Super Dense Core plasmas in LHD

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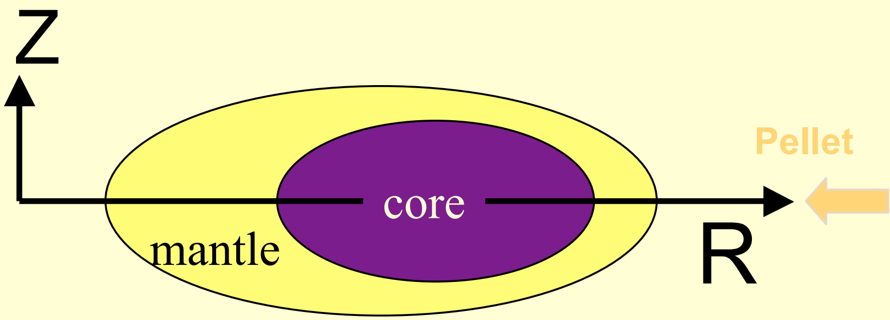
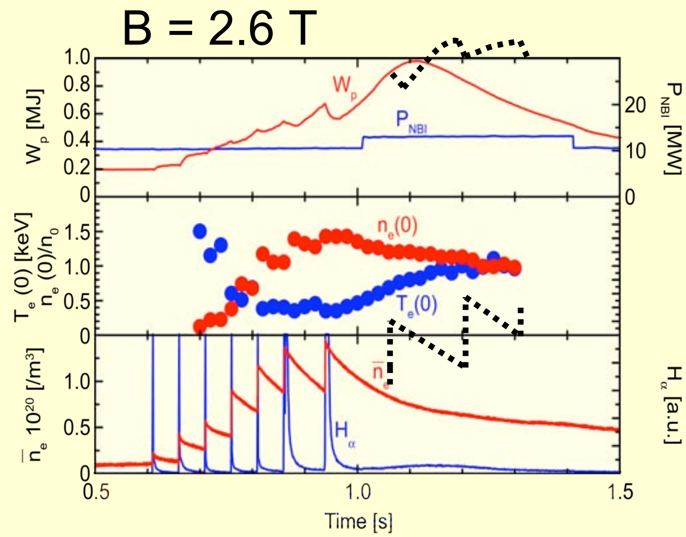
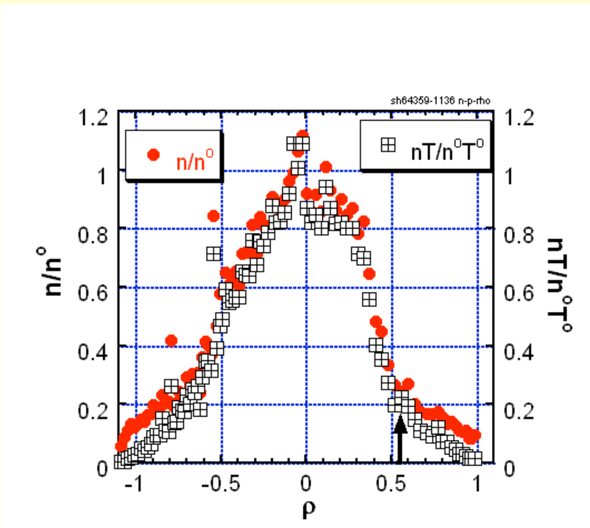
LHD Super Dense Core plasmas test both instability and confinement barrier physics

N. Ohyabu et al, PRL **97**, 055002 (2006)

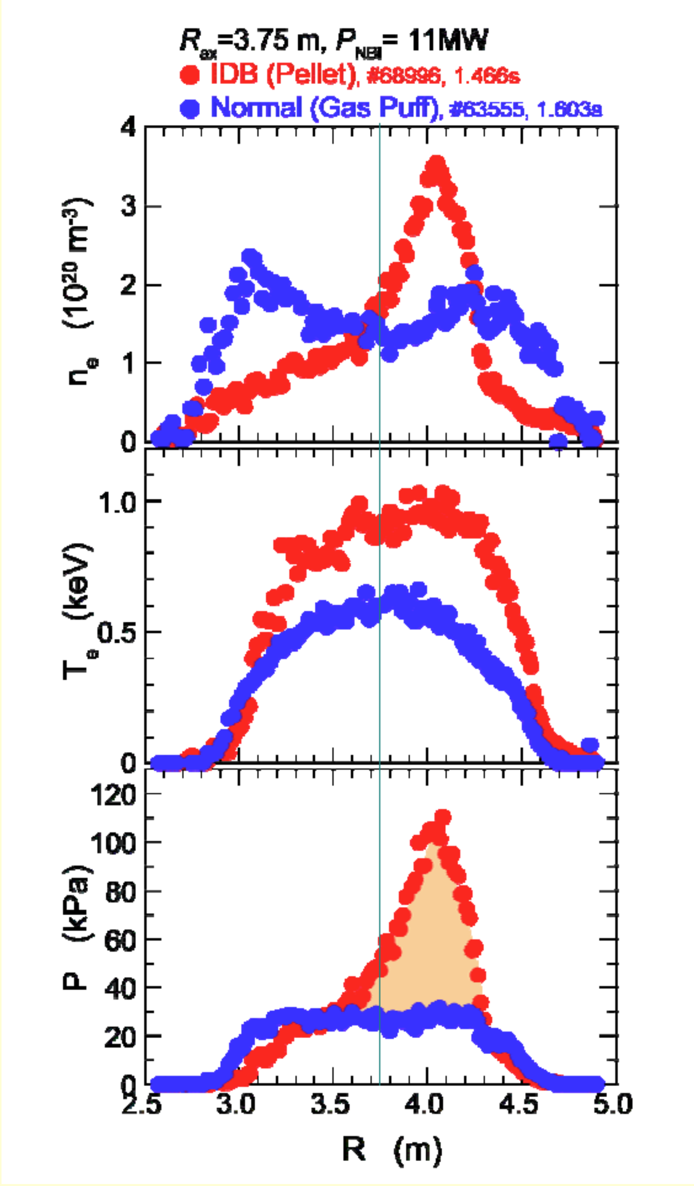






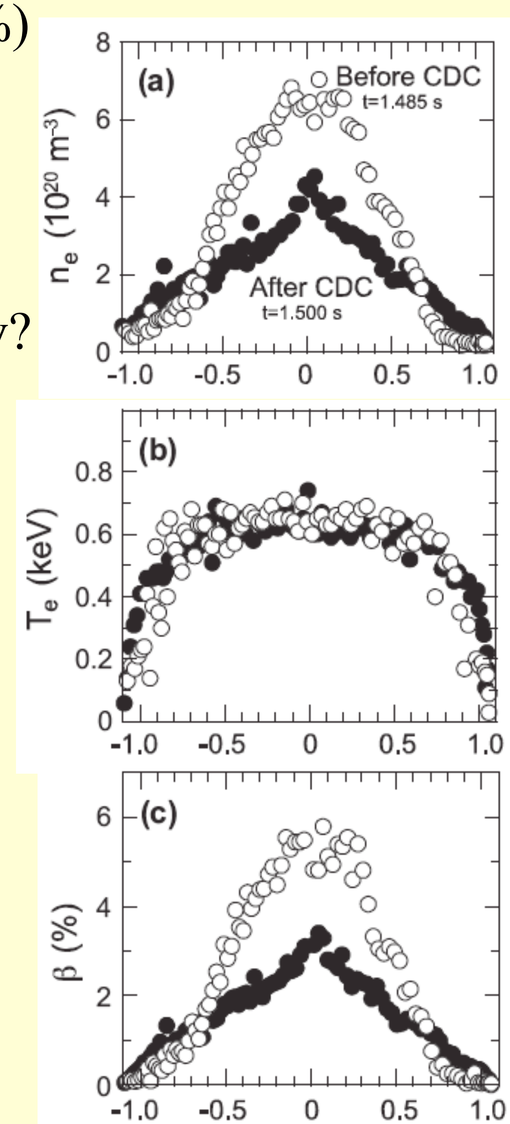
- Island or helical divertor lowers recycling
- Internal diffusion barrier @ ρ ~ 0.4-0.7
  - Very steep ∇n
  - Radial width varies with configuration, β
  - Macroscopically stable, quiescent
- Likely physics mechanisms (?)
  - ∇p drives sheared flow ⇒ confinement
  - MHD stability helps maintain steep ∇p
- High n, low T reactor ?

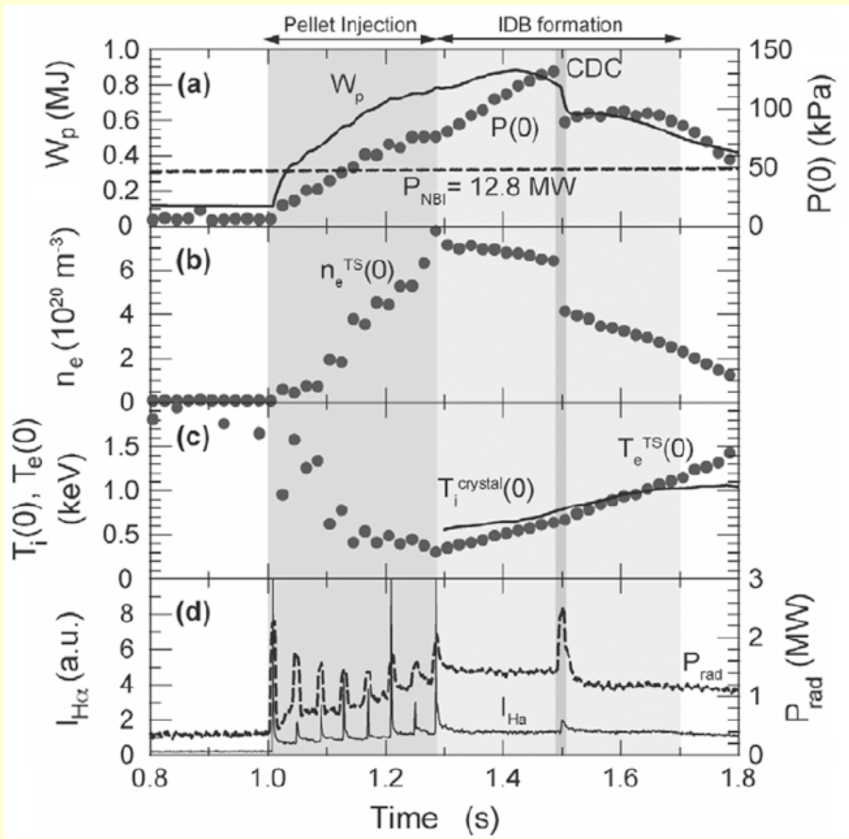
Pellet fueling ⇒ peaked n(r), p(r)



Core density collapse (CDC) events

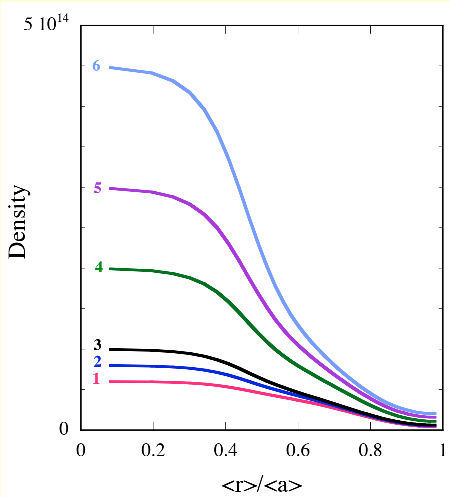
- Density, β can collapse at large Shafranov shift (~50%)
- Increasing elongation (and $\iota(0)$) reduce shift, mitigate/avoid CDC. Dynamic configuration control planned for 2009.
- Equilibrium limit? Reconnection? Flux surface quality?

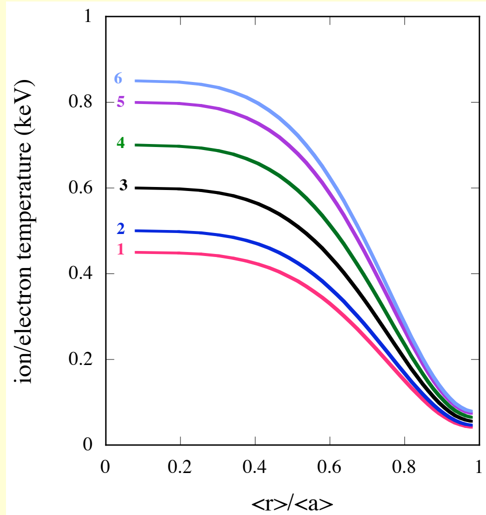




Yamada et al, PPCF, 49 (2007) B487

LHD SDC: steep ∇n ⇒ flow shear (DKES, Spong)





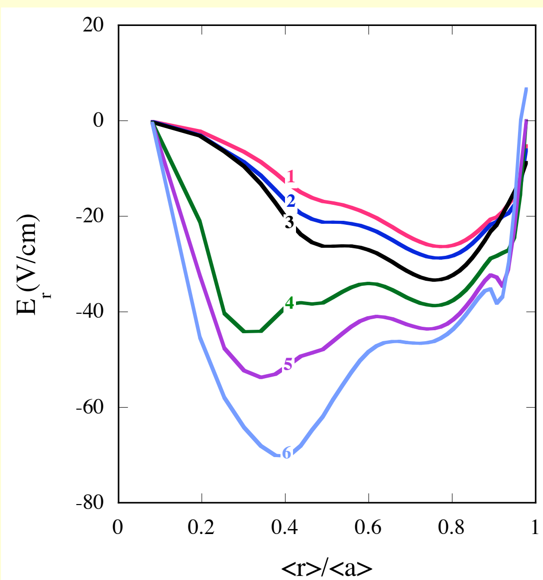
Radial force balance

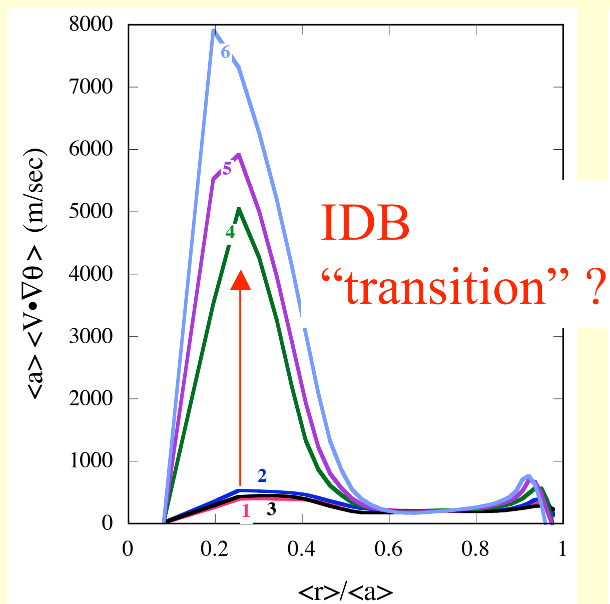
$$\frac{\nabla p}{qn} = E_r + \left(v_p B_T + v_T B_p\right)$$

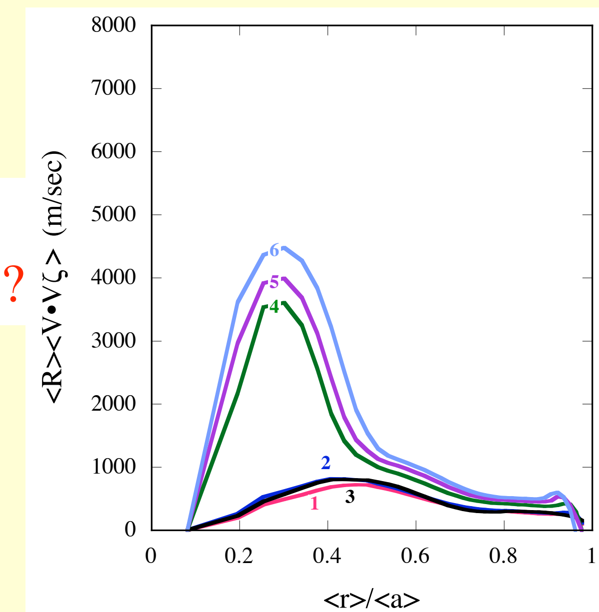
viscosity ⇒ magnitudes

Reduces turbulent xport?

Need to confirm in exp't

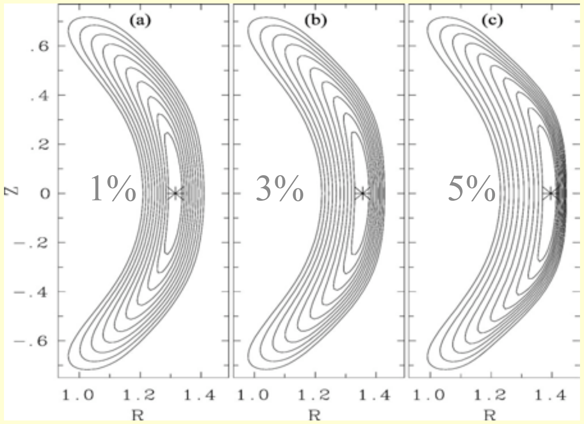






MHD equilibrium & stability in stellarators

QPS, Ware et al 2004



Strong self-stabilization of interchanges (theory + exp't)

Shafranov shift ➙ magnetic well ➙

Experimentally tested thru β = 4.3%

➙ ATF, CHS, W7AS, LHD

Exp't tolerant: can even start from magnetic hill

Stable to kink

zero-to-modest current,avoids major resonances

Second stability for ballooning modes ?

Theory: ballooning appear @ β ~ 2%, but . . .

➙ predicted limiting inst. *not* seen in stell. exp'ts

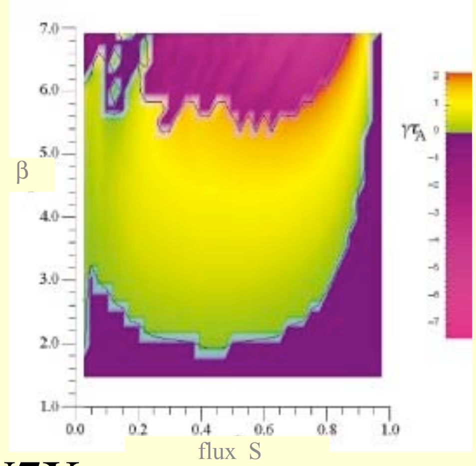
3-D truncation of ballooning spectrum or FLR?

Local chg to ∇p ⇒ non-linear stabilization?

Small set of unstable field lines?

Chance to isolate ballooning ➙ definitive exp't

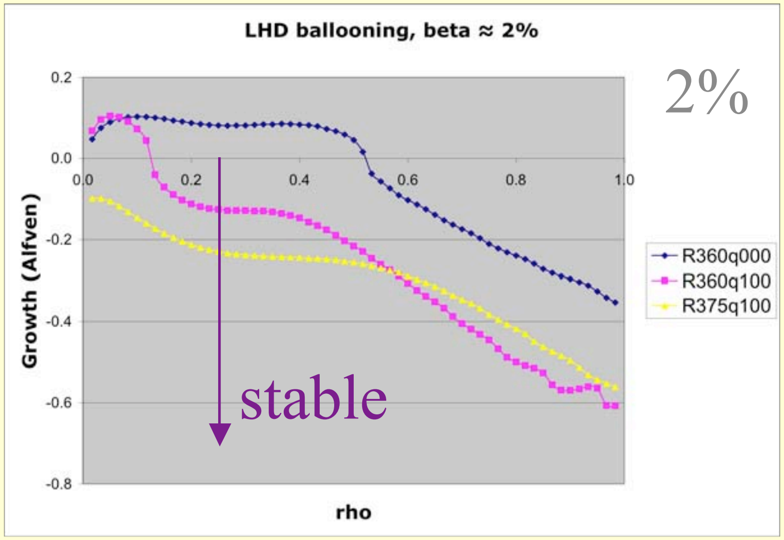
If ballooning benign ➙ more freedom for optimization

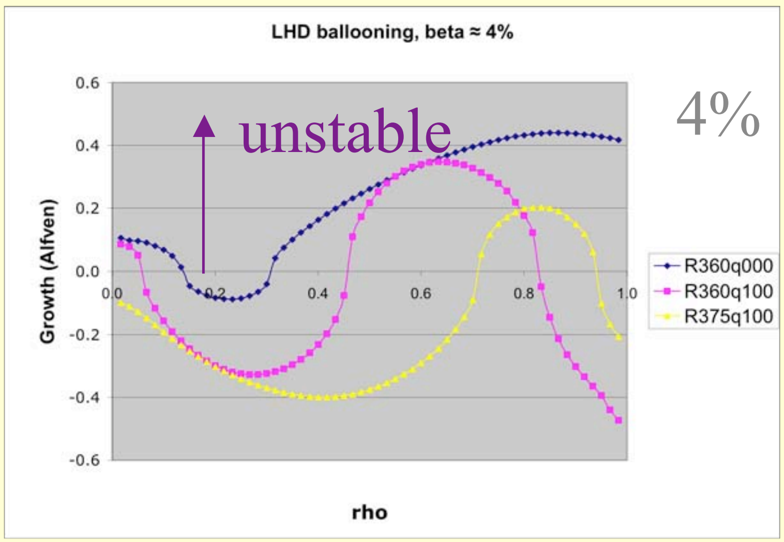


Important research on LHD, Heliotron-J,TJ-II, NCSX, W7X . . .

NB that ballooning mode is 3-D even in tokamaks (TFTR, Fredrickson et al)

LHD: configuration scan affects ballooning





COBRA code (R. Sanchez)

Ballooning *only*

Very fast (seconds)

$p \propto (1-\rho^2)$ (imposed)

Mostly stable at lower β

At higher β, unstable regions depend on configuration

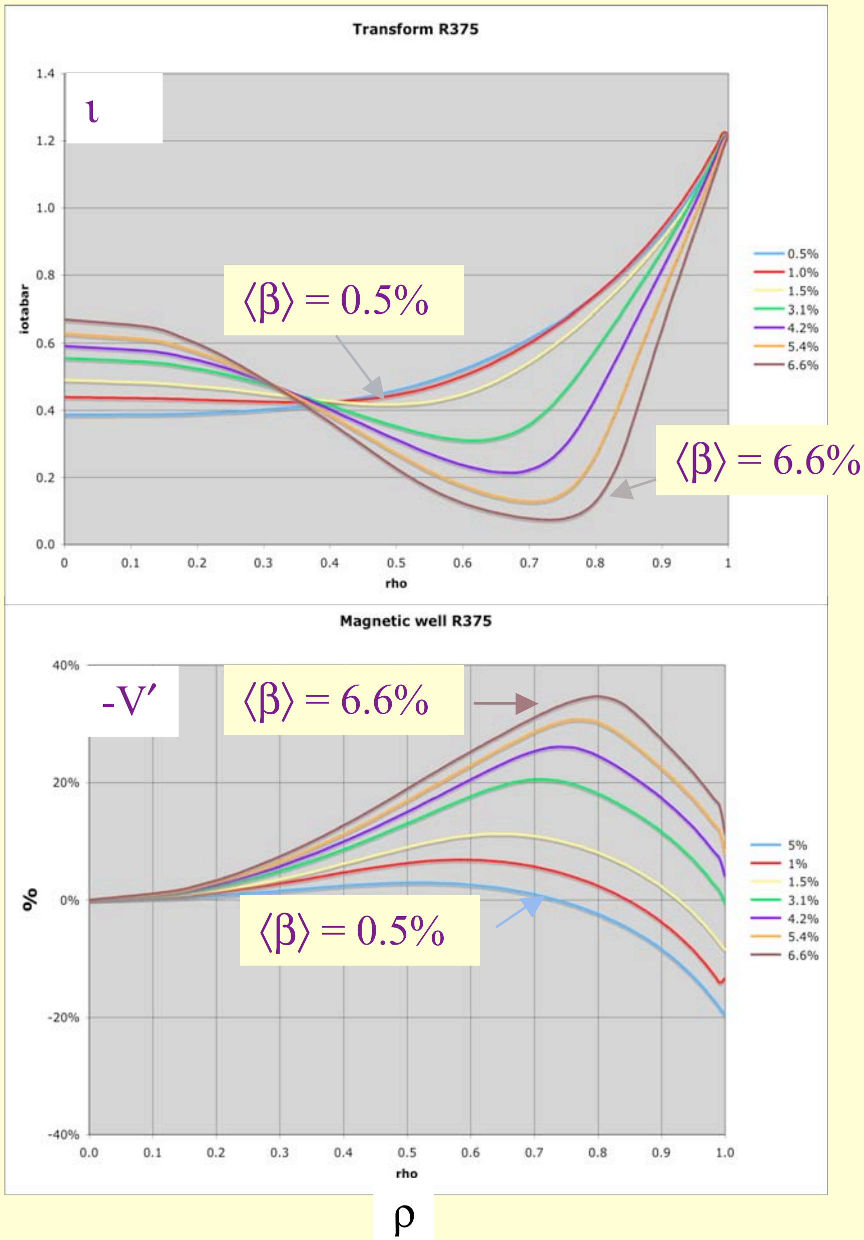
These β already achieved (LHD).

Macroscopically stable.

Local profile effects, fluctuations under study (database)

Is ballooning important?

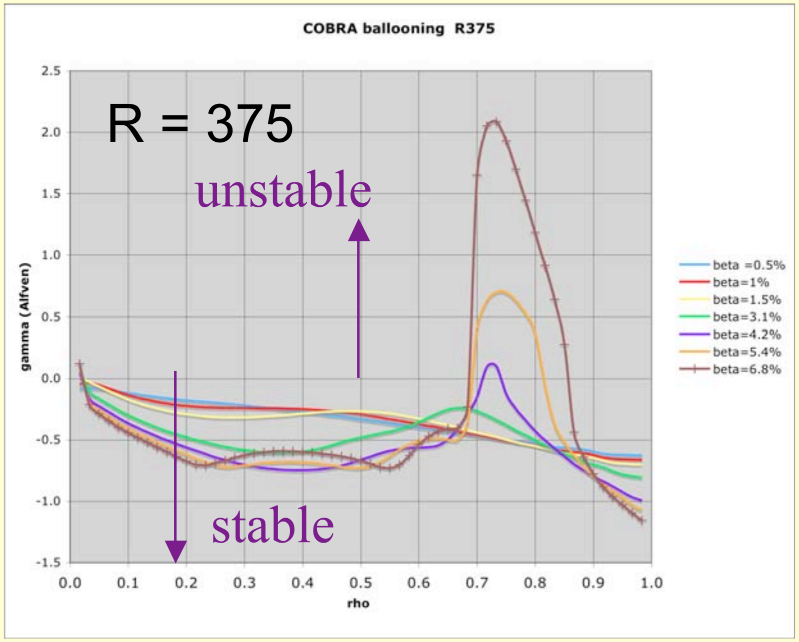
LHD SDC equilibria: reversed shear

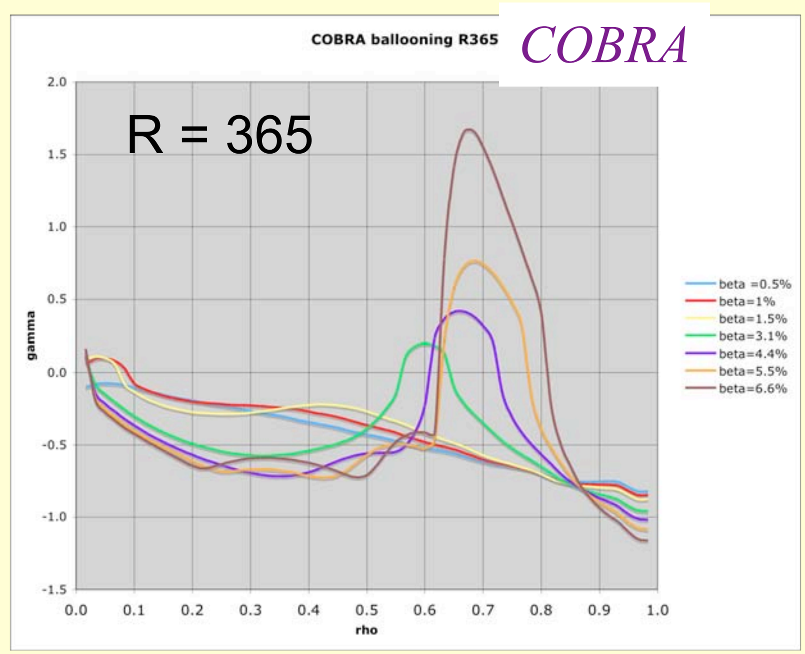


VMEC

- Zero shear radius moves out with increasing β
- Tokamak shear inside zero shear radius, stellarator shear outside
- Magnetic well ⇒ hill just outside zero shear radius
- Zero shear radius moves inward in ρ as configuration R_{axis} is decreased with external coils
- Note drop in ι : breeding ground for topology changes--reconnection, etc. Contributes to collapse events?

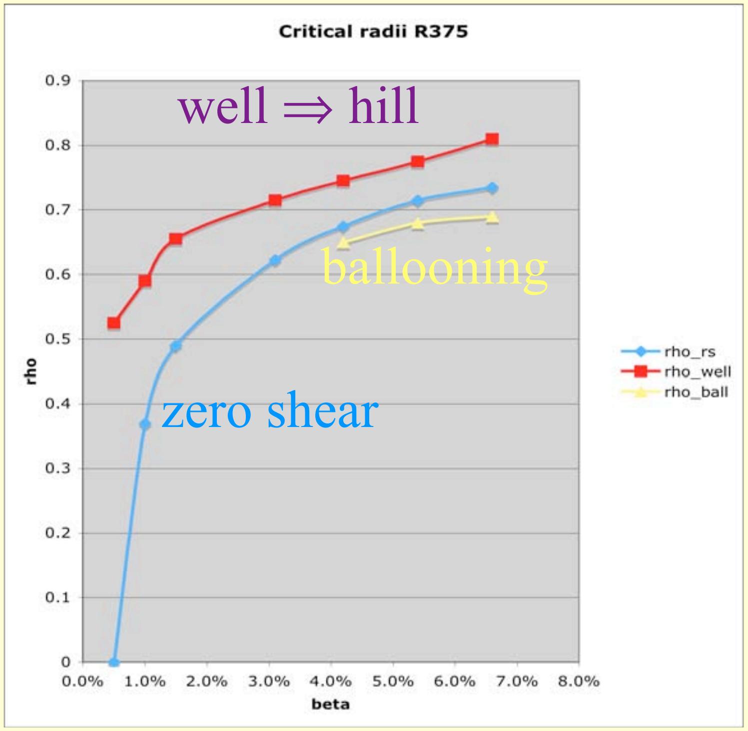
Ballooning stability in core & mantle differ

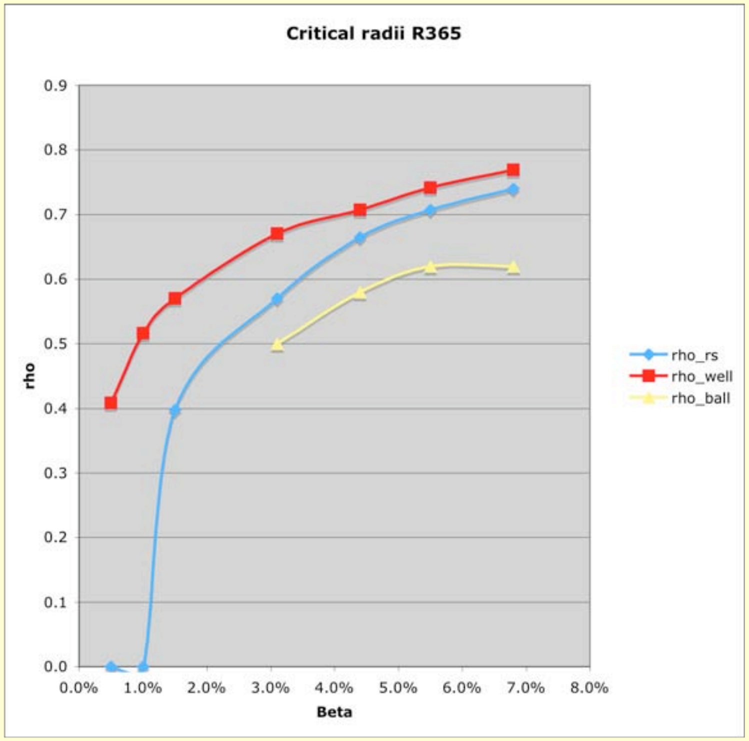




- Core plasma ($\iota' < 0$) becomes *more stable* as β increases $\Rightarrow$ (2nd stability)
- Ballooning instability in mantle ($\iota' > 0$) *increases* with β: regulates ∇p?
- Present exp'ts still ideally stable ($\beta \leq 1.5\%$); resistive modes can be active
- Core region smaller for shifted-in configuration
- Does stability physics improve core and limit edge confinement?
- Could be hunting ground for ballooning modes, but difficult to find because of finite spatial coherence

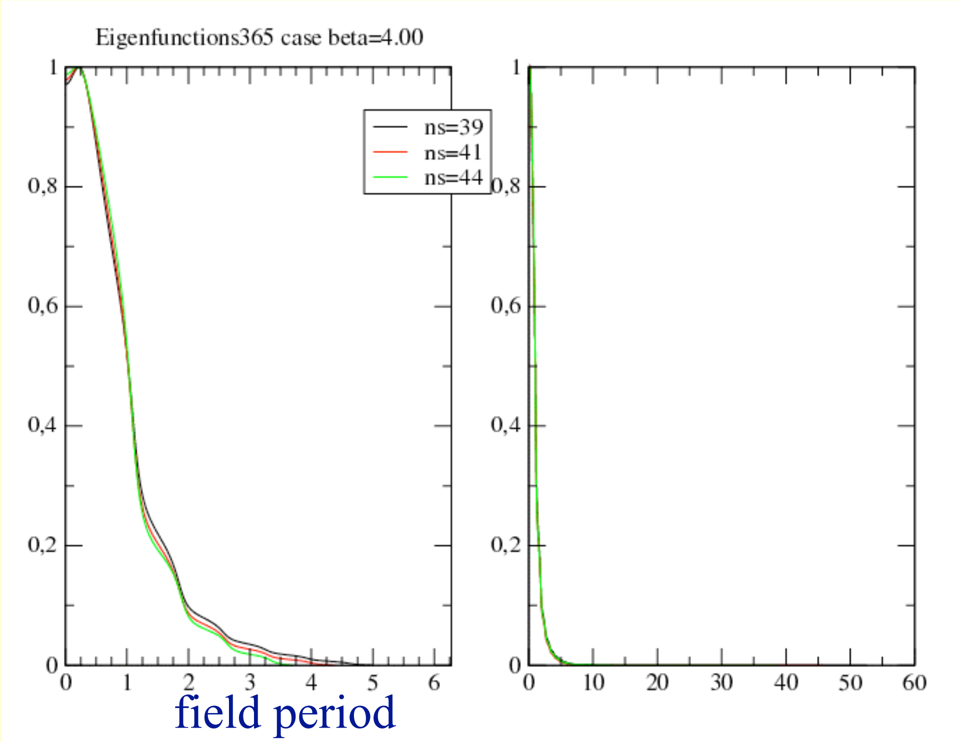
Location of critical surfaces as *f* (configuration, β)





- Zero shear and inner edge of ballooning region stay inside magnetic well
- Inward shift of R_{ax} (3.75⇒3.65) shifts critical radii inward in ρ

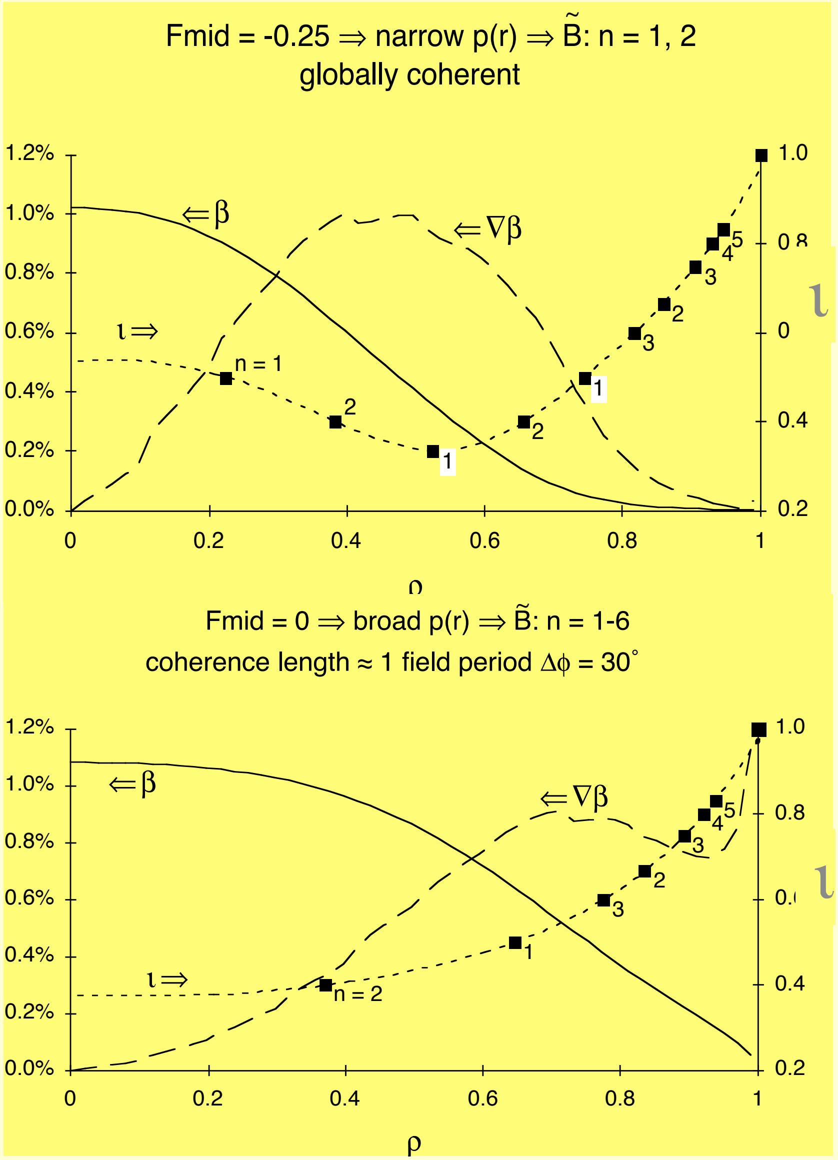
Ballooning mode localized to 1-2 field periods



- Chance to identify ballooning mode in stellarator configuration
- Should be short coherence length, high n (5-10) fluctuations, low field side
- LHD Mirnov coils underneath helical windings, in good curvature; internal imaging diagnostic probably necessary.
- Some magnetic fluctuations like this seen in ATF with broad p(r)

Configuration variation changes character of $\tilde{B}$

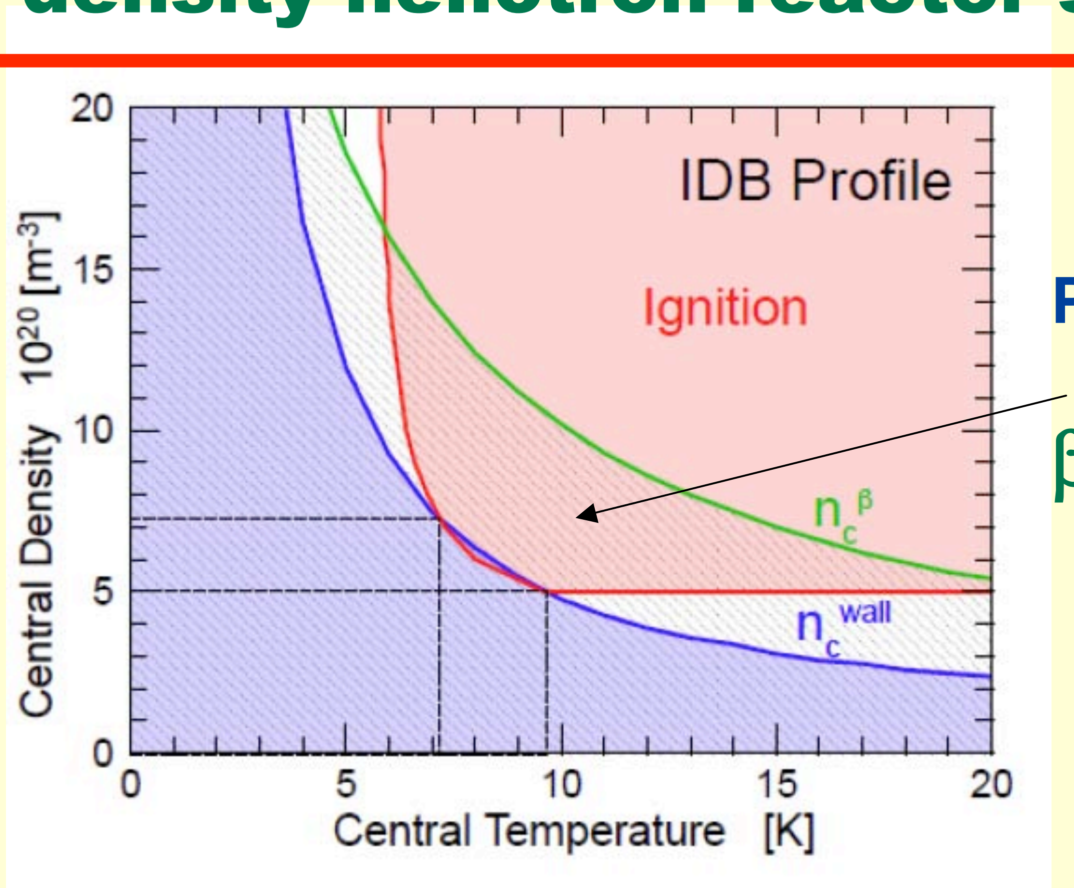
ATF:
quadrupole
field varies
ι(ρ)



global low n
(coherent over torus)

localized high n
coherent *only* over
1 field period
⇒ballooning?

High-density heliotron reactor scenario

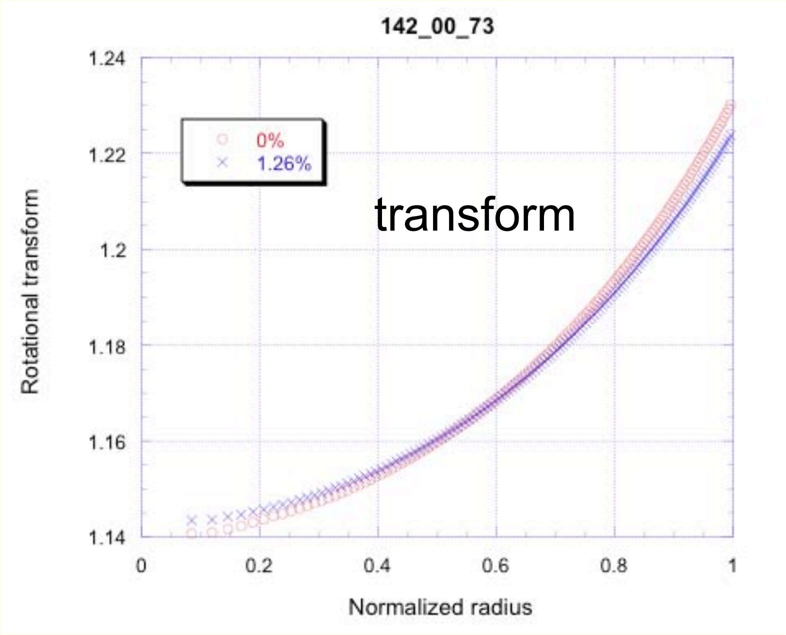


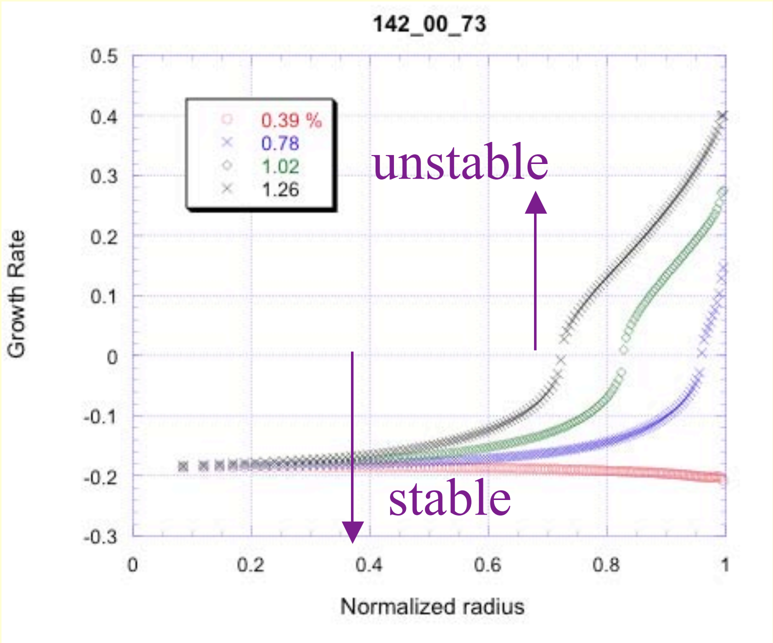
P_{wall} < 2 MW/m²
and
β < 7%

- High collisionality ⇒ mitigates 1/ν losses
- What is optimal magnetic configuration?
- System design with relatively lower volume hot plasma?

Looking for ballooning modes in TJ-II

- Use configuration variation find lowest threshold in β
  - Unique feature of flexible heliac: low shear, $1 < \iota < 2.5$ (TJ-II)
  - Small (few kA) induced currents allow adj. of central ι'
- Tailor heating & fueling to make most unstable p(r)
  - Near term: ECH + NBI to > 1 MW (two beams) in 2007-8
  - Longer term: pellets, EBW
- Fluctuation diagnostics
  - Data mining of mag. fluct. trialed on H-1 heliac (Australia)





LHD super dense core plasmas ⇒ performance, physics

- Pellet injection + low recycling
  ⇒ very high central densities (> $10^{20}m^{-3}$) at moderate B
  ⇒ improved core confinement
- Magnetic configuration affects onset and performance
  ⇒ possibility for dynamic control
- Tests of important 3-D confinement physics:
  ⇒ high β effects on topology
  ⇒ ballooning instability
  ⇒ confinement enhancement mechanisms
- Possible high-density reactor scenario
  ⇒ reduce energy wall particle flux and alpha effects
- IMHO, a lovely experiment

Future developments

- Dynamic control of vertical field ~ 2009 (VF power supply)
  ⇒ control of Shafranov shift
- Full helical divertor with cooling (major upgrade)
  ⇒ detailed design 2008
  ⇒ available 2012 ?
- Increase NBI from from ~14 MW to ~32 MW
  ⇒ comparable tangential and perpendicular power
  ⇒ available 2012?
- Investigations of
  ⇒ configuration control at finite beta
  ⇒ sustainment of high density plasmas
  ⇒ effects of pressure anisotropy on equil. & stability