Active MHD Control Needs in Helical Configurations

M.C. Zarnstorff[1]

Presented by E. Fredrickson[1]

With thanks to A. Weller[2], J. Geiger[2], A. Reiman[1],

and the W7-AS Team and NBI-Group.

[1] *Princeton Plasma Physics Laboratory*

[2] *Max-Planck Institut für Plasmaphysik, Germany*

9th Workshop on MHD Stability Control

22 November 2004

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Introduction and Outline

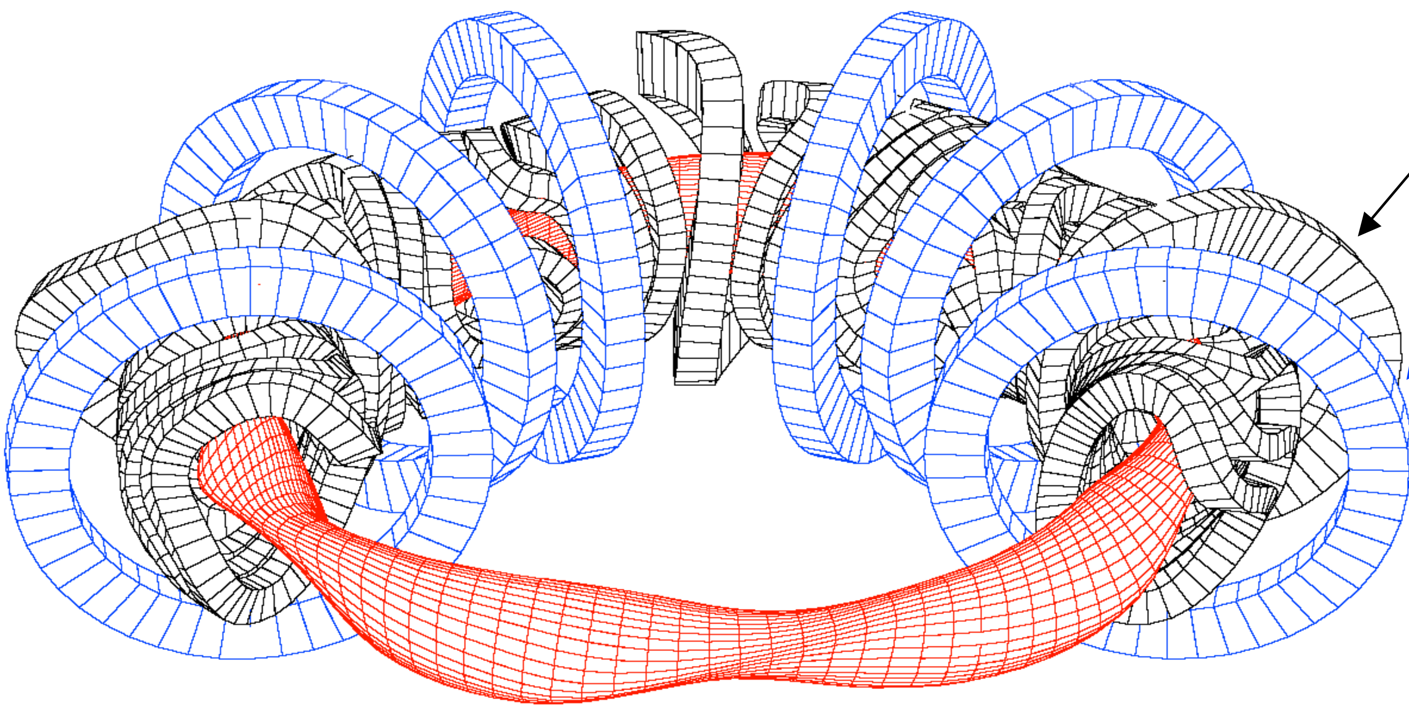
- New stellarators designed to have high β-limits
  NCSX and W7X marginally stable for β ≥5%,
  compatible with steady state without current drive
  Is active control needed or useful?

- Wendelstein-7AS experience
  expected β limit < 2%, achieved β =3.5%
  - When do MHD instabilities occur?
  - What limits β?
  - What control is needed?

- Implications for future experiments

W7-AS – a flexible experiment

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



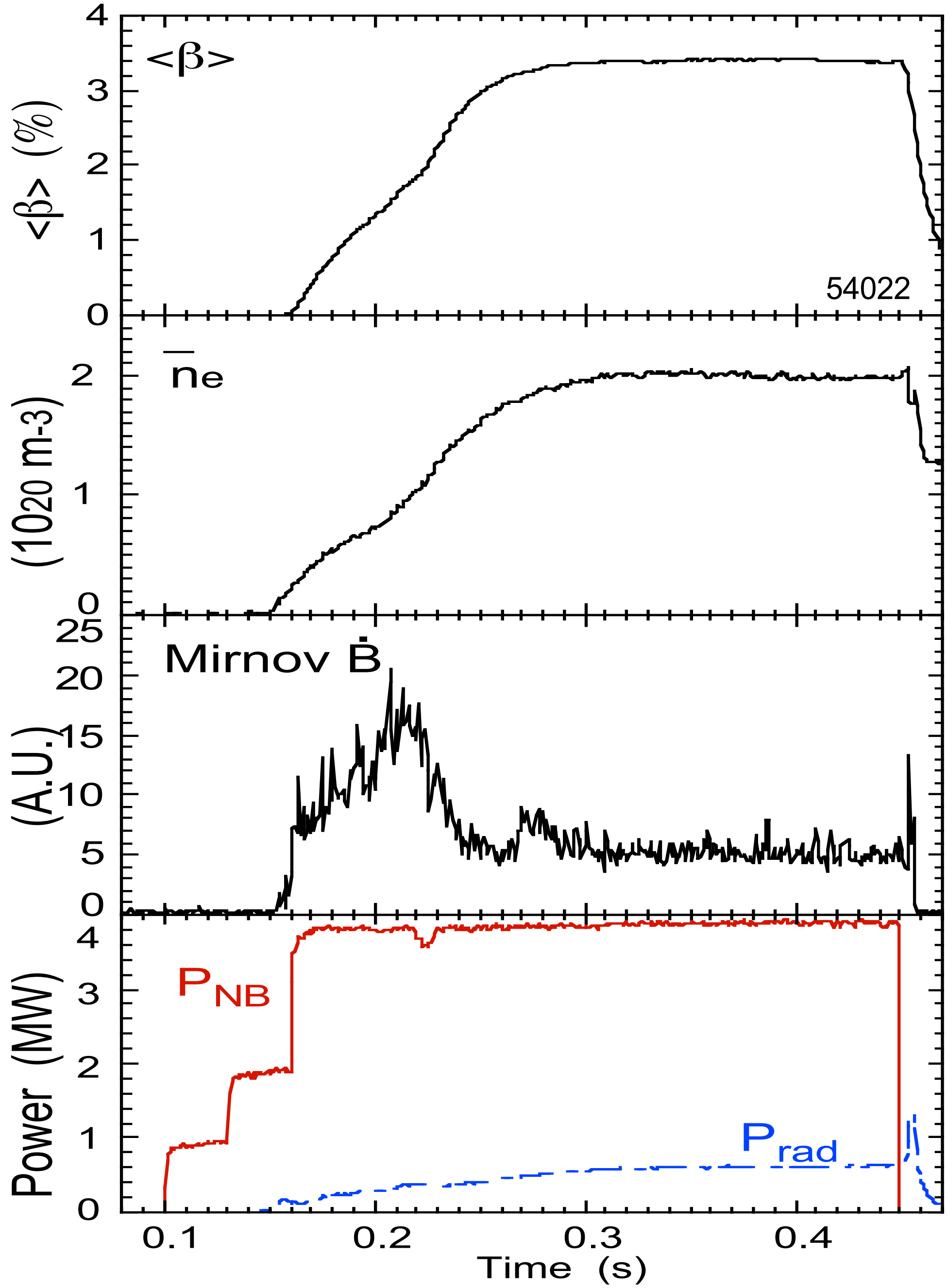
Flexible coilset:

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

W7-AS

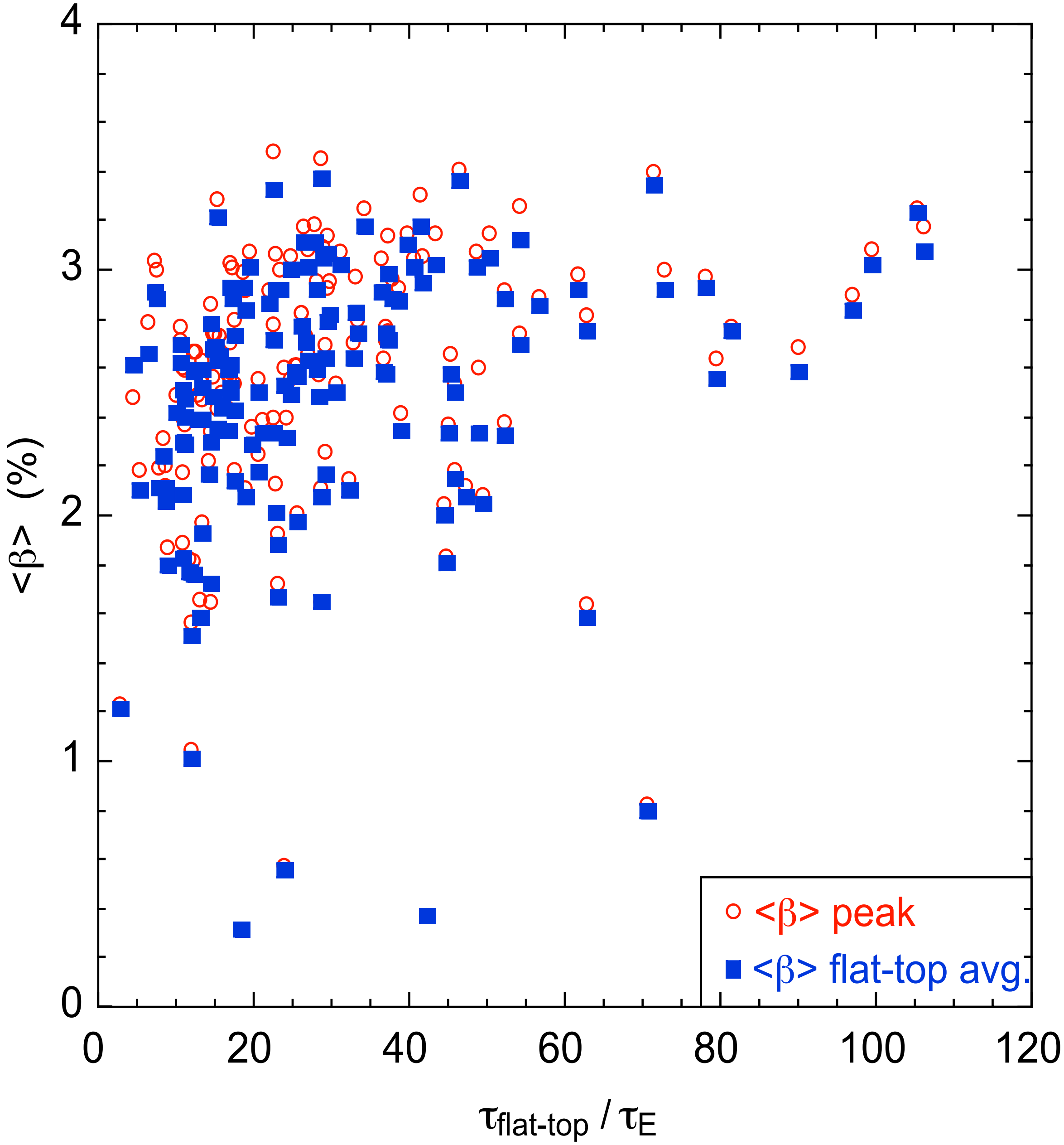
Completed operation in 2002

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



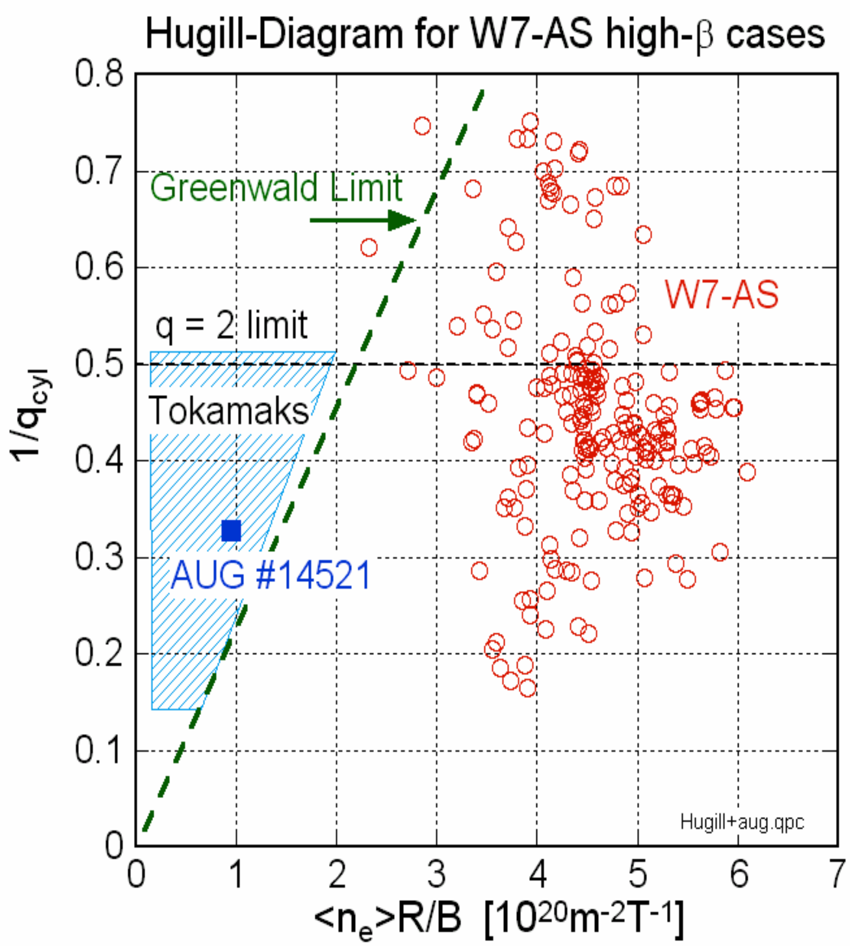
- B = 0.9 T, $iota_{vac}$ ≈ 0.5
- Almost quiescent high- β phase, MHD-activity in early medium-β phase
- In general, β not limited by any detected MHD-activity.
- I_P = 0, but there can be local currents
- Similar to High Density H-mode (HDH)
- Similar β>3.4% plasmas achieved with B = 0.9 – 1.1 T with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

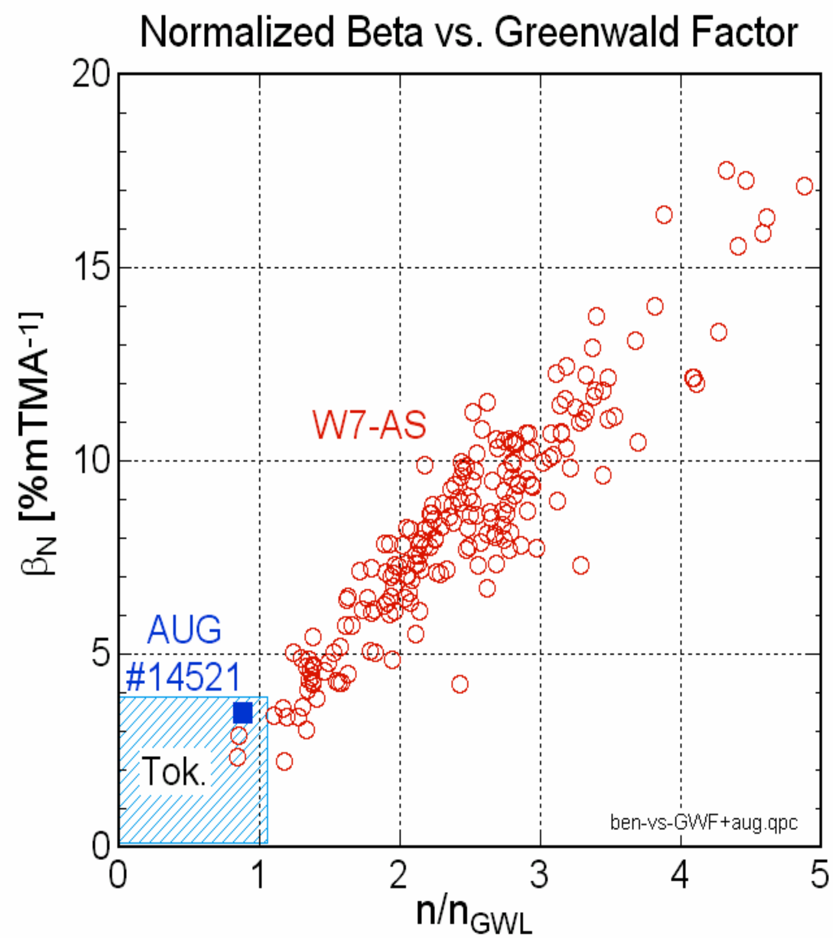
$\langle\beta\rangle$ > 3.2% maintained for > 100 τ_E



- Peak <β> = 3.5%
- High-β maintained as long a 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?

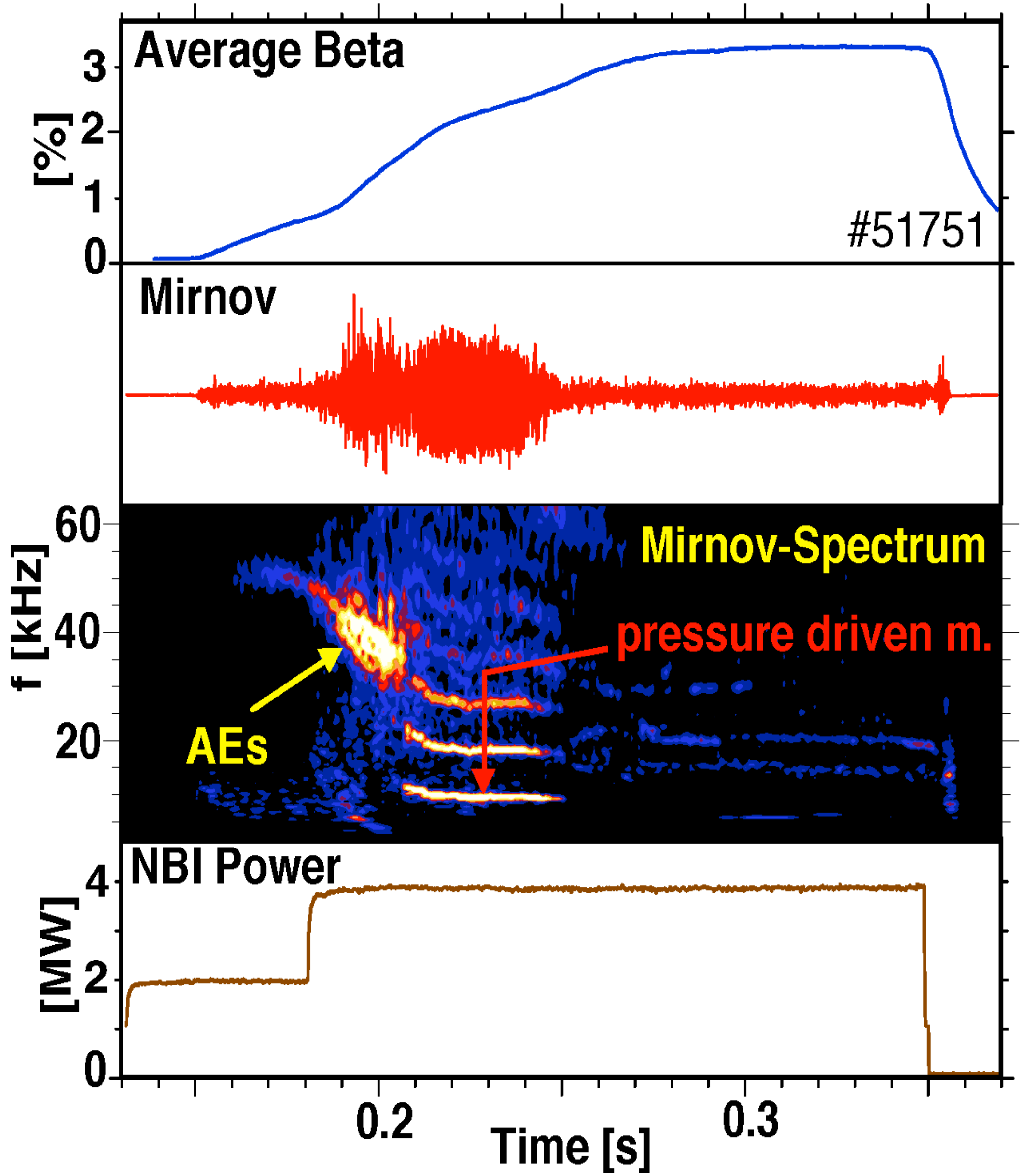
W7-AS Operating Range much larger than Tokamaks

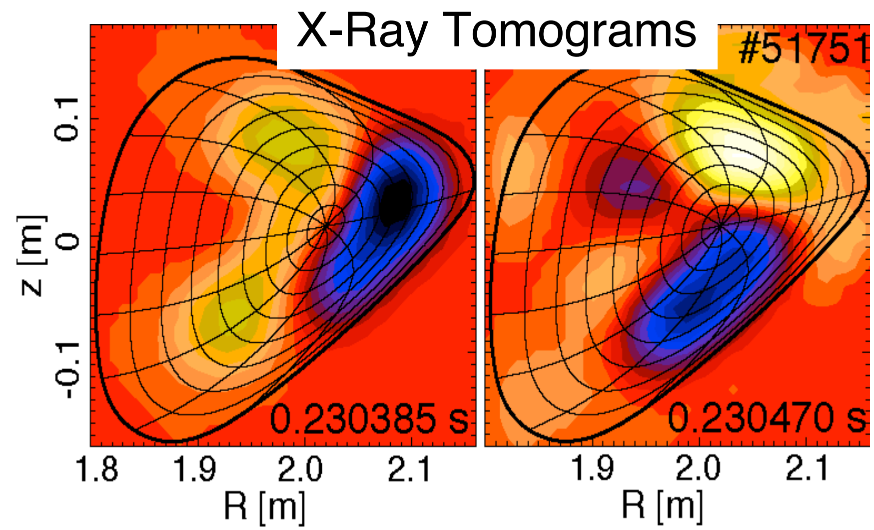




- Using equivalent toroidal current that produces same edge iota
- Limits are not due to MHD instabilities.
  Density limited by radiative recombination
- high-β is reached with high density (favourable density scaling in W7-AS)
- Almost all **W7-AS** high-β data points beyond operational limits of tokamaks

Pressure Driven Modes Observed, at Intermediate β

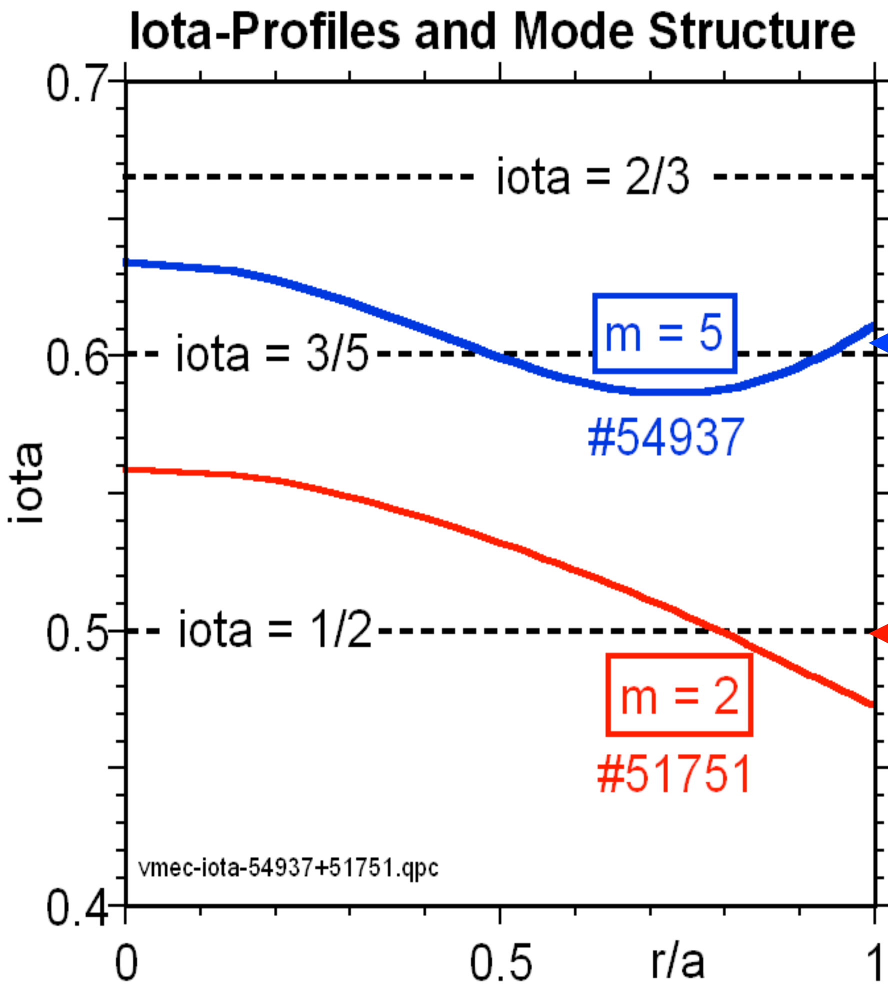


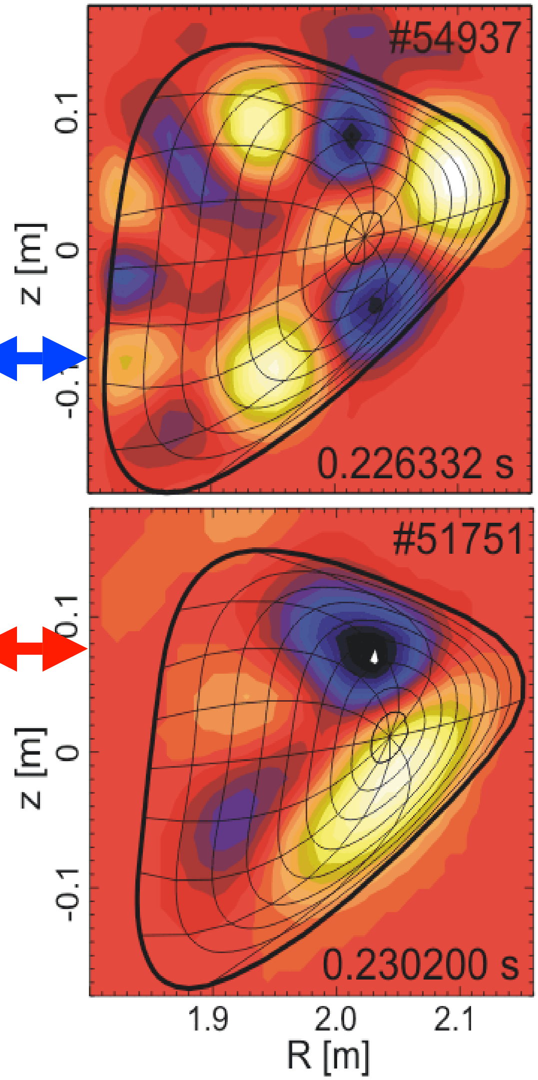


- Dominant mode m/n = 2/1.
- Modes disappear for β > 2.5% (due to inward shift of iota =1/2?)
- Reasonable agreement with CAS3D and Terpsichore linear stability calcs. Predicted threshold β < 1%
- Does not inhibit access to higher β

Linear stability threshold is not indicative of β limit.

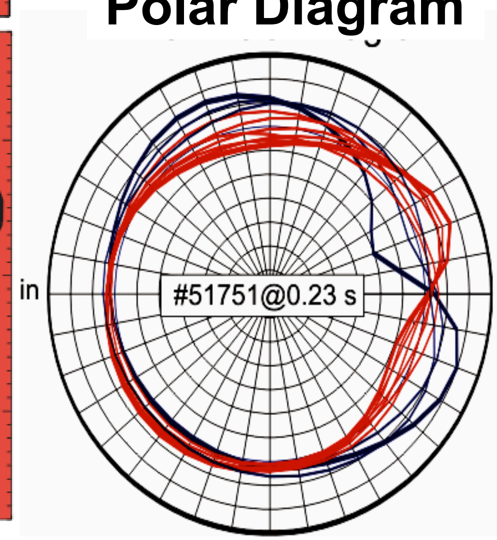
Observed Mode Structure Corresponds to Iota-Profile (VMEC)





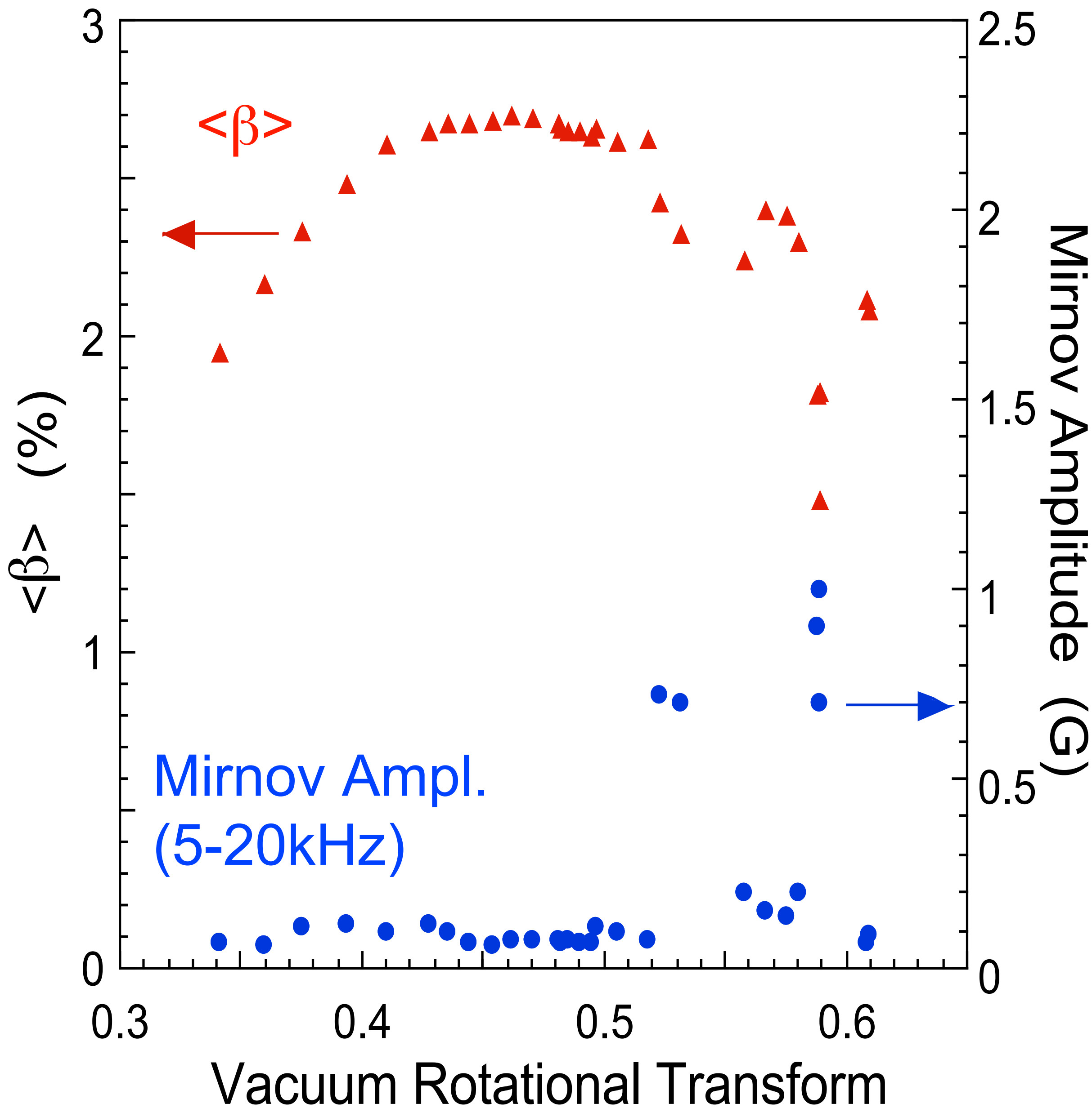
Perturbed X-Ray Emissivity (Tomog.

Mirnov-Ampl. Polar Diagram



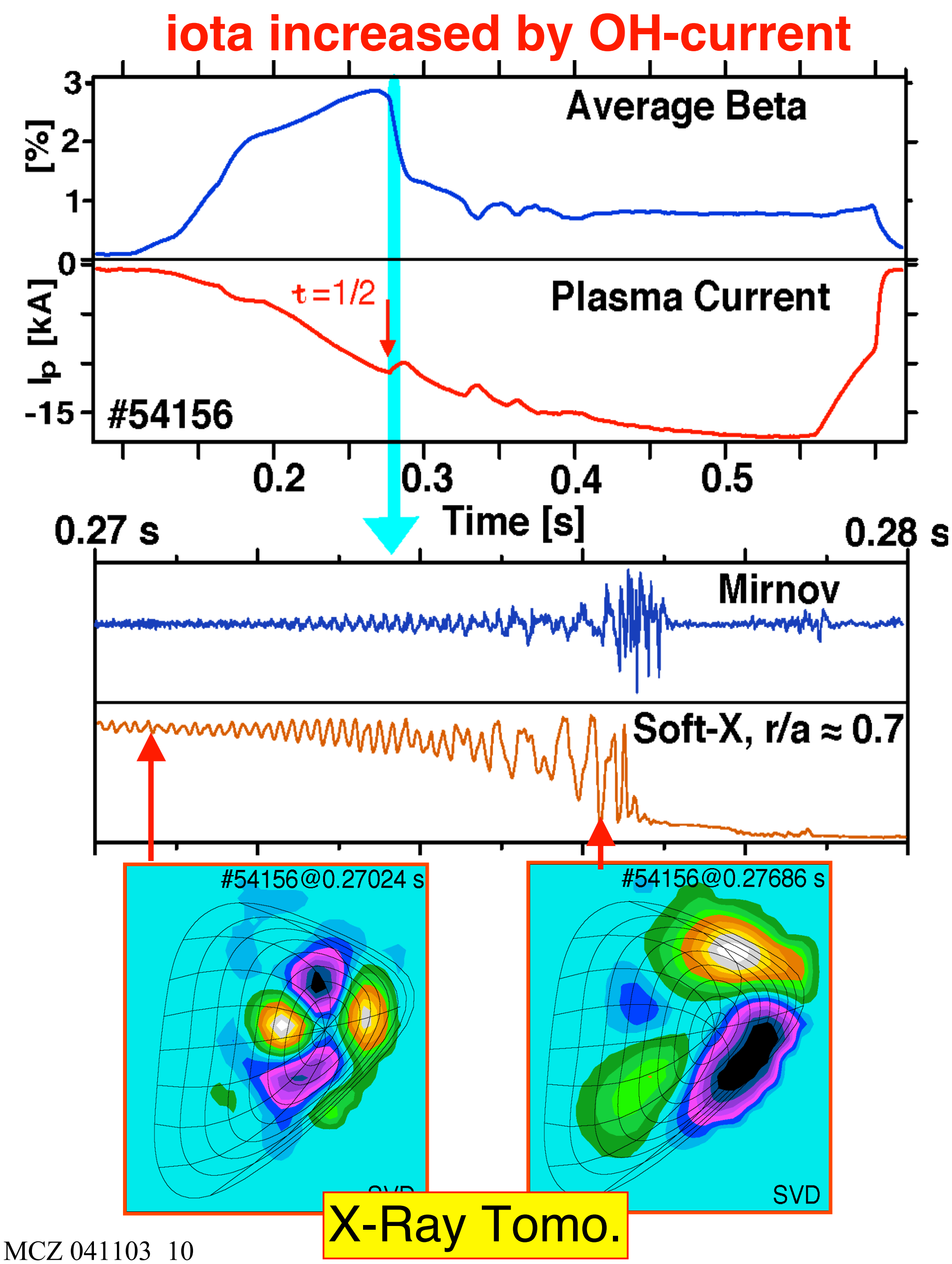
- In both cases, MHD observed transiently during pressure rise. Edge iota drops as β increases, due to equilibrium deformation.
- Strong ballooning effect at outboard side in X-ray and magnetic data

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 degrade confinement
- Strong MHD activity only in narrow ranges of external io
- 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 curren

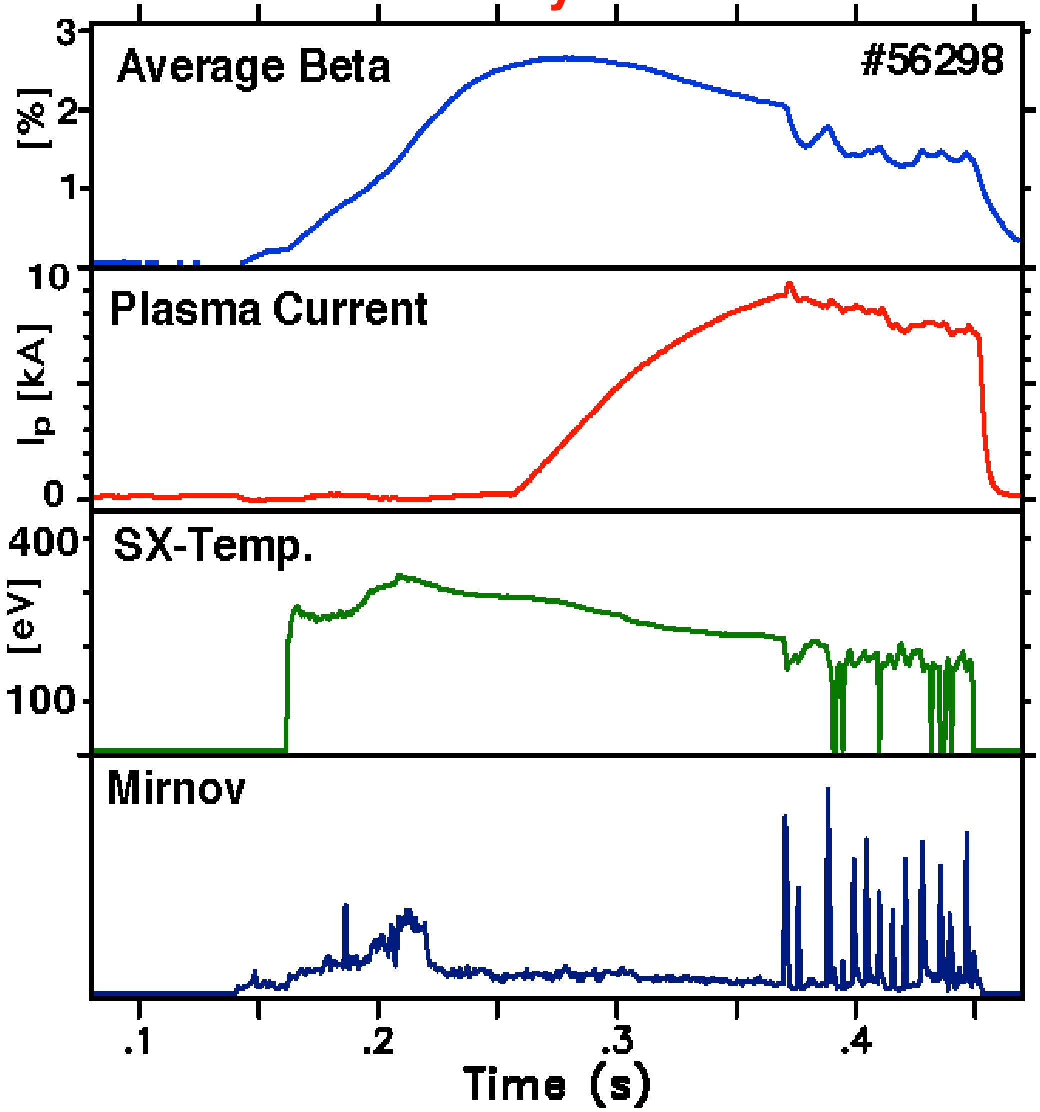
Significant I_P<0 makes Tearing Modes at iota=1/2



- 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

iota decreased by OH-current



- 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 mode"

MHD stability control

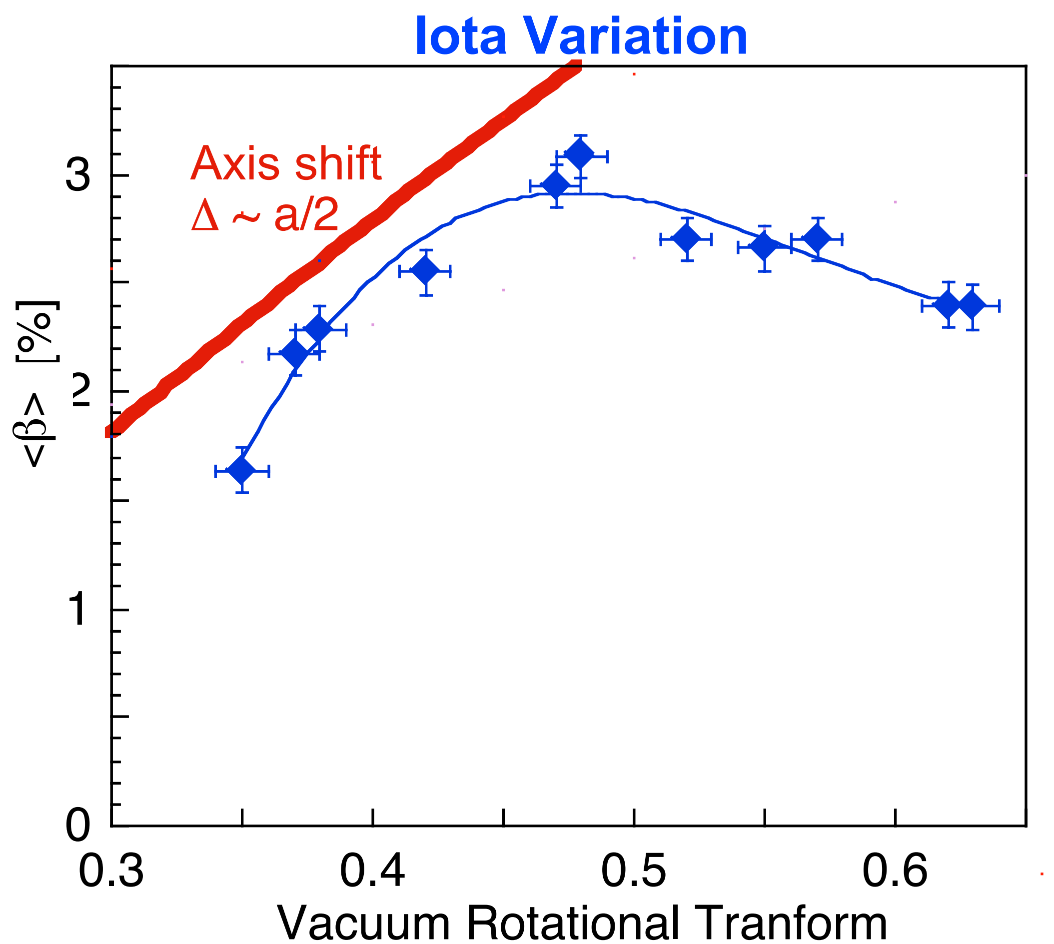
- Pressure-driven MHD activity and tearing modes appear to be significant only when edge-iota = low order rational (1/2 and 3/5, in particular)

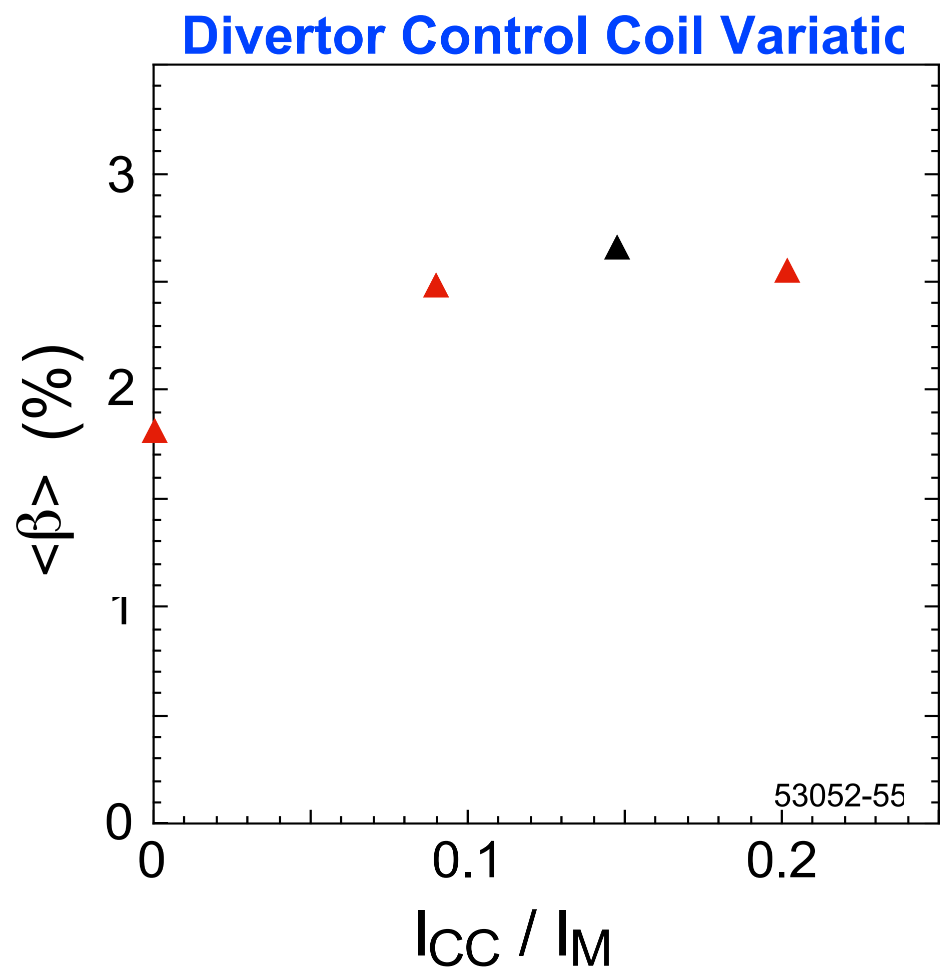
  $\Rightarrow$ avoid low-order rational iota values at edge

- Reversed shear may stabilize tearing modes, as in tokamaks.

What sets β-value?

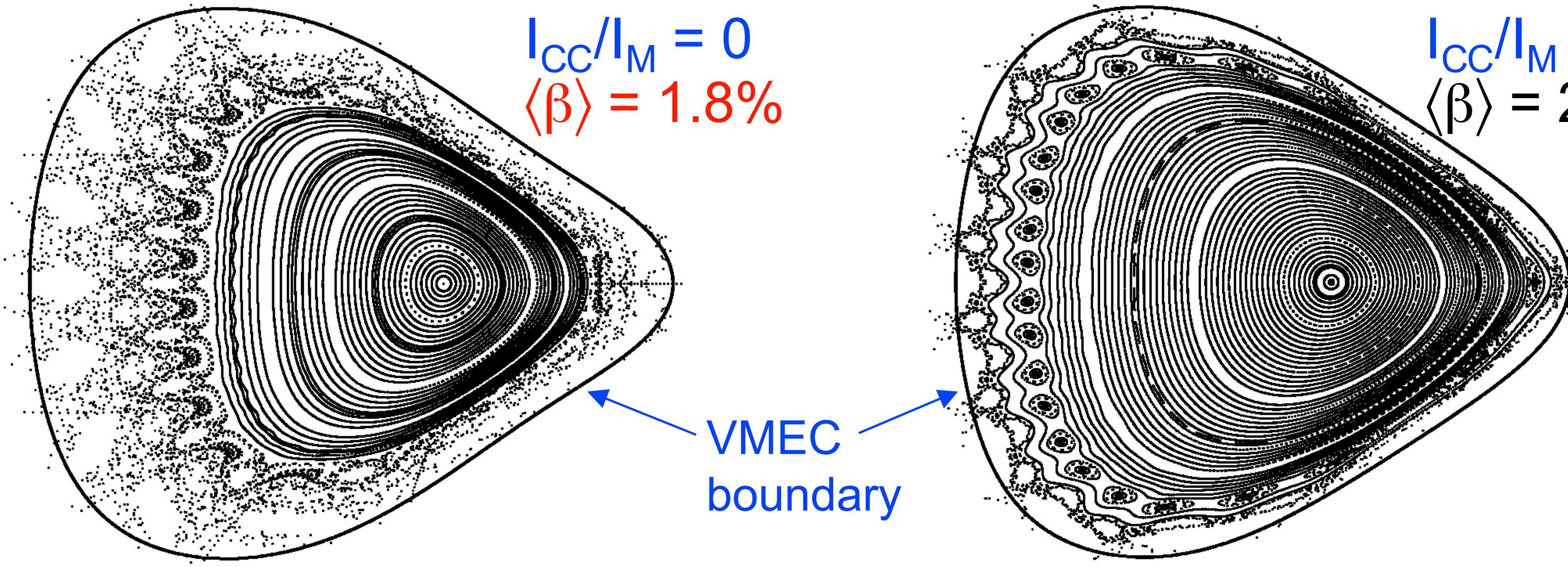
Clues: ⟨β⟩ Sensitive to Equilibrium Characteristics



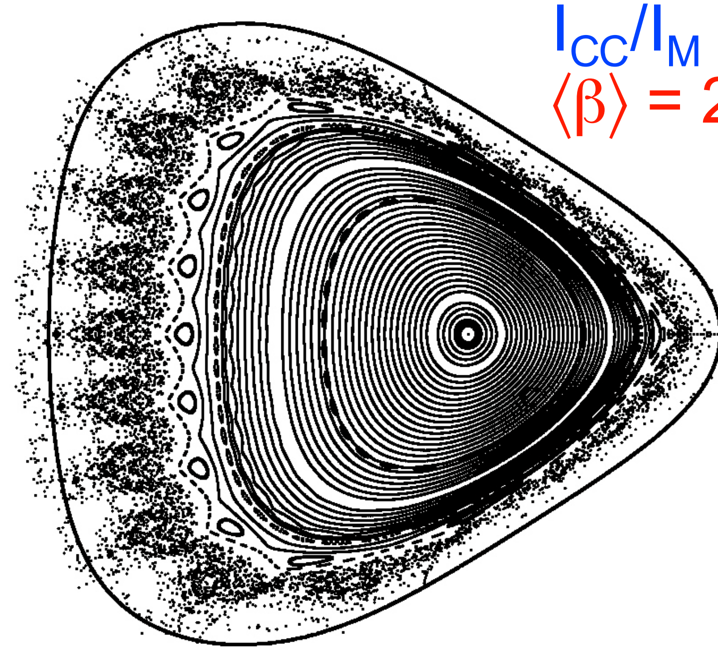


- Achieved maximum β is sensitive to iota, control coil current, vertical field, toroidal mirror depth.
- At low iota, maximum β is close to classical equilibrium limit Δ ~ a/2
- Control coil excitation does not affect iota or ripple transport
- Is β limited by an equilibrium limit?

Control Coil Variation Changes Flux Surface Topology

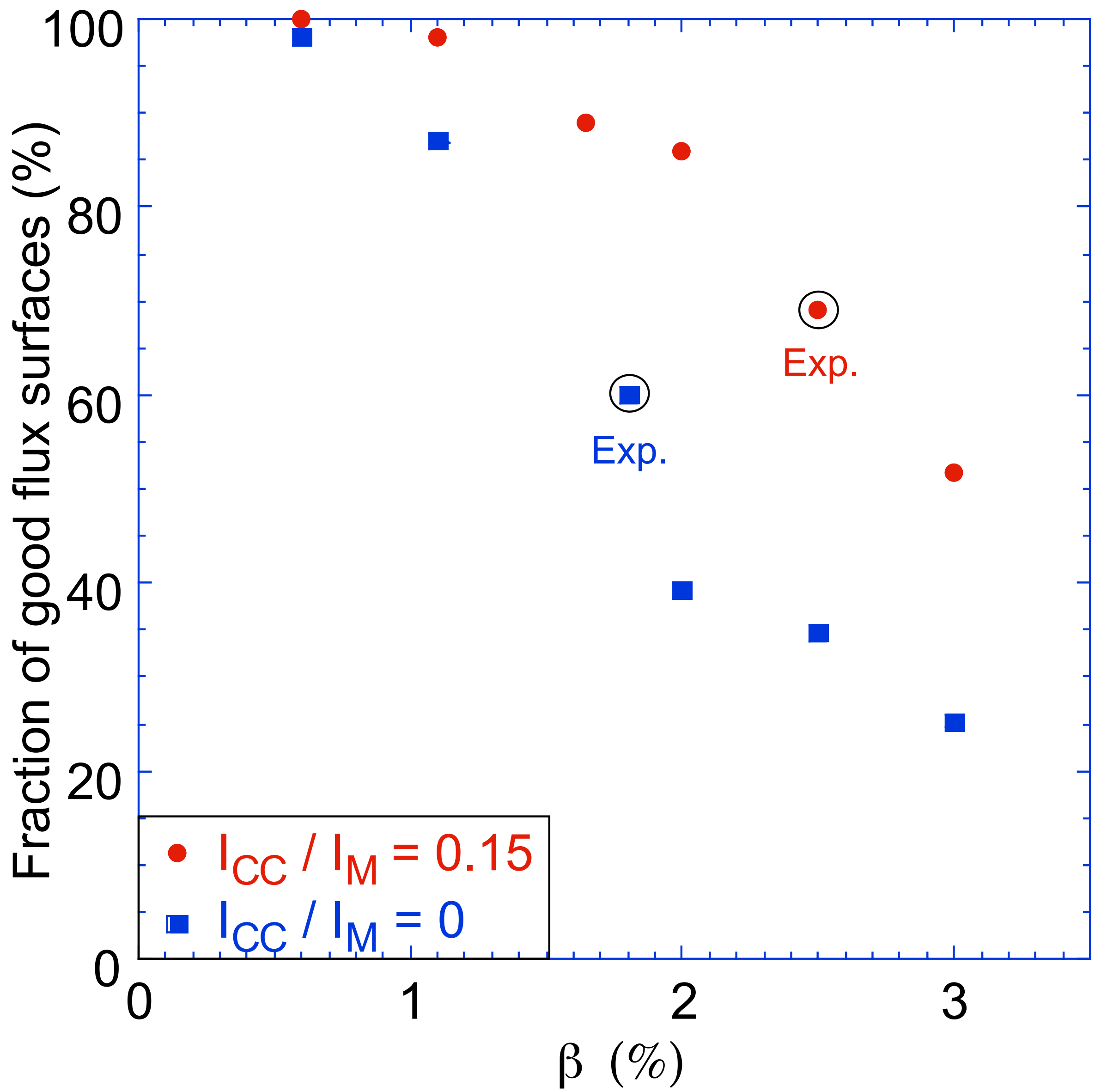


- PIES equilibrium analysis using fixed pressure profile from experiment.
- Calculation: at ~ fixed β, I_{CC}/I_M=0.15 gives better flux surfaces
- At experimental maximum β values
  -- 1.8% for I_{CC}/I_M =0
  -- 2.7% for I_{CC}/I_M = 0.15
  calculate similar flux surface degradation



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.



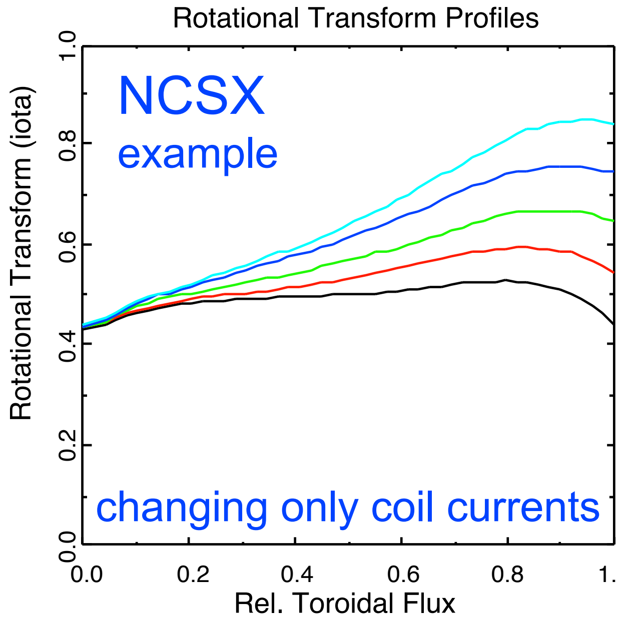
Implications for future devices

- Design configuration to have good flux surfaces at high-β
  - NCSX & W7X both designed to have good flux surfaces at high β
  - Include triNm coils to control flux surface quality

- Two approaches to MHD instability control:

  W7X: design configuration so edge iota does not change, and is not at a low-order resonance.
  - So far, only possible with good confinement at large aspect ratio

  NCSX: have flexible coil-set to be able to control iota, avoid resonances
  - May need 3D equilibrium control, to dynamically avoid low-order edge resonances. Will be possible in NCSX.



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 not limited by MHD activity.
  - No disruptions observed
- Pressure driven MHD activity & tearing modes observed with edge iota at low order resonances: 1/3, 1/2, 3/5.
  - Exists in narrow range of iota $\Rightarrow$ easily avoided by adjusting coil currents.
  - May want real-time equilibrium control to avoid resonances
- Maximum β correlated with calculated loss of ~35% of minor radius to stochastic magnetic field. May limit β.
  - May want to control equilibrium topology using trim coils