COIL FLEXIBILITY AND PROFILE ROBUSTNESS

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OUTLINE

To achieve the scientific goals of the NCSX mission, the NCSX device must be capable of supporting a wide range of variations in plasma configuration about the reference baseline equilibrium.

- We will demonstrate the flexibility of NCSX coils to support such configuration variations,

and

- Demonstrate the robustness of performance of NCSX plasmas for substantial variations about reference design values of the plasma current, beta, and profile shapes.

NCSX COIL SYSTEM

Modular coilset M1017

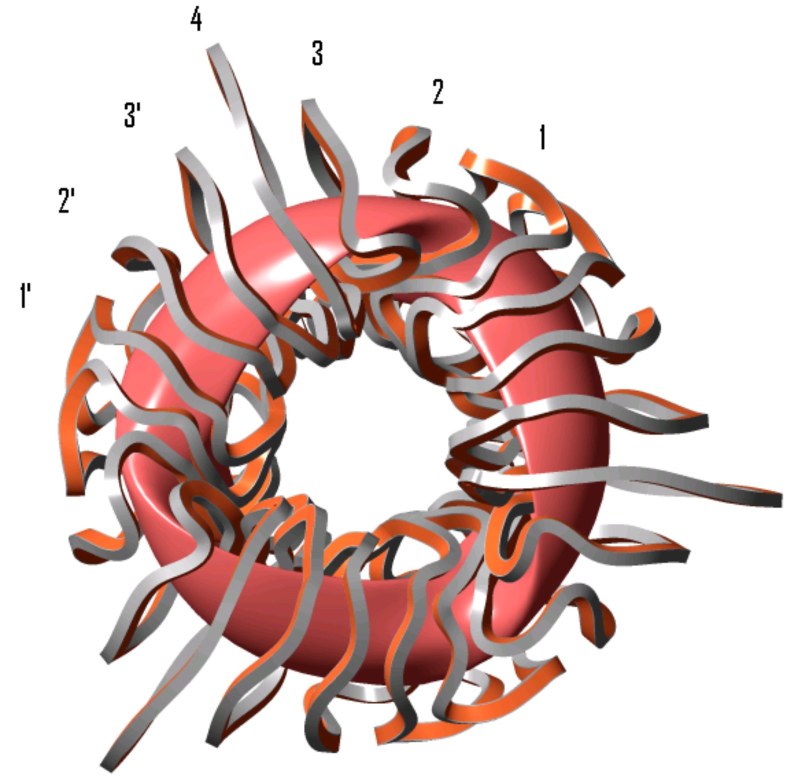
- **4 independent coil currents (independent coils labelled 1, 2, 3, 4)**

Auxiliary TF coils

- **provide ± 0.3 T at R=1.4 m**

Axisymmetric PF coils

- **provide at least 4 lowest order multipoles**



COMPUTATIONAL TOOLS

STELLOPT – a VMEC based free-boundary optimizer which varies coil currents to target configurations with good physics:

- Stable to Kink and Ballooning modes
- Good quasi-axisymmetry (QA)

Essential code modules within STELLOPT are:

VMEC$_{\textbf{(Hirshman)}}$ => Equilibrium,

TERPSICHORE$_{\textbf{(Cooper)}}$ => Kink evaluation (incl. modes with n up to $n_{max} = 7$)

COBRA$_{\textbf{(Sanchez)}}$ => Ballooning evaluation,

NEO$_{\textbf{(Kermbichler)}}$ => QA-ness measured by effective helical ripple, ε_h.

PLASMA PERFORMANCE AS β AND I_p ARE VARIED

Question:

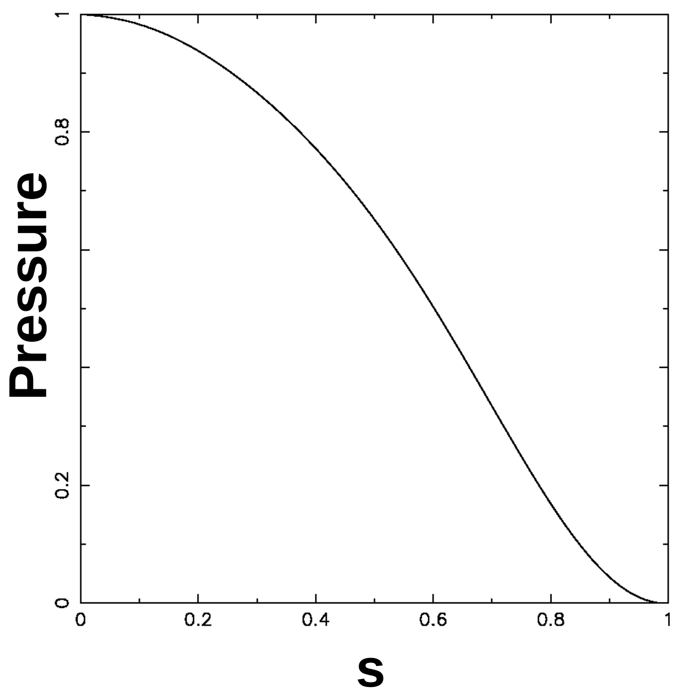
- Can coil currents be found which produce stable plasmas with good QA as I_p and β are varied from their reference values?
- Are there stable paths from S1 states with I_p = 0 kA, β = 0% to S3 states with I_p = 174 kA, β=4%, or states at full current with even higher β?

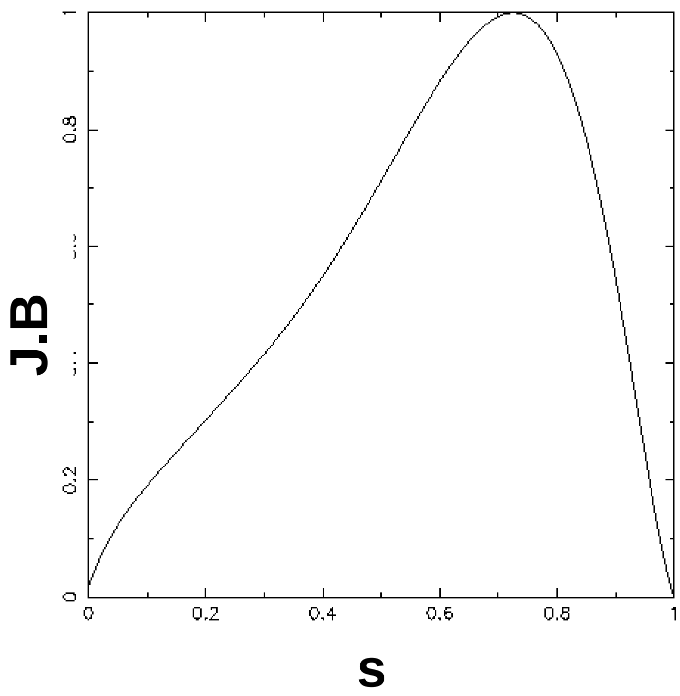
Answer:

- YES! – Using reference P(s) and J.B(s) profiles, stable configurations with low ε_h are found over a wide region of the I_p - β plane, including a stable configuration at β = 5%.

‘REFERENCE PROFILES’ FOR I_p – β SCAN

(and about which variations will be made)





I_p - β SCAN RESULTS (B_T = 1.7 T)

β[%] Ip[kA]	0.0	1.0	2.0	3.0	4.0	5.0
43.5		ε_h = 2.11%	ε_h = 1.30%	ε_h =1.30%	ε_h = 0.86%	
87		ε_h = 1.56%	ε_h = 1.60%	ε_h =1.28%	ε_h = 0.86%	
130.5		ε_h = 0.77%	λ^K_0 = -6.0e-5 λ^K_1 = -2.7e-5 ε_h = 0.84%	λ^K_0 = -8.8e-6 λ^K_1 = -2.2e-5 ε_h =1.14%	ε_h = 0.67%	
174	ε_h = 0.79%	λ^K_0 = -1.9e-5 λ^K_1 = -2.0e-5 ε_h = 0.81%	λ^K_0 = -2.3e-5 λ^K_1 = -2.3e-5 ε_h =1.43%	ε_h = 0.79%	ε_h =1.29%	ε_h =1.66%

- Blue boxes => Kink and Ballooning modes are stable at that I_p,β.
- Red boxes => Kink unstable with small λ^K, but ballooning stable.

NOTE: Config with I_p = 174 kA, β = 5.0% is stable!

(Stable plasmas with β up to 6.5% have been found for the M0907 coilset)

• SUMMARY OF I_p – β SCAN RESULTS

- 14 of 18 optimized configurations with different I_p, β values were stable w.r.t. kink and ballooning modes.
- The remaining 4 configurations were stable to ballooning modes and had small kink eigenvalues. Re-optimization with adjusted weights will probably stabilize these cases.
- Each configuration is marginally stable at the given I_p, β (=>configurations with low β-limits are easily dialled).
- In all cases, good QA-ness was obtained, measured by effective ripple amplitudes, $\varepsilon_h < 1.5\%$ at s = 0.5.
- A stable configuration at β = 5% was found with I_p = 174 kA and B_T = 1.7 T.
- Modular coil currents vary < ±15% over the I_p – β plane.
  B_T^{Aux} varies < ±0.10 T.

PLASMA PERFORMANCE AS PROFILES ARE VARIED

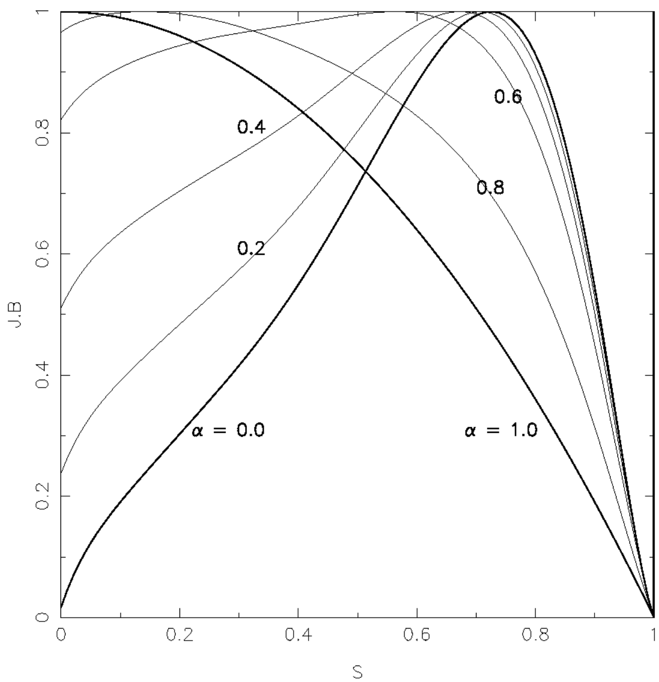
Question:

- What happens to plasma performance (β-limits, QA measure ε_h) when plasma profiles are varied about reference forms at fixed I_p, B_T?
- Is the reference configuration sitting atop a pinhead optimum so that as the profiles are varied the performance drops off a cliff?

Answer:

- **NO!** – We find configurations with a wide range of current and pressure profiles which have β-limits in excess of 3.0% and which have good QA.

CURRENT PROFILE VARIATION IN CORE REGION



Question:

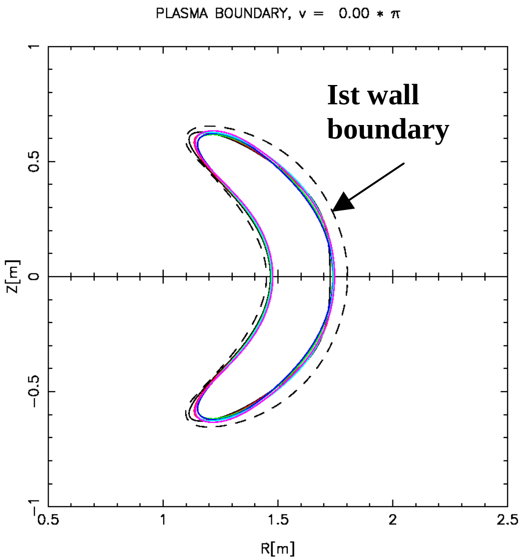
- Using the reference p(s), and I_p = 174 kA, B_T = 1.7 T, for what range of J.B profiles can we find stable configurations with $\beta \geq 3.0\%$?

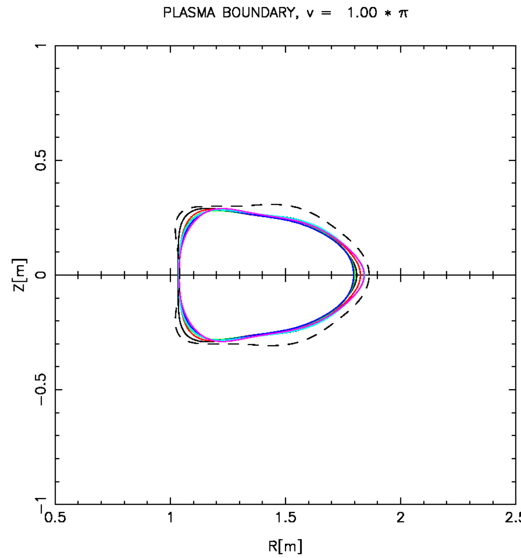
Answer:

- Stable range is $0 \leq \alpha \leq 0.5$.
- Stable profiles have $\varepsilon_h \leq 1.3\%$ at s=0.5:

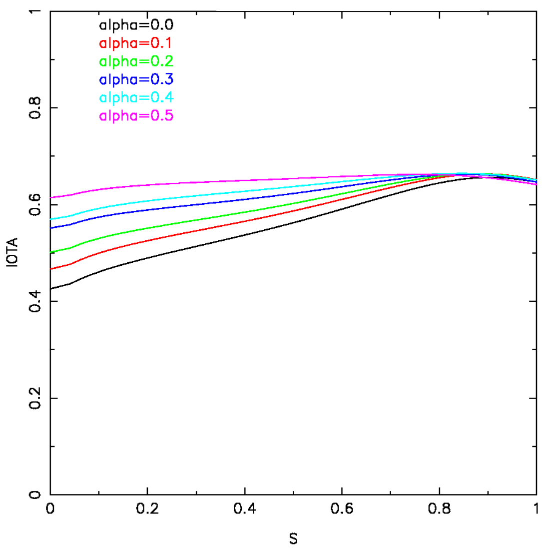
α	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
λ^K_0	S	S	S	S	S	S	-7.3e-4	-9.1e-4
λ^K_1	S	S	S	S	-1.5e-5	-2.8e-5	-5.1e-5	-8.0e-5
λ_B	S	S	S	S	S	S	S	S
$\varepsilon_h[\%]$	1.29	1.16	0.90	0.88	1.32	1.27	1.13	1.05

Plasma Boundaries for J.B^{core} variation with β=3.0%

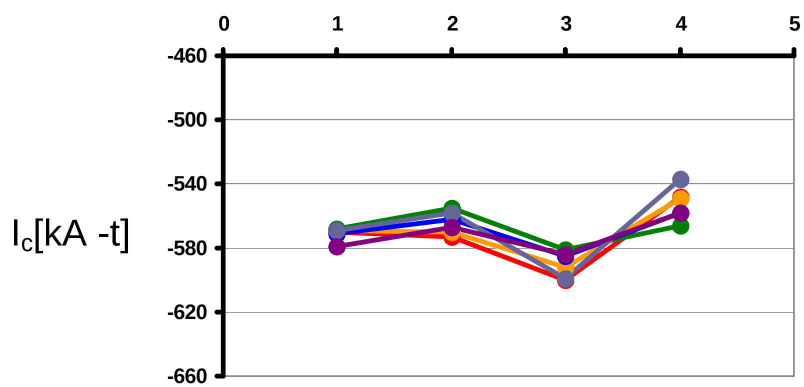




ι(s) profiles

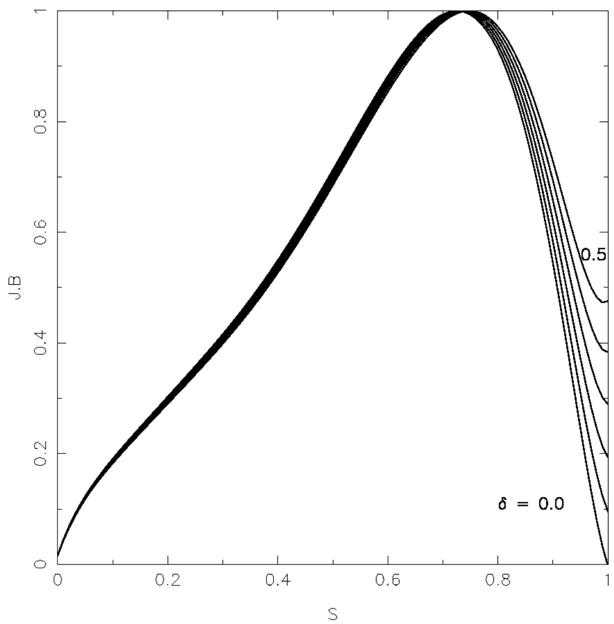


Modular Coil #



Loss of stability for α > 0.5 possibly due to loss of shear.

CURRENT PROFILE VARIATION IN EDGE REGION



Question:

- What happens to plasma performance when J.B is made finite at the plasma edge?
- Use coil currents from the I_p=174 kA, β=5.0% configuration obtained in the I_p - β scan.

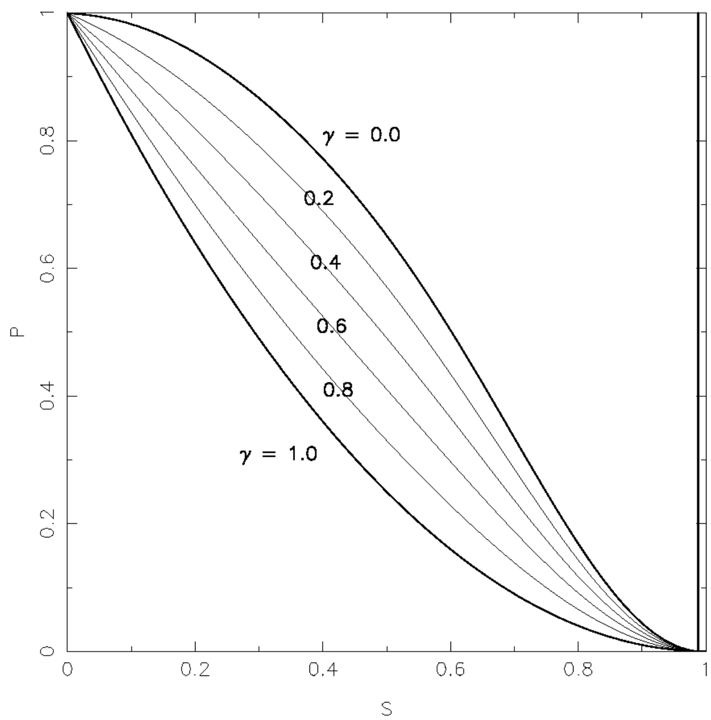
Answer:

- Keeping β=5.0% as a target for all configurations in the scan, the configurations remains stable even as $J.B^{edge}/J.B^{max}$ is raised to 50%!

- **Contrast with Tokamak behavior.**
- **H-mode profiles may be beneficial to NCSX.**

M.I. Mikhailov, V.D. Shafranov
"Stable Current Profile in a Stellarator with Shear",
Nucl. Fusion **30**, 413 - 421 (1990).

PRESSURE PROFILE VARIATION



- By how much can we peak the p(s) and maintain stable configurations with good QA at β = 3.0%?

- Use reference J.B and the pressure profiles shown.

- Stable range of pressure profiles is $0 \leq \gamma \leq 0.8$. (with γ =1.0 stable at β = 2.5%).

γ	0.0	0.2	0.4	0.6	0.8	1.0
λ^K_0 λ^K_1	S S	S S	S S	S S	S S	-3.0e-4 -5.4e-5
λ_B	0	0	0	0*	0*	0*
ε_h[%]	0.80	0.72	0.78	1.05	0.73	0.62

- Low ε_h values obtained in almost all cases.
- Max coil current variation ~ 50 kA (Modulars 3 and 4).

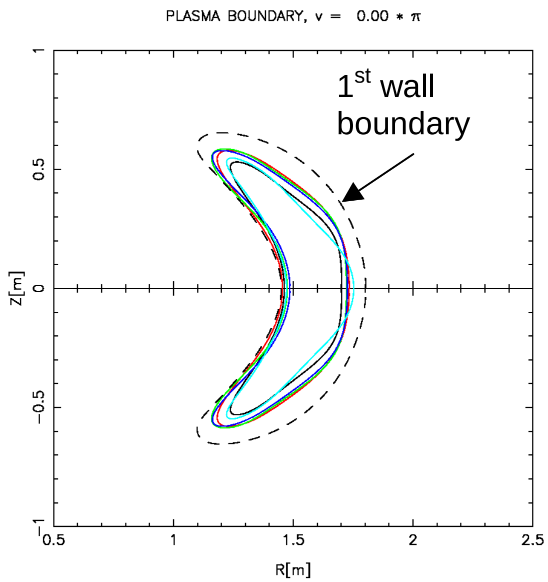
FLEXIBILITY TO CONTROL EXTERNAL TRANSFORM

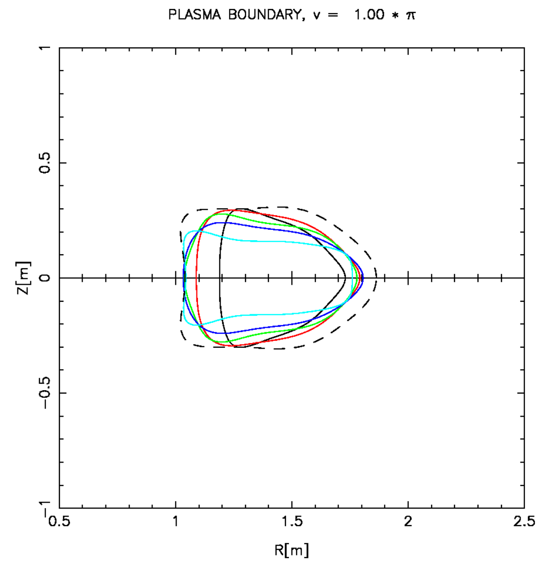
- Will be an important control knob in the experiment
  - can be used to test importance of avoiding low order rational surfaces in the plasma region.
  - is a means of controlling discharge evolution.

- We demonstrate the capability of NCSX coils to effect substantial changes in the external field contribution to $\iota(s)$.

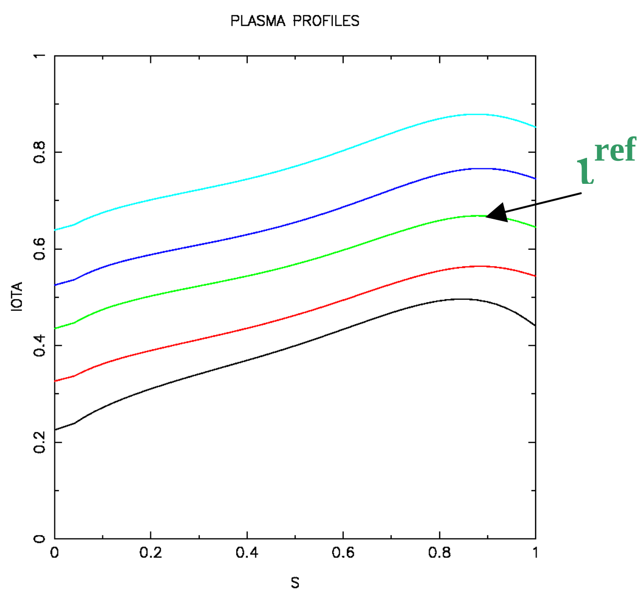
- Flexibility experiments shown here assume fixed B_T and I_p, and induce $\Delta\iota$ by causing appropriate changes in plasma shape.

FLEXIBILITY TO CHANGE $\iota(s)$ AT FIXED I_p, B_T





- I_p = 174 kA, B_T = 1.7 T
- β = 0%

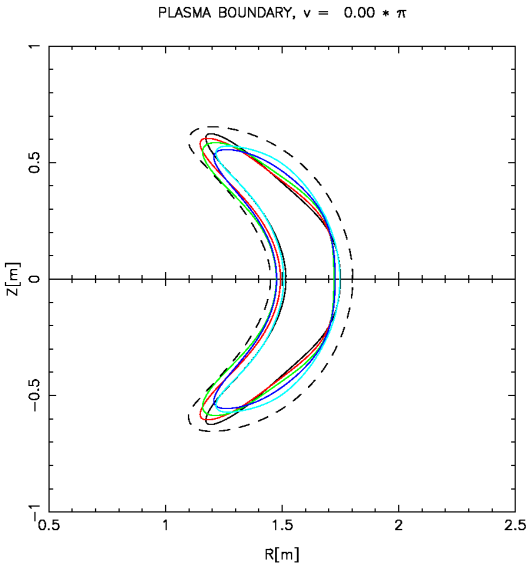


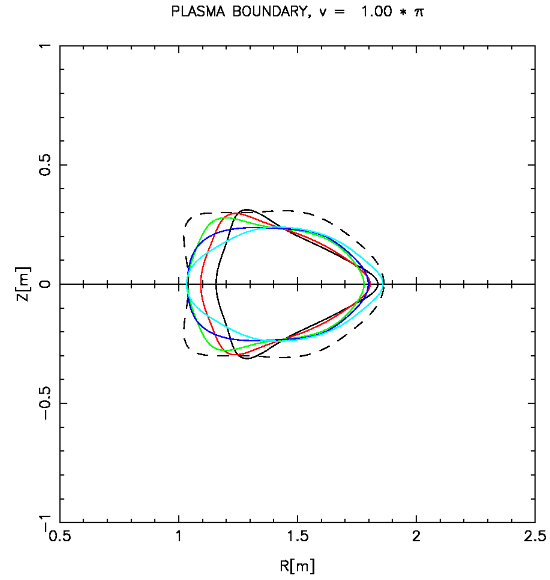
- raise/lower $\iota(s)$ at constant shear.
- $\Delta\iota = \pm$ 0.2 is possible:

~50% of $\iota^{ref}(0)$, ~30% of $\iota^{ref}(1)$.

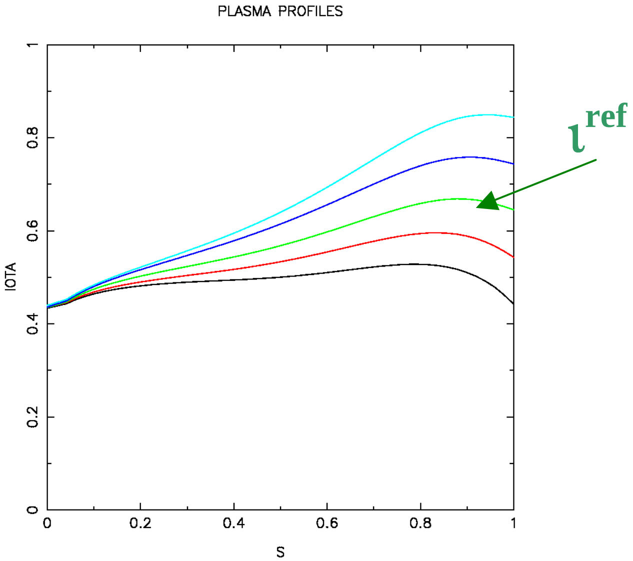
- For $\Delta\iota$ = +0.2, coil currents vary ~120 -150 kA-t (all coils).
- Max $B_T^{Aux} \approx$ - 0.1 T, for $\Delta\iota = +\ 0.2$

FLEXIBILITY TO CONTROL SHEAR AT FIXED I_p, B_T





- I_p = 174 kA, B_T = 1.7 T
- β = 0%



- raise/lower $\iota(1)$ at fixed $\iota(0)$ = 0.45
- $\Delta\iota(1) = \pm$ 0.2 is possible

  ($\iota^{ref}(1)$ = 0.65)
- For $\Delta\iota(1) = \pm$ 0.2, $\Delta I_c^{Mod. 4} \approx$ 80 kA-t

  (others less)
- Max $B_T^{Aux} \approx$ + 0.4 T, for $\Delta\iota(1)$ = - 0.2

FLEXIBILITY TO VARY QA-NESS

- The ability to generate configurations with good QA is an essential requirement for NCSX.

- For a systematic exploration of the role of QA in improving the transport properties of stellarator plasmas it is necessary to have the ability to control the degree of QA-ness.

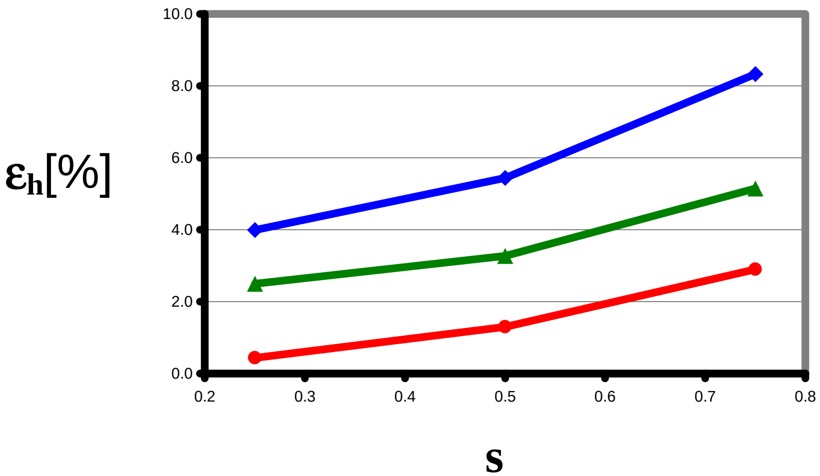
Question:

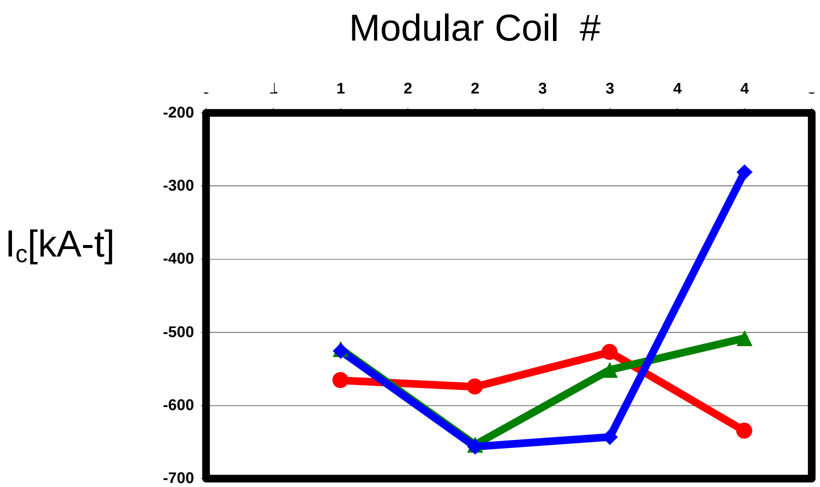
- Do we have QA control while maintaining plasma stability?

Answer:

- YES!

FLEXIBILITY TO VARY QA-NESS





- 3 configurations, each with I_p = 43.5 kA, β=3.0%.
- Among configurations ε_h varies by a factor of 9 at s=0.25 (r/a≈0.5), and factor of 4 at s= 0.5.
- Each configuration is stable to kink and ballooning modes
- To obtain case with highest ε_h, the I_c for modular coil 4 was artificially fixed at –281 kA.
- Yet the kink and ballooning modes were able to be stabilized using just 3 coils!

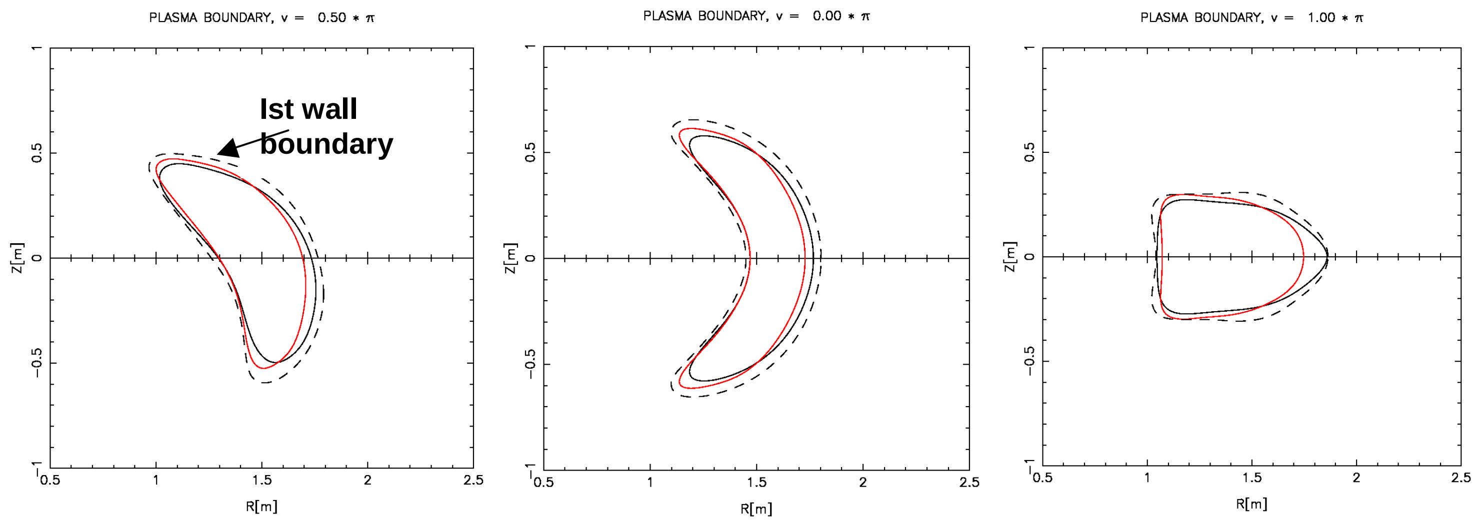
FLEXIBILITY TO EXPLORE STABILITY BOUNDARIES AND 3D SHAPE STABILIZATION

- Each stable free-boundary configuration in the I_p - β scan lies at a point of marginal stability w.r.t. kink and ballooning modes for the given profiles.

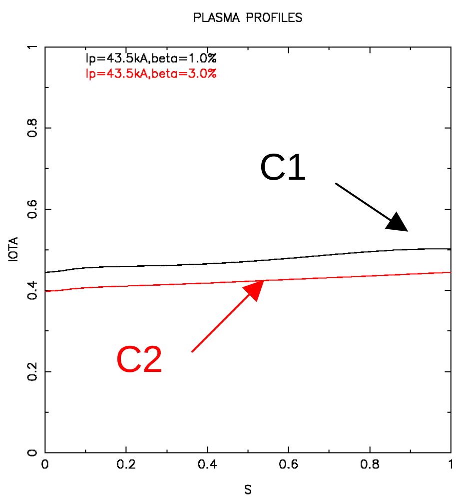
- To illustrate the type of experiment that can be run on NCSX aimed at understanding the physics that determines stability boundaries, consider two configurations from the I_p - β scan:

C1		C2
I_p = 43.5 kA, β = 1.0%	and	I_p = 43.5 kA, β = 3.0%

EXAMPLE OF 3D SHAPE STABILIZATION



C1 (black)
C2 (red)



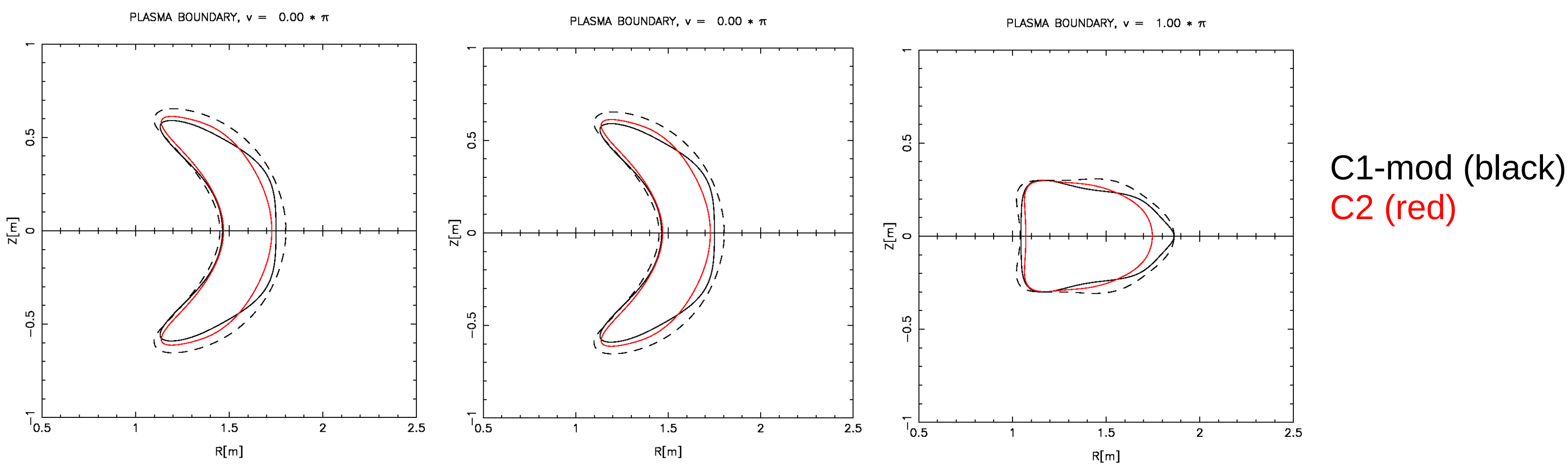
(ι(1)≈0.5)

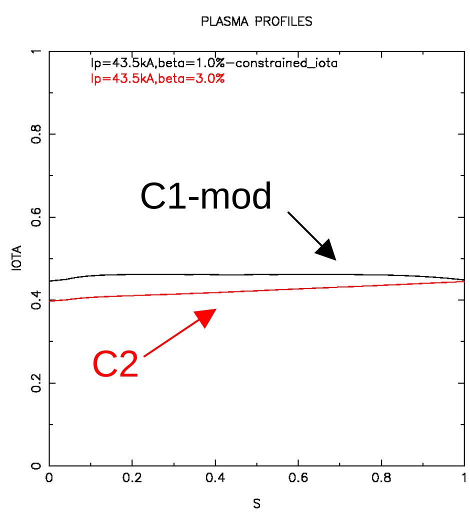
β_{Lim} **= 1.0% for C1**

β_{Lim} **= 3.0% for C2**

- **Difference in β-limits is due to difference in shape.**

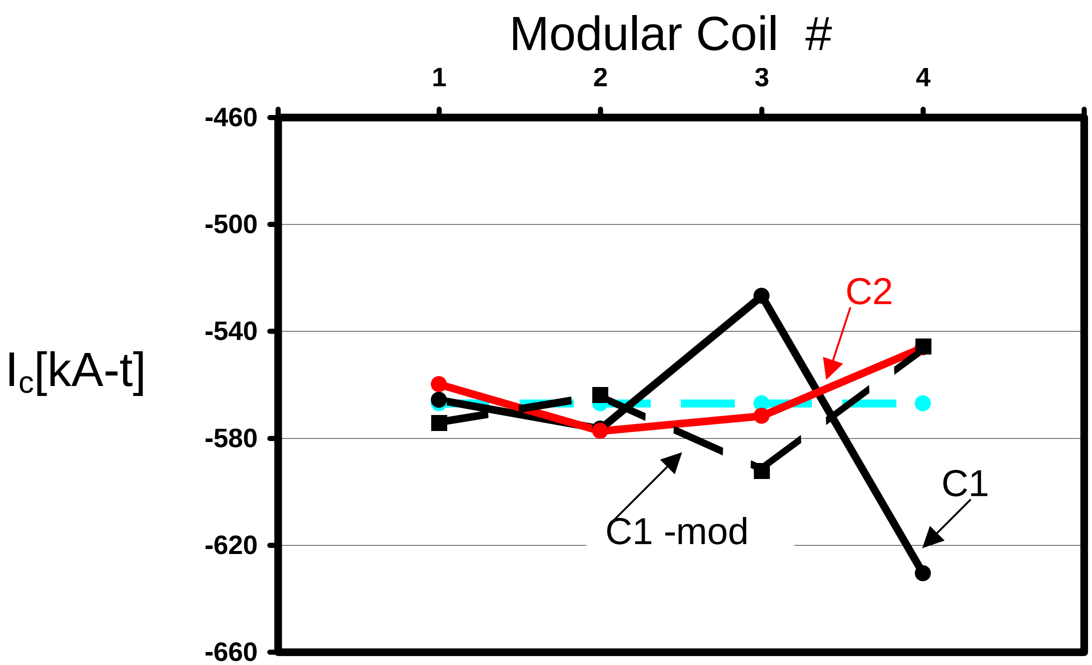
REMOVE AMBIGUITY OF ROLE OF $\iota(1) \approx 0.5$





- Impose ι-control on C1 to produce new configuration, C1-mod, whose β-limit is 1.0%, but which has the same ι_{edge} as the β_{Lim} = 3.0% configuration.

MODULAR COIL CURRENTS FOR THE 3D SHAPE STABILIZATION 'EXPERIMENTS'

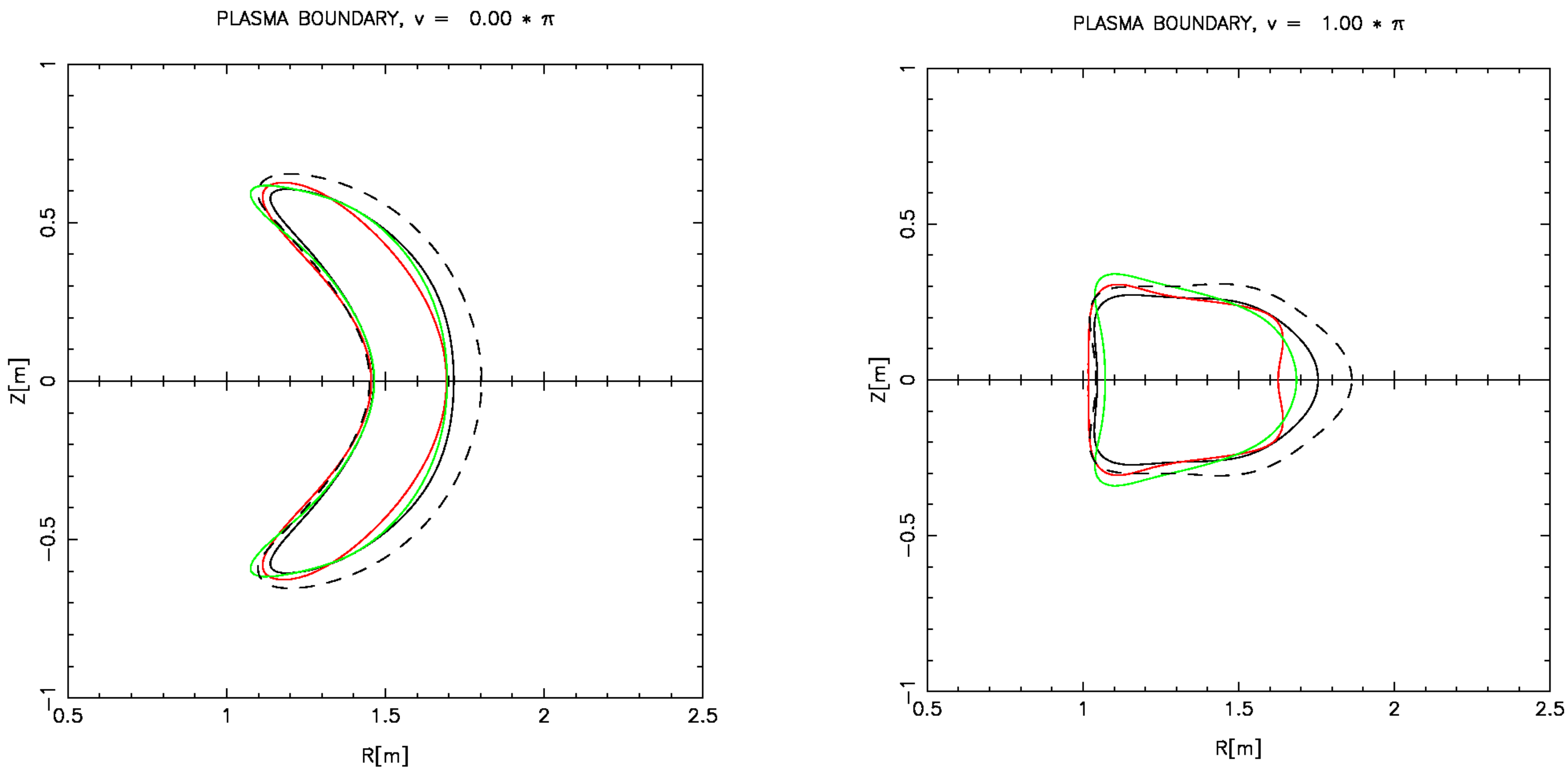


- Max ΔI_c variation = 10% => controllable.

SUMMARY

- **The performance (β-limits, QA-ness measure ε_h) of NCSX plasmas is robust w.r.t. substantial variations of I_p and profile shapes about reference design values.**
- **The NCSX coil system has considerable flexibility to support the wide variety of experiments required by the NCSX mission.**

SUPPLEMENT–1: EFFECT OF β and Ip QUENCHES

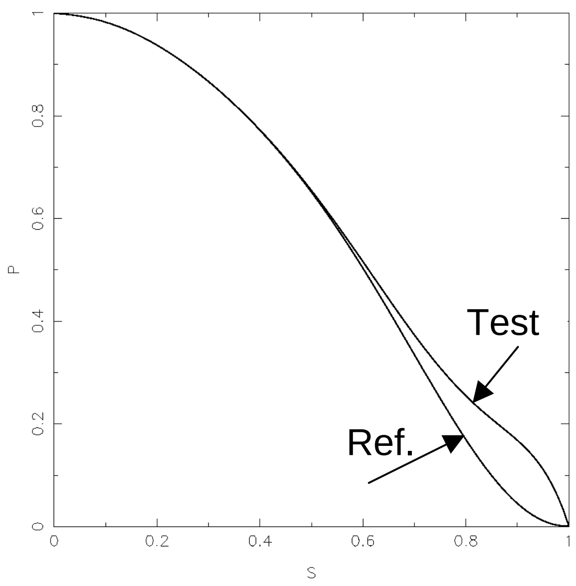


Black: Ip = 174 kA, β = 4.2% Red: Ip = 174 kA, β = 0.0% Green: Ip = 0 kA, β = 4.2%

Max. Inward radial shifts: ΔR_{min} = 2.2 cm ΔR_{min} = 4.7 cm

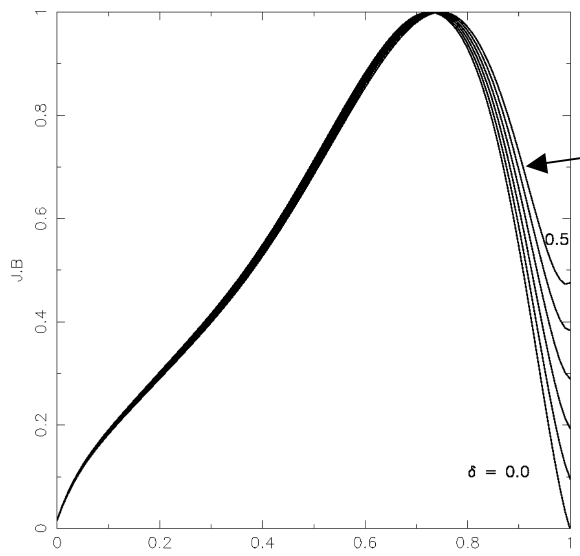
SUPPLEMENT-2:EFFECT OF PRESSURE PEDESTAL ON STABILITY

-The road to H-mode profiles.



- “Test” pressure profile with finite edge gradient is stable at $\beta = 4.0\%$.

I_p = 174 kA, B_T = 1.7 T



Used this current profile (50% edge current density)