NCSX Coil Flexibility

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Princeton Plasma Physics Laboratory

OUTLINE

PAC-4 emphasized the need to demonstrate the ability of the NCSX device to support a wide range of variations in plasma configuration about the reference baseline equilibrium.

For the PVR, a 21-coil modular coil design (M1017) with 4 independent modular coil currents was used to demonstrate a remarkable (surprising?) degree of flexibility, and a comprehensive set of flexibility experiments was documented.

We will review this flexibility, and show that recent coil designs which incorporate 18 modular coils with 3 independent modular coil currents, together with a 5-coil poloidal field system, can access the same corners of flexibility space delineated in the original PVR studies.

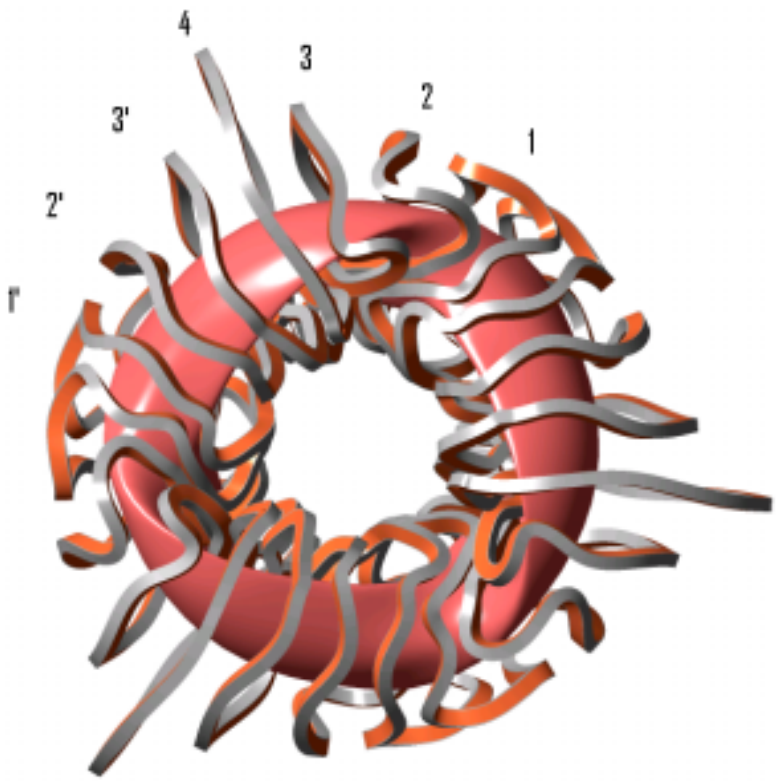
OUTLINE (Cont)

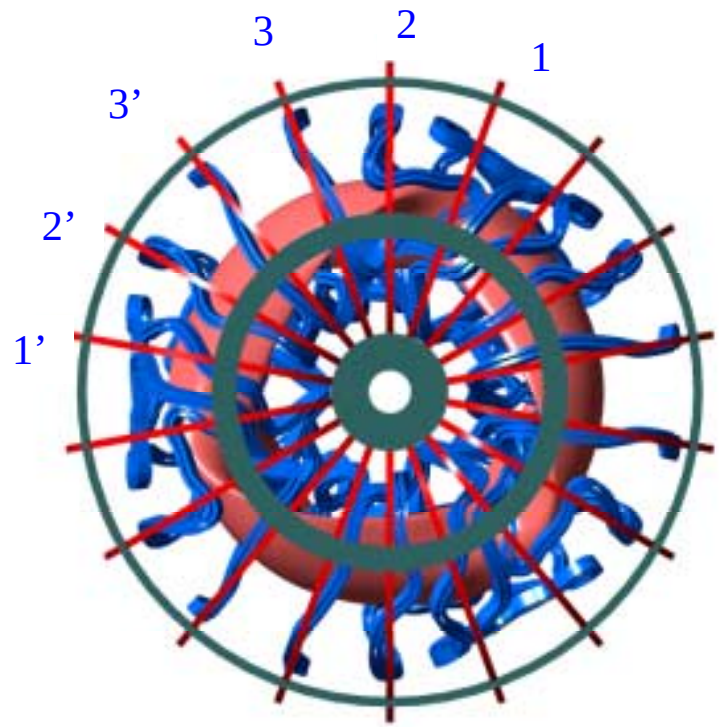
The Flexibility studies include:

- I_p - β scans.
- Examination of plasma performance as current and pressure profile shapes are varied (including edge current and pressure pedestals).
- Ability to control external transform at fixed I_p, B_T by targeting changes in the plasma shape.
- Ability to systematically vary QA-ness so that its role in improving transport properties of stellarator plasmas can be investigated.
- Ability to explore stability boundaries and 3D shape stabilization.

Studies use STELLOPT, a VMEC-based free-boundary optimizer.

NCSX COIL SYSTEMS: OLD (PVR) and NEW (CDR)





PVR

4 independent modular coil groups.
TF system modeled as pure 1/R.
PF fields modeled as multipoles.

CDR

3 independent modular coil groups.
18 discrete TF coils.
5 poloidal field coils (outer 3 shown).

No significant loss of flexibility results from having one fewer stellarator control knobs.

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?**

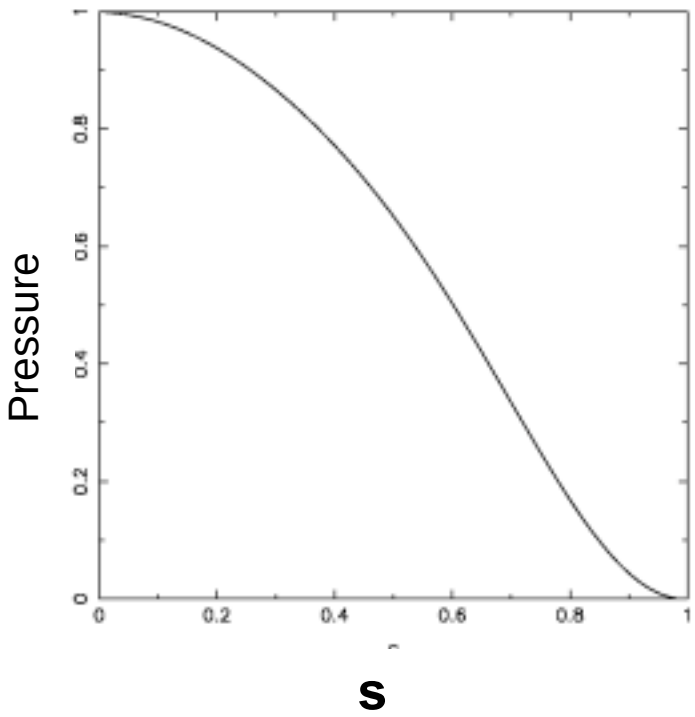
- **Are there stable paths connecting vacuum and high – β states?**

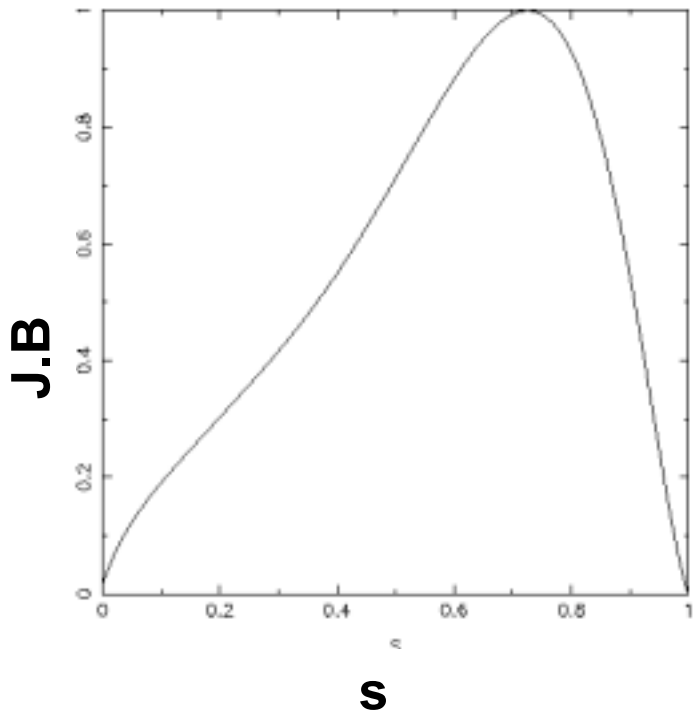
Answer:

- **YES!**

‘REFERENCE PROFILES’ FOR I_p – β SCAN

(and about which variations are made)





- Current profile is bootstrap consistent with assumed pressure profile.
- Pressure profile is contained within stellarator database.

D. Mikkelsen, Ch 8 of PVR

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 = 0.70% 0.39%	ε_h = 0.43% 0.46%	ε_h = 0.43%	ε_h = 0.29%	
87		ε_h = 0.52% 0.24%	ε_h = 0.53%	ε_h = 0.43%	ε_h = 0.29%	
130.5		ε_h = 0.26% 0.27%	ε_h = 0.28%	ε_h = 0.38%	ε_h = 0.22%	
174	ε_h = 0.26%	ε_h = 0.27% 0.17%	ε_h = 0.48%	ε_h = 0.26%	ε_h = 0.43%	ε_h =0.55% 0.77%

β = 5% is stable!

- **18 stable configs with different I_p, β values were generated for the PVR.**
- **Many stable paths from vacuum to high - β states are possible.**
- **QA is very good (ε_h < 1% at s = 0.5 surface).**
- **Selected cases were regenerated using the 18-coil modular coil system. These are shown in red.**
- **Each "stable" configuration is marginally stable at the given I_p, β.**

==> CONFIGS WITH LOW β-LIMITS ARE EASILY GENERATED

PLASMA PERFORMANCE AS PROFILES ARE VARIED

Question:

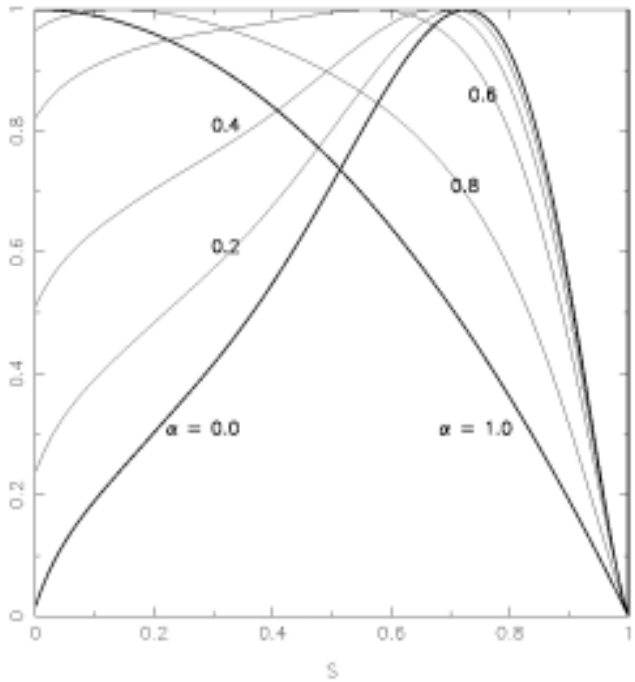
- What happens to plasma performance when plasma profiles are varied about reference forms at fixed I_p, B_T?
- Is the reference configuration sitting atop a pinhead optimum so that as the profiles are varied the performance drops off a cliff?

Answer:

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

CURRENT PROFILE VARIATION IN CORE REGION

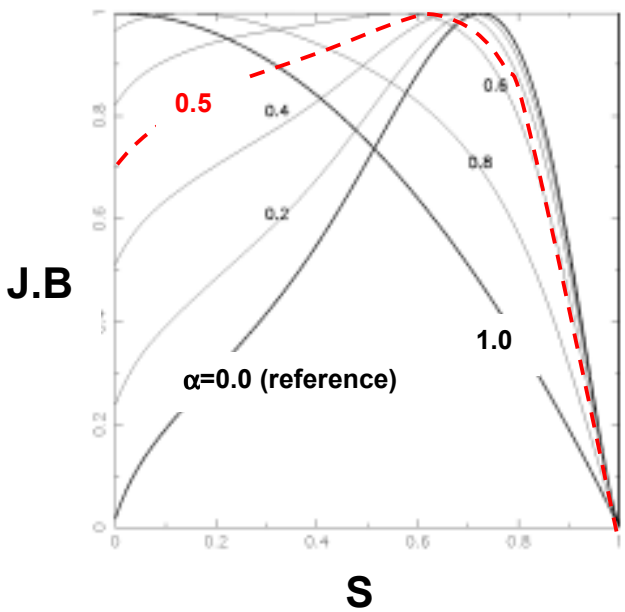
J.B



- **For what range of J.B profiles can stable configurations be found with $\beta \geq 3.0\%$?**
- **Using the reference P(s), vary the J.B profile over the range shown.**
- **As parameter α is increased from 0 → 1, successively more current is added to the core region.**
- **I_p = 174 kA, B_T = 1.7 T for all cases.**

- **For each J.B profile, run STELLOPT to determine coil currents which produce a configuration that fits within the 1st wall boundary, optimizes the QA-ness, and maintains kink and ballooning stability.**

CURRENT PROFILE VARIATION IN CORE (Results)

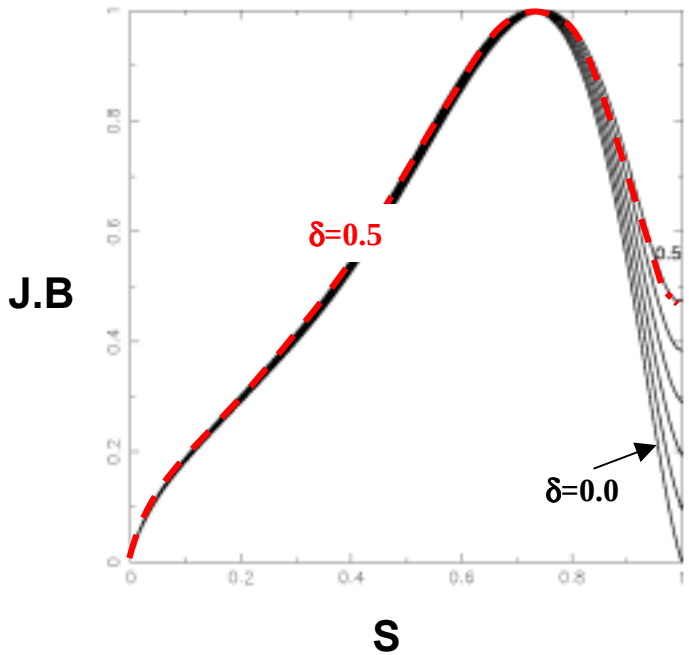


- **Stable range identified for PVR is $0 \leq \alpha \leq 0.5$.**
- **Stable profiles have $\varepsilon_h \leq 0.5\%$ at s=0.5:**

α	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
λ^K_0 λ^K_1	S S	S S	S S	S S	S -1.5e-5	S -2.8e-5	-7.3e-4 -5.1e-5	-9.1e-4 -8.0e-5
λ_B	S	S	S	S	S	S	S	S
ε_h[%]	0.43	0.39	0.30	0.29	0.44	0.42	0.38	0.35

- **The cases α = 0.0, 0.3 and 0.5 were re-run using the 18- modular coil system. Stable configurations were found in each case. For α = 0.5, the QA measure is ε_h = 0.35%.**

CURRENT PROFILE VARIATION IN EDGE REGION



Question:

- What happens to plasma performance when J.B is made finite at the plasma edge?
- Examine I_p = 174 kA, β = 5.0% configuration (obtained in $I_p - \beta$ scan). Track stability as edge current is added.

Answer:

- The β = 5.0% configuration remains stable even as $J.B^{edge}/J.B^{max}$ is raised to 50% (red curve)!

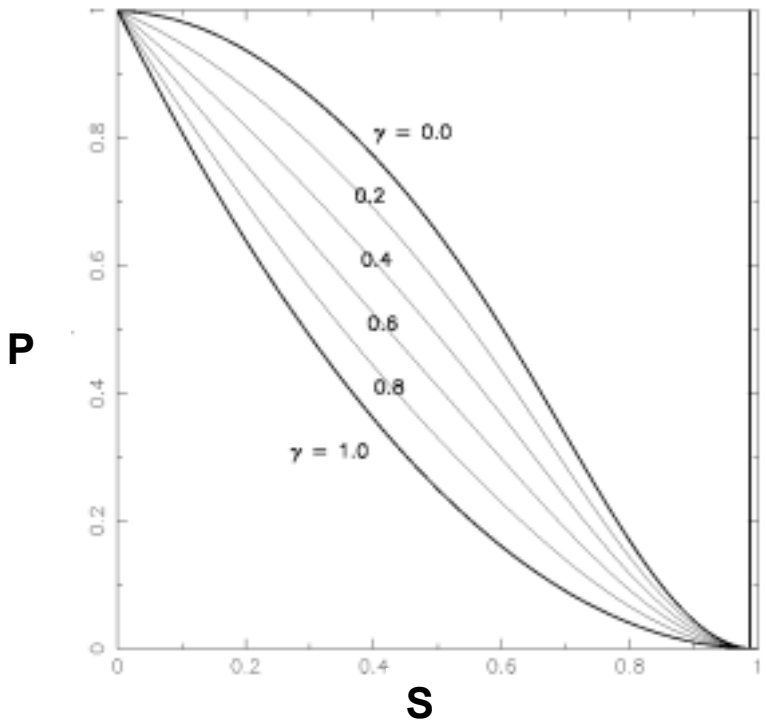
- Explanation is stabilizing influence of edge shear.

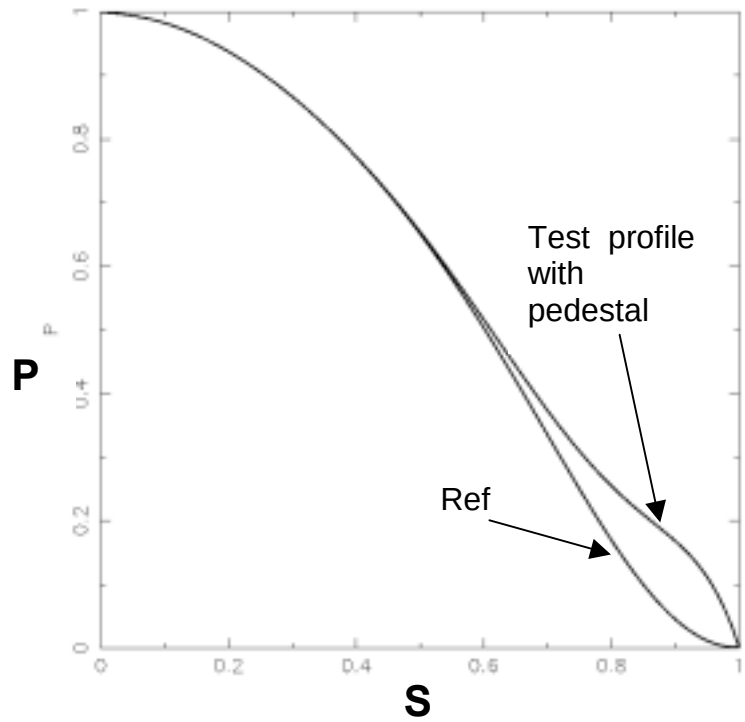
M.I. Mikhailov, V.D.Shafranov
"Stable Current Profile in a Stellarator with Shear"
Nucl. Fusion 30, 413-421 (1990)

- H-mode profiles may be beneficial to NCSX stability (contrast with tokamaks).

PRESSURE PROFILE VARIATION

- Similar profile variations were studied for pressure profiles.





Stable configurations with β = 3.0% found for $0 \leq \delta \leq 0.8$ - i.e., includes peaked profiles (δ = 1.0 was stable at β = 2.5%).
Same range of stable profiles was found using 18-modular coil system.

Pressure profile with finite edge gradient shown above was stable at β = 4.0% for I_p = 174 kA, B_T = 1.7 T.

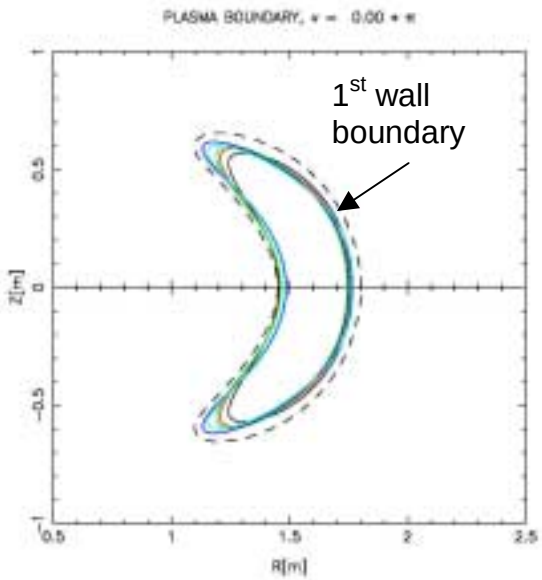
FLEXIBILITY TO CONTROL EXTERNAL TRANSFORM

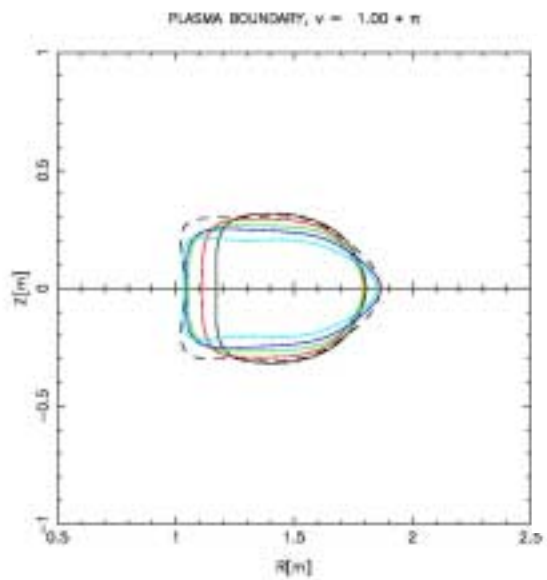
- **Will be an important control knob in the experiment**
  - **can be used to test importance of avoiding low order rational surfaces in the plasma region.**
  - **is a means of controlling discharge evolution.**

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

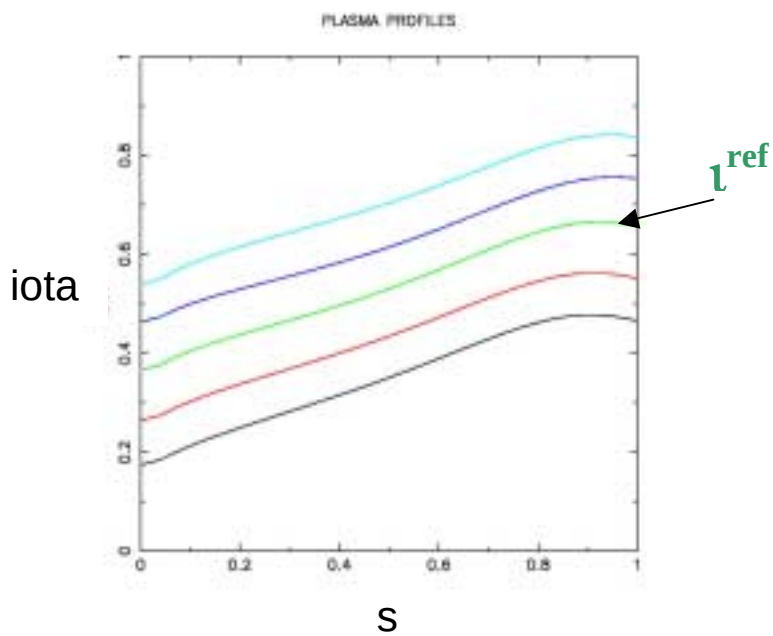
- **Flexibility experiments shown here assume fixed B_T and I_p, and induce $\Delta\iota$ by causing appropriate changes in plasma shape.**

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



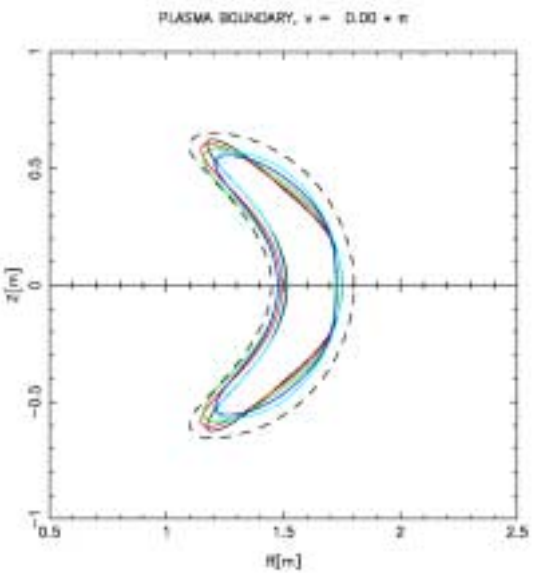


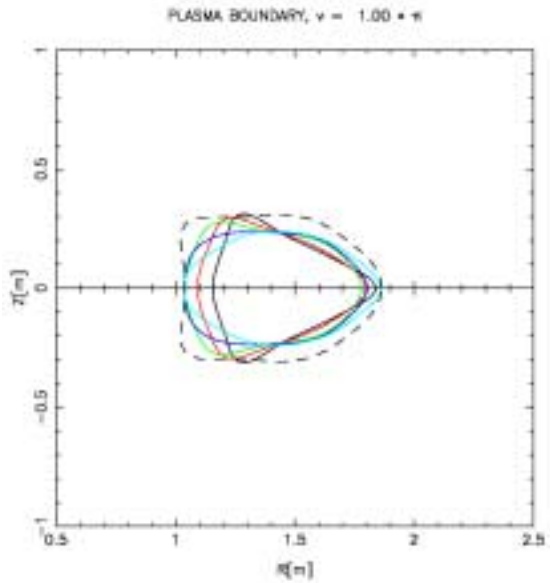
- **Raise/Lower $\iota(s)$ at constant shear**
- I_p = 174 kA, B_T = 1.7 T
- β = 0%
- **All calculations here used 18-modular coil set.**



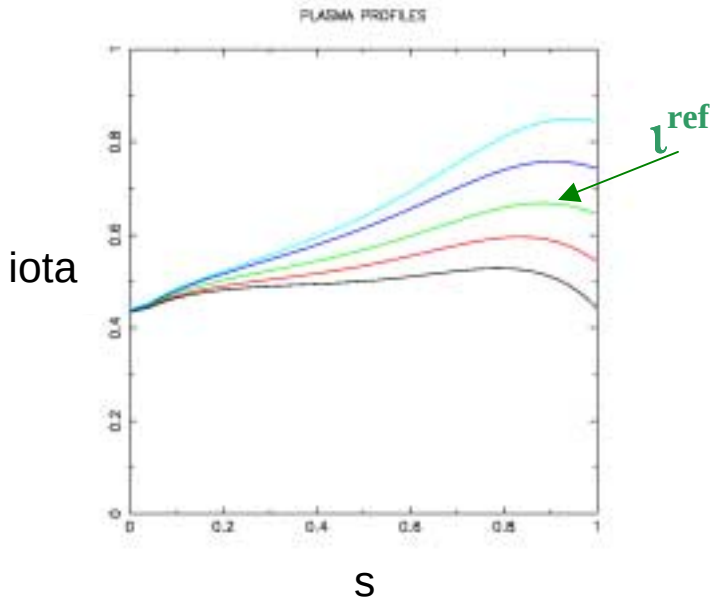
- $\Delta\iota \sim \pm$ 0.2 possible: (~50% of $\iota^{ref}(0)$, ~30% of $\iota^{ref}(1)$)
- For $\Delta\iota$ = - 0.2, current in PF3 predicted by optimizer presently too large (~ 2MA). However, PF locations not yet optimized.

FLEXIBILITY TO CONTROL SHEAR AT FIXED I_p, B_T





- **Raise/Lower $\iota(1)$ at fixed $\iota(0) = 0.45$**
- I_p = 174 kA, B_T = 1.7 T
- β = 0%
- **Calculations mostly done with PVR coilset, with spot checks performed using 18-modular coilset.**



- $\Delta\iota(1) = \pm$ 0.2 is possible

  ($\iota^{ref}(1) = 0.65$)

  i.e., substantial increase/decrease

  in shear can be obtained.

FLEXIBILITY TO VARY QA-NESS

- **The ability to generate configurations with good QA is an essential requirement for NCSX.**
- **A systematic exploration of the role of QA in improving the transport properties of stellarator plasmas will require an ability to control the degree of QA-ness.**

Question:

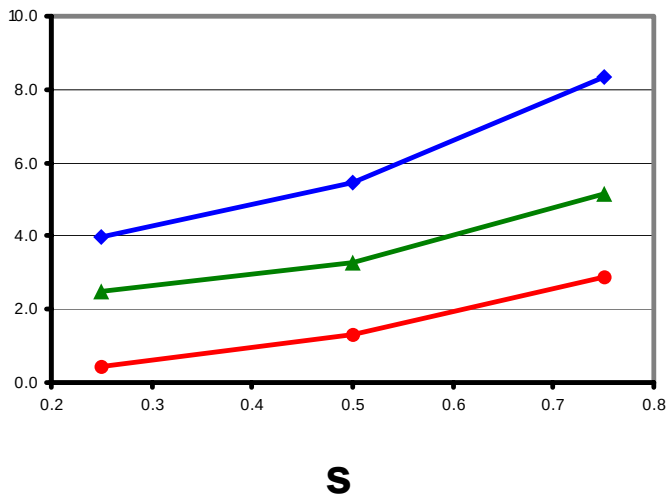
- **Do we have QA control <u>while maintaining plasma stability</u>?**

Answer**:**

- **YES!**

FLEXIBILITY TO VARY QA-NESS

Radial profile of ε_h[%]



- 3 configurations, each with I_p = 43.5 kA, β=3.0%, each stable to kink and ballooning modes (selected from I_p – β scan results).
- 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.

FLEXIBILITY TO EXPLORE STABILITY BOUNDARIES AND 3D SHAPE STABILIZATION

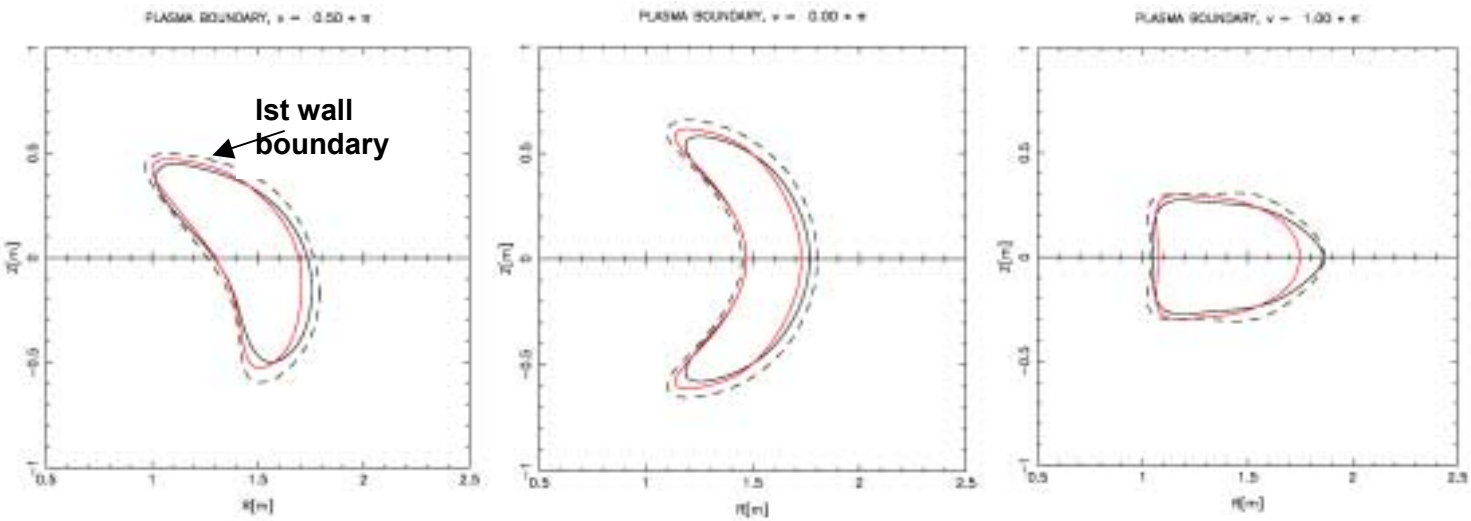
- **To illustrate the type of experiment that can be run on NCSX aimed at understanding the physics that determines stability boundaries, consider two configurations from the I_p - β scan:**

- **We can make use of fact that 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. Eg. consider**

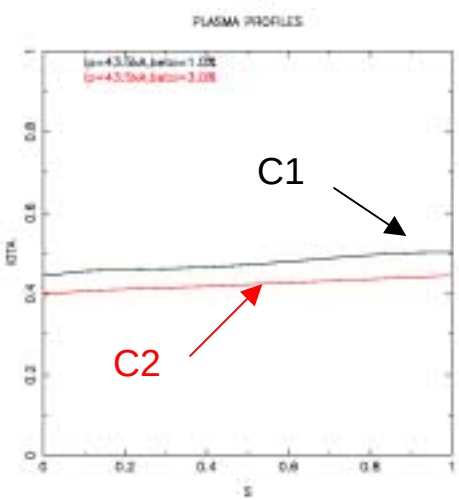
C1 **C2**

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)



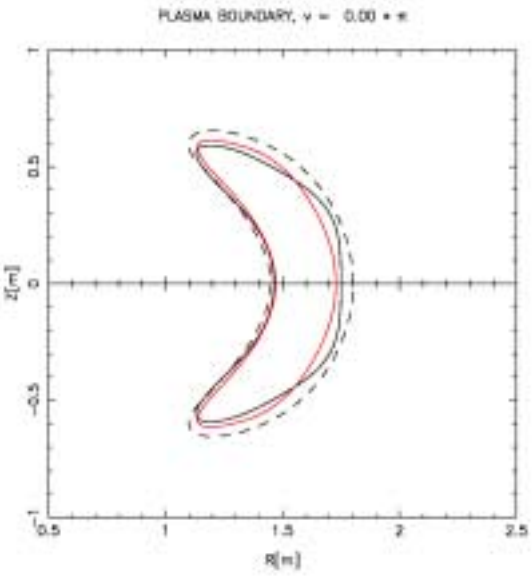
(ι(1)≈0.5)

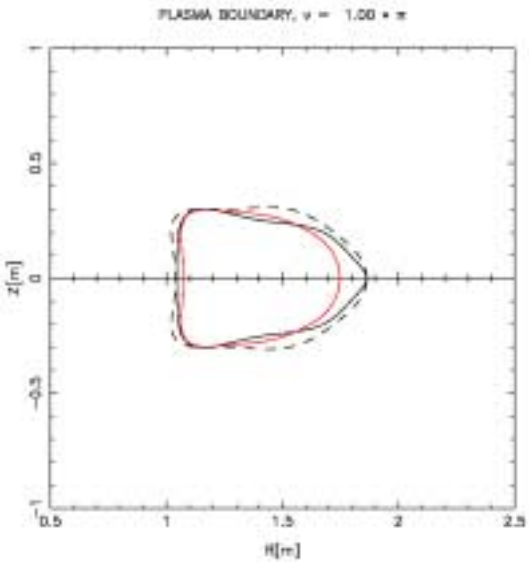
β_{Lim} = 1.0% for C1

β_{Lim} = 3.0% for C2

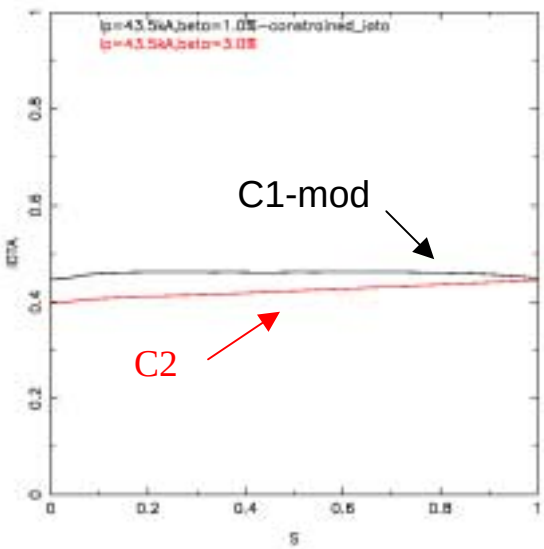
- **Difference in β-limits is due to difference in shape.**

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



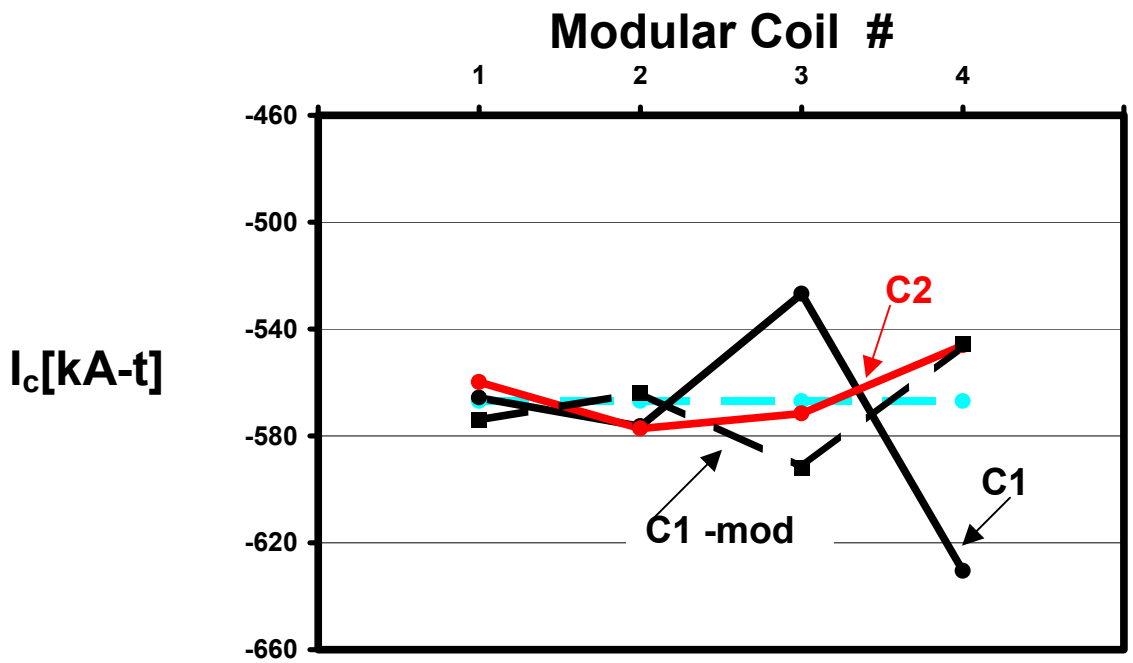


C1-mod (black)
C2 (red)



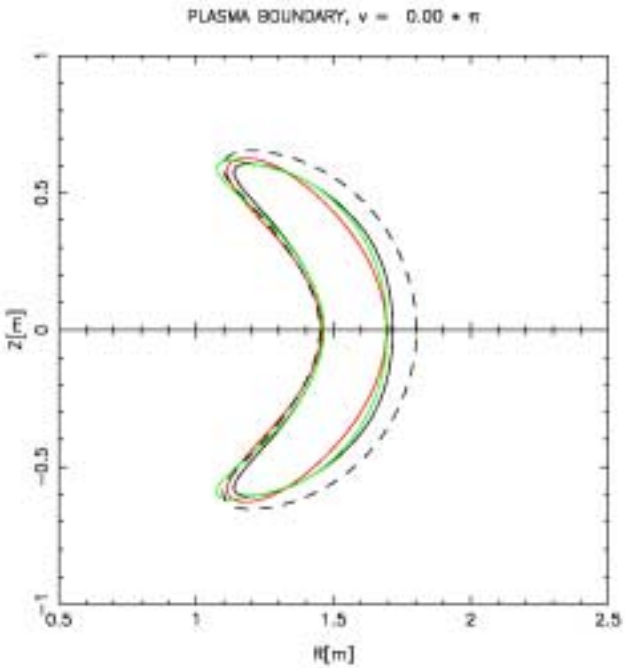
- **Impose ι-control on C1 to produce new configuration, C1-mod, whose β-limit is 1.0%, but which has the same ι_{edge} as the β_{Lim} = 3.0% configuration.**

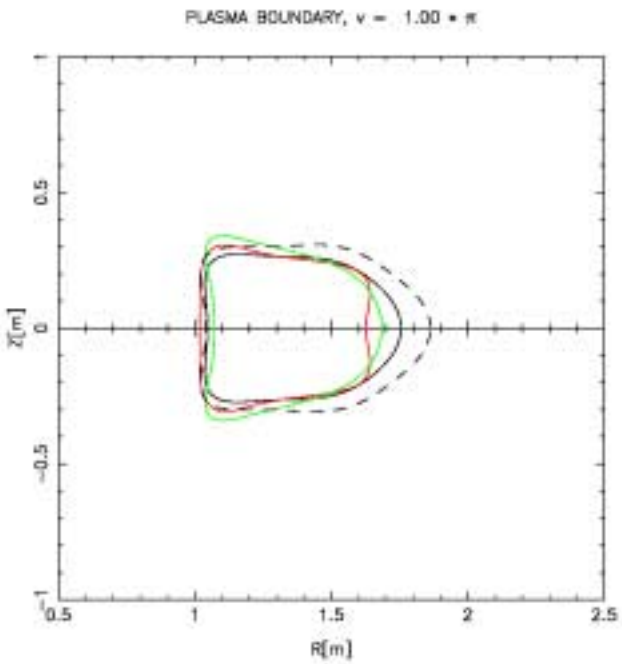
MODULAR COIL CURRENTS FOR THE 3D SHAPE STABILIZATION 'EXPERIMENTS'



- Max ΔI_c variation = 10%
  => controllable.

BENIGN EFFECT OF β and Ip QUENCHES ON RADIAL POSITION





Starting from reference Ip = 174 kA, β = 4.2% config (black), imagine the effect on plasma position of an instantaneous loss of all the β, or all the I_p:

Red: Ip = 174 kA, β = 0.0% (beta drop) → ΔR_{min} = 2.2 cm

Green: Ip = 0 kA, β = 4.2% (current quench) →: ΔR_{min} = 4.7 cm

Contrast with tokamak behavior!

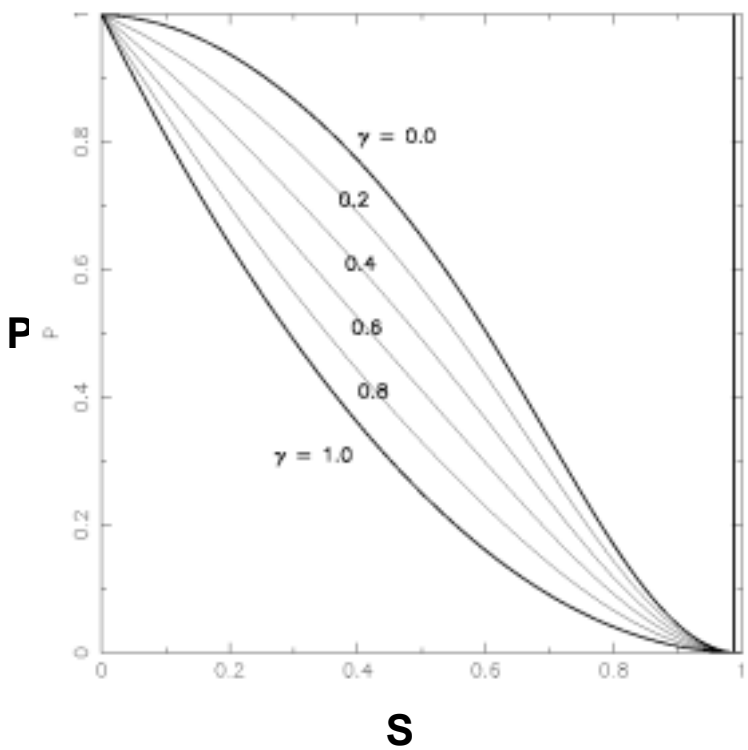
SUMMARY

- 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.

- After finalization of coilset for CDR, an extensive set of flexibility experiments will be re-done.

PRESSURE PROFILE VARIATION



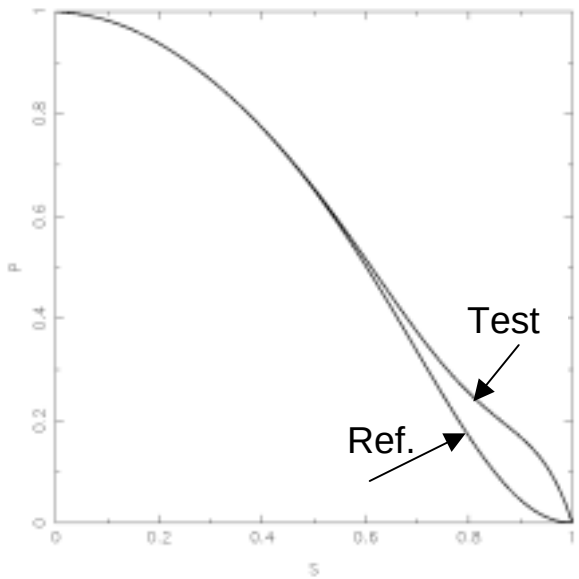
- **How much can we peak P(s) and maintain stable configs with good QA at β = 3.0%?**
- **Use reference J.B and the pressure profiles shown.**
- **For PVR, showed stable range of pressure profiles is $0 \leq \gamma \leq 0.8$. (γ =1.0 is stable at β = 2.5%).**

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

Used 18-modular coil system to verify that γ = 1.0 is table, with ε_h = 0.23%.

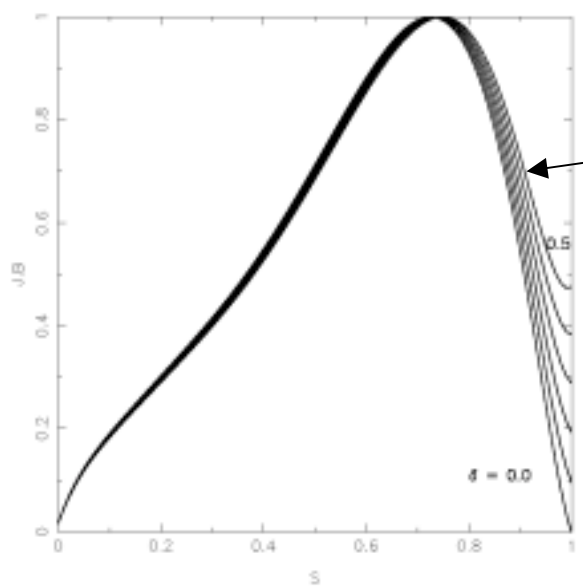
EFFECT OF PRESSURE PEDESTAL ON STABILITY

-The road to H-mode profiles.



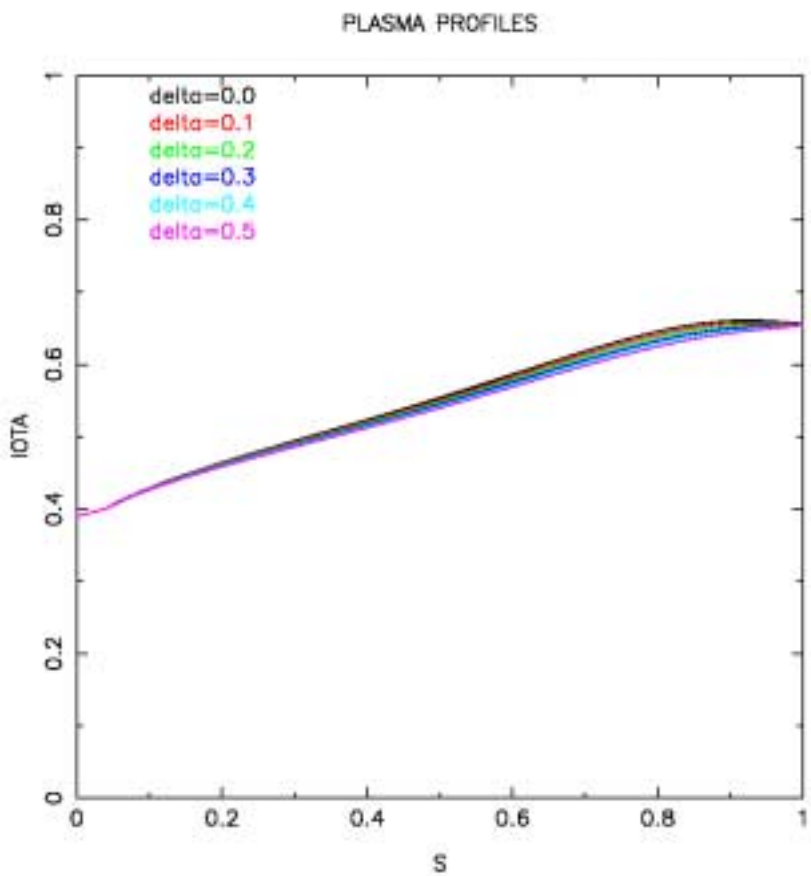
- "Test" pressure profile with finite edge gradient is stable at β = 4.0%.

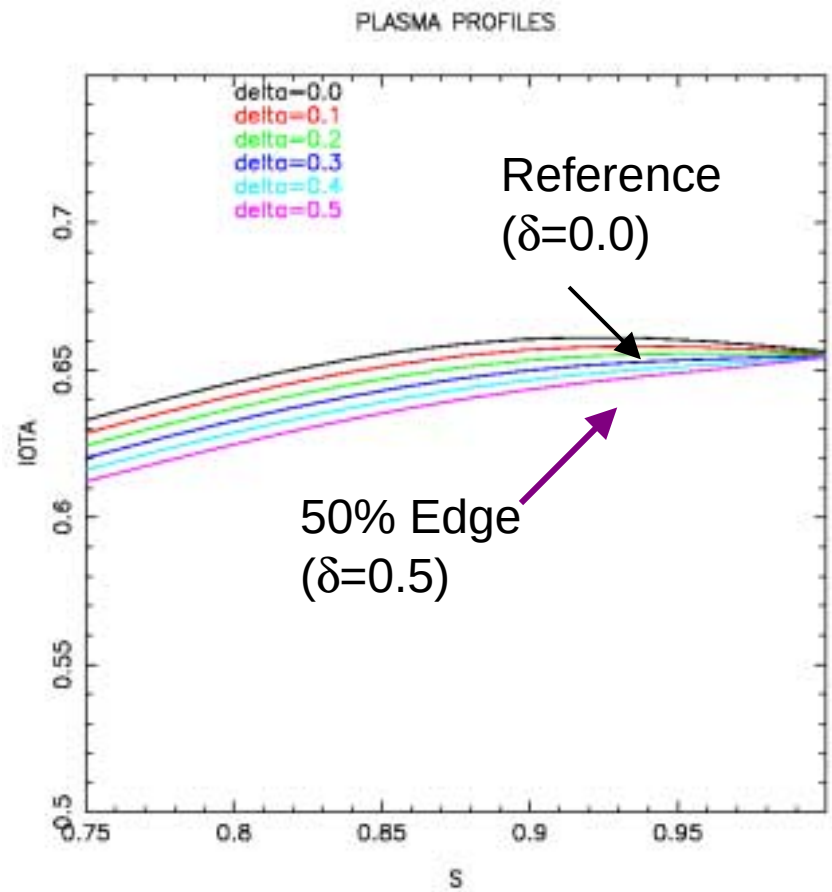
I_p = 174 kA, B_T = 1.7 T

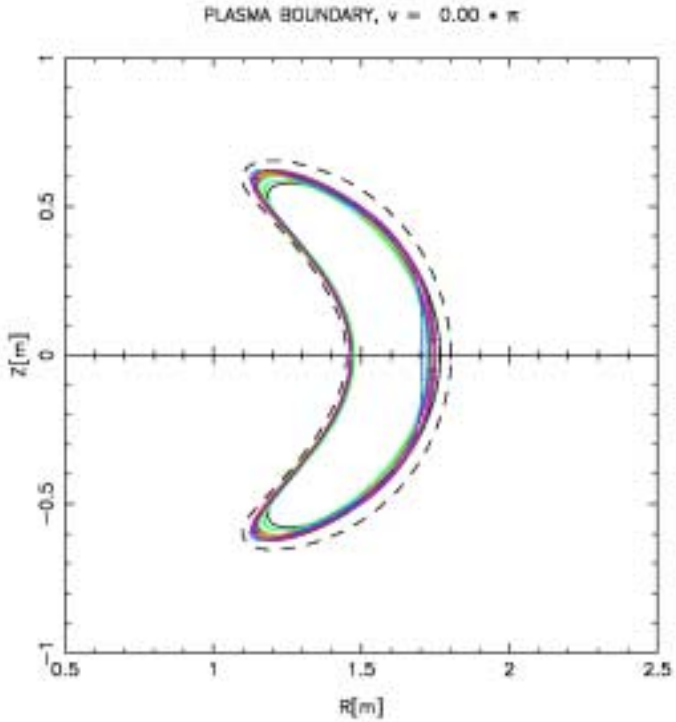


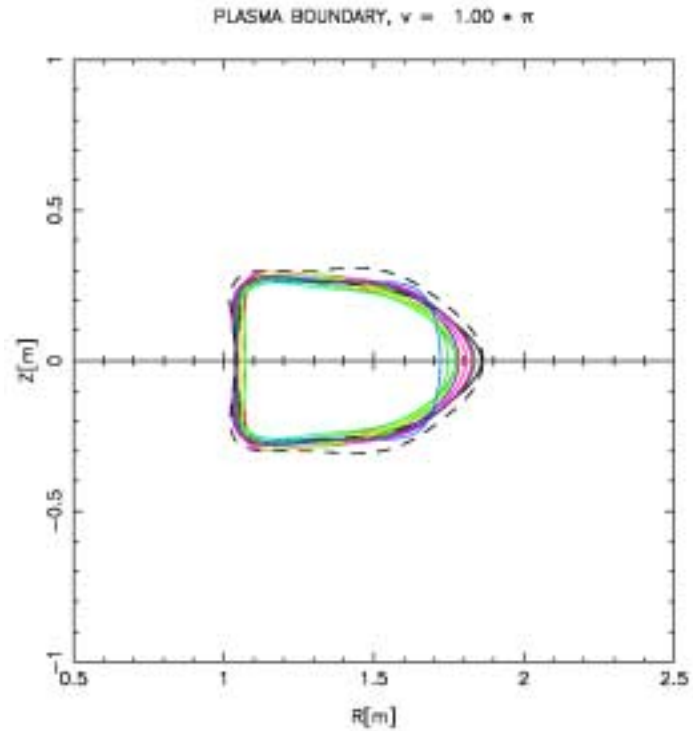
Used this current profile (50% edge current density)

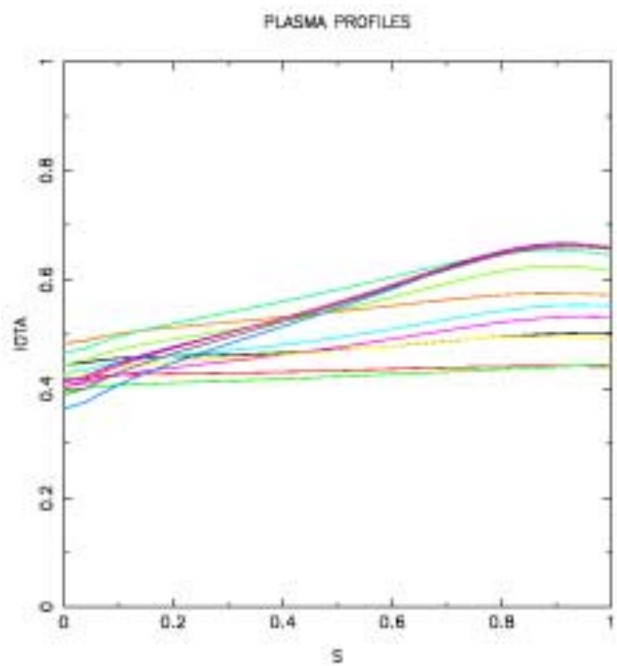
IOTA PROFILES FOR EDGE CURRENT PROFILES











- PLASMA BOUNDARIES AND ι(s) PROFILES from Ip – β scan.