FREE-BOUNDARY VMEC FLEXIBILITY AND ROBUSTNESS STUDIES

N. Pomphrey and R.Hatcher

NCSX Project Meeting, July 12-13, 2000

The coil design philosophy adopted for NCSX is to:

- Design a primary set of coils (saddle, modular, or "alternate topology") for a plasma configuration with good quasisymmetric transport and high kink and ballooning beta limits ($\sim 4\%$) using reactor relevant (bootstrap consistent current and pressure profiles.

Since there will not be detailed current profile control in NCSX[‡], the design profiles are unlikely to be obtained in the actual experiment. Therefore, for the advertised mission of NCSX to succeed:

- We must demonstrate that the designed coils are capable of supporting plasma shapes which, for realizable profiles, have high beta limits and/or good quasisymmetry.

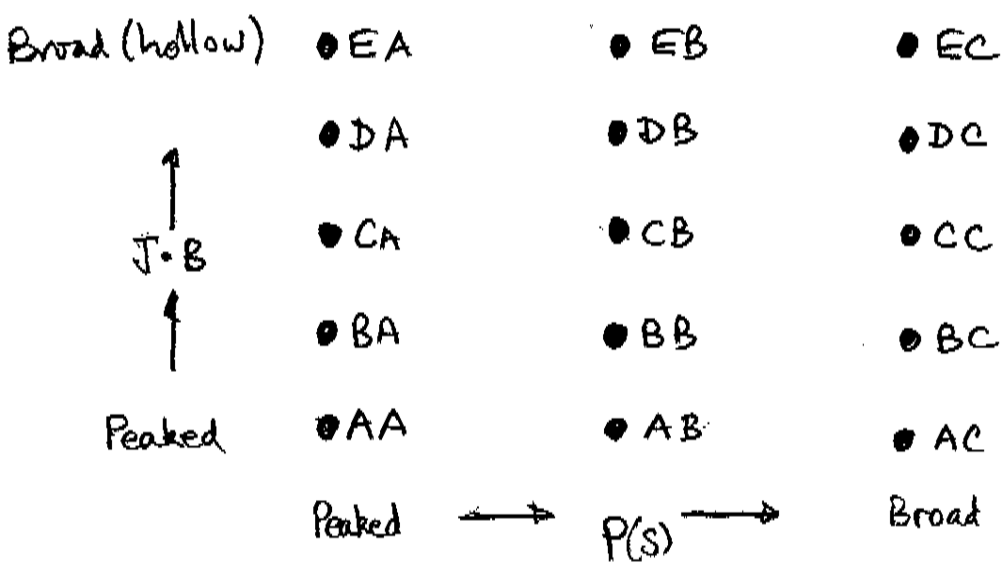
[‡] Traditional current drive rather than external transform provided by coils

ROBUSTNESS STUDIES

We have defined a wide range of current and pressure profiles with which to study rubustness issues

- "Robustness" = ability of the designed coils to support a variety of assumed profiles within the vacuum chamber.

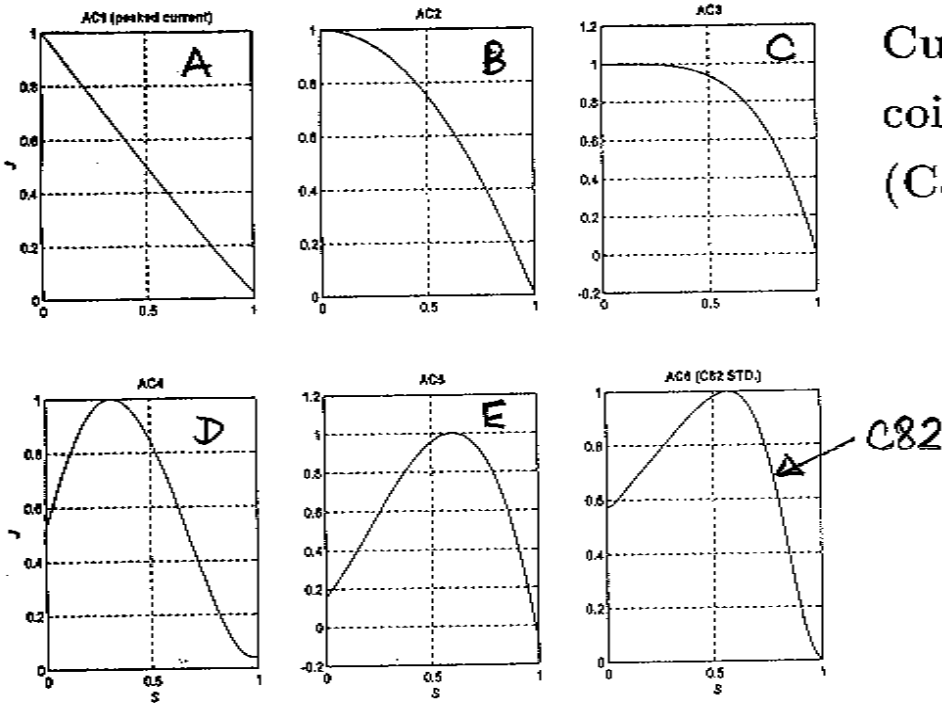
Five current profile shapes are considered (ranging from very peaked to very broad and hollow), as well as three pressure profile shapes (taken from Dave Mikkelsen's data base).



⇒ 15 combinations.

The profiles are shown as a function of normalized toroidal flux on the next slide (Fig 1).

Current and pressure profiles used for coil robustness and flexibility studies (C82 ~~and LI383~~ profiles shown for comparison)



5 current profiles

A, B, C, D, E

3 pressure profiles

A, B, C

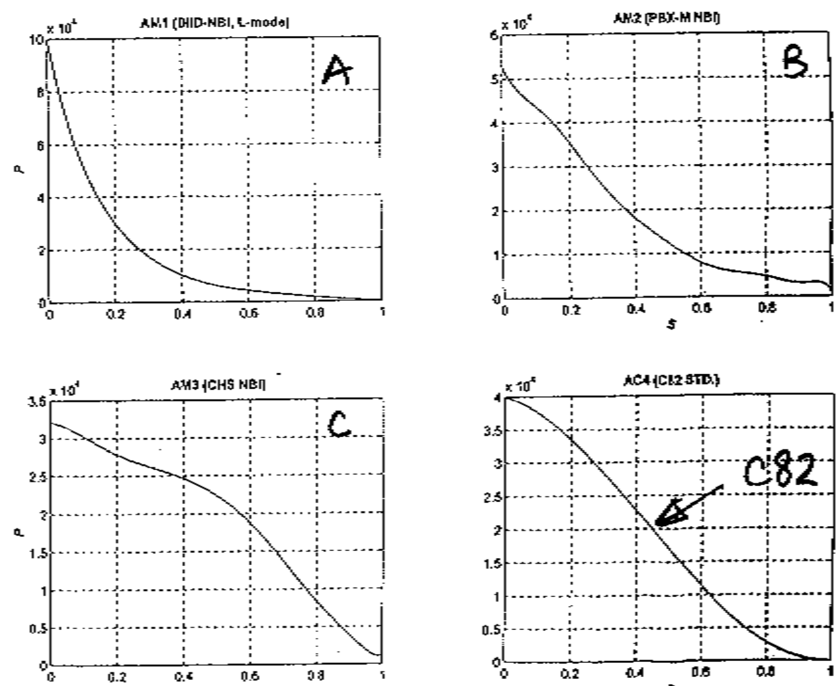


Fig. 1

RESULTS USING LI383-328 MODULAR COILS

- Coil currents were held fixed equal to values determined by Strickler et al., for their "best fit" to the LI383 plasma.
- Free boundary equilibria were sought for the full range of profiles shown in Fig. 1, assuming $I_p = 150kA$, and $\beta \approx 3.6\%$
  - Except for the profile combination "EA" (most hollow current, most peaked pressure), equilibria were successfully obtained for the wide range of assumed profile combinations. (Interestingly, this is in contrast to similar calculations for the C82 configuration where we were unable to get converged equilibria for AA, BA, CA, DA, EA and EB. This is probably a numerical issue, but should be looked at at some point).
- An overlay of the resulting plasma boundaries is shown in Fig. 2.
  - The plasma shape, especially on the inboard side, remains remarkably constant as the profiles are changed.

Overlay of free-boundary plasma shapes for a wide range of plasma profiles using fixed currents in the LI383-328 modular coils. -Various poloidal cross sections are shown.

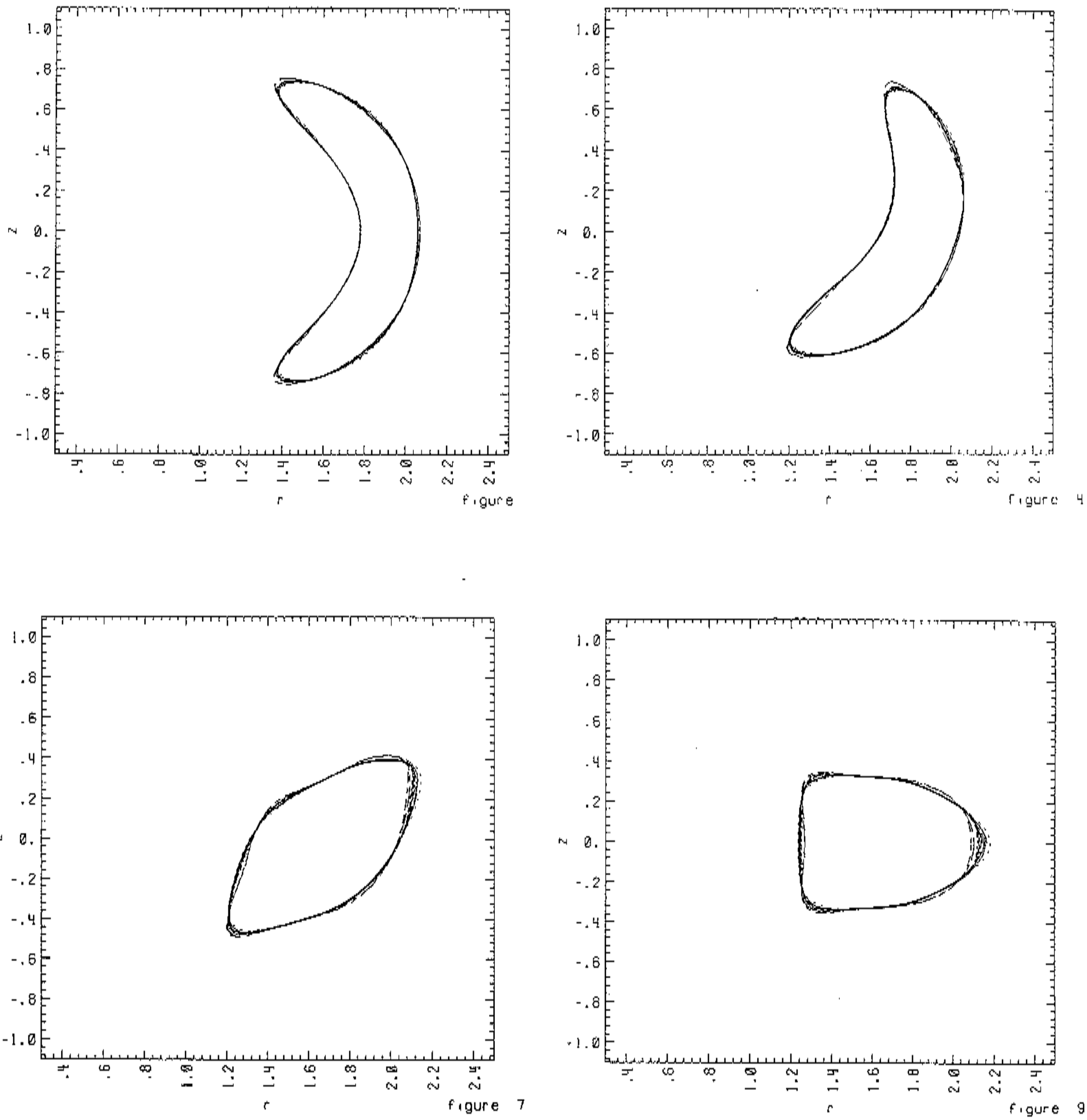


Fig. 2

- A similar set of runs was repeated, see Fig. 3, where enough vertical field was added to keep R_{max} = constant =2.12m (actually a dipole field was added - see later). The winding surface on which the saddles lie is also shown. Ample coil to plasma clearance is shown (too much??).

A vertical (dipole) field is added to keep R_{max} = constant = 2.12m for each equilibrium.

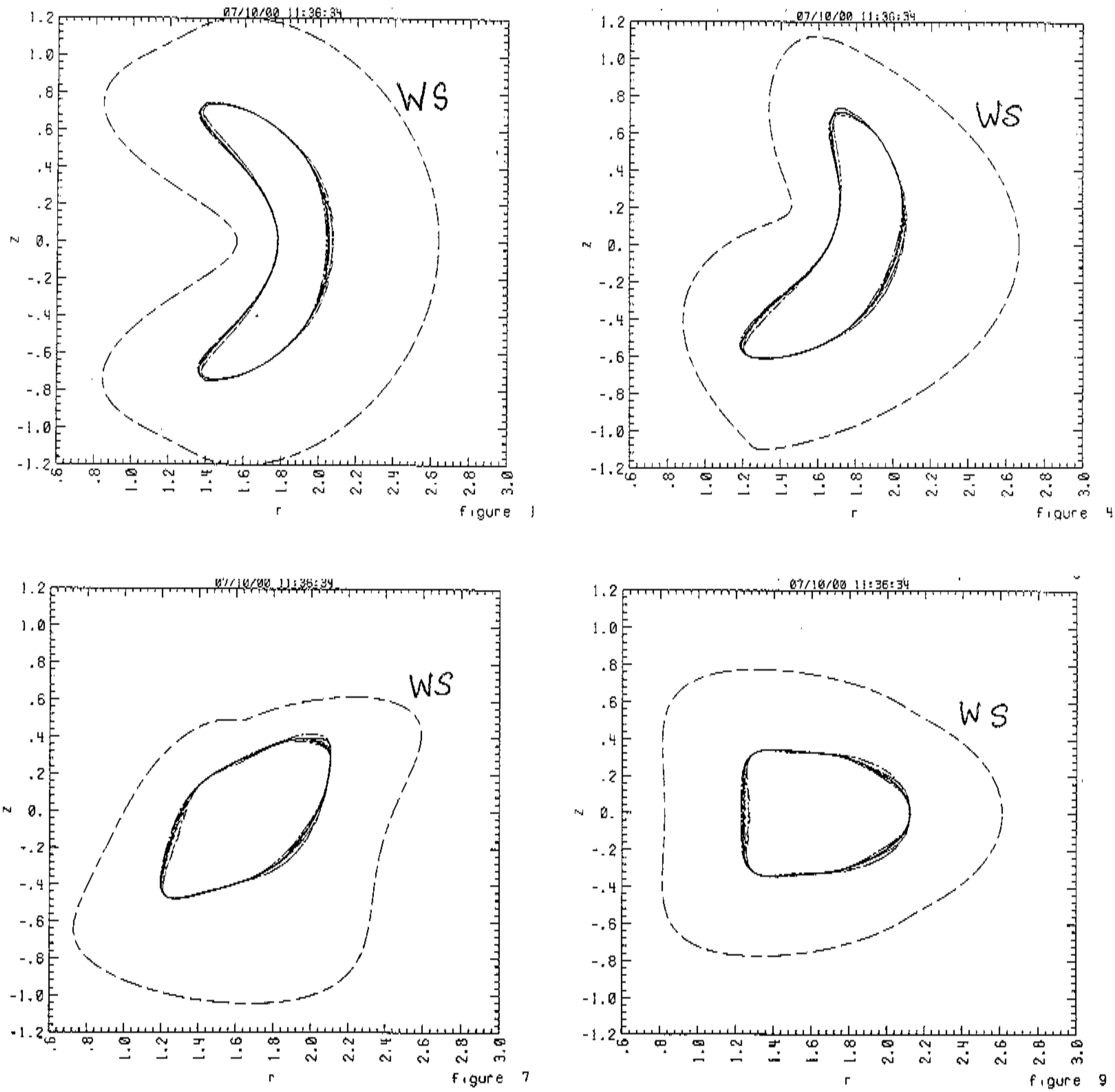


Fig. 3

FLEXIBILITY STUDIES

"Flexibility" = ability of coil set to dial changes in the plasma shape which produce desired changes in physics properties.

We can imagine shape changes of two types:

- (C1) Changes that improve stability/transport primarily through changes in the GLOBAL SHEAR (i.e., the iota profile).
- (C2) Changes that improve stability/transport primarily through changes in the LOCAL SHEAR (i.e., changes in the flux surface shape)

C1 is obvious. To understand C2 think of tokamaks and the ability to improve kink stability of elongated plasmas by increasing the triangularity.

Here, we ask:

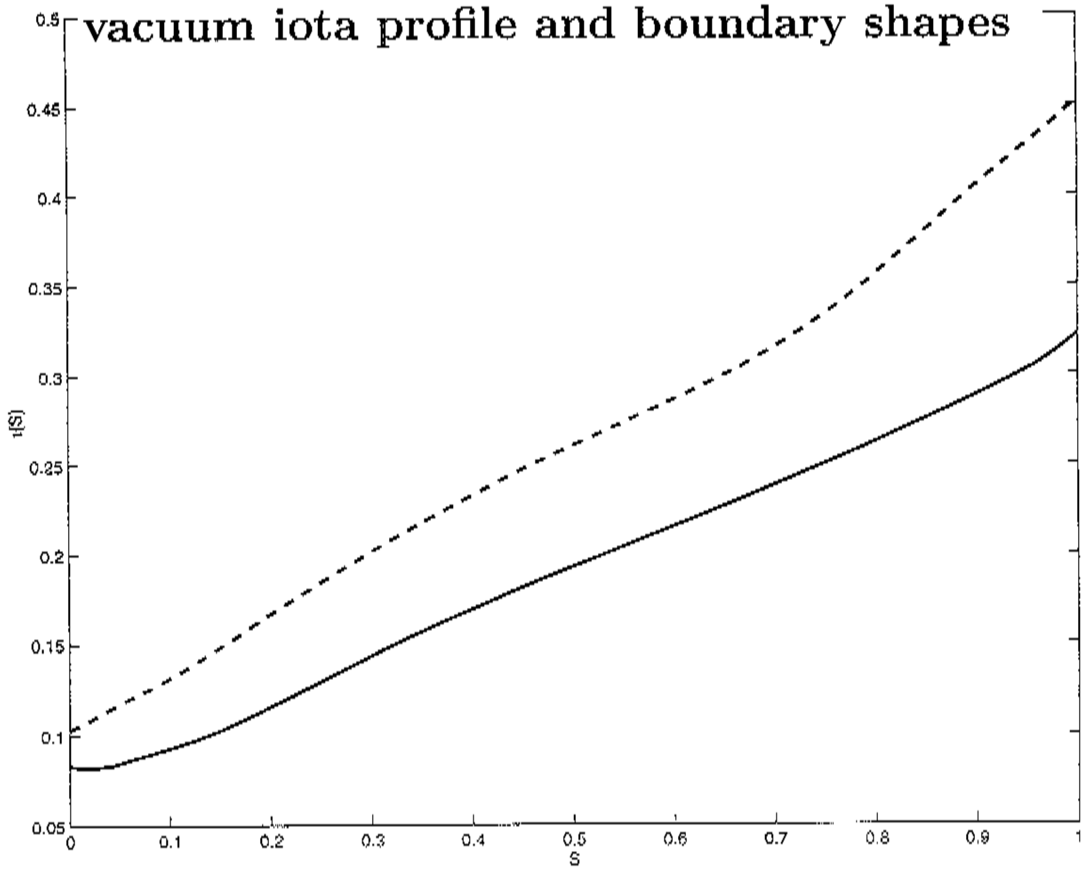
- To what extent can primary coils (especially saddles) and/or axisymmetric "secondary" (control) coils achieve C1 and C2?

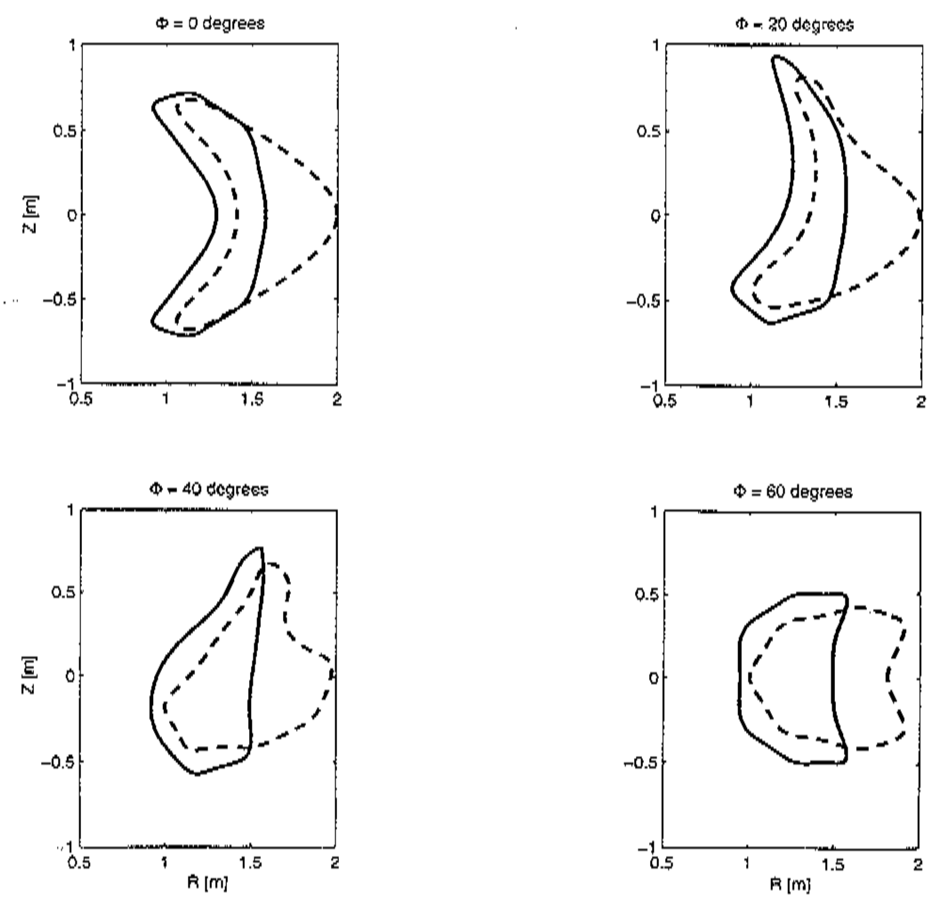
ABILITY OF C82 SADDLES TO PROVIDE VACUUM TRANSFORM WITH SHEAR

We use the C82 saddle coil set 4064-rev7 (5 saddles + TF + 4 axisymmetric EF's) to produce a programmed change in the vacuum iota profile.

- S3 coil currents (ie for full current, full beta c82 plasma) produce a monotonically increasing $\iota_{vac}(s)$ with $\iota_{vac}(0) = 0.08, \iota_{vac}(1) = 0.32$.
- We ask the optimizer to change the plasma shape to give $\iota_{vac}(0) = 0.10, \iota_{vac}(1) = 0.47$. The saddle and EF coils were allowed to vary. Results are shown in Fig. 4.
- The run was successful insofar as the target iota was achieved. However the boundary shape has changed a lot (for serious flexibility studies WE NEED TO GET THE "LIMITER OPTION" WORKING IN VMEC!). Also (see EXTCUR values), the longest and third longest saddles have substantially increased current.

"before" (solid) and "after" (dash) vacuum iota profile and boundary shapes





EXTCUR = 10*-2.762600E+06

===>

EXTCUR = -2.034730E+06 -2.814749E+06 -5.287878E+06 -2.095225E+06 -5.339498E+06
-2.762600E+06
-1.110865E+06 -2.369473E+06 -5.031926E+06 -2.818324E+06

Fig. 4.

ABILITY OF LI383-328 SADDLES TO PROVIDE NET TRANSFORM WITH SHEAR

We use the LI383-328 saddle coil set comprising 5 saddles + TF (no EF) to produce a programmed change in the total iota.

- The LI383 "standard" profiles lead to a fixed boundary kink beta limit of $\beta_{lim}^{kink} \approx 5.0\%$ for a plasma current of $I_p = 150kA$.

- If, instead of using standard profiles, we use C82 pressure and current profiles (see Fig. 5 for comparison of C82 profiles with LI383 profiles) and calculate the fixed boundary beta limit using the LI383 plasma boundary, we find $\beta_{lim}^{kink} \approx 2.6\%$ at $I_p = 150kA$, or $\beta_{lim}^{kink} \approx 2.9\%$ if I_p is decreased to 120kA.

- By examining the iota profiles in Fig. 5, it is reasonable to guess that we will improve the kink stability of the LI383 configuration with C82 profiles if we can change the plasma shape in such a way that the LI383 iota profile is obtained. This requires a decrease in the value of the central iota from $\iota(0) = 0.57$ to $\iota(0) = 0.40$.

- We ask the f-b optimizer to do this by varying the saddle coil currents. Results are shown in Fig. 6.

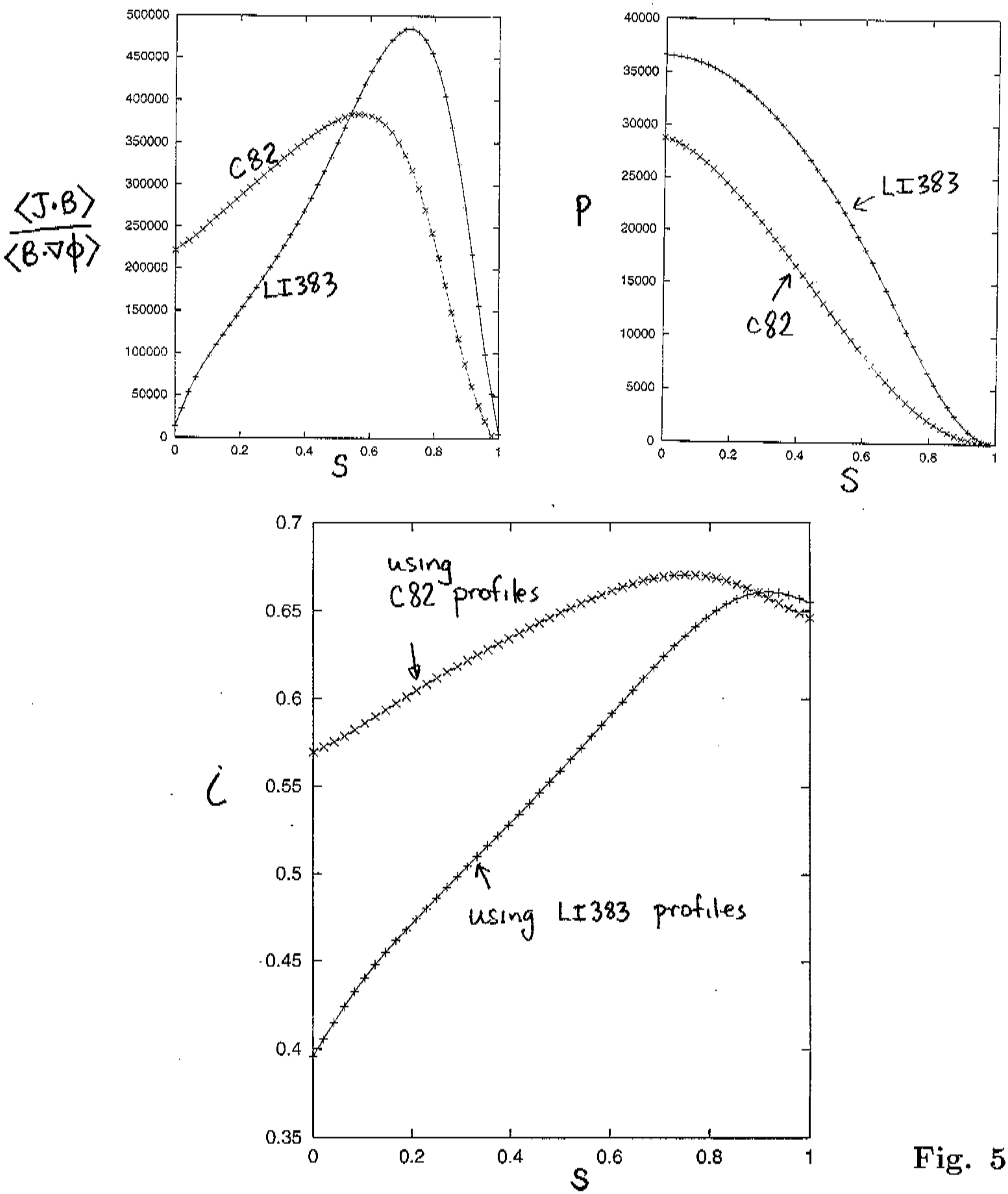
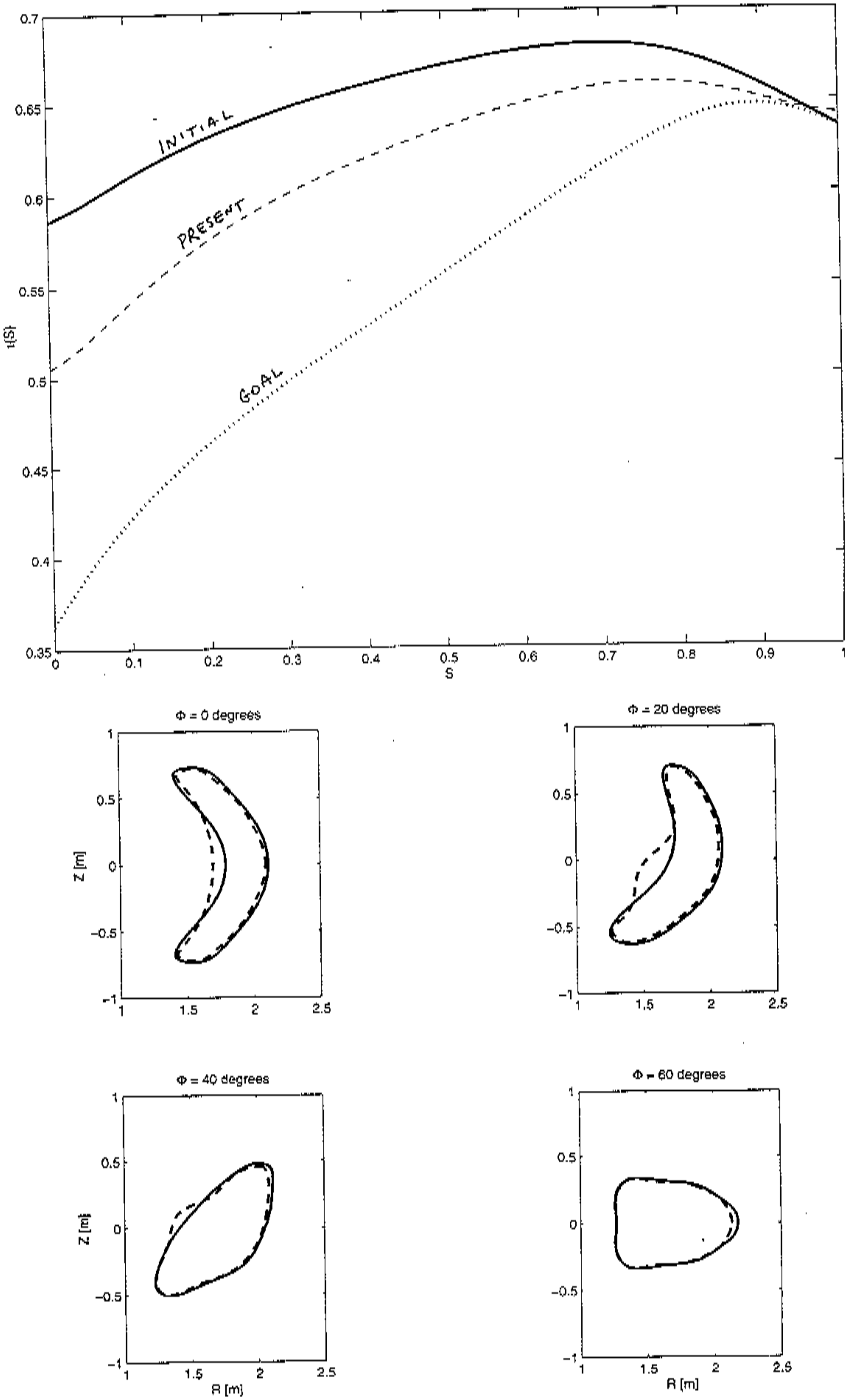

⟨J·B⟩ / ⟨B·∇φ⟩
C82
LI383
S
P
LI383
C82
S
ι
using C82 profiles
using LI383 profiles
S

Fig. 5.

The iota profile is changed from solid curve to dashed curve by varying the LI383 saddle coil currents. The initial and final plasma boundaries are also shown.



EXTCUR = 6* -3.410213E+06

Long → Short

EXTCUR = -3.417448E+06 -3.372795E+06 -3.491873E+06 -3.685386E+06 5.386535E+06
-3.410213E+06

Fig. 6.

USE OF AXISYMMETRIC FIELDS TO CONTROL NCSX PHYSICS

We have begun a study of the effects of axisymmetric fields on NCSX physics properties.

- Rather than consider a specific axisymmetric coil system, we include an ideal axisymmetric system comprising the lowest four toroidal multipoles.

For some time we have known that a dipole (vertical) field can efficiently control the radial position of the plasma (and we exploited this knowledge to produce the results shown in Fig. 3). Now we ask:

- How efficient are the multipoles for producing shape changes of type (C1) and (C2)?

Axisymmetric ring coils would be a relatively simple secondary control coil system.

EARLY RESULTS USING MULTIPOLE FIELDS

Here we fix currents in the LI383-328 modular coil set and calculate the vacuum transform with various amounts of multiple field added to the background field. (Table incomplete).

Dipole	Quadrapole	Hexapole	Octapole	$\iota(0)$	$\iota(1)$
0	0	0	0	0.31	0.37
+4.e5	0	0	0	0.38	0.40
-2.e5	0	0	0	0.29	0.36
0	+4.e5	0	0	0.39	0.36
0	-4.e5	0	0	0.22	0.37
+4.e5	-4.e5	0	0	0.29	0.40
+4.e5	+4.e5	0	0	0.45	0.41

- These vacuum transform results look promising.
- We have made a single attempt to induce a change in the iota profile in the case of full plasma current and beta. Although the result was disappointing, the stage of work is much too early to draw any conclusions!
- In addition to these C1-type experiments, we have near-term plans to also look at the effect of quadrapole and hexapole field perturbations on C2-type plasma changes.