Experimental Stellarator High-β Plasmas

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ARIES Project Meeting

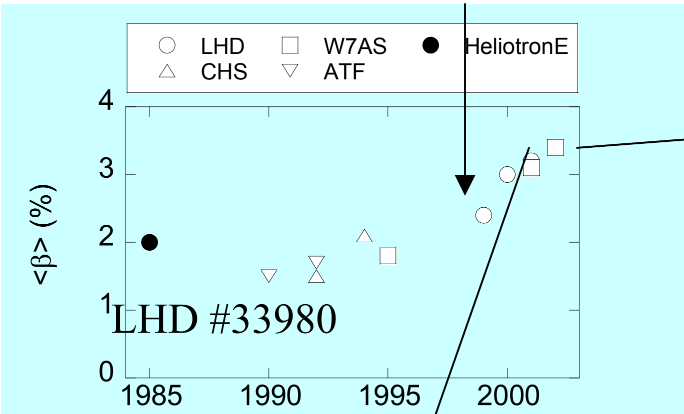
PPPL

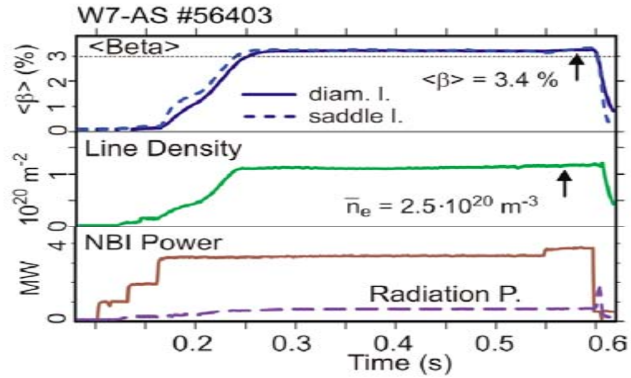
3 December 2003

Progress of Beta Values Achieved in Stellarator/Heliotron

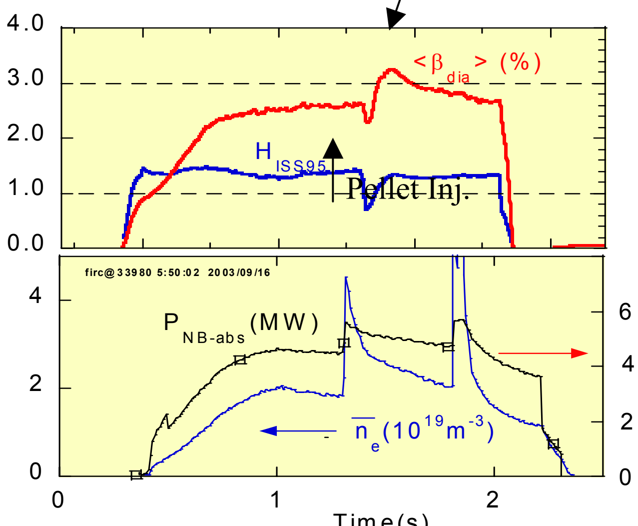
K. Watanabe, ISW 2003

LHD exp. started from 1998.





(ι_a~0.5, B_0=0.9T, P_{INJ}~3.2MW)



(R_{ax}=3.6m, B_0=0.5T, with Pellet Inj.
$n_e \sim 3 \times 10^{19}$ m^{-3}, P_{abs} = 5.6 MW, $H_{DL\text{-}eff(sudo)}$~110%)

Achievement

LHD; $<\beta>$=3.2% with Pellet(2001)

$<\beta>$=3.0% (2001)

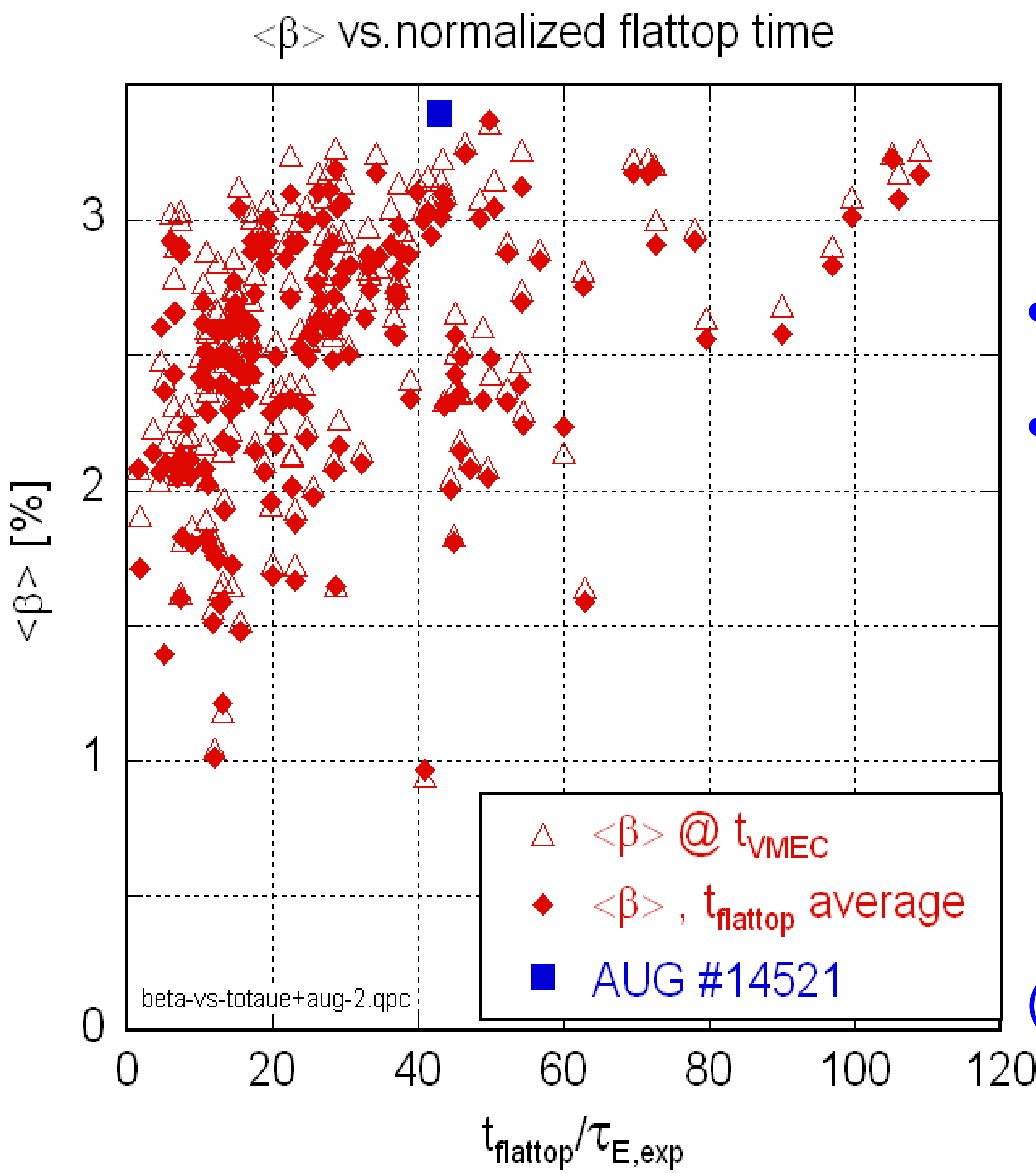
Good confinement due to mainly scale up of device size

W7AS; $<\beta>$=3.4% (2002)

Finding confinement improvement close to density limit

Make sure that the achieved beta values (~2%) was not limited by MHD phenomena before LHD.

Parameter Range



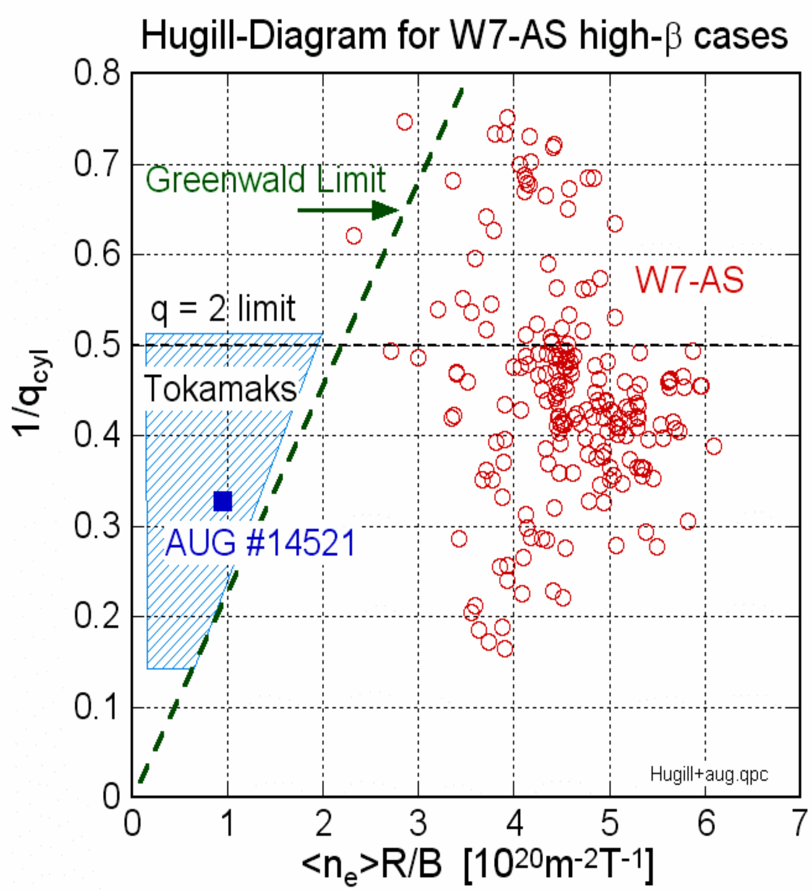
- number of cases with ⟨β⟩ > 3 %
- discharges can be maintained over many confinement times

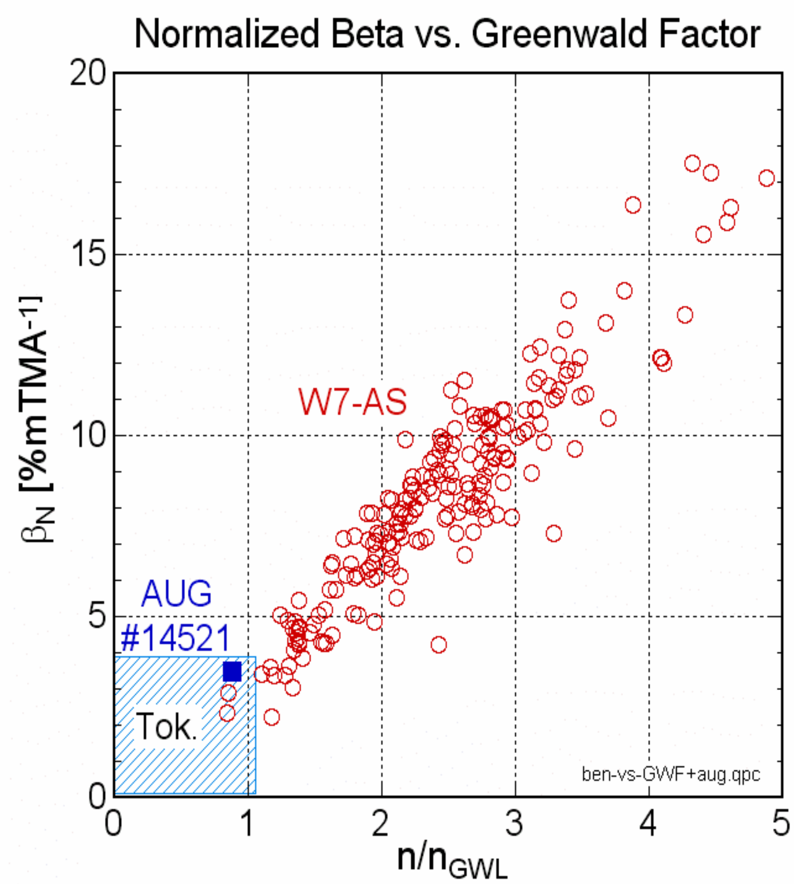
→ steady state capability of confinement regime demonstrated

typ. shot of Asdex Upgrade (AUG) courtesy of H. Zohm

Comparing to Tokamak Operation Diagrams ... ?

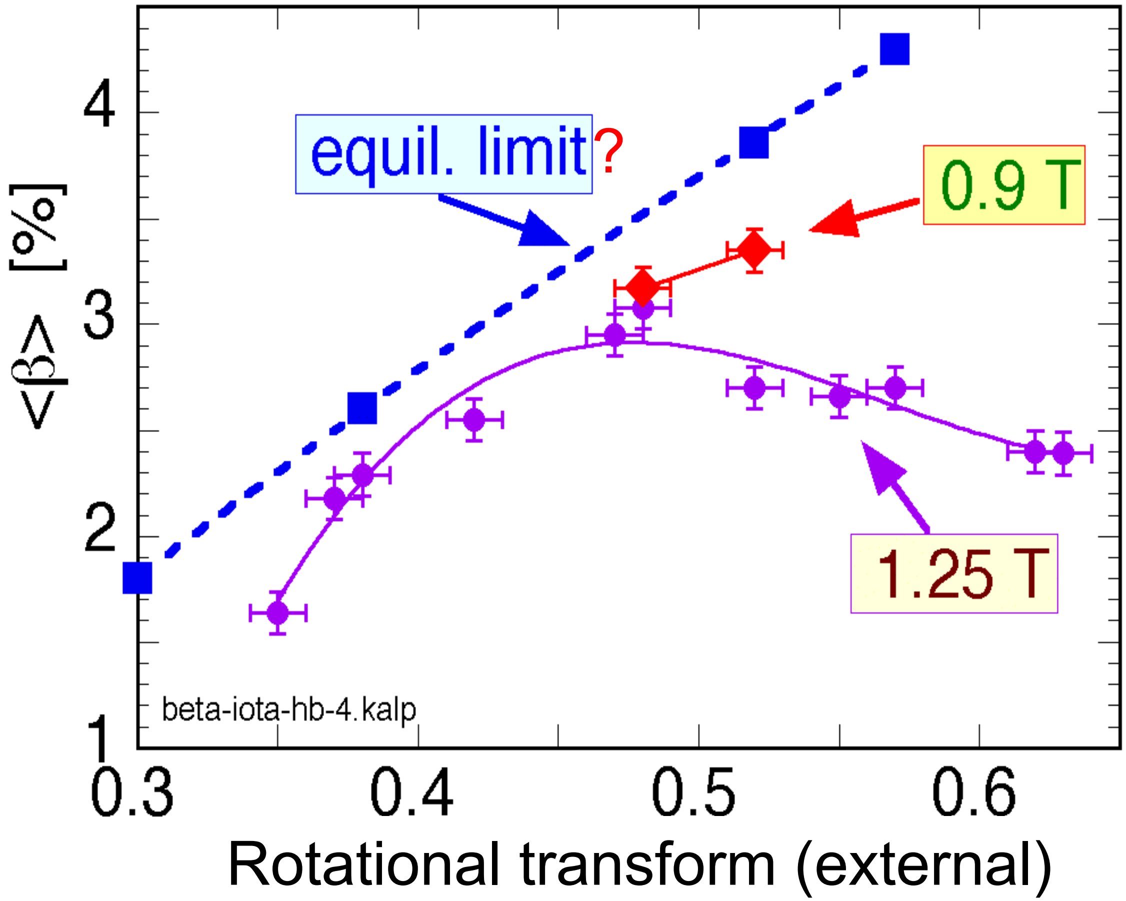
… by using equivalent toroidal current that produces same edge iota





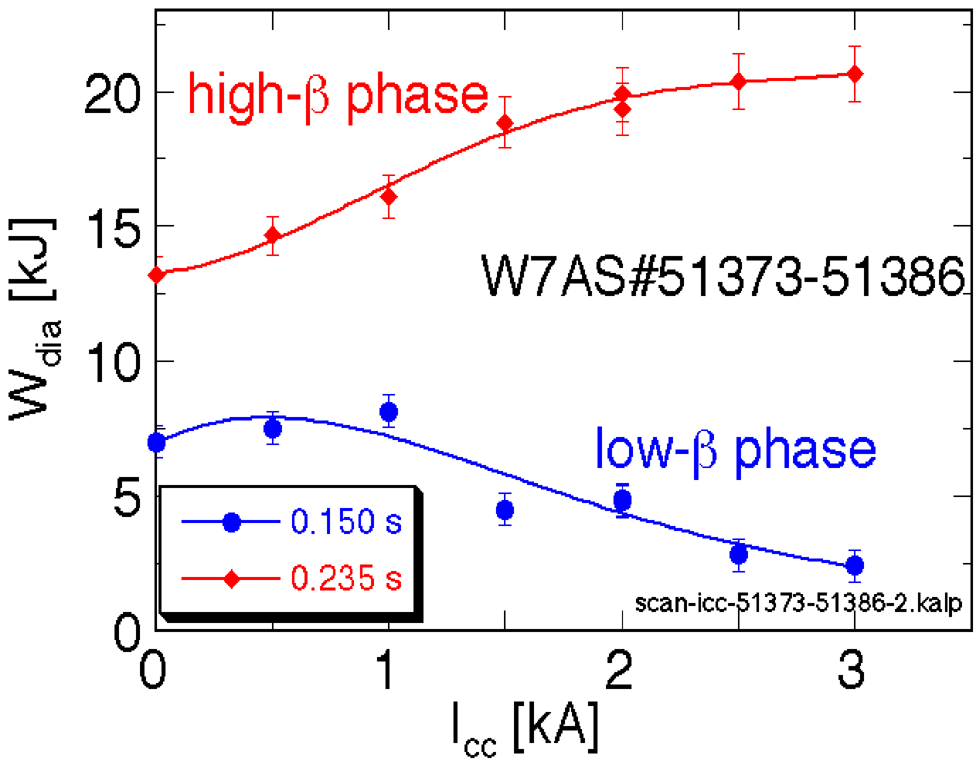
- high-β is reached with high density (favourable density scaling in W7-AS)
- All **W7-AS** data points beyond operational limits of tokamaks, **no MHD limits**

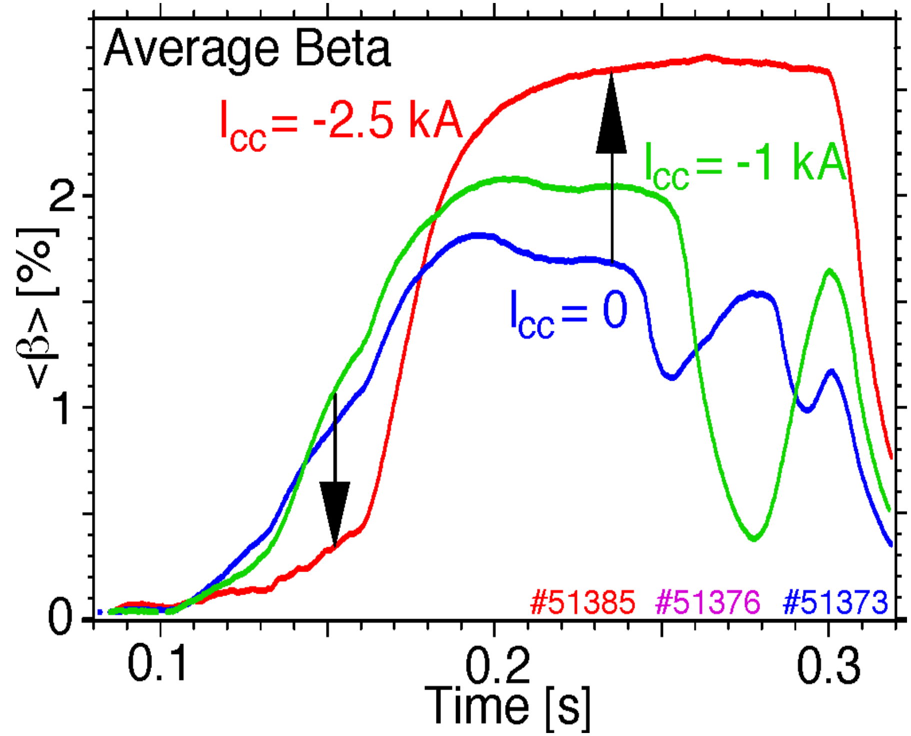
β May be Limited by Deterioration of Equilibrium



- 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

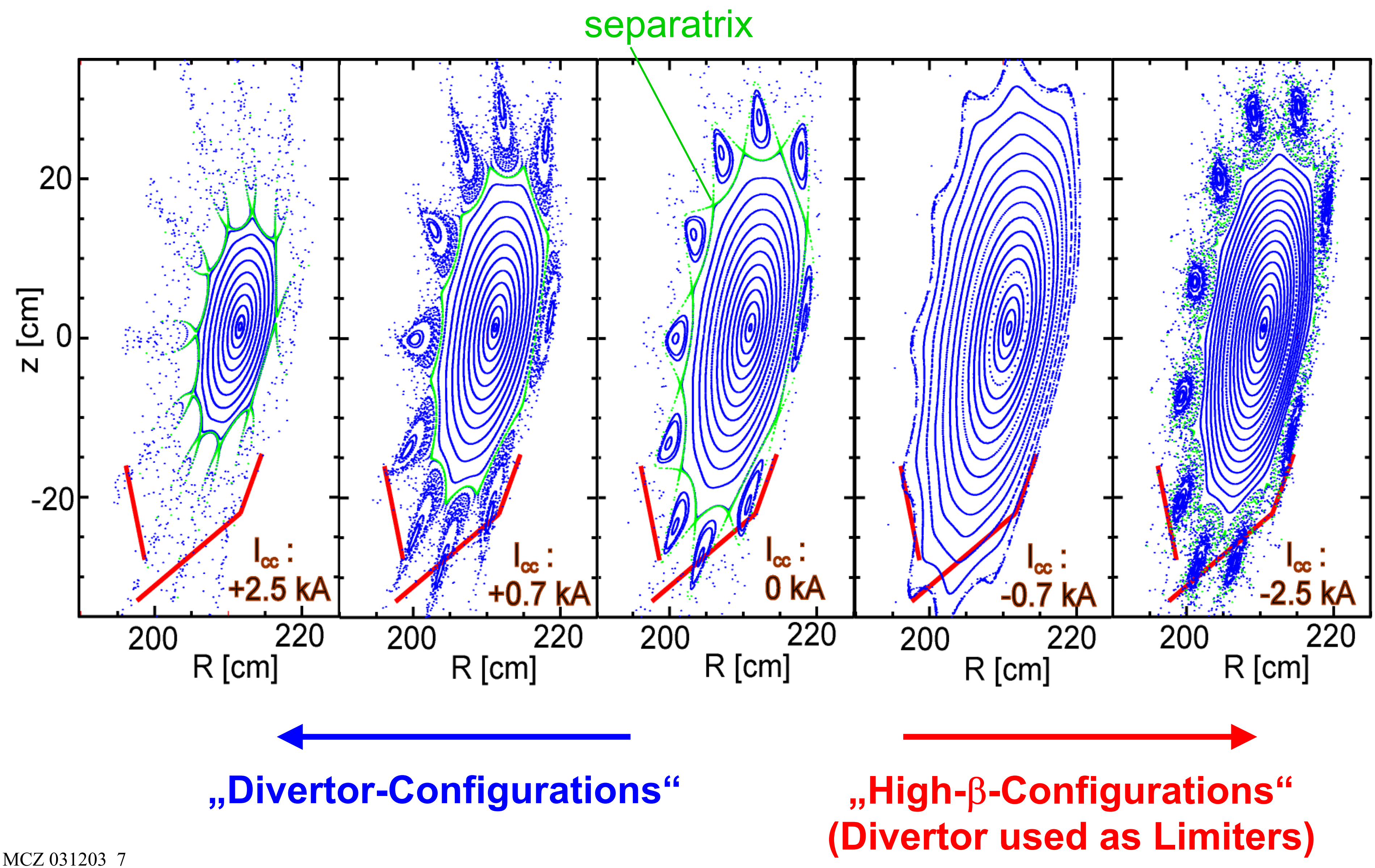
β is sensitive to Control Coil Current





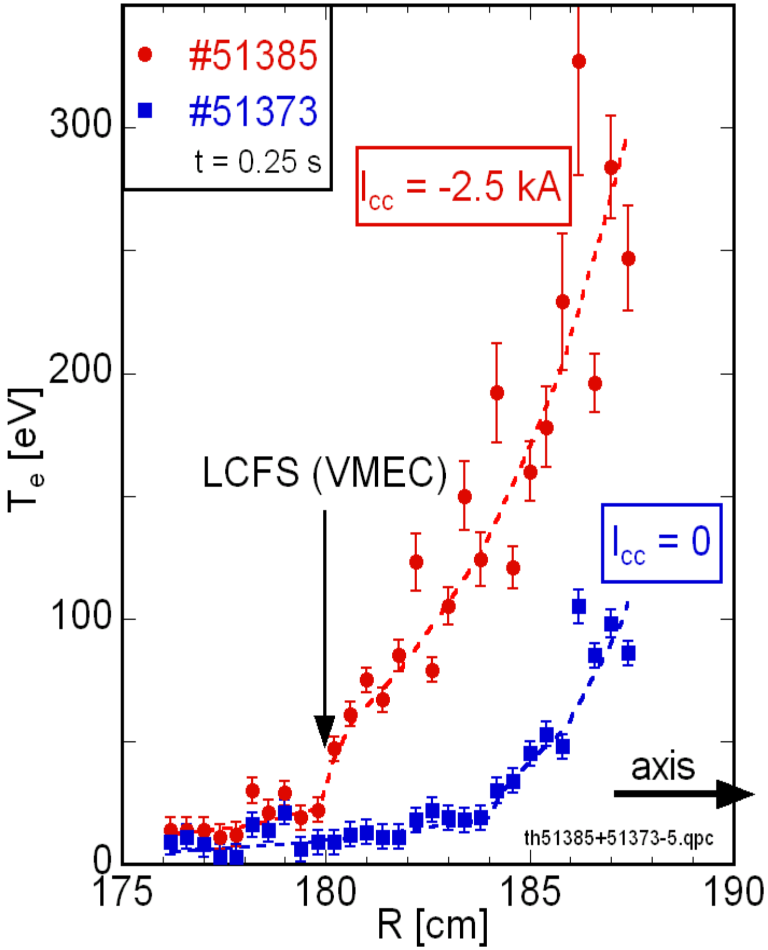
- <B> = 1.25T
- Low-β phase approximately agrees with vacuum calculations
- High β phase optimizes with much higher Control Coil Current
- Indicates the importance of islands to confinement.
- Preliminary PIES calculations: all mainly stochastic at high β

Effect of Control Coils
(Vacuum Configuration iota ≈ 1/2)

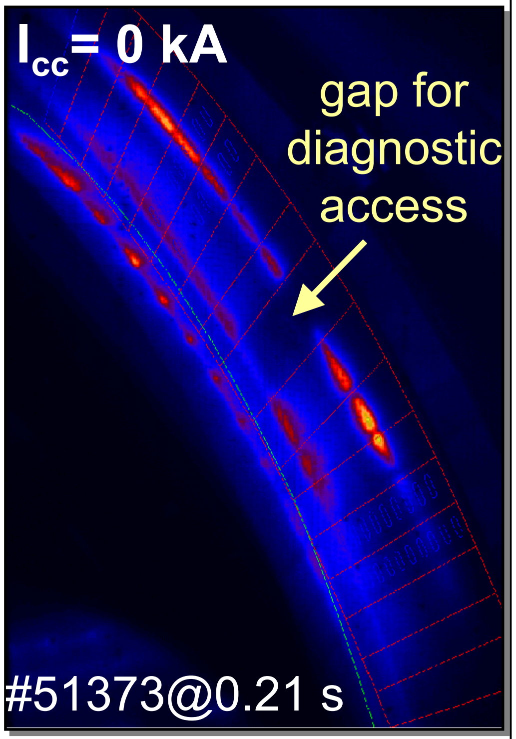


Effect of Control Coils at iota ≈ 0.5

T_e Profiles (Edge Thomson)

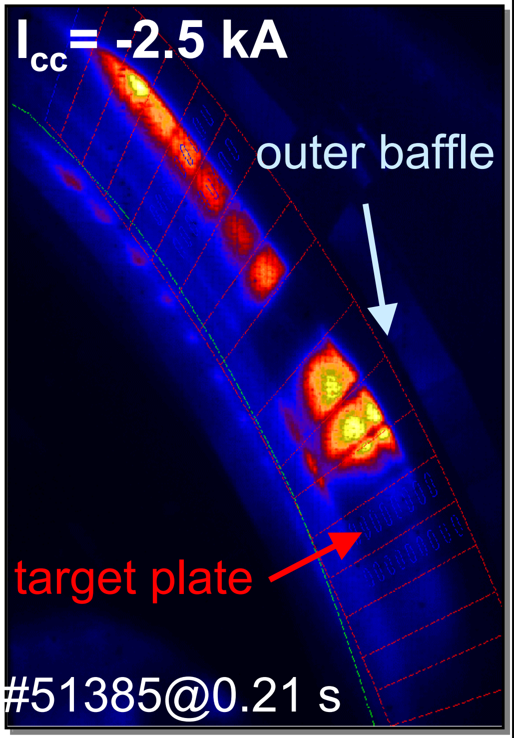


H_α - light in front of the target plates



narrow deposition pattern: presence of edge islands

narrow T_e, n_e, profiles



broad deposition pattern: smooth flux surfaces

broad T_e, n_e, profiles

- measurements indicate pressure induced islands or ergodic region at the edge

Initial PIES-Calc.*) of W7-AS High-β Equilibria

$\langle\beta\rangle = 1.8\ \%,\ I_{cc} = 0$

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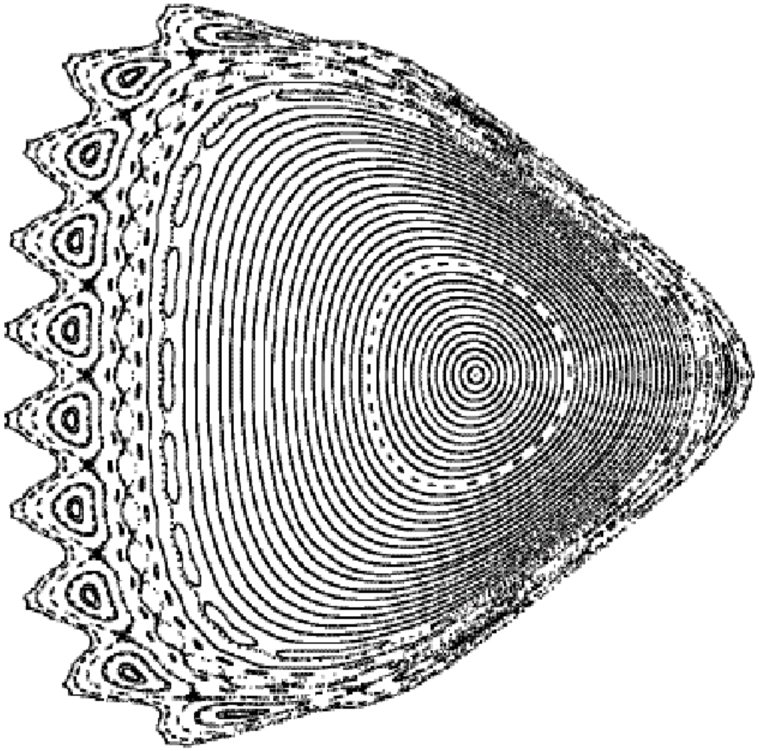

$\langle\beta\rangle = 2.0\ \%,\ I_{cc} = -2.5\ \mathrm{kA}$

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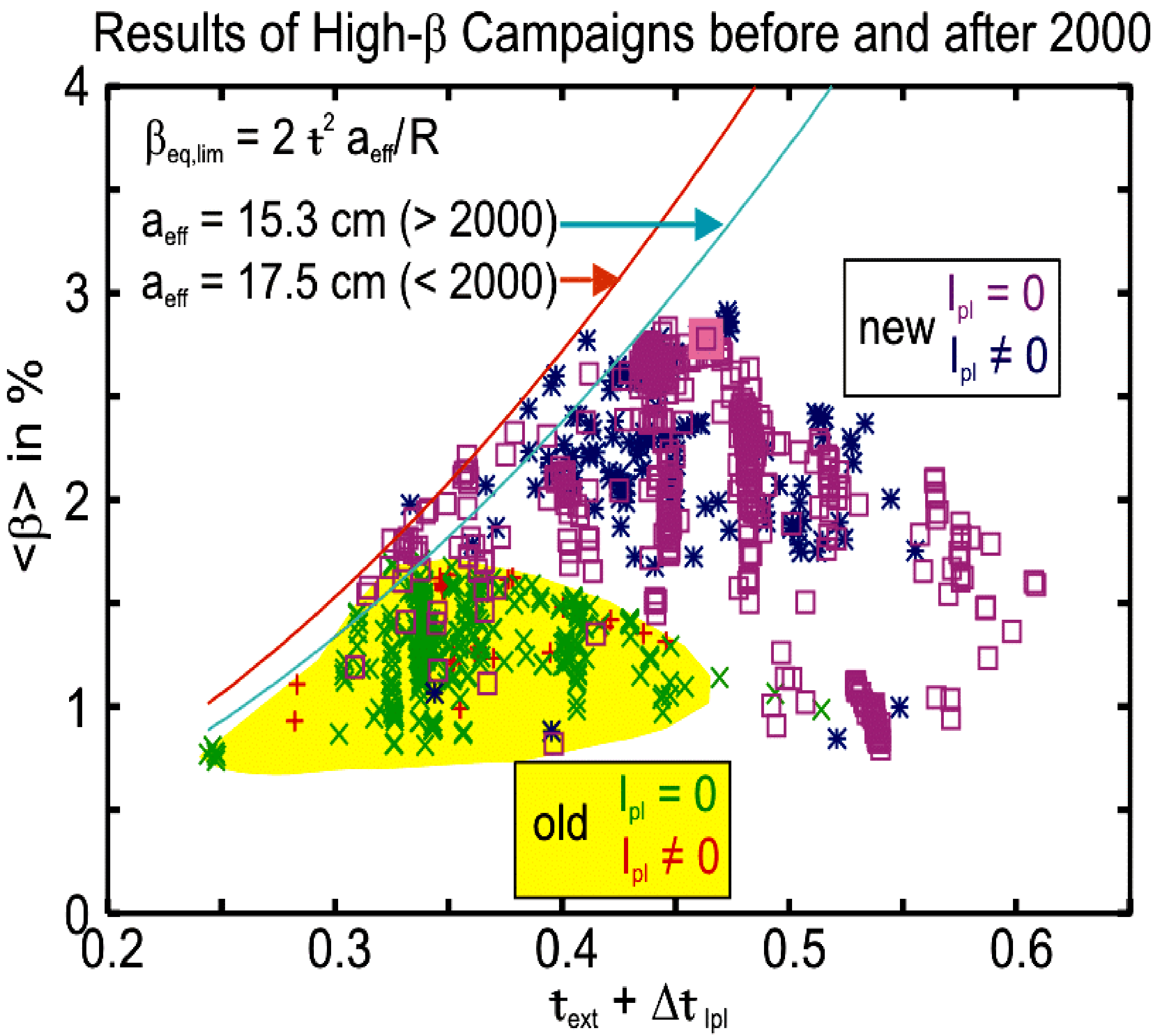
*) A. Reiman, M. Zarnstorff
(modified PIES, preliminary !)

- High-β equilibria with island regions and lost boundary flux surfaces
- Uses experimental pressure profile, no further flattening
- Standard PIES runs with flattening are stochastic

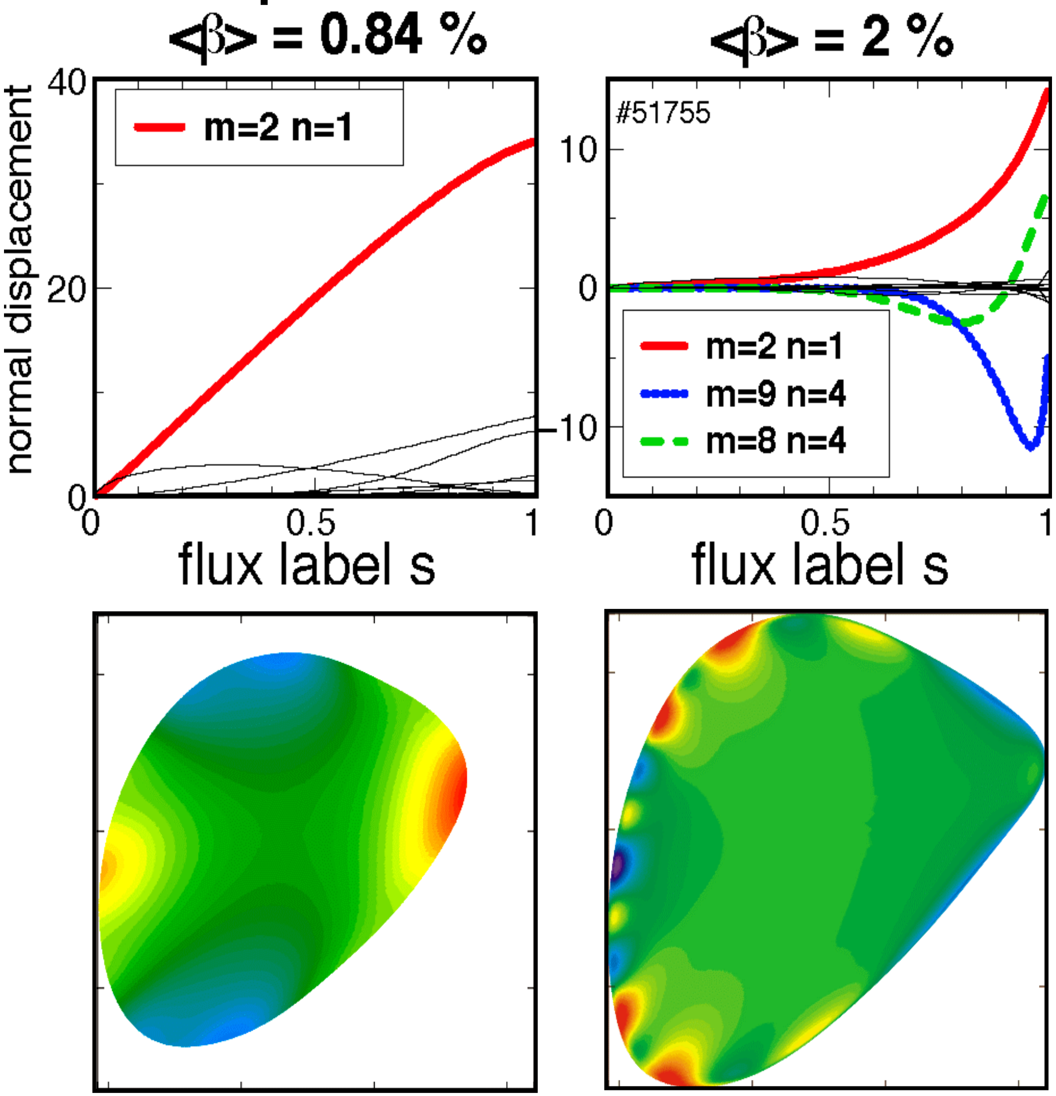
Beta Range Similar With and Without Current

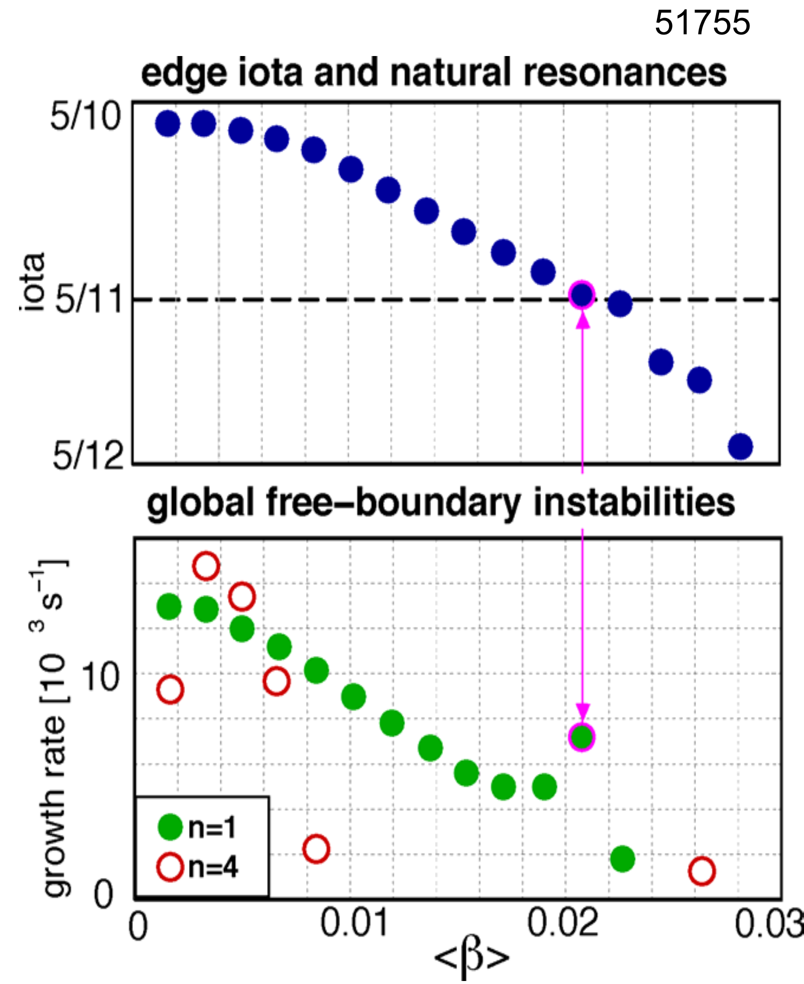


- before 2000: mainly low-iot (edge islands avoided)
- after 2000: higher iota, edge islands compensated, increased absorbed P_{NBI}
- limitation of <β> at low iota by equilibrium
- Plasmas with current can be unstable to tearing modes

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

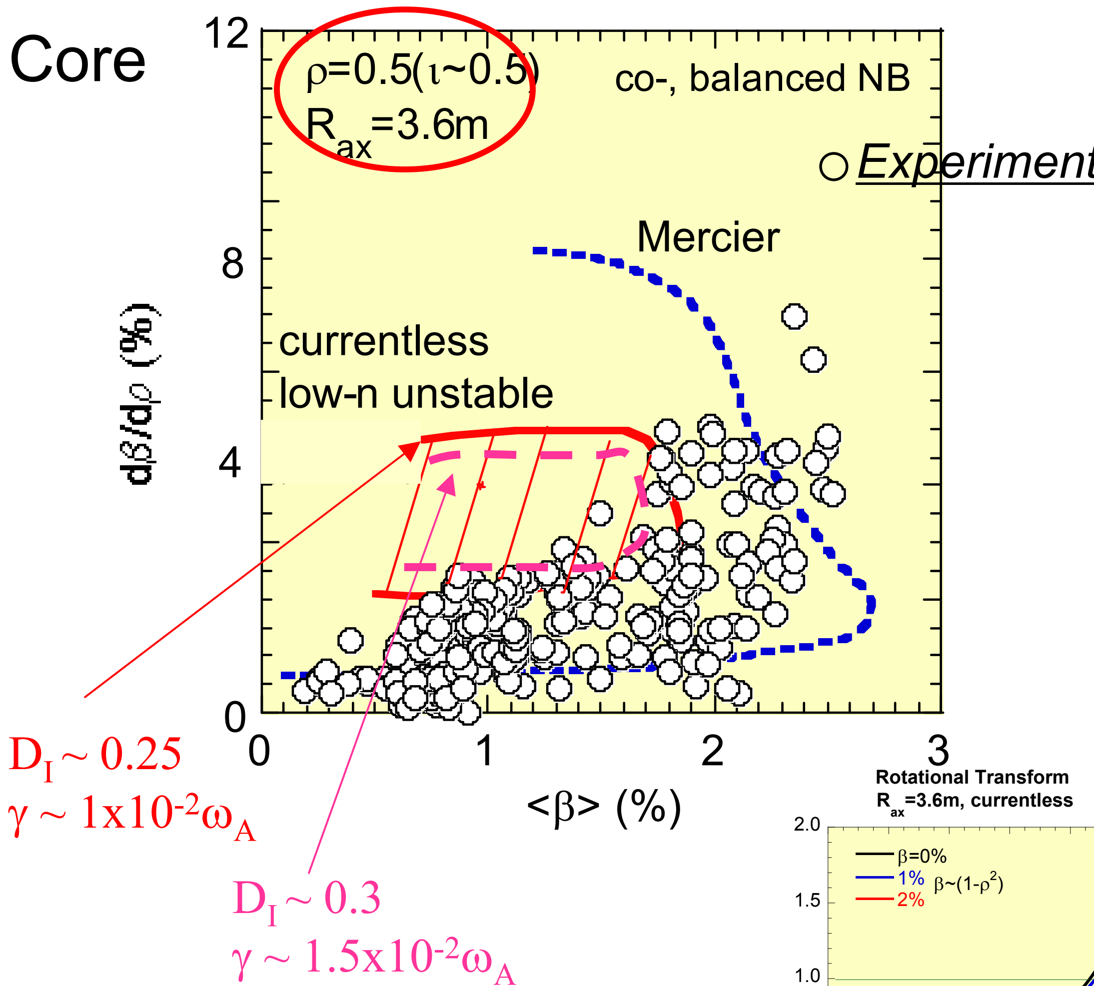
– C. Nuhrenberg

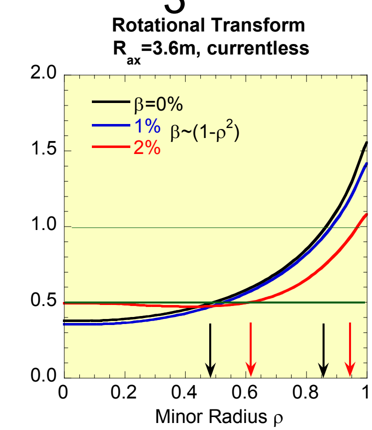
- Saturated 2/1 Mode is often observed at β ~ 2%,
- Why does it saturate?

Role of Ideal MHD Mode in Core (R_{ax}=3.6m)

K. Watanabe, ISW 2003

Compare between observed pressure gradient and low-n unstable region based on ***linear ideal MHD mode analysis*** by TERPSHICORE code in dβ/dρ-β diagram





Core region

Gradient seems to avoid low-n unstable region.

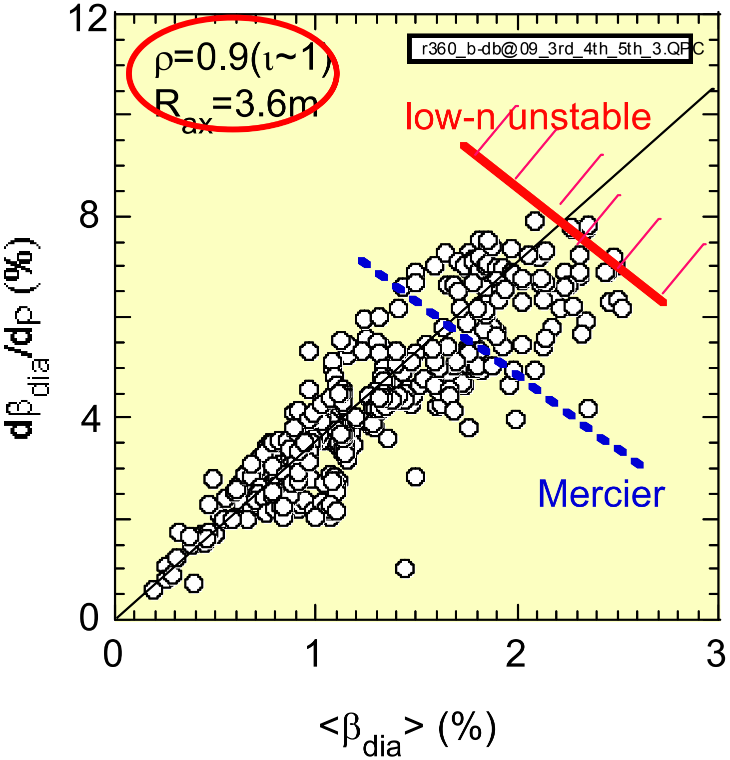
 # Gradient does not care Mercier unstable region in both core and edge regions!!

One final goal of this work is to obtain a criterion (parameter) that low-n mode is effective by using on D_I or γ.

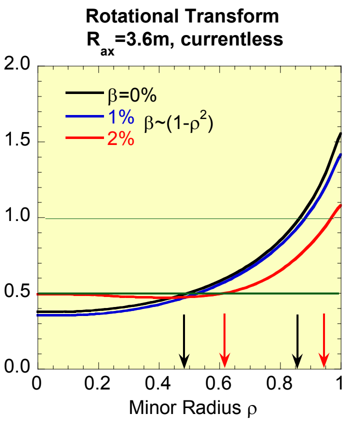
Role of Ideal MHD Mode in Edge (R_{ax}=3.6m)

Compare between observed pressure gradient and low-n unstable region based on ***linear ideal MHD mode analysis*** by TERPSHICORE code in dβ/dρ-β diagram

○*Experiment*



Edge



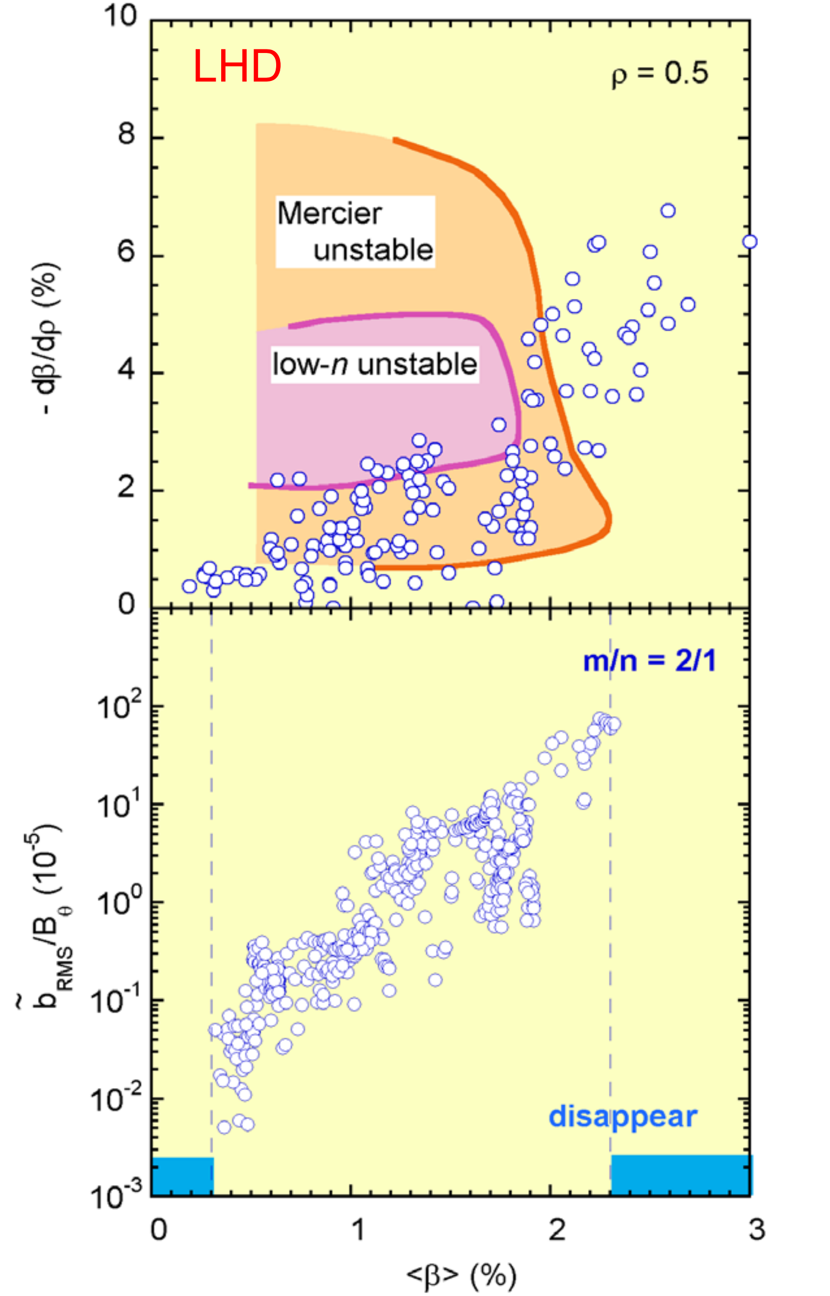
Edge region

The β-gradients are in low-n marginal region

 # Gradient does not care Mercier unstable region in both core and edge regions!!

Pressure Driven MHD does not Limit LHD

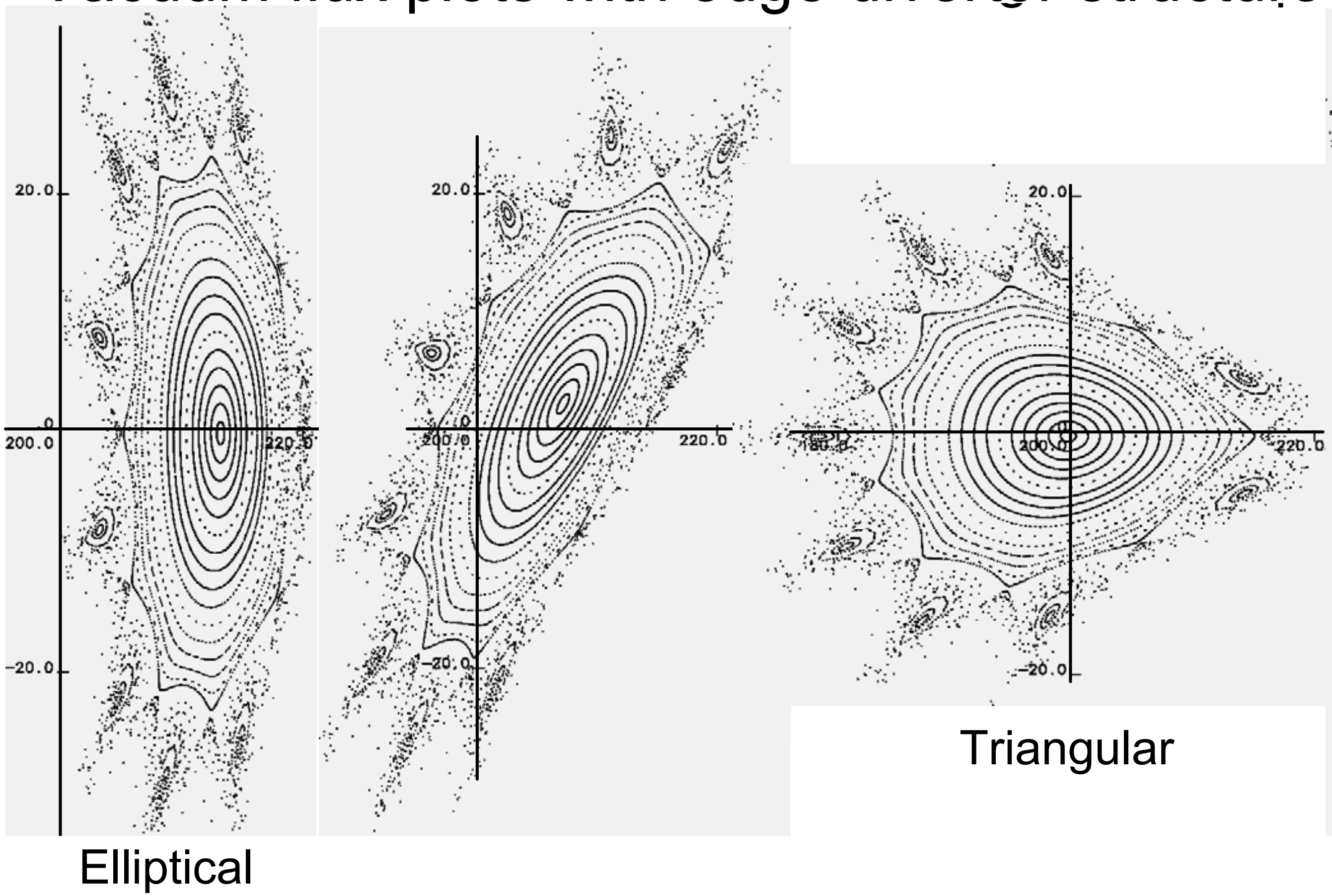
- LHD observes saturated m/n = 2/1 modes at moderate β
  - – does not prevent access to higher β
- 2/1 mode disappears for β > 2.3%
- Some correlation between observed mode and theoretical linear-stability threshold
- Typically, lower collisionality than W7AS
- Why do they saturate?

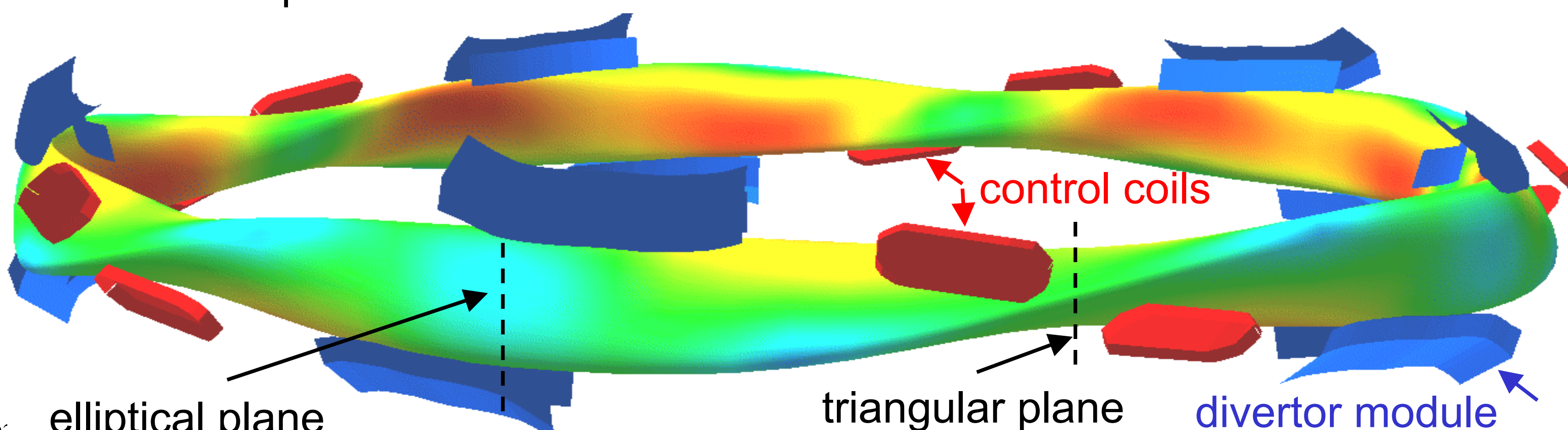


Conclusions

- Quasi-stationary, quiescent plasmas with β > 3% easily produced in W7-AS. Maximum β ~ 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
  - Flux-surface quality ('equilibrium limit') may be the limiting mechanism
- Pressure driven MHD activity is sometimes observed, but typically saturates at ~harmless level.
  - LHD and W7AS
  - Why?
- Still: How to design ARIES-CS? What is maximum β?
  - Tokamak criteria are not consistent with stellarator experiments !

Vacuum flux plots with edge divertor structure



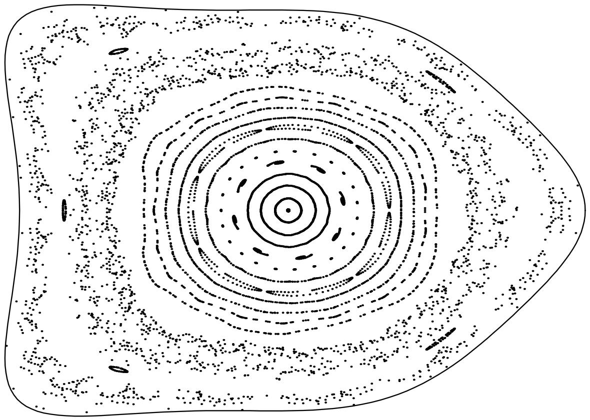


Initial Non-Linear Two-Fluid Indicate Possible Higher β-Limit for NCSX

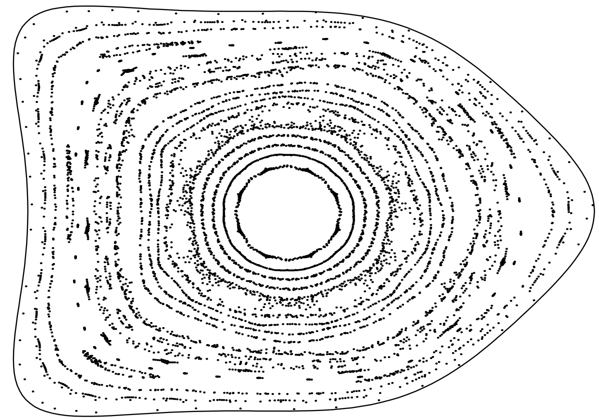
Single Fluid (resis. MHD)

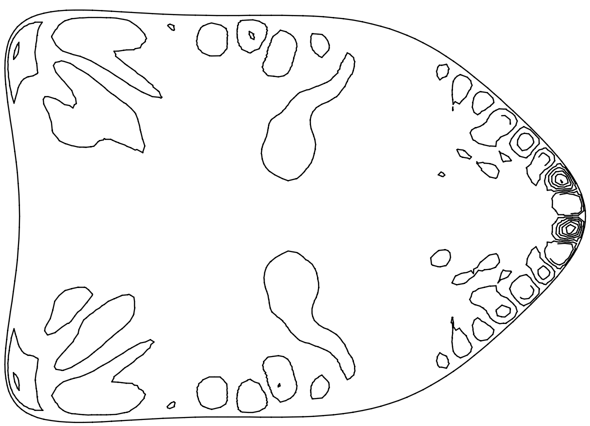
$\langle\beta\rangle = 7\%$

Two Fluid

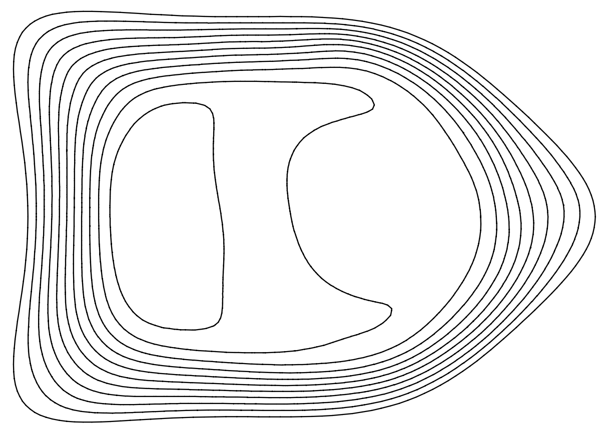


Magnetic Flux Surfaces





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.