Investigations of Discharge Evolution Scenarios for the Li383 Configuration

Ed Lazarus

Oak Ridge National 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?

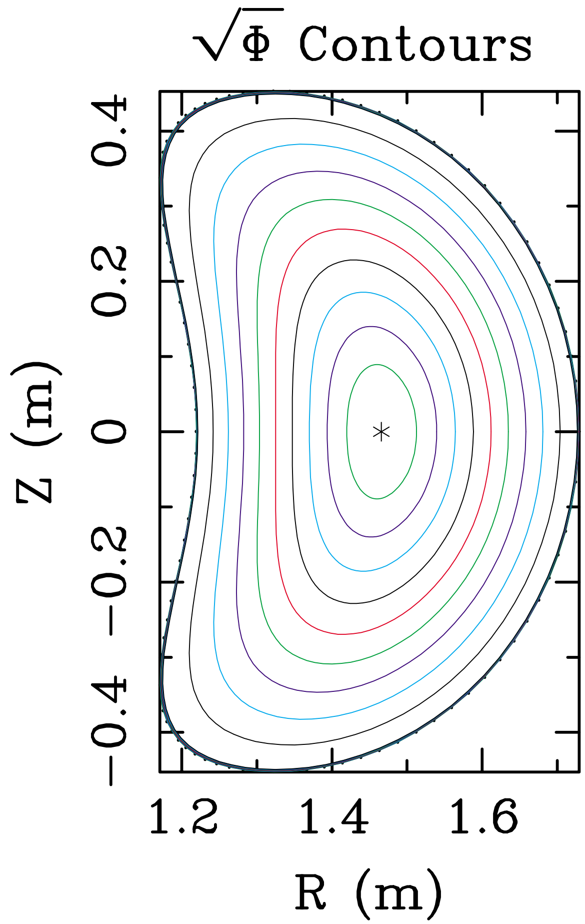
A more specific goal is to accomplish this in a 0.3 second beam pulse when the current relaxation time is about 1 sec in the core of the plasma.

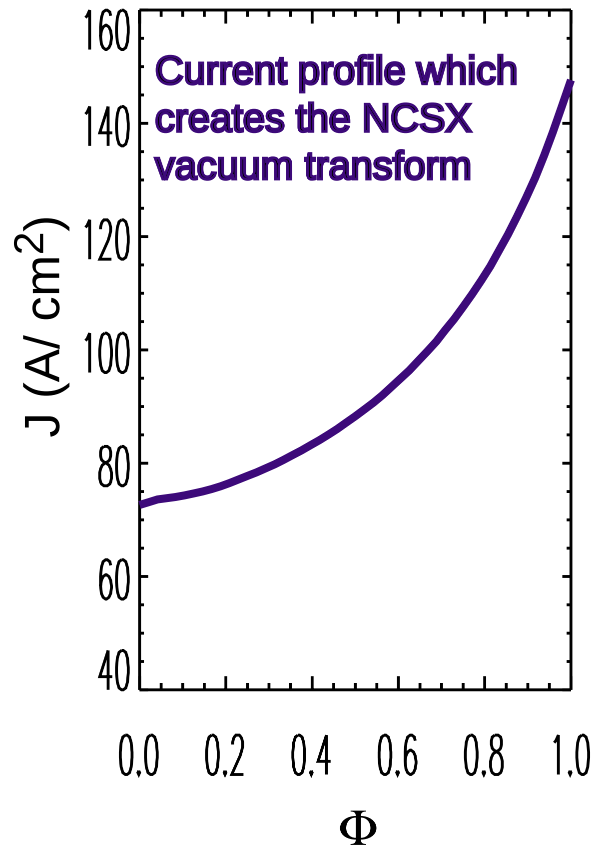
Simulation Process

- **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(ρ) 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 – it will not diffuse. 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, magnitude is similar at high β to that in talk by D. Mikkelsen**
- **n_e shape is specified, amplitude is adjusted to give desired β.**
- **$\chi_i = 3\,\chi_i^{neo}$ results in T_I as in Dave's talk.**

Computations in TRANSP

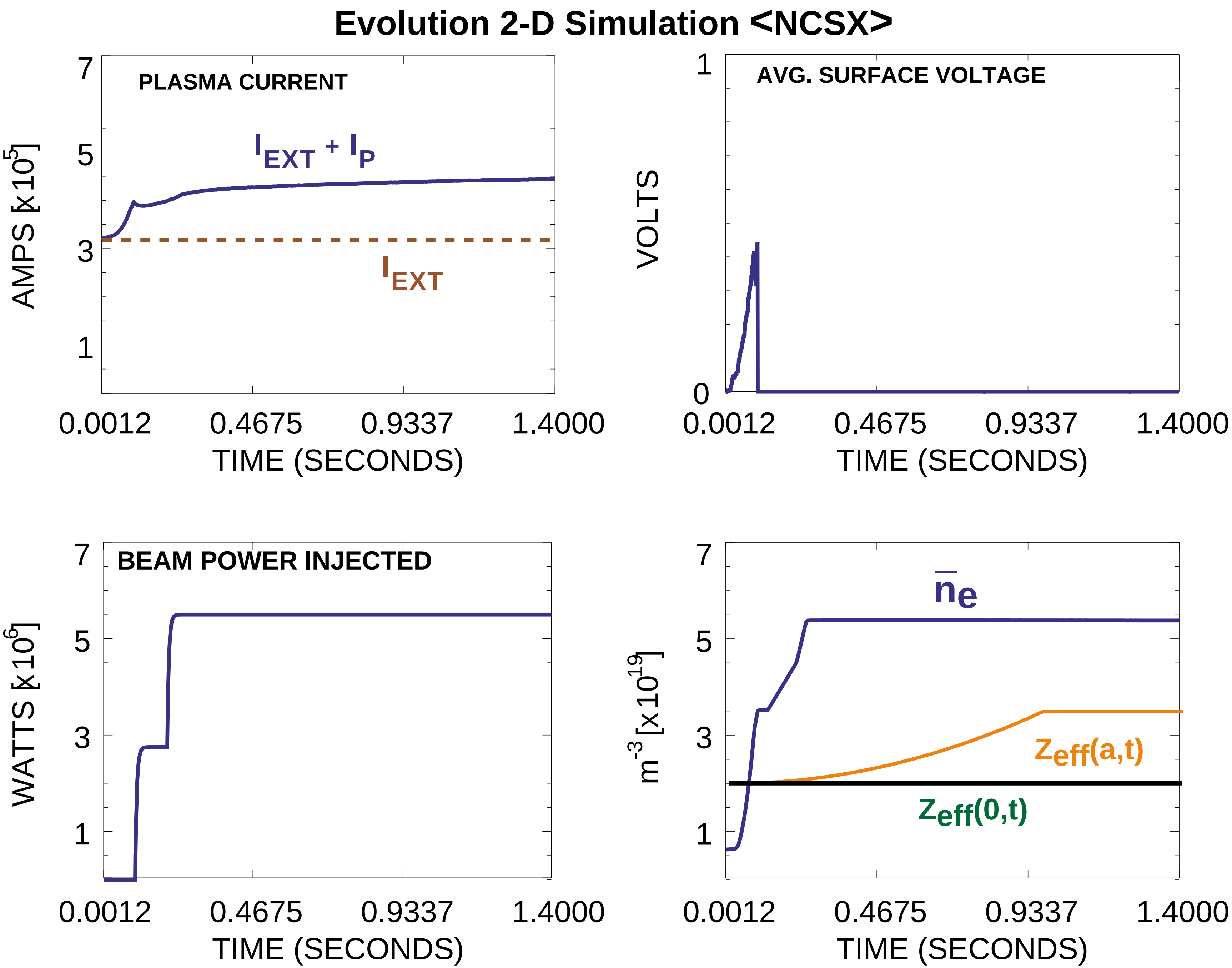
- **Poloidal flux diffusion**
- **Beam deposition and slowing down, NBCD**
- **Power balance => T_I only**
- **Fast ion pressure**

Manual iteration of TRANSP runs to get desired discharge.

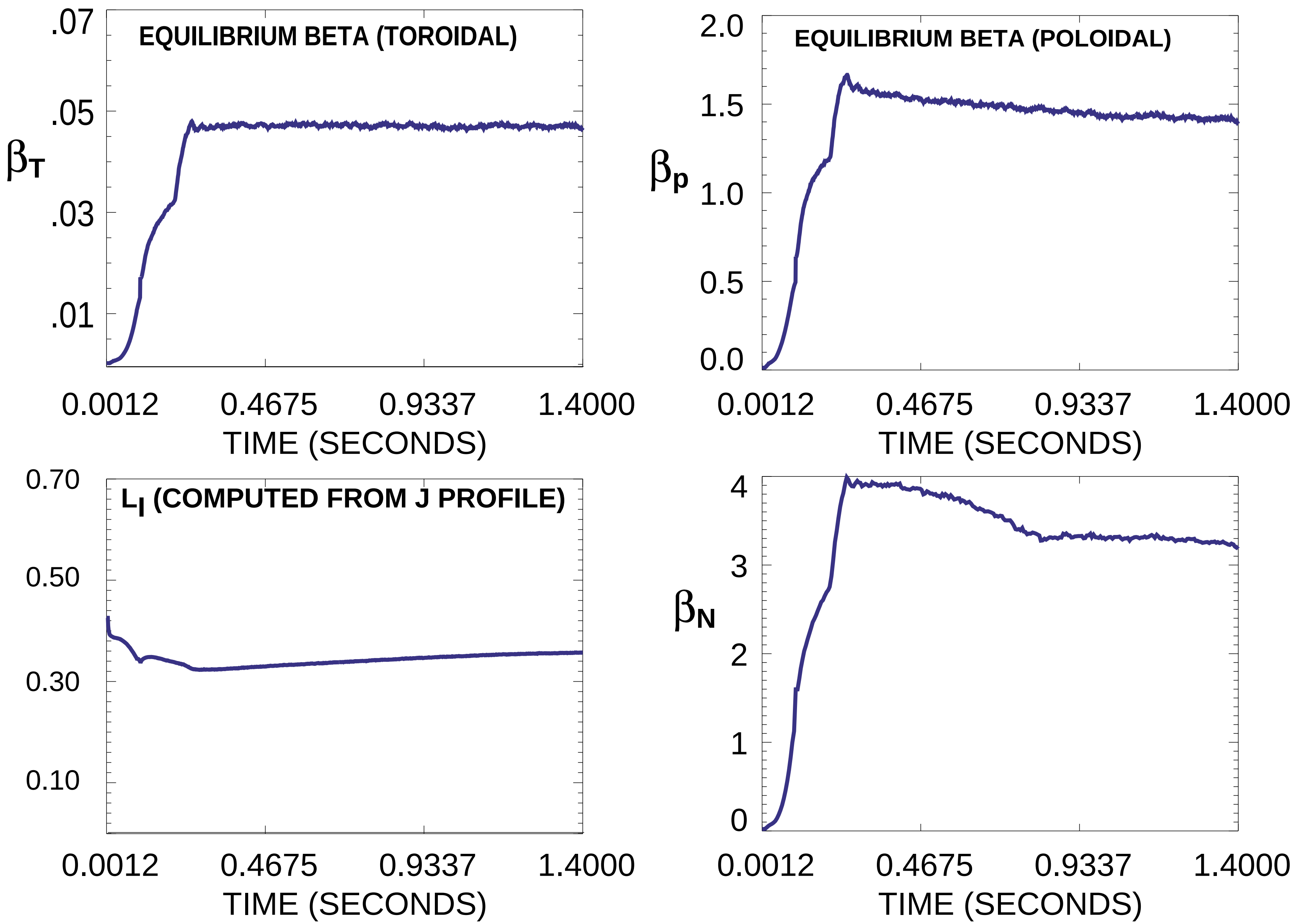
Results in 2-D

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

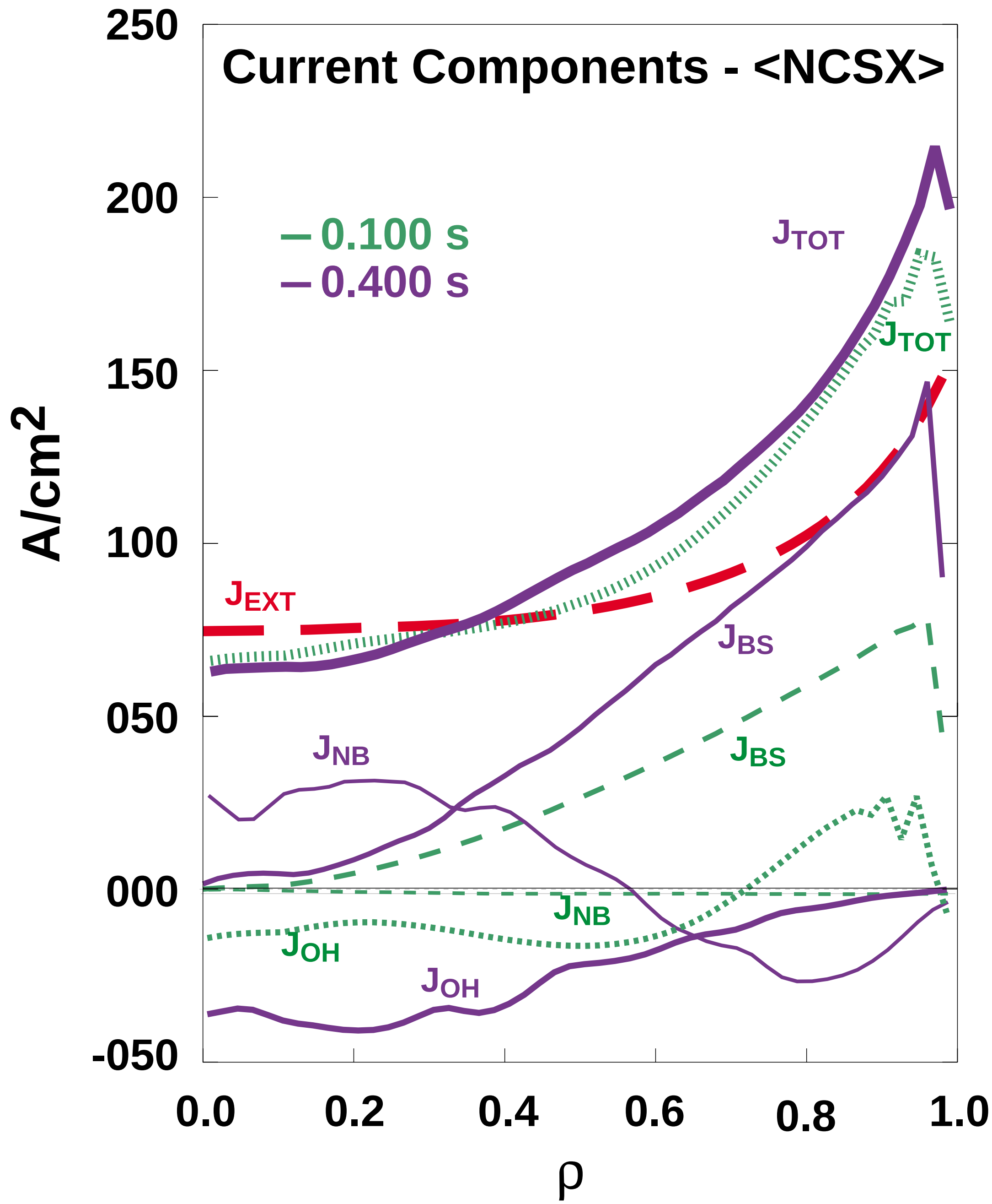
- **Evolution of primary quantities**
- β **and** ℓ_i
- **balance of NBCD and OHCD**
- **iota and pressure**


Evolution 2-D Simulation <NCSX>
PLASMA CURRENT
AMPS [x 10^5]
I_EXT + I_P
I_EXT
AVG. SURFACE VOLTAGE
VOLTS
BEAM POWER INJECTED
WATTS [x 10^6]
m^-3 [x 10^19]
n_e
Z_eff(a,t)
Z_eff(0,t)
TIME (SECONDS)
0.0012
0.4675
0.9337
1.4000

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.

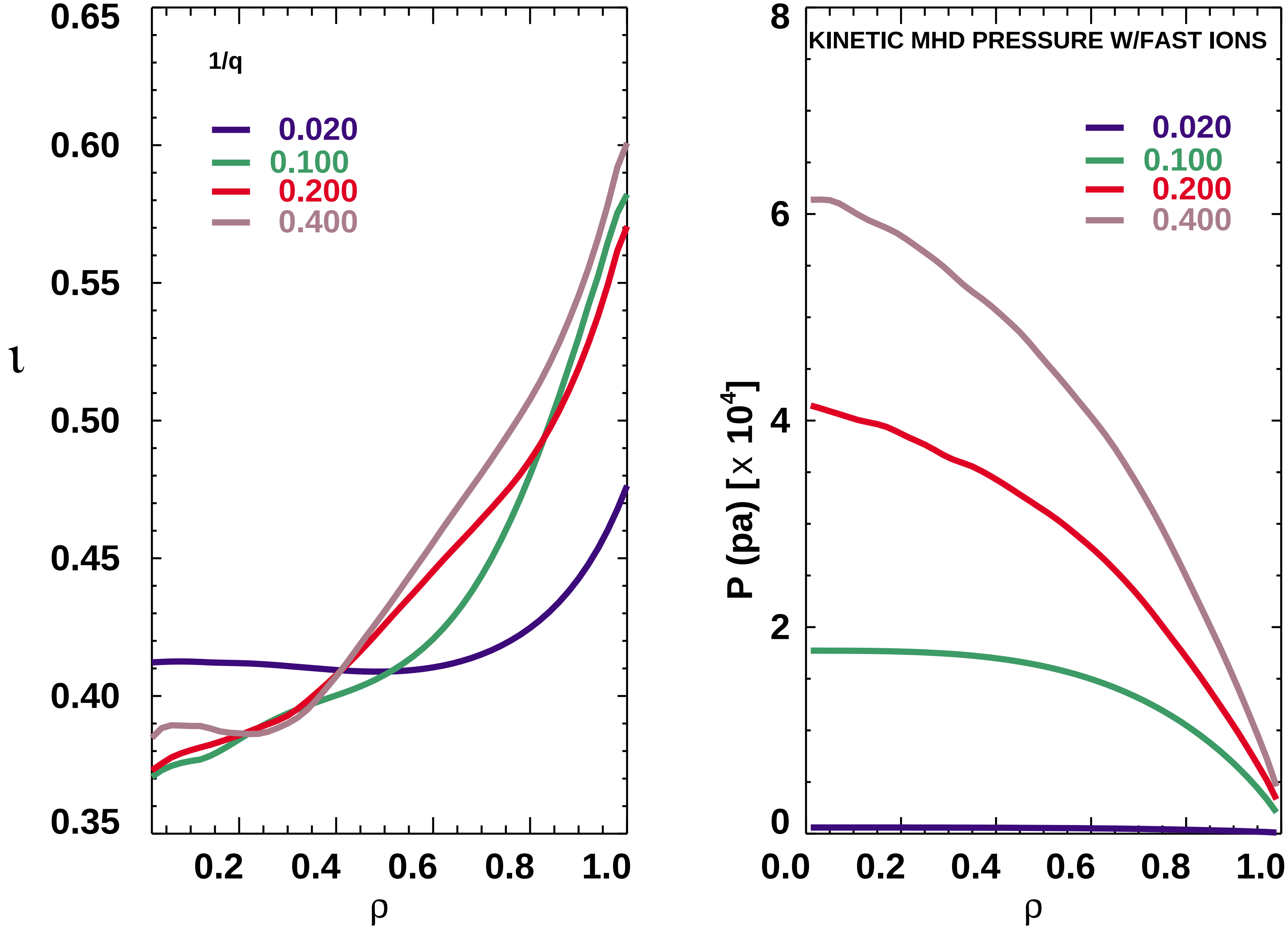
2.) External is a large fraction of the total current.

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

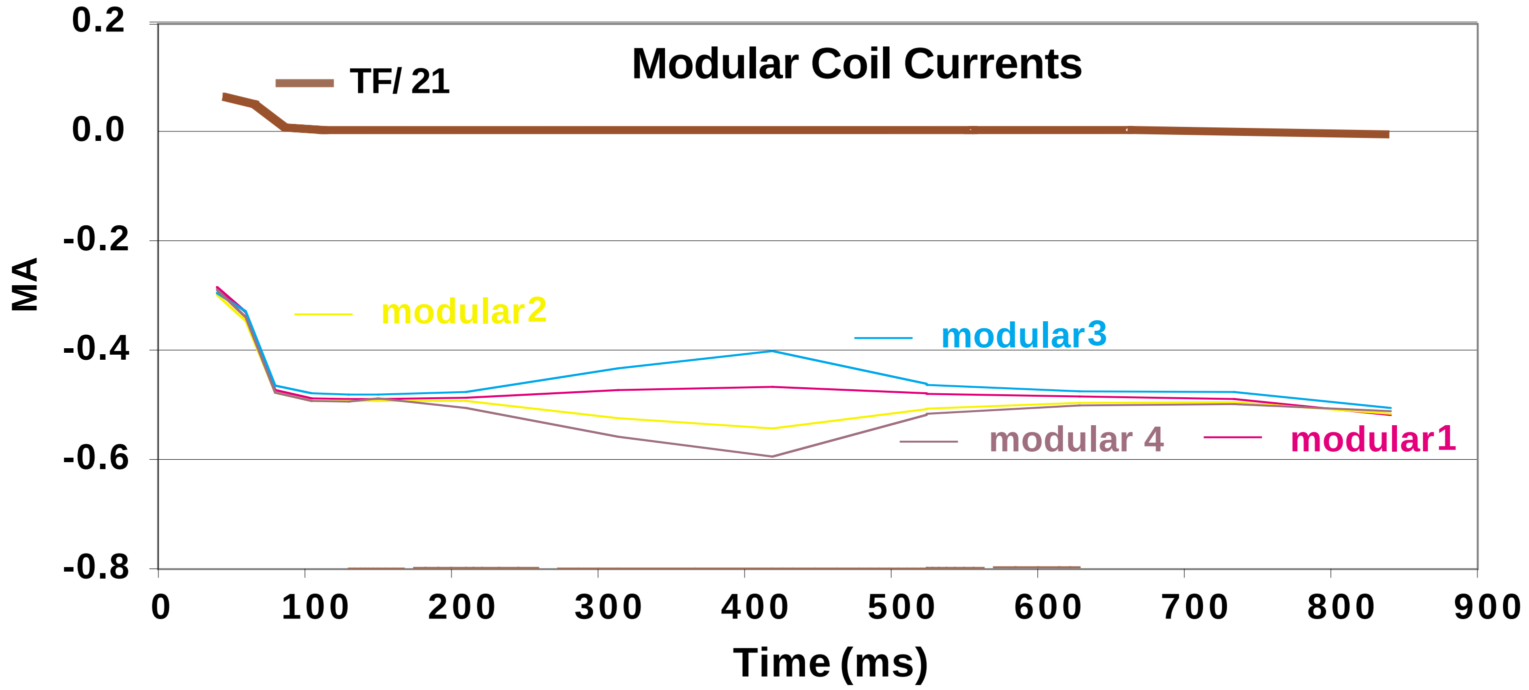
The profiles generated in 2-D are now used in a series of free-boundary optimizations.To find coil currents that result in attractive physics, we have used two approaches to this task with the 0907a2 coil set (21 modular coils, 4 types; 14 polodial coil pairs).

- **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

The modular coil current variations are modest and gradual.

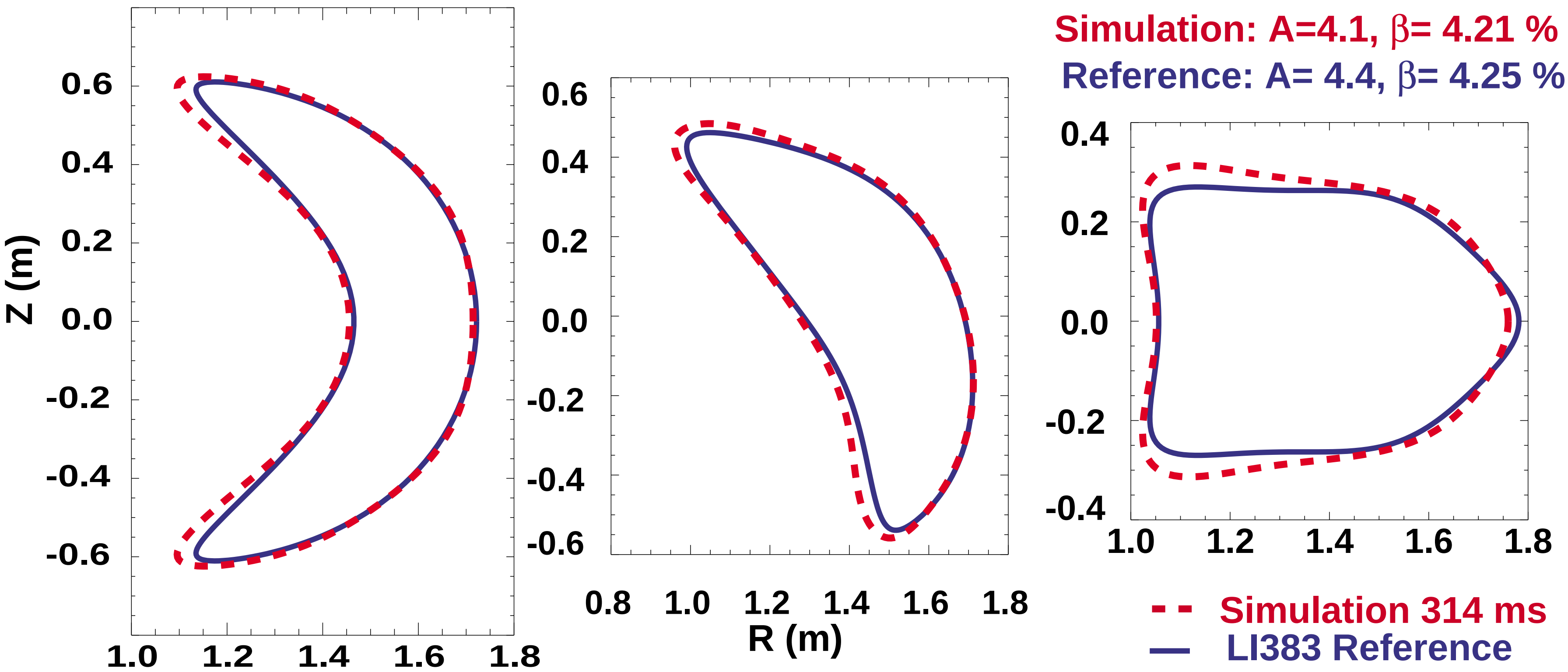


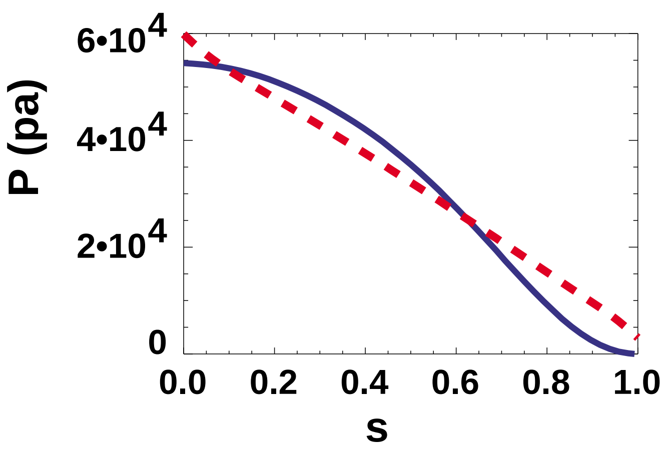
Results in 3-D

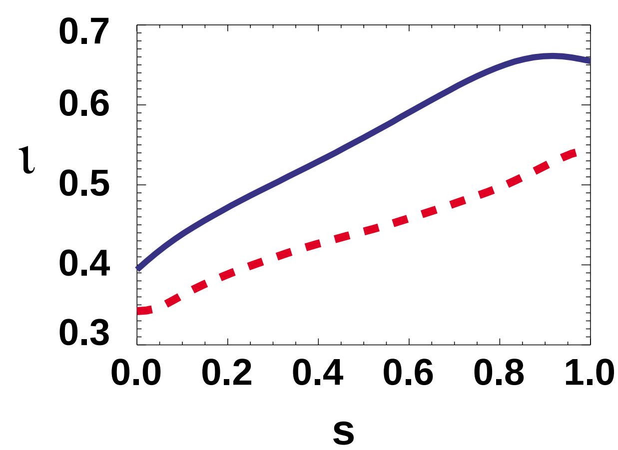
Time (ms)	A	<β>	I_P (A)	‡N=1 & N=0 Max γ x10^{-5}	χ^2_{Bmn}	ε_h (s=1/2) Effective Ripple	Ballooning Unstable Zones
li383	4.365	0.043	150000	0	0.0151	0.61%	42,43,45,46,47
0041	4.118	0.001	6590	3.00	0.0291	-	0
0061	4.123	0.002	18580	0	0.0303	2.38%	0
0081	4.123	0.006	42860	0	0.0337	1.55%	0
0106	4.123	0.016	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.

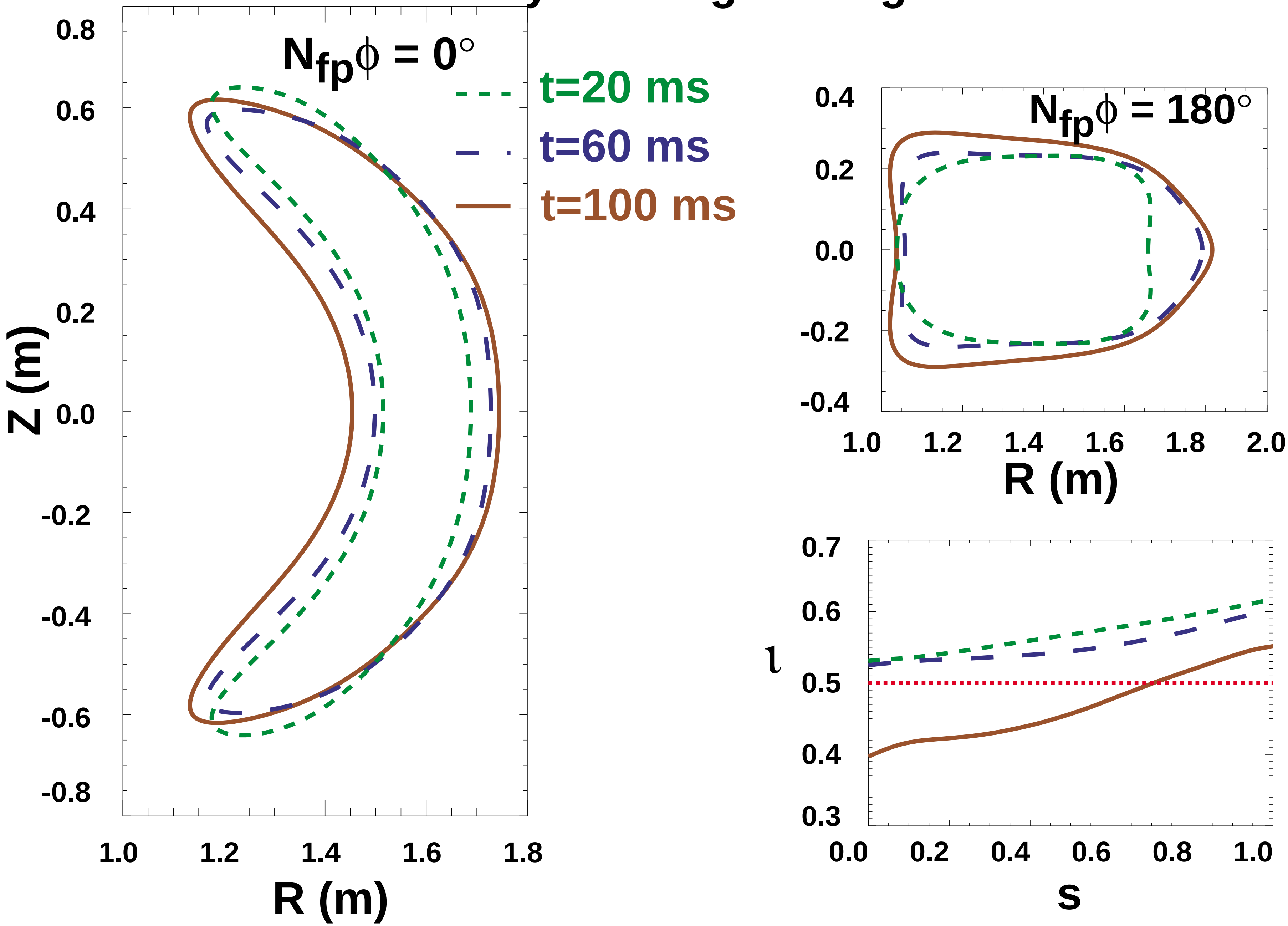
Simulation results are qualitatively similar to li383 reference. Differences result largely from fast ion physics.







An Alternative Startup Path Avoids the Boundary Passing Through ι = 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.

- 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.

Future work will focus on resolving this issue and then proceeding to determining the simplest adequate PF coil set.

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.