Modeling of the Current Profile Evolution for the NCSX Stellarator

E. Lazarus[1], D. McCune[2] and M.Zarnstorff[2]

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A Quasi-Axisymmetric Stellarator, NCSX is being designed for construction at PPPL. The designs under consideration are capable of achieving β values of several percent with about half the transform produced by internal current. An issue is whether plausible trajectories exist from the vacuum fields to the target plasma. The current sources are Ohmic, bootstrap, and neutral beams. Discharge evolution is being studied in a 2-D approximation with the TRANSP code. The external transform is mocked-up as a lower-hybrid driven current that does not diffuse. The other source terms diffuse with neoclassical plasma resistivity. For plausible, assumed profiles the current can be programmed to reach near steady-state conditions in a 500 ms pulse length. Results will be presented.

[1] **Oak Ridge National Laboratory**
[2] **Princeton Plasma Physics Laboratory**

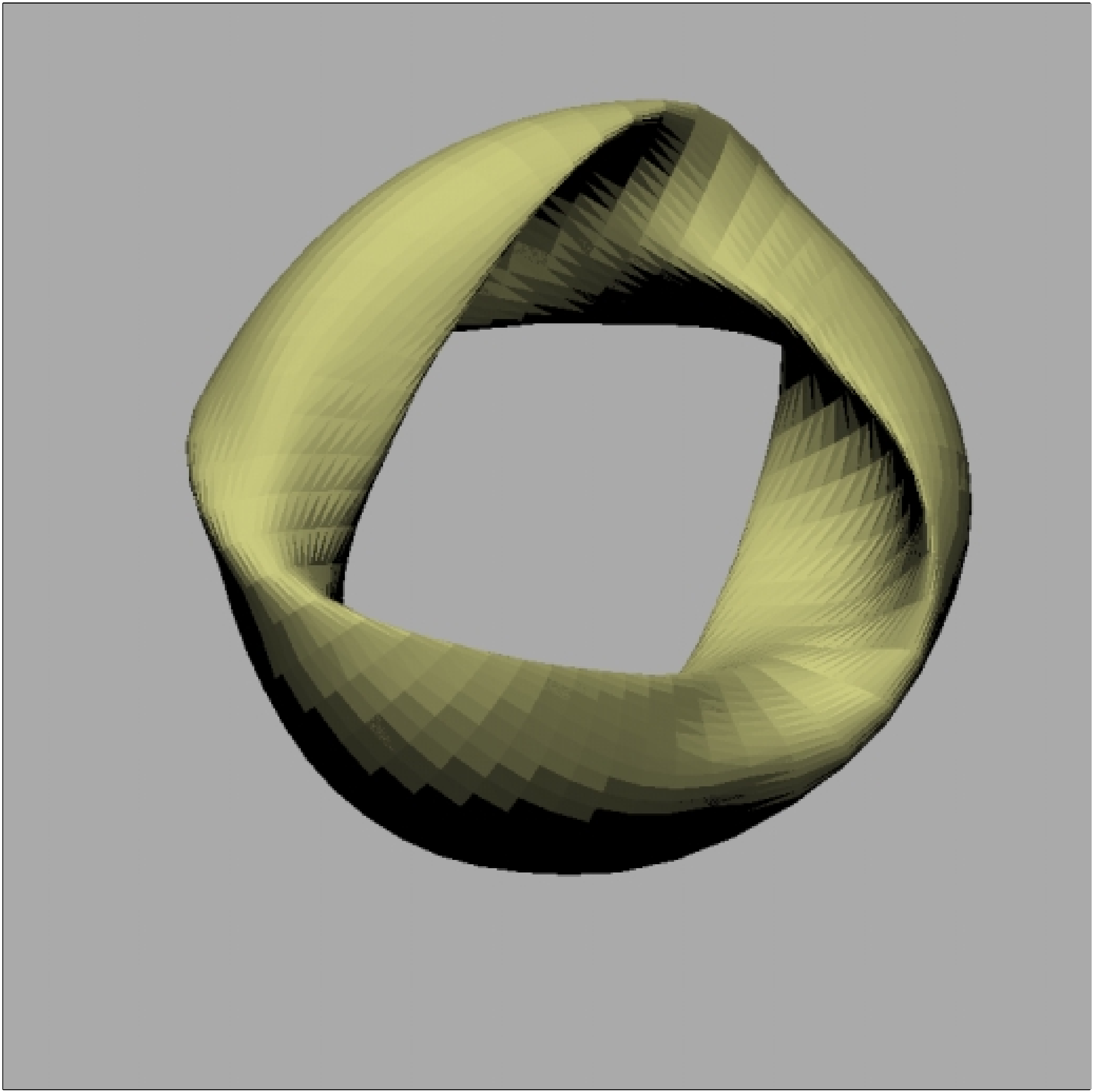
[*]Available for download as ftp://fusion.gat.com/pub/lazarus/aps2000.pdf

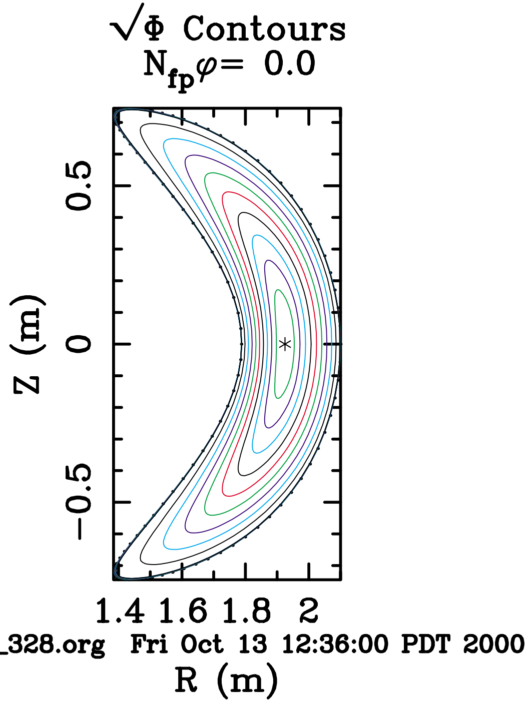
SIMULATING THE EVOLUTION OF THE CURRENT PROFILE

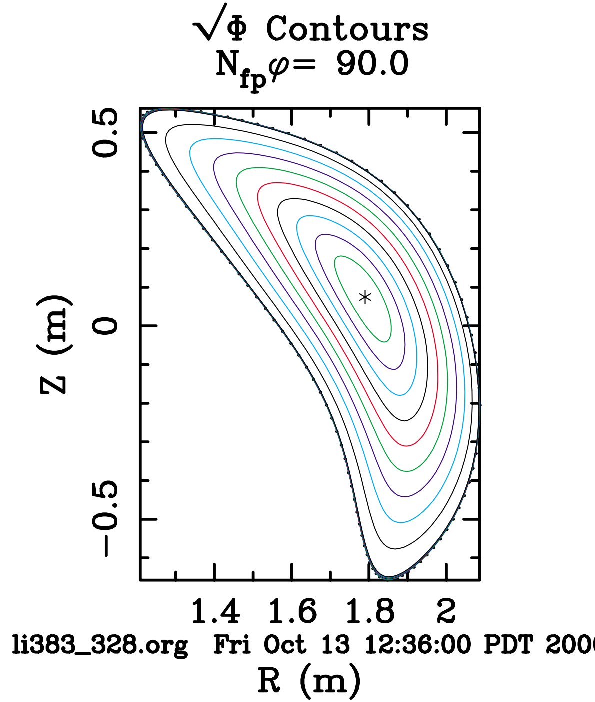
- TRANSP is used to simulate the discharge evolution.
- Profiles for Te and n_e are assumed, based on tokamak and stellarator experience.
- In the context of TRANSP, the external transform is simulated as a lower hybrid driven current, i.e. the LHCD does not diffuse, it is fixed in time.
- To determine this LHCD current profile , first the target configuration is modified to $\beta = 0$, $I_p = 0$ to get the vacuum iota
- The vacuum iota is put into a second VMEC run with $R_{bdy}(n \neq 0)=0$, $Z_{bdy}(n \neq 0)=0$ (The axisymmetric components of the shape.)
  - Since iota is specified and there is no 3D shaping VMEC calculates the current profile required for this iota.
- The resulting toroidal current profile is extracted, to be used as LHCD (a non-diffusing component of the current density) in TRANSP
  - Now TRANSP is started with this current profile and $\beta \approx 0$ ($T(0) \approx 50$ eV, $\langle n_e \rangle \approx 5\text{x}10^{12}$ cm^{-3}).

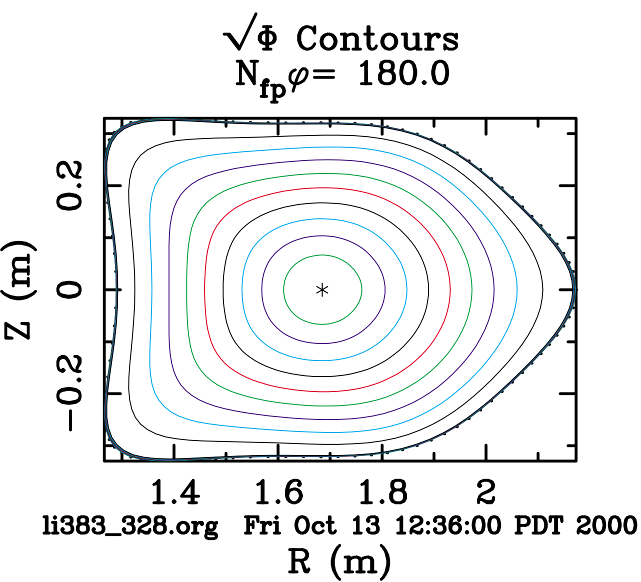
$$x = \sqrt{s} = \sqrt{\Phi / \Phi_B}$$

LI383 QAS Configuration



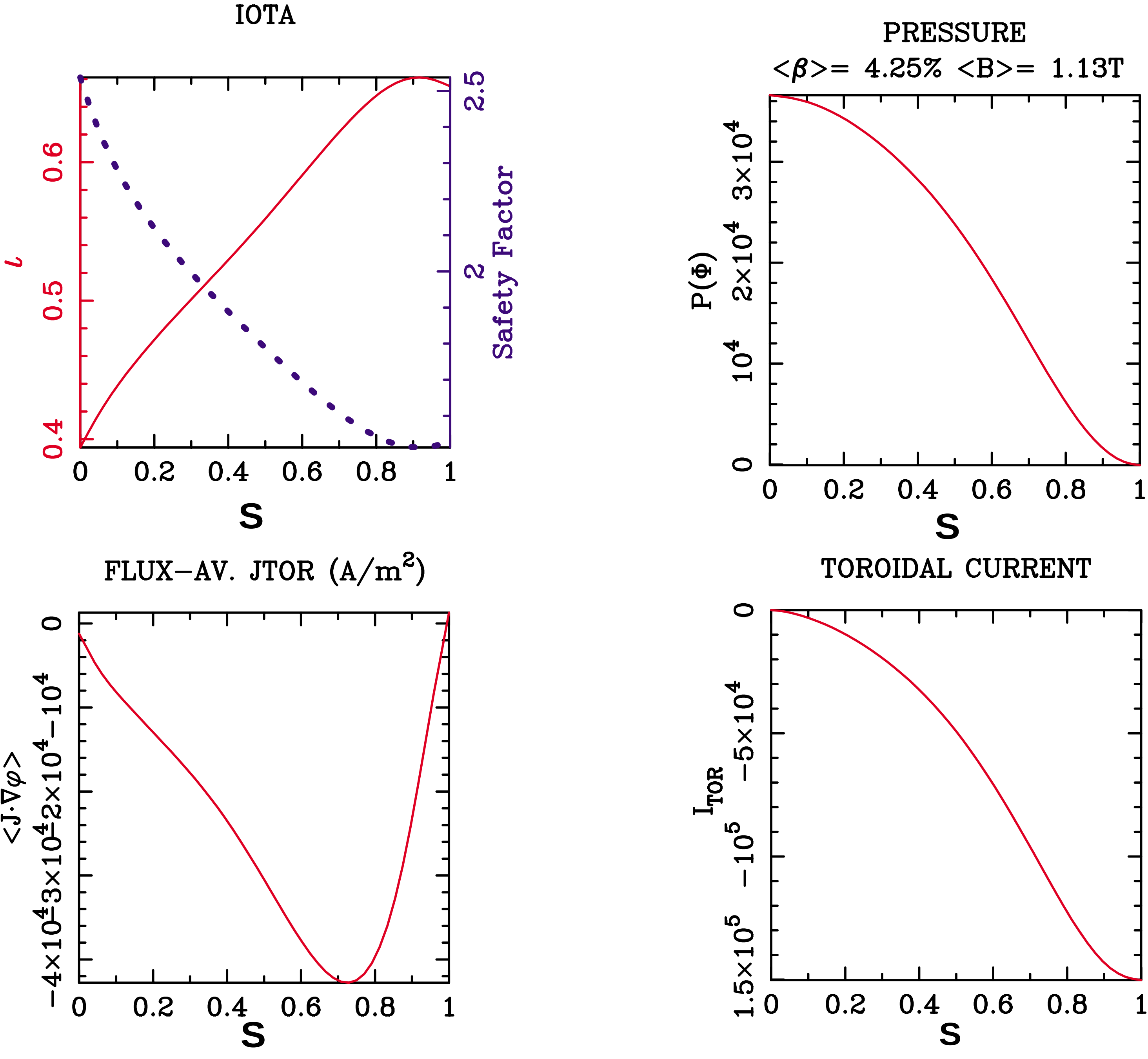




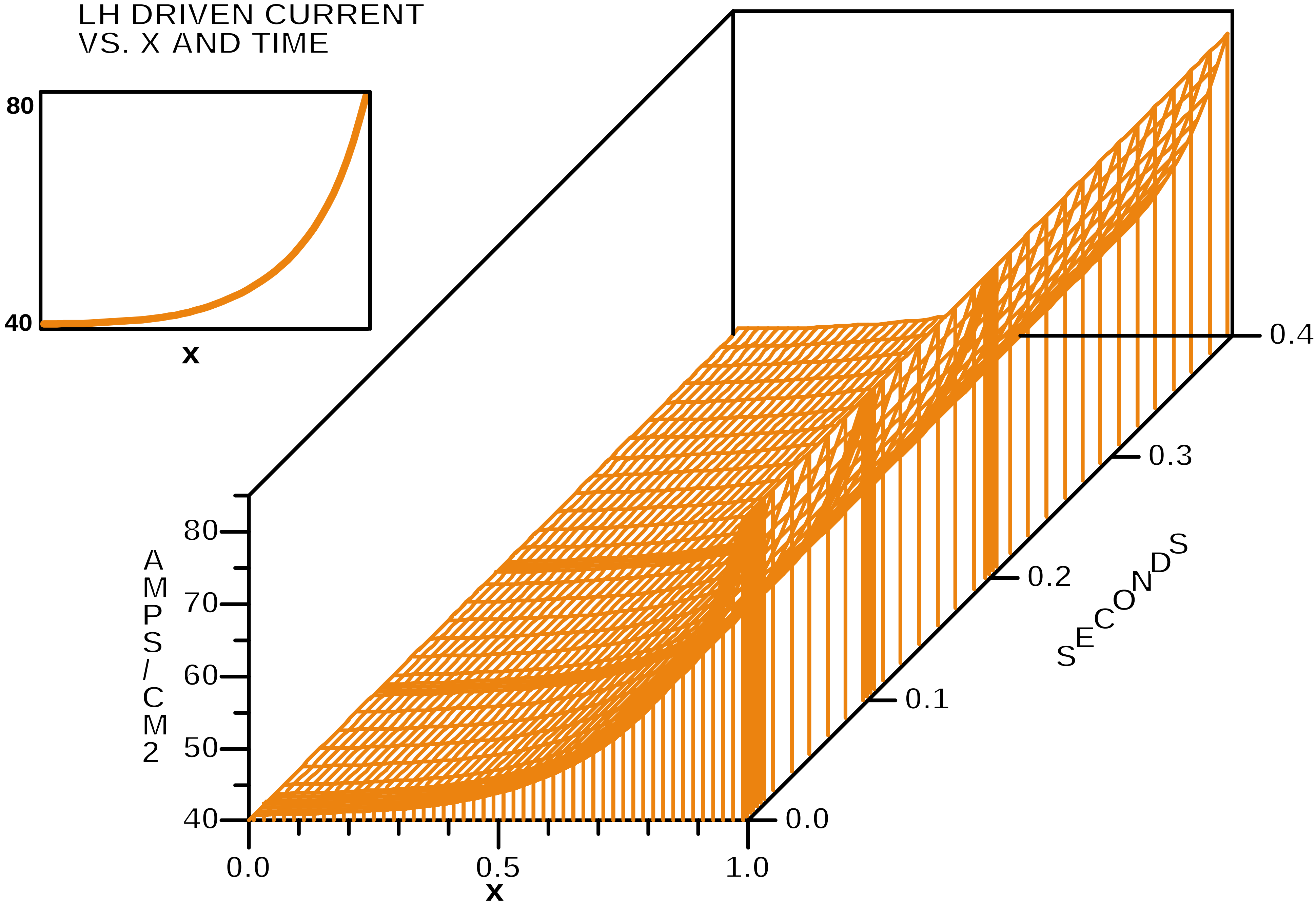


The present focus is the "li383" configuration. Flux contours in 3 planes are shown here.

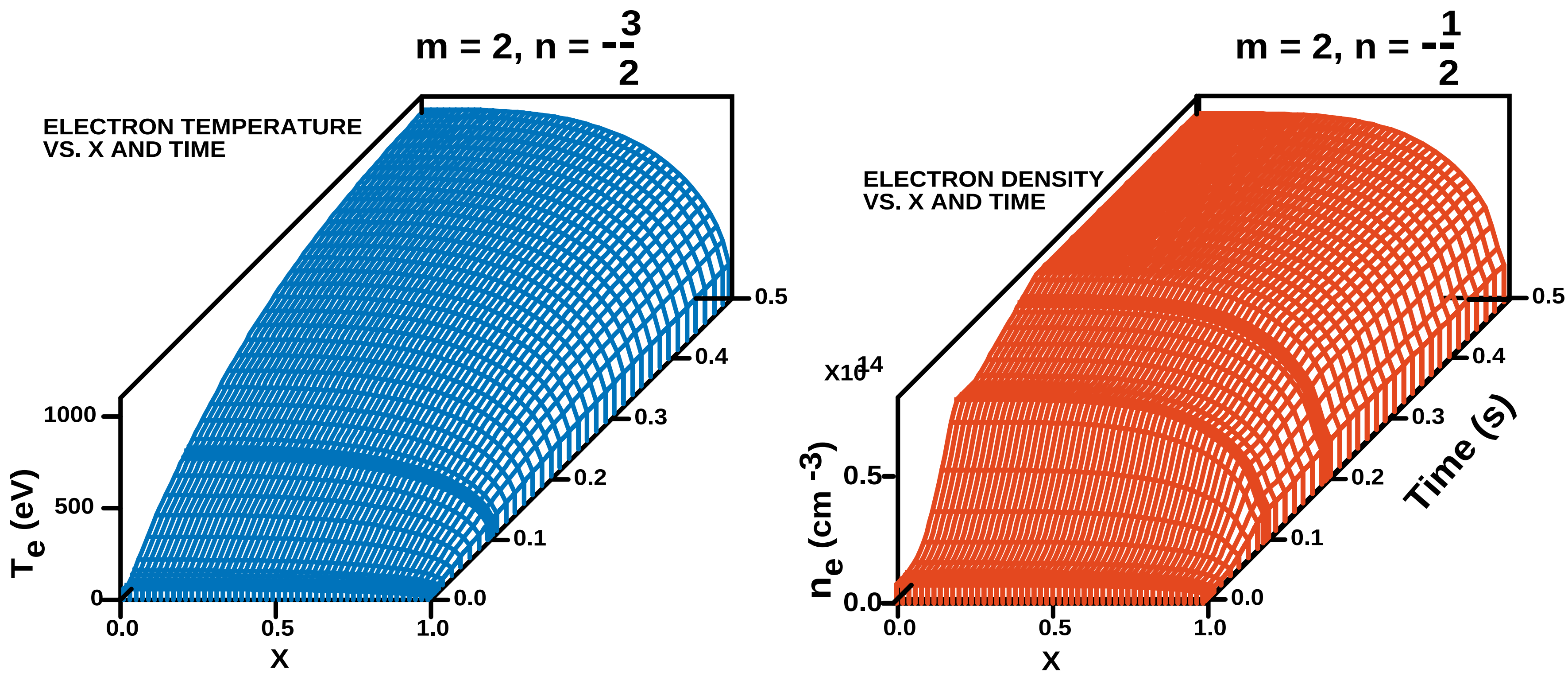
LI383 Profiles vs Normalized Toroidal Flux



External Transform Simulated as LHCD in TRANSP



Profiles are simple functions $(1-x^m)^n$
T_i , similar to T_e, is obtained using $\chi_i = 8\,\chi_{NC}$



We do have hopes of replacing assumed profiles with transport models,
but the proiflies are reasonable and it is useful to change profile assumptions
and observe the changes in the plasma current profile.

Simulation Results

The focus here is on the evolution of iota and the various contributions to it; vacuum transform, OH current, bootstrap current, and NBCD.

I will start with a general survey of the results in the context of tokamaks.

One way to view the QAS stellarator is to compare it to the AT tokamak. A distinction is that the magnetic shear is reversed all the way to the edge. Instead of tailoring the current profile sources to produce shear reversal, magnets are used. The equivalent in a tokamak would be to actually produce the LHCD profile shown above, and then add the bootstrap current to it.

For the li383 configuration, most of the transform is external

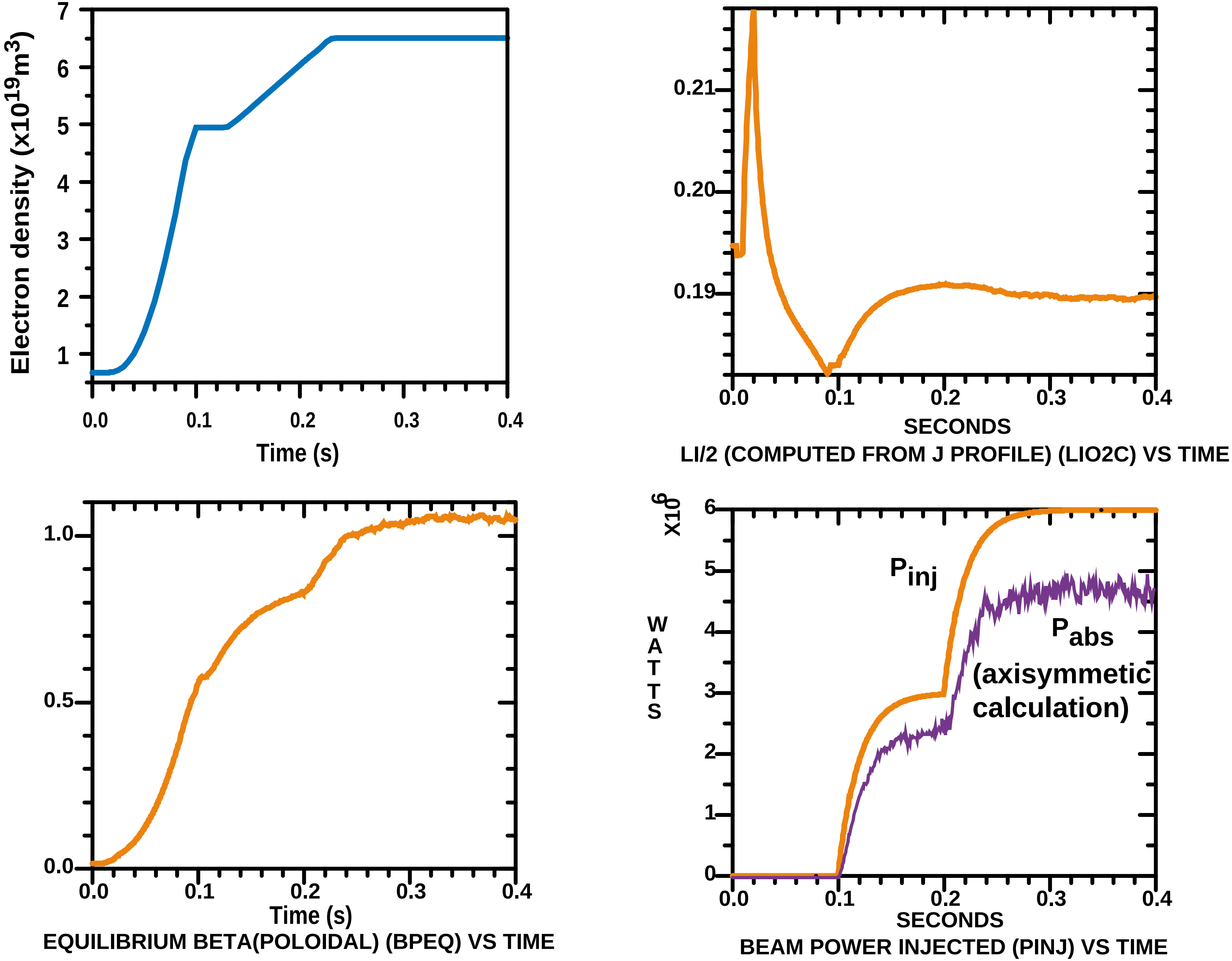
(I_{LH} = 320 kA, I_{tot}-470 kA, B_t = 1 T).

The plasma current is ramped at 2 MA/s to its final value. Since the plasma initiation is in a configuration which has closed surfaces there should be no problem with breakdown.

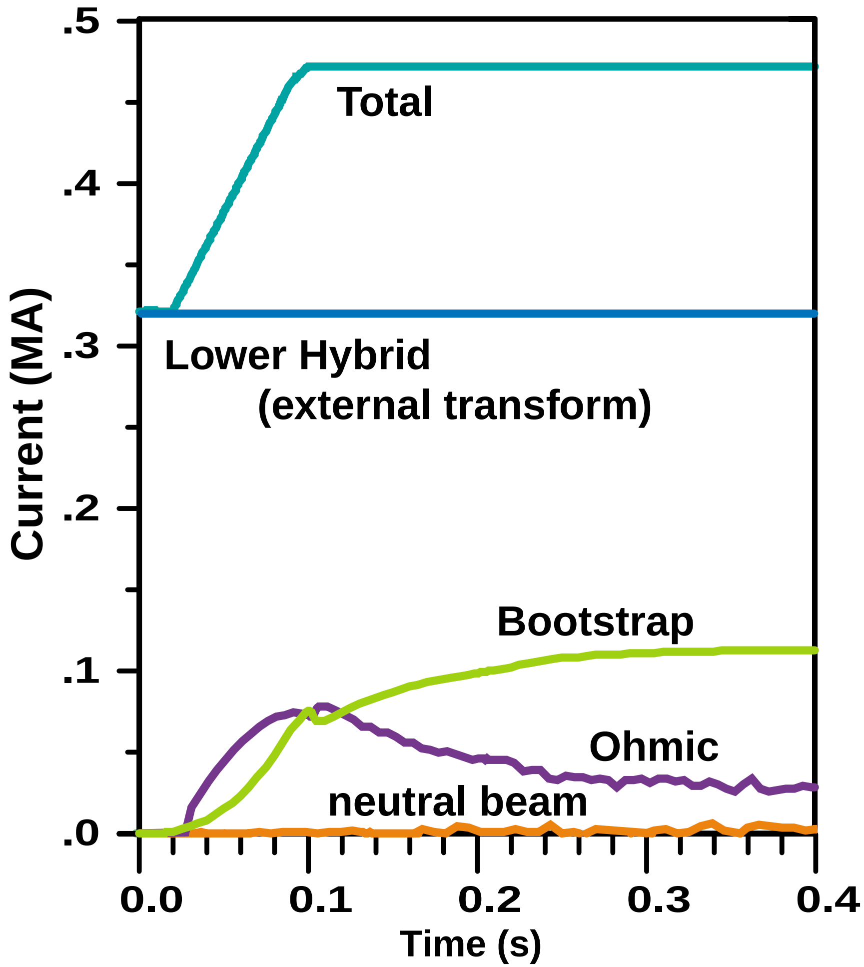
Then NBI begins. The NBI is with balanced beams to avoid NBCD. Using coinjection would raise central ι, ruining the shear reversal.

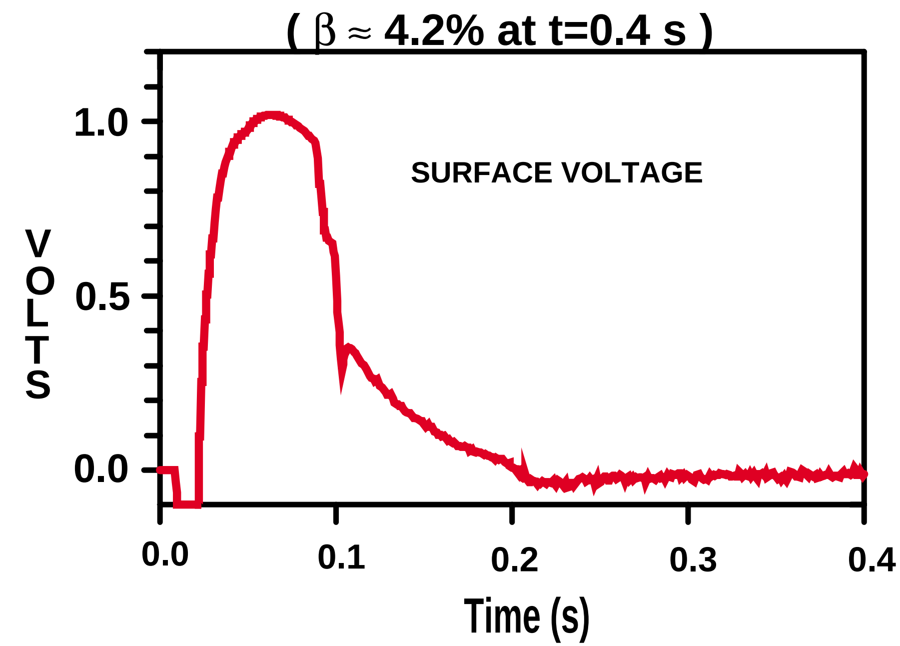
One reason this configuration is preferable to the C82 configuration is that it has higher ι, improving beam confinement and allowing balanced neutral beam injection.

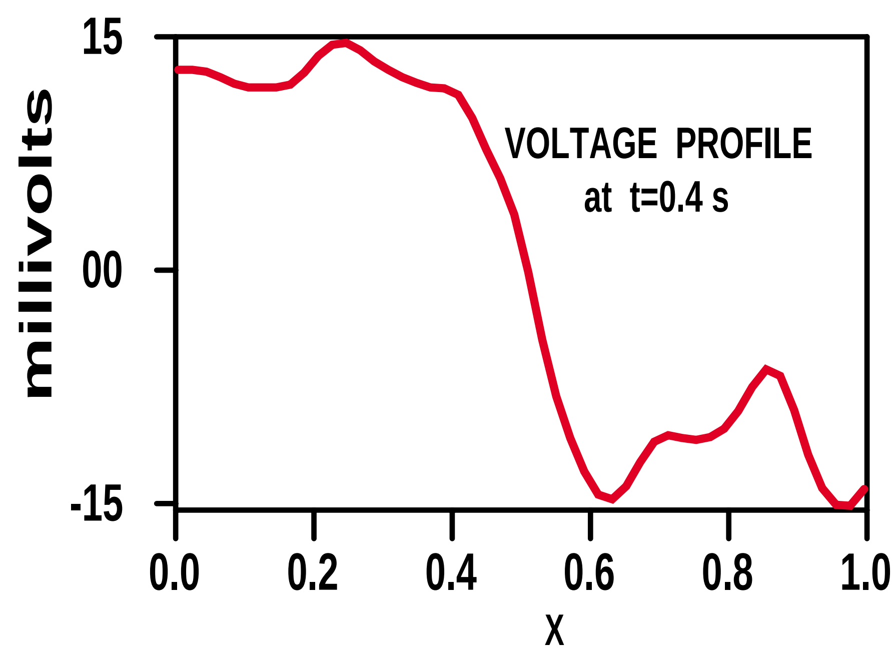
Results from 2-D TRANSP Simulation - Assumed Profiles - Balanced Beams

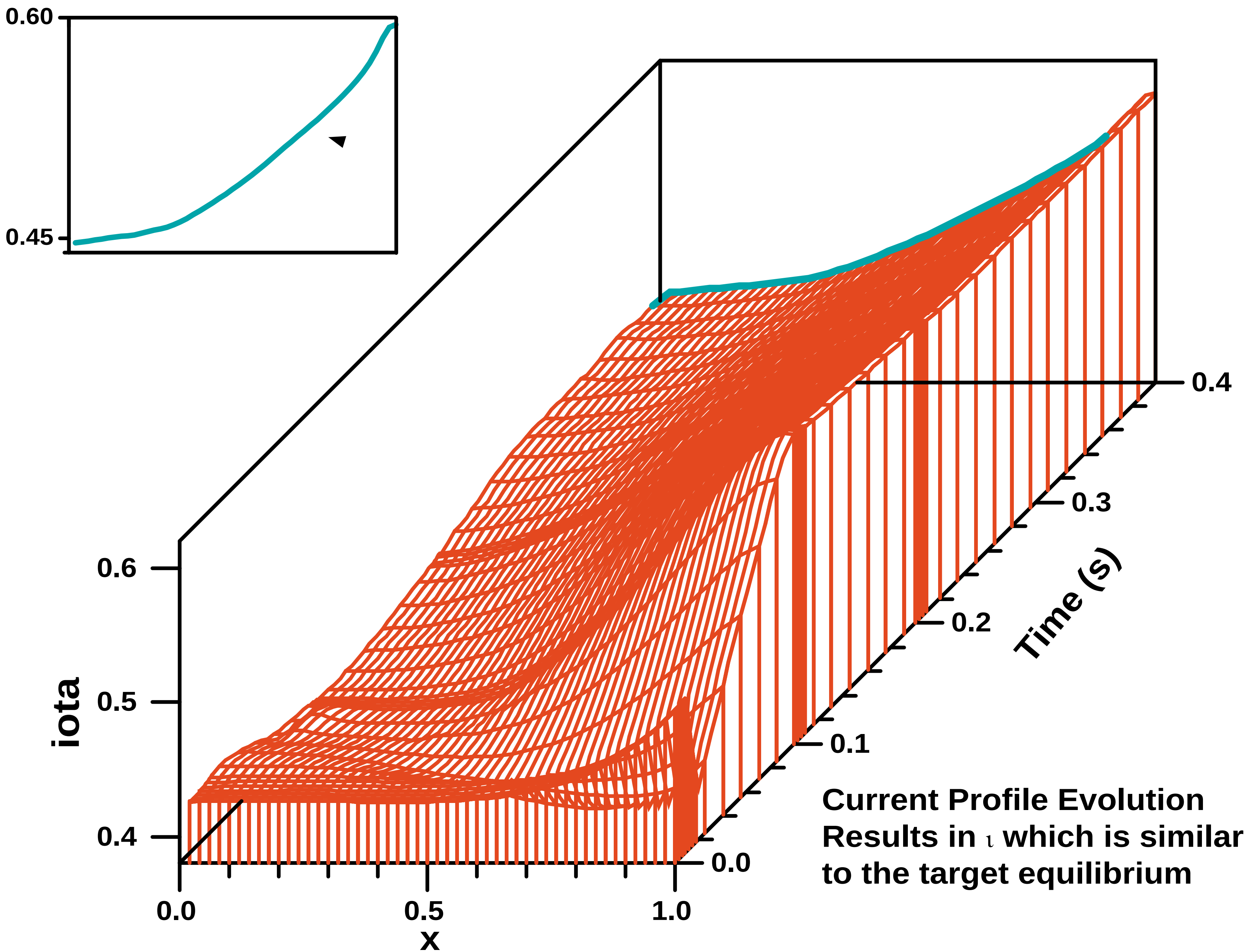


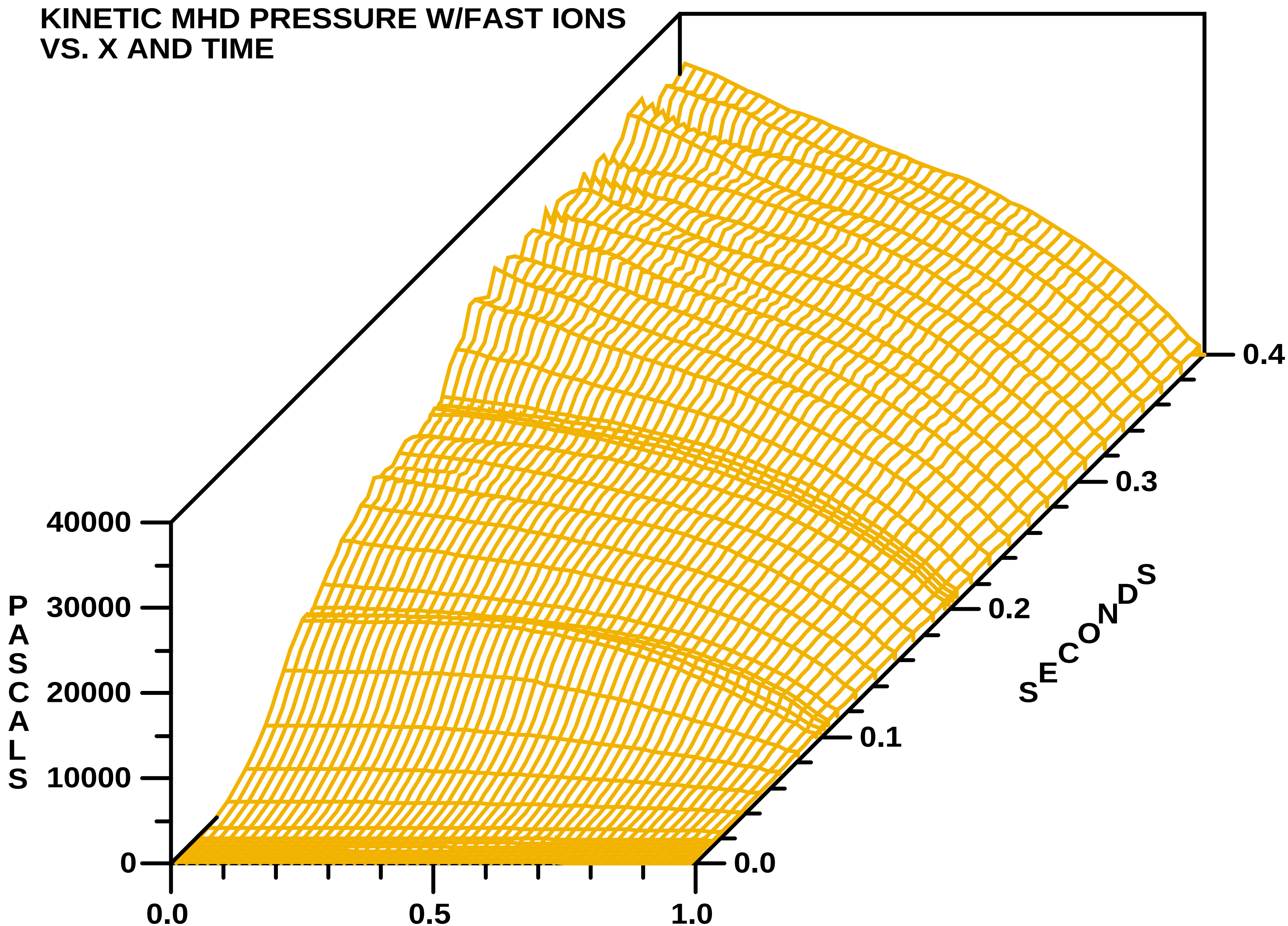
Time Evolution of Plasma Current Components








0.60
0.45
0.6
0.5
0.4
iota
0.0
0.5
1.0
x
0.0
0.1
0.2
0.3
0.4
Time (s)
Current Profile Evolution
Results in ι which is similar
to the target equilibrium


KINETIC MHD PRESSURE W/FAST IONS
VS. X AND TIME
PASCALS
40000
30000
20000
10000
0
0.0
0.5
1.0
SECONDS
0.0
0.1
0.2
0.3
0.4

Simulation Results

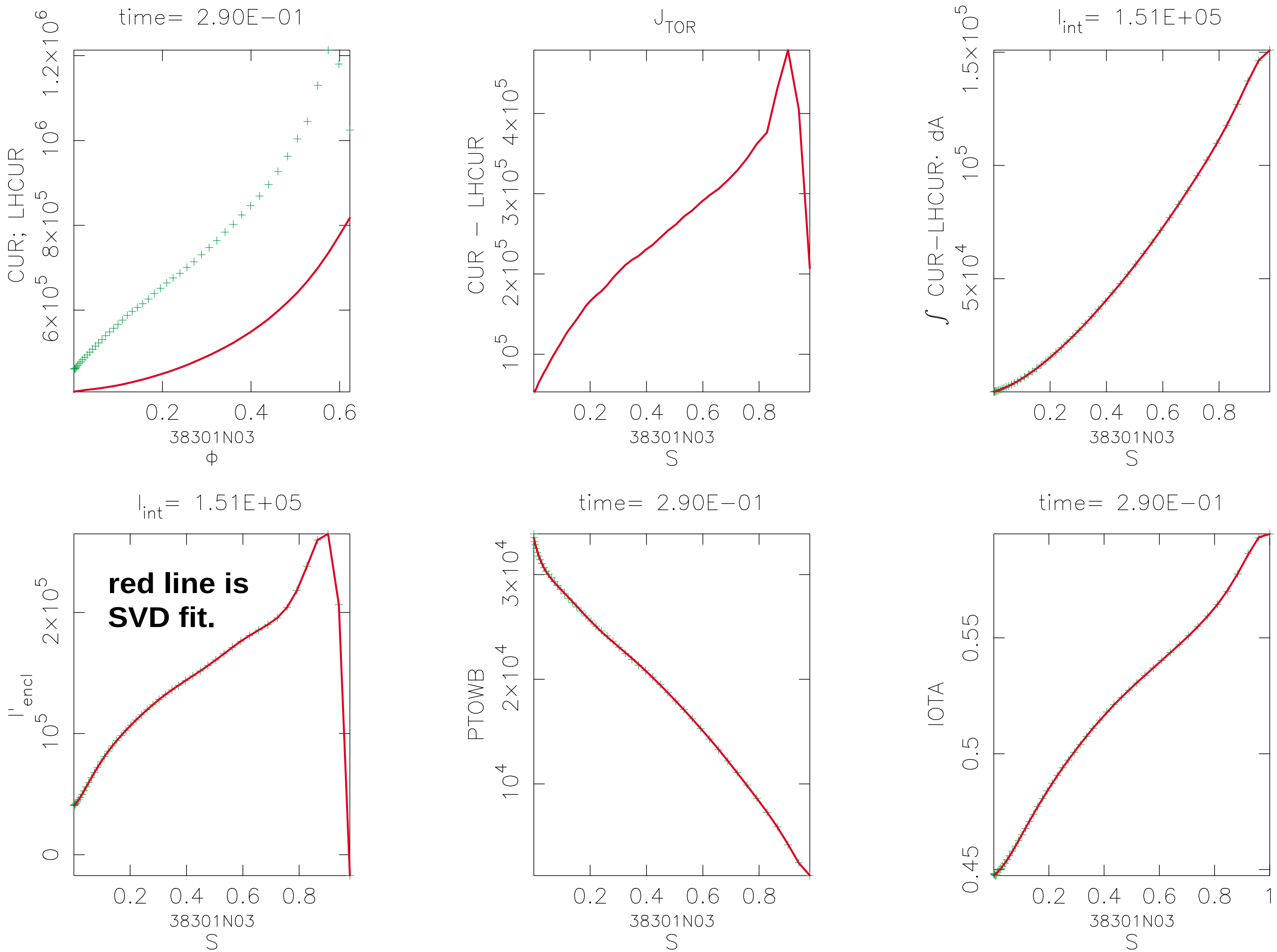
It is reasonable to expect the current evolution to yield a correct iota profile.

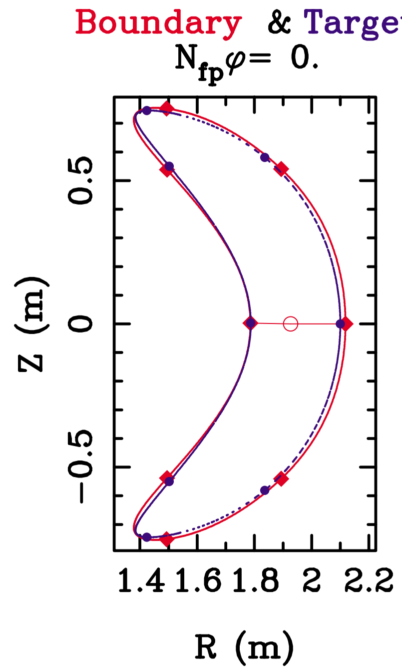
- The external transform is 2/3 of the total.
- At the target beta the remainder is bootstrap current, which also peaks to the outside of the plasma.
- If the confinement does not yield adequate beta and OH current becomes important, the current profile will fill in at the center raising central ι.
- Similarly, if the NBI is not balanced, NBCD will raise central ι.
- The fine details of iota ultimately depend on confinement through the bootstrap current.

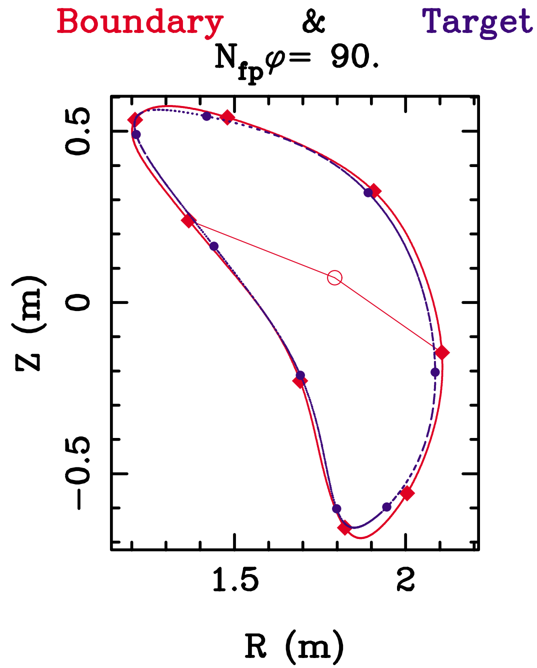
The profile evolution can now be used in VMEC to follow the plasma evolution and examine coil current requirements.

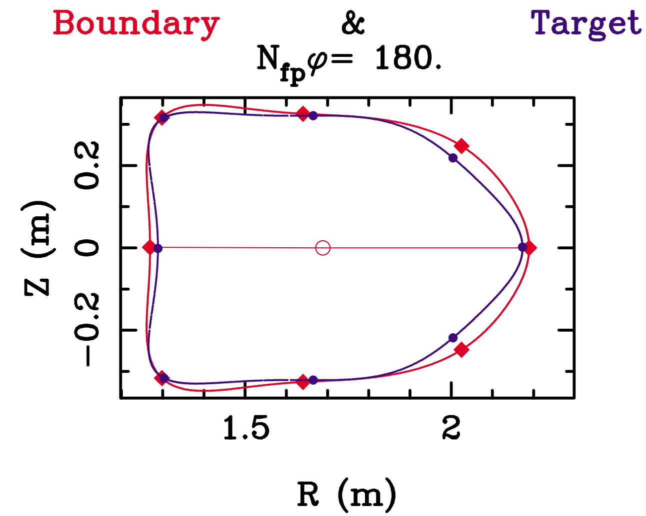
We first try to preserve the boundary shape through this evolution. The coil sets designed thus far do not reproduce some of the details of the shape. However, the match with the modular coil set “0907” shown below does preserve kink stability for many of the equilibria generated from this simulation. For the others it will be necessary to do another optimization to see if small changes in the coil currents will regain kink stability. (Not done yet.)

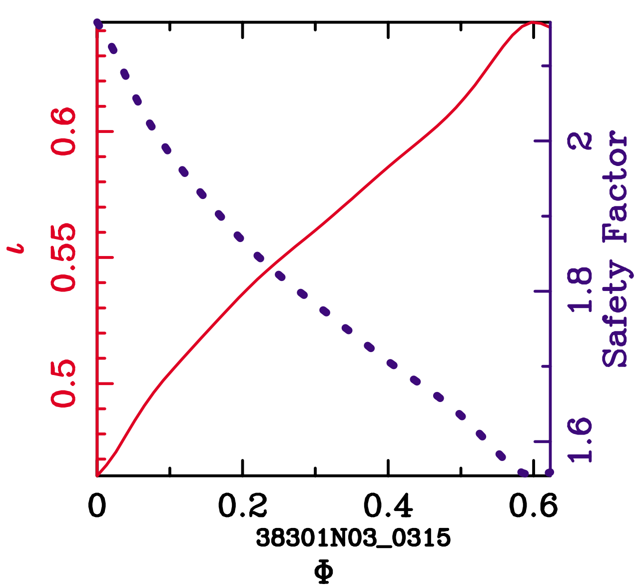
The pressure and curent profiles now are put back into VMEC to generate a sequence of 3d equilibria to be studied in free-boundary. The current is differenced to obtain the internal current density which is transformed to the VMEC variable I'(s) which is expressed as a 10th order polynomial along with p(s). ι(s) is also fit and can be used as an alternative to I'(s) in VMEC.

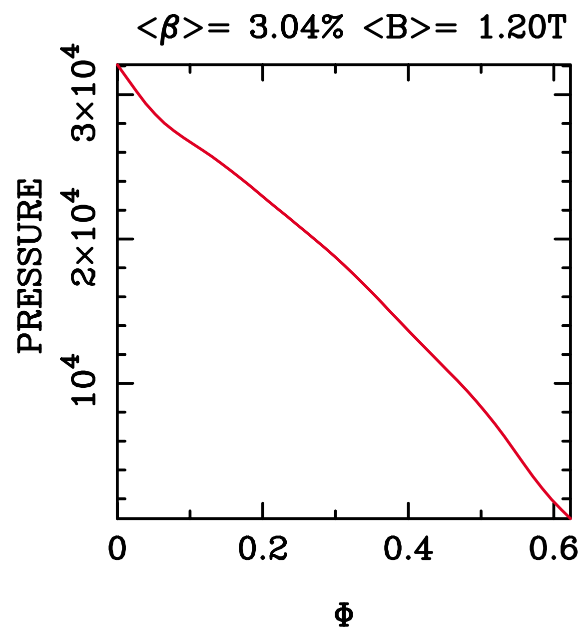



Boundary & Target
$N_{fp}\varphi$= 0.
Z (m)
0.5
0
−0.5
1.4 1.6 1.8 2 2.2
R (m)

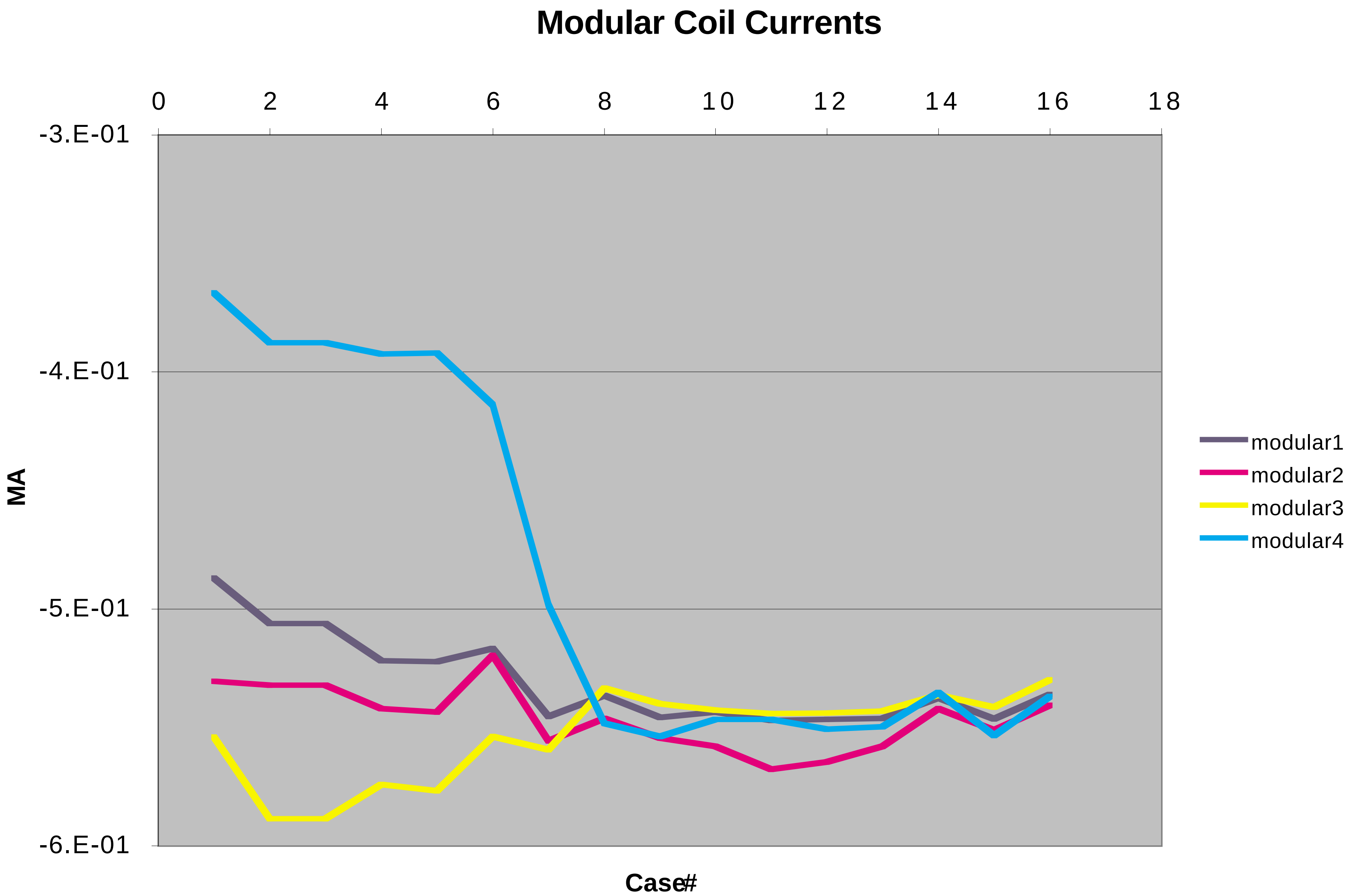

Boundary & Target
$N_{fp}\varphi$= 90.
Z (m)
0.5
0
−0.5
1.5
2
R (m)


Boundary & Target
$N_{fp}\varphi$= 180.
Z (m)
0.2
0
−0.2
1.5
2
R (m)


ι
0.5
0.55
0.6
Safety Factor
1.6
1.8
2
0 0.2 0.4 0.6
38301N03_0315
Φ


<β>= 3.04% <B>= 1.20T
PRESSURE
10^4
2×10^4
3×10^4
0 0.2 0.4 0.6
Φ

The results from the TRANSP simulation are used in free-boundary equilibrium calculations to find the coil currents required to best maintain the plasma shape.



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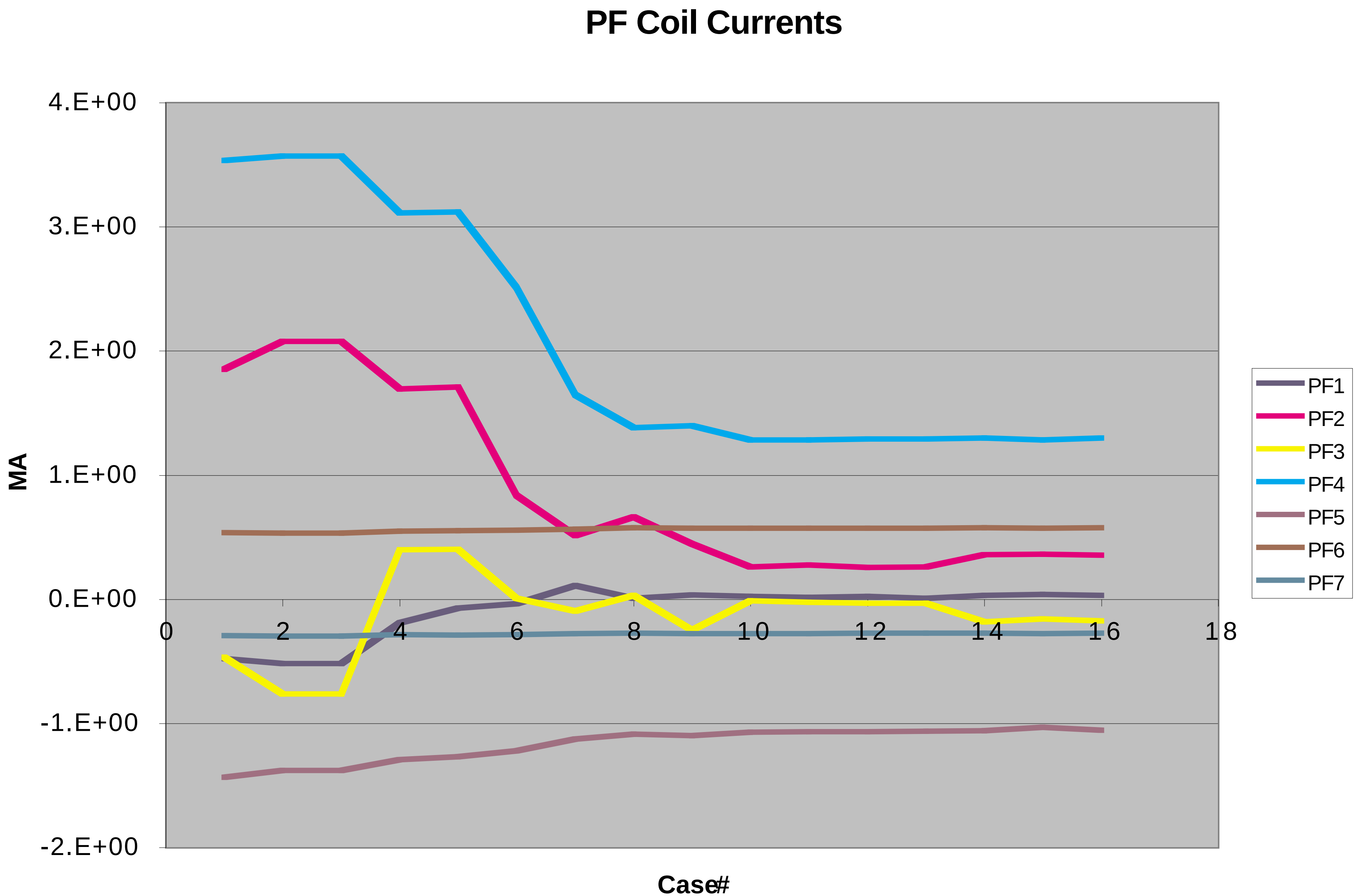

The PF coil currents are large. Refinement of the coil set may be needed.

Summary

- Discharge evolution for NCSX has been modeled using TRANSP.
  - Lower Hybrid Current Drive is used as a substitute for the external part of the transform.
  - A plasma current ramp of 2 MA/s requires only a modest loop voltage.
  - The plasma can reach nearly steady-state current profile within the 300 ms NBI pulse for B_t = 1 T. (Residual loop voltage of 30 mV across the plasma with $I_{OH} \approx 0$.)
  - NBCD from co-injected beams is not consistent with the desired iota profile, but with balanced injection this is removed.

- Results have been generated using assumed profiles for T_e and n_e. In the future we hope to add transport models and avoid direct assumption of the profiles.

- The results from TRANSP for pressure and current density profiles are used in VMEC to generate a series of 3D equilibria that are used to assess coil current requirements.

  - This has been done for the proposed alternatives of saddle and modular coils.
  - For the modular coil option the PF currents are large and further optimization is needed.

- The simulation results have been examined for kink stability.
  - For the modular coil set the growth rate is between negligible and small.
  - I expect small changes in coil currents will make the all the equilibria stable.
  - For the saddle coils the growth rates are higher if we simply try to make the best free-boundary approximation to the li383 shape and further study is needed.