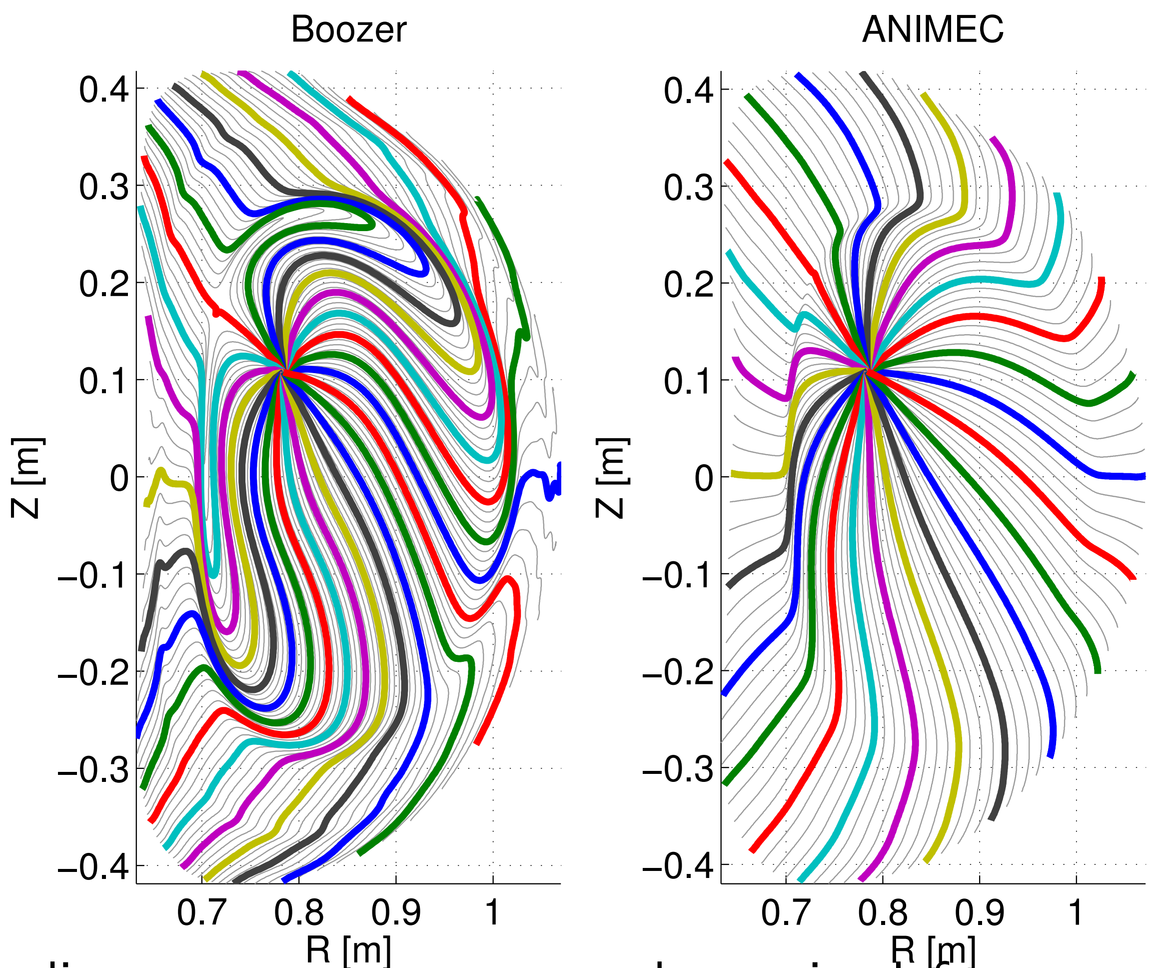
•MAST neutron emissivity



D. Pfefferlé et al., Varenna-Lausanne International Workshop on Theory of Fusion Plasmas, 2012.

TCV Boozer mesh grid

- Boozer coordinate mesh grid shows distortions at the interface of the helical core and the axisymmetric mantle



- Boozer coordinate spectrum may not be optimal for energetic particle guiding centre orbit confinement analysis.

Summary

- Axisymmetric tokamak systems: 2 solutions
  - 2D axisymmetric branch
  - 3D helical core branch
- Helical core predicted for
  - hybrid scenario.
  - standard scenario before first sawtooth crash (MAST).
- Reversed magnetic shear with $q_{min} \sim 1$ off-axis can trigger a core helical structure solution similar to a snake.
- The predictions are relevant for the ITER hybrid scenario operation.

Conclusions

- Internal helical structures weakly modulate plasma-vacuum interface.
- External perturbations do not alter 3D helical core.
- Standard nonlinear stability calculation consistent with 3D helical core equilibrium states.
- Helical core degrades fast ion confinement.