FLEXIBILITY STUDIES —Update

N. Pomphrey NCSX Project Mtg, Jan 30-31, 2001.

- At Dec 19-20 mtg, iota scan results were presented which demonstrate the ability of the 10/17/00 modular coils to effect substantial changes in ι_{ext}:
  - up/down shifts
  - increase/decrease of shear
- Here, we focus on numerical experiments which demonstrate the ability of coils to maintain robustness of performance as plasma profiles are changed from their baseline forms.
  - The NCSX coil design has largely focussed on trying to reproduce a single configuration - the li383 configuration. This was obtained from an optimizer which optimized stability and QA-ness for a single set of plasma profiles. A valid concern has been that as the plasma profiles deviate in form from the baseline profiles, the plasma performance may seriously degrade.
  - However we find that good plasma performance is obtained for a wide range of profile variations, allaying this concern.

Plasma Performance when I_p and β are varied

- Ed Lazarus has shown (will present at PVR) a sequence of free-boundary equilibria corresponding to the "evolution" of NCSX from an S1 state ($I_p = 0, \beta = 0$), to a final S3 state ($I_p = 0, \beta = 4.2\%$) whose profiles of pressure and current are the same as the li383 baseline profiles. Profile evolution is consistent with a 1-D transport model.

- Here we show results from running the free-boundary optimizer using baseline current and pressure profiles, but a wide range of I_p and β values. For each value of I_p and β, we ask to minimize χ^2_{Bmn} while trying to maintain stability w.r.t. $n = 1$ kink and $n = \infty$ ballooning modes. Results are presented in Table 1 below

- **For the assumed profiles, the performance w.r.t. variation in I_p and β is robust.**

- We can also view this Table as an exploration of accessibility to S3 by many routes.

I_p[MA] \ β[%]	0.0	1.0	2.0	3.0	4.0	5.0
0						
62.5		i0625b10.rstrt2 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0369$	i0625b20 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0259$	i0625b30.rstrt3 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0350$		
125			i1250b20.rstrt1 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0309$	i1250b30.again.rstrt3 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0260$	i1250b40 λ_K = -1.8e-5 λ_B = unstable $\chi^2_{Bmn} = 0.0231$	
187.5			i1875b20 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0204$	i1875b30.rstrt1 $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0303$	i1875b40.again.rstrt4 λ_K = -1.9e-6 λ_B = unstable $\chi^2_{Bmn} = 0.0167$	
250	s2.001.again $\lambda_K = 0$ $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0337$	i25000b10 λ_K = -2.8e-5 $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0219$	i25000b20 λ_K = -1.0e-5 $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0245$	i25000b30 λ_K = -5.8e-6 $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0221$	i25000b40 λ_K = -2.8e-6 $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0239$	i25000b50.rstrt1 λ_K = -4.6e-5 $\lambda_B = 0$ $\chi^2_{Bmn} = 0.0515$

Table 1: $I_p - \beta$ performance scan using baseline current and pressure profiles. (Table still to be completed).

Note: The performance (Max stable β) for the 10/17/00 coils exhibited here is not so good as for the 09/07 coils (stable up to 6% in Mike Z.'s beta vs ip.xls spreadsheet) - Why?!

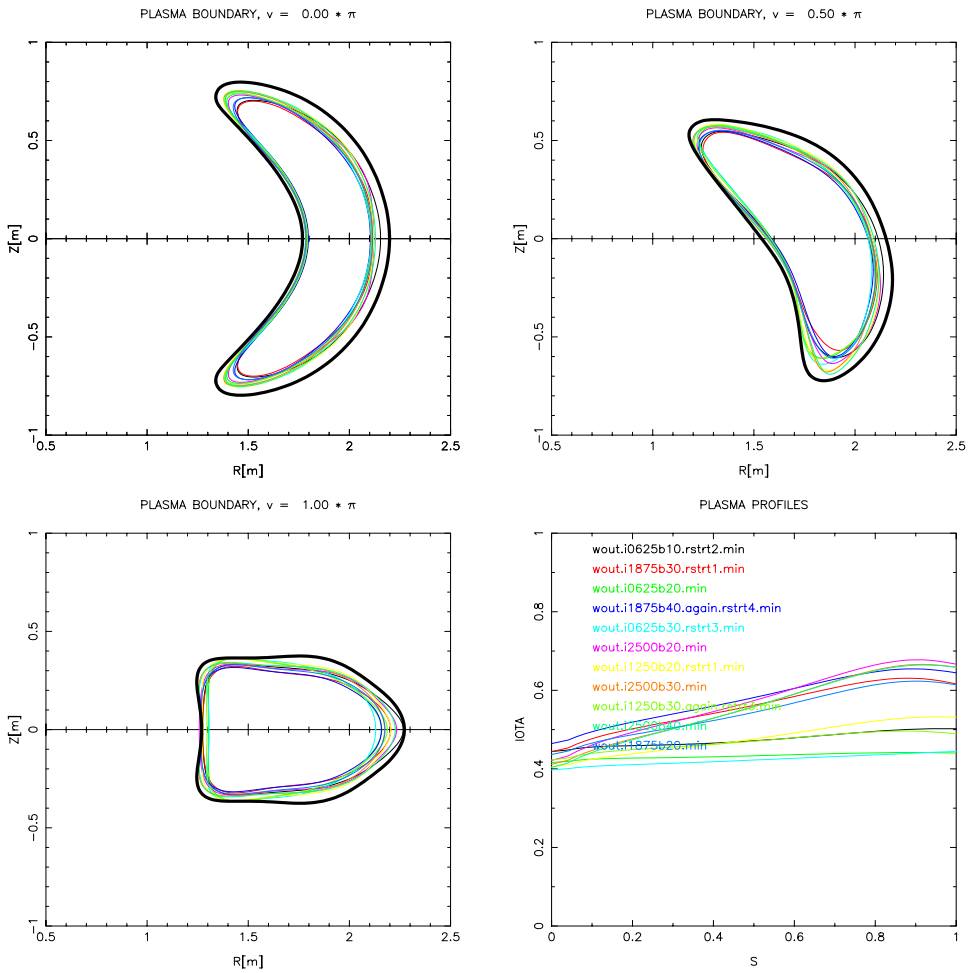


Fig: Plasma boundaries for $I_p - \beta$ scan (incomplete)

Flexibility w.r.t. changing (exploring) QA-ness

In most of the tabulated results seen to date, we have seen modest variations in the QA-ness measure, χ^2_{Bmn} (up to $\sim$ factor of 2 or 3 from the li383 fixed boundary target value of 0.015. This is because we usually try to beat down hard on χ^2_{Bmn} with the optimizer. The question is:

- Can we produce stable configurations with the NCSX coils which vary the QA-ness by much greater factors? The greater the factor, the more convincing is the argument we can perform experiments to test the concept of QA-ness.

- In the course of running the $I_p - \beta$ scan simulations, we found cases for $I_p = 62.5$kA, $\beta = 1.0\%$ (using baseline profiles) which show a large variation ($\sim$ factor of 75) in the variation of χ^2_{Bmn} as the shape is changed by the external fields (see Table on next page + Figure that follows the Table).

ID	i0625b10	i0625b10.rstrt2
Ip[A]	-6.25E+04	-6.25E+04
Beta[**Chisq(Bmn)**	2.8375	0.0369
lambda-Kink	0	0
lambda-Ball	0	0
Aspect	4.56	4.32
AuxTF[A]	-3.598E+01	-4.472E+02
Mod1[A]	-1.424E+06	-8.116E+05
Mod2[A]	-2.076E+05	-8.270E+05
Mod3[A]	-1.423E+06	-7.558E+05
Mod4[A]	+7.673E+04	-9.110E+05
Dipole	+9.716E-01	+8.419E-01
Quad	+1.041E+00	+1.319E+00
Hex	+8.379E-03	-8.837E-01
Oct	-1.867E+00	2.032E+00

Yes! $\cdots$ the sign of current in Mod 4 has flipped.....Is this allowed by the power supplies?

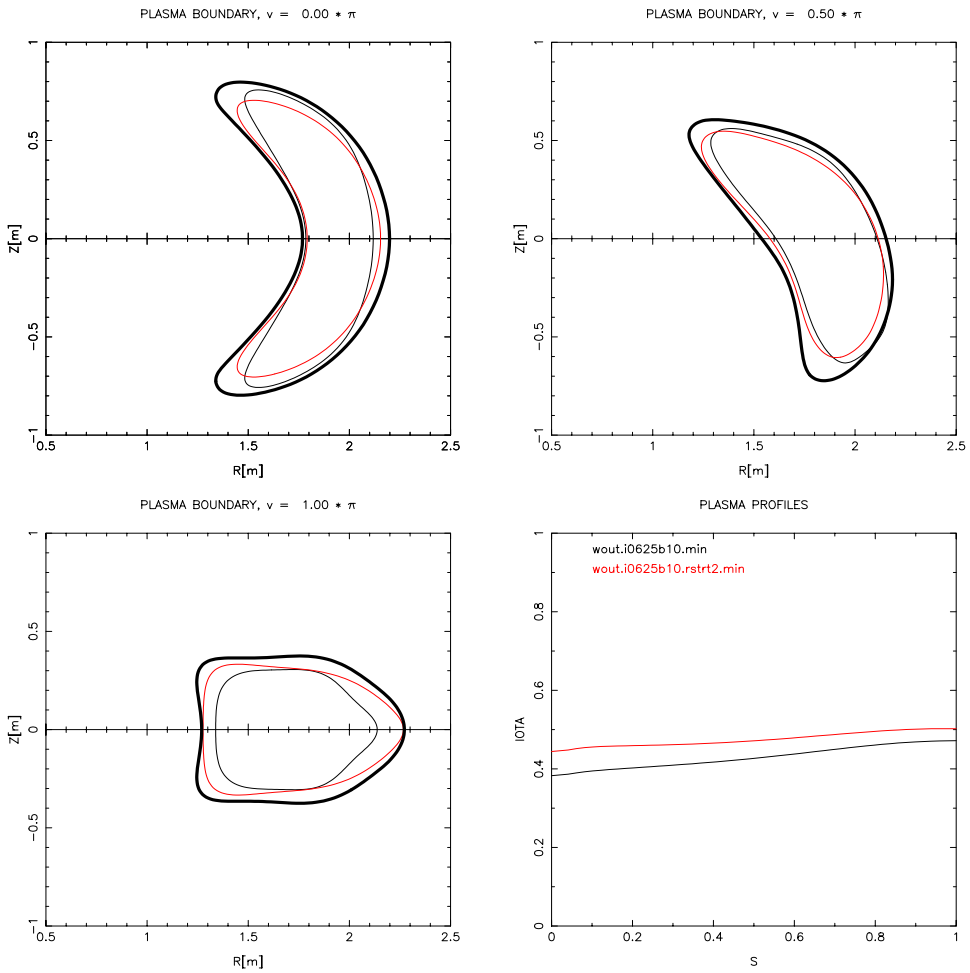


Fig: Plasma boundaries for large QA variation; $I_p = 62.5$kA, $\beta = 1.0\%$.

Performance Robustness (P.R.) when Profiles are varied

Our baseline configuration (li383) was stable to ballooning and kink modes at $\beta = 4.2\%$ with QA-ness measure $\chi^2_{Bmn} = 0.015$. (Ballooning modes were limiting; the β-limit for kinks was $\approx 5.0\%$).

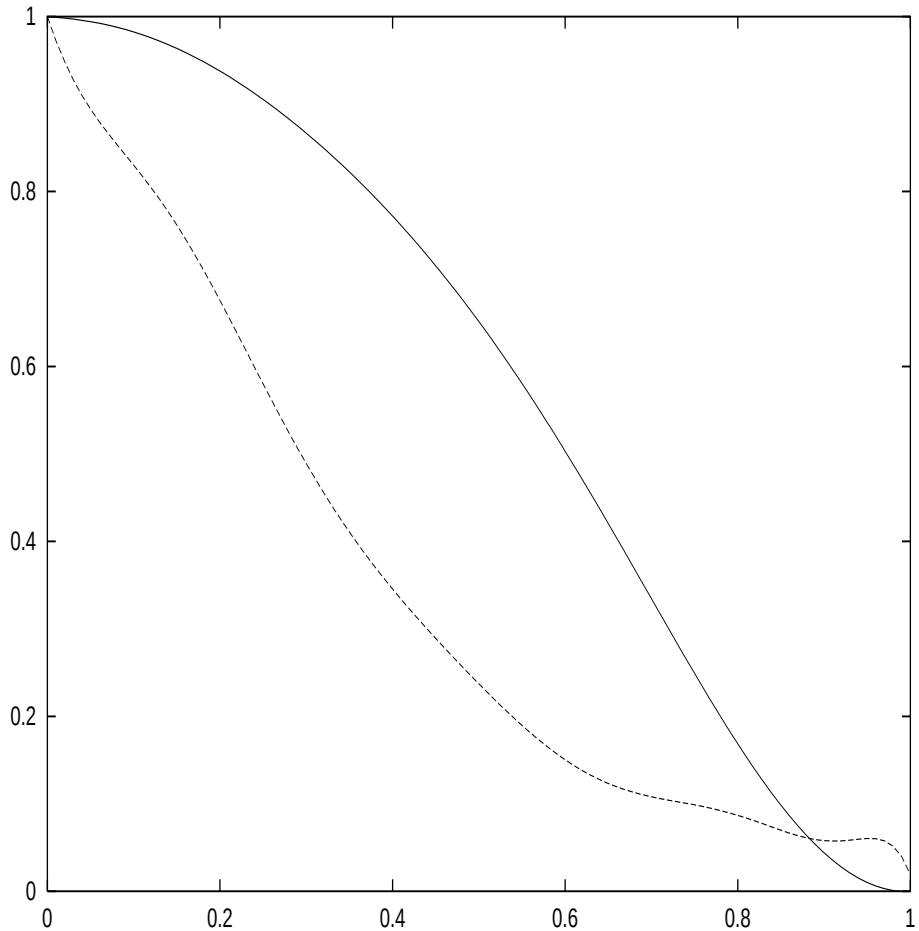
We now examine NCSX performance using non-baseline profiles

P.R.-1: Use a **more peaked pressure profile** with the baseline current profile. - (The baseline li383 pressure profile would be classed as broad when compared with the Dave Mikkelsen's collection of 11 experimental profiles taken from stellarators + tokamaks that bracket NCSX in size).

- The pressure profile selected for the P.R-1 sequence is the PBX-M NBI (shot 3113-1). A comparison of the baseline pressure profile with this more peaked profile is shown in the Figure below.

Strategy for runs:

- Start from S2 ($I_p = 250$kA, $B_T = 2.0$T, $\beta = 0.0\%$) state of li383. Then, with new pressure profile, run sequence of optimizer runs stepping β in increments of 0.5%.
- $I_p = 250$kA in all runs.



Peaked pressure profile used in P.R.-1 performance study, compared with li383 baseline profile.

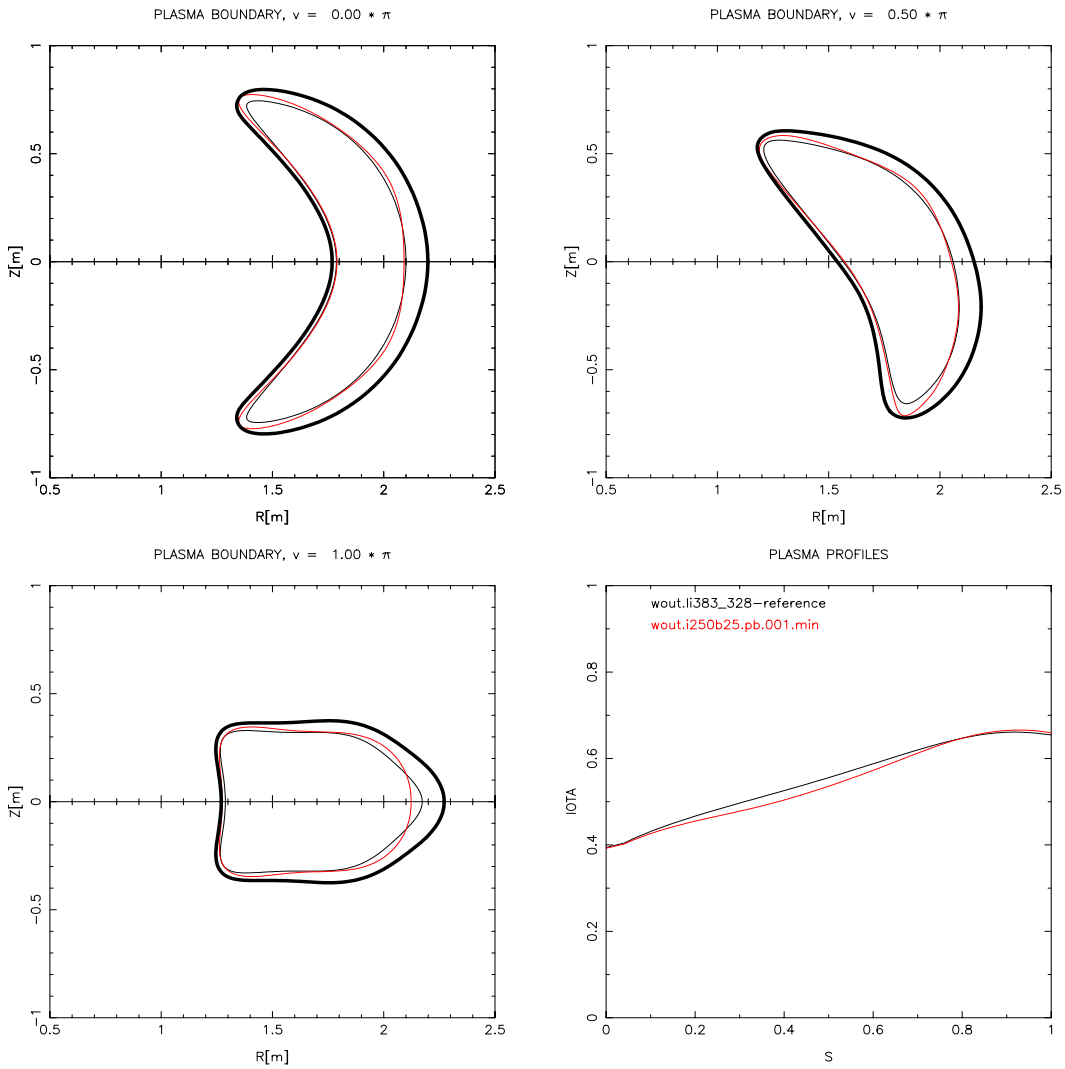
P.R.-1 Results Summary

- $\beta^{lim} \approx 2.6\%$.
- Kink modes are limiting (we only investigate the $n = 1$ family)
- Coil Currents at the beta limit are:

  Aux TF:-2.002E+05,

  Mod1: -8.274E+05, Mod2: -8.254E+05, Mod3: -8.011E+05, Mod4: -8.367E+05,

  Dipole: 2.278E-01, Quad: -7.630E-01, Hex: -2.459E-01, Oct: -5.027E+00
- The plasma boundary shape and ι profile for the peaked pressure equilibrium at the beta limit are shown below, in comparison with the li383 S3 baselines.



Plasma boundary shape and ι profile for the peaked pressure equilibrium at the beta limit. Also shown are the li383 S3 baselines

A second set of experiments on "Robustness of Performance"

P.R.-2: In a second series of performance robustness experiments where plasma profiles other than the baseline profiles are studied, we **modify the current profile and retain the baseline pressure profile.**

- The baseline current profile is hollow (due to bootstrap consistency) and broad. Regarding this as an extreme case, we consider modified J.B profiles which have a seed current which fills the core.

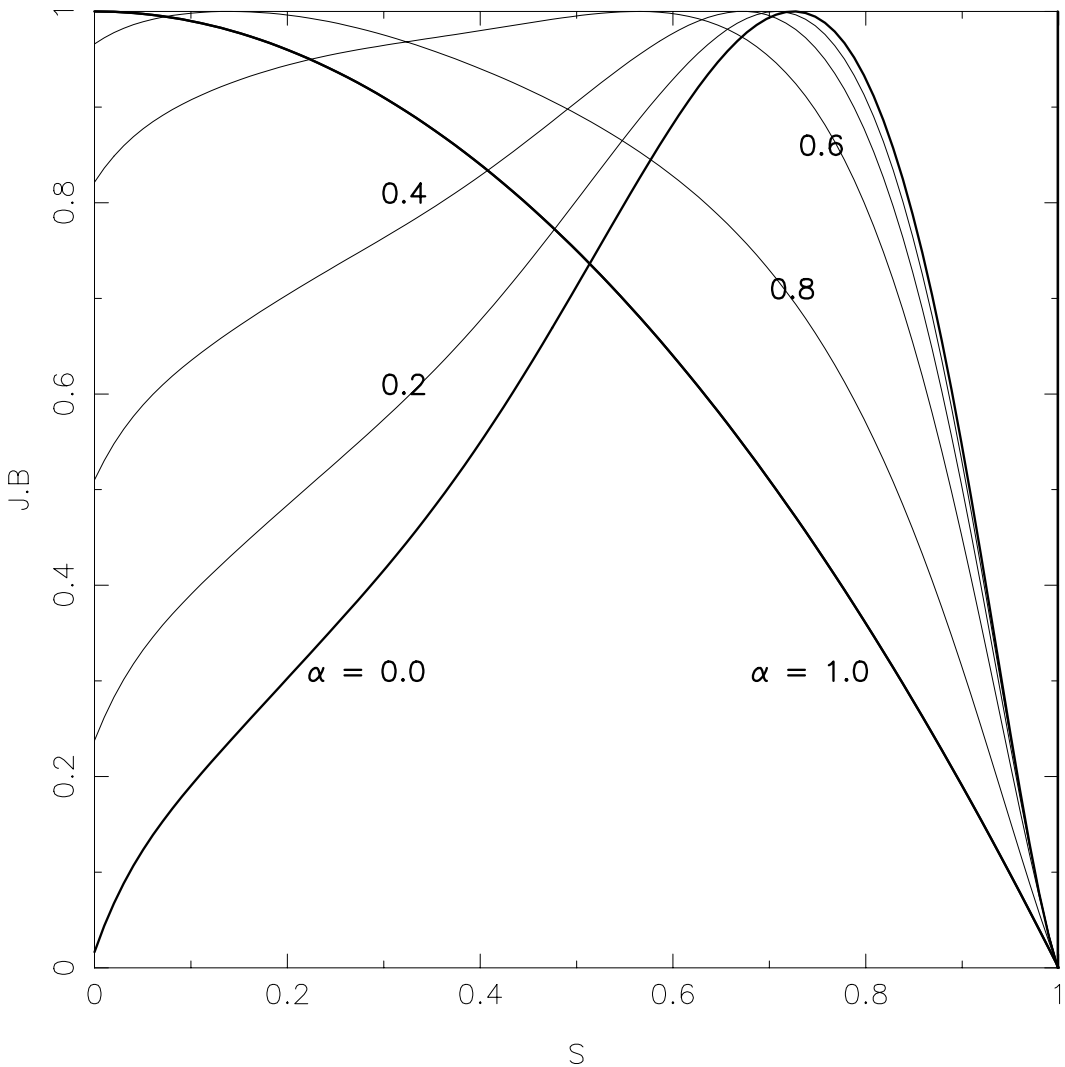
- In fact, we consider a 1-parameter family of profiles defined by

$$J_\alpha = (1-\alpha) * J_{baseline} + \alpha * J_{peaked},$$

  where J denotes J.B, $J_{baseline}$ denotes the baseline li383 current profile, and $J_{peaked} \propto 1 - s^2$ represents a peaked current profile. The parameter α lies in the range ($0 < \alpha < 1$). A plot of the current profile, for different values of α is shown in the Fig. below.

- In the optimizer runs we back off in β from the β-limit obtained using the baseline profiles, and ask for what range in α (ie., range of curent profiles) are stable plasmas (kink + ballooning) obtained at a β of 3.0%, for $I_p = 250$kA, $B_T = 2.0$T?

- The answer is — for $\alpha \lessapprox 0.5$ (see Table) $\Rightarrow$ we have considerable robustness of performance!



Current profiles parameterized by α used in P.R.-2 robustness of performance experiments.

α	λ_{Kink}	λ_{Ball}	χ^2_{Bmn}	ID
0.0	-1.4e-5	0	0.0289	i250b30.sp-0.0.rstrt1
0.1	-2.7e-5	0	0.0294	i250b30.sp-0.1.rstrt3
0.2	-3.2e-5	0	0.0280	i250b30.sp-0.2.again
0.3	-2.5e-5	0	0.0303	i250b30.sp-0.3.rstrt3
0.4	-4.3e-5	?	0.0306	i250b30.sp-0.4.rstrt2
0.5	-3.7e-5	0	0.0297	i250b30.sp-0.5.rstrt2
0.6	-8.7e-5	?	0.0432	i250b30.sp-0.6.rstrt2
-	-4.8e-5	0	0.0918	i250b30.sp-0.6.rstrt1
0.7	-7.6e-5	?	0.0375	i250b30.sp-0.7.rstrt2

Table: Results of P.R.-2 sequence. Current profiles with $0 < \alpha < 0.5$ are stable to ballooning and $n = 1$ kink.

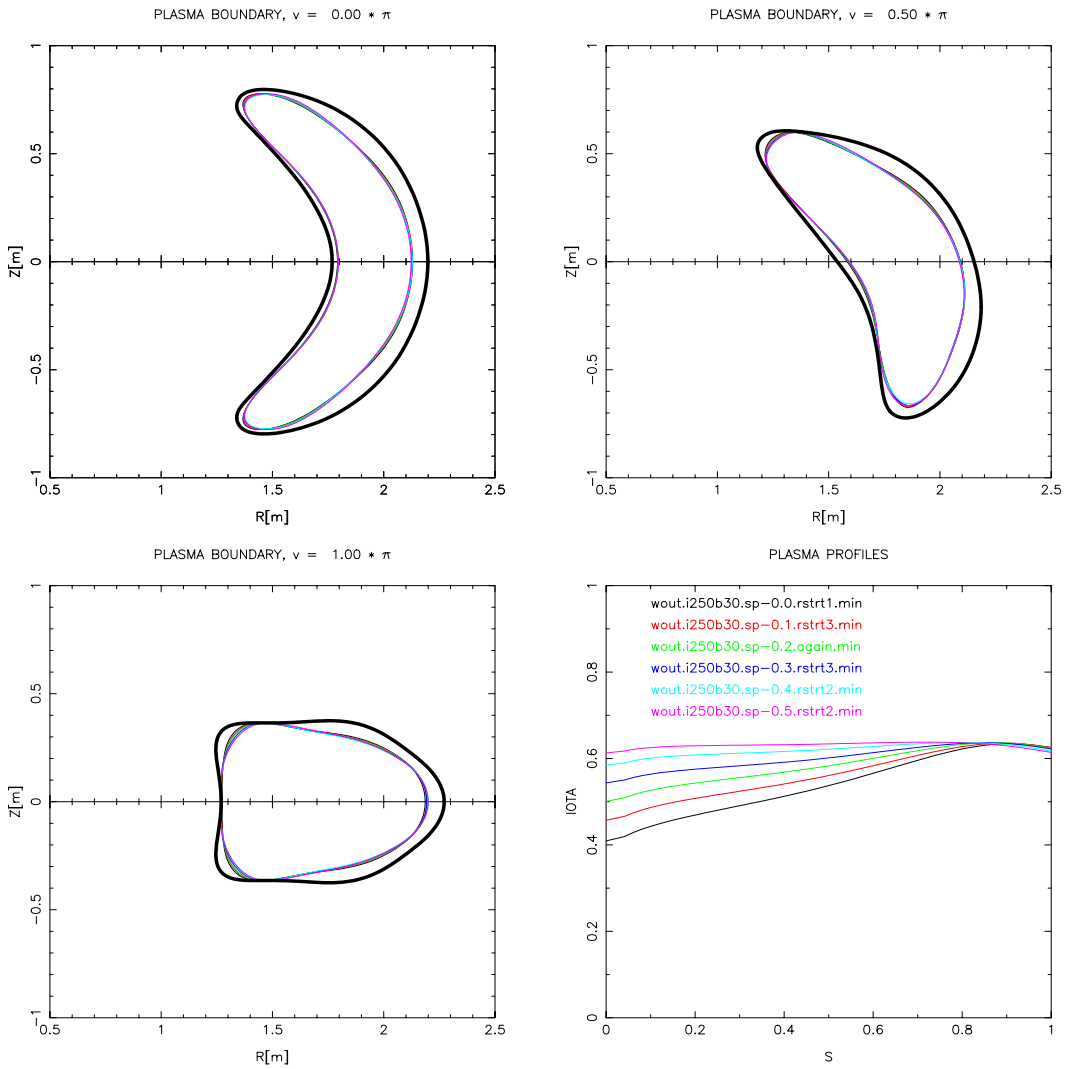


Fig: Plasma boundaries and ι profiles for P.R.-2 sequence

Summary

- The results presented today indicate a substantial range of profiles lead to configurations which have decent performance. Moreover, these configurations can be supported by fields produced by the NCSX 10/17/00 modular coils.
- Caveat: None of the cases shown today have yet been passed over to engineering for analysis of coil currents.
- Although the results were presented with emphasis on robustness of performance, they can be viewed as flexibility experiments.
- Taken along with the previous results showing control of ι_{ext}, I believe we have demonstrated that our NCSX coils have rather good flexibility.
- It is certain that the actual flexibility is much greater than that which we have so far demonstrated.
- We need to pass over some of the final equilibrium states to Dave Mikkelsen for an estimate of τ_E instead of relying on the χ^2_{Bmn}.