Equilibrium and Stability of High-β Plasmas in Wendelstein 7-AS

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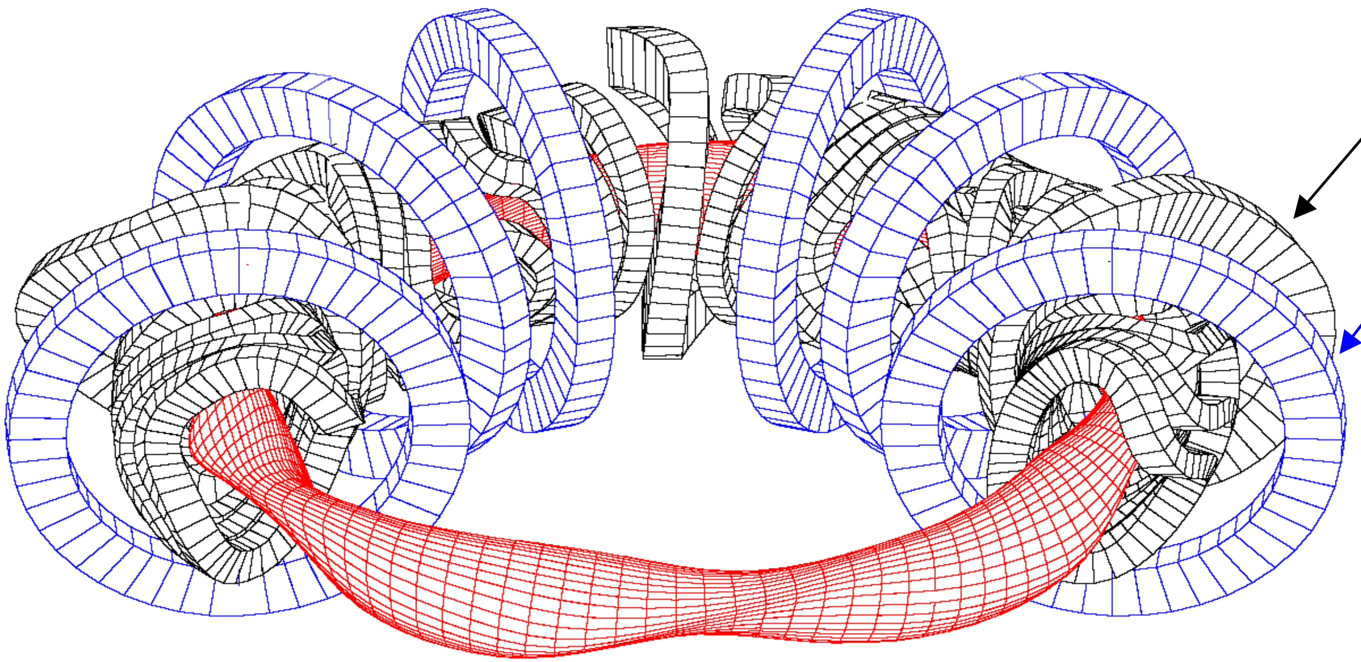
Outline

- β limits and sustainment in Wendelstein-7AS
- Limiting mechanisms
- Equilibrium & Stability properties
- Conclusions

W7-AS – a flexible experiment

5 field periods, R = 2 m, minor radius a ≤ 0.16 m, B ≤ 2.5 T,

vacuum rotational transform $0.25 \leq \iota_{ext} \leq 0.6$



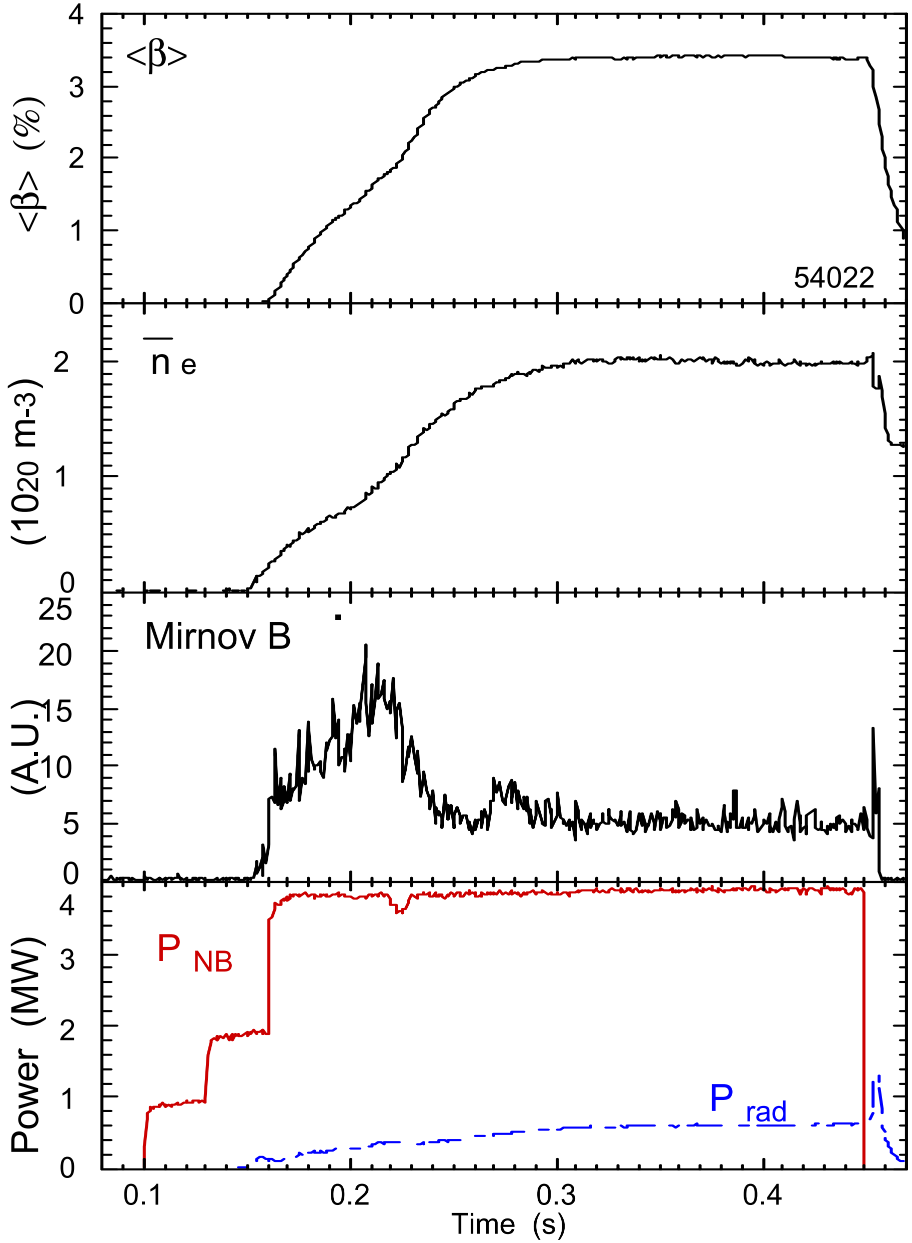
Flexible coilset:

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

W7-AS

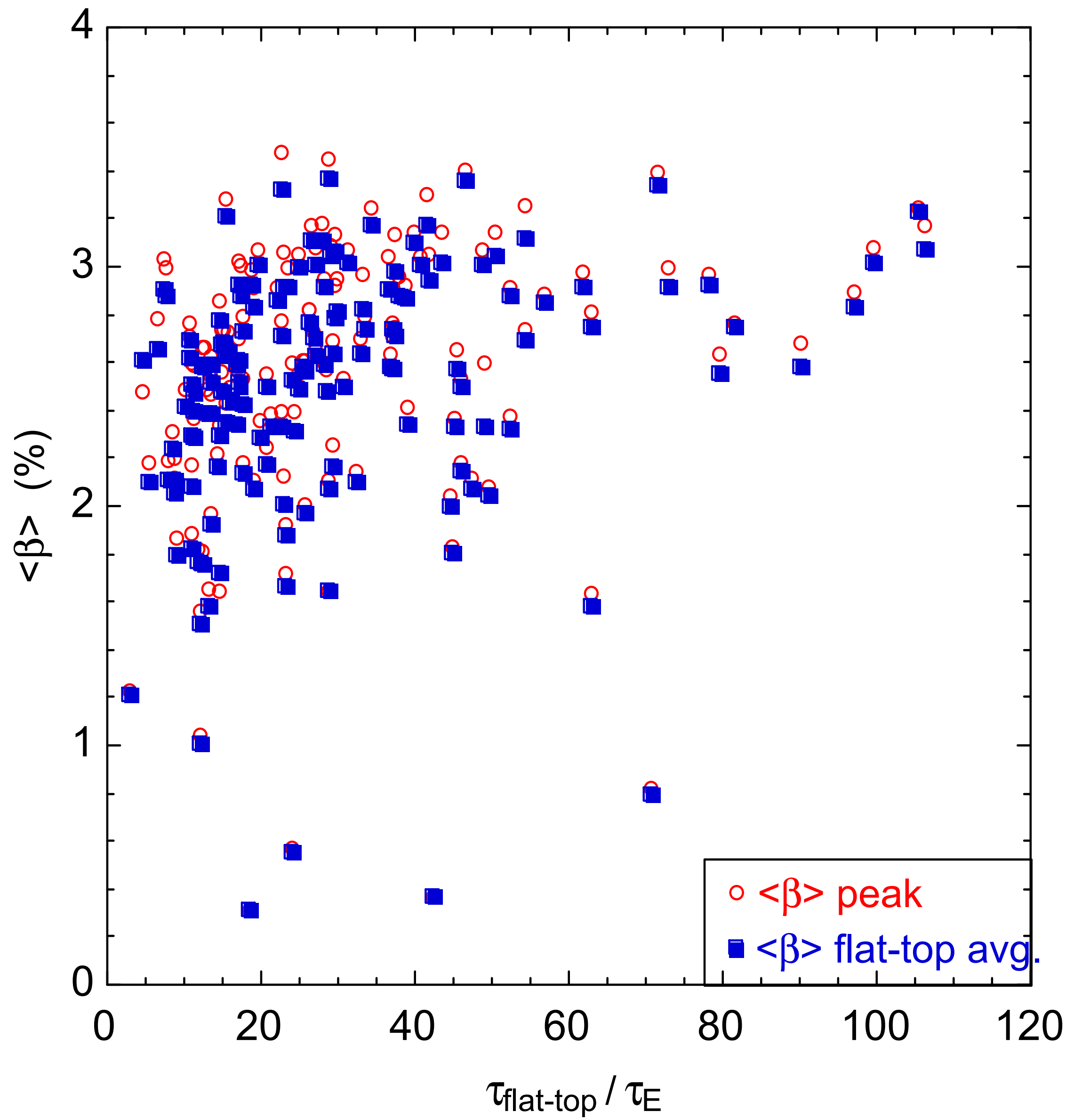
Completed operation in 2002

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



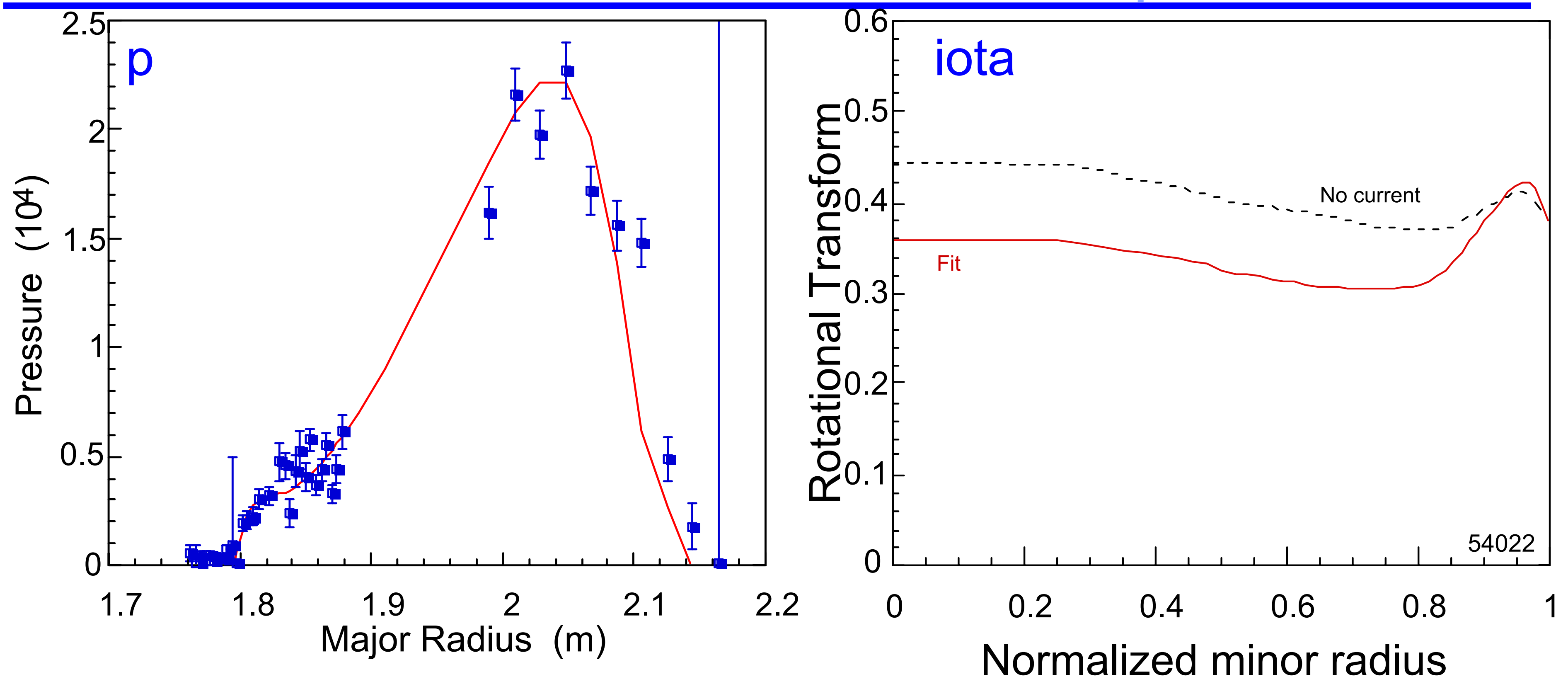
- $B = 0.9$ T, $iota_{vac} \approx 0.5$
- Almost quiescent high- β phase, MHD-activity in early medium-β phase
- In general, β not limited by any detected MHD-activity.
- $I_P = 0$, but there can be local currents
- Similar to High Density H-mode (HDH)
- Similar β>3.4% plasmas achieved with B = 0.9 – 1.1 T with either NBI-alone, or combined NBI + OXB ECH heating.
- Much higher than predicted β limit ~ 2%

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



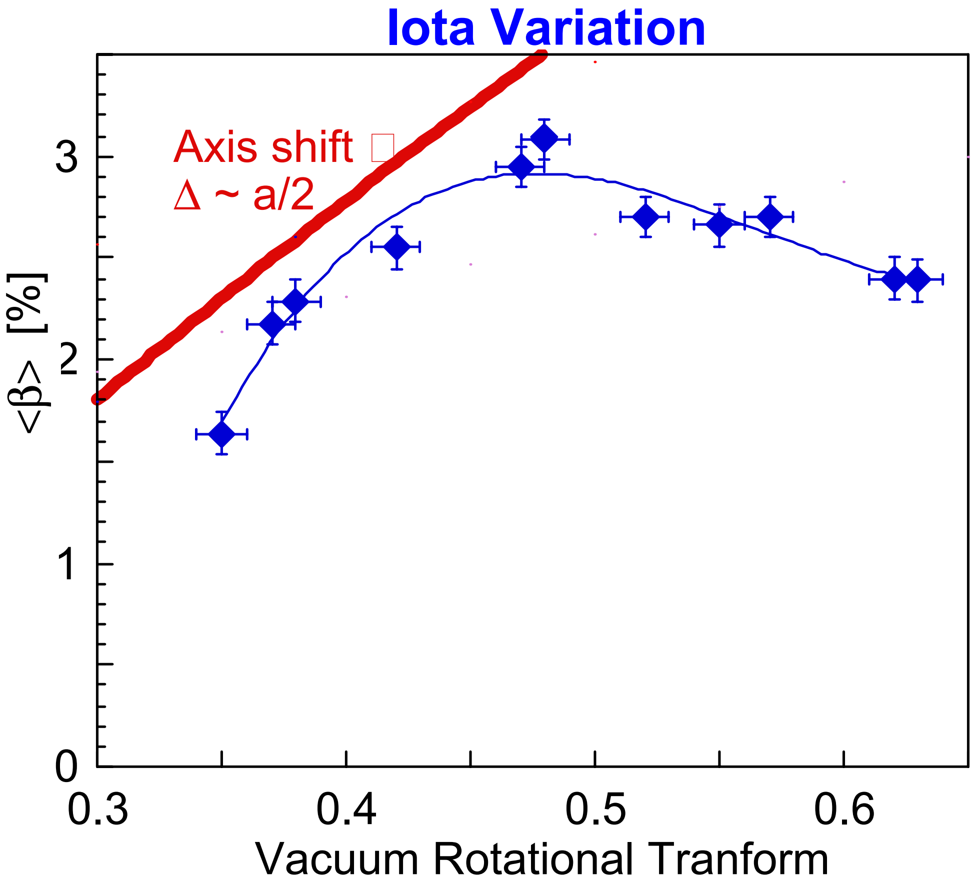
- Peak <β> = 3.5%
- High-β maintained as long as heating maintained, up to power handling limit of PFCs.
- ⟨β⟩-peak ≈ ⟨β⟩-flat-top-avg
  ⇒ very stationary plasmas
- No disruptions
- Duration and β not limited by onset of observable MHD
- What limits the observed β value?

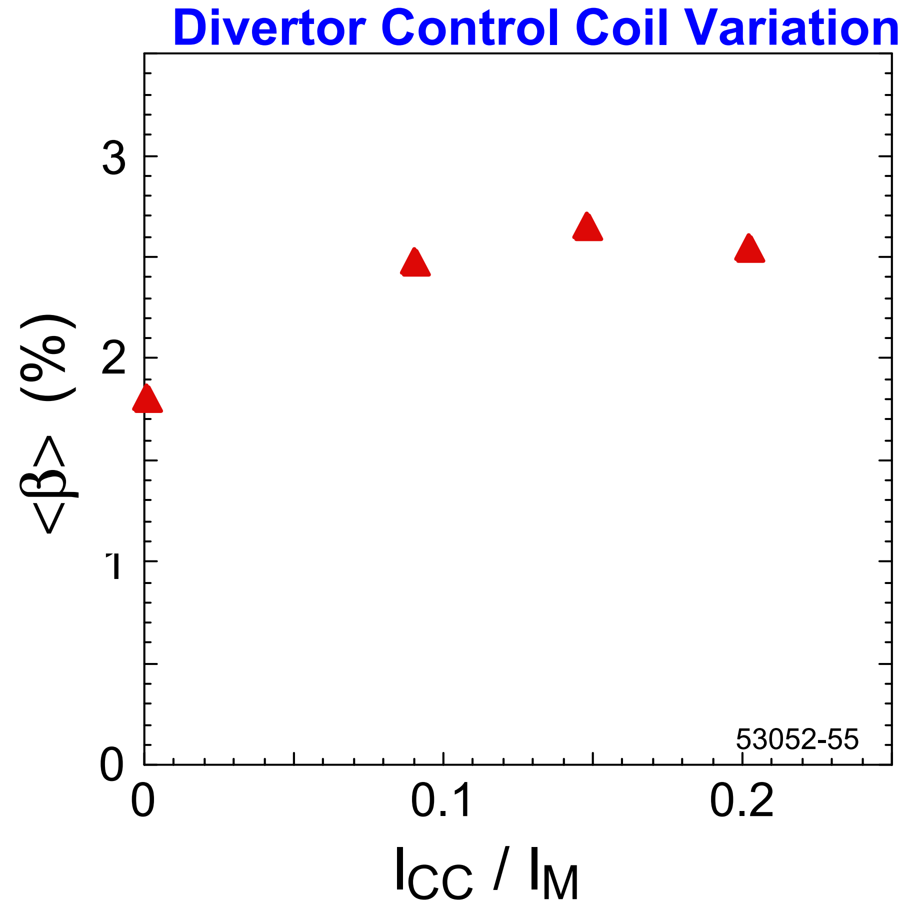
Reconstructed Self-Consistent Equilibrium



- STELLOPT/VMEC design-optimization code adapted to be a free-boundary equilibrium reconstruction code: fit p & j profiles to match measurements
- Available data:
  - 45 point single-time Thompson scattering system
  - 19 magnetic measurements
- Reconstructed equilibrium of β=3.4% plasma : lower central iota, flatter profile

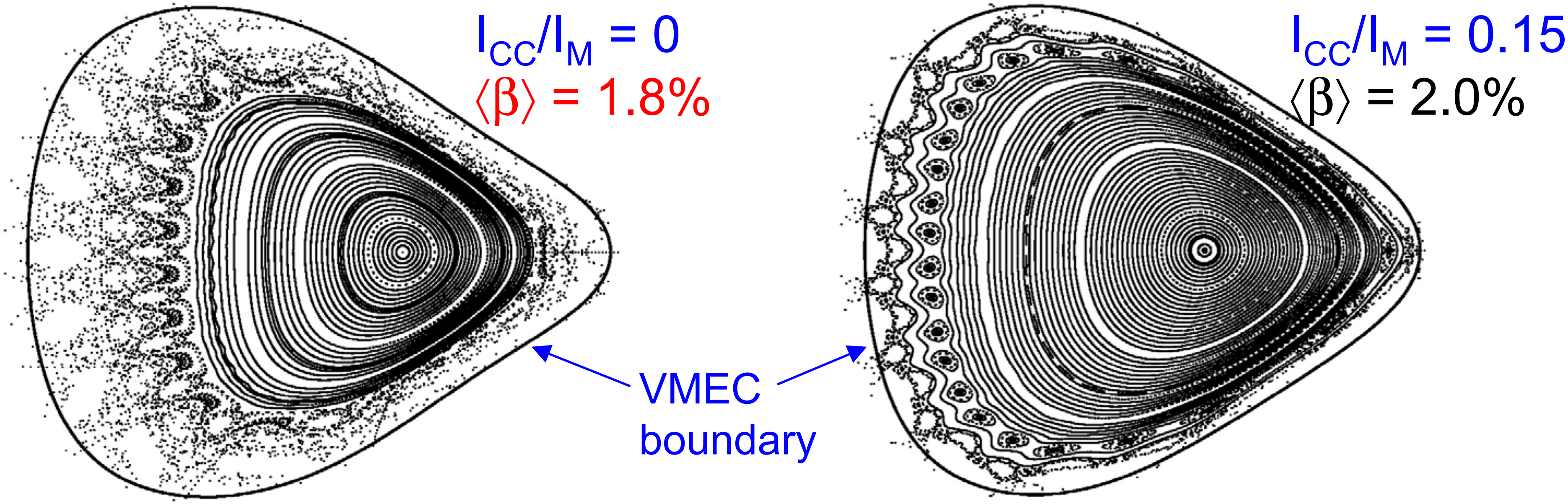
⟨β⟩ Sensitive to Equilibrium Characteristics

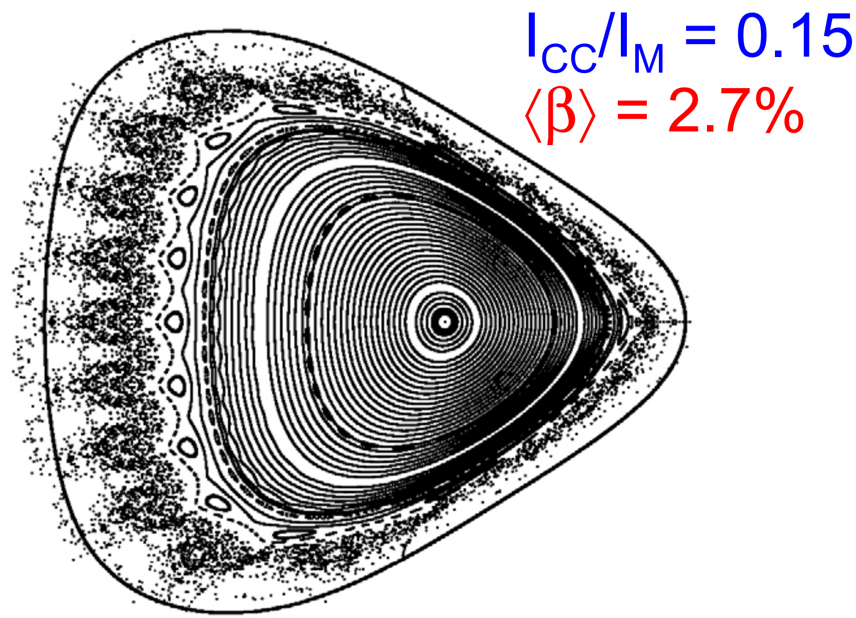




- Achieved maximum β is sensitive to iota, control coil current, vertical field, toroidal mirror depth.
- At low iota, maximum β is close to classical equilibrium limit Δ ~ a/2
- Control coil excitation does not affect iota or ripple transport
- Is β limited by an equilibrium limit?

Control Coil Variation Changes Flux Surface Topology

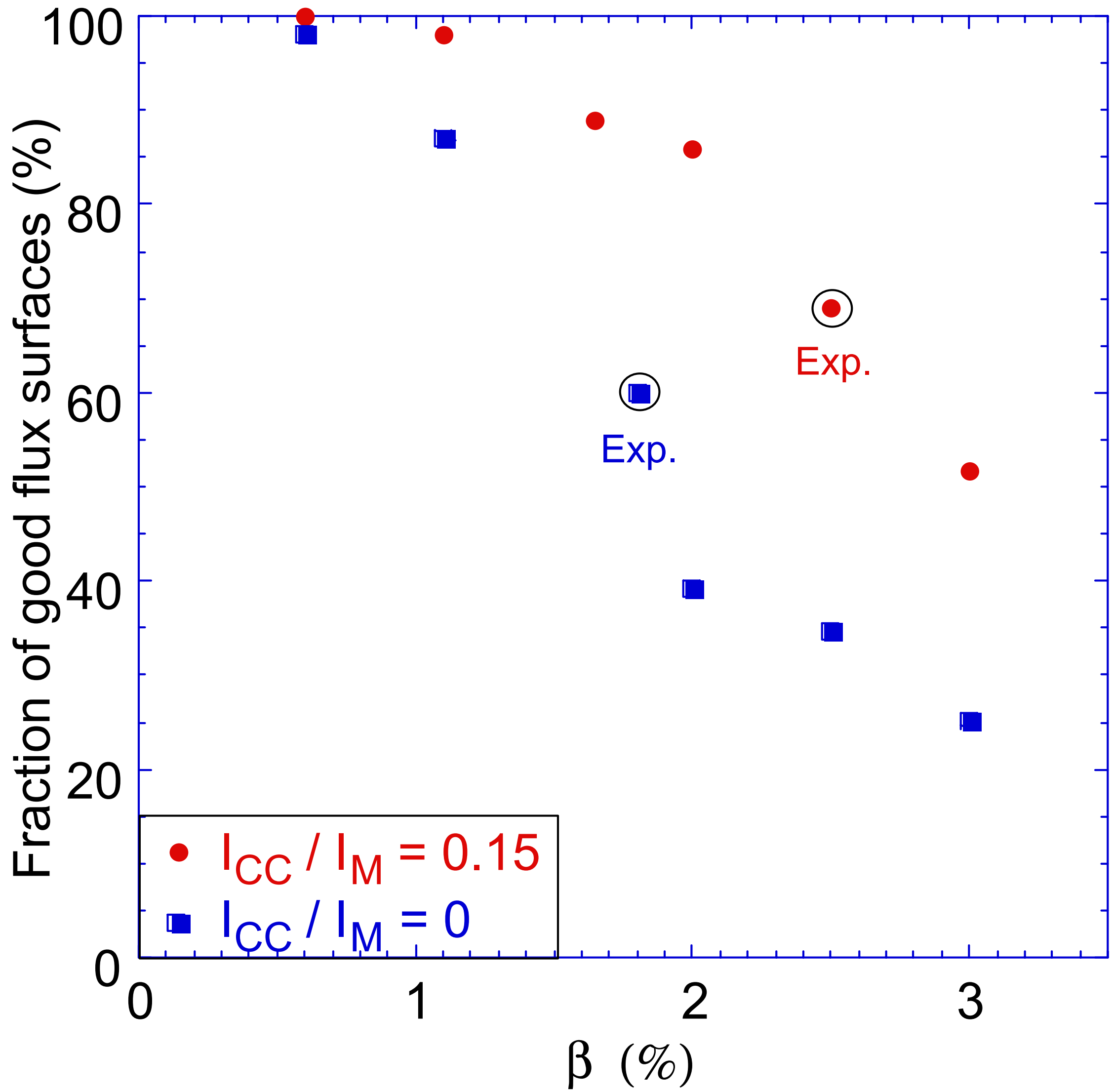




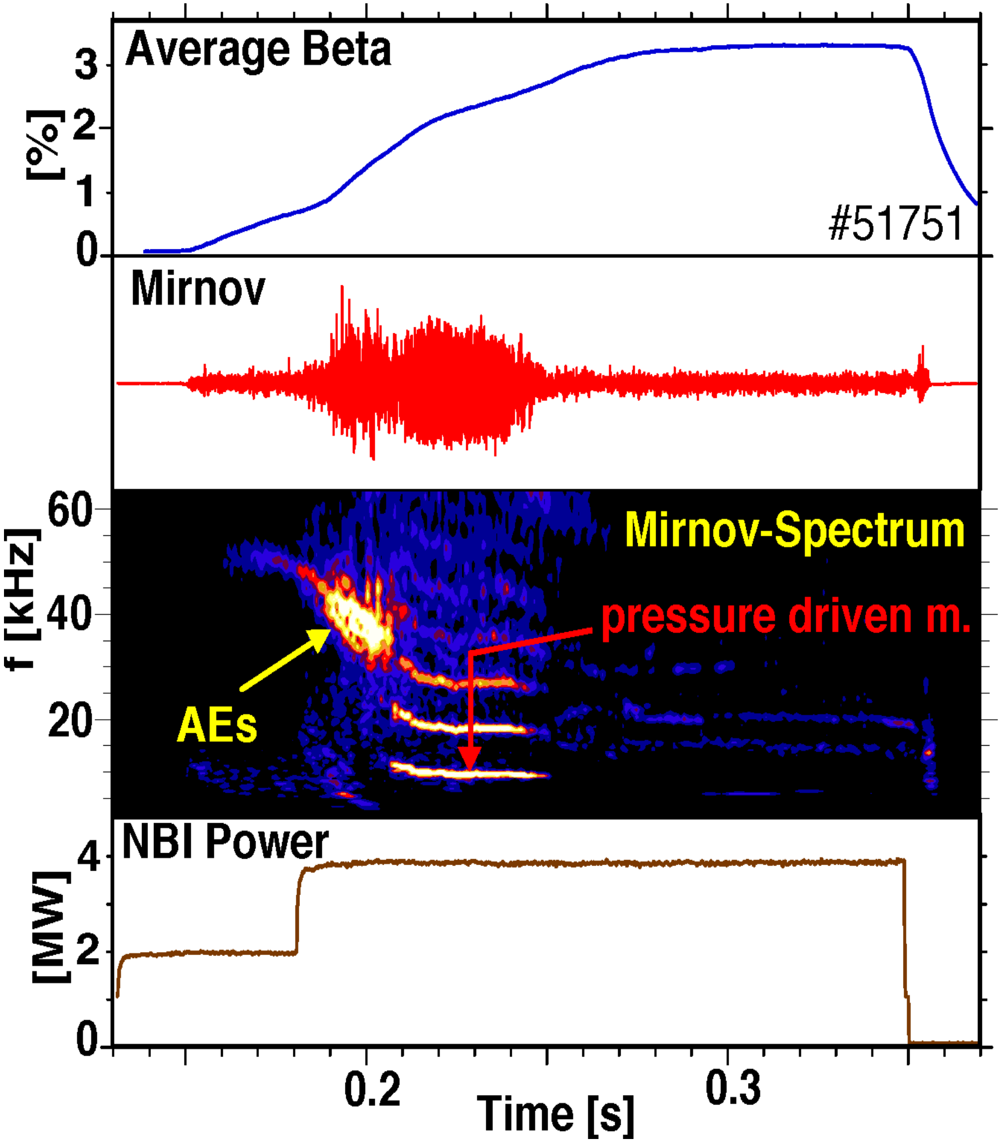
- PIES equilibrium analysis using fixed pressure profile from equilibrium fit (not yet including current profile).
- Calculation: at ~ fixed β, I_{CC}/I_M=0.15 gives better flux surfaces
- At experimental maximum β values
  -- 1.8% for I_{CC}/I_M =0
  -- 2.7% for I_{CC}/I_M = 0.15
  calculate similar flux surface degradation

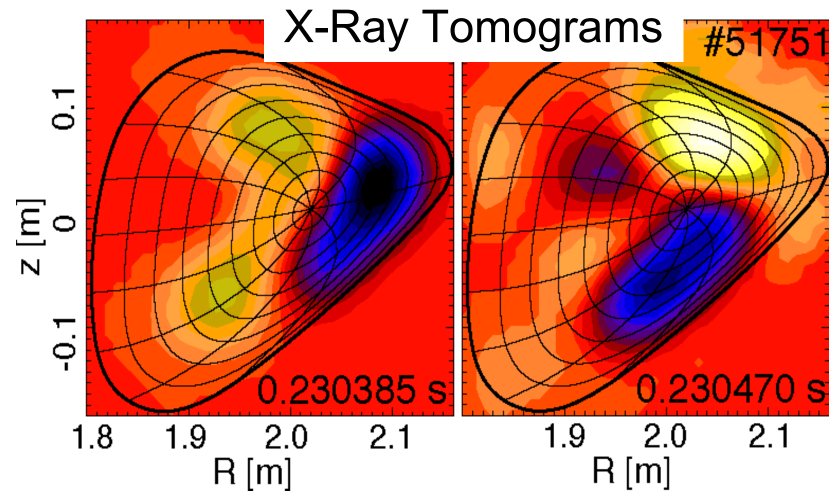
Degradation of Equilibrium May set β Limit

- 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
- Loss of flux surfaces to islands and stochastic regions should degrade confinement. May be mechanism causing variation of β.



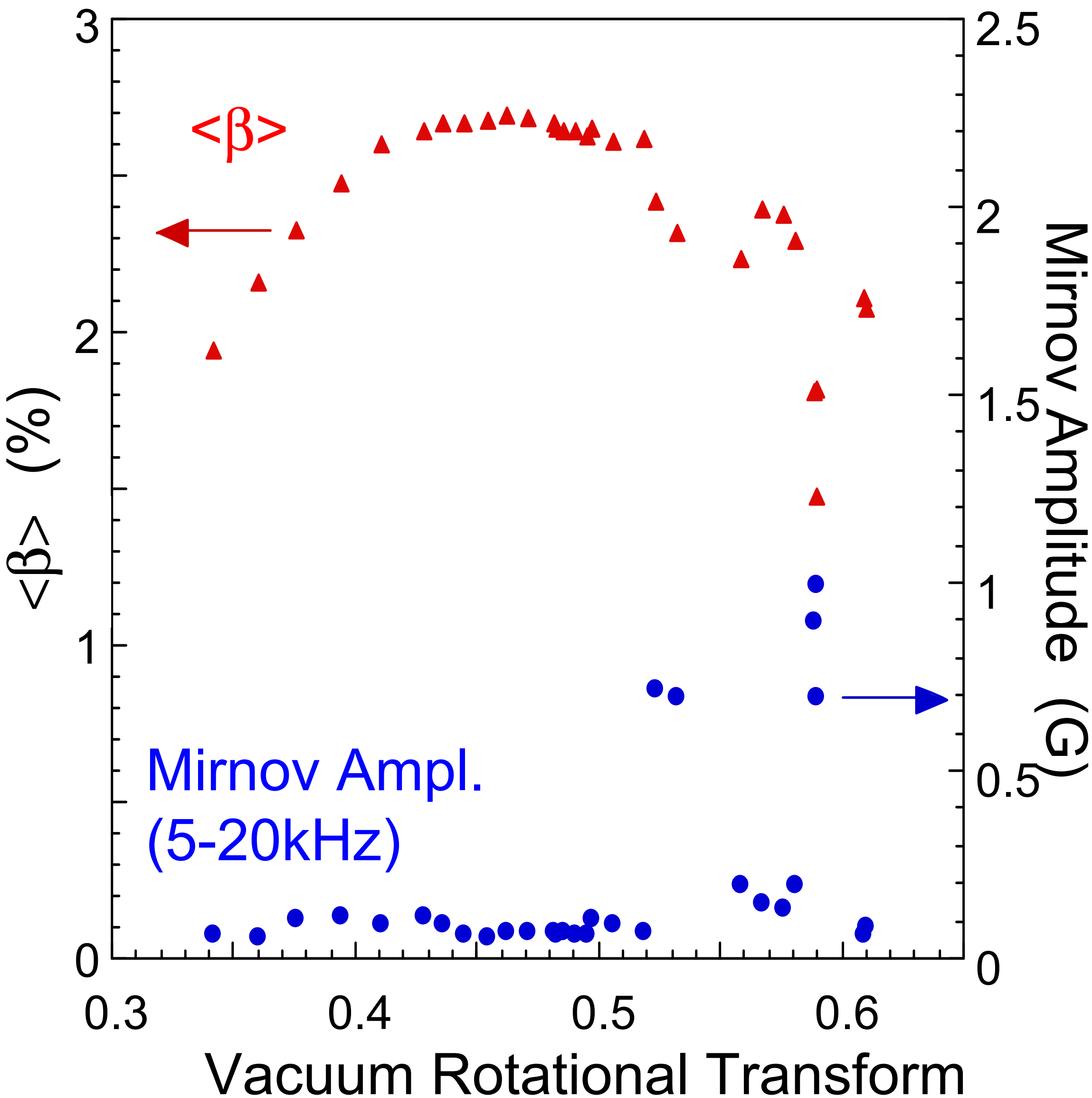
Pressure Driven Modes Observed, at Intermediate β





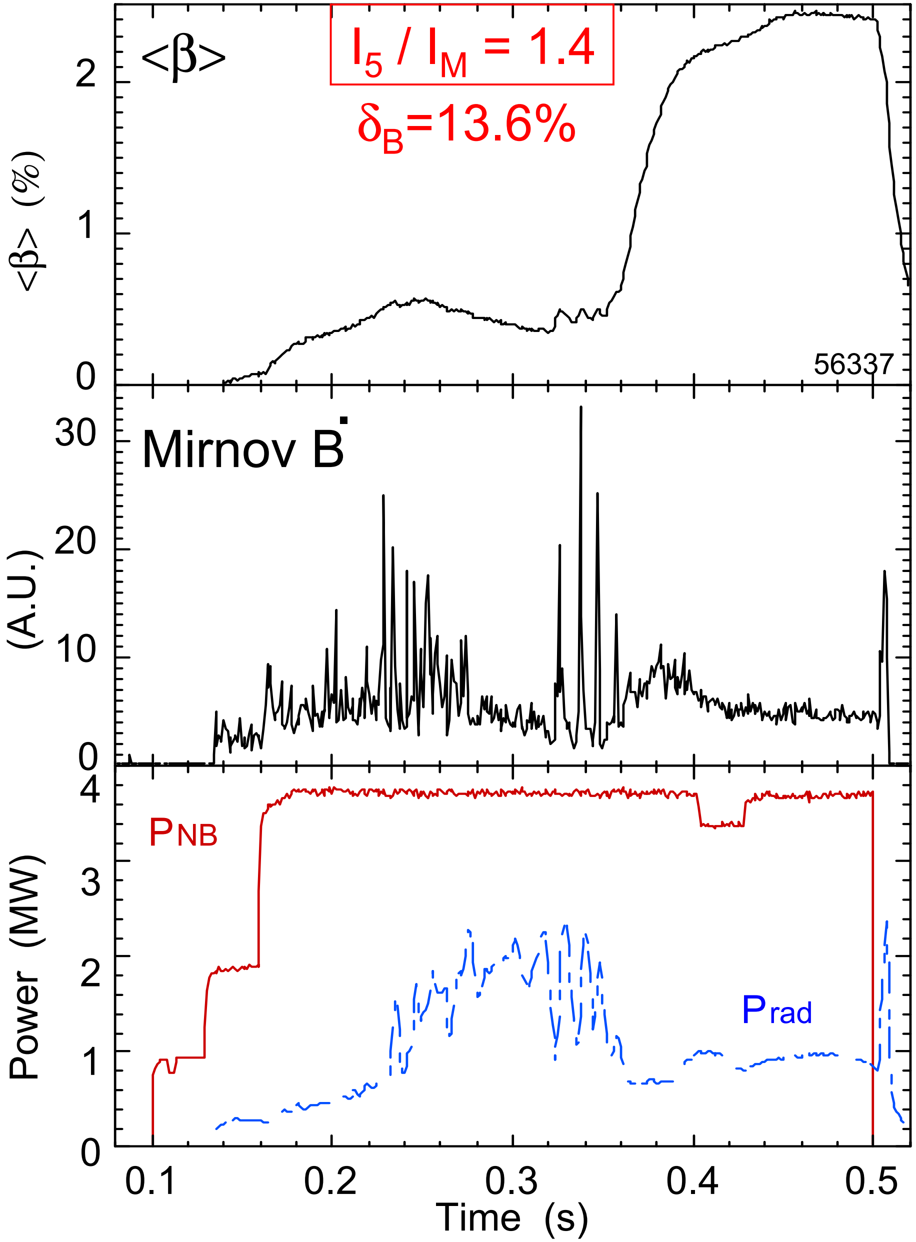
- Dominant mode m/n = 2/1.
- Modes disappear for β > 2.5% (due to inward shift of iota = ½?)
- Reasonable agreement with CAS3D and Terpsichore linear stability calcs. Predicted threshold β < 1%
- Does not inhibit access to higher β ! Linear stability threshold is not indicative of β limit.

Low-mode Number MHD Is Very Sensitive to Edge Iota



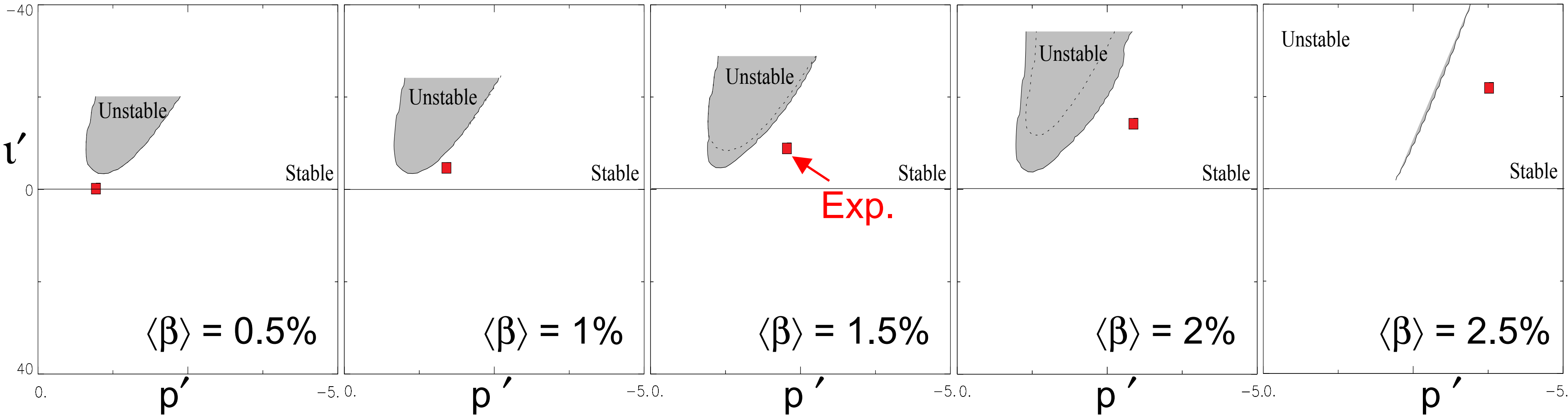
- Controlled iota scan, varying I_{TF} / I_M, fixed B, P_{NB}
- Flattop phase
- Strong MHD clearly degrades confinement
- Strong MHD activity only in narrow ranges of external iota
- Equilibrium fitting indicates strong MHD occurs when edge iota ≈ 0.5 or 0.6 (m/n=2/1 or 5/3)
- Strong MHD easily avoided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

High-n Instabilities Observed in Special Situations



- Typical high-β 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-β phase, then spontaneous transition and rise to moderate β.
- In later β > 2% phase, plasma calculated to be in ballooning 2nd stability regime.
  How does it get there?

Access to 2nd Stability: Via Stable Path



- Local stability diagrams for infinite-n ballooning evaluated using technique of Hudson and Hegna. Plots shown for r/a = 0.7

- For ⟨β⟩ > 2%, plasma is calculated to be in second regime for r/a < 0.8

- Thomson pressure profile measurement is only available for ⟨β⟩ = 1.6%. Measured pressure profile shape was scaled up/down to evaluate other ⟨β⟩ values.

∴ 2nd stability to ballooning can be accessed on stable path, due to increase of shear with β and deformation of stability boundary.

Conclusions

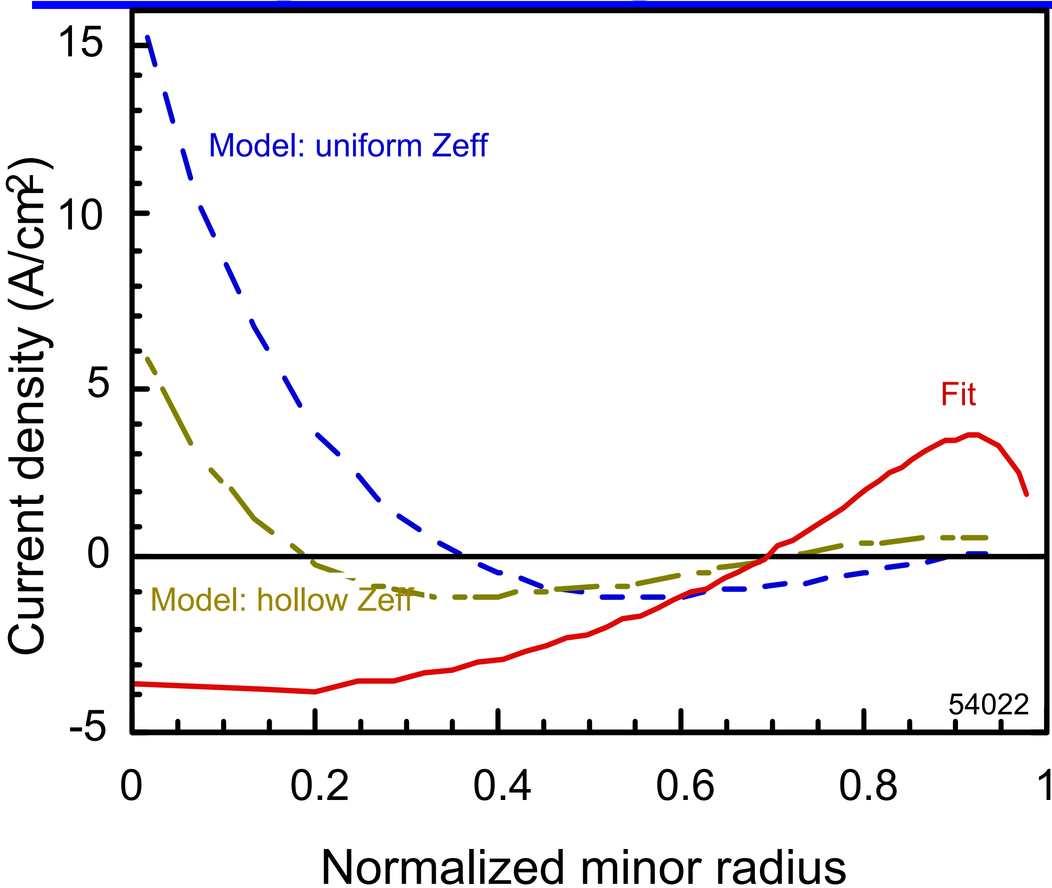
- Quasi-stationary, quiescent plasmas with $\langle\beta\rangle$ up to 3.5% produced in W7-AS for B = 0.9 – 1.1T, maintained for >100 τ_E

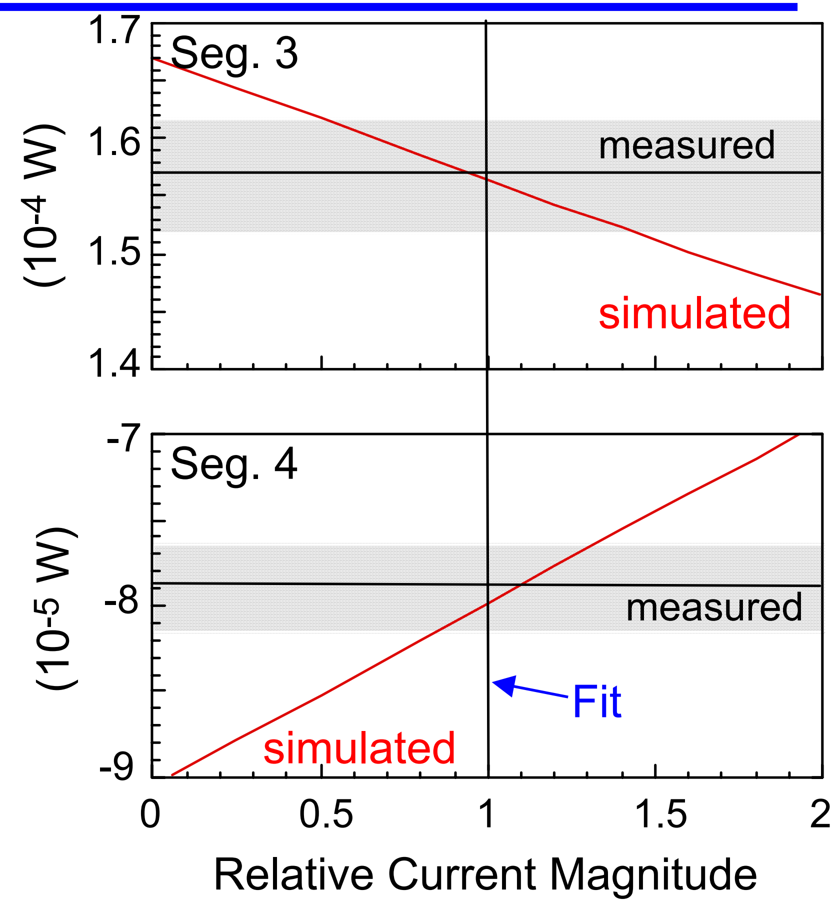
- Maximum β-value appears to be controlled by changes in confinement, not MHD activity
  - No disruptions observed
  - No stability limit observed. Maximum β not limited by MHD activity.
  - Maximum β much higher than linear stability threshold.
  - Maximum β correlated with calculated loss of ~35% of minor radius to stochastic magnetic field. May limit β.

- Pressure driven MHD activity is observed in some cases
  - Usually saturates at ~harmless level. Why?
  - Strong when edge iota ≈ 0.5 or 0.6
  - Exists in narrow range of iota ⇒ easily avoided by adjusting coil currents.

- In increased mirror-ratio plasmas, calculations indicate second-stability for ballooning modes can be accessed via a stable path due to the evolution of the shear and stability boundary.

Magnetic Diagnostics are Sensitive to Current





- Small, but significant current inferred from equilibrium fit. Estimated uncertainty of magnitude approx. ± 20% from Rogowski segments
- Three moments used to fit current profile, higher order moments used to force j(a)=0
- Fitted current is larger (in outer region) than model calculations of net current from beam + bootstrap + compensating Ohmic currents.