A Discharge Evolution Scenario
For the M45h NCSX Configuration

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The goal of this work is to establish the existence of a plausible trajectory from the vacuum state to the high beta, bootstrap-driven final state.

Simulation Process

- **Build "equivalent tokamak" - <NCSX> in order to use our axisymmetric tools. (These should be good for QAS device.)**
  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>, and adjust as necessary to obtain satisfactory results.**
  - Primarily a satisfactory evolution of iota (couples to β and ν_*)
- **Put resulting profiles, $p(\rho)$ and $J_{TOT}(\rho)$ - $J_{EXT}(\rho)$ back into NCSX.**
  - Find free-boundary equilibria that have desirable stability properties and quasi-symmetry with STELLOPT.
- **Examine the surface quality of representative free-boundary equilibria from this series of optimizations with PIES.**

The 2-D evolution modeling is done with TRANSP.

Computations in TRANSP

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

The “vacuum” current density shown above is modeled as lower hybrid current (LHCD) in TRANSP. It 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.

- **n_e shape is specified, amplitude is adjusted to give desired plasma properties.**
- **Confinement matches empirical scaling: min(neo-Alcator, ITER97L)**
- χ_i , χ_e : $\chi^{total} = \chi^{symmetric\_nclscl} + \chi^{ripple} + \chi^{anomalous}$ **; feedback loop adjusts** $\chi^{anomalous}$ **to match $\tau_E^{thermal}$ to the specified scaling. (PVR issue)**

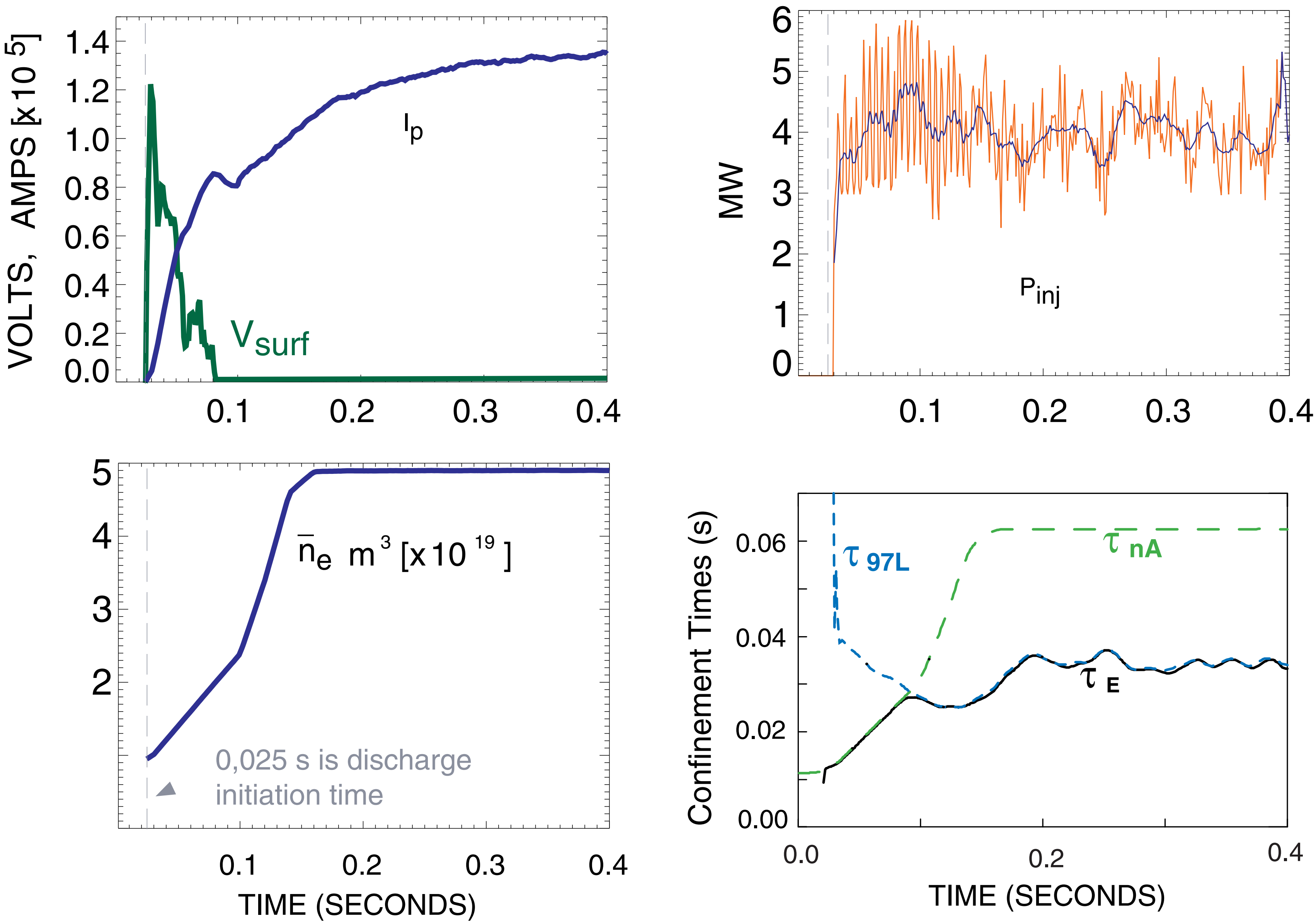
Manual iteration of TRANSP runs to get desired discharge.

- **I_P waveform to closely match bootstrap & NBCD buildup**
- **P_{inj} to control β**
- **Density to affect beam deposition**

Inputs

(a) Ip (or V_{loop}) waveform, (b) neutral beam power and (co/counter mix)
(c) line averaged density, (d) confinement assumption.

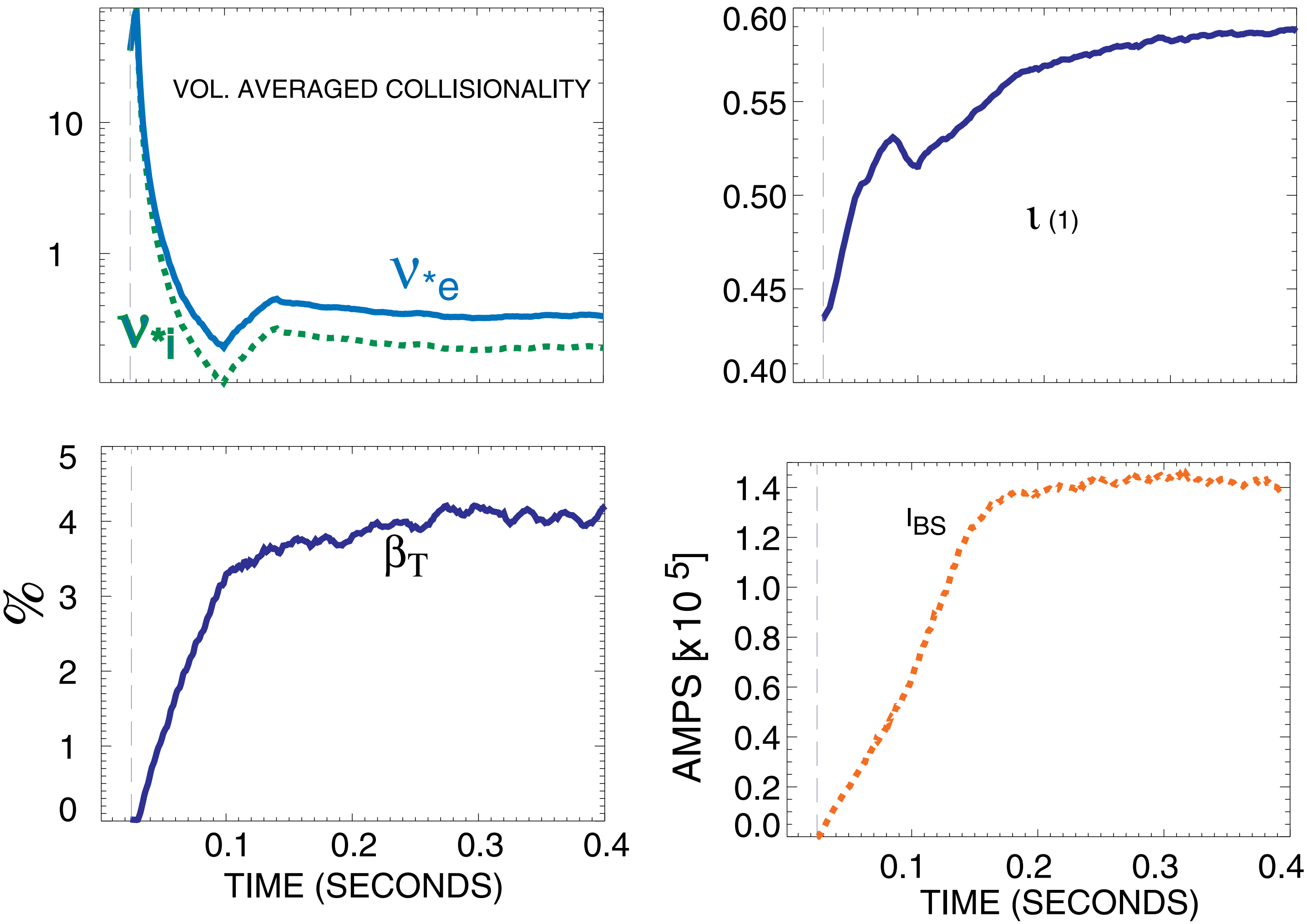
A complex, strongly coupled system.



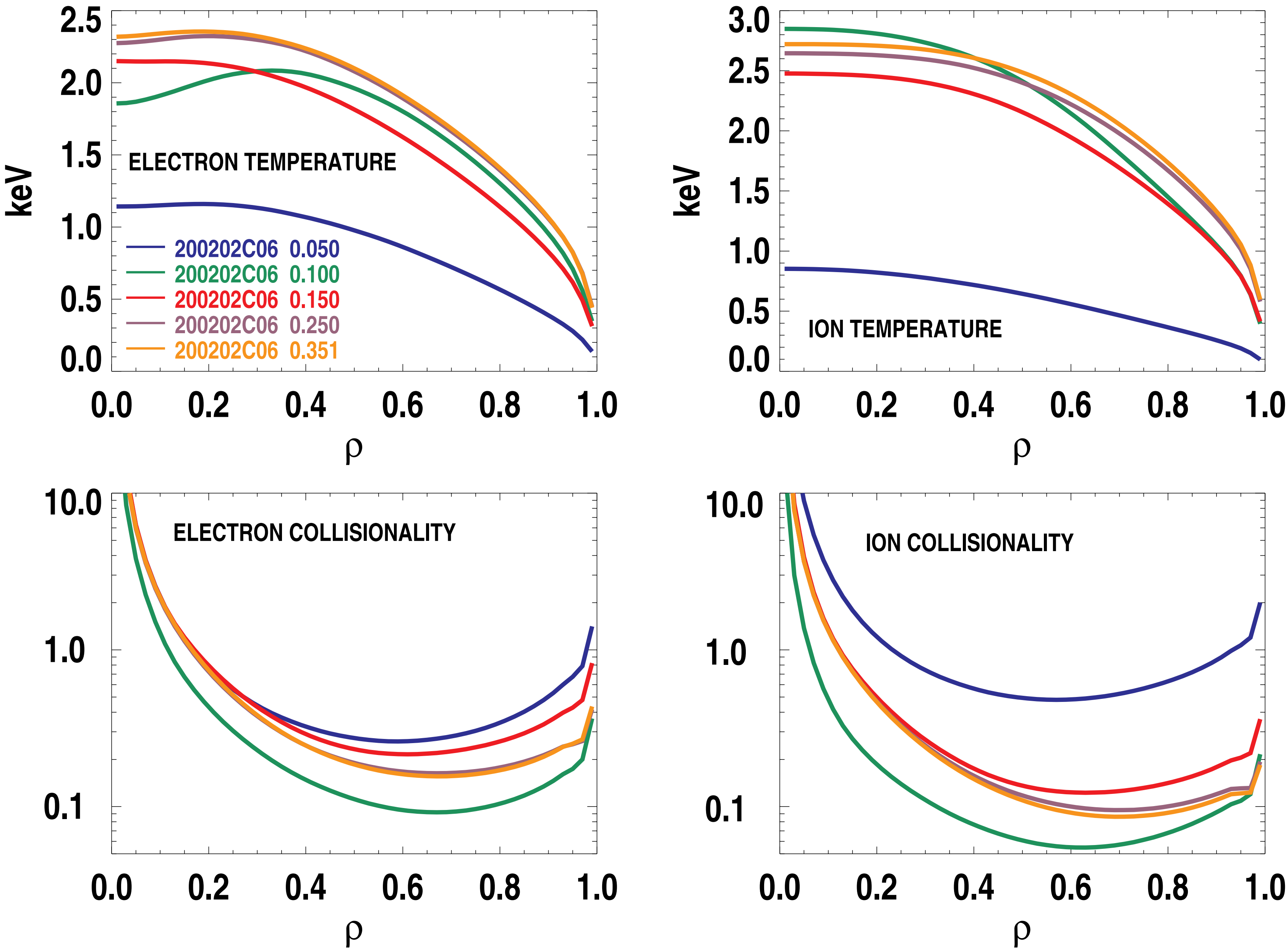
The outputs are the profiles, pressure and current density vs time which are then used in stellarator optimization.

The collisionality remains consistent with the energy balance througth the feedback loop.

These and the global quantities below can only be changed by changing the discharge programming (or confinement assumption).



If the confinement is as good as an L-mode tokamak low collisionality can be reached at high β.

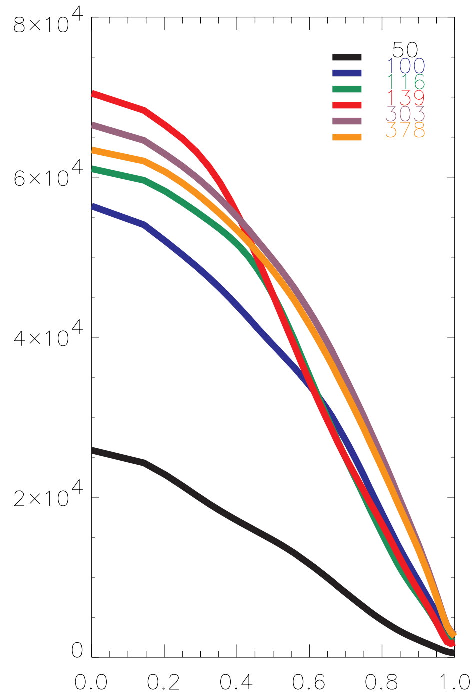


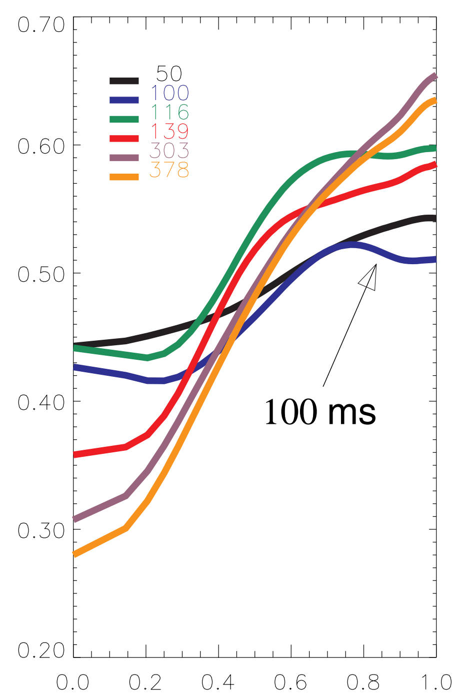
Optimization over coil currents. Results at R·B=2.05 m-T.

Time (ms)	Aspect Ratio	Plasma Current (A)	beta %	Distance to wall (m)	Ballooning $\sum$unstable	Kink (N=1) family (λ <0 stable) ‡	Kink (N=0) Family (λ <0 stable) ‡	Effective Ripple $\varepsilon_h^{3/2}$ (s=0.3)
30	4.368	4.57E+03	.0184	-8.31E-03	0	1.80E-06	0	1.69E-04
40	4.379	2.95E+04	.668	-6.05E-03	0	0	0	1.31E-04
50	4.415	5.34E+04	1.22	5.18E-03	0	0	0	1.65E-04
70	4.405	7.78E+04	2.23	-6.25E-03	0	8.49E-05	0	2.00E-04
80	4.391	8.56E+04	2.67	-3.63E-03	0	0	2.10E-05	1.12E-04
100	4.39	8.16E+04	3.38	-2.68E-02	0	3.66E-05	0	8.72E-05
110	4.443	8.86E+04	3.85	7.75E-03	0	0	6.20E-05	1.93E-04
116	4.383	9.02E+04	3.67	-9.58E-03	0	0	6.27E-05	9.96E-05
139	4.427	9.97E+04	3.93	2.99E-03	0	0	0	1.33E-04
172	4.389	1.14E+05	4.06	-2.79E-03	0	0	0	2.00E-04
203	4.452	1.20E+05	4.25	9.41E-03	0	0	0	2.07E-04
241	4.482	1.25E+05	4.38	6.83E-03	0	0	4.18E-05	1.52E-04
271	4.427	1.29E+05	4.53	6.50E-03	0	0	0	1.64E-04
303	4.466	1.32E+05	4.58	1.14E-02	0	3.09E-05	0	2.63E-04
339	4.429	1.34E+05	4.52	4.22E-03	0	0	0	1.09E-04
378	4.436	1.33E+05	4.41	7.50E-03	0	1.08E-05	0	1.38E-04
398	4.386	1.33E+05	4.55	-1.06E-02	0	0	0	1.58E-04
LI383	4.365	1.75E+05	4.25	1.49E-02	1.41E-02	0	0	2.17E-05
M45h	4.366	1.75E+05	4.08	5.47E-04	4.15E-02	0	0	9.66E-05

‡ The goal is $\gamma<10^{-4}$. This is judged as sufficiently low as to be avoidable.

The pressure and iota profiles indicate the plasma will be touchy near 100 ms

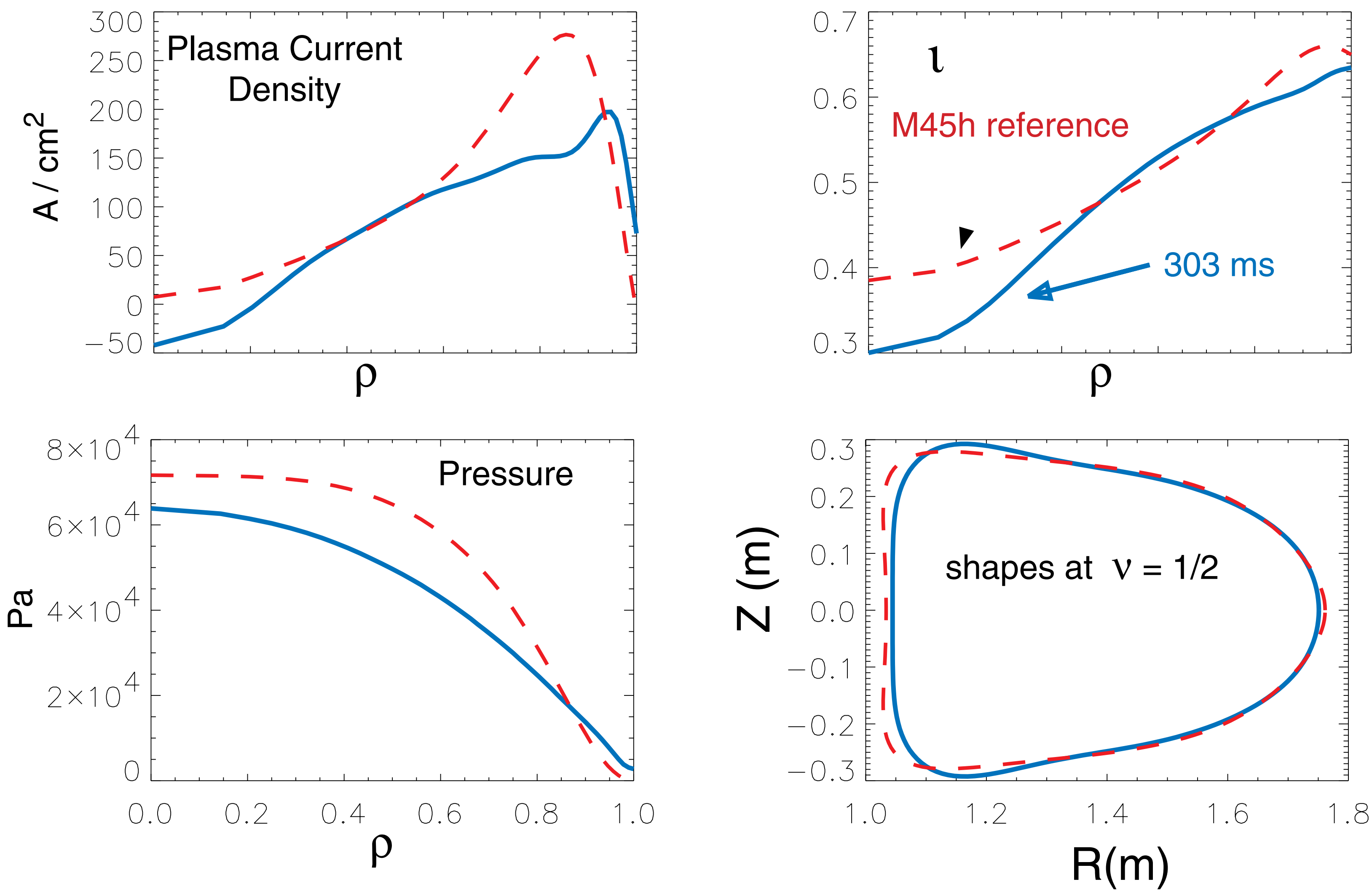




There are some problems with interference with the vacuum vessel that need to be fixed. This clearance demand degrades kink stability. At t=100ms I cannot relieve this interference and maintain an acceptable kink growth rate. At times near 100 ms it is still very difficult.

- **My own thinking is that I allowed beta to rise too rapidly, that is, while a region of near zero shear exists in the plasma.**
- **I think this can be changed by programming the density and NB waveforms a bit differently. There are other options to try as well.**

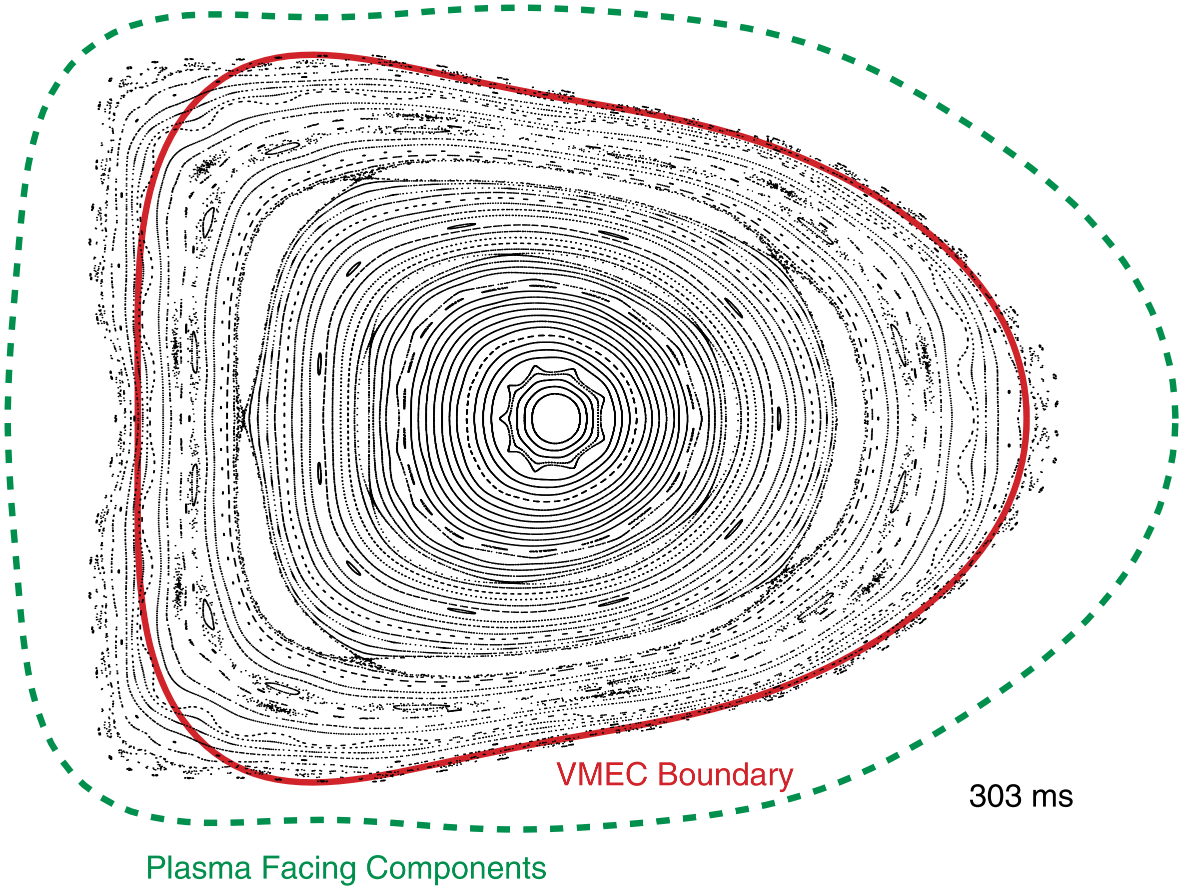
The profiles obtained from the TRANSP calculations differ from the reference.At the boundary neither p or J vanish. One consequence of this is that the flat spot in iota no longer exists in the high beta phase. The edge conditions leading to this shear at the edge are consistent with expectations based on tokamaks. It is encouraging that stable equilibruia are found for both the reference and these profiles. We are not sitting atop a flagpole with β = 4 1/2 %.



Equilibrium calculation with PIES shows good surface quality.

When $\chi_{||}/\chi_{\perp}$ and neoclassical effects are accounted for the effective width reduces the fraction of surfaces lost to 2%

β=4.5%, I_{BS}/I_P=0.99



Summary

We have found a stable path to a 4 1/2 % beta plasma with 99% of the current resulting from the bootstrap effect with the M45h coil set. There is no reason to expect that this path is unique.

- The plasma is stable to ballooning modes and external kinks.
- The effective ripple is comparable to the reference case and sufficiently small to cause negligible transport.
- These statements apply from vacuum to the final state.
- A final state is reached 210 ms after the beams are turned on, well within the expected 300 ms heating pulse.

Surface quality has been examined with PIES. Good surfaces are maintained.