□ Limits for Compact Stellarators: Are they Real?

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With acknowledgements to M.C. Zarnstorff[1], A. Ware[2] for major contributions

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ARIES-CS Project Meeting

24 February 2005

General Atomics, San Diego CA

W7-AS and LHD Have Exceeded the Predicted Ideal MHD □ Limits

- W7-AS: Achieved < □ > = 3.4%

  (M.C. Zarnstorff and A. Weller)

  – High Density Low T_e
  – MHD activity in early medium □ phase
  – Robustly achieved for B = 0.9 to 1.1 T and varying heating methods
  – Predicted ideal MHD stability limit □ ~ 2%

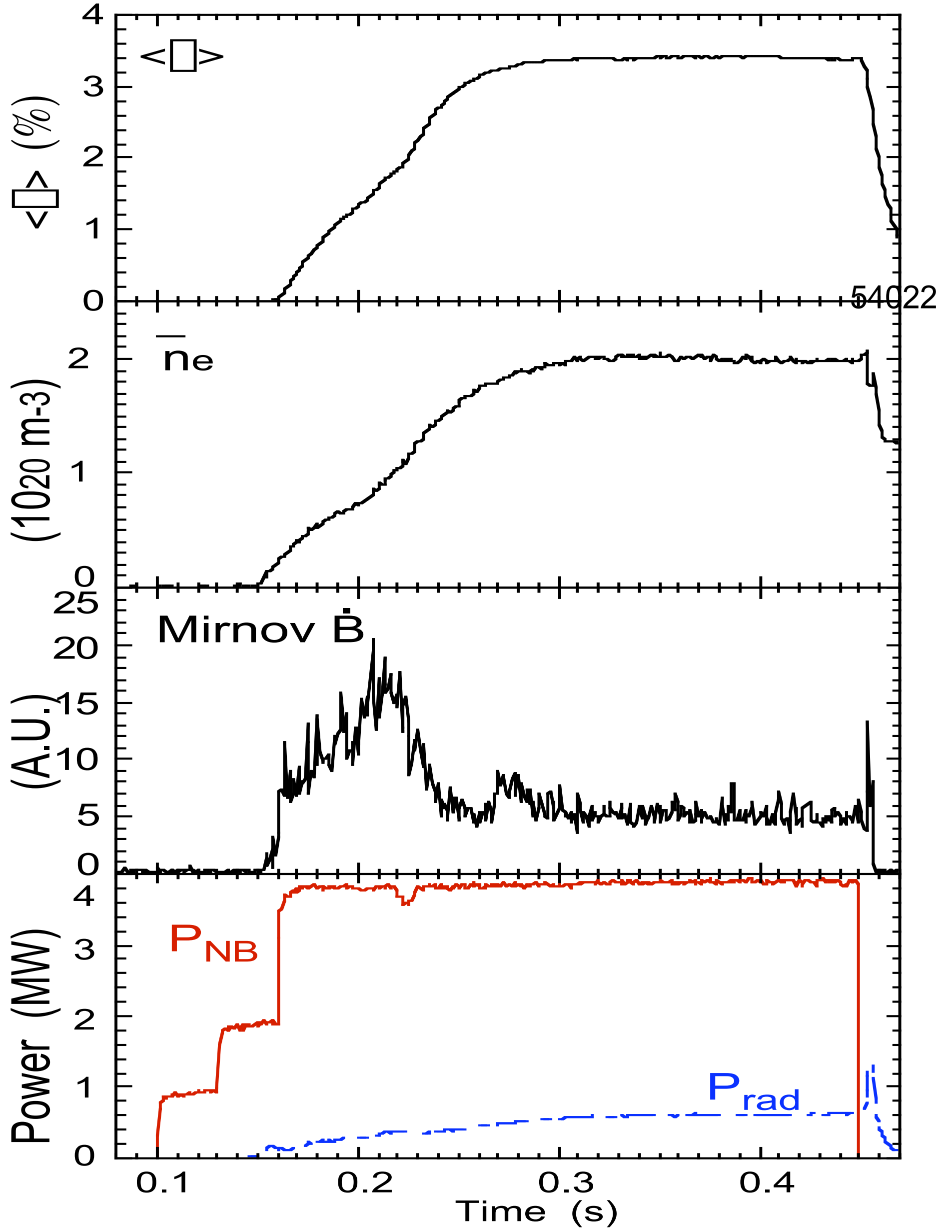
LHD Results Are Similar to W7-AS

- LHD: Achieved < □ > ~ 4%

  (S. Sakakibara and N. Nakajima)

  – Low Density High T_e
  – 2/1 MHD activity in core for □ < 2.5%
  – No core MHD observed at high □
  – Edge modes observed for □ > 3.4%
    - □ 1/1 surface at □ > 0.9
    - □ May set □ limit
  – Predicted interchange limit at low □ is clearly violated
    - □ Resistive and ideal both unstable

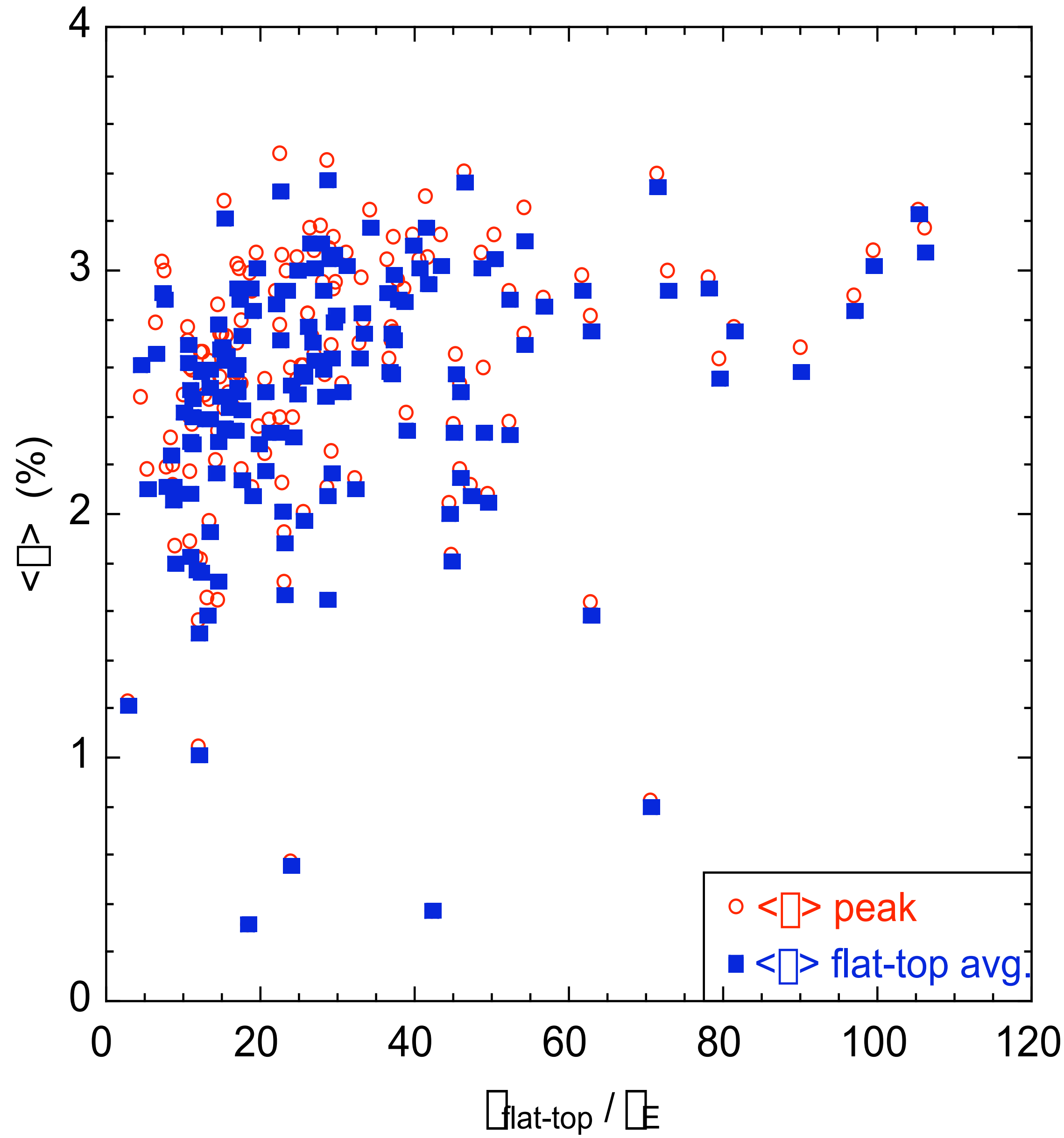
Quiescent Quasi-stationary Discharge: □ ≈ 3.4%



- B = 0.9 T, $iota_{vac}$ ≈ 0.5
- Almost quiescent high- □ phase, MHD-activity in early medium-□ phase
- **□ not limited by any detected MHD-activity.**
- I_P = 0: local currents may exist
- Similar □ > 3.4% plasmas achieved with B = 0.9 – 1.1 T with either NBI-alone, or combined NBI + OXB ECH heating.
- **Much higher than predicted □ limit ~ 2%**

(M.C. Zarnstorff)

$\langle\beta\rangle$ > 3.2% maintained for > 100 τ_E



- **Peak $\langle\beta\rangle$ = 3.5%**
- High-β maintained as long as heating is maintained
- $\langle\beta\rangle_{peak} \approx \langle\beta\rangle_{flat\text{-}top}$ → very stationary
- **Duration and β not limited by onset of observable MHD**

What limits the observed β value ?

(M.C. Zarnstorff)

MHD Activity is Sometimes Observed in W7-AS at Intermediate □

- m=2, n=1 pressure driven modes.
  Sometimes also m=3 or 5
  Does not usually strongly affect confinement

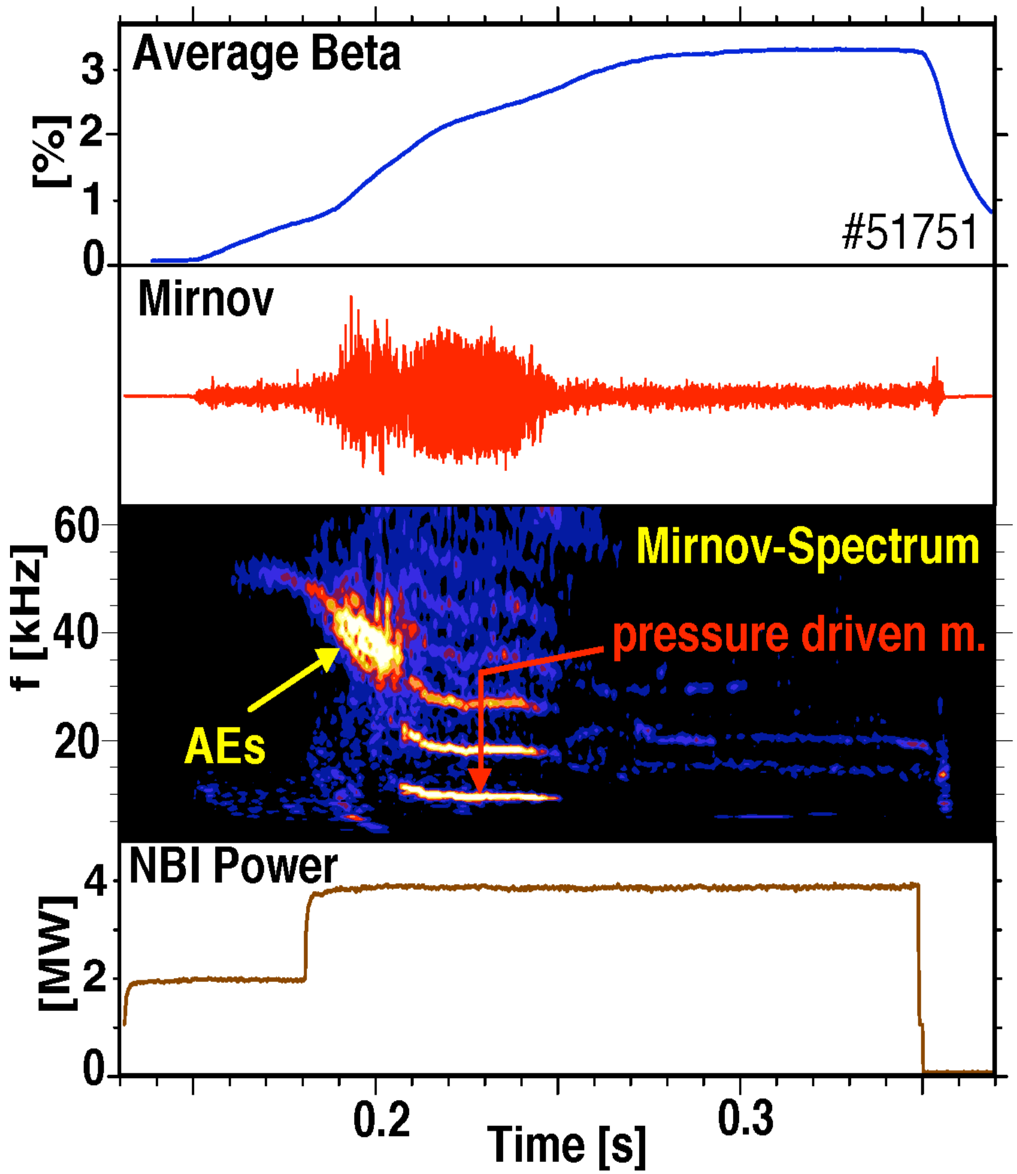
- Alfvenic instabilities at low density

- (2,1) tearing modes with significant $I_P < 0$
  (increasing iota) and tokamak-like shear

- High n instabilities at very low T_e

(M.C. Zarnstorff)

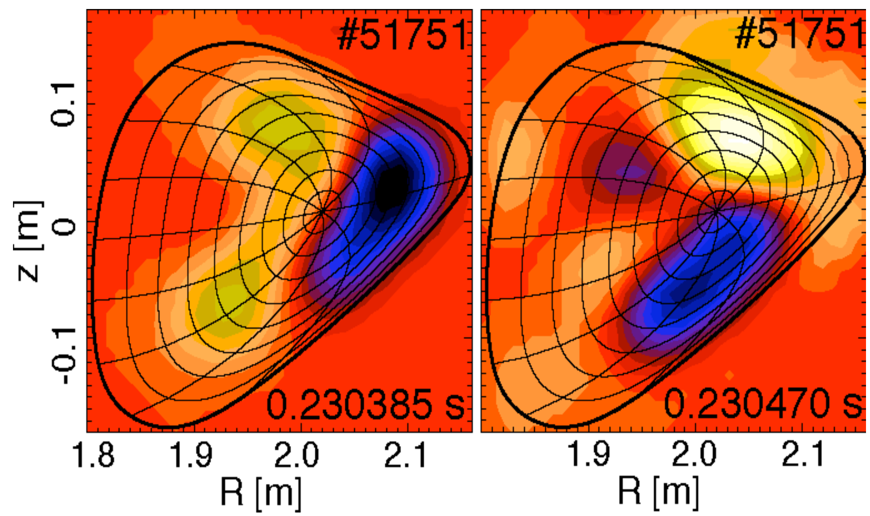
Pressure Driven Modes Observed at Intermediate β



- Dominant mode m/n = 2/1
- Modes disappear for β > 2.5%

(inward shift of iota = 1/2 surface?)

X-Ray Tomograms



- Reasonable agreement with CAS3D and Terpsichore linear stability calculations: Predicted threshold β < 1%

Does not inhibit access to higher β !

Linear stability threshold is not indicative of β limit.

(M.C. Zarnstorff)

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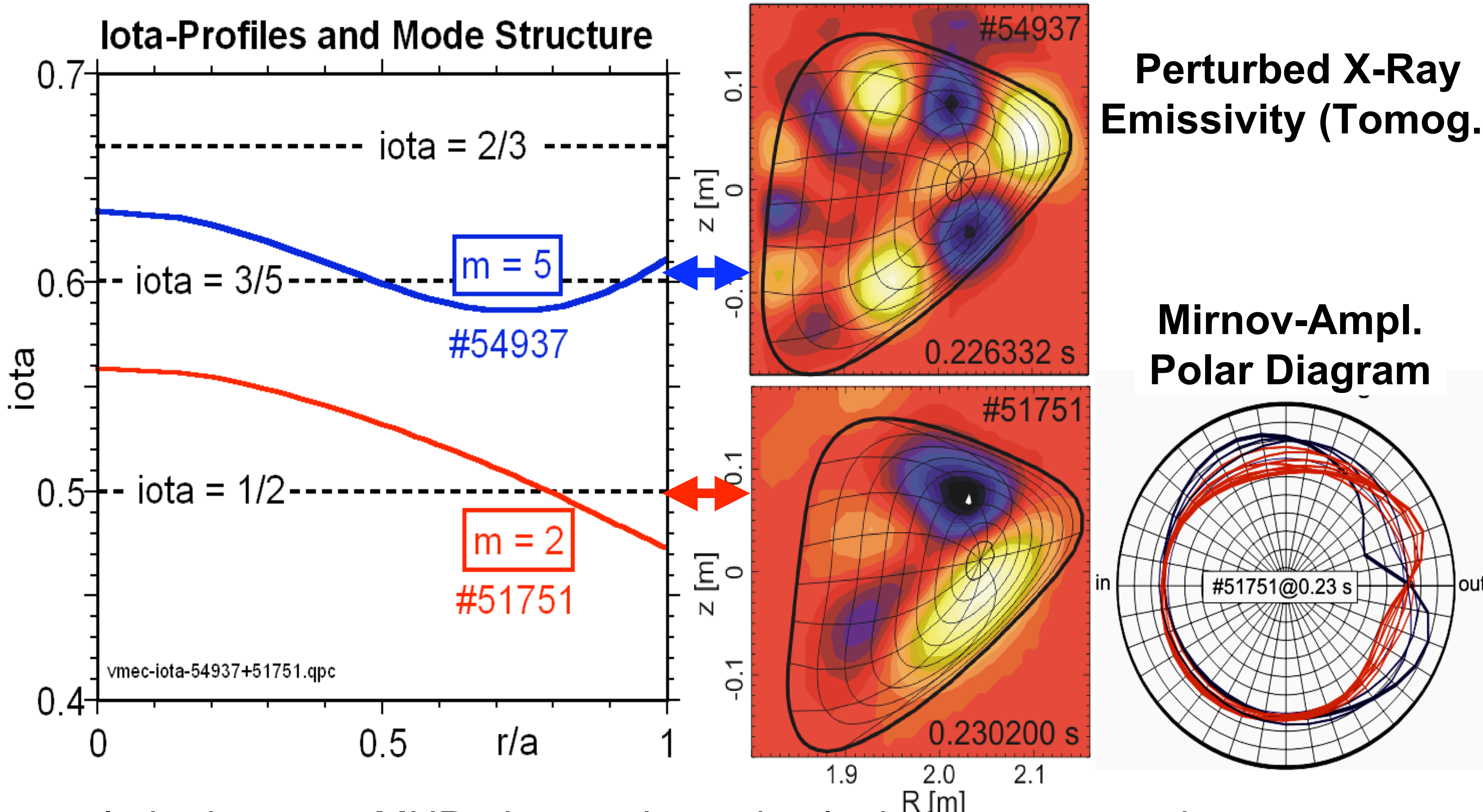
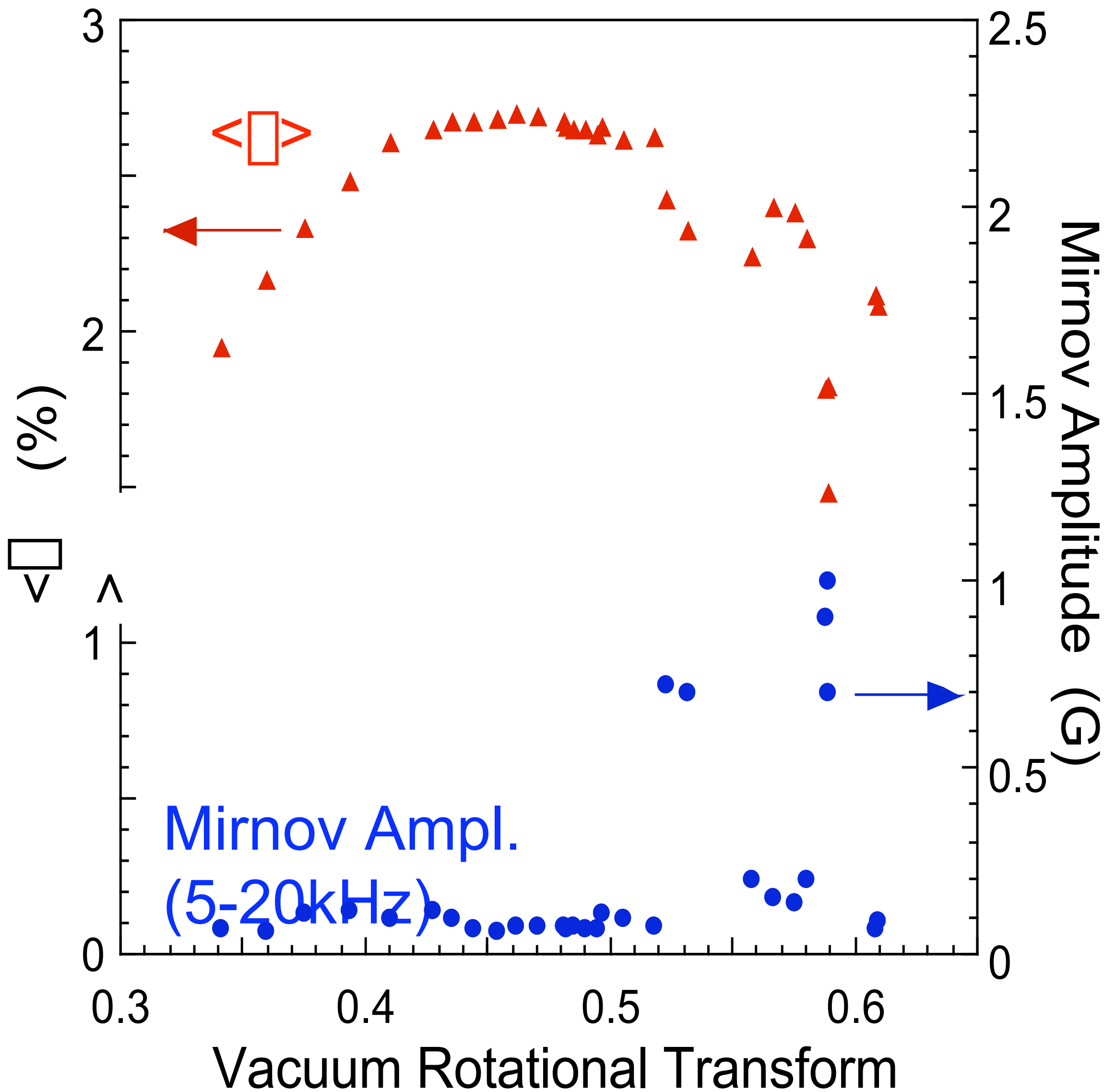
Observed Mode Structure Corresponds to Near-Edge Iota (VMEC)



- In both cases, MHD observed transiently during pressure rise. Edge iota drops as β increases, due to equilibrium deformation.
- Strong ballooning effect at outboard side

(M.C. Zarnstorff)

Low-mode Number MHD Is Very Sensitive to Edge Iota During Flat-top in W7-AS

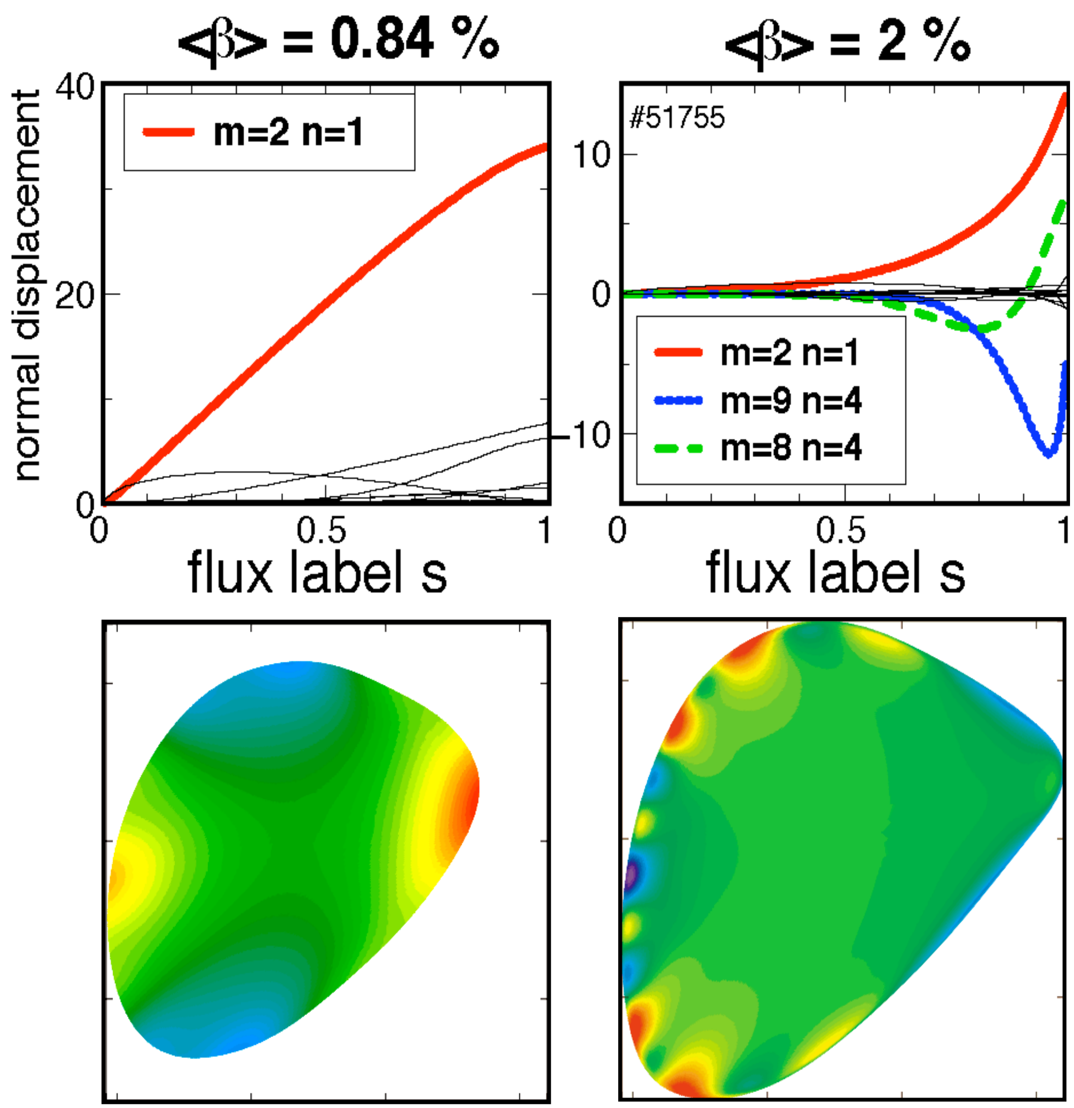


- Controlled iota scan, varying I_{TF} / I_M, fixed B, P_{NB}
- Flattop phase
- Strong MHD clearly degrades confinement
- Strong MHD activity only in narrow ranges of external iota
- Equilibrium fitting indicates strong MHD occurs when edge iota ≈ 0.5 or 0.6 (m/n=2/1 or 5/3)
- Strong MHD easily avoided by ~4% change in TF current

(M.C. Zarnstorff)

Linear Stability Calculations (CAS3D) Indicate 2/1 Should be Unstable in W7-AS

Mode Displacement & Perturbed Pressure



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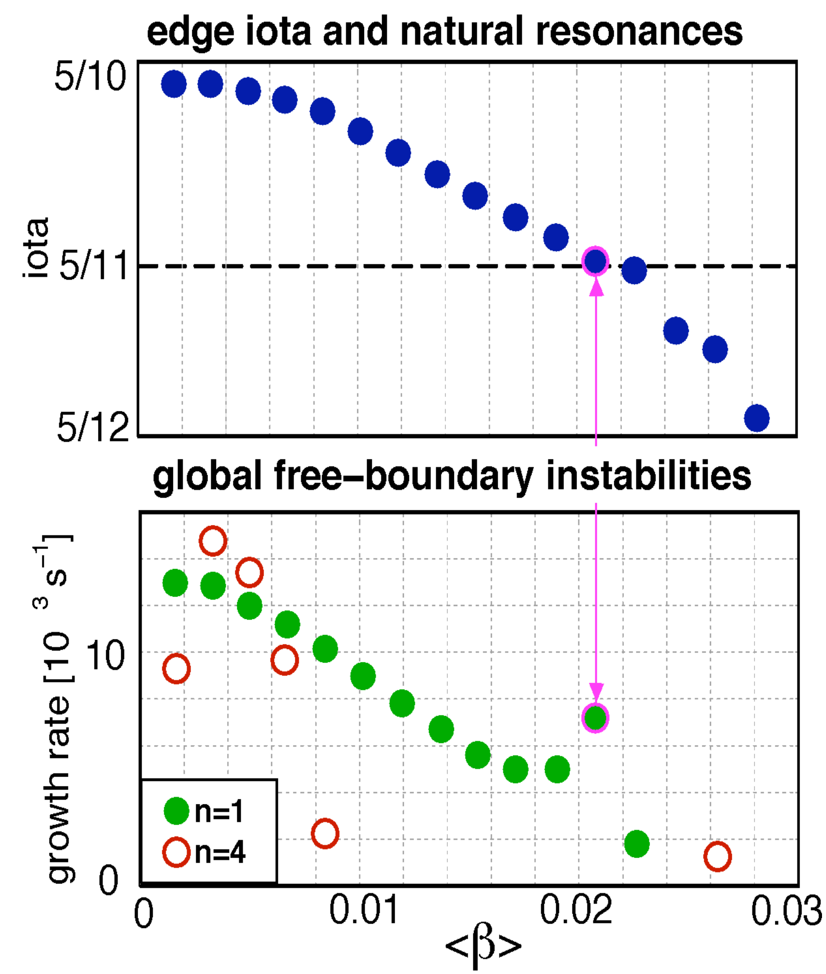

External global modes most unstable at low ▯

(C. Nuhrenberg)

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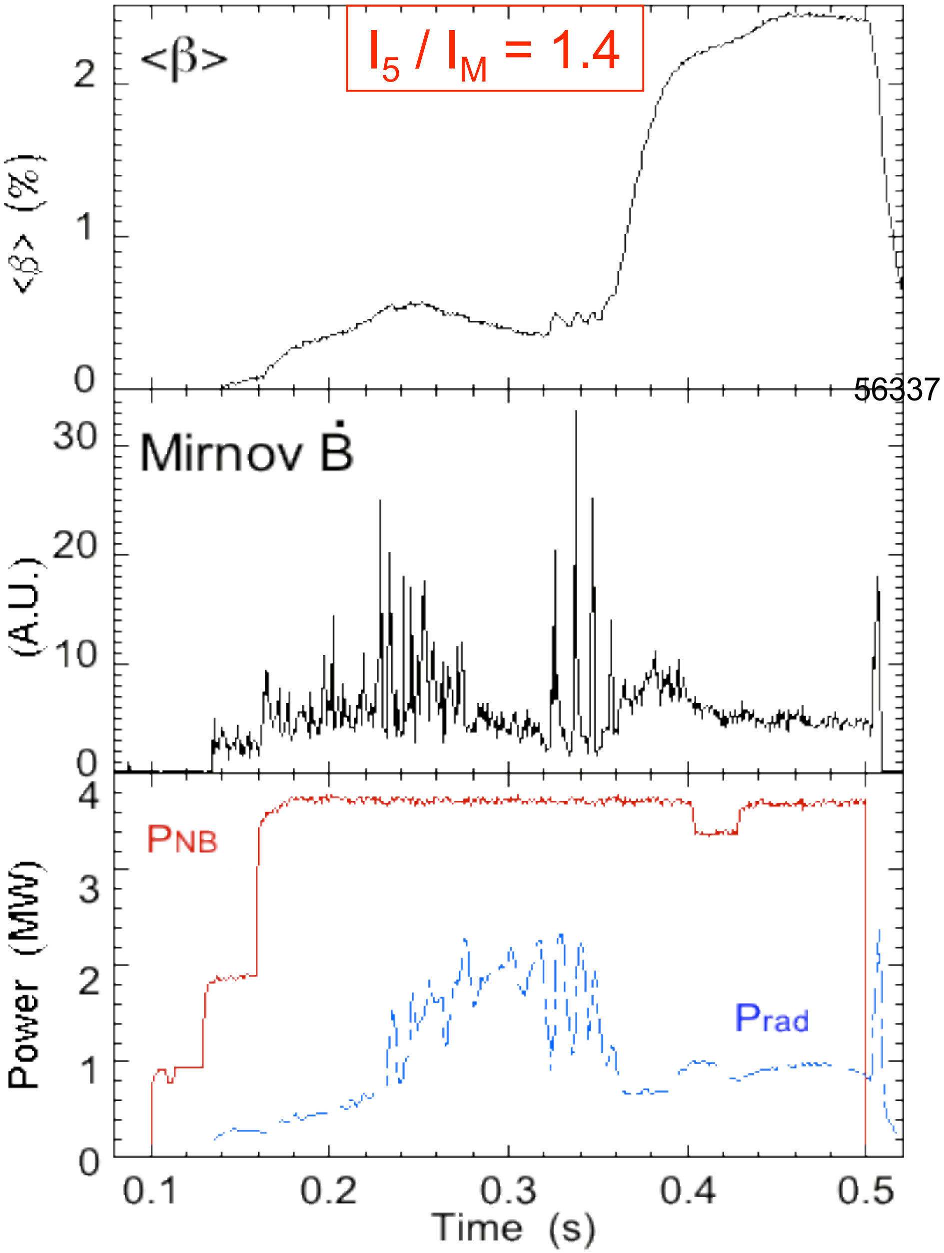
High-n Instabilities Sometimes Observed in W7-AS



- Typical high-□ plasmas are calculated to be ballooning stable. No high-n instabilities are observed.

- High-n instabilities are observed if T_e drops below ~ 200eV. Probably a resistive instability.

- W7AS can vary the toroidal ripple or mirror ratio using ‘corner coils’ (I_5)

- For $I_5 > I_M$, very unstable low-□ phase, then spontaneous transition and rise to moderate □.

- In later □ > 2% phase, plasma calculated to be in ballooning 2nd stability regime.
How does it get there?

(M.C. Zarnstorff)

Experimental Studies of MHD Instabilities in LHD Also Show MHD Stability at Low β

- Beta dependence of MHD activity:
  - Core MHD activity suppressed with β
  - Edge MHD activity increased with β
- Optimization of R_{ax}: $R_{ax} > 3.5$ is better
- High A reduces Shafranov shift, can produce plasma with $\beta_{dia} \sim 4\%$
- Why are the MHD modes stabilized?
  - (a) Profile flattening caused by MHD mode?
  - (b) Stopping of mode rotation? (but frequency unchanged)
  - (c) Variation of magnetic surface due to β?

(A. Ware/S. Sakakibara)

Plasma Boundary Has a Significant Influence on MHD Stability in Heliotrons

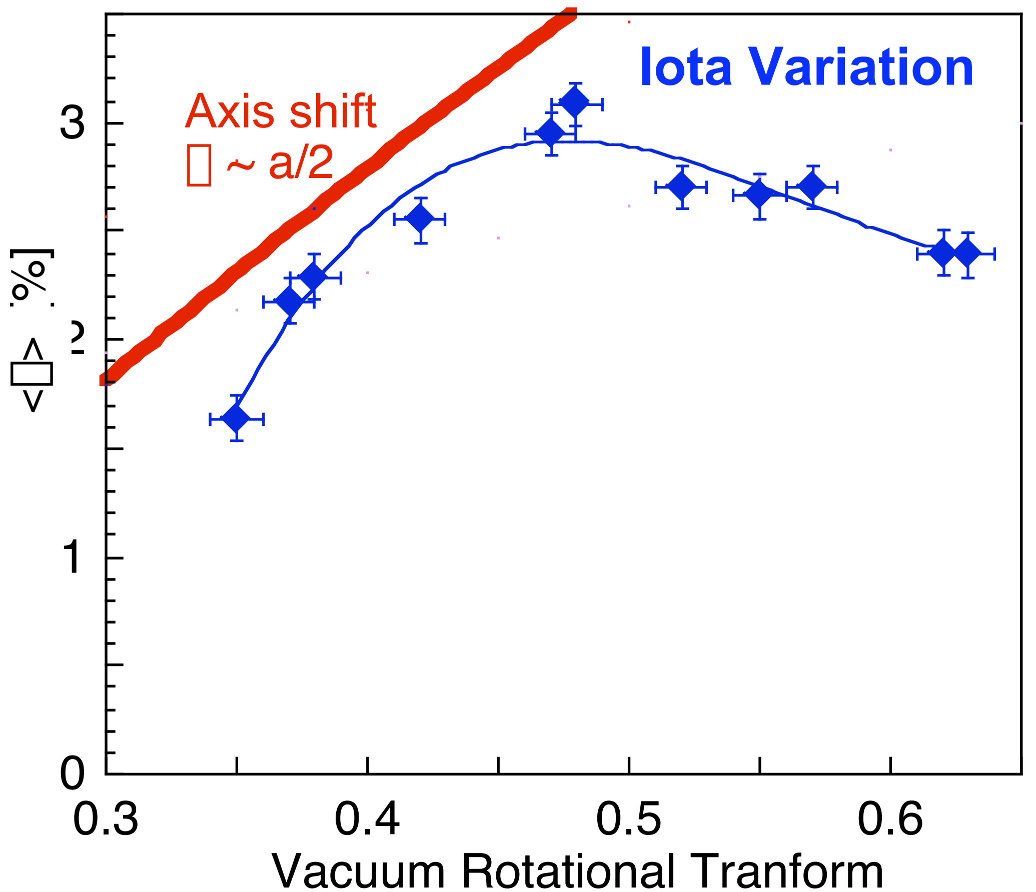
- Discrepancy on MHD equilibria & stability:
  - Experiment: $\langle\beta\rangle > 3\%$ plasmas
  - Theory: Strong MHD instabilities for fixed boundary plasmas
  - Finite pressure gradient observed beyond a clear vacuum LCFS

- Assume average flux surfaces in stochastic region
  - Inward shifted configurations have narrowest stochastic layer
  - For $\langle\beta\rangle = 3\%$, unstable for fixed boundary but marginally stable for free boundary
  - At high β, growth rates decrease with increasing $\langle\beta\rangle$ due to boundary modification
  - Density profile effects can be important in lowering growth rates as well

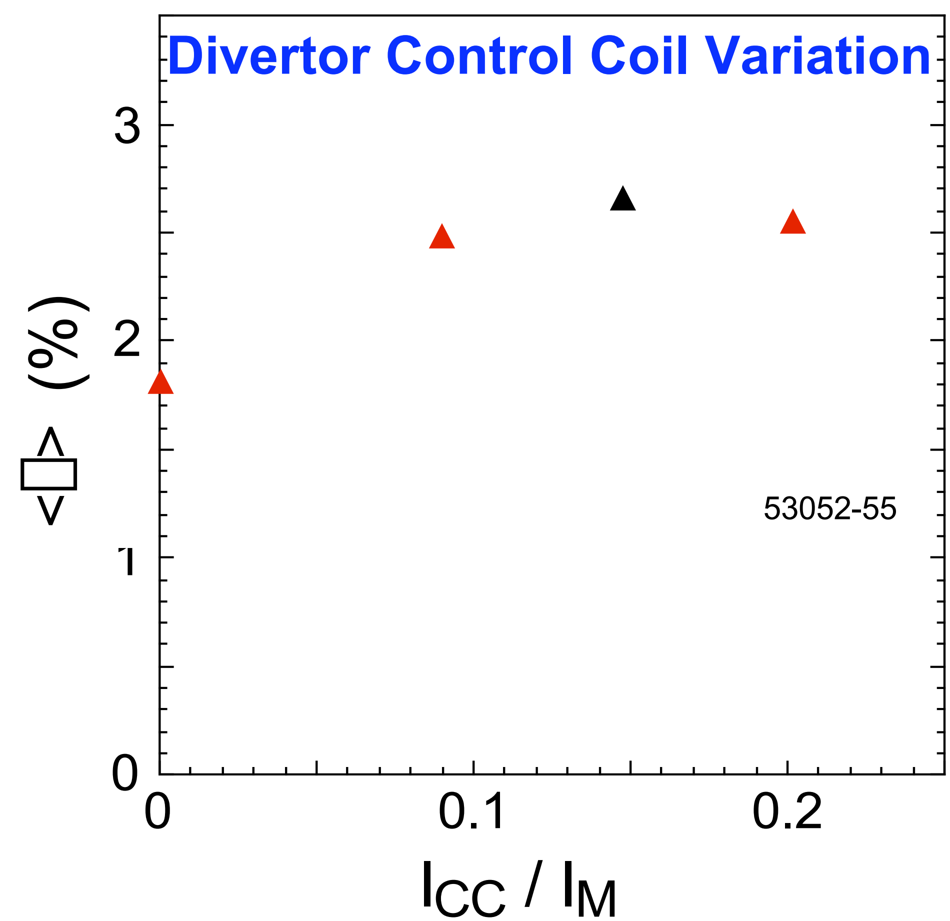
(A. Ware/N. Nakajima)

Is β Limited by an Equlibrium Limit ?

Maximum β at low ι is close to classical equilibrium limit Δ ~ a/2

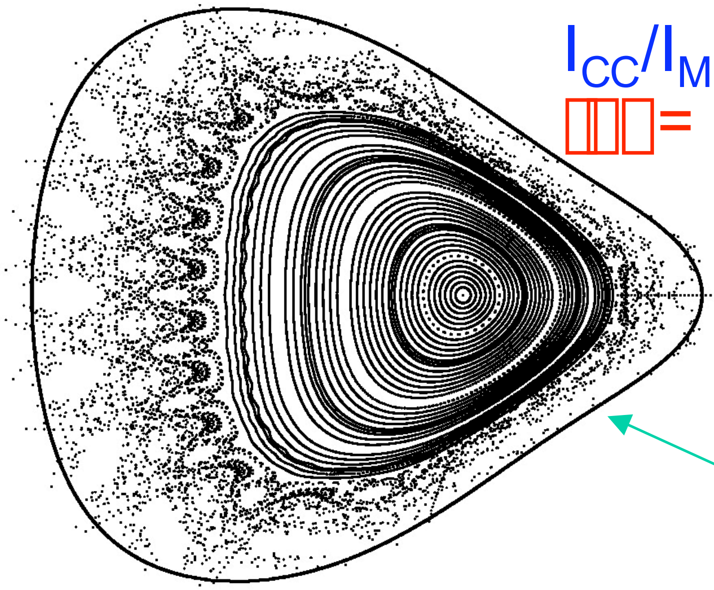


Control coil excitation does not affect iota or ripple transport



(M.C. Zarnstorff)

Control Coil Modulation Can Improved Flux Surface Topology as □ is Increased

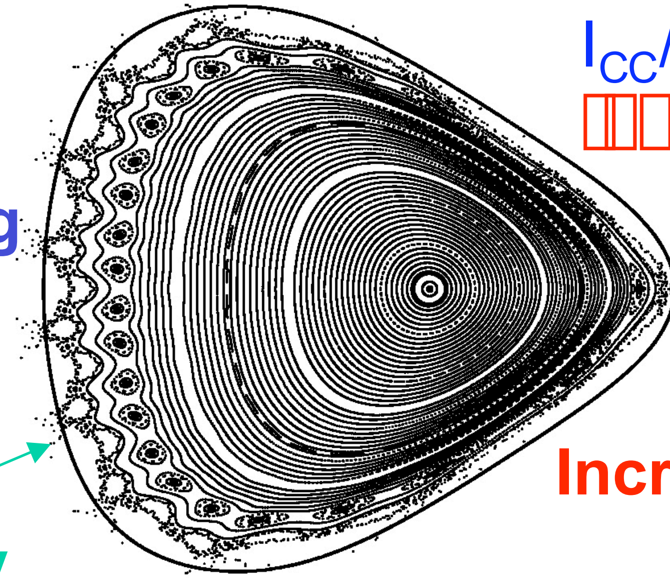


$I_{CC}/I_M = 0$

□□□= 1.8%

Increasing

I_{CC}/I_M □



$I_{CC}/I_M = 0.15$

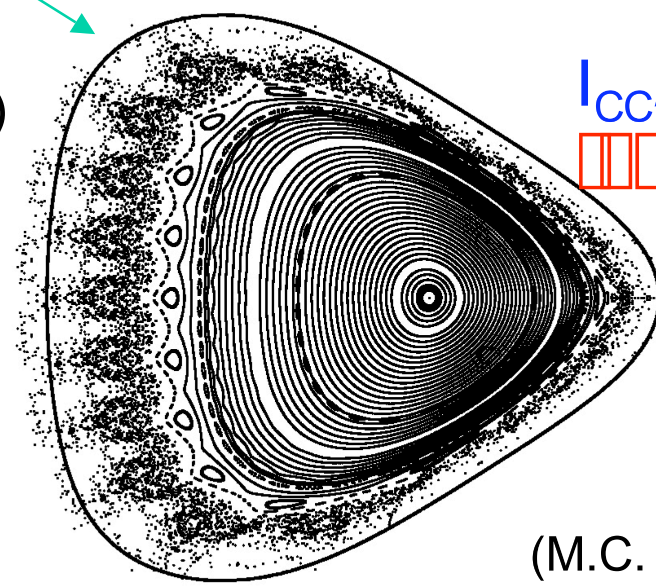
□□□= 2.0%:

Improved topology

Increasing □

□

VMEC boundary



$I_{CC}/I_M = 0.15$

□□□= 2.7%

Degraded topology

- PIES equilibrium: fixed pressure profile from equilibrium fit (not fitted current profile)
- Pies calculates similar flux surface degradation at the experimental maximum □ values !
  - -- 1.8% for $I_{CC}/I_M = 0$
  - -- 2.7% for $I_{CC}/I_M = 0.15$

(M.C. Zarnstorff)

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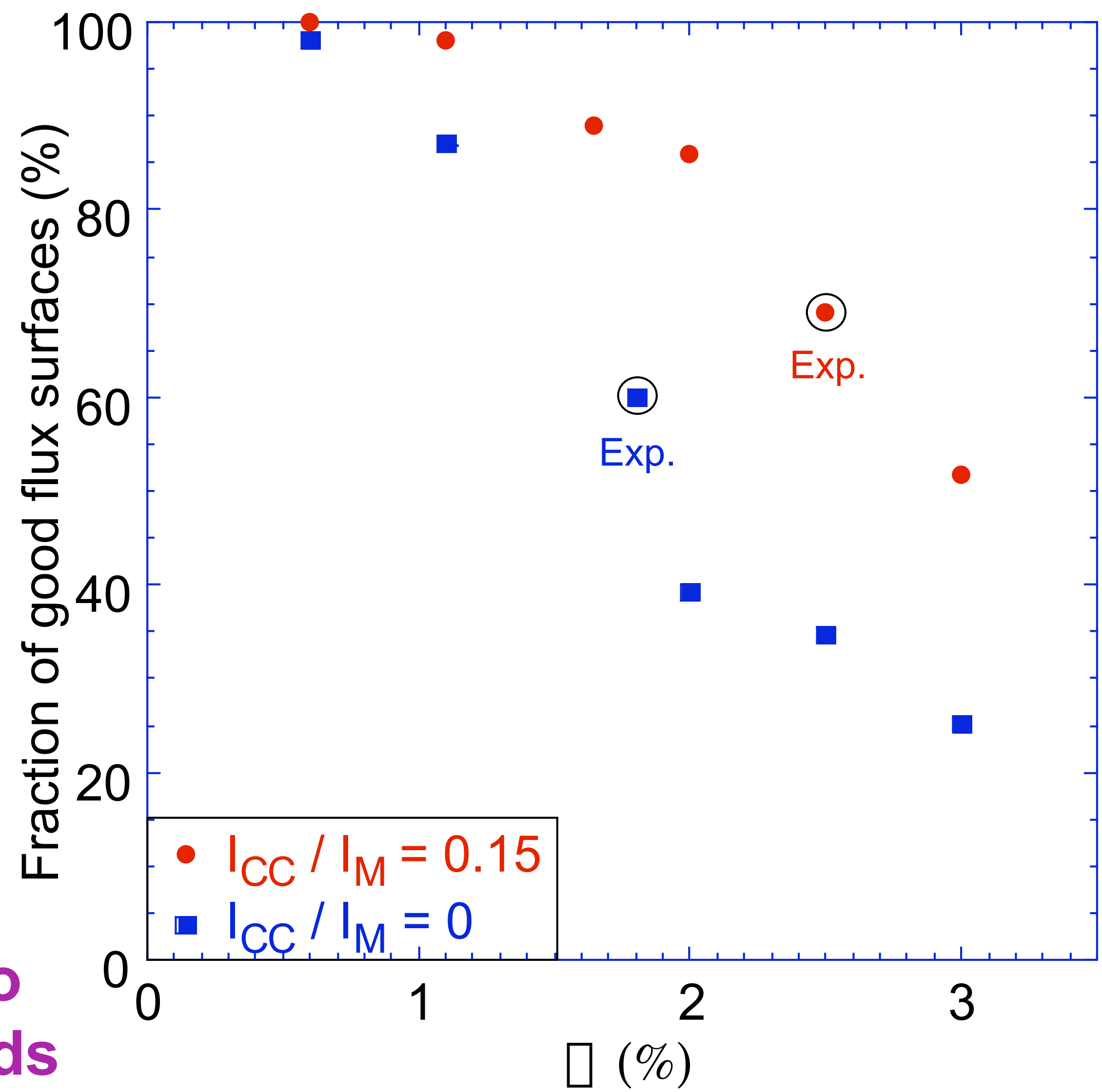
Degradation of Equilibrium May set W7-AS β Limit

- PIES equilibrium calculations indicate that fraction of good surfaces drops with β
- Drop occurs at higher β for higher I_{CC} / I_M

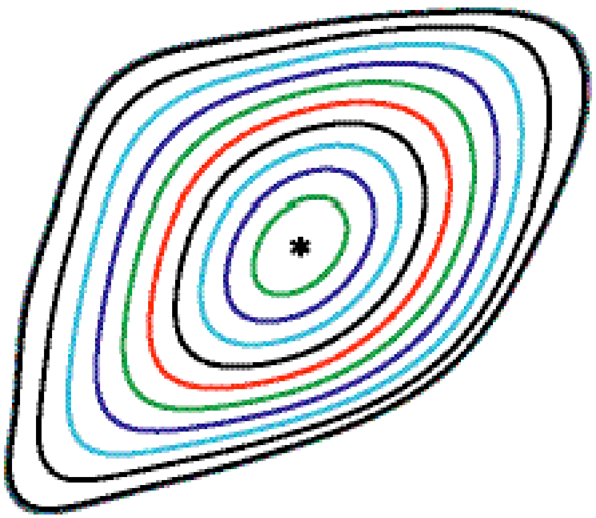


Experimental β value Correlates with loss of ~35% of minor radius to stochastic fields or islands

(M.C. Zarnstorff)

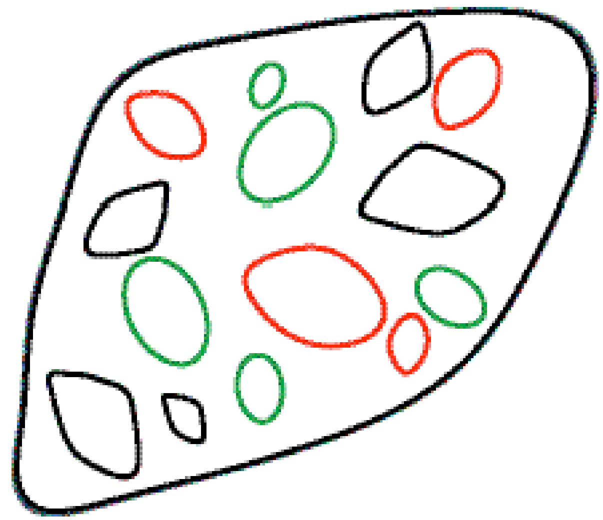
A New Proposed Model for Stellarator Equilibrium and Confinement □ Limit

- Is a stellarator equilibrium really like a simple container?



Add pressure up to point where container breaks
□ Major leak: All energy lost

- Or is it more like a leaky sponge?

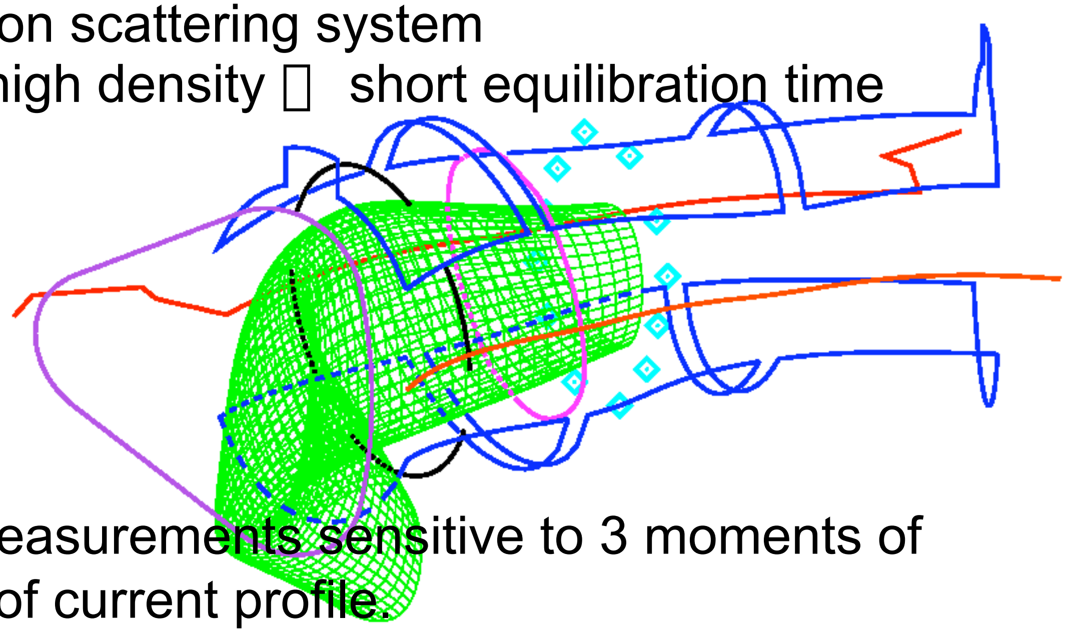


Add pressure to saturation point
□ Holes expand as confinement degrades until pressure finally leaks as fast as it is absorbed

Recent Progress Made in Equilibrium Reconstructions

Need to reconstruct self-consistent equilibrium for further analysis:
pressure and iota profiles, plasma shape

- Available data:
  - 45 point single-time Thompson scattering system
    assume $p_i = p_e$, due to very high density $\rightarrow$ short equilibration time
  - 19 magnetic measurements,
    including:
    segmented Rogowski,
    flux loops,
    diamagnetic loops

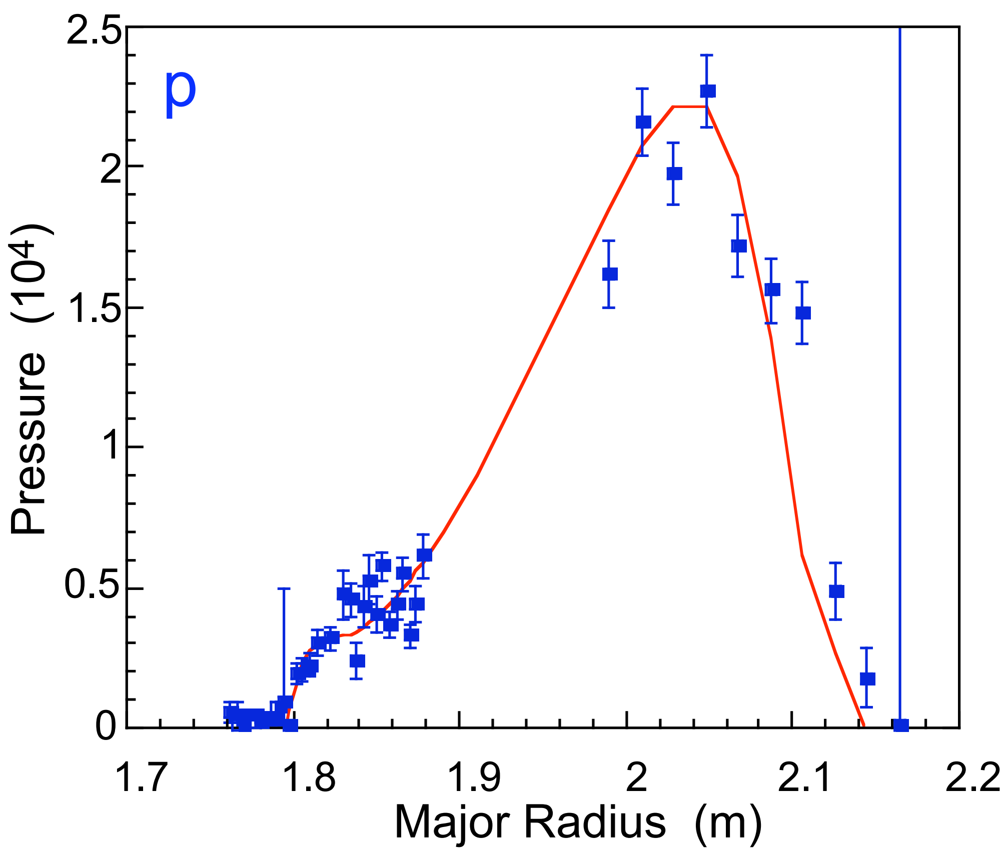


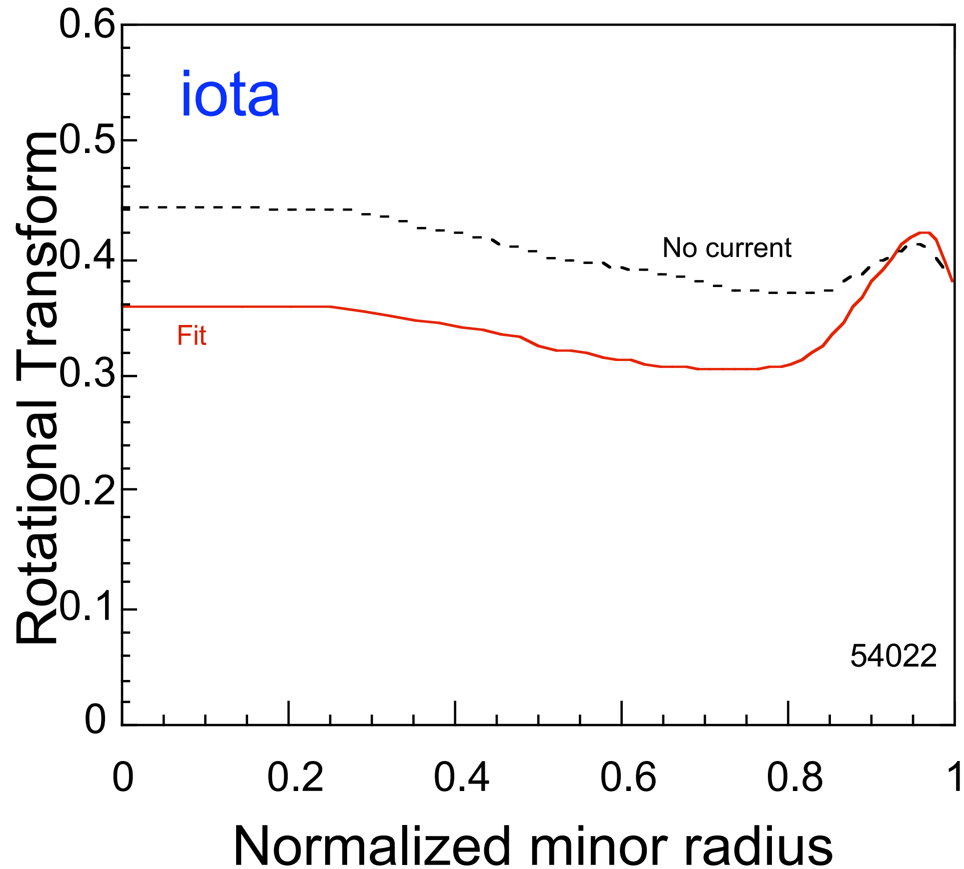
- From SVD analysis: magnetic measurements sensitive to 3 moments of pressure profile and 2 moments of current profile.

- Adapted STELLOPT design-optimization code to be a free-boundary equilibrium reconstruction code

(M.C. Zarnstorff)

Reconstructed Self-Consistent W7-AS Equilibrium





- Reconstructed equilibrium of β=3.4% plasma
- Lower central iota, flatter profile
- Central β=8.0%
- Edge pressure pedestal: present in many (but not all) high- β plasmas

(M.C. Zarnstorff)

Consistent Picture Emerging on Role of MHD Stability and the β Limit in Stellarators

- Both W7-AS and LHD show similar results regarding the ideal MHD stability limits:
  - Maximum β is not limited by MHD activity.
  - Maximum β reached is much higher than predicted linear stability thresholds
- Pressure driven MHD activity is observed in some cases at low or intermediate β
  - Usually saturates at harmless levels
  - Exists in narrow range of iota → easily avoided by adjusting coil currents
  - MHD at high β in LHD
- Predicted MHD stability correlates reasonably with observations at low β
  - Predicted MHD stability at high β depends sensitively on the boundary assumed

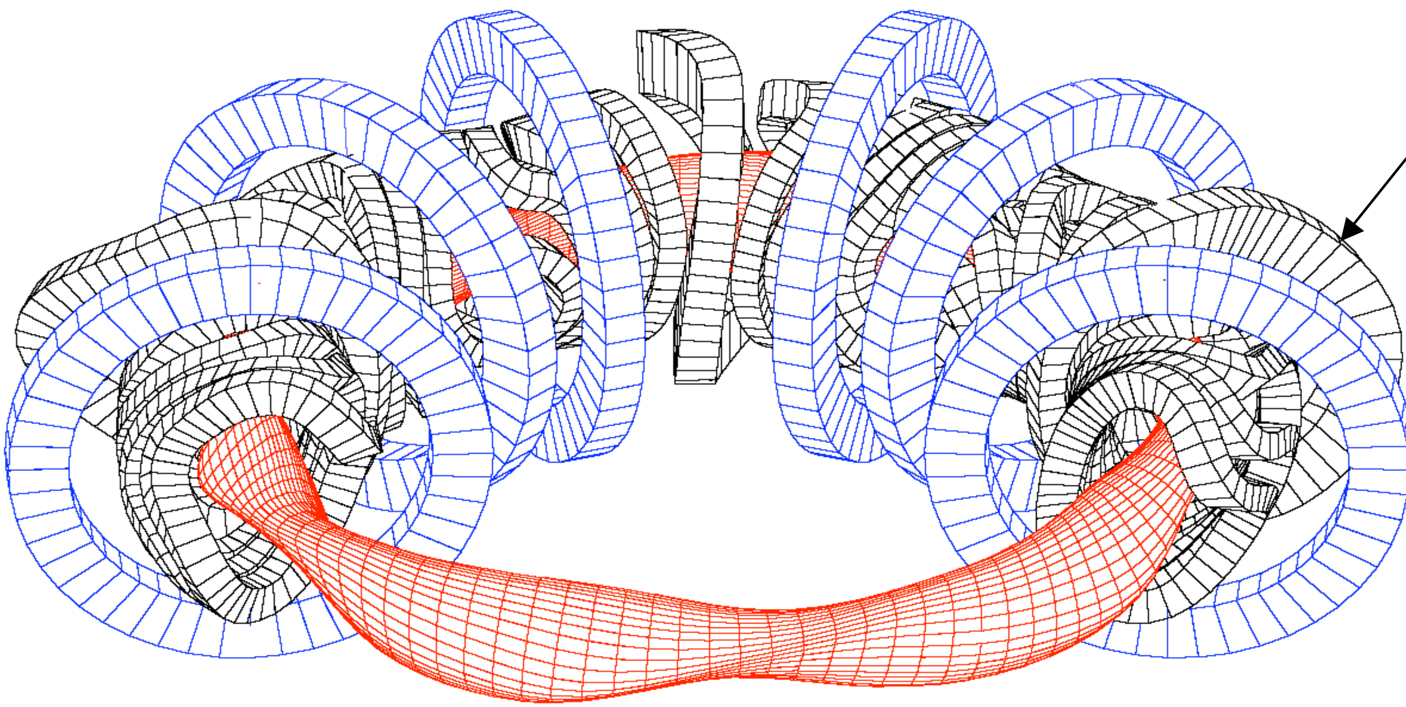
Maximum β Appears to be Controlled by Loss of Flux Surface Quality in Stellarators

- Maximum β correlated with calculated loss of ~35% of minor radius to stochastic magnetic field
  - May limit β
  - Leaky sponge model may be more appropriate
  - Maximum β is not generally limited by MHD activity
- Loss of minor radius has a significant effect on the predicted MHD stability properties
  - Generally stabilizing by removing edge resonances!
  - Ideal MHD stability predictions using fixed boundary VMEC equilibria are probably not valid at high β
  - Ideal MHD may still play a role in the limit at high β in some cases
  - Ideal MHD might be avoided at high β by small modulations of the boundary
  - BUT: Proximity to ideal MHD instability may contribute to deteriorating flux surfaces
- More accurate equilibrium reconstructions with measured profiles and flux surfaces are clearly needed
  - With sensitivity studies against possible variations in the discharge equilibria !

W7-AS – a flexible experiment

5 field periods, R = 2 m, minor radius a ≤ 0.16 m, B ≤ 2.5 T, vacuum rotational transform $0.25 \le \iota_{ext} \le 0.6$

W7-AS



Flexible coilset:

- Modular coils produce helical field
- TF coils, to control rotational transform ι
- Not shown:
  - divertor control coils
  - OH Transformer
  - Vertical field coils

Completed operation in 2002

(M.C. Zarnstorff)