Comparisons of Stability and Transport between Stellarators and Tokamaks

Discussion

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1 March 2005

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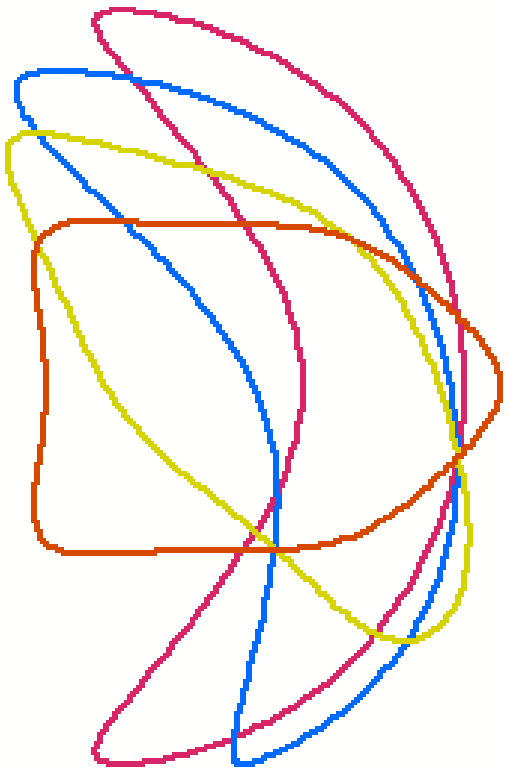
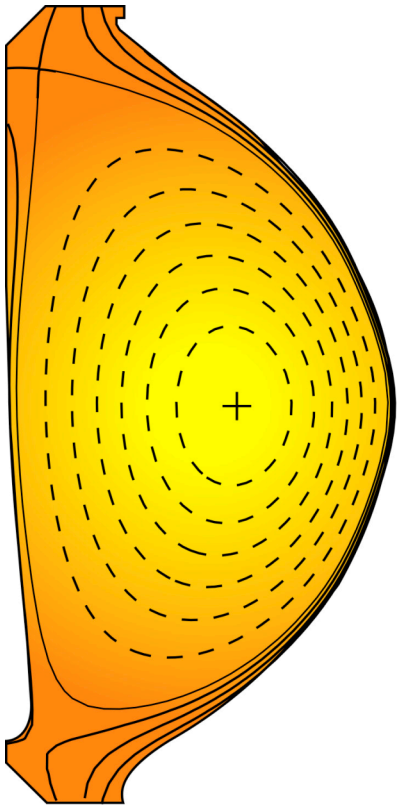
Stellarators & Tokamaks: Key characteristics





- Both: toroidal toroidal magnetic confinement configurations,
- Tokamaks: Axisymmetric Stellarators: fully 3D shaped

Stellarators & Tokamaks: Key characteristics

- Tokamaks: Rotational transform (iota = 1/q) or Bp produced by plasma toroidal current

→ Control q-profile & shear via current

→ Sustain configuration using external current drive, & high-bootstrap currents

- Stellarators: Most or all of the rotational transform due to 3D shape, *not* plasma current

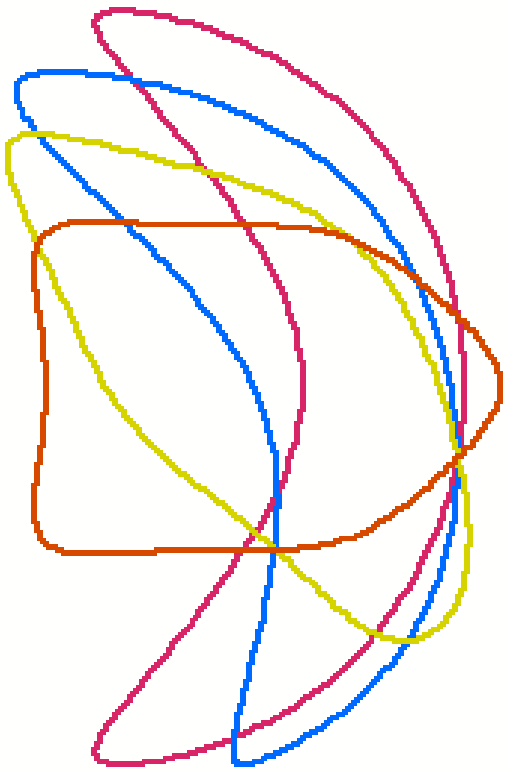
→ Control magnetic rotational transform & shear from external coils

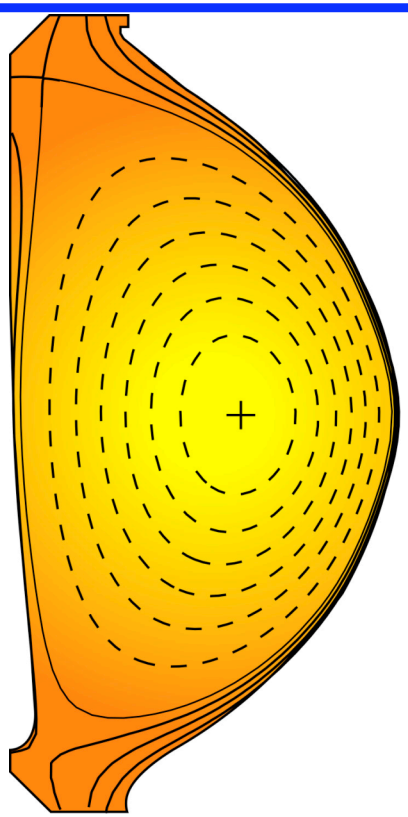
→ No need for current drive to sustain configuration. Naturally compatible with steady state.

- Stellarators are typically disruption free

Equilibrium is not lost due to changes in pressure or current.

Stellarators & Tokamaks: design flexibility



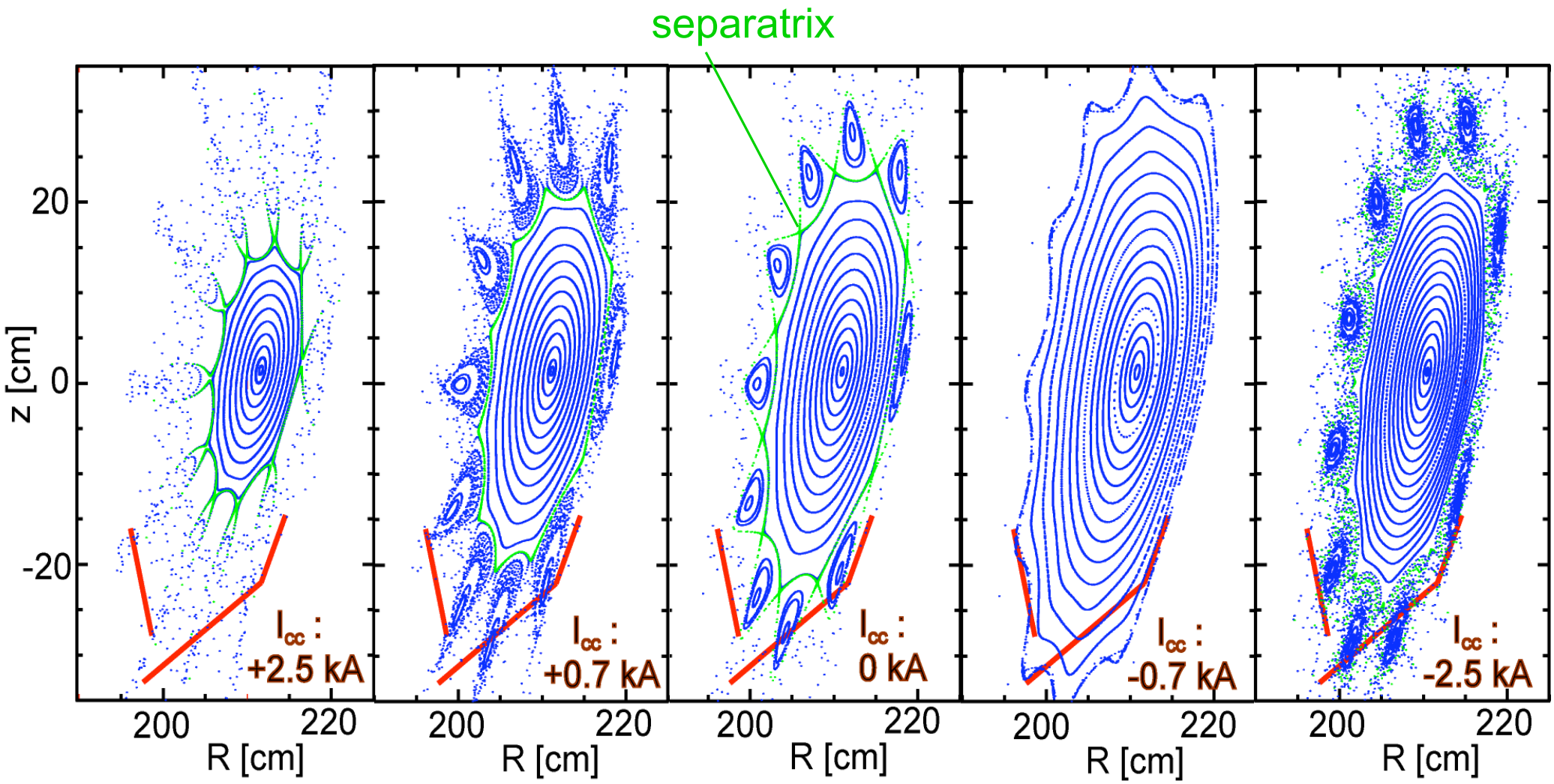


- Tokamaks: ~4 shape parameters for design
- Stellarators: ~40 shape parameters

→ Can control more aspects of physics in stellarator design (e.g. reversed shear, higher stability limits)

→ Lack of symmetry direction => must design more aspects of physics in stellarators

Stellarator Flux Surfaces May Be Open Sensitive to Resonant Perturbations



- W7-AS control coil current scan, vacuum
- Stellarators have vacuum flux surfaces
- Similar sensitivity in tokamaks, but no vacuum equilibrium
- Use trim coils in both configurations to control field-error effects

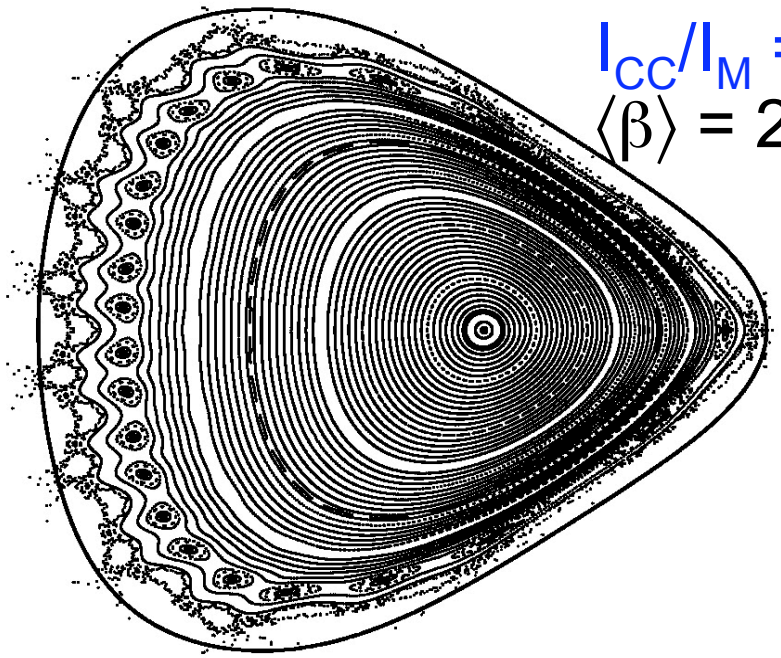
Stellarator Flux Surface Topology Can change with Plasma Pressure

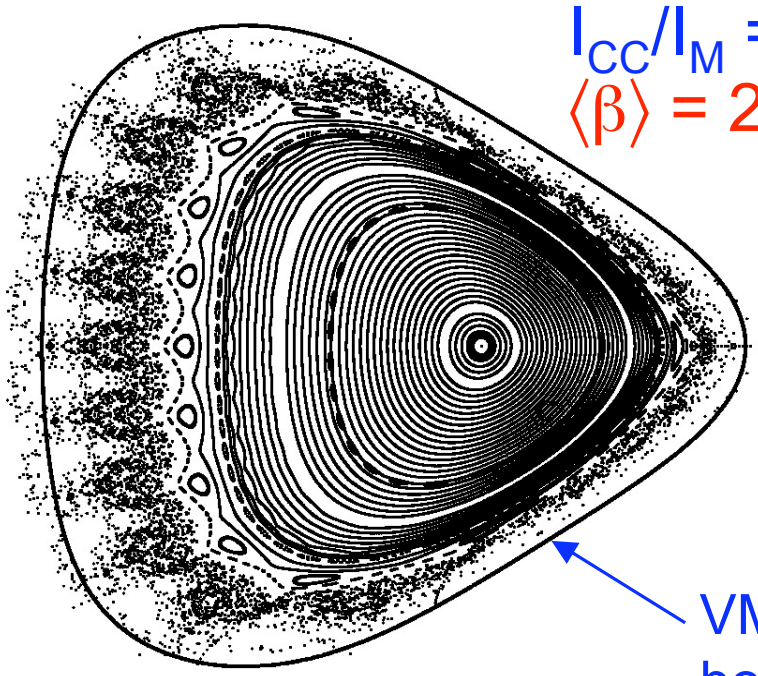
- Plasma-pressure generated currents (diamagnetic, Pfirsch-Schluter, bootstrap) can produce resonant perturbations, changing flux surface topology

- Similar to effect of pressure-generated currents on tokamak equilibrium shape, including equilibrium limits. Tokamak only has n=0.

- Change in topology can modify plasma confinement and pressure profile

- Theoretically, finite plasma equilibrium islands have the same physics as NTMs in tokamaks, just Ω=0.



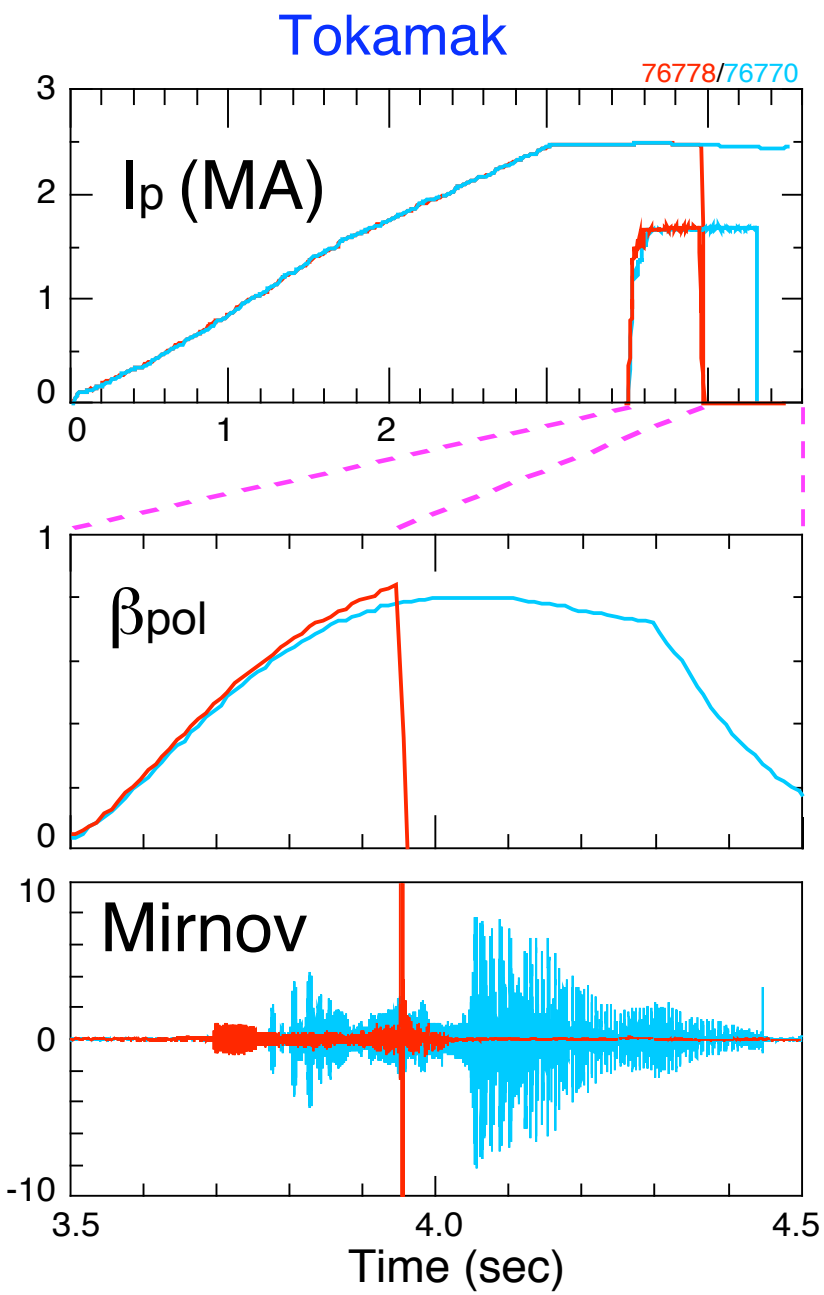


Tokamak Operating Limits Set by Instabilities

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

- Density limits, q-limits also given by instabilities

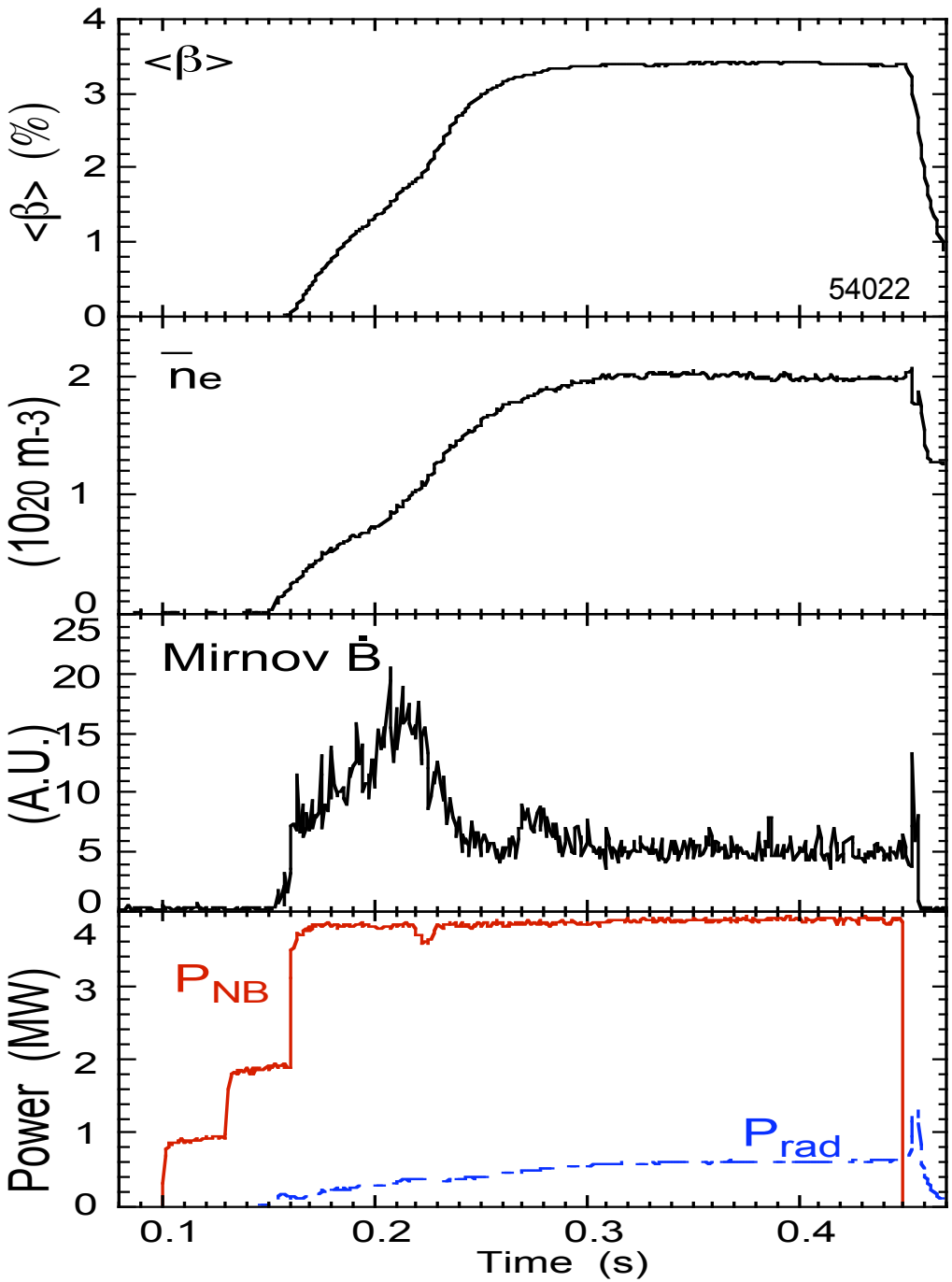
- Also see NTM saturation of confinement; fish-bones, etc.



n = 1

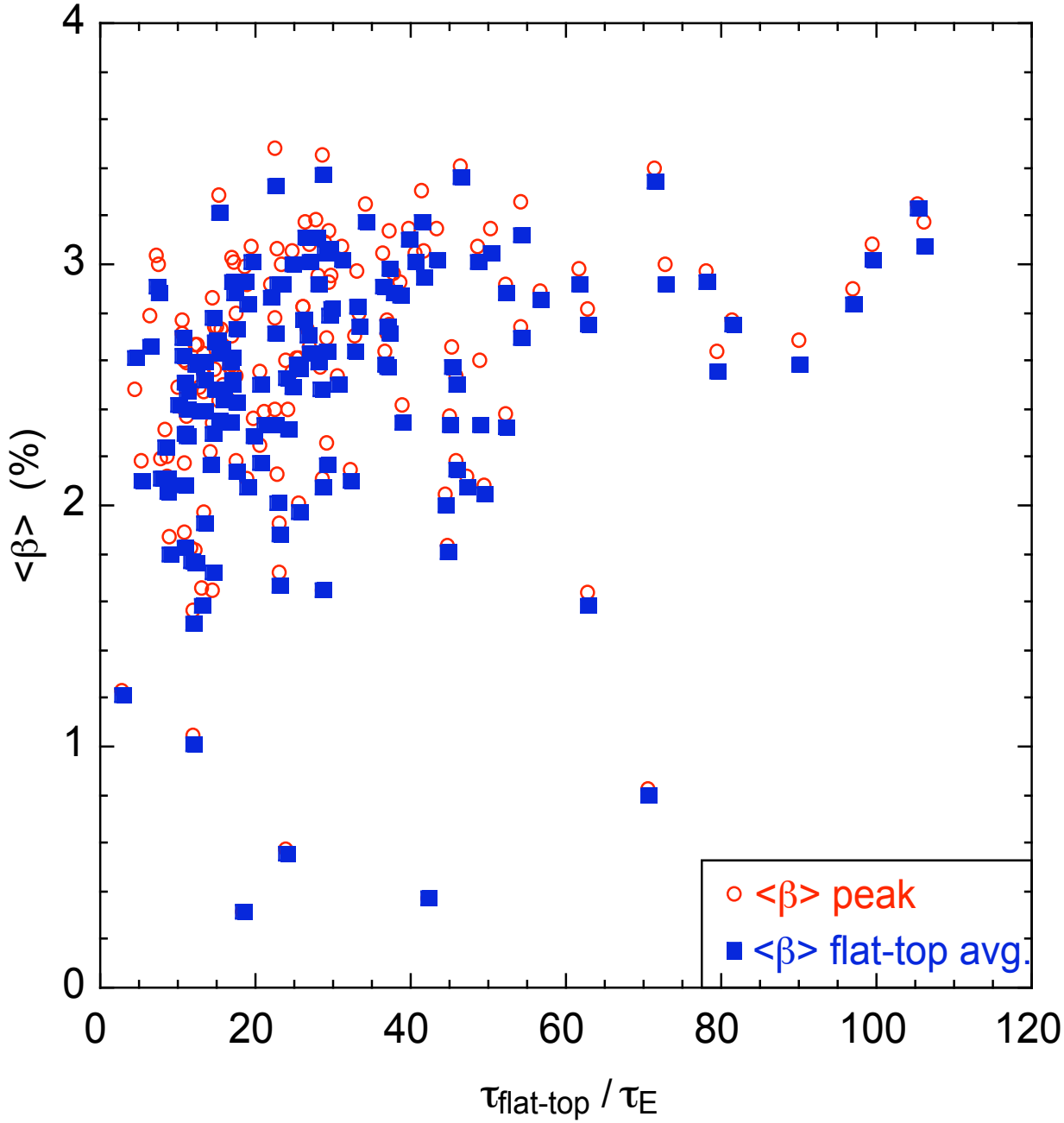
TFTR
E. Fredrickson

W7AS: $\langle\beta\rangle \approx 3.4$ % : 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%

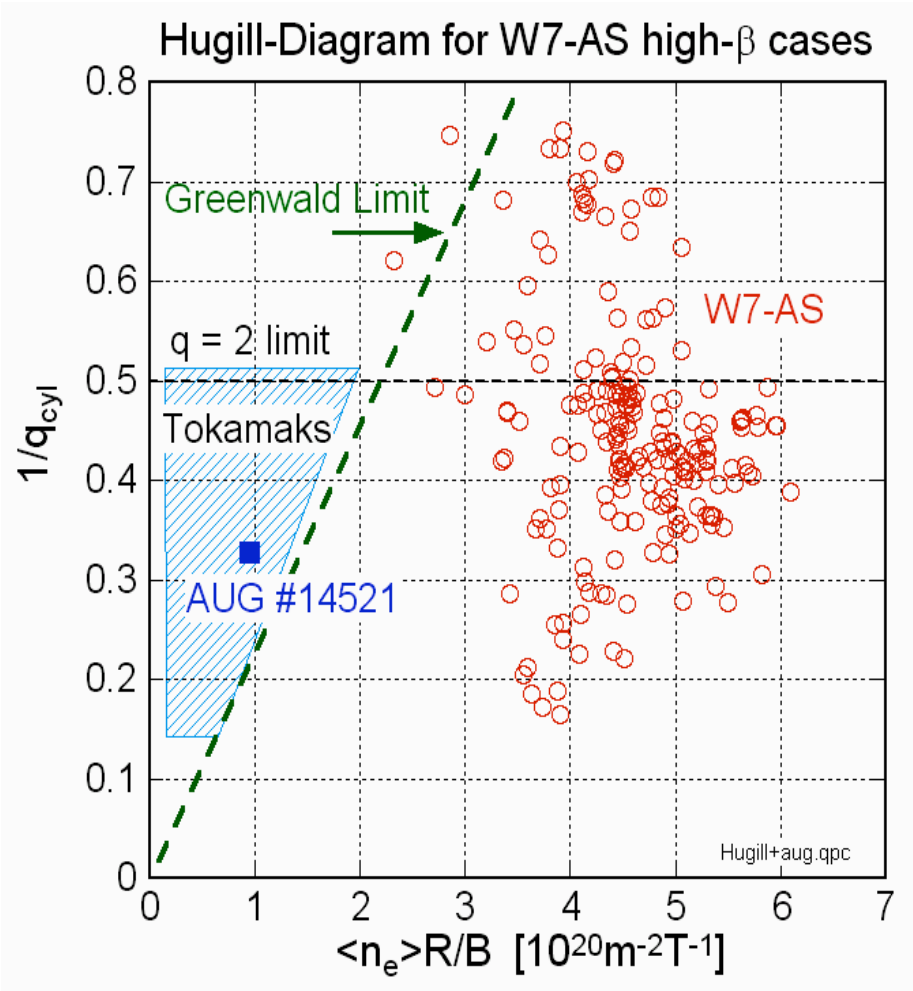
W7-AS: $\langle\beta\rangle$ > 3.2% maintained for > 100 τ_E

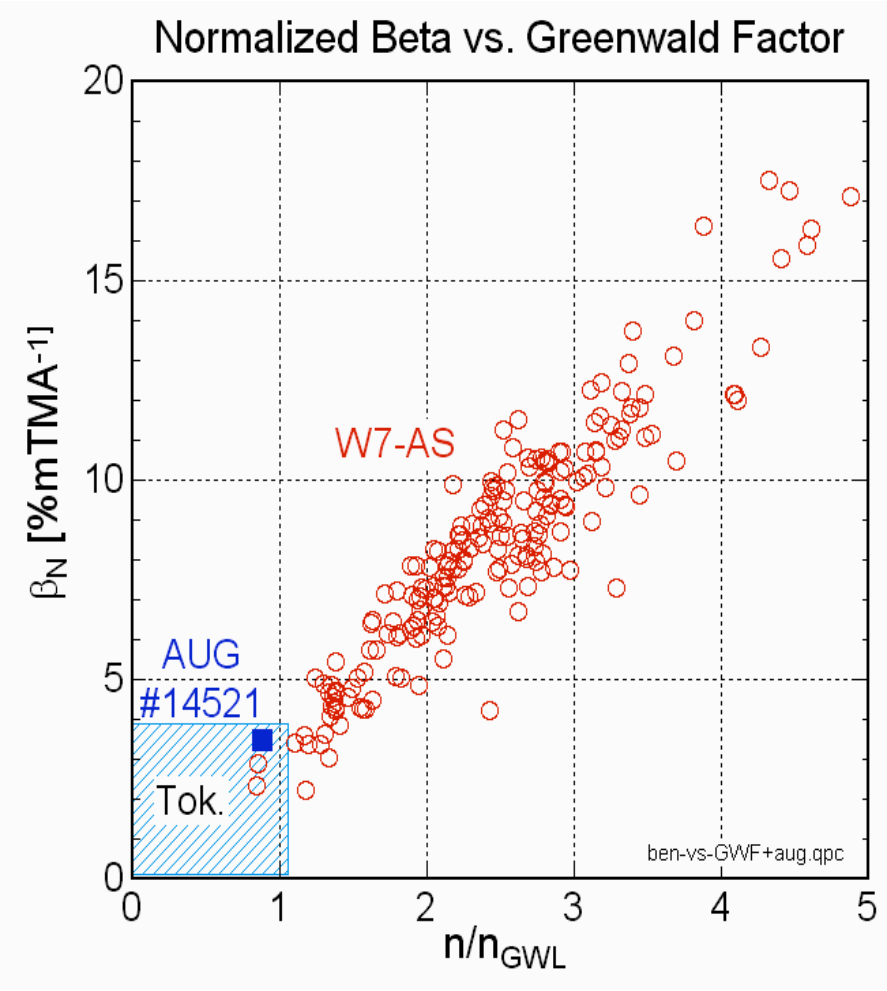


- Peak <β> = 3.5%
- High-β maintained as long as heating maintained, up to power handling limit of PFCs.
- $\langle\beta\rangle$-peak ≈ $\langle\beta\rangle$-flat-top-avg ⇒ very stationary plasmas
- No disruptions
- **Duration and β not limited by onset of observable MHD**

What limits the observed β value?

W7-AS Operating Range much larger than Tokamaks





- Using equivalent toroidal current that produces same edge iota
- Limits not due to MHD instabilities. Density limited by radiative recombination
- High-β is reached with high density (favourable density scaling in W7-AS)
- Almost all **W7-AS** high-β data points beyond operational limits of tokamaks
- High density favorable for divertor; control of fast-particle instabilties

MHD Activity is Sometimes Observed

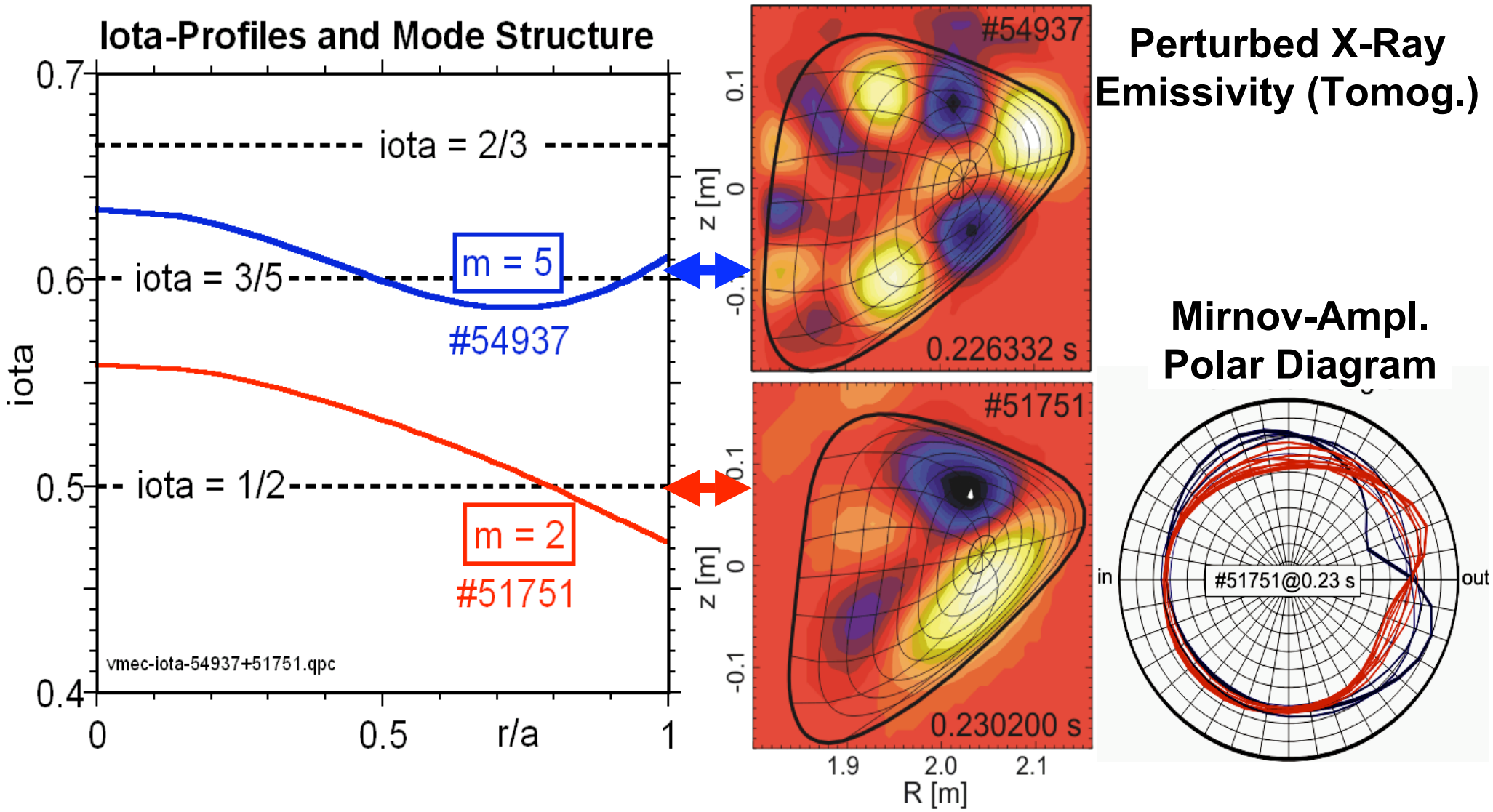
- m=2, n=1 pressure driven modes.
  Sometimes also m=3 or 5
  Does not strongly affect confinement (usually)

- 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

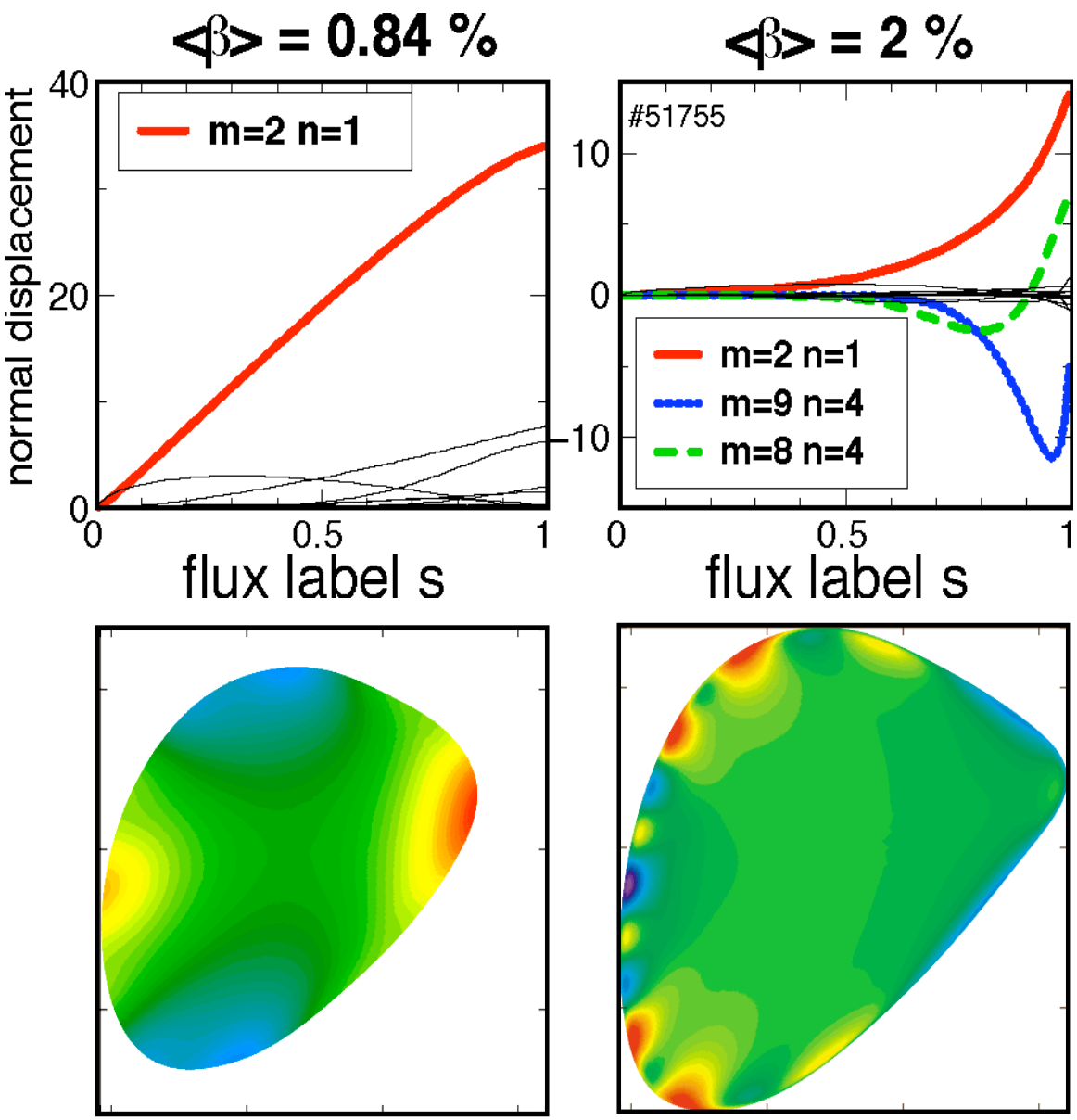
Observed Mode Structure Corresponds to Near-Edge Iota (VMEC)

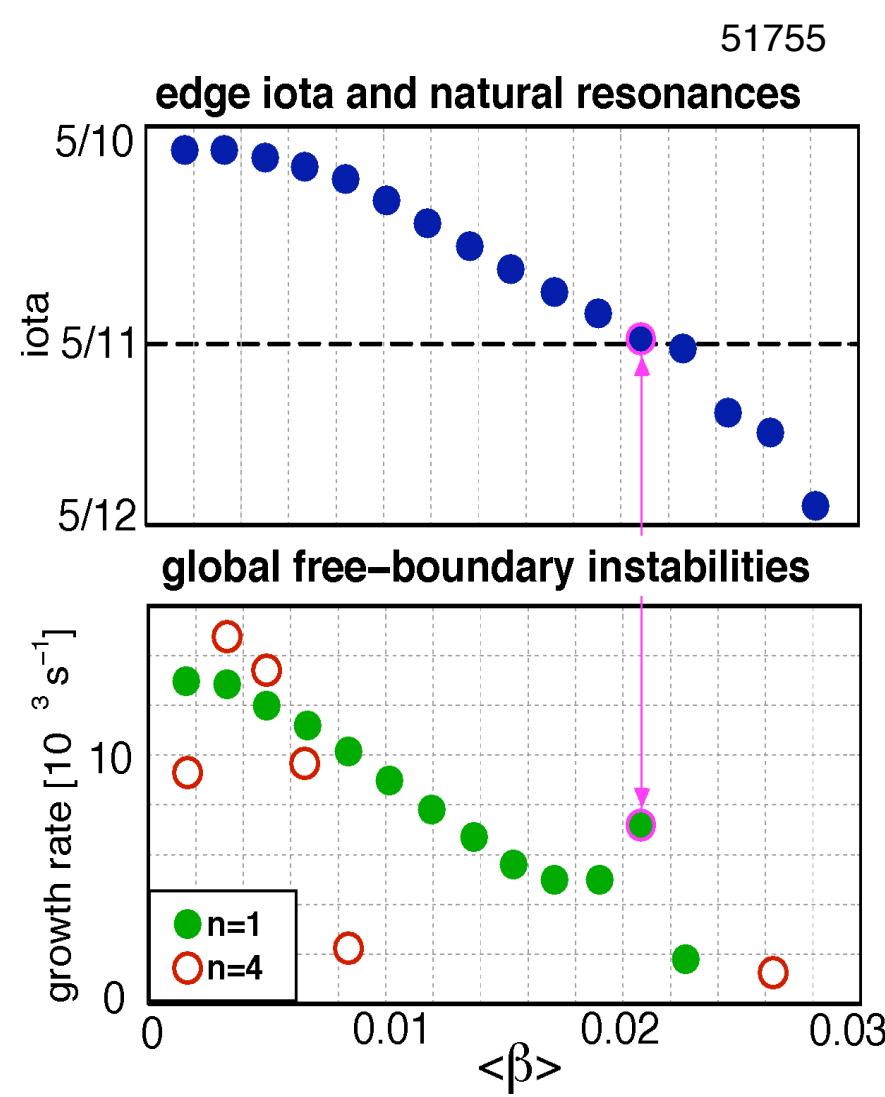


- In both cases, MHD observed transiently during pressure rise. Edge iota drops as β increases, due to equilibrium deformation.
- Strong ballooning effect at outboard side in X-ray and magnetic data

Linear Stability Calculations (CAS3D) Indicate 2/1 Should be Unstable

Mode Displacement & Perturbed Pressure

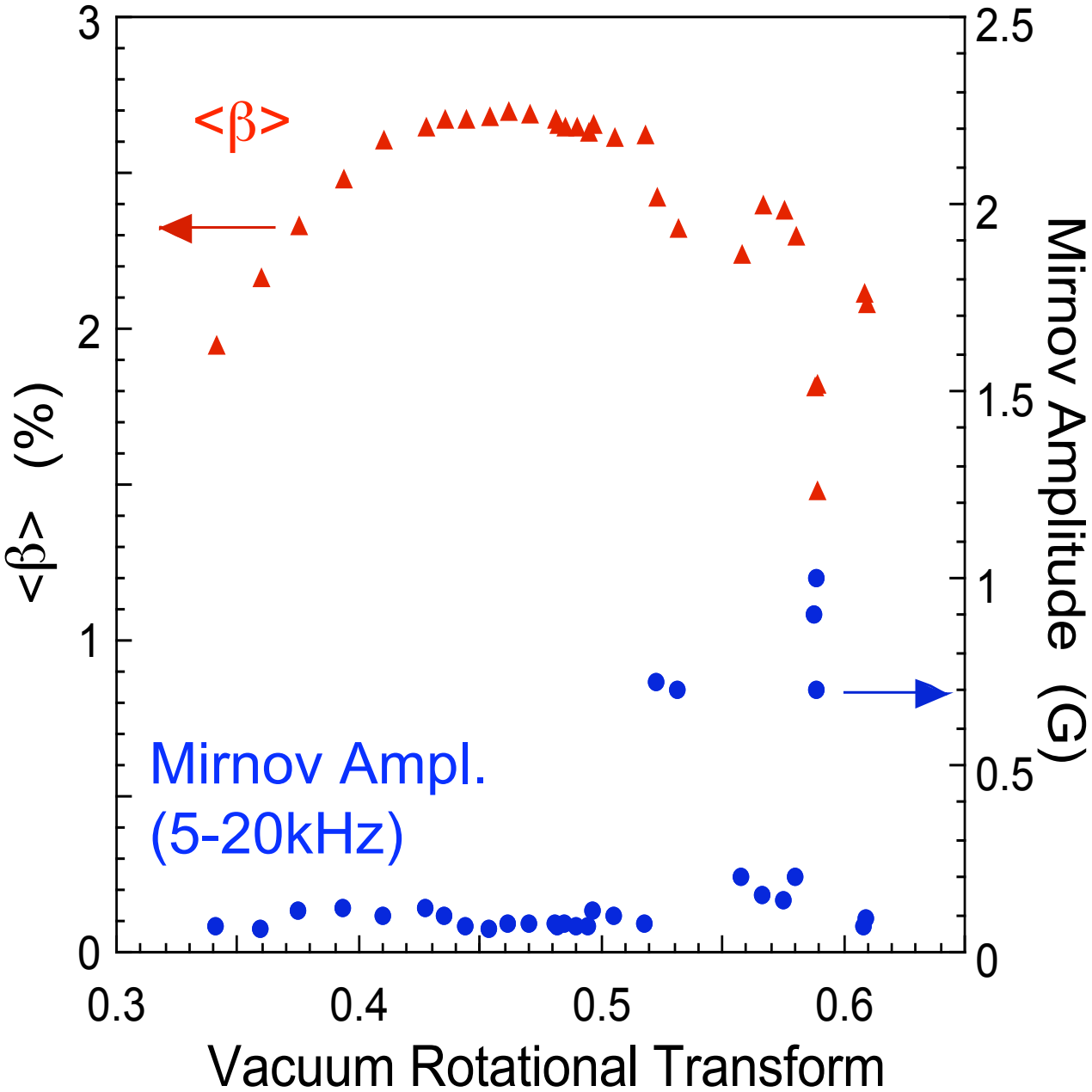




External global modes, most unstable at low β

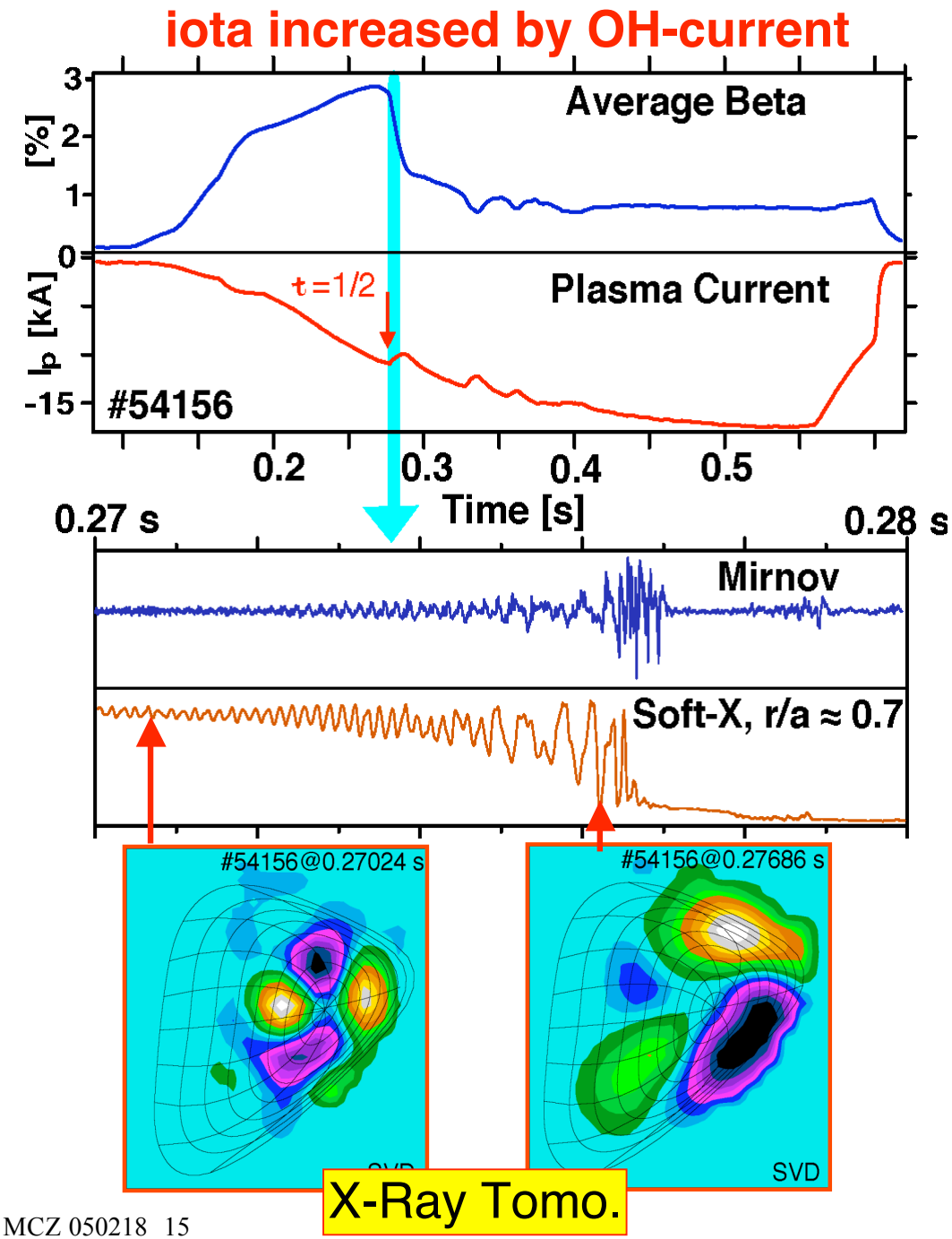
– C. Nuhrenberg

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



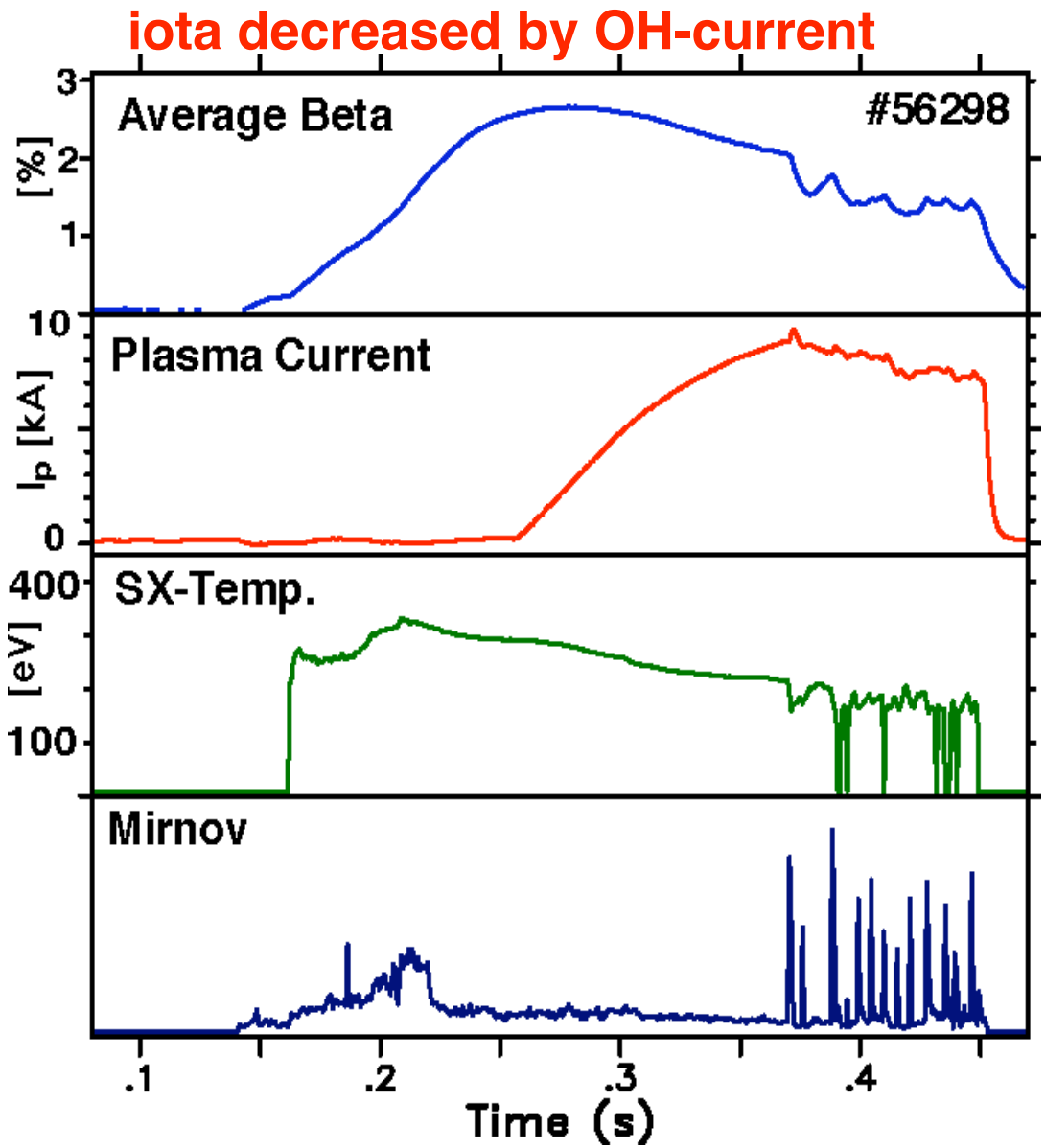
- Controlled iota scan, varying I_{TF} / I_M, fixed B, P_{NB}
- Flattop phase
- Strong MHD clearly degrades confinement
- Strong MHD activity only in narrow ranges of external iota
- Equilibrium fitting indicates strong MHD occurs when edge iota ≈ 0.5 or 0.6 (m/n=2/1 or 5/3)
- Strong MHD easily avoided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

Significant I_P<0 makes Tearing Modes at iota=1/2



- $I_P < 0$ increases iota, increases tokamak-like shear
- Iota and shear increase, improves confinement and β
- When iota=1/2 crossed near edge $\Rightarrow$ tearing mode triggered

Significant I_P>0 appears Tearing-stable

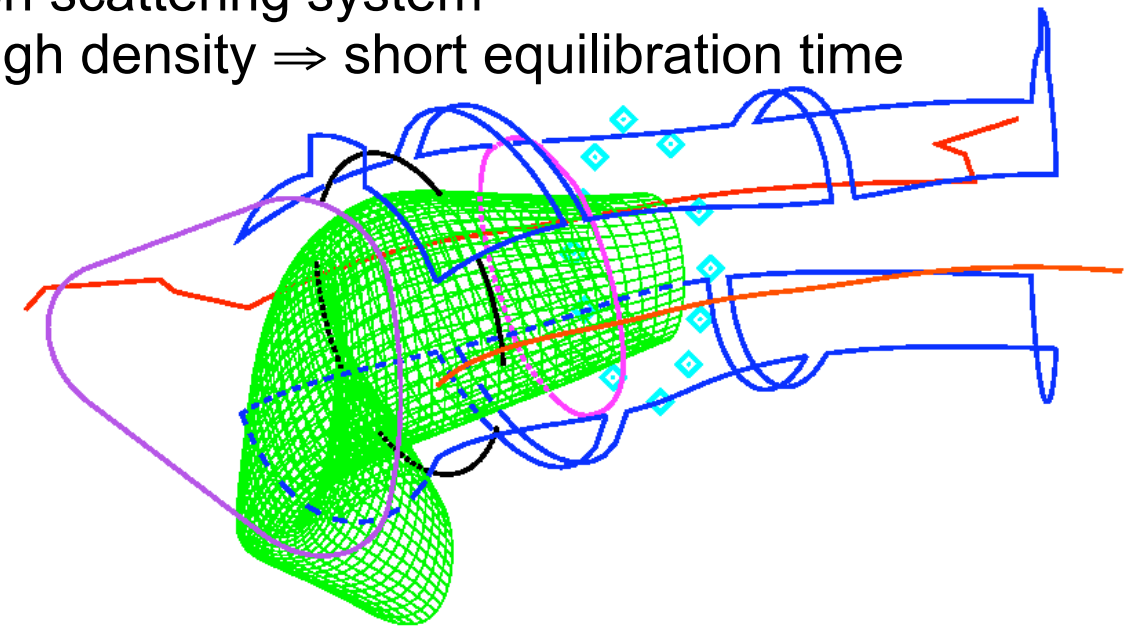


- $I_P > 0$ decreases iota, reduces tokamak-like shear, makes flat or reversed shear
- Iota and shear decrease reduces confinement and β
- No tearing modes observed for $I_P > 0$, even when crossing iota=1/2 or 1/3 ! Possibly indicating neoclassical-tearing stabilization
- As T_e drops < 200eV, see high-mode number MHD activity. "Low T_e instability"

Equilibrium Reconstruction Required

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

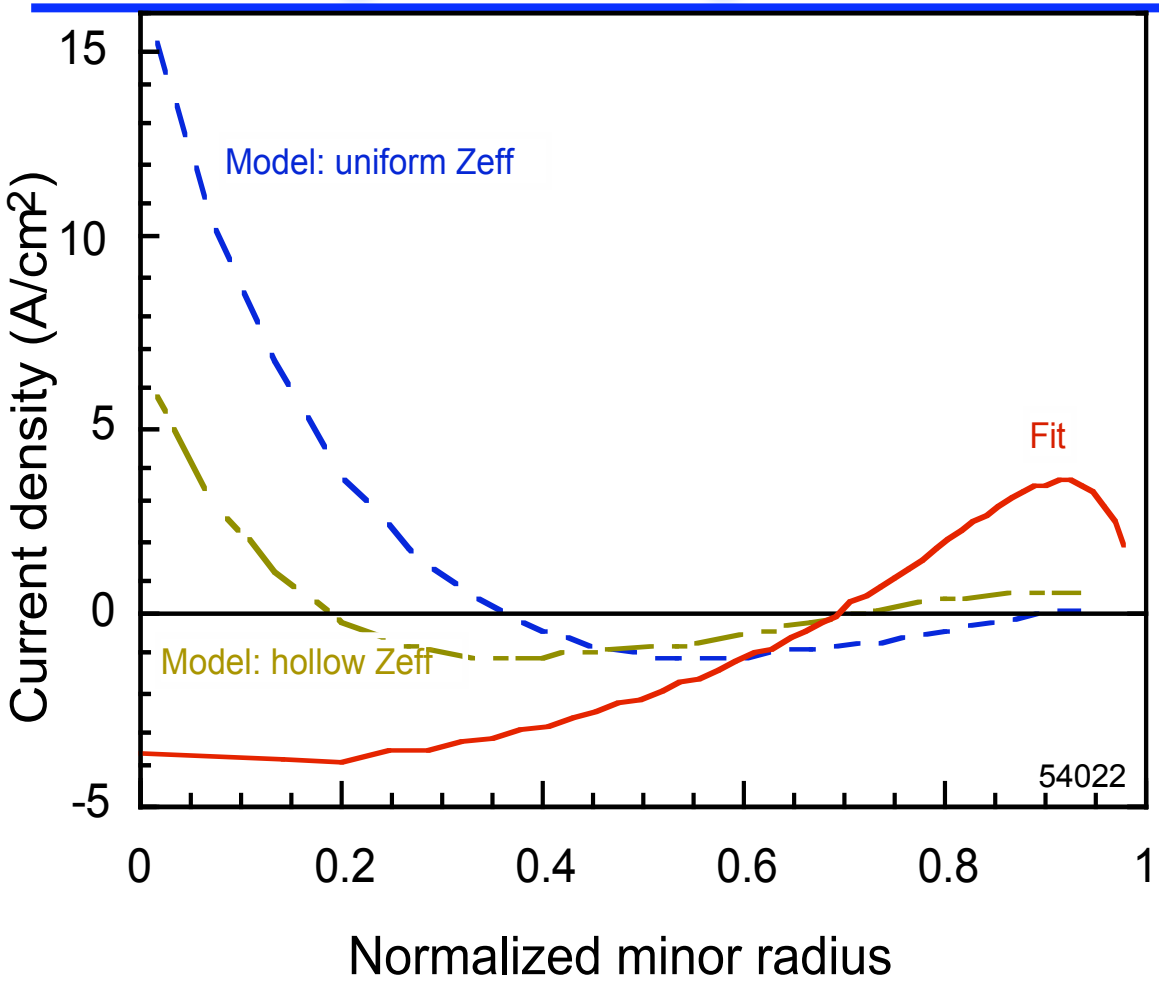
- Available data:
  - 45 point single-time Thompson scattering system
    assume $p_i = p_e$, due to very high density ⇒ short equilibration time
  - 19 magnetic measurements,
    including:
    segmented Rogowski,
    flux loops,
    diamagnetic loops

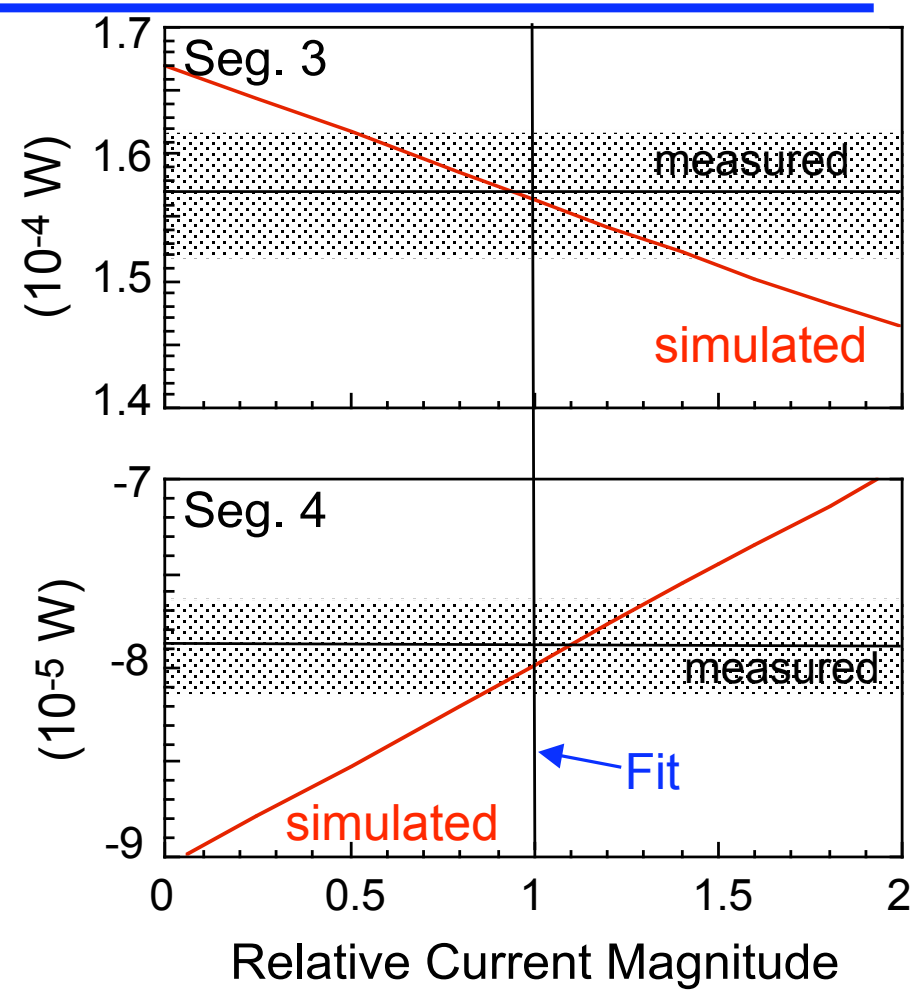


- From SVD analysis: magnetic measurements sensitive to 3 moments of pressure profile and 2 moments of current profile.

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

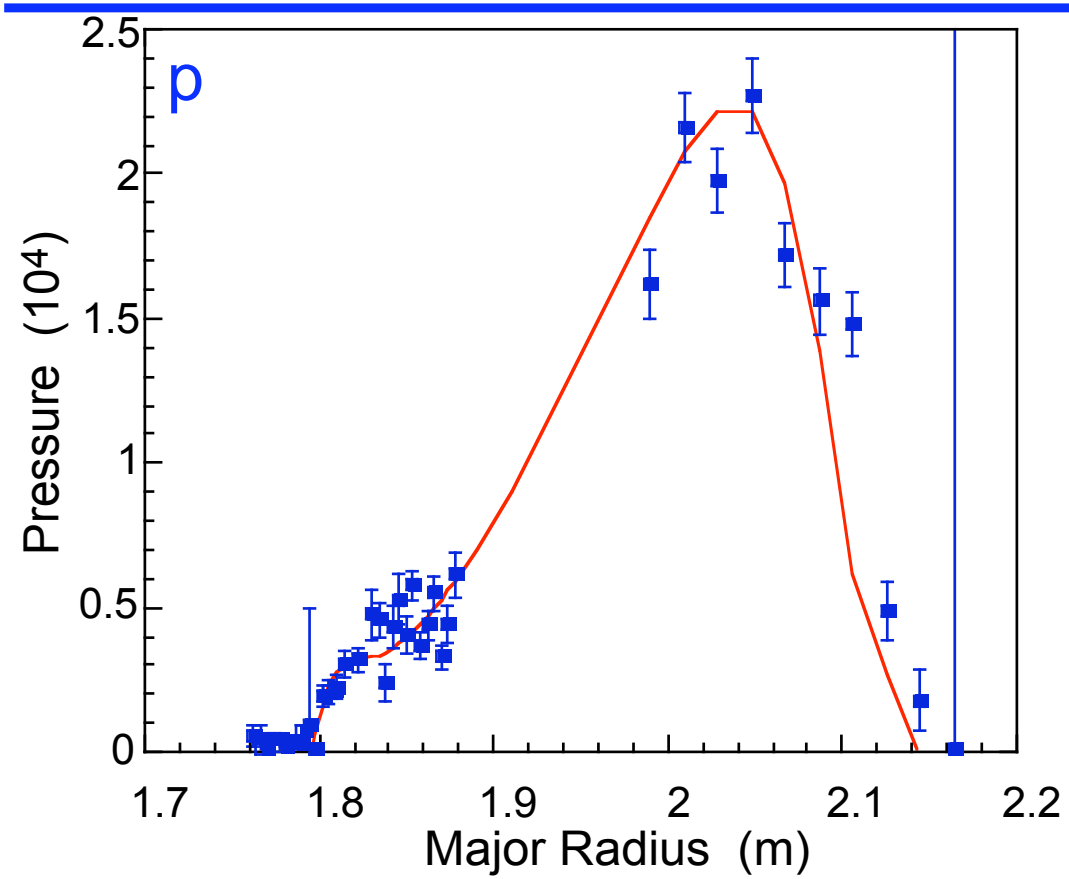
Magnetic Diagnostics are Sensitive to Current

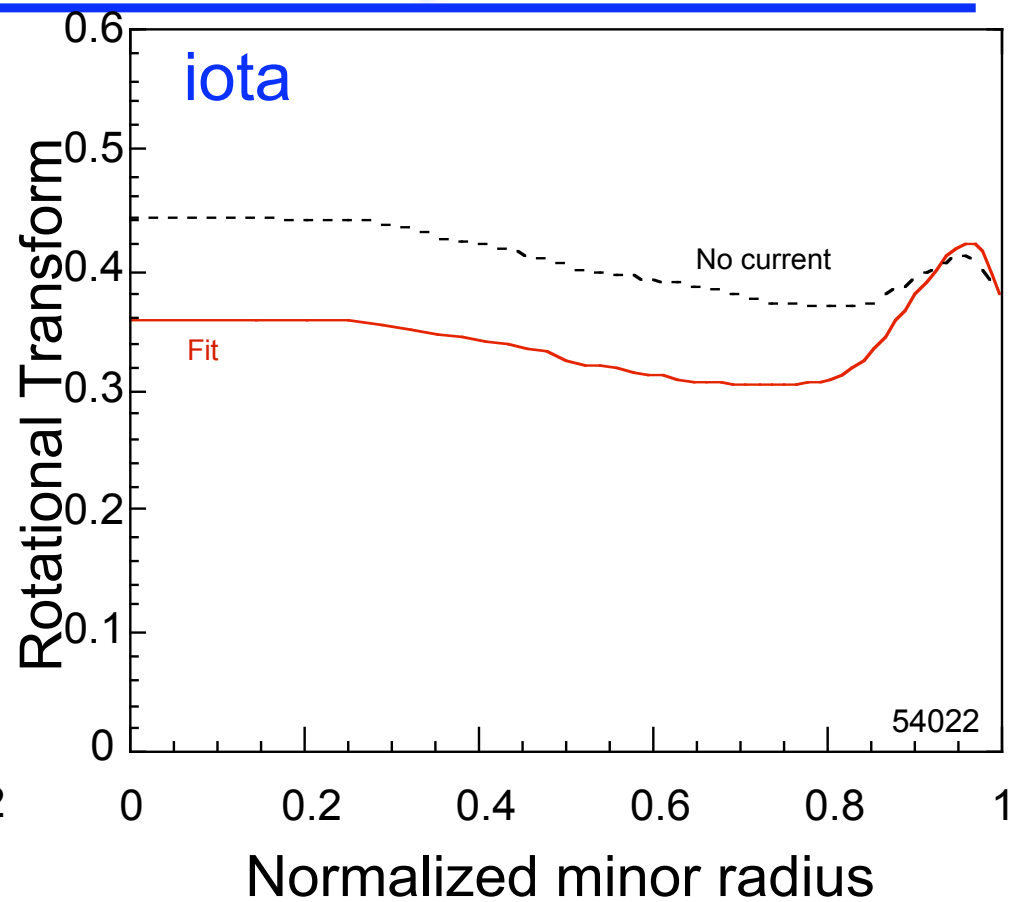




- Small, but significant current inferred from equilibrium fit. Estimated uncertainty of magnitude approx. ± 20% from Rogowski segments
- Three moments used to fit current profile, higher order moments used to force j(a)=0
- Fitted current is larger (in outer region) than model calculations of net current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

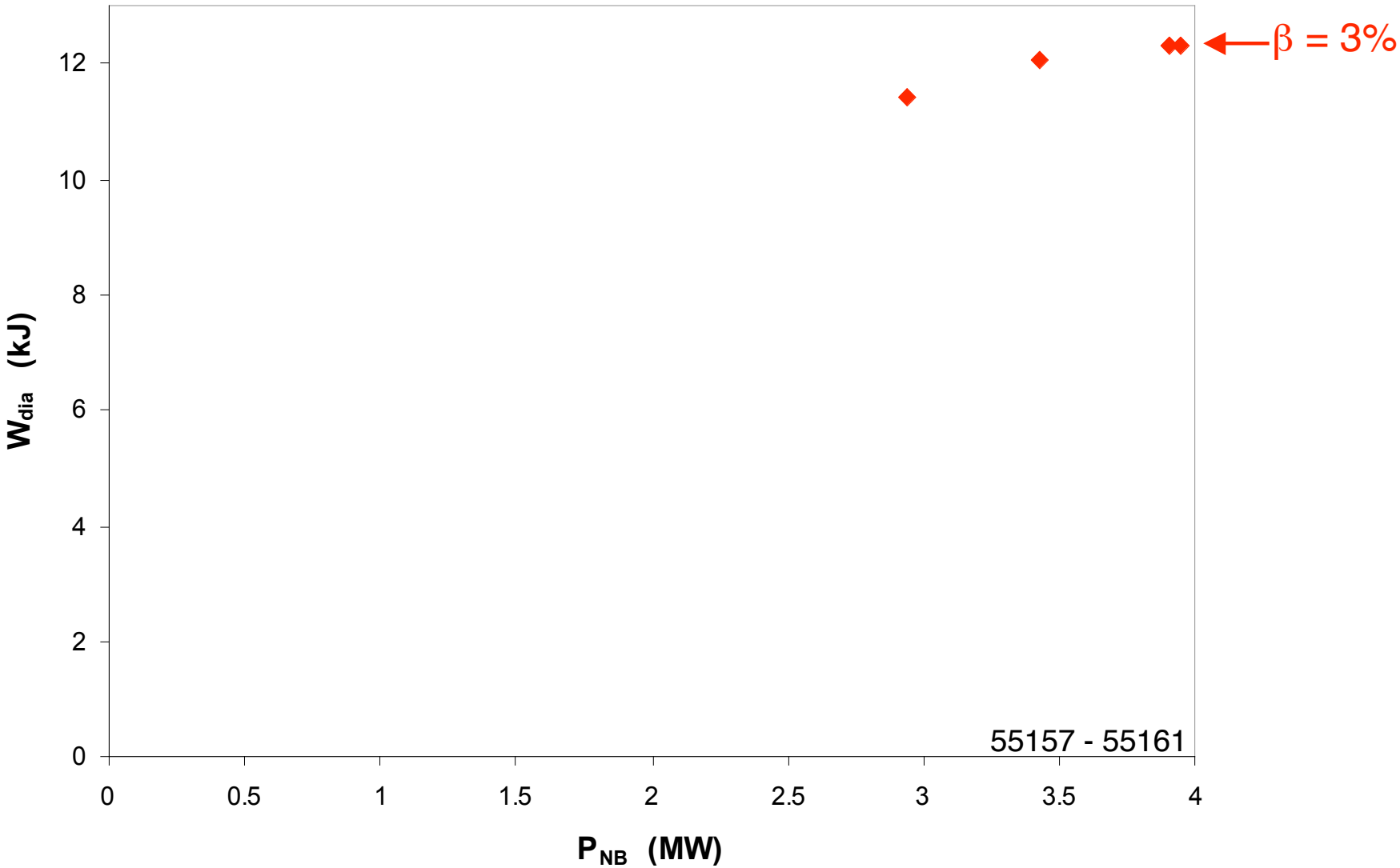
Reconstructed Self-Consistent Equilibrium





- 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

β depends weakly on P_{NB} at low B



- <B> = 0.9 T, B_z / <B> = 0.021
- Indicates $\tau_E \propto P^{-0.75}$, for these plasmas! Much stronger than typical! May indicate some limiting mechanism at high β