

High- β Experiments on W7AS and Possible Implications

M.C. Zarnstorff,
Princeton Plasma Physics Laboratory

*In collaboration with
MP-Institut für Plasmaphysik, Germany*

ARIES Project Meeting
Livermore, CA
7 May 2003

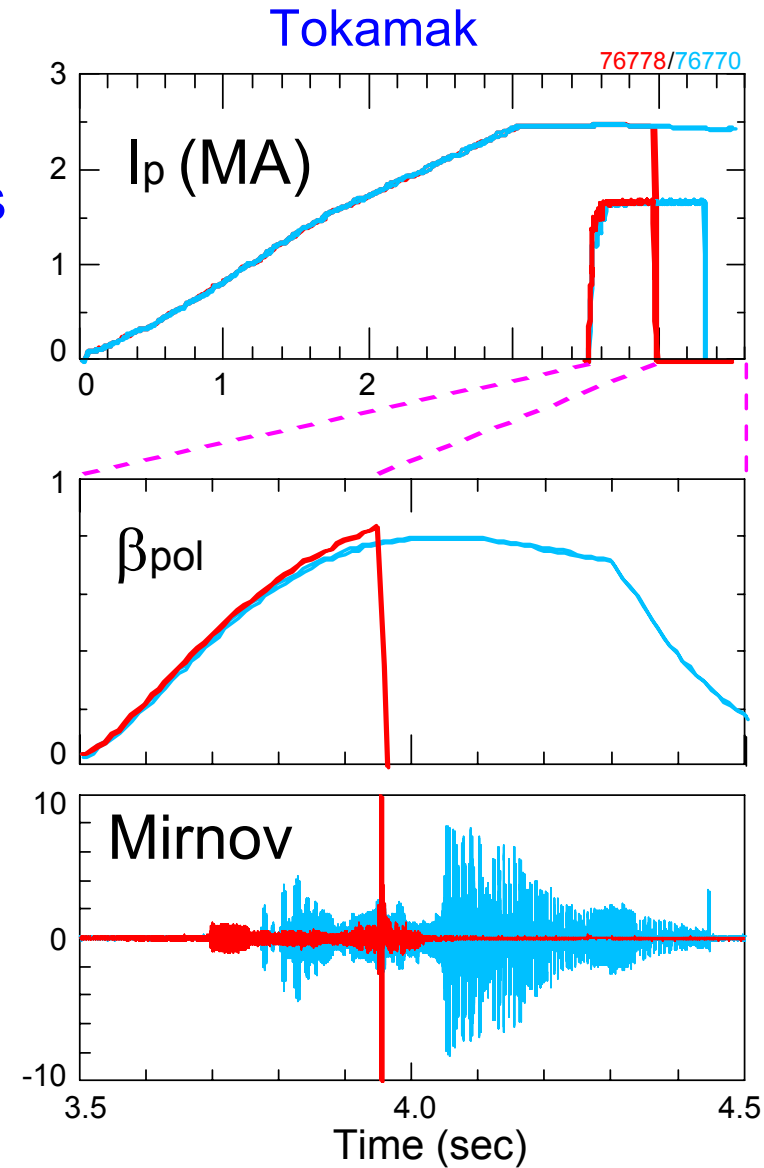
IPP



Stellarator β -limit Are Not Understood

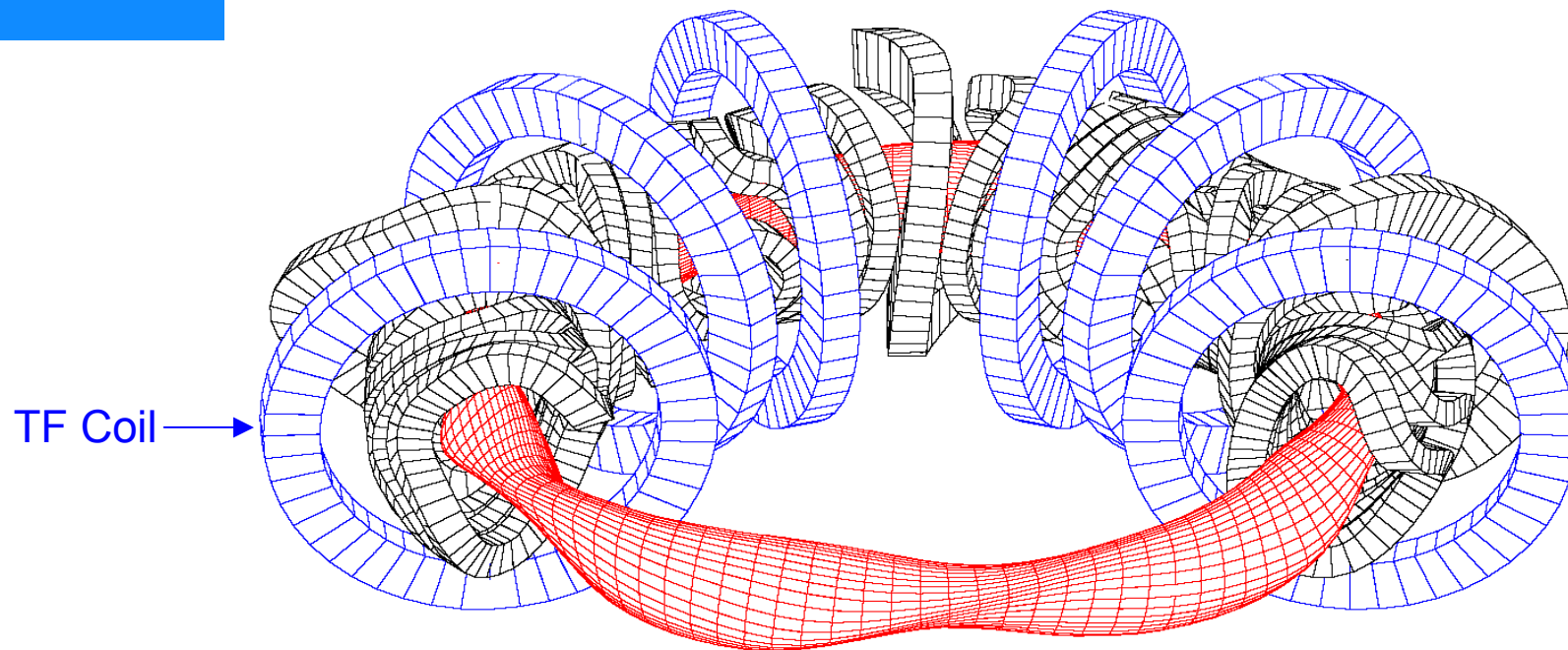
- Tokamak β limit extensively studied:
 - set by instabilities
 - Ideal-like instabilities $\rightarrow$ disruptions
 - Saturated instabilities: degraded confinement
- Historically: **stellarators** designed using idealized criteria: Mercier criteria and resistive-interchange stability.
- Stellarator β limits not yet observed
 - Heliotron-E and CHS achieved $\beta \sim 2\%$, transport/power limited
 - Recently, LHD achieved $\beta \sim 3.2\%$, transport/power limited

In both CHS and LHD, these plasmas violate Mercier criteria



$n = 1$

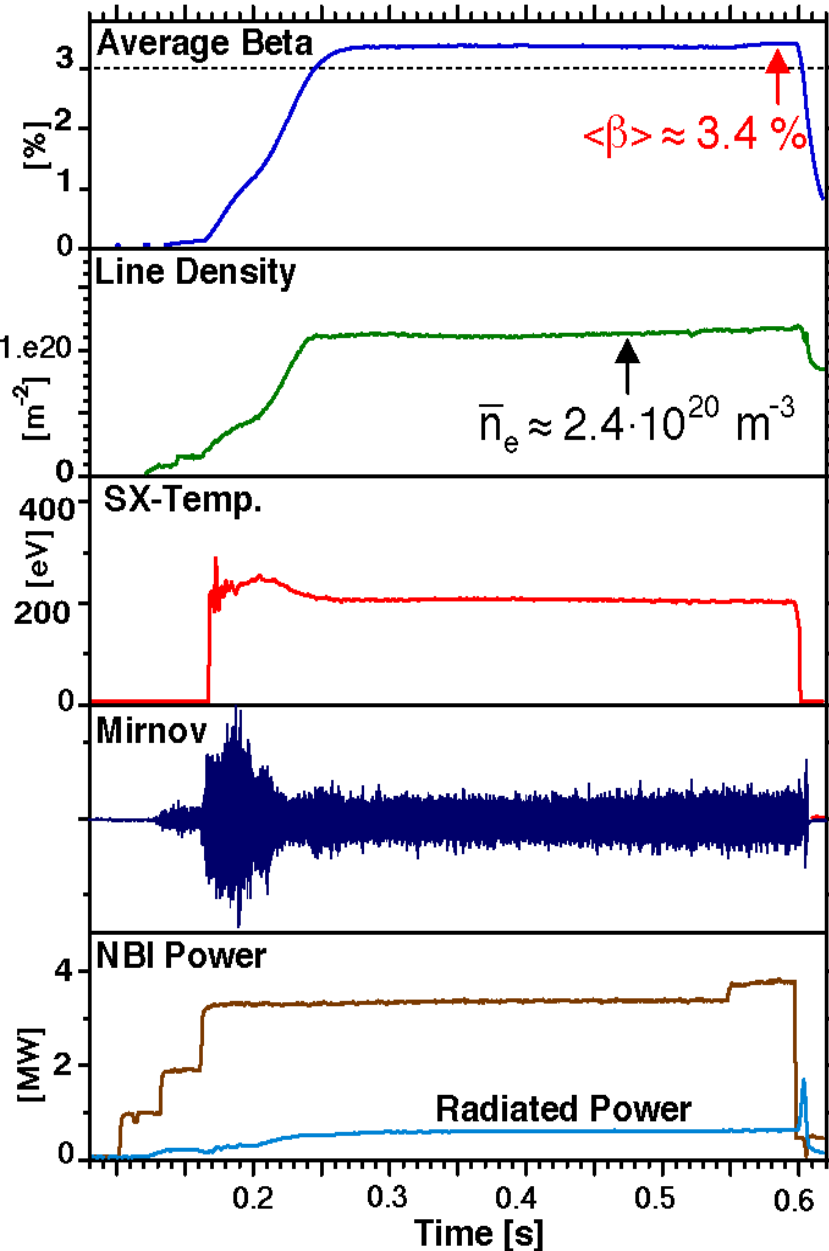
TFTR
E. Fredrickson



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

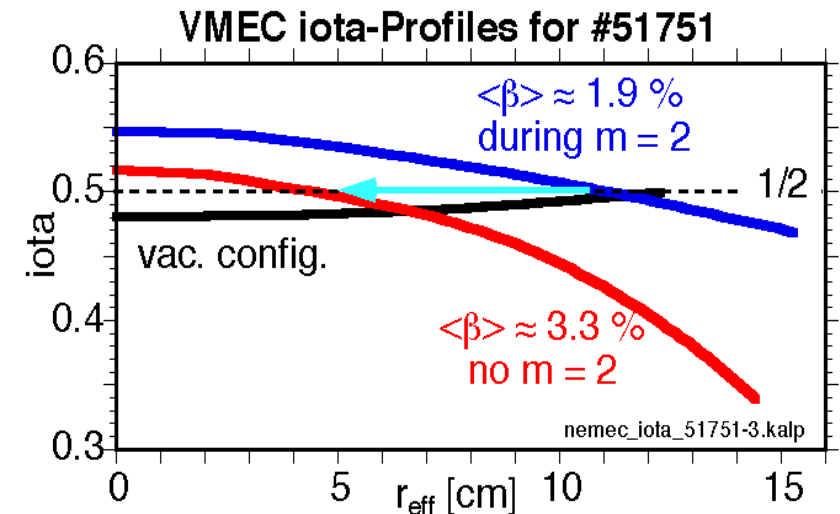
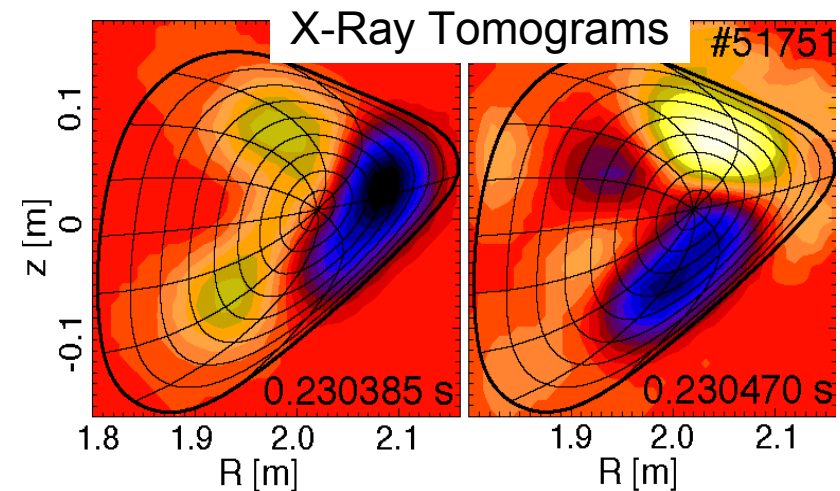
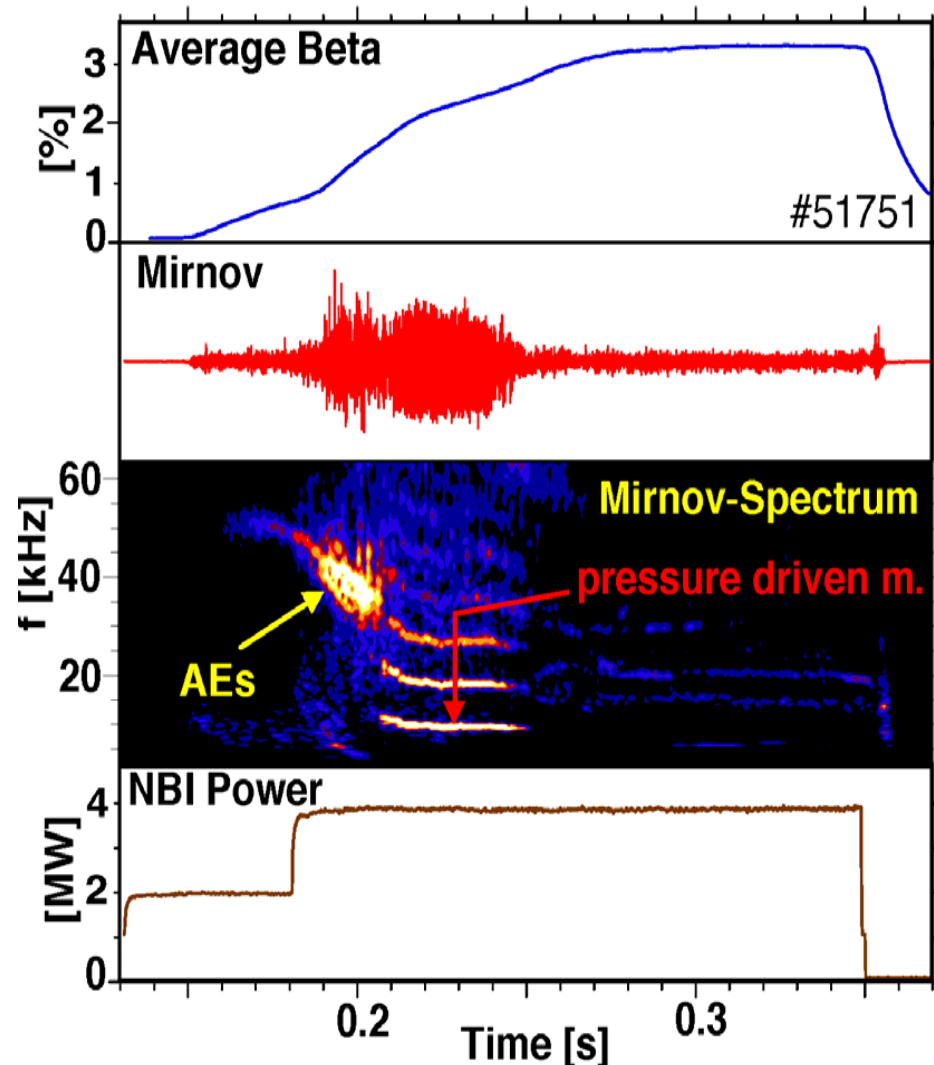
Highest $\langle\beta\rangle \approx 3.4\%$: Quiescent, Quasi-stationary

W7-AS #56403



- $B = 0.9 \text{ T}$, $i_{\text{ext}} \approx 0.5$, $B_z/\langle B \rangle = 0.026$
- Similar to **H**igh **D**ensity **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 $\sim 75 \tau_E$ quasi-stationary with density control and low radiated power
- $\tau_i / \tau_E \approx 2\text{--}3$ 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 $\text{iota} = 1/2$?)

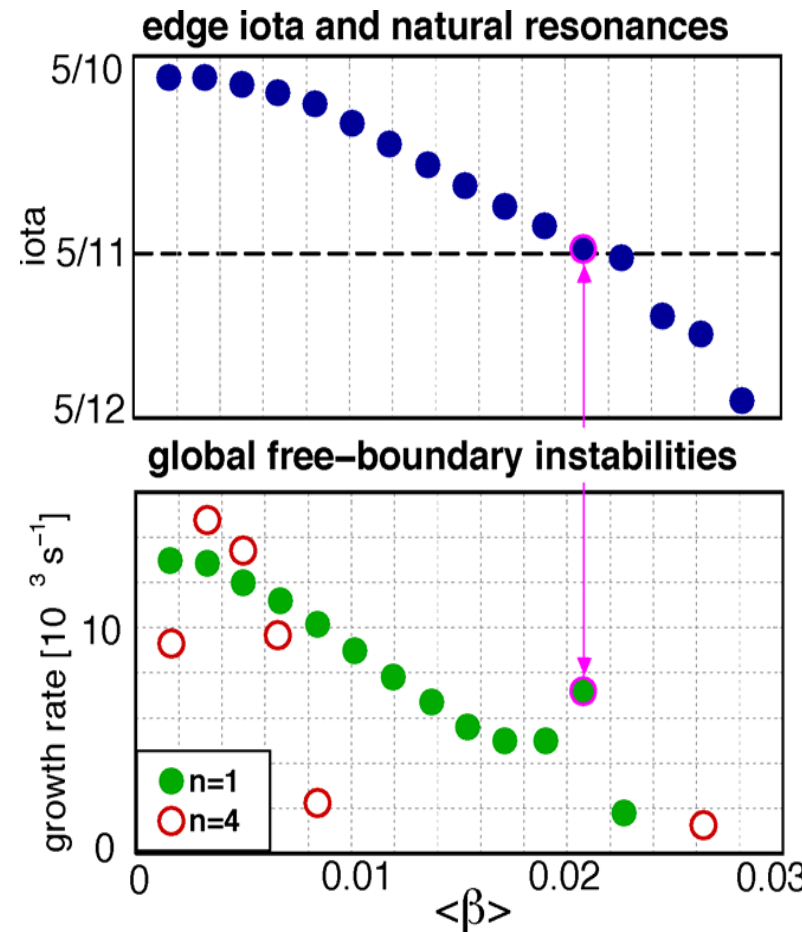
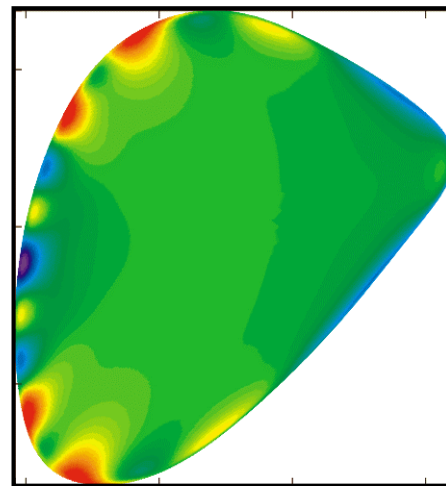
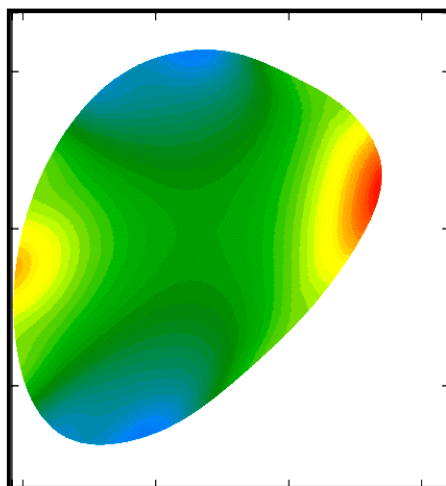
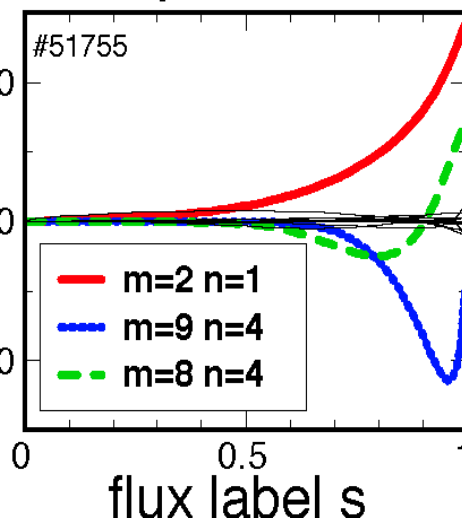
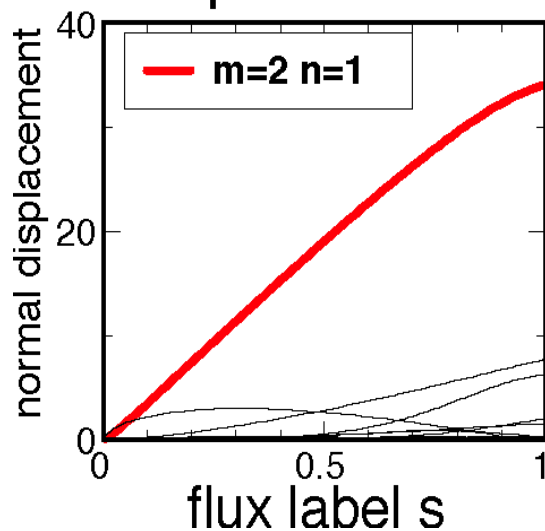
Linear Stability Calculations (CAS3D) Indicate 2/1 Should be Unstable, even at low β !

Mode Displacement & Perturbed Pressure

51755

$\langle \beta \rangle = 0.84 \%$

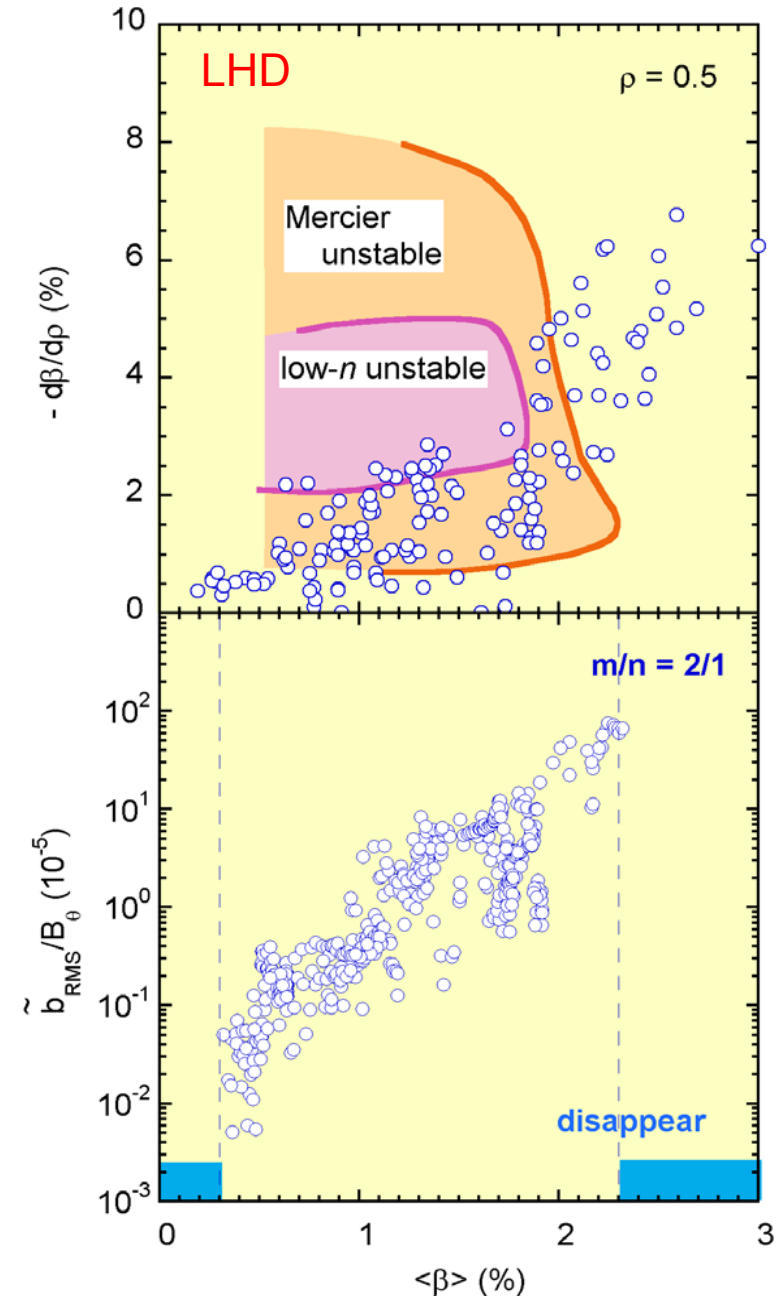
$\langle \beta \rangle = 2 \%$



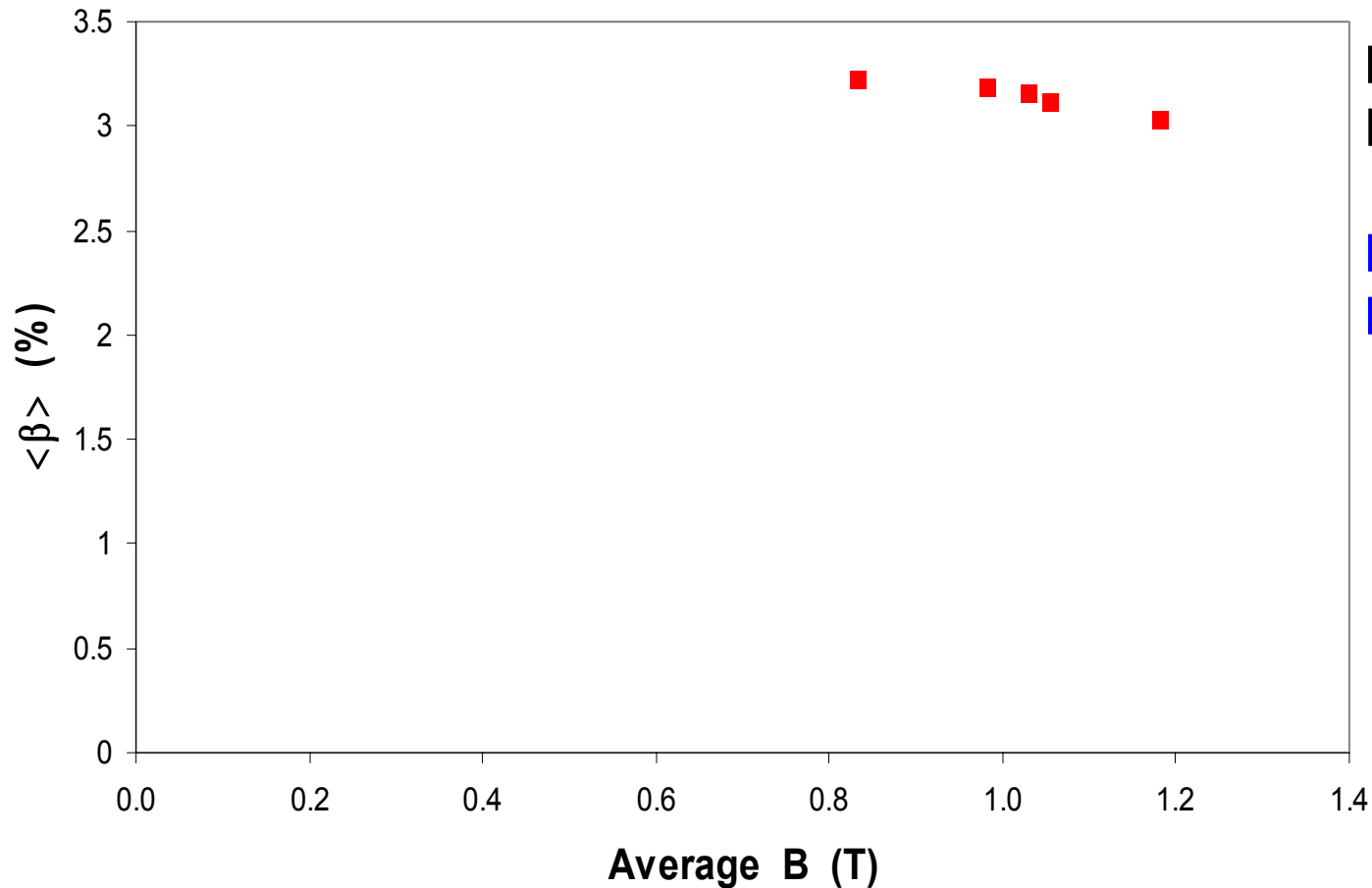
External global modes,
most unstable at low β

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 $\beta > 2.3\%$
- 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

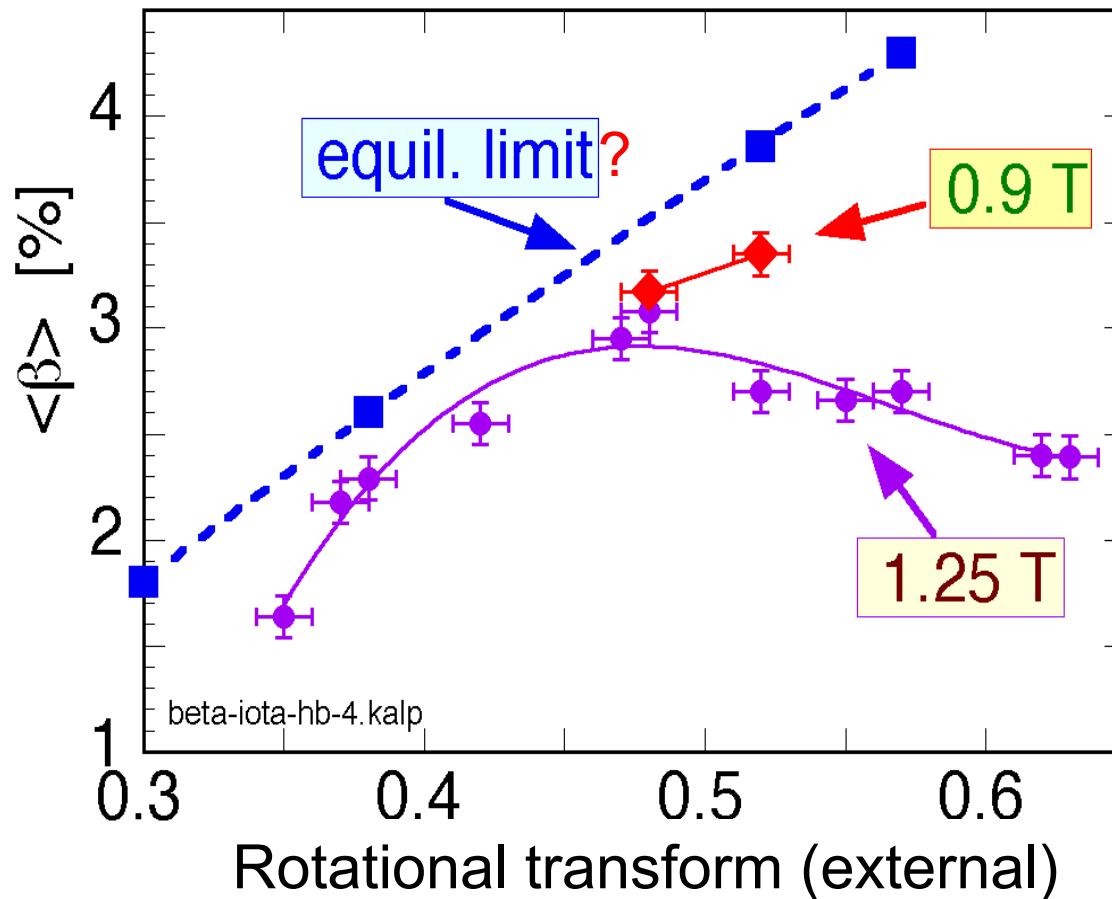


$P_{inj} = 3.9$ MW
Fixed plasma shape

Plasmas quiescent
No MHD Activity

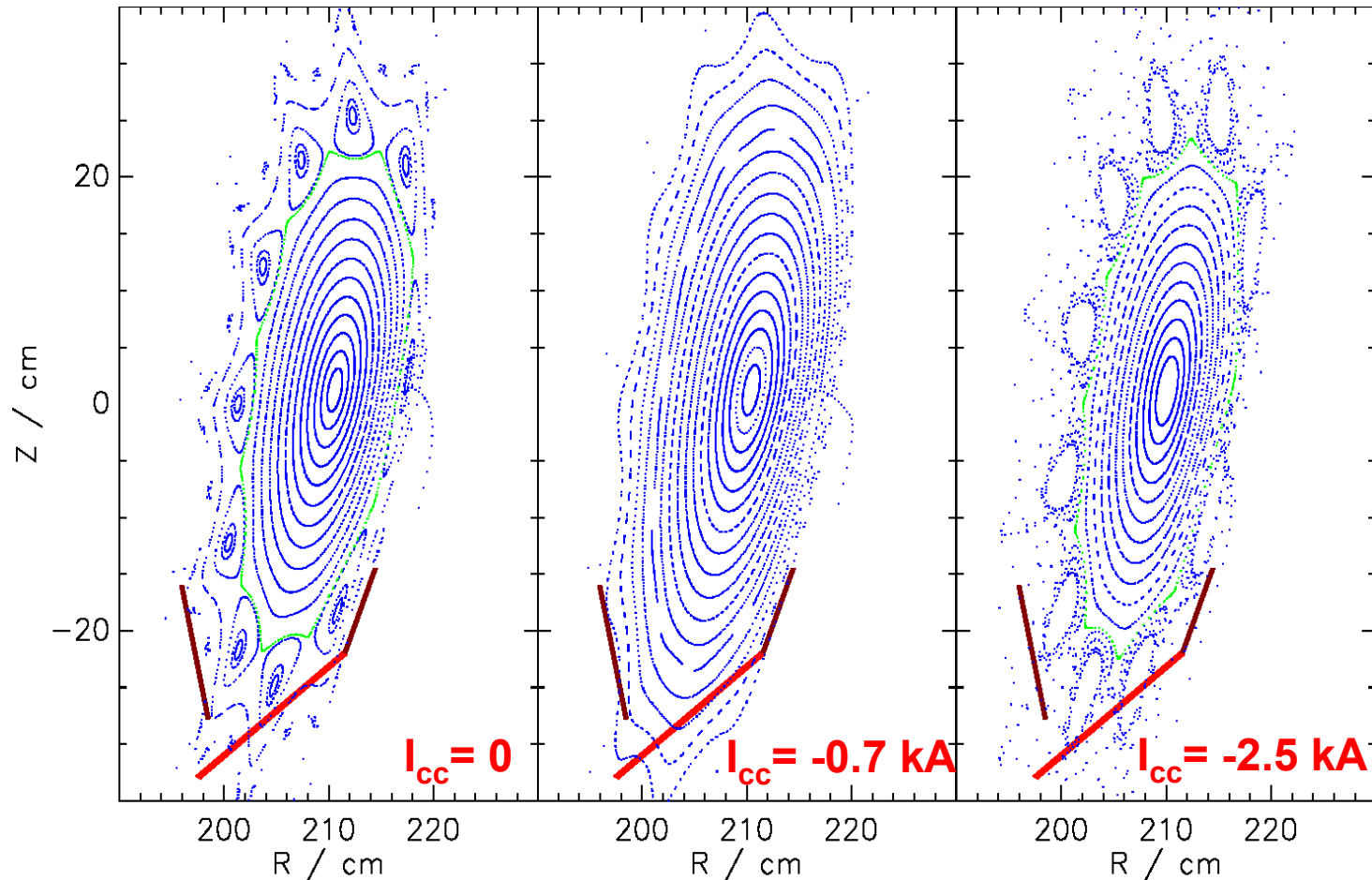
- Indicates energy confinement $\propto B^{1.8}$! Much stronger than usual!
- At B=0.9 T, $\langle \beta \rangle$ is almost independent of heating power!
Energy confinement $\propto P_{inj}^{-3/4}$!
- May indicate β is constrained, but what is mechanism?

β May be Limited by Deterioration of Equilibrium



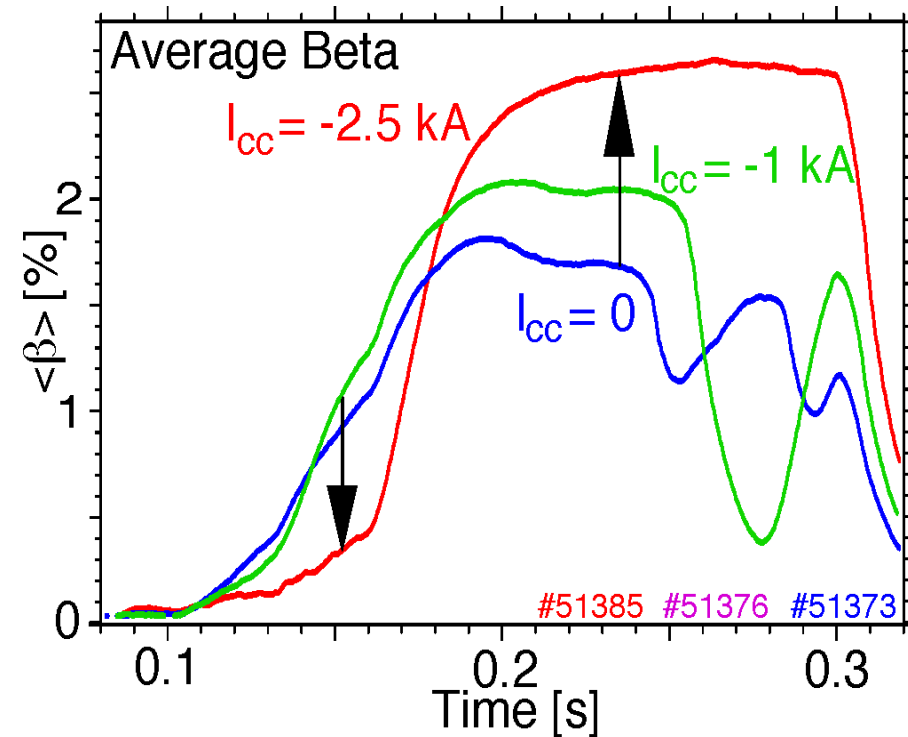
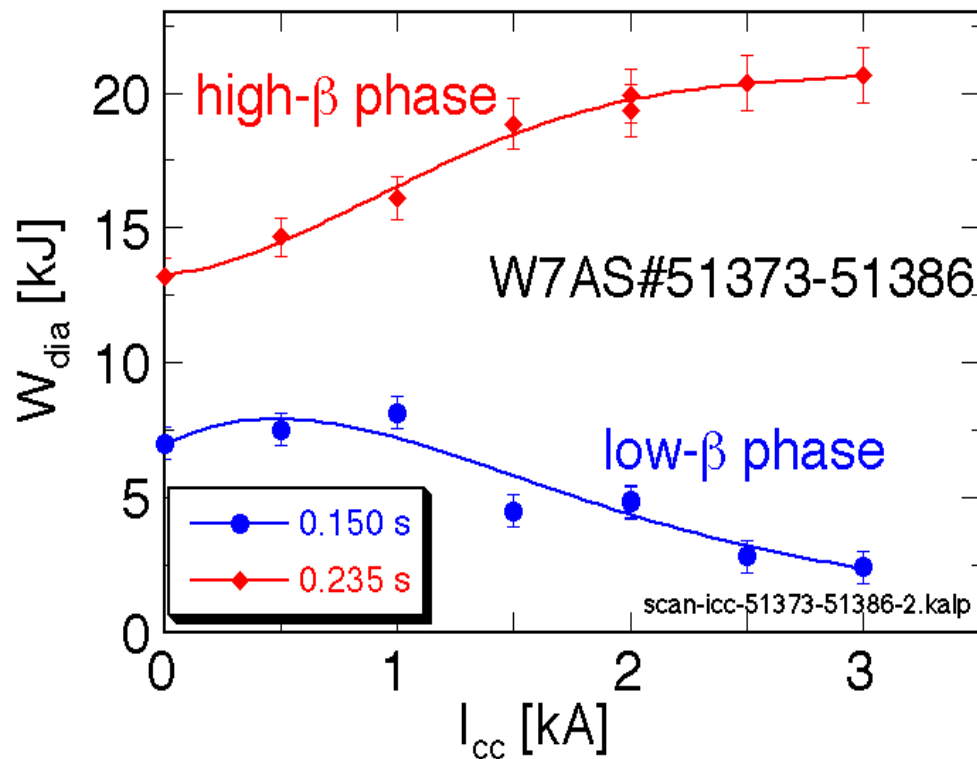
- Constraint on highest- β may be due 'equilibrium β -limit' where axis shift $\sim \frac{1}{2}$ of plasma minor radius ??
- In previous calculations, this shift generated large equilibrium islands = $\Rightarrow$ confinement degradation
- Calculations underway to assess flux-surface deterioration

Control Coils Designed to Control Edge Islands



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

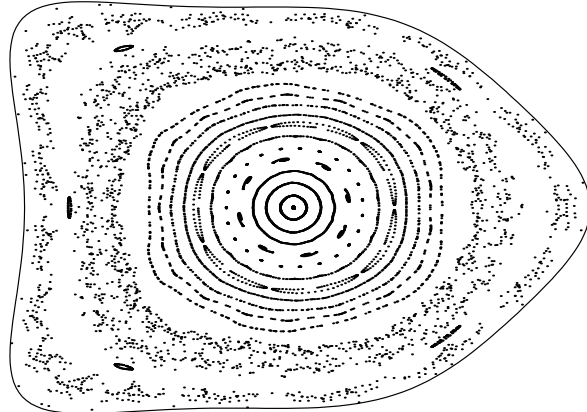
β is sensitive to Control Coil Current



- $\langle B \rangle = 1.25$ T
- 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

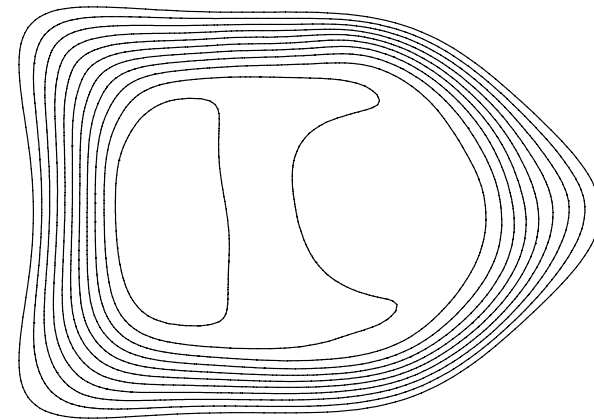
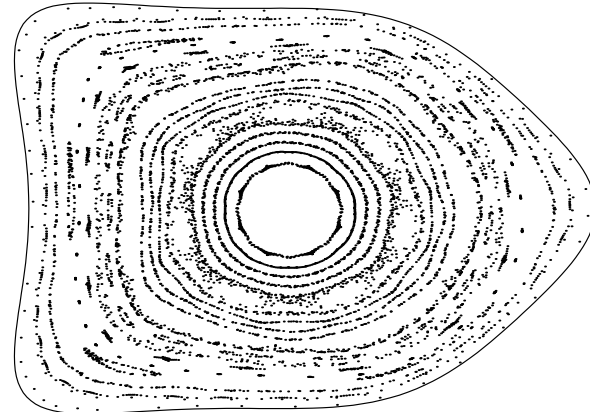
Single Fluid (resis. MHD)



$$\langle \beta \rangle = 7\%$$

Magnetic
Flux Surfaces

Two Fluid



ExB Flow
Surfaces

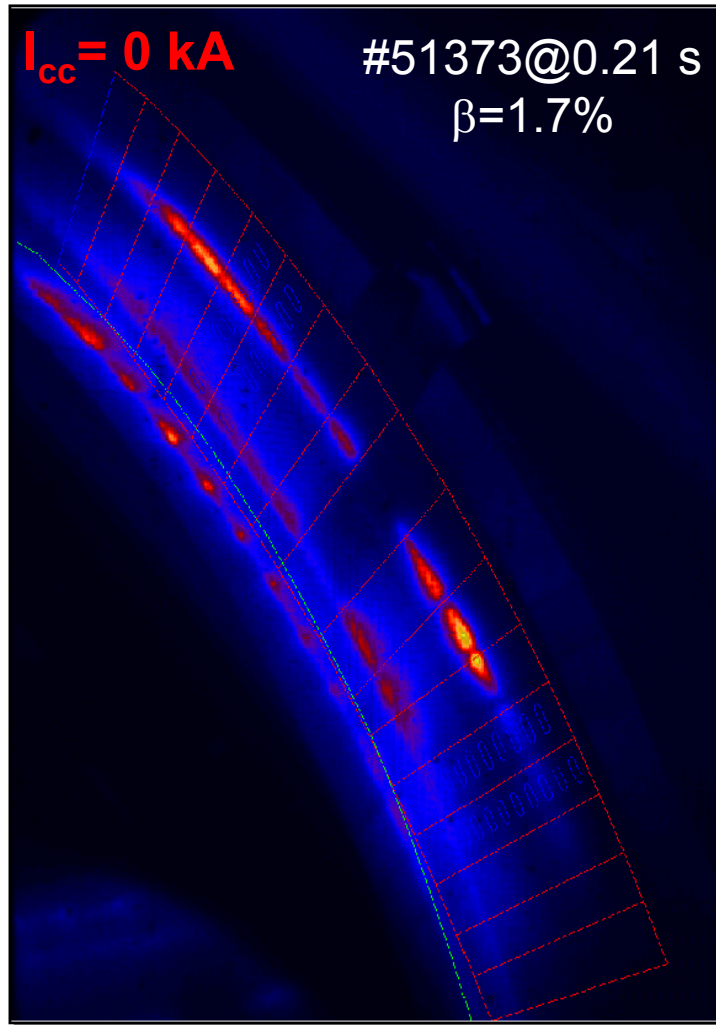
L. Sugiyama, H. Strauss

- 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.

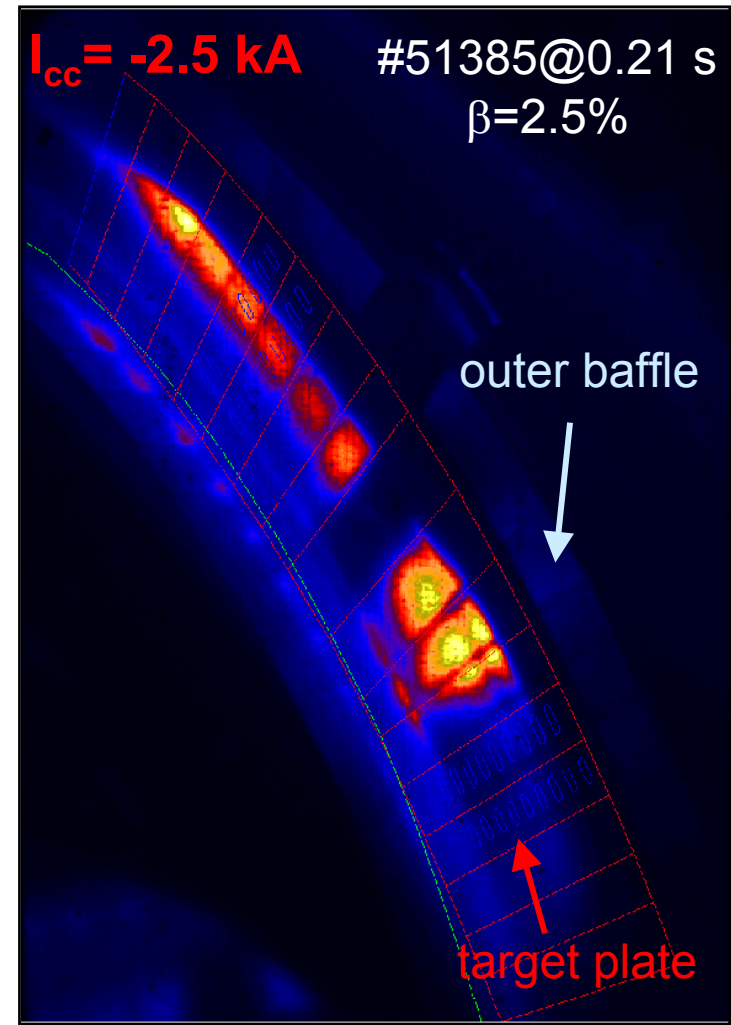
Conclusions

- 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 ARIES-CS? What is maximum β ?
 - Tokamak criteria are not consistent with stellarator experiments !

Divertor H_α Emission Indicates Edge Structure

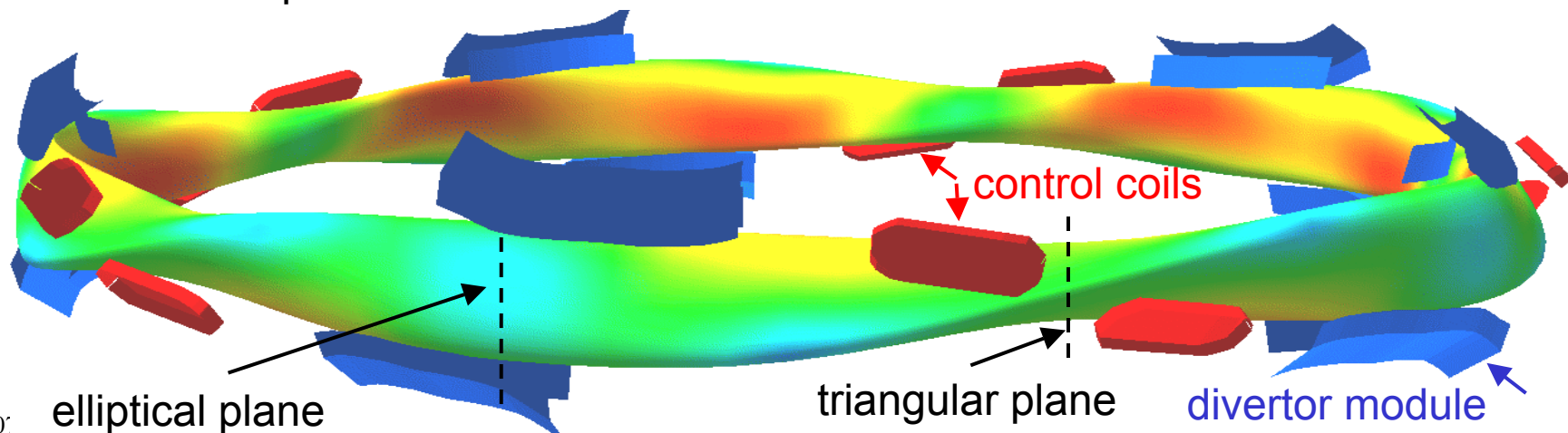
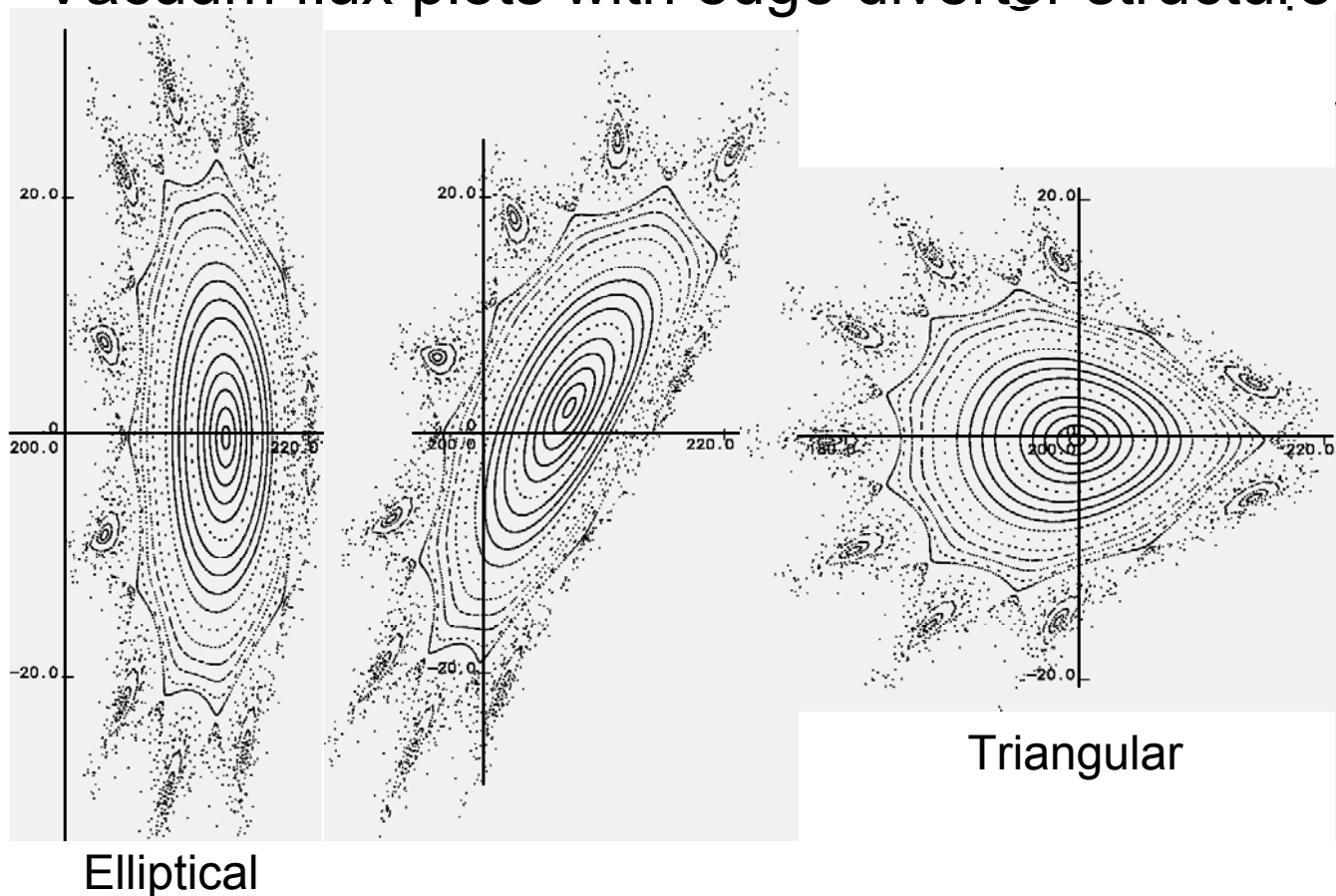


Narrow Deposition Pattern
indicates Presence of Edge
Islands



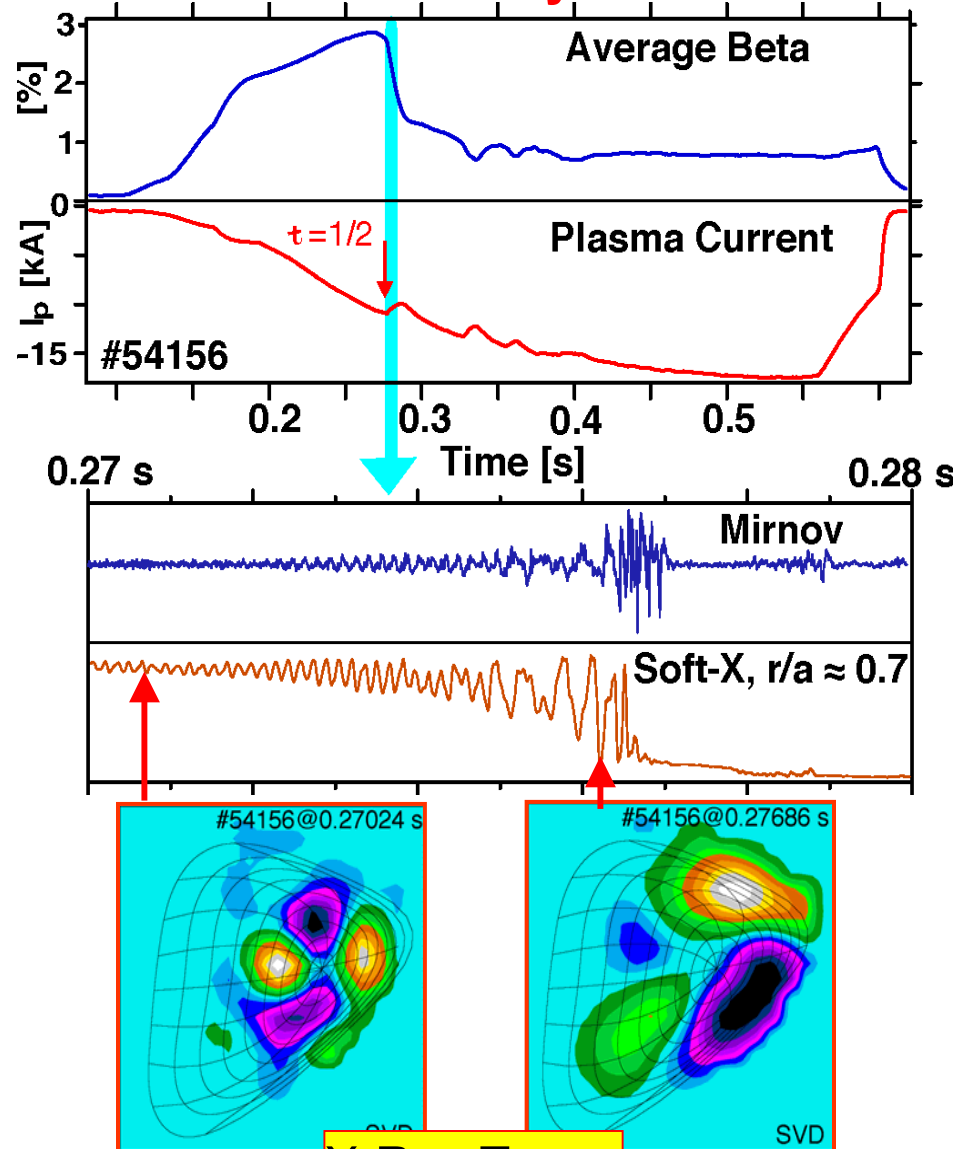
Broad Deposition Pattern
indicates smooth Flux Surfaces

Vacuum flux plots with edge divertor structure



Significant $I_p < 0$ makes Tearing Modes at $\iota = 1/2$

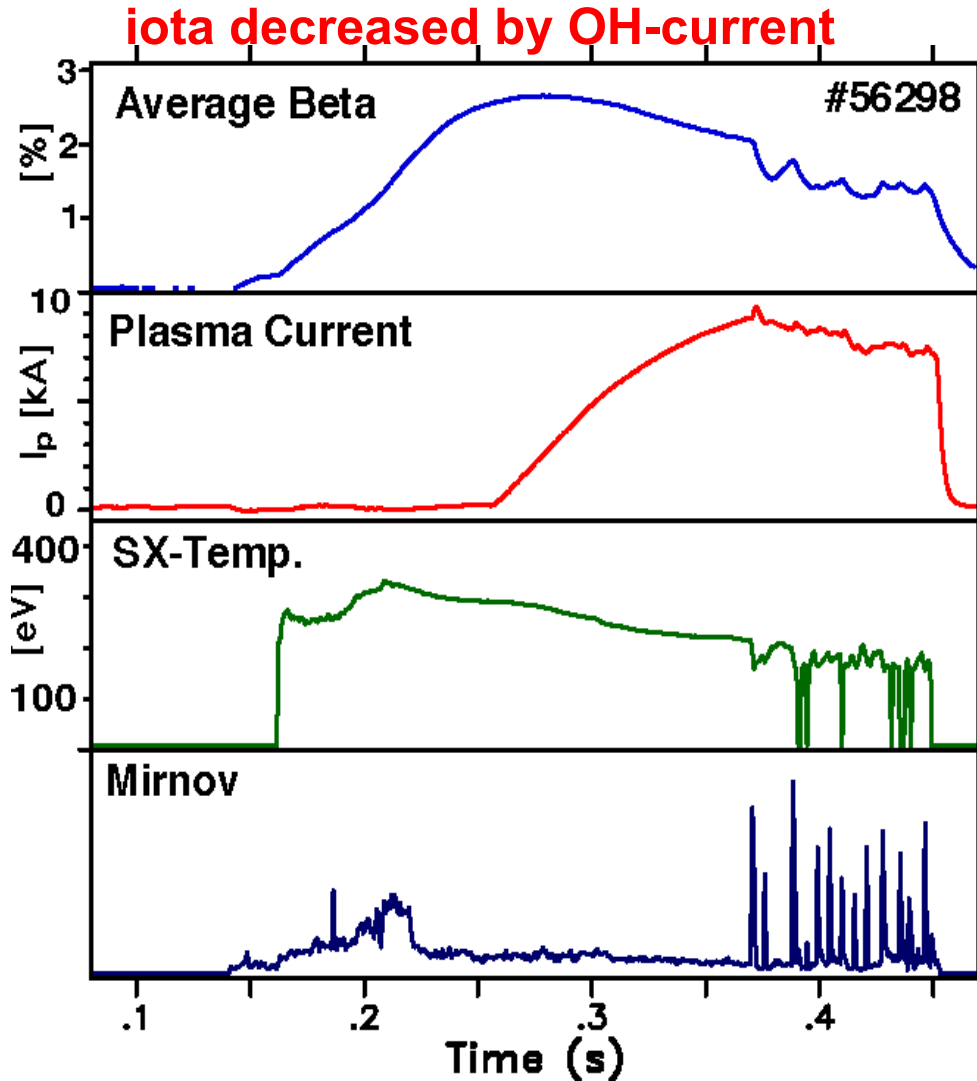
ι increased by OH-current



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

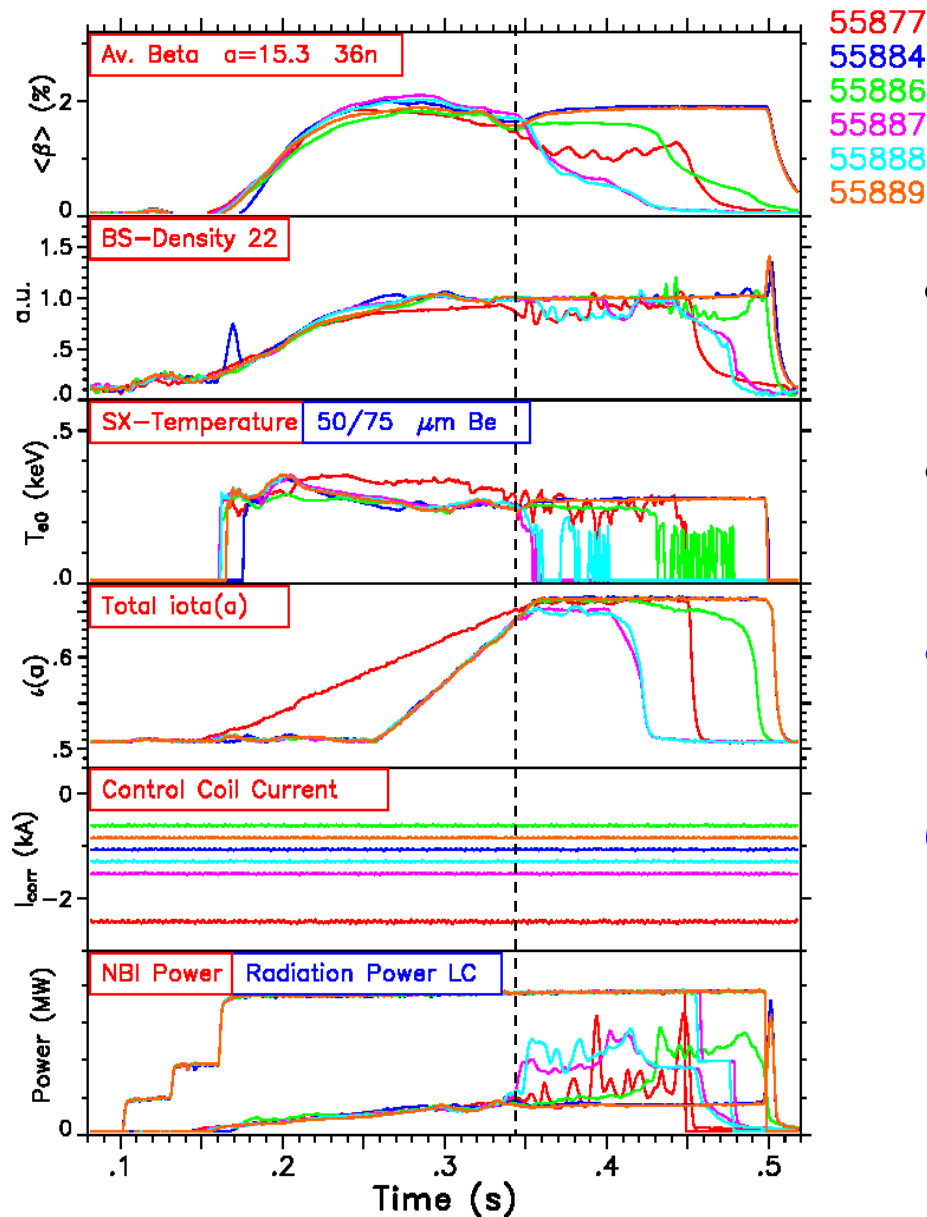
X-Ray Tomo.

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 stability
- As T_e drops $< 200\text{eV}$, see high-mode number MHD activity.
“Low T_e mode”

$I_p < 0$ Tearing Modes can be Stabilized Using Control Coils !

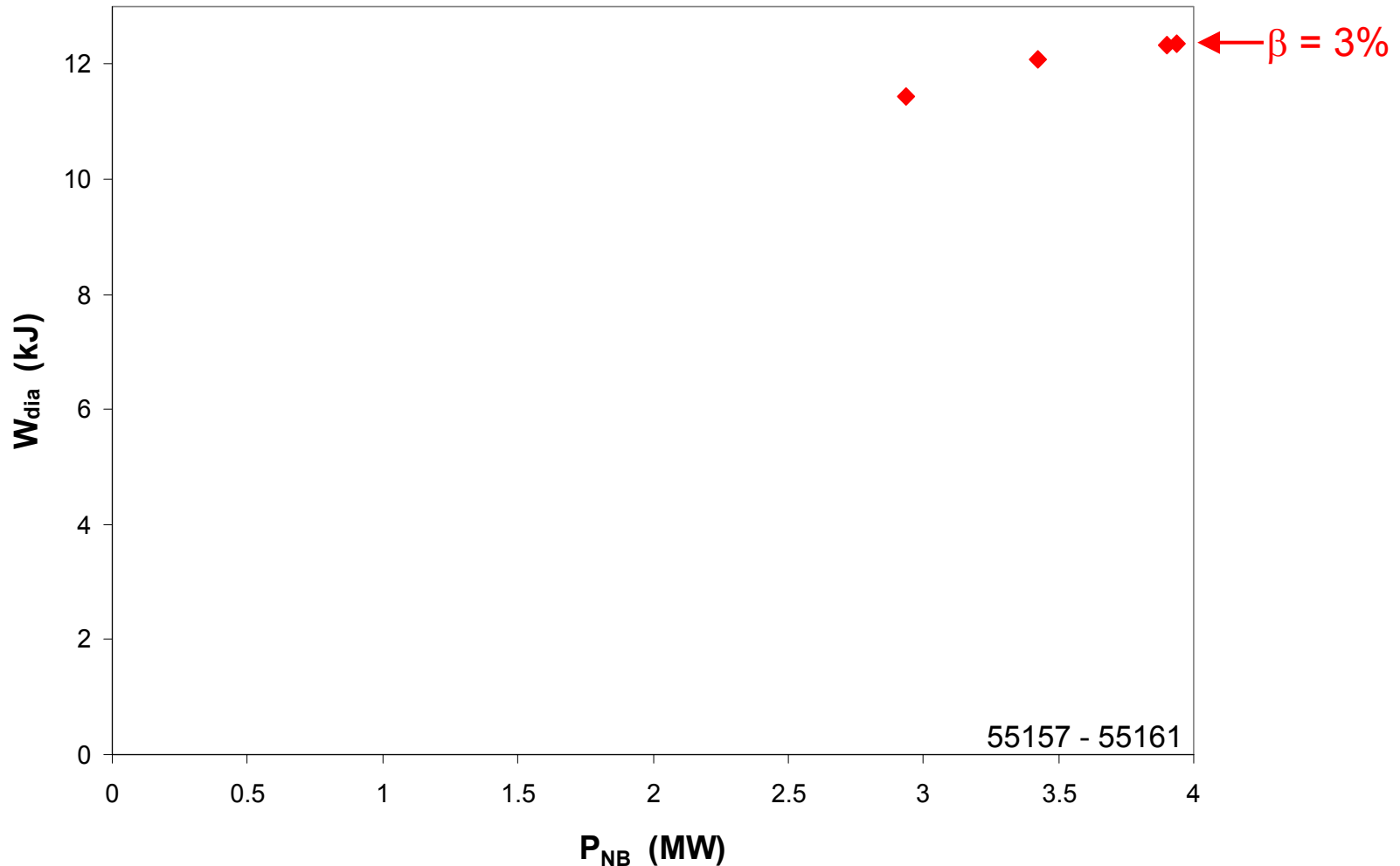


- $I_p = -7\text{kA}$, generates tearing mode at $iota=1/2$
 - No tearing mode observed with control coil current $I_{cc} \sim -1\text{ kA}$
 - Is external B_r perturbation stimulating tearing mode??
- (e.g. Seed island for neoclassical tearing)
- then being repaired by choice of I_{cc}

Parametric Variations of Maximum β

- Accessible β is sensitive to magnetic equilibrium on W7AS
- Systematic scans of the available equilibrium parameters were used to optimize and understand confinement
- Parameters varied:
 - Control-coil current (islands)
 - External rotational transform (portion from coils)
 - Magnetic field strength (B)
 - Radial position (B_z)

β depends weakly on P_{NB} at low B



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