Discharge Evolution and Plasma Control for NCSX

Ed Lazarus
Oak Ridge National Laboratory
Mike Zarnstorff
Princeton Plasma Physics Laboratory

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The question to be addressed: Is there a plausible, stable path from the vacuum state to a high β NCSX equilibrium?

A more specific goal is to accomplish this in a 0.3 second beam pulse when the current relaxation time is about 1 sec in the core of the plasma.

Available at ftp://fusion.gat.com/pub/lazarus/aps2001.pdf

[CP1.035] Discharge Evolution and Plasma Control for NCSX

E. Lazarus (ORNL), M.C. Zarnstorff (PPPL)

The evolution of the plasma from the vacuum state to the desired high beta state with the bootstrap current profile have been studied. Stable trajectories have been found with a final state having beta of 4.3% and a bootstrap current of 125 kA. In this case, iota is 0.41 on axis and 0.62 at the boundary. The plasma current contributes about 30% of the total transform.

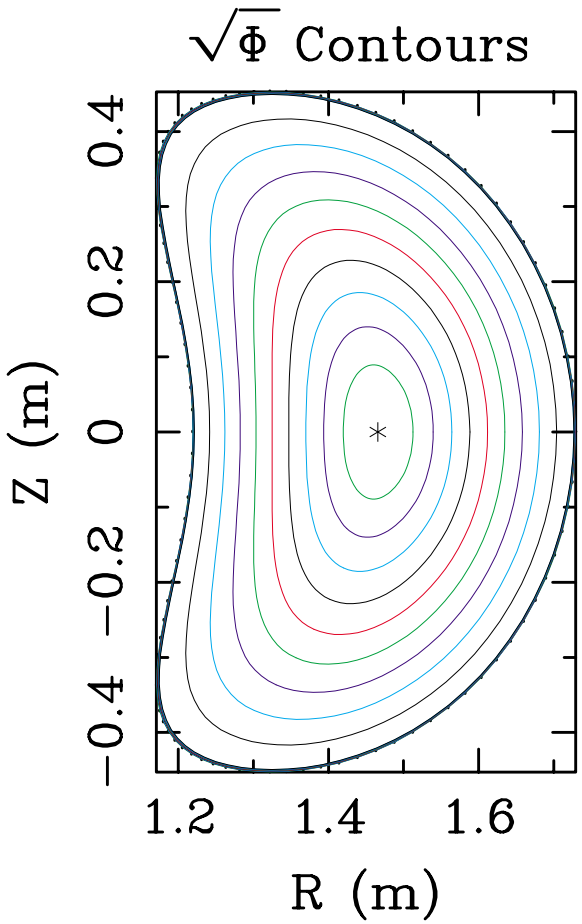
A solution which preserves quasi-axisymmetry and stability as the internal profiles evolve can be obtained by controlling the plasma boundary shape. The variations in the modular coil currents are within the capabilities of the planned power systems. The ability to recognize the boundary shape will be a determining factor in the specification of the magnetic diagnostic set. We anticipate that initial efforts will focus on the design of a diagnostic set which can be linearly related to the boundary. The implications of these results for an overall plasma control system for NCSX will be discussed.

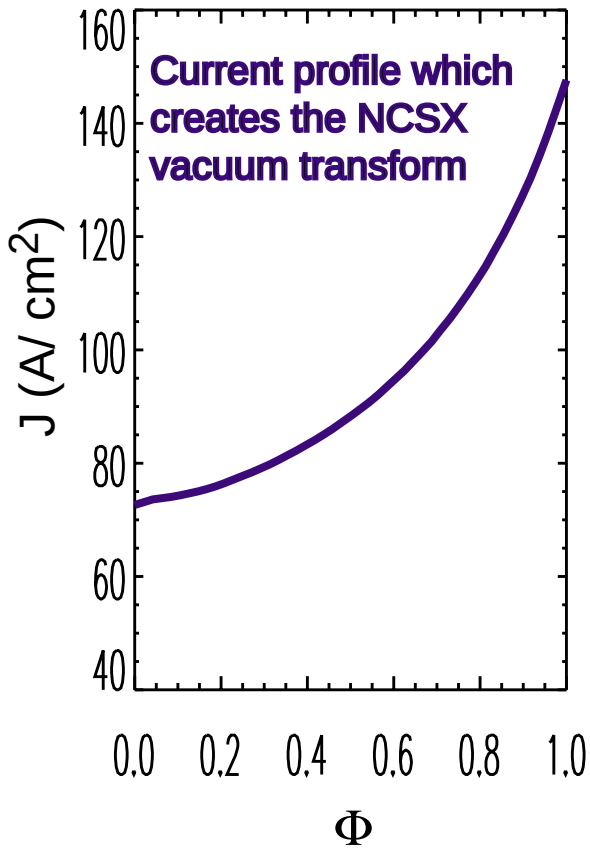
Simulation Process

- **Build "equivalent tokamak" - <NCSX>**
  1. **The "equivalent tokamak" will have the toroidally averaged NCSX shape.**
  2. **The volume will be equal to NCSX as will A=<R>/<a>.**
  3. **There will be a fixed (not diffusing) current density, J_{EXT}, which represents the vacuum transform.**
- **Study the discharge evolution in this 2-D device, <NCSX>**
  1. **neutral beam physics**
  2. **poloidal flux diffusion, $I_{TOT} = I_{EXT} + I_P$**
  3. **discharge programming**
  4. **power balance**
- **Put resulting profiles, $p(\rho)$ and $J_{TOT}(\rho) - J_{EXT}(\rho)$ back into NCSX.**
  1. **Find free-boundary equilibria that have desirable stability properties and quasi-symmetry.**

The equivalent tokamak, <NCSX>

For the vacuum (β=0, I_P=0) we compute ι, then make an axisymmetric shape, demand that same ι and solve the equililibrium. Since the 3-D shaping is now removed, the equilibrium requires a current density profile to produce the ι.





The 2-D evolution modeling is done with TRANSP.

The "vacuum" current density shown above is modeled as lower hybrid current (LHCD) in TRANSP. I t is assumed to be stationary and driven by an unspecified external source – <u>it will not diffuse</u>. We will refer to this current as I_{EXT} (= $\int J_{EXT} dA$)

Other assumptions in modeling discharge evolution.

- **$T_e(\rho,t)$ is completely specified, and its magnitude is similar at high β to transport estimates for the device**
- **n_e shape is specified, amplitude is adjusted to give desired β.**
- **$\chi_i = 3\,\chi_i^{neo}$ results in T_I similar to other transport modeling for NCSX.**

Computations in TRANSP

- **Poloidal flux diffusion**
- **Beam deposition and slowing down, NBCD**
- **Power balance => T_I only**
- **Fast ion pressure**

Manual iteration of TRANSP runs needed to get desired discharge.

The iteration procedure is to do a run to time t, then replace the I_P waveform with I_{BS}. This will change β_P, requiring further modification of I_P to accommodate this change in bootstrap current. . If the Ohmic flux is allowed to penetrate to the core while building the cold plasma, it will be frozen in leading to an unattractive ι profile.

There is a deficiency in the energy balance in the interval 20-100 ms, the time before NBI. In doing these iterations I did not account for the fact that this was continually decreasing the Ohmic power.

It turns out that keeping the energy balance along with poloidal flux balance in a scheme of manual iteration is nearly impossible if the electron pressure is specified. This year we will add an electron confinement model (Lackner-Gottardi) to TRANSP and then we can specify χ_e rather than T_e.

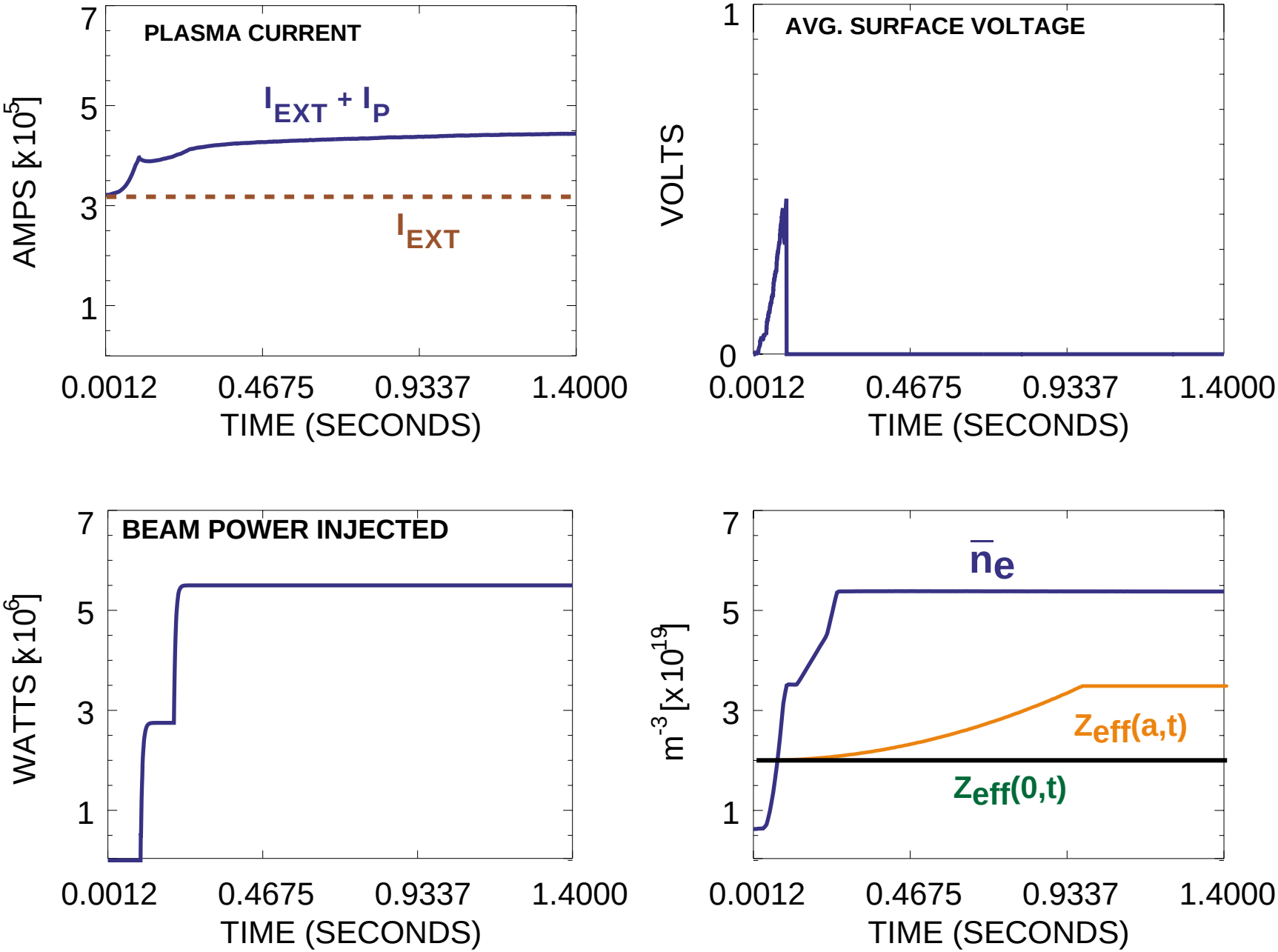
At this time it is unclear whether a solution will be found that allows the merging of OH heated and an NBI heated regimes without too much penetration of Ohmic flux. The alternative would be additional heating.

Results in 2-D

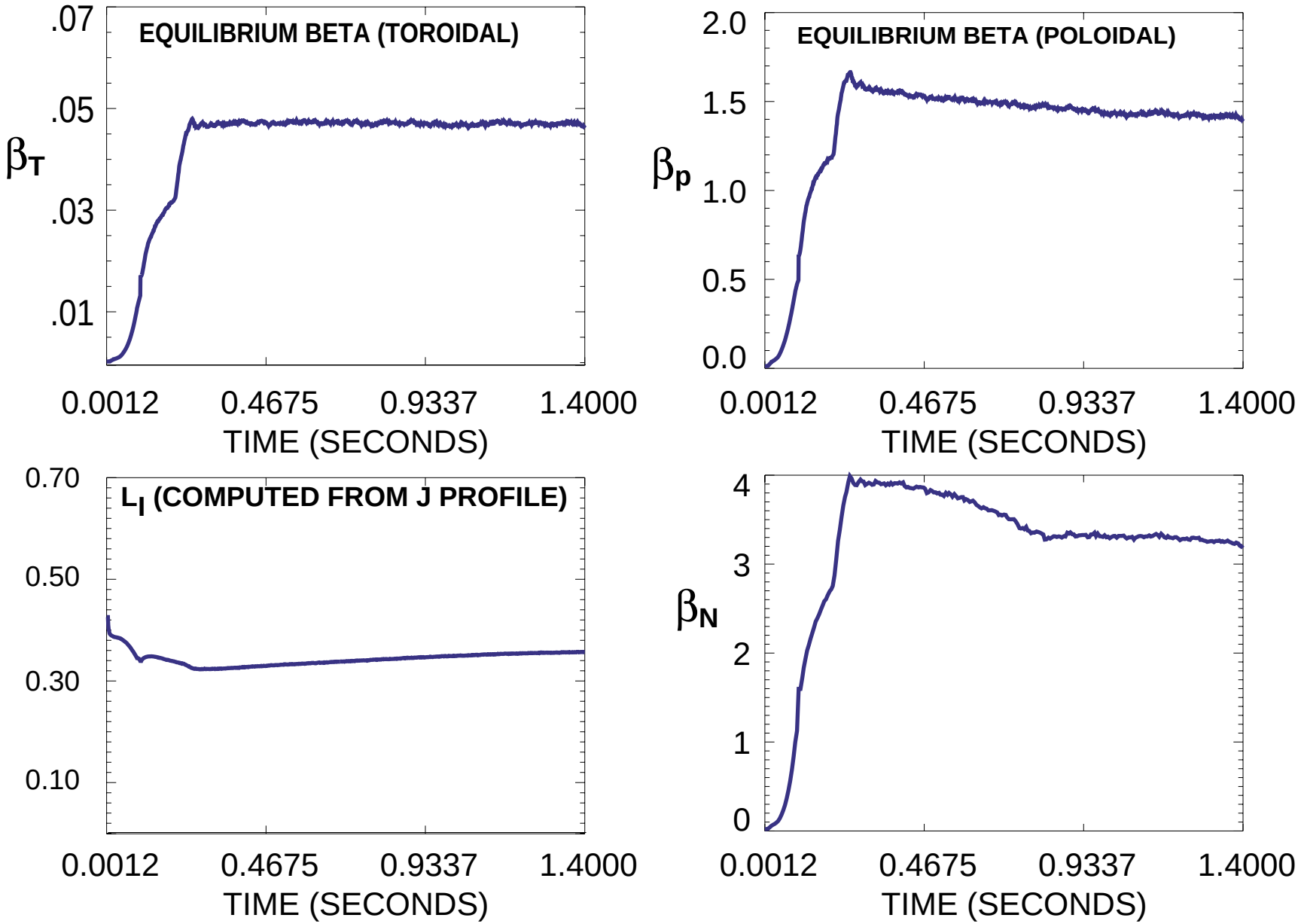
The dominant characteristics of <NCSX> are shown in the next few slides:

- **Evolution of primary quantities**
- β **and** ℓ_i
- **balance of NBCD and OHCD**
- **iota and pressure**

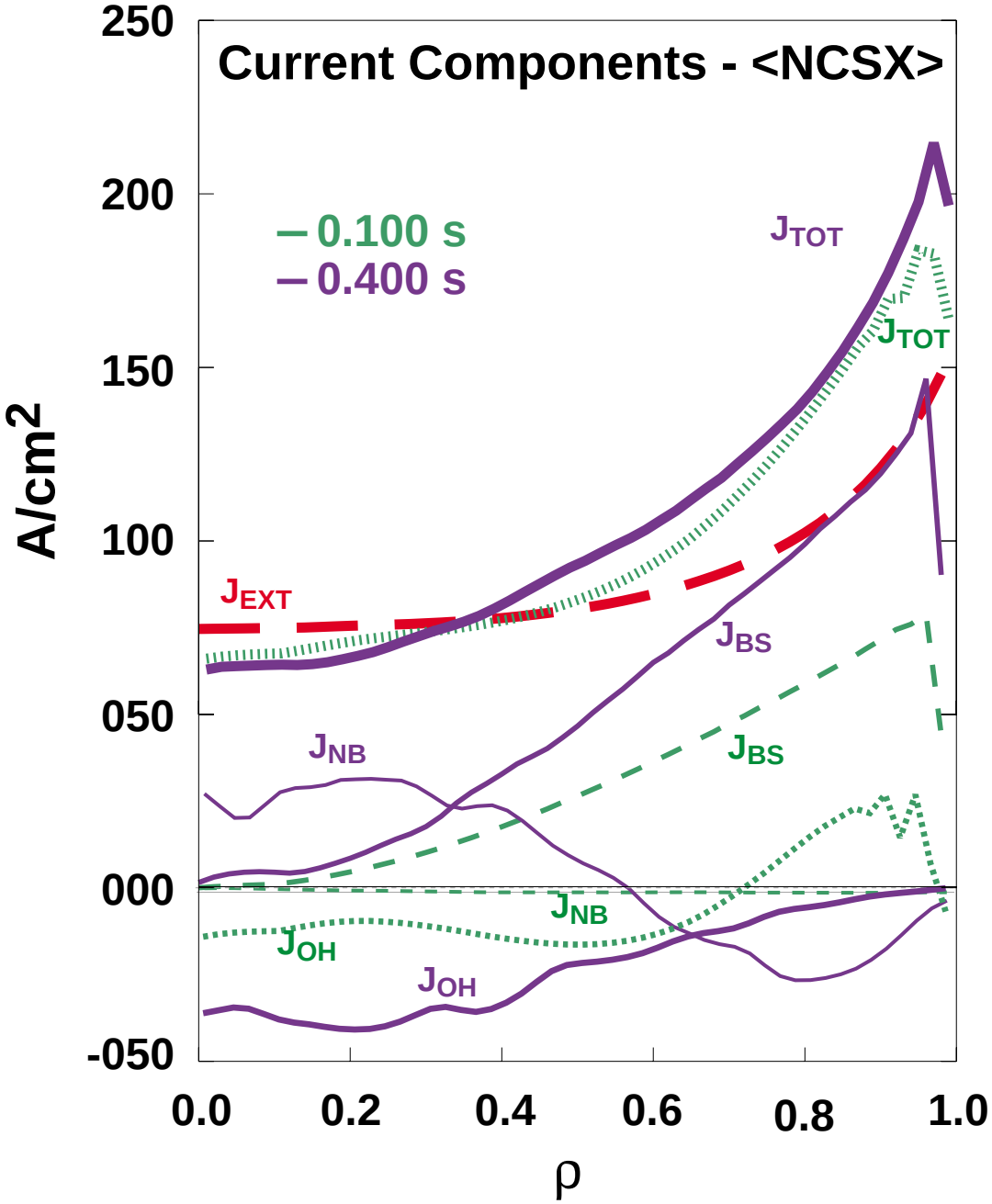
Evolution 2-D Simulation <NCSX>



Evolution of β and inductivity



Careful Discharge Programming will allow nearly constant iota over the duration of the neutral beam pulse.



1.) Beams are balanced to minimize NBCD.

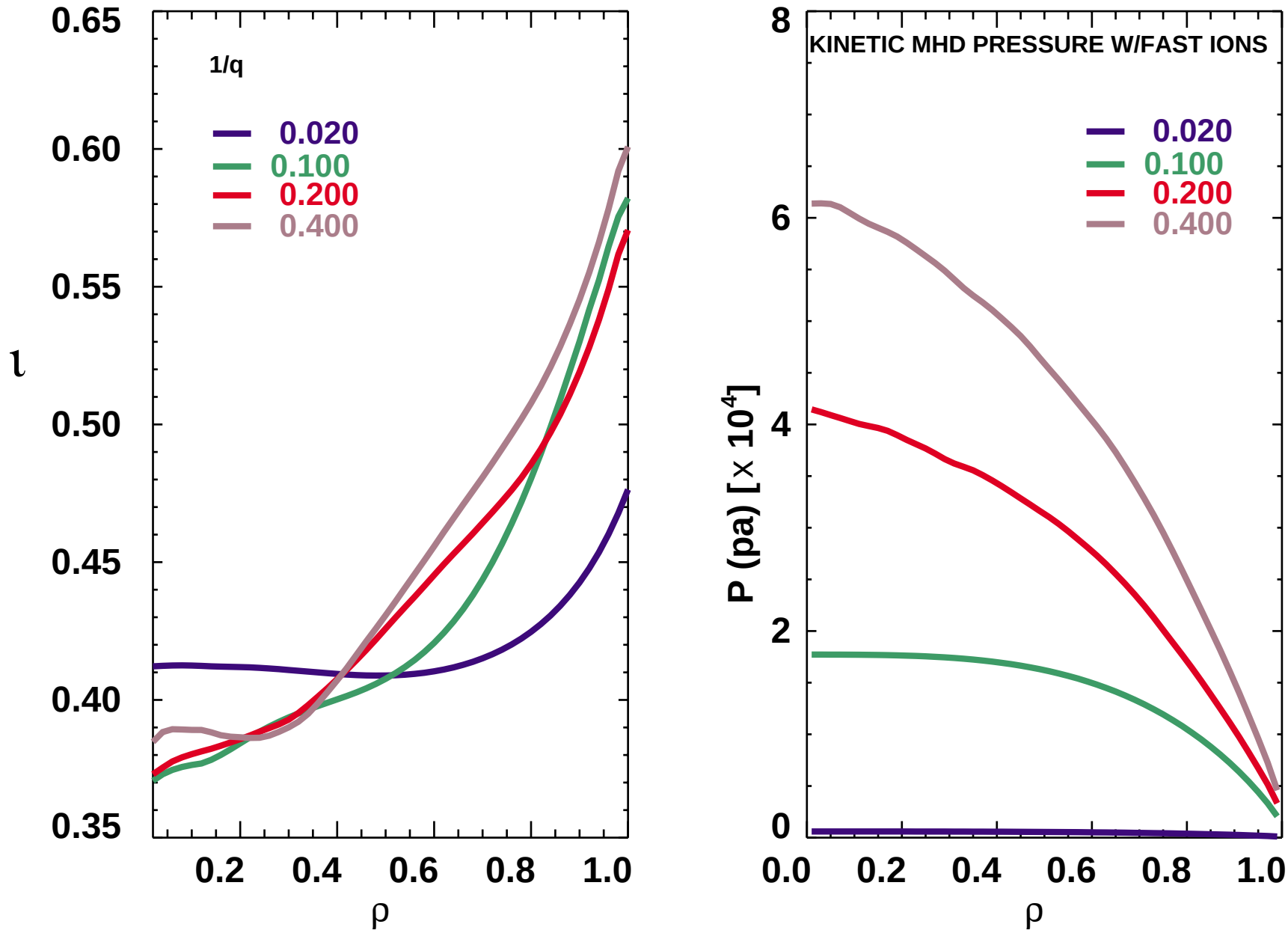
2.) External is a large fraction of the total current.

3.) Bootstrap is dominant plasma component.

4.) All that remains is to artfully balance OHCD against NBCD

Balance deteriorates after 0.75 s

Evolution of transform and pressure profiles (for the β_p and I_p trajectory that was specified)



Results in 3-D

The profiles generated in 2-D are now used in a series of free-boundary optimizations.To find coil currents that result in attractive physics, we have used two approaches to this task with the 0907a2 coil set (21 modular coils, 4 types; 14 polodial coil pairs).

- **The first was to simply target a shape which had shown good physics properties in the full current, high β state. Then, after the optimization evaluate the physics properties are examined.**

- **The second is to directly target the physics properties in the optimization process (R·B, kink stability, ballooning stability and quasi-symmetry).**

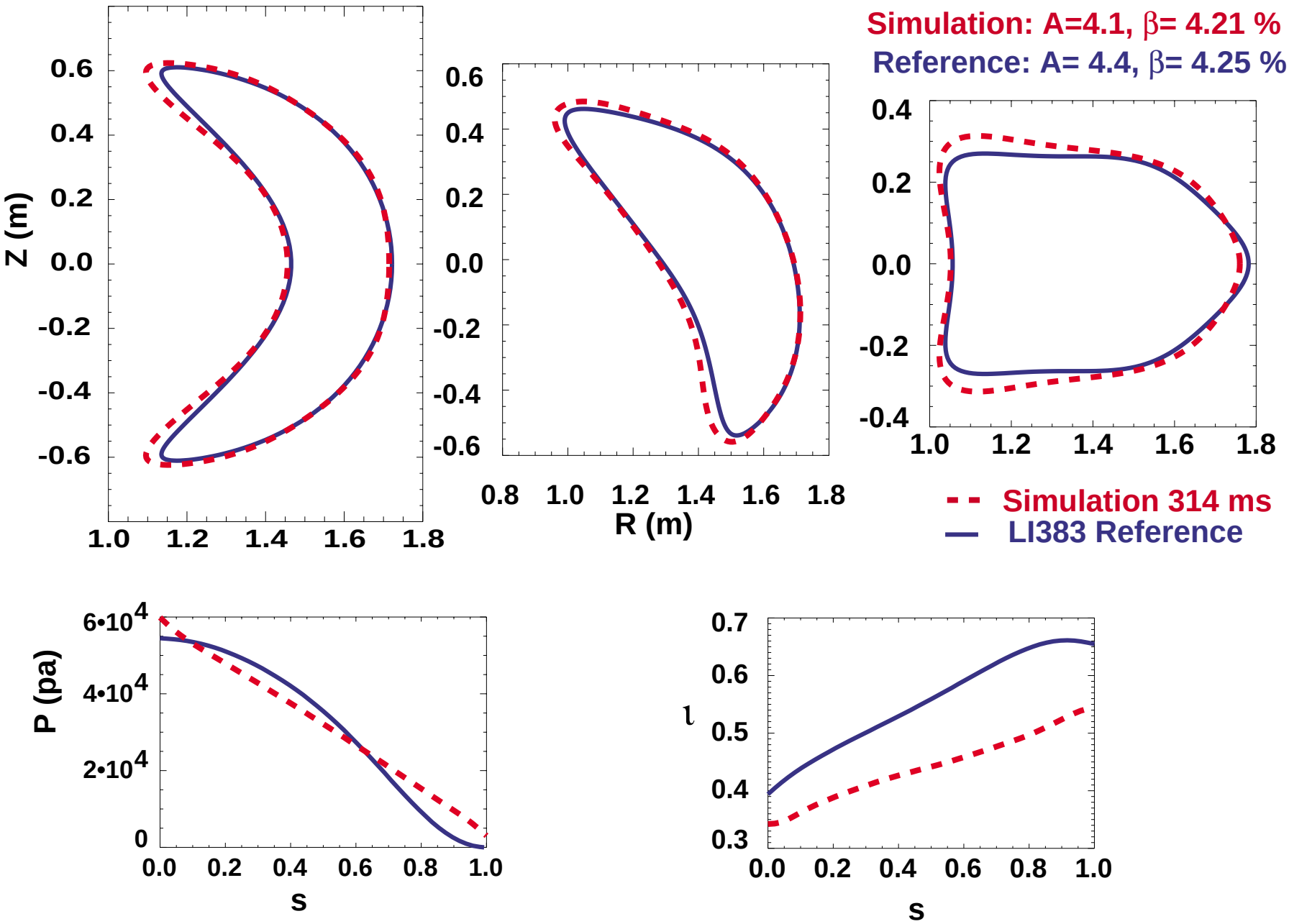
Both have led to satisfactory results, typified below. As discussed in the PVR document, Chapter 10; this optimization is directly on the physics properties and we chose to lower the aspect ratio to 4.1 to obtain these results. In earlier work to $\beta \approx$ 3 1/2 % we obtained good results at A=4.4

Results in 3-D

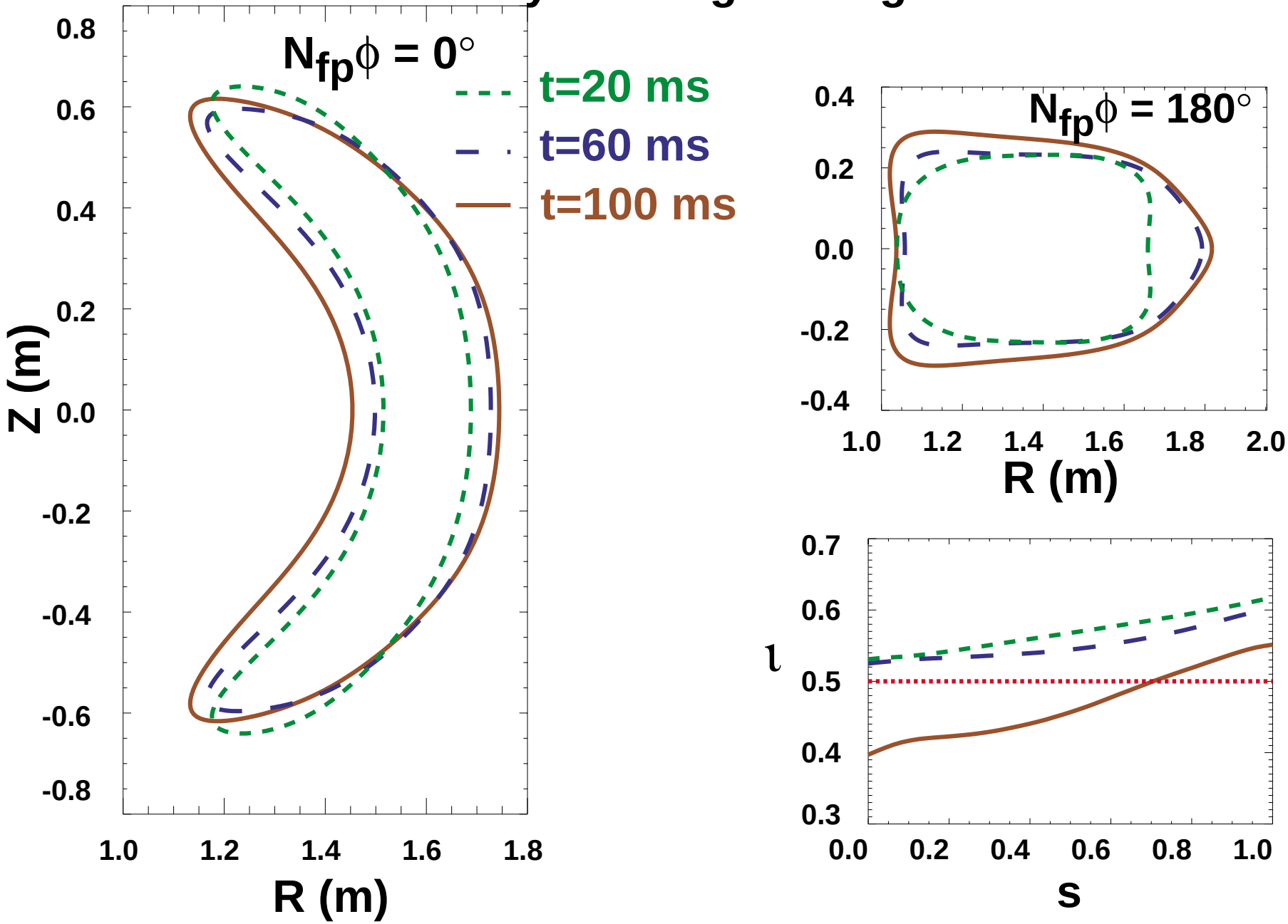
Time (ms)	A	<β>	I_P (A)	‡N=1 & N=0 Max γ x10^{-5}	χ^2_{Bmn}	ε_h (s=1/2) Effective Ripple	Ballooning Unstable Zones
li383	*4.365*	*0.043*	*150000*	*0*	*0.0151*	*0.61%*	*42,43,45,46,47*
0041	4.118	0.001	6590	3.00	0.0291	-	0
0061	4.123	0.002	18580	0	0.0303	2.38%	0
0081	4.123	0.006	42860	0	0.0337	1.55%	0
0106	4.123	0.016	71860	1.38	0.0327	1.37%	0
0131	4.123	0.022	68340	8.40	0.0324	1.39%	2
0151	4.123	0.025	69980	9.11	0.0334	1.25%	2
0211	4.122	0.032	80700	7.52	0.0356	1.14%	2,3
0315	4.123	0.042	100200	6.10	0.0407	1.25%	2,3
0420	4.122	0.042	105500	10.7	0.0515	1.55%	2,3
0525	4.122	0.042	109000	7.45	0.0353	0.89%	2,3
0630	4.123	0.042	111800	5.70	0.0300	0.96%	2.3.48
0735	4.132	0.043	114000	3.18	0.0298	1.21%	2,3,48
0842	4.122	0.043	116900	5.74	0.0330	0.88%	2,3,48

‡The goal is $\gamma<10^{-4}$. This is judged as sufficiently low – an art of experiment is avoiding weak instability.

Simulation results are qualitatively similar to li383 reference.
Differences result largely from fast ion physics.



An Alternative Startup Path Avoids the Boundary Passing Through i = 1/2



Other Coil Sets

The successful development was done with the 0907a2 coil set

Efforts with other sets, notably 1017a2, have not been as successful. The important distinction is that the 0907a2 coil set will not accommodate the neutral beams and the other sets tried have coils "pulled out" to allow beam access.

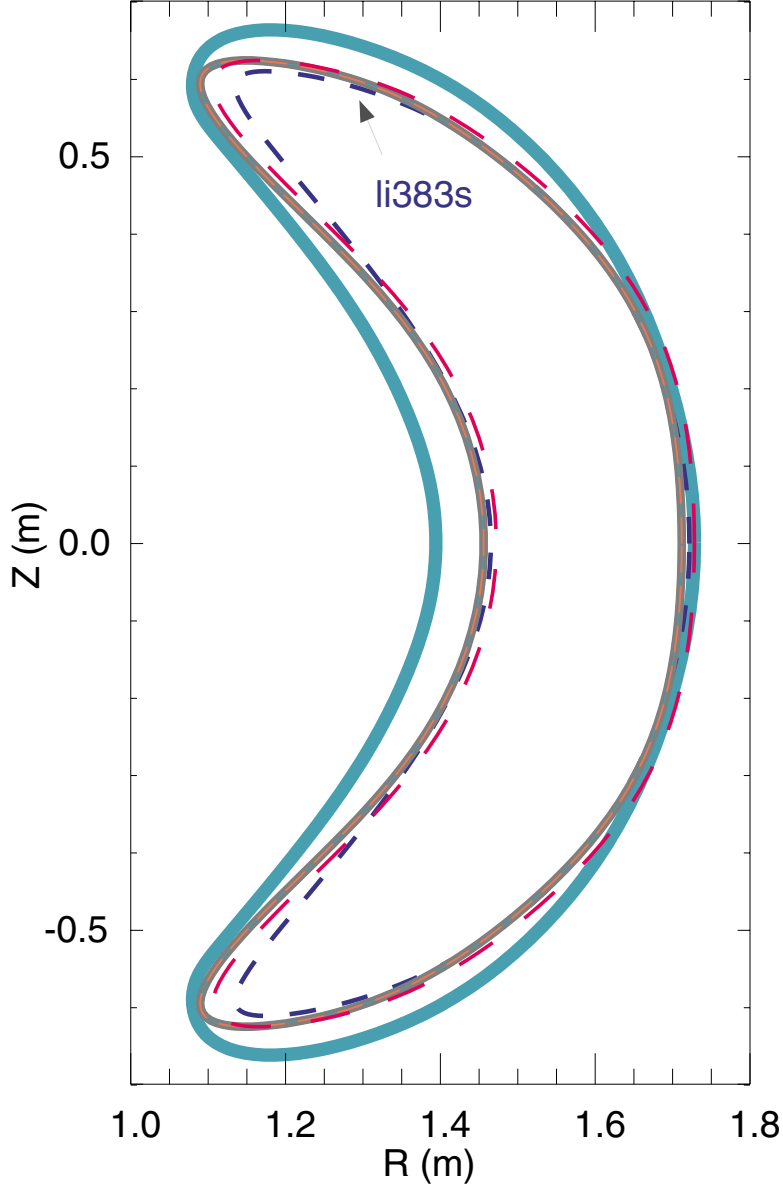
- **It is not known at this time whether stable solutions at the desired parameters do not exist or the methodology used for 0907a2 is inadequate.**
- **We have obtained solutions for 1017a2 allowing some deterioration in physics goals.**
  1. **We have solutions where B is allowed to rise, lowering β to 3.6%.**
  2. **We have solutions where β is preserved, but the quasi-symmetry is reduced, χ^2_{Bmn}~0.05.**
  3. **.**

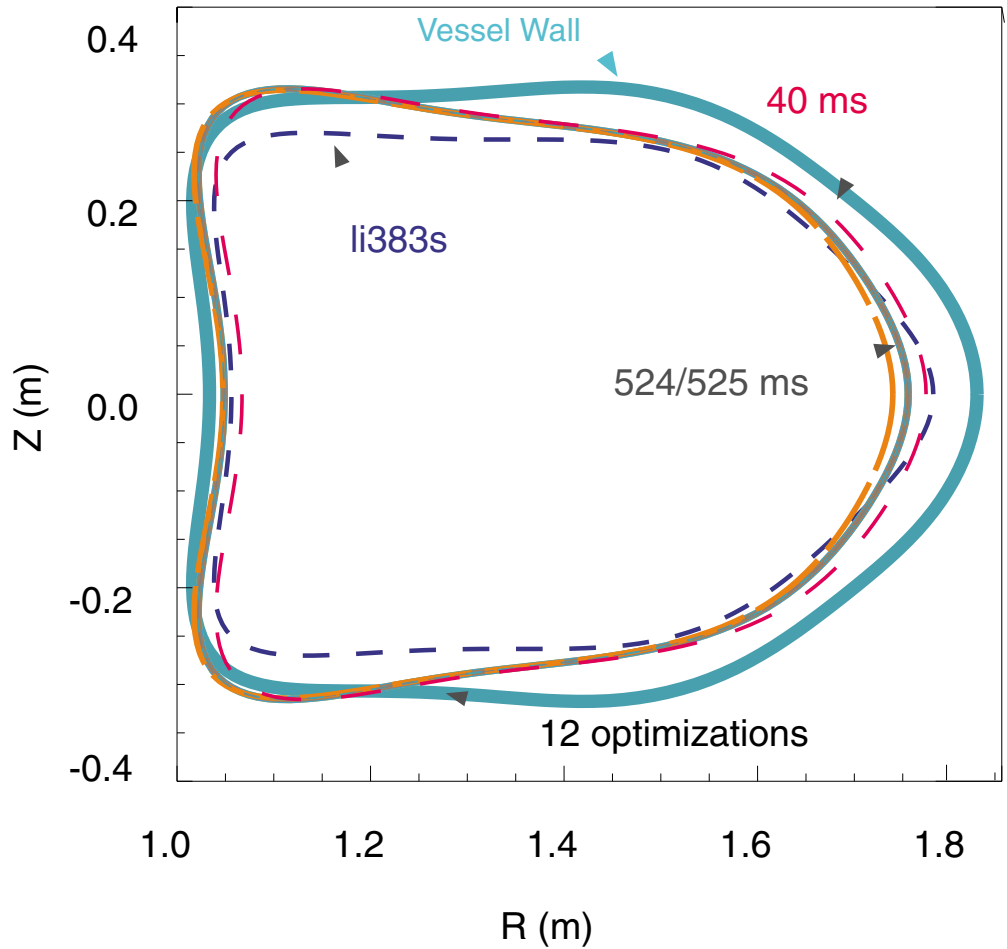
Future work will focus on resolving this issue.

Plasma Control

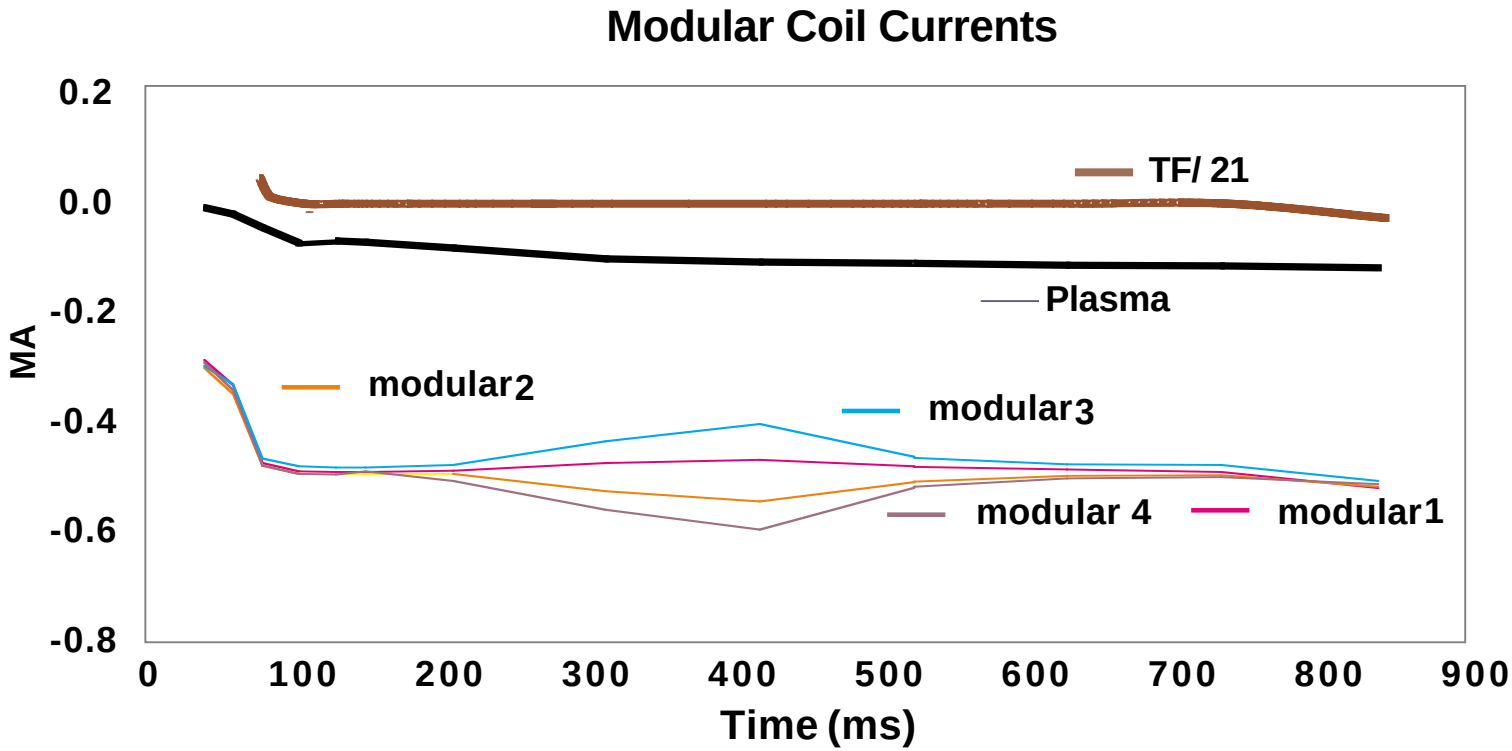
Last year we presented work (for a different configuration) where the procedure used was to use the optimizer to directly address the plasma shape. This shape was known to produce good results with the coil set used at that time. After the fact, we evaluated the physics targets and found them to be in the acceptable range.

In this years work the optimization was done on explicit physics targets, Kink & ballooning symmetry and quasi-symmetry. After the fact we look at the plasma shape, shown below in the symmetry planes. Twelve cases are identical in shape. The one at 40 ms would not be a problem. The 524/525 ms shapes are a quirk of the optimization due to a minor ballooning unstable region.


li383s
0.5
0.0
-0.5
Z (m)
1.0
1.2
1.4
1.6
1.8
R (m)


Vessel Wall
40 ms
li383s
524/525 ms
12 optimizations
0.4
0.2
0.0
-0.2
-0.4
Z (m)
1.0
1.2
1.4
1.6
1.8
R (m)

The changes in modular coil currents are modest.



This is an excellent result. All that is needed to maintain a stable, quasi-axisymmetric discharge is to control the plasma boundary shape.

The first requirement for control is the generatrion of simulated signals for the postulated magnetic diagnostic set. Than signals and boundary shapes are generated for a plausible range of discharge. It is not yet known what set of magnetics will yield the boundary in adequate detail. To study this control problem one needs a code to generate diagnostic responses to equilibria. We hope to begin on this code in the near future.

We would hope to use flux projection as a first approach. It is not clear our intuition will allow flux projection as we need to maintain shape in more than one toroidal plane and the coil currents are not related to shape in a simple way.

If this proves too difficult then principal component analysis will relate the boundary shape to the sensors. (If this fails, the postulated magnetic diagnostic set was not a good choice.) A refinement is to generate algorithms with coefficients which are functions of β, I_P, etc. A next level of sophistication would be to use neural networks.

Summary

1. We have developed a plausible scenario to evolve from the vacuum state to approximately the reference scenario in the 0.3s beam pulse length. The path is sufficiently stable and has adequate quasi-symmetry.

- The evolution is studied in an “equivalent tokamak” using TRANSP. A calculation of 3-D flux evolution is not currently available. For a QAS device we expect the 2-D evolution is quite adequate.
- The pressure and current are self-consistent and include (OHCD, NBCD, Bootstrap and Pfirsch-Schluter Currents.
- Monte-Carlo beam deposition and slowing-down.
- Diffusion of poloidal flux using neo-classical resistivity.
- The key to rapid equilibration of iota is to minimize the Ohmic flux in the cold startup plasma.

Summary (cont'd)

- There is no expectation of difficulty when ι=1/2 passes through the plasma boundary based on cylindrical calculation of island width. The shear is sufficient to keep the island at ~1% of the minor radius.
- An alternative startup was developed where ι=1/2 does not pass through the boundary by changing the shape during the I_p ramp. This path is sufficiently stable and has adequate quasi-symmetry.
- Within the uncertainty in confinement this scenario is energetically plausible, $H_{89p} \leq 2$ at B=1.4 T. Lower B would require less confinement, resulting in a colder plasma and a wider tolerance in matching $I_p(t)$ to $\beta(t)$.
- Other scenarios for a colder plasma ($T_e(0)$~1.1 keV) have been examined up to β~3.5% with similar results and easier discharge programming will equilibrate to the bootstrap current in a 0.4 s pulse.
- NCSX will be the first stellarator to provide active control of the helical (and poloidal) fields for control of the plasma shape.