High-β Experiments on W7AS and Possible Implications

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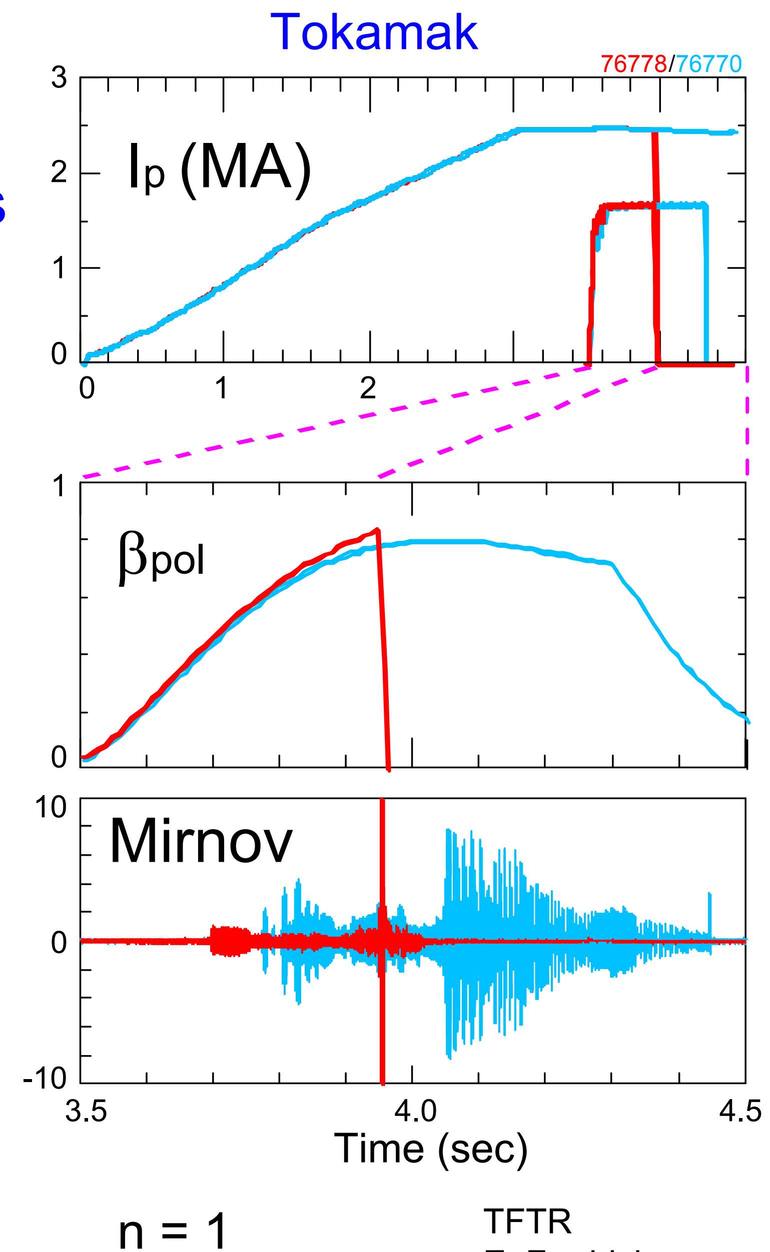
Stellarator β–limit Are Not Understood

- Tokamak β limit extensively studied: set by instabilities
  - Ideal-like instabilities → disruptions
  - Saturated instabilities: degraded confinement

- Historically: stellarators designed using idealized criteria: Mercier criteria and resistive-interchange stability.

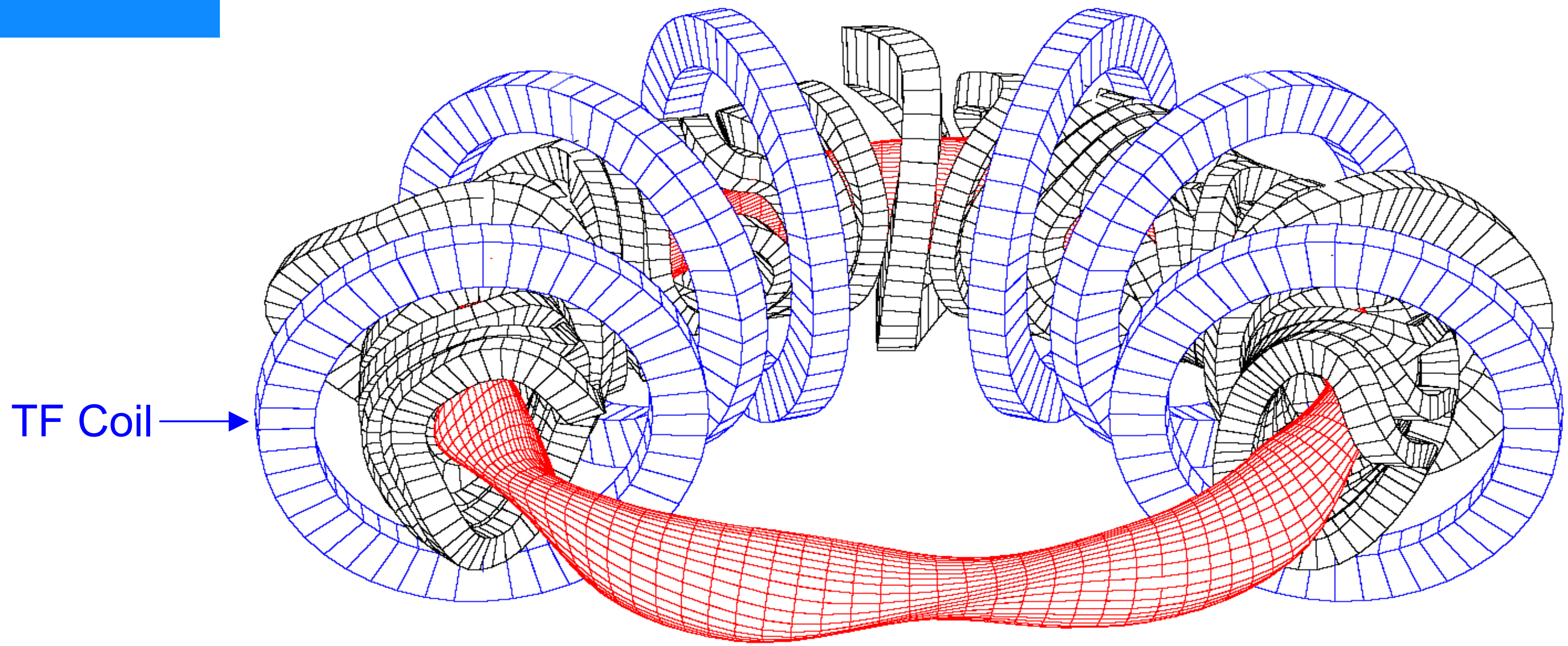
- Stellarator β limits not yet observed
  - Heliotron-E and CHS achieved β~2%, transport/power limited
  - Recently, LHD achieved β~3.2%, transport/power limited

In both CHS and LHD, these plasmas violate Mercier criteria



TFTR
E. Fredrickson

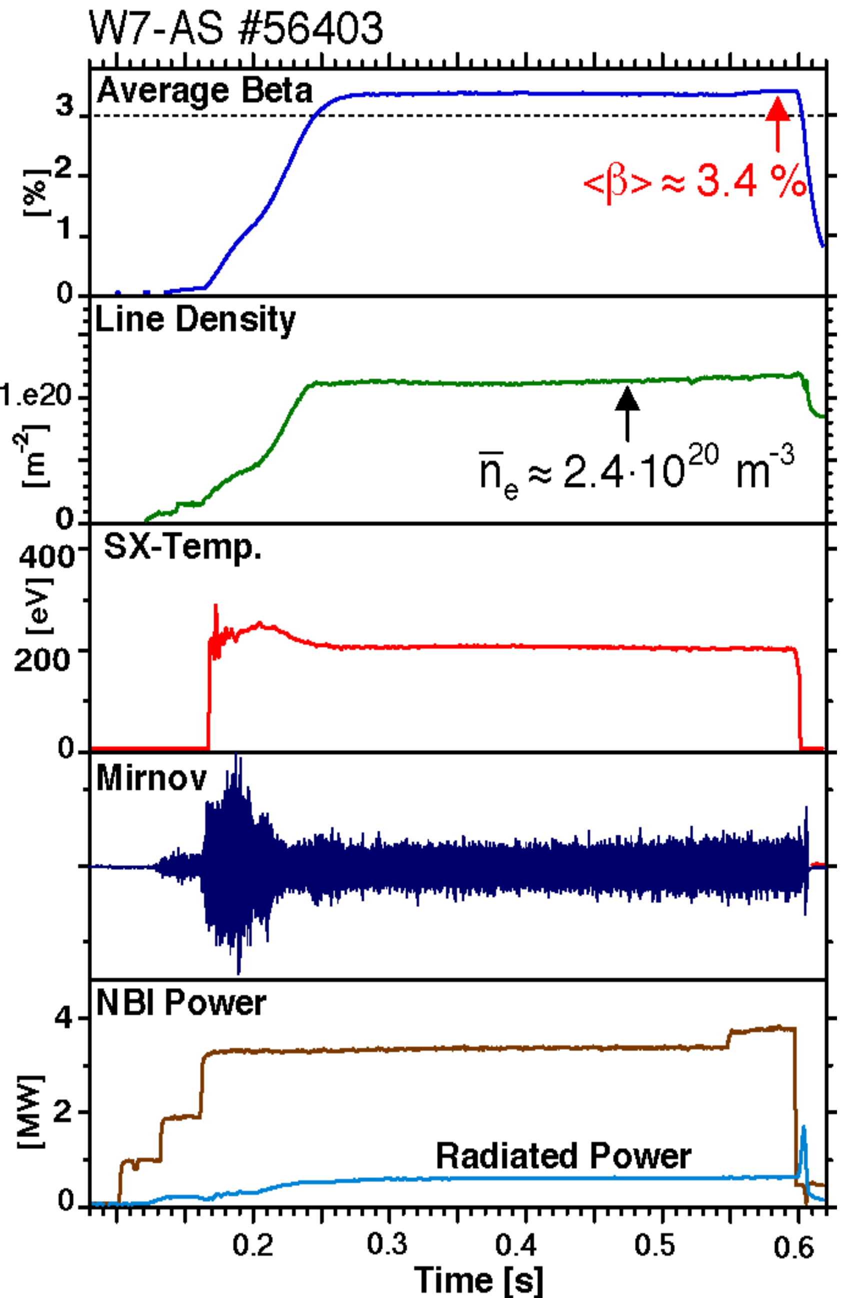
Wendelstein 7-AS



- 5 field periods, R = 2 m, minor radius a ≤ 0.16 m, B ≤ 2.5 T, rotational transform $0.25 \leq \iota_{ext} \leq 0.6$
- Non-planar modular coils produce helical field

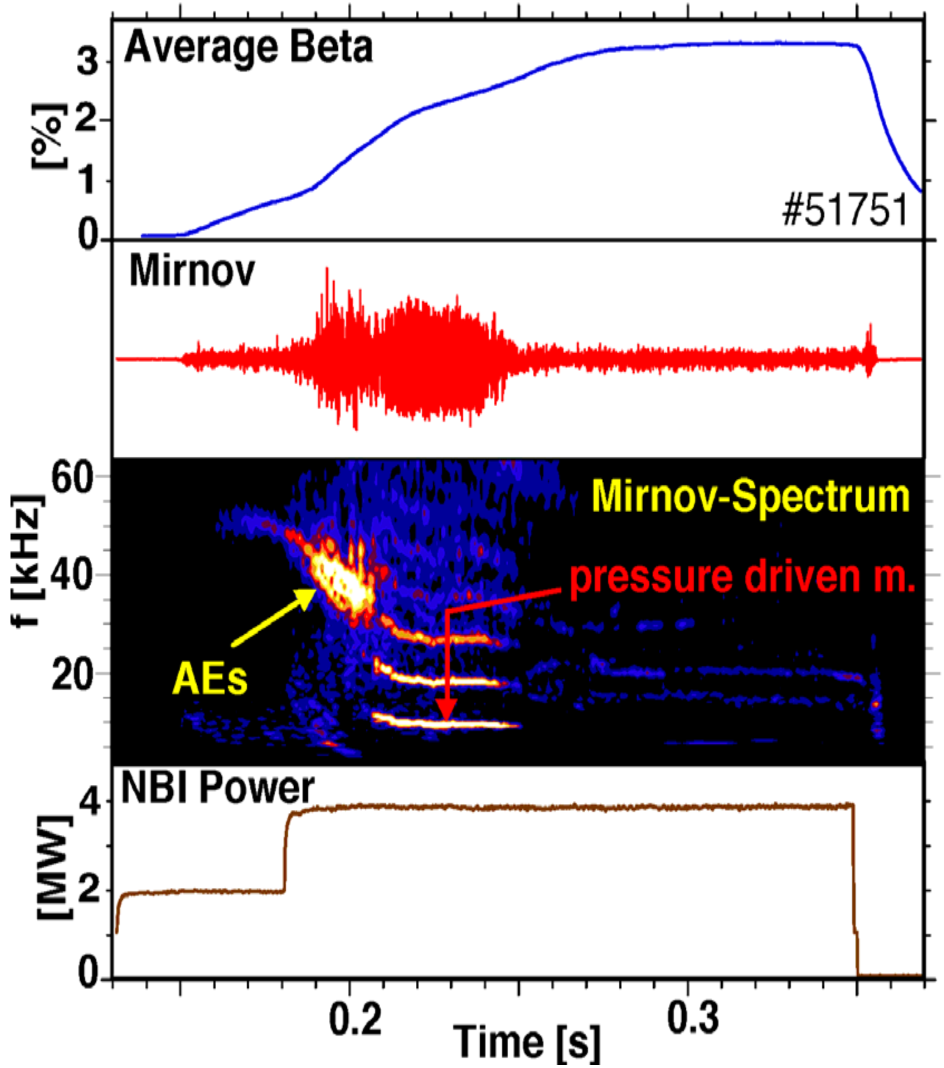
- TF coils, for adjusting rotational transform ι and avoiding resonances
- Not shown: OH-transformer, vertical field coils control coils (two per field period) for controlling edge islands

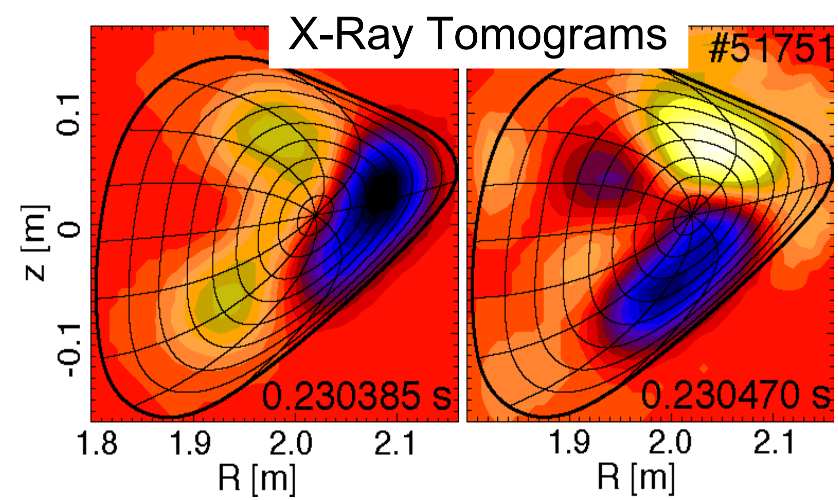
Highest ⟨β⟩ ≈ 3.4 % : Quiescent, Quasi-stationary

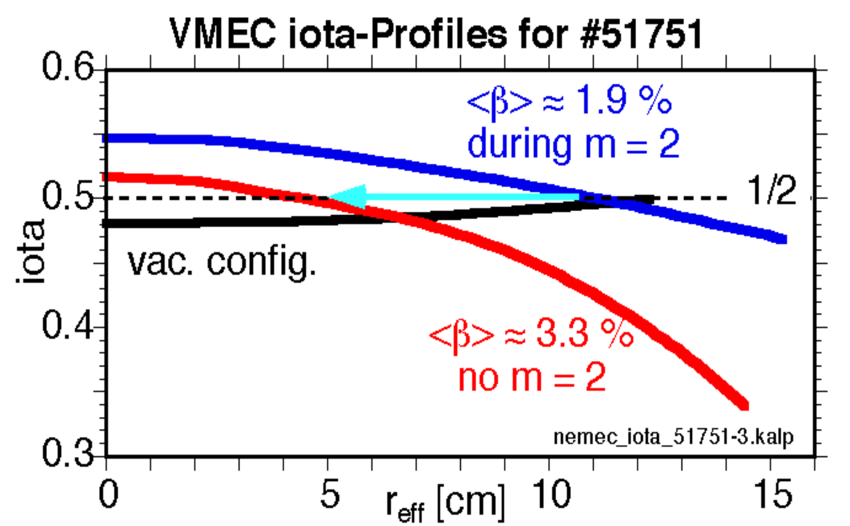


- B = 0.9 T, $iota_{ext} \approx 0.5$, $B_z/<B>=0.026$
- Similar to High Density H-mode (HDH)
- Almost quiescent high-β phase, MHD-activity in early medium-β phase
- $I_P = 0$, but there can be local currents
- In general, β not limited by any detected MHD-activity.
- Duration of high-β phase ~ 75 τ_E quasi-stationary with density control and low radiated power
- $\tau_I / \tau_E \approx 2–3$ from impurity injection

Pressure Driven Modes Observed, at Intermediate β







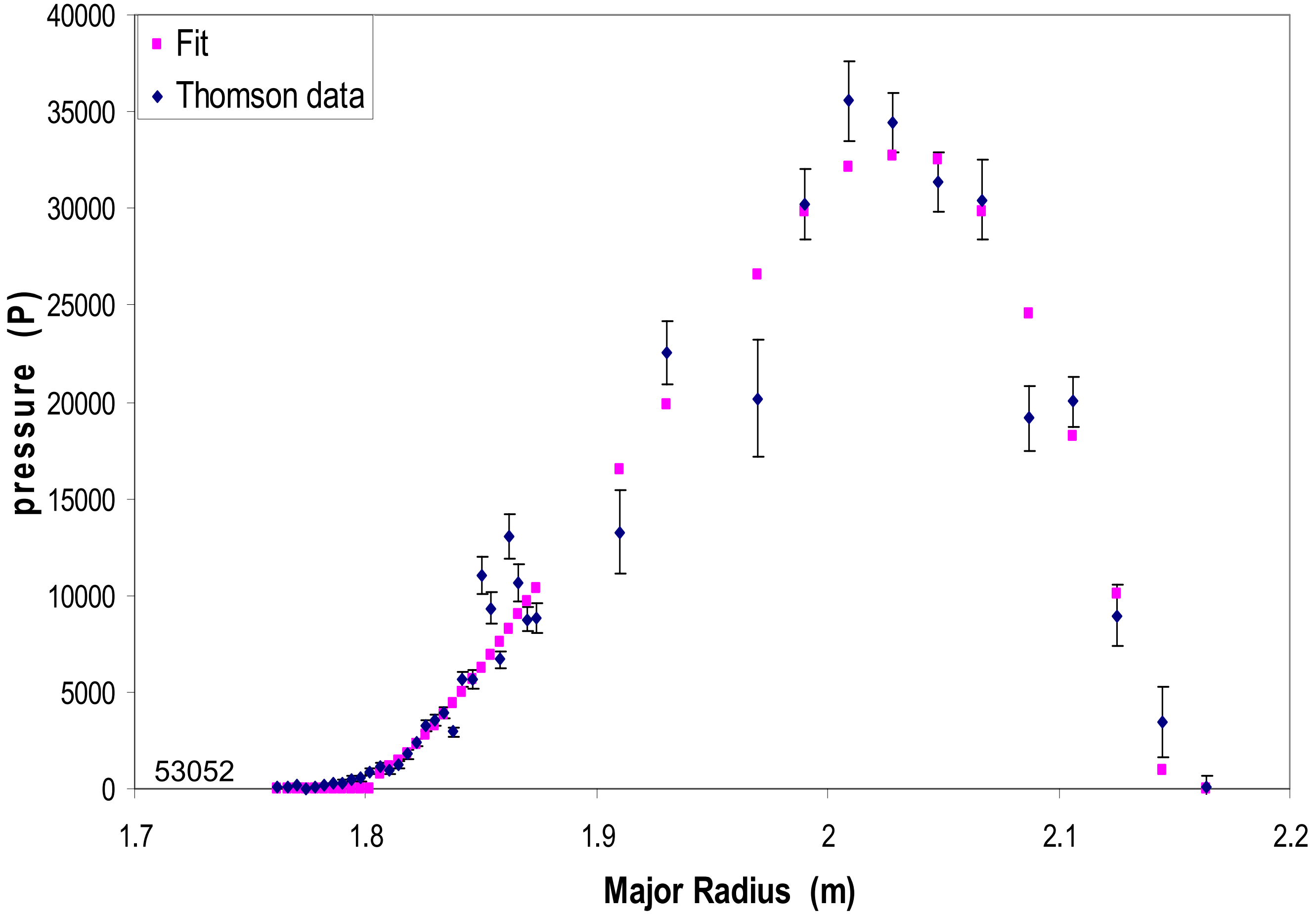
- Dominant mode m/n = 2/1.
- Does not inhibit access to higher β ! Why does it saturate at low level??
- Modes disappear at high β (due to inward shift of iota = ½?)

Equilibrium Modeling and Analysis

- Primary tool is free-boundary VMEC (courtesy of S. Hirshman, ORNL)
- In order to match experimental boundary conditions and measurements, the STELLOPT optimizer (which uses VMEC) has been extended towards a proto-reconstruction code for 3D systems.
- Computes maximum plasma volume constrained by PFCs
  $\Rightarrow \beta$ is a lower limit (volume might be reduced due to edge islands)
- Can self-consistently fit to Thomson scattering data to determine pressure profile shape

– Not fast. ~ 1 hour per case (parallel Power4)
  due to using complete VMEC runs during fitting process

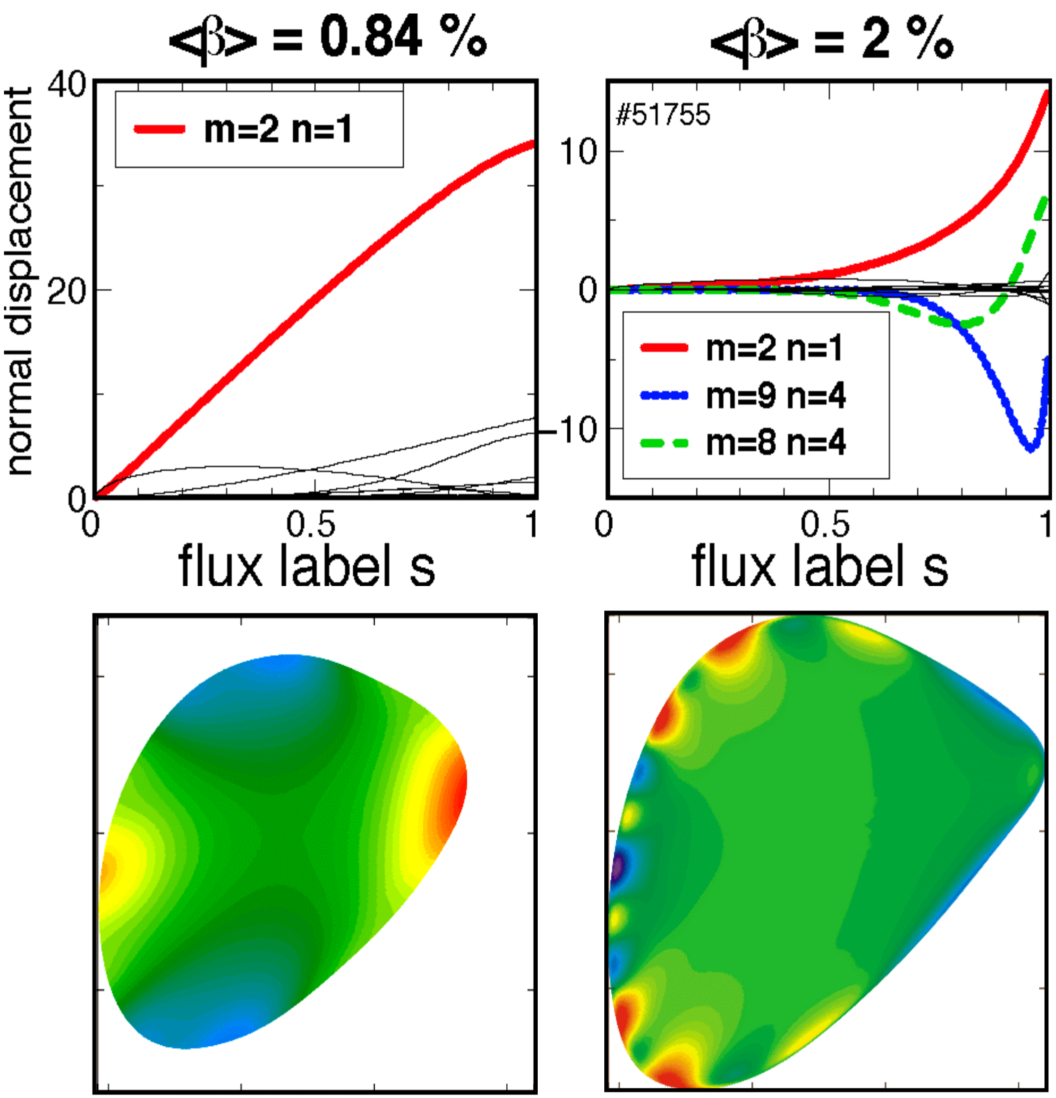
Thomson Scattering Data Well Fit by STELLOPT Pressure Profile

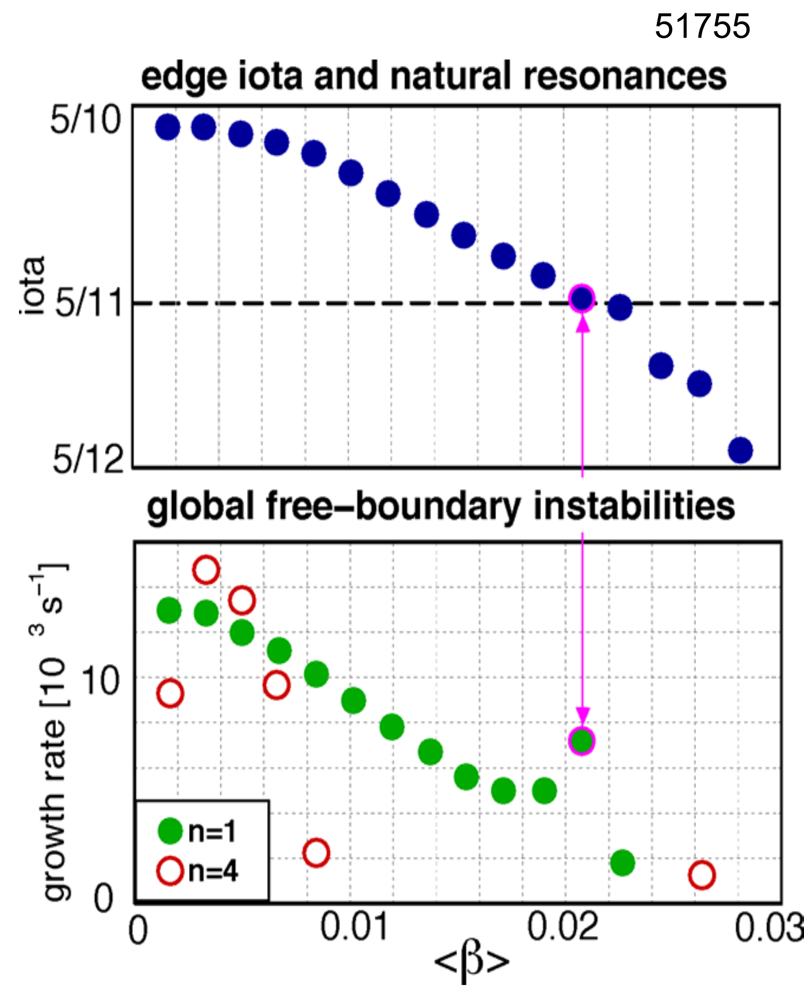


- Thompson pressure profile mapped to equilibrium and fit to 10^{th} order polynomial in flux. One-sigma error-bars.
- Volume integrated pressure normalized to match diamagnetic measurement

Linear Stability Calculations (CAS3D) Indicate 2/1 Should be Unstable, even at low β !

Mode Displacement & Perturbed Pressure





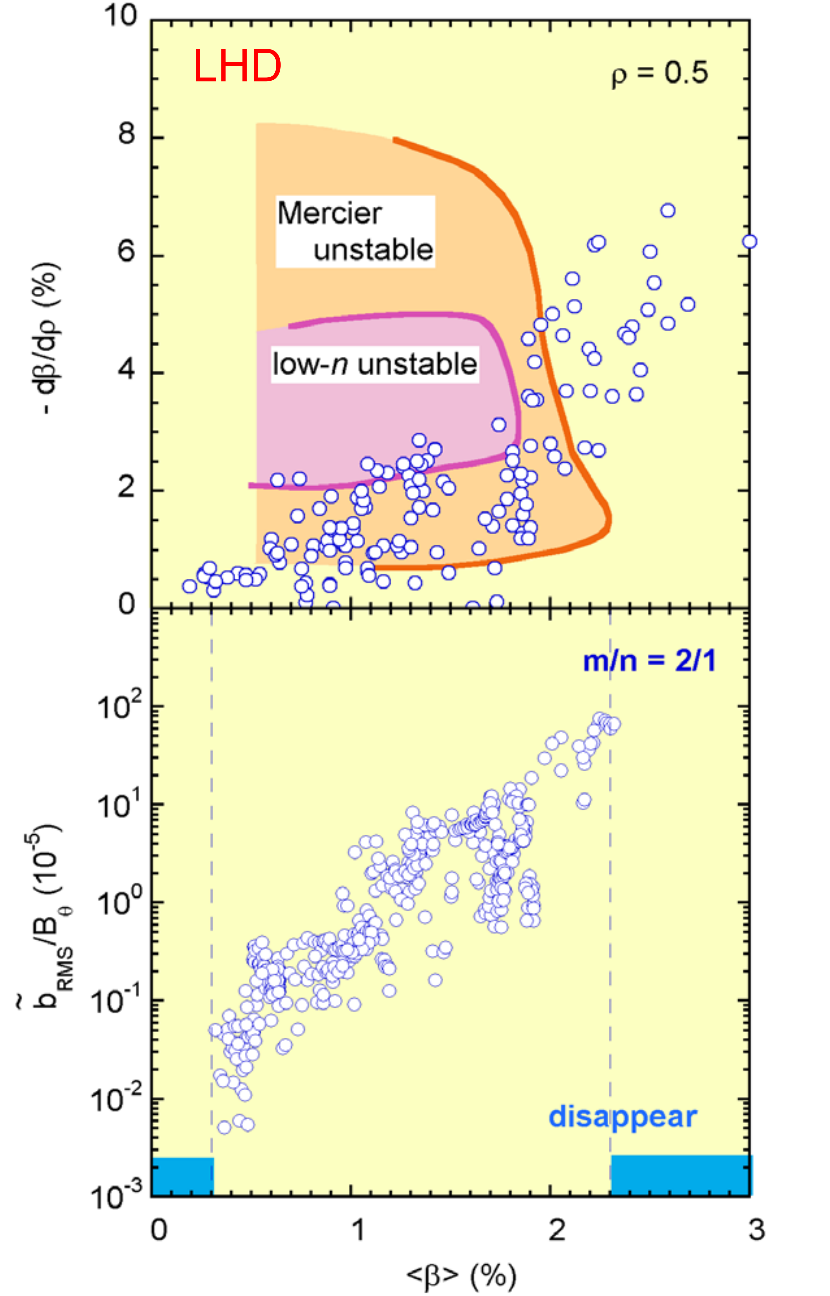
External global modes, most unstable at low β

– C. Nuhrenberg

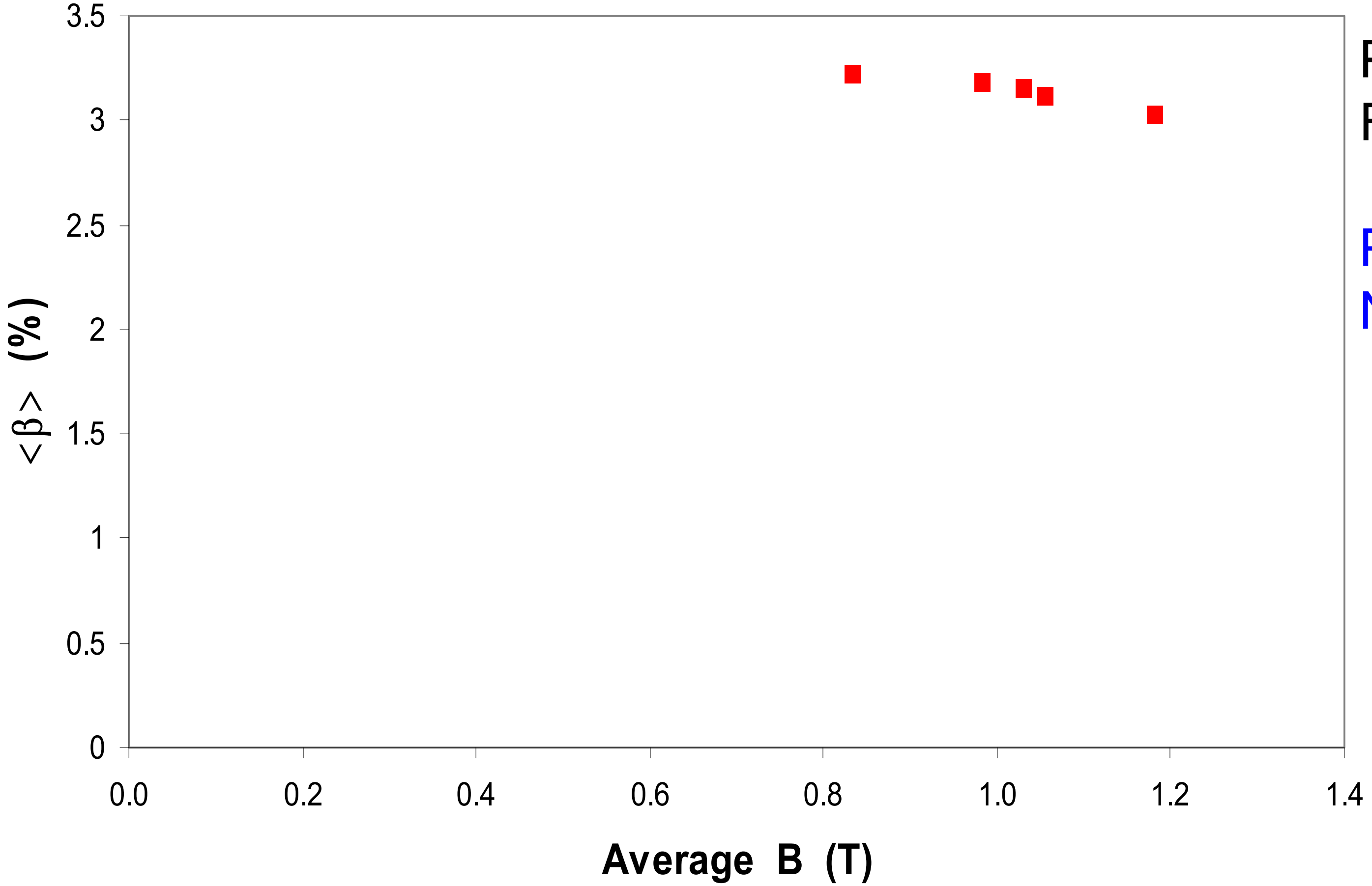
Pressure Driven MHD Similar in LHD

- LHD observes saturated m/n = 2/1 modes at moderate β
  - does not prevent access to higher β
- 2/1 mode disappears for β > 2.3%
- Some correlation between observed mode and theoretical linear-stability threshold
- Typically, lower collisionality than W7AS

- Why do they saturate?



β depends weakly on B in W7AS



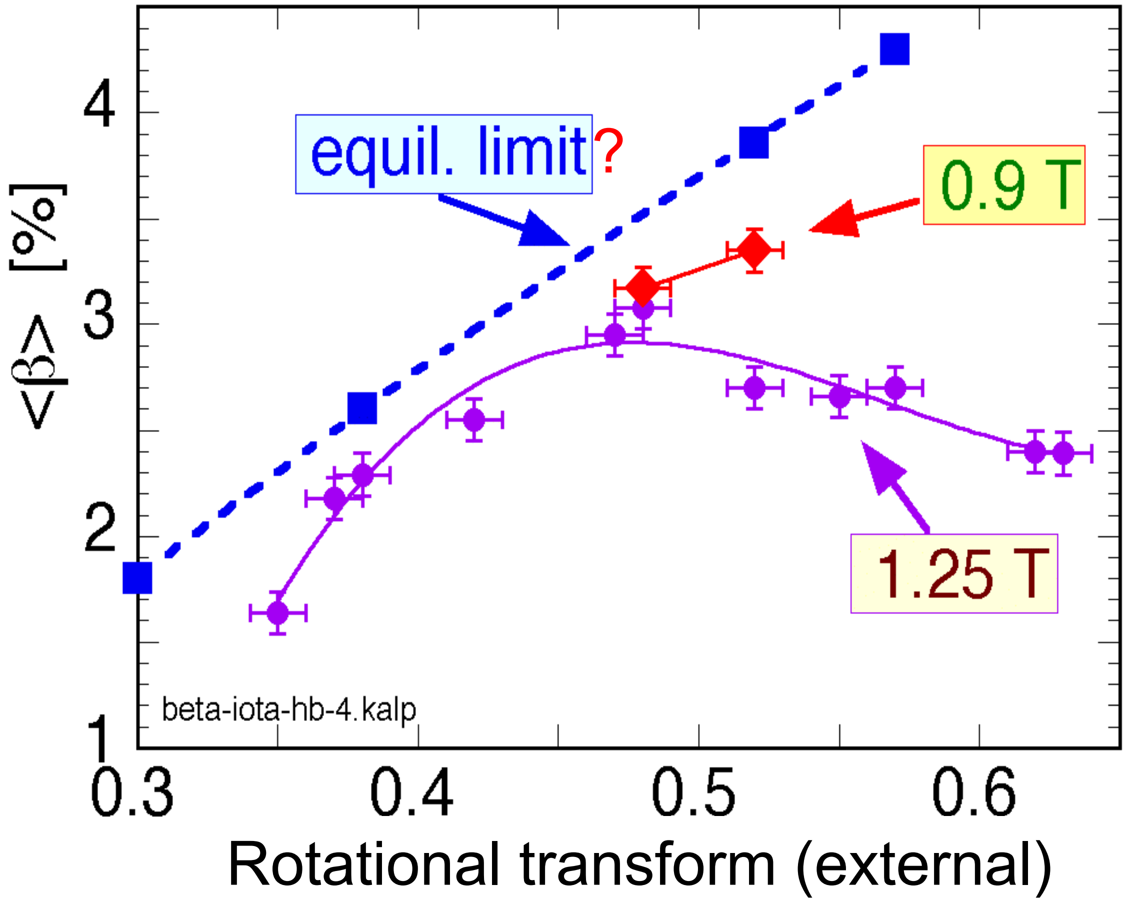
P_{inj} = 3.9 MW
Fixed plasma shape

Plasmas quiescent
No MHD Activity

- Indicates energy confinement $\propto B^{1.8}$! Much stronger than usual!
- At B=0.9 T, $\langle\beta\rangle$ is almost independent of heating power!
  Energy confinement $\propto P_{inj}^{-3/4}$!

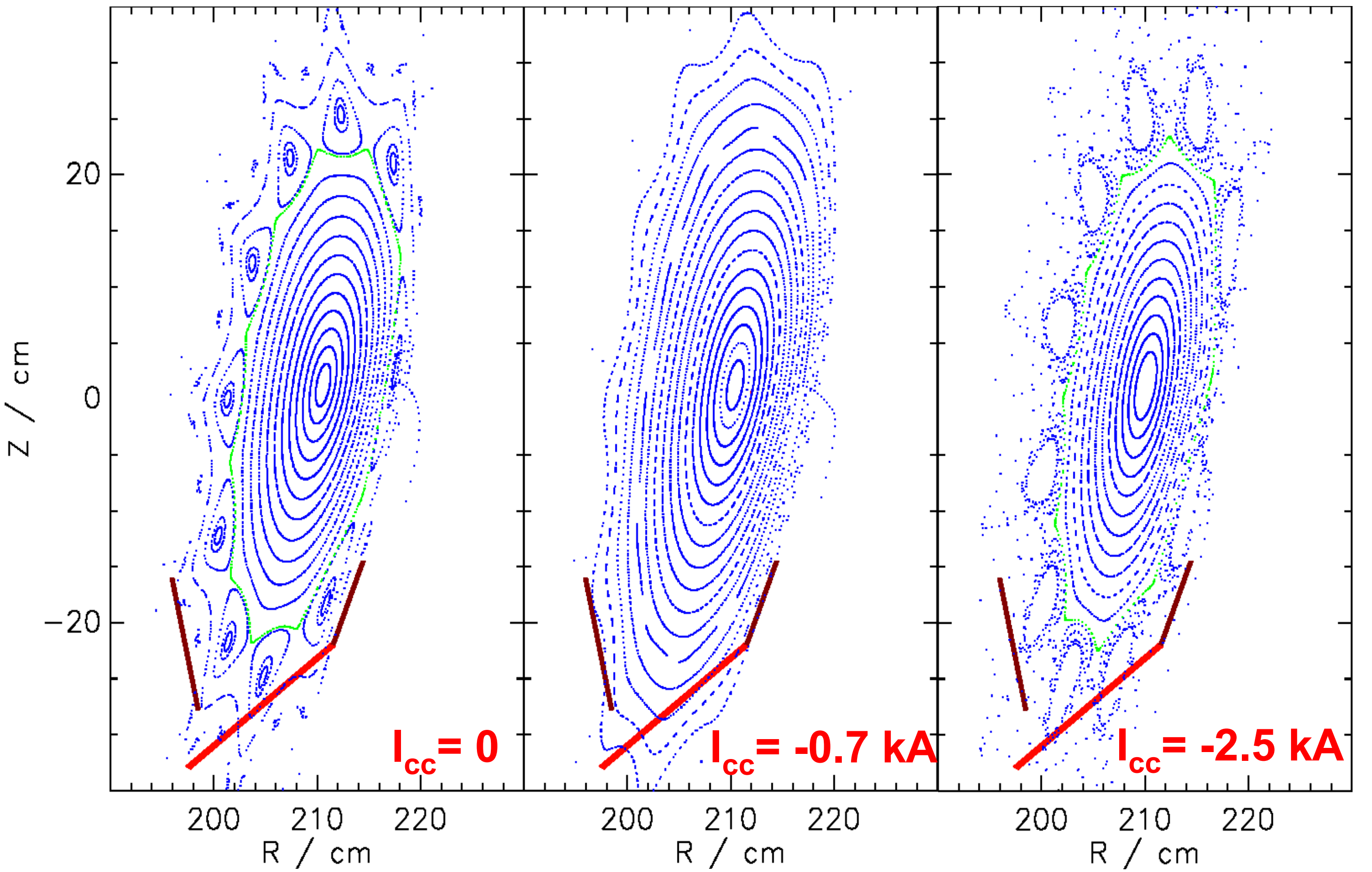
- May indicate β is constrained, but what is mechanism?

β May be Limited by Deterioration of Equilibrium



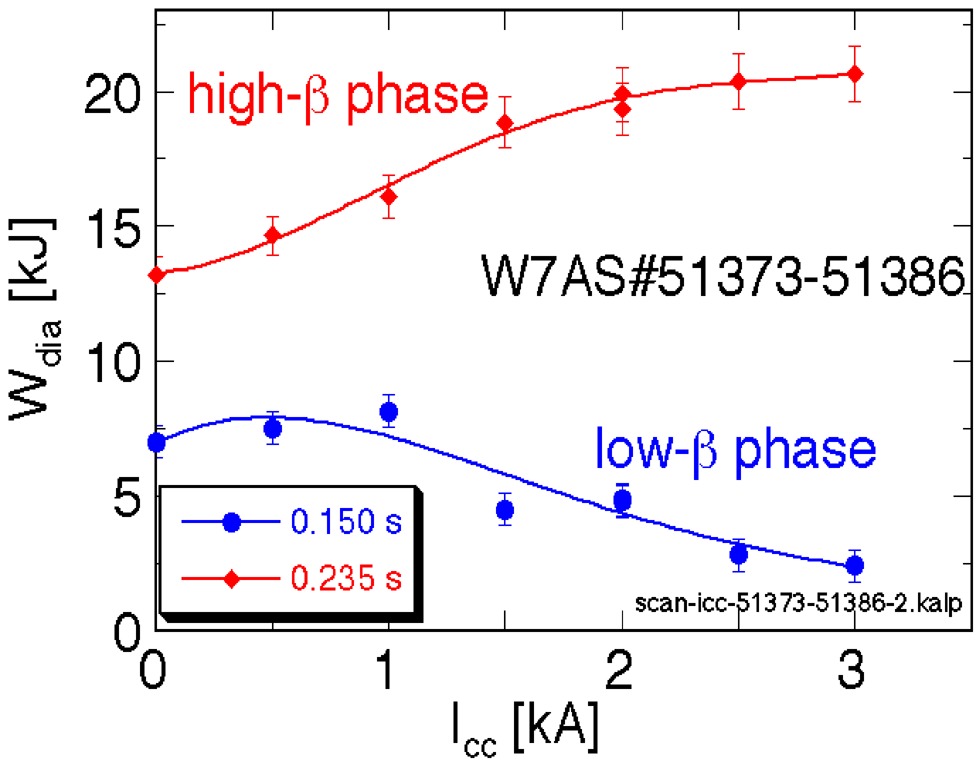
- Constraint on highest-β may be due 'equilibrium β-limit' where axis shift ~ ½ of plasma minor radius ??
- In previous calculations, this shift generated large equilibrium islands = ⇒ confinement degradation
- Calculations underway to assess flux-surface deterioration

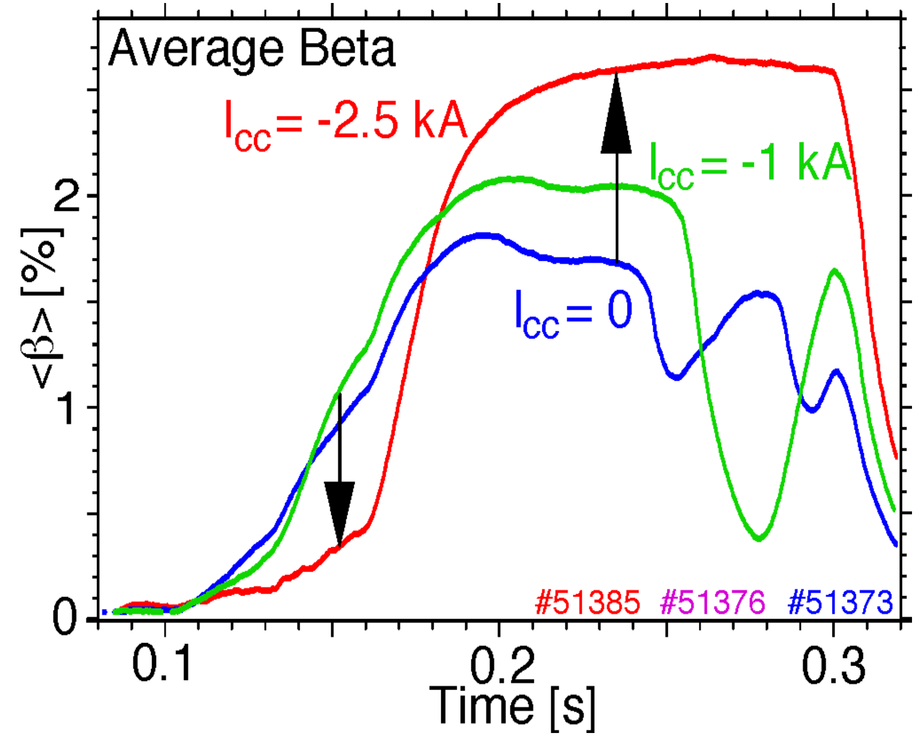
Control Coils Designed to Control Edge Islands



- Calculated vacuum flux surfaces
- For vacuum, maximum volume is obtained with I_{cc}=-0.7kA
- Control coils designed to control island divertor

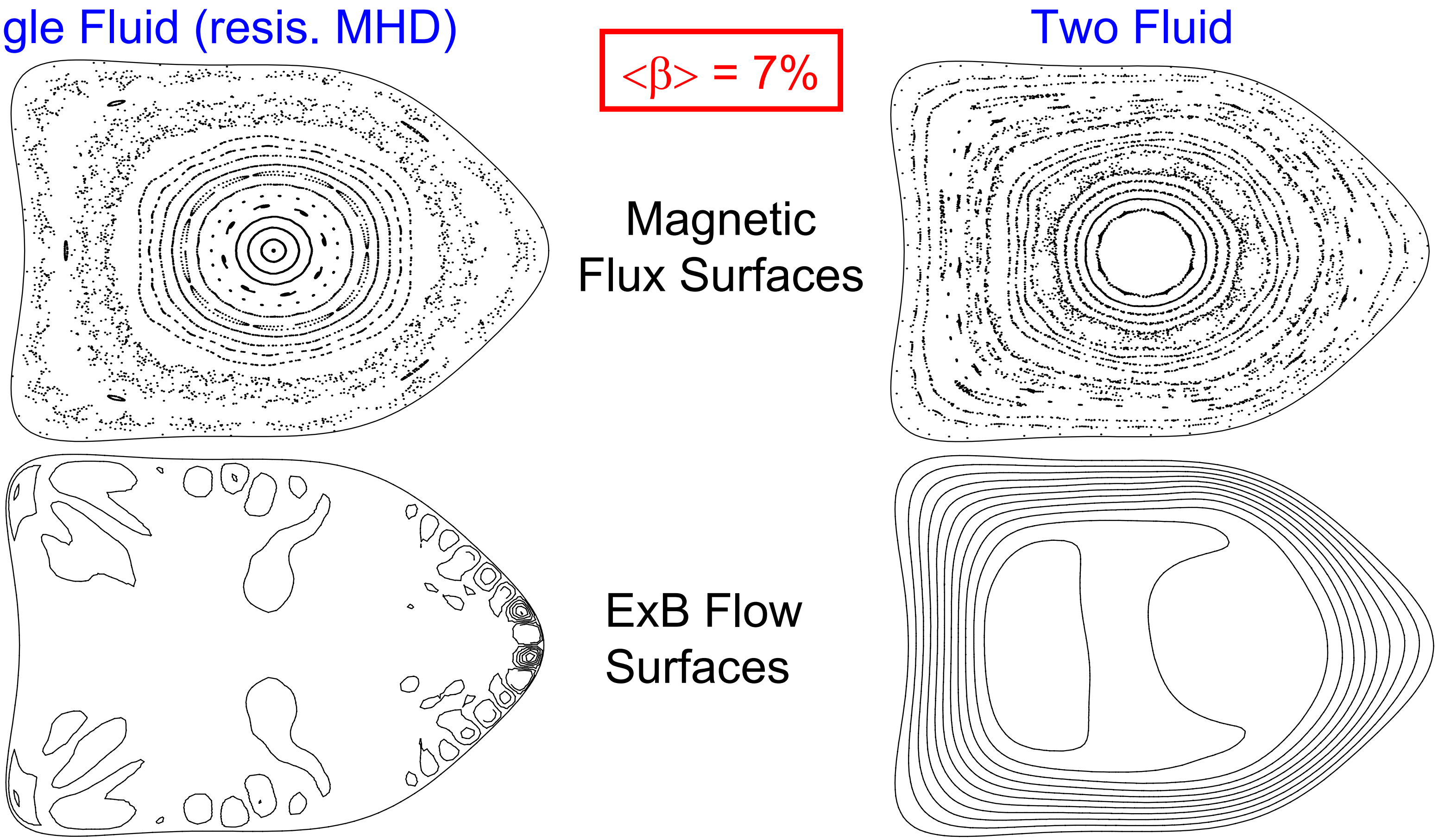
β is sensitive to Control Coil Current





- <B> = 1.25T
- Low-β phase approximately agrees with vacuum calculations
- High β phase optimizes with much higher Control Coil Current
- Indicates the importance of islands to confinement.
- Preliminary PIES calculations: all mainly stochastic at high β ?

Initial Non-Linear Two-Fluid Indicate Possible Higher β-Limit for NCSX



L. Sugiyama, H. Strauss

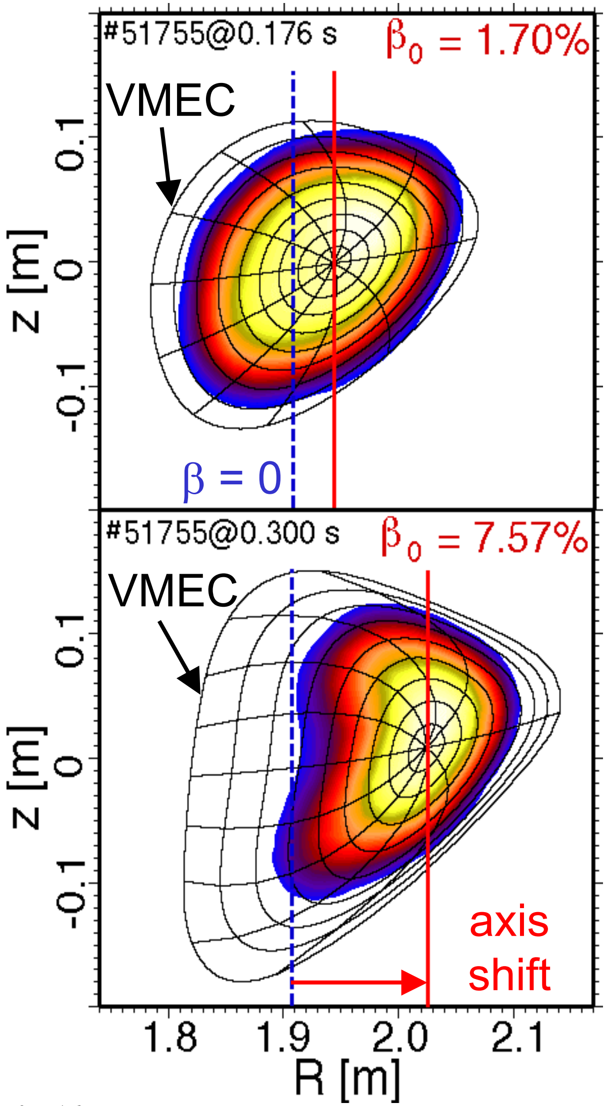
- Preliminary M3D calculations. Fixed boundary.
- Two fluid: finite gyro-radius and self-generated flows stabilize equilibrium
- Does not include neoclassical effects yet. Should increase stabilization.

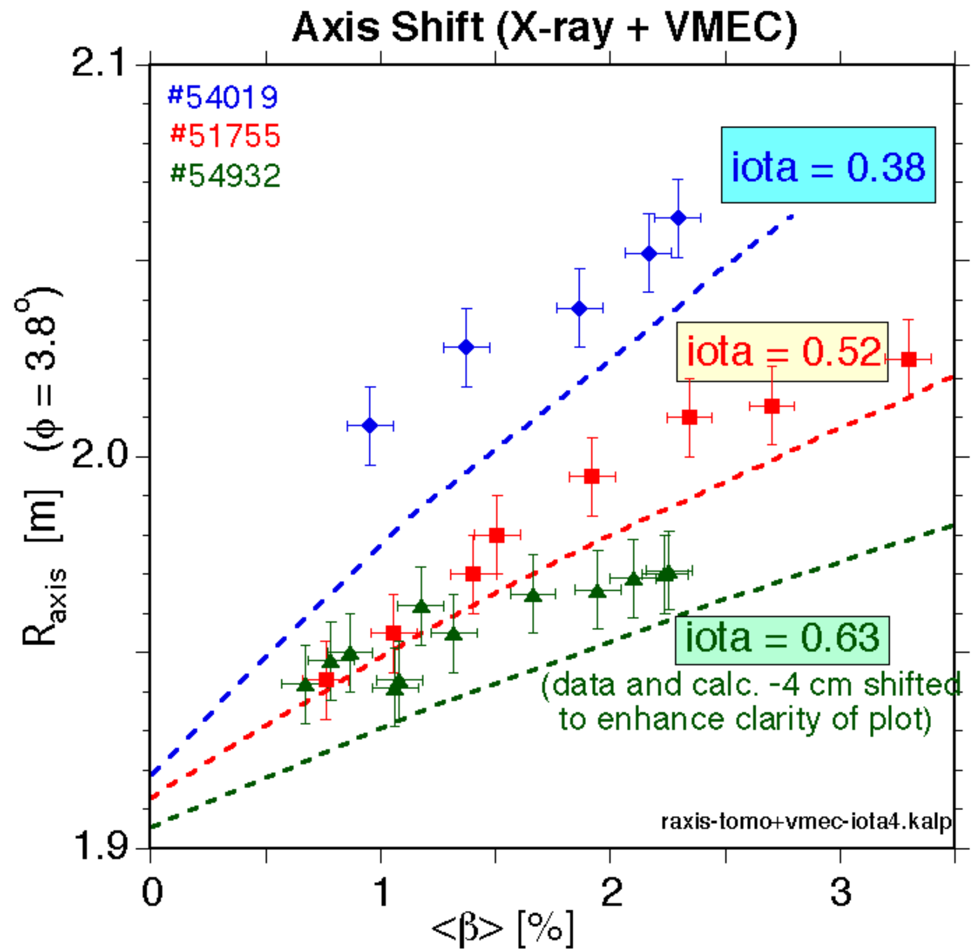
Conclusions

- Quasi-stationary, quiescent plasmas with $\beta > 3\%$ easily produced in W7-AS. Maximum $\beta \sim 3.4\%$.
  - Far above predicted linear stability limit to low-n ideal modes !
- Maximum β-value appears to be controlled by changes in confinement, not strong MHD activity
  - No pressure-limiting modes or disruptions observed
  - What is limiting mechanism? flux-surface quality ('equilibrium limit')?
- Pressure driven MHD activity is sometimes observed
  - Typically saturates at ~harmless level. Why?
- Situation appears similar on LHD
- Preliminary two-fluid non-linear MHD calculations may indicate two-fluid stabilization of NCSX at higher β values…?
- How to design future machines? What is maximum β?
  - Tokamak criteria are not consistent with stellarator experiments !

VMEC Agrees with SXR Tomography
Current-free plasmas

X-Ray Tomograms





- measured axis shift in agreement with equilibrium calculations
- $I_P = 0$