Equilibrium Flux Surface Calculations for W7AS and NCSX

A. Reiman[1], M. Zarnstorff[1], D. Monticello[1], S. Hudson[1], L. Ku[1], A. Weller[2], J. Geiger[2], and the W7-AS Team[2]

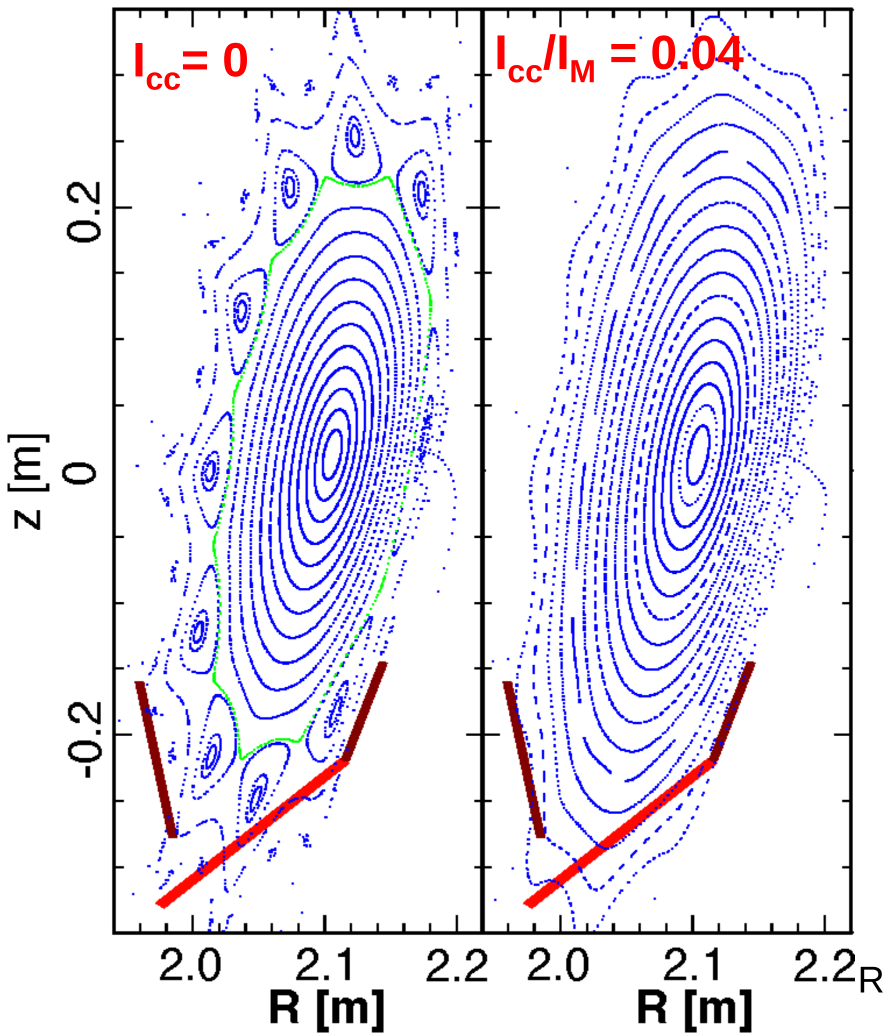
[1]*Princeton Plasma Physics Laboratory, Princeton, NJ, USA*
[2]*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

US-Japan Workshop

Princeton, March 16, 2006

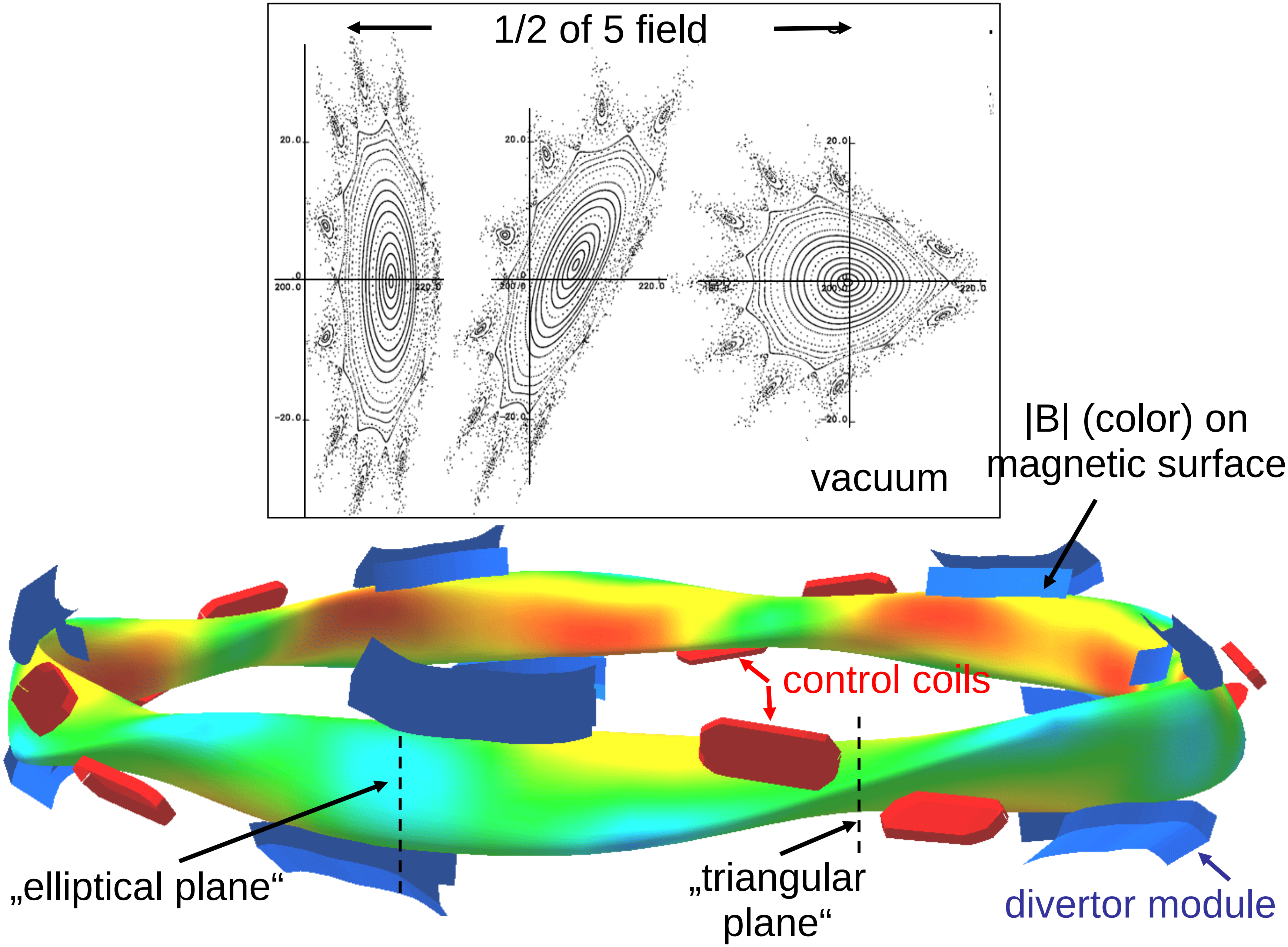
Divertor control coil on W7AS stellarator designed to control resonant magnetic field near plasma edge.

Calculated Vacuum Surfaces

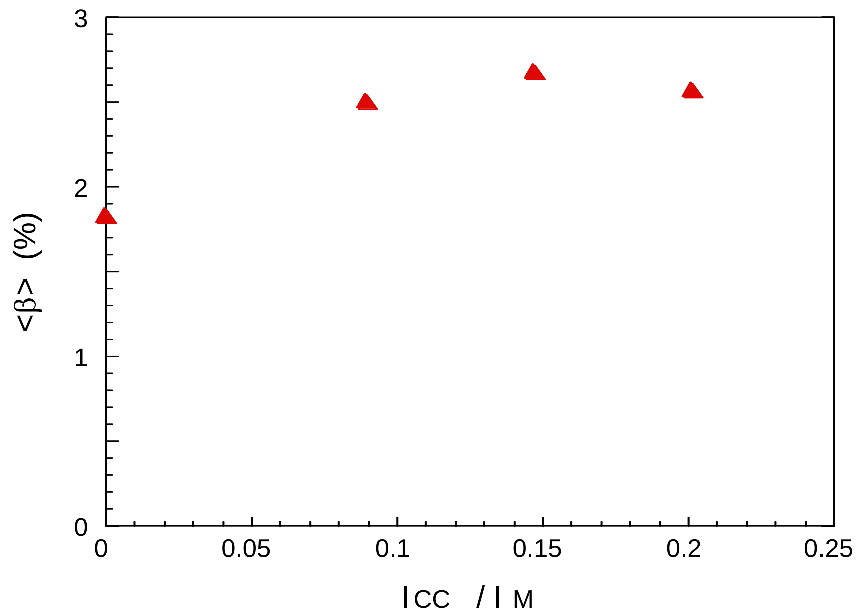


Coil calculated to have little effect on rotational transform ($\equiv ι \equiv 1/q$), or on neoclassical ripple transport, or on magnetic axis shift.

Magnetic Configuration, In-Vessel Comp.



W7AS: Effect of Divertor Control Coil Current on Peak ⟨β⟩

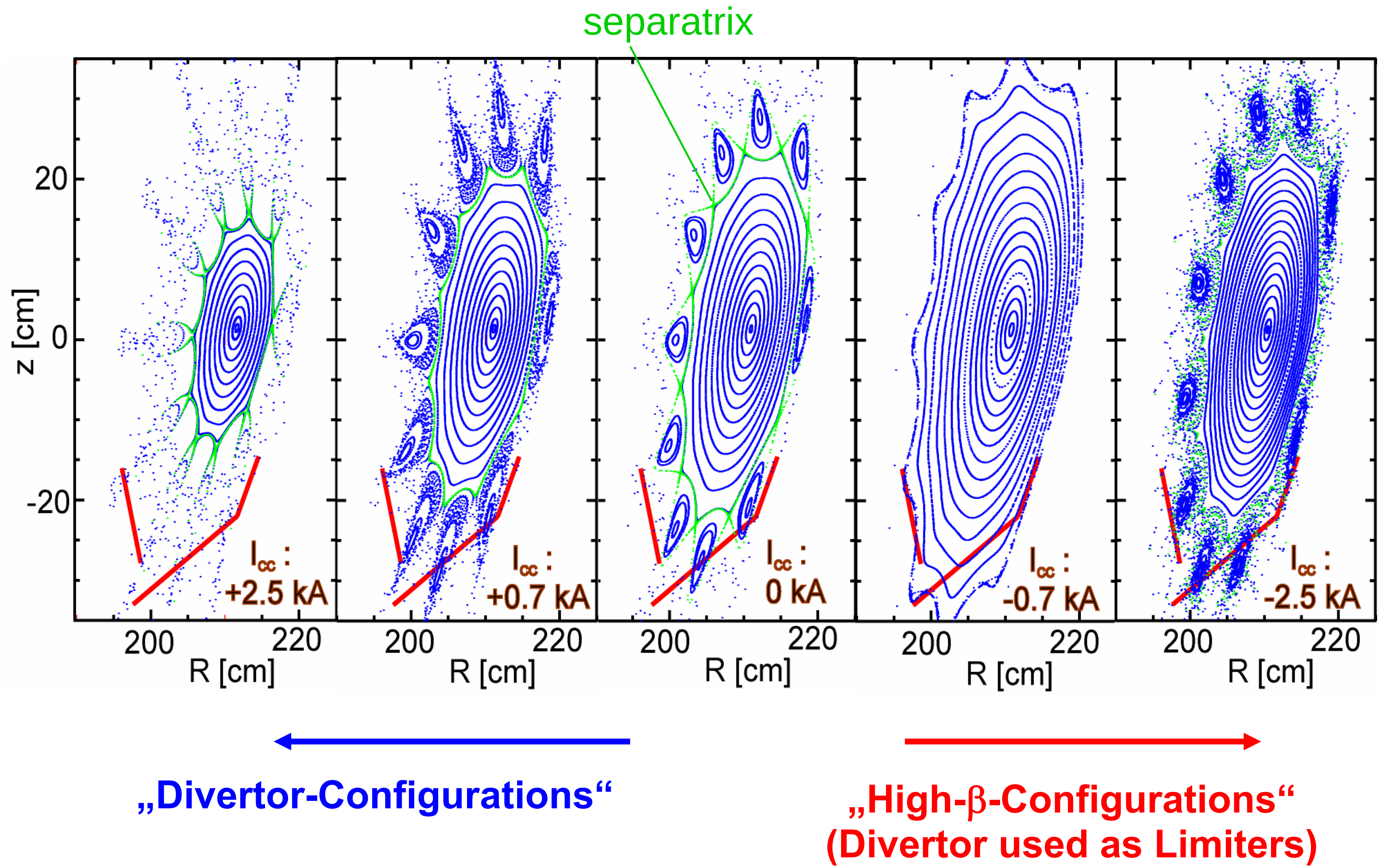


Variation of peak-⟨β⟩ versus the divertor control-coil current I_{CC} normalized by the modular coil current, for B=1.25 T, P_{NB} = 2.8 MW absorbed and ι_{vac} = 0.44.

Divertor control coil designed to control resonant magnetic field near plasma edge, for control of edge islands.

Coil calculated to have little effect on rotational transform, or on neoclassical ripple transport, or on magnetic axis shift.

Effect of Control Coils
(Vacuum Configuration iota ≈ 1/2)



W7AS modeling uses experimentally determined pressure profiles

- Optimizer used to construct VMEC equilibrium which provides best fit to experimental data.
- VMEC reconstructed equilibrium used as starting point for PIES calculation. Pressure profile preserved, with no flattening in edge stochastic region.
- Assume zero net current ($\mu_{00} = 0$).

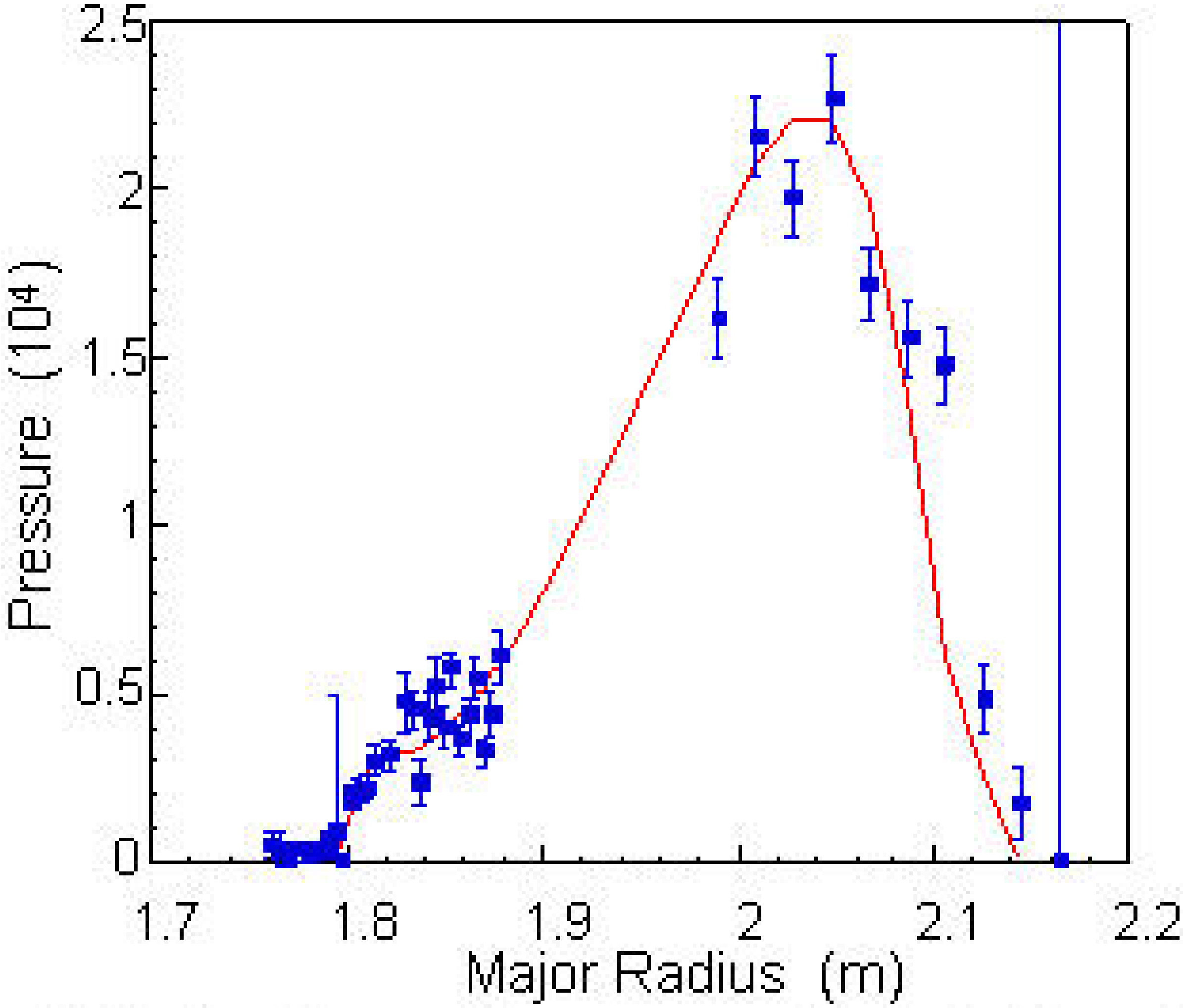
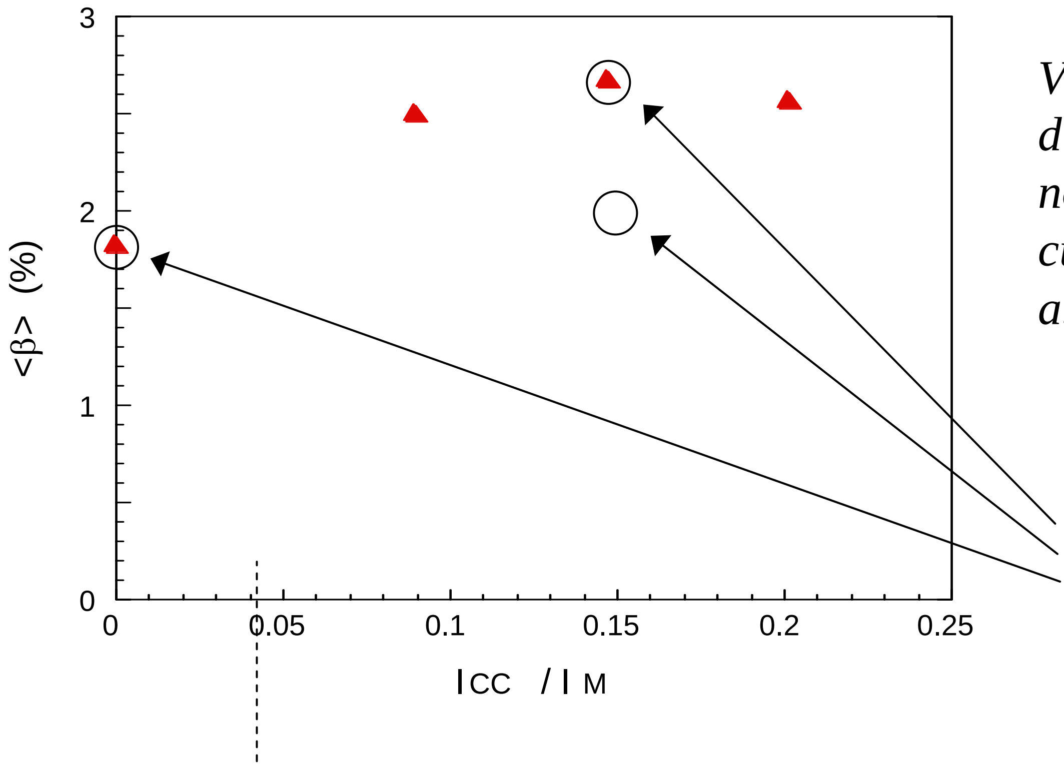


FIG. 4. *Measured pressure profile (points) and fit profile from reconstruction (line) for plasma of Fig. 1. The data points are twice the measured electron pressure.*

PIES code has been modified to allow specification of experimentally determined profiles.

- PIES code solves 3D MHD equilibrium equation using general representation of magnetic field.
  Can handle islands and stochastic regions.
- Initial implementation of code assumed flat pressure and current profiles in islands and stochastic regions.
- For modeling experimental data, code modified to allow specification of current and pressure profiles in islands and stochastic regions.
  Finite pressure gradient in stochastic region reasonable when particle mean free paths << field line connection length to wall.

The control coil substantially affects the achievable β on W7AS.



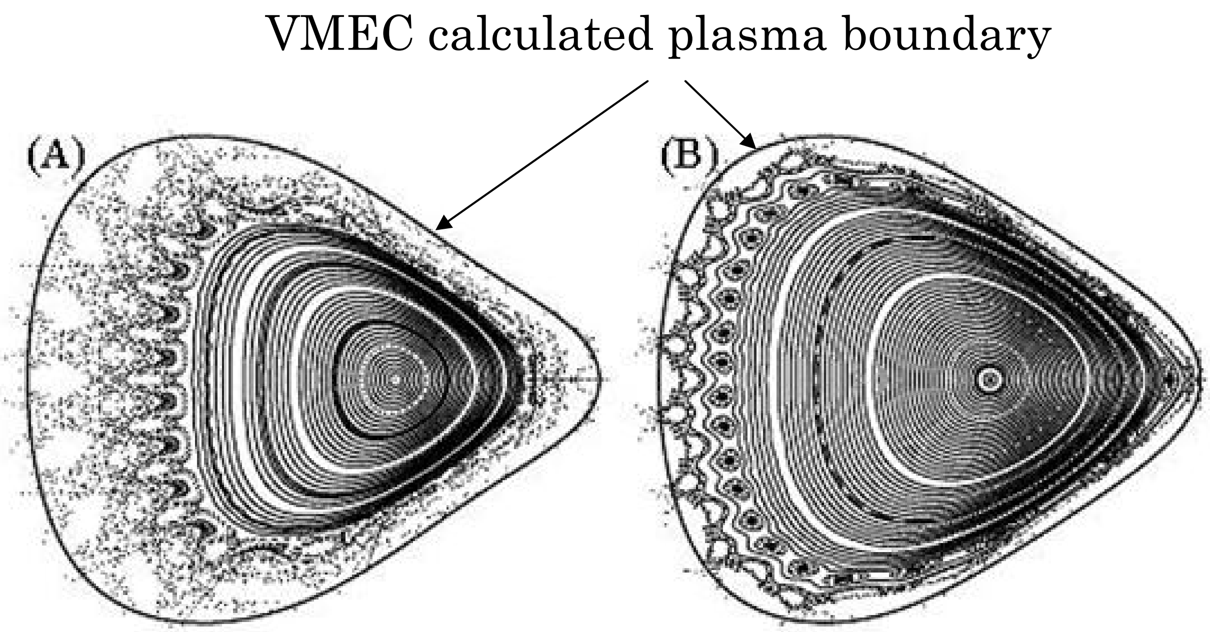
Variation of peak-⟨β⟩ versus the divertor control-coil current I_{CC} normalized by the modular coil current, for B=1.25 T, P_{NB} = 2.8 MW absorbed and ι_{vac}= 0.44.

PIES code run for these parameters.

Island width zero for vacuum field.

Vacuum island width does not provide useful guide for choice of optimal I_{cc}.

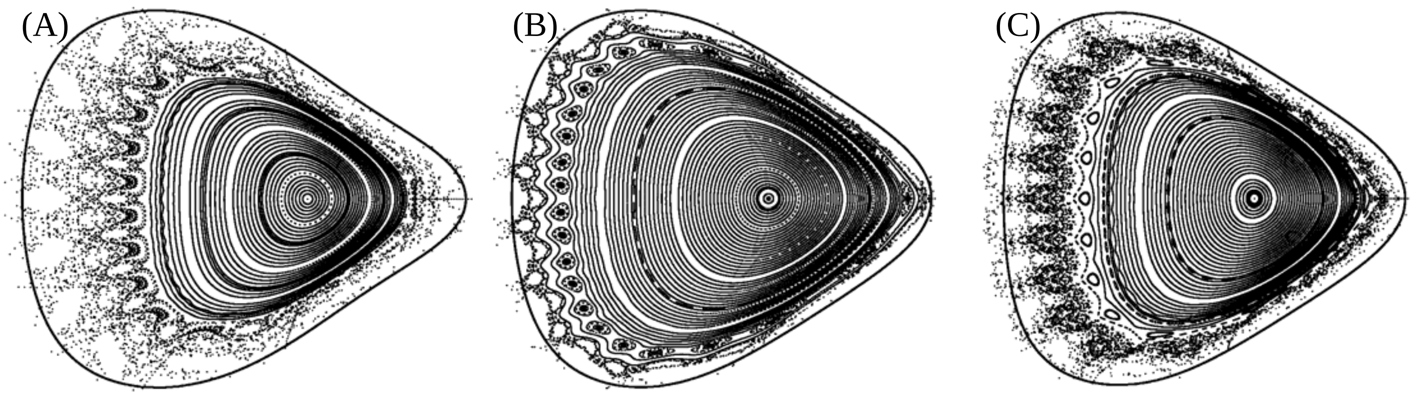
PIES calculations for two different values of control coil current are consistent with observed trend.



$I_{CC} = 0, \langle\beta\rangle = 1.8\%$ $I_{CC} = -2.5kA, \langle\beta\rangle = 2.0\%$

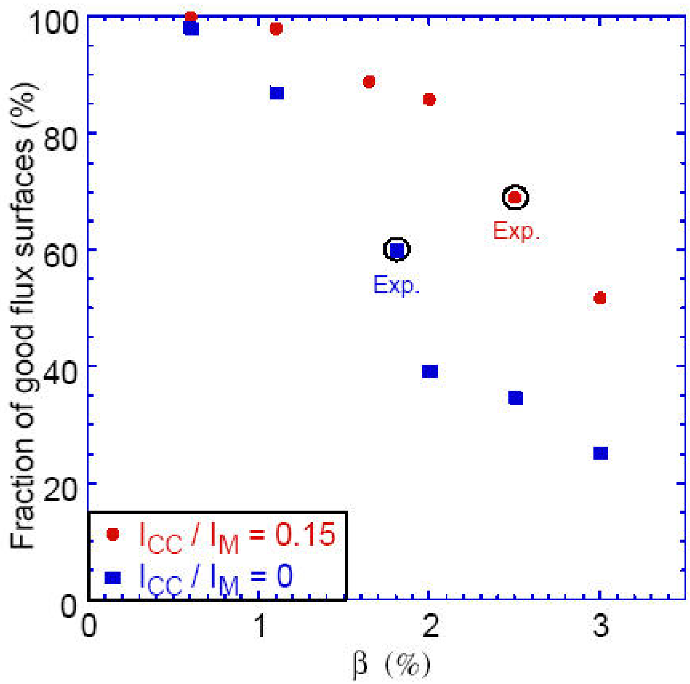
Width of stochastic region larger for $I_{CC} = 0$, even though it has somewhat lower β.

Experimentally achieved β in each case corresponds to loss of about 1/3 of the minor radius.



PIES calculated flux surface topologies at the triangular symmetry plane for: (A) ICC=0 and ⟨β⟩ = 1.8%, (B) ICC=-2.5kA and ⟨β⟩ = 2.0%, (C) ICC=-2.5kA and ⟨β⟩ = 2.7%. In each case, the dark line is the VMEC calculated plasma boundary.

Same trend emerges from PIES β scan for two different values of control coil current.



Fraction of good flux surfaces versus β as predicted by PIES for two different values of the control coil current for the W7AS stellarator. The circles indicate the PIES calculations done for the experimentally achieved value of β.

PIES results sensitive to pressure profile in stochastic region.
Stochastic region collapses inward if pressure flattened there.

PIES Calculations: β Scan for Two Different Values of Control Coil Current

- Using reconstructed W7AS equilibria for two different values of I_{CC}/I_M (0.0 and 0.15), PIES calculations performed for a series of β values. Pressure profile retained in each case, with peak value scaled.
- PIES sees β threshold above which stochastic region appears at plasma edge. Width of stochastic region increases with increasing β.
- For a given β, width of stochastic region larger for $I_{CC}/I_M = 0.0$ than for $I_{CC}/I_M = 0.15$.
- Results are sensitive to pressure profile in stochastic region. If pressure flattened there, stochastic region collapses inward and equilibrium lost.
- Mean free paths short compared to connection length, so finite pressure gradient in stochastic region is reasonable.

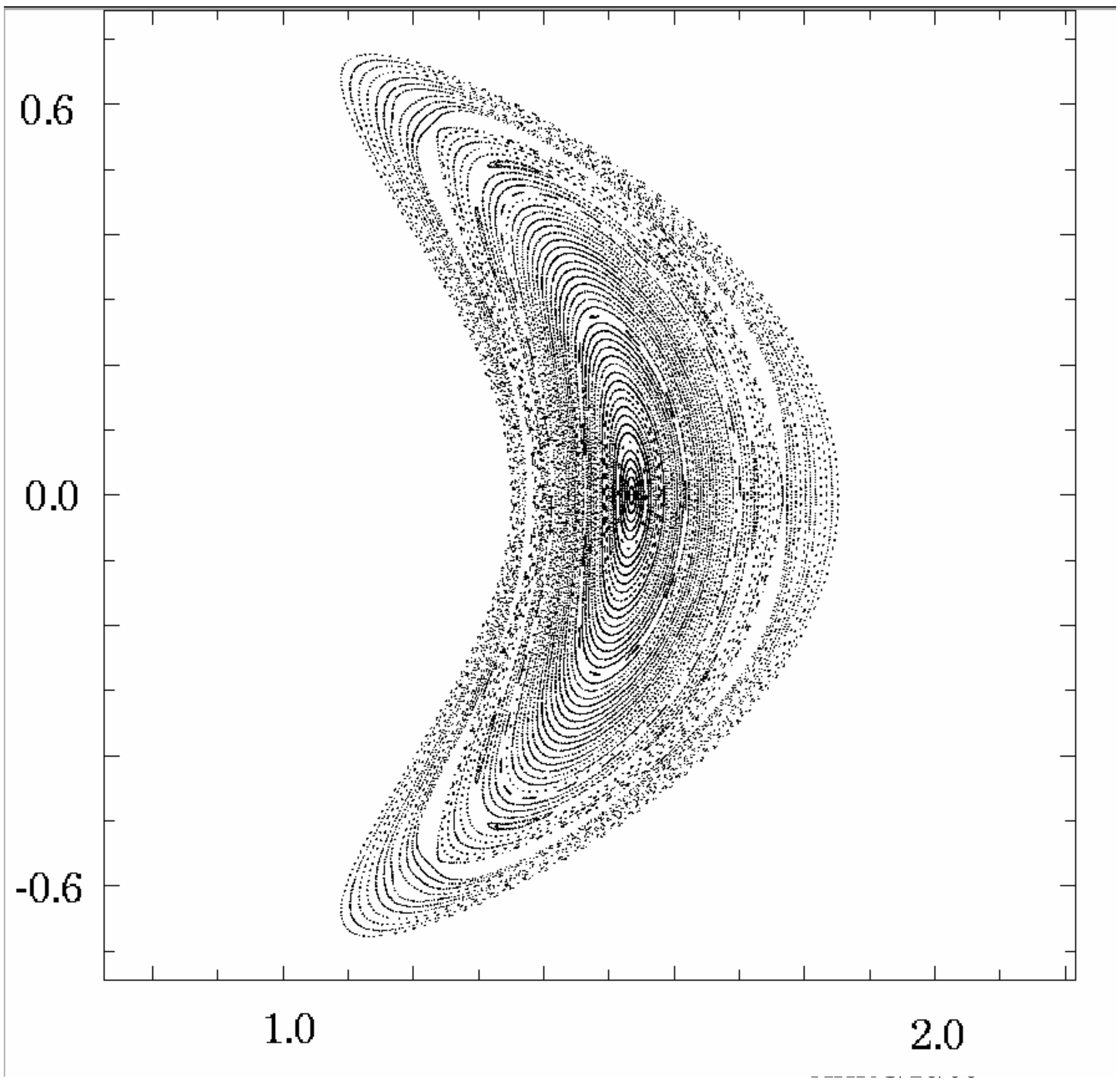
NCSX: PIES code used as guide to design configuration with good flux surfaces.

1. PIES code used to identify fixed boundary configuration with intrinsically good flux surfaces.
2. Optimizer built around PIES code used to design coils which preserve flux surfaces, while also preserving desired physics properties of configuration and engineering properties of coils

These calculations flatten the pressure gradient in the stochastic region.

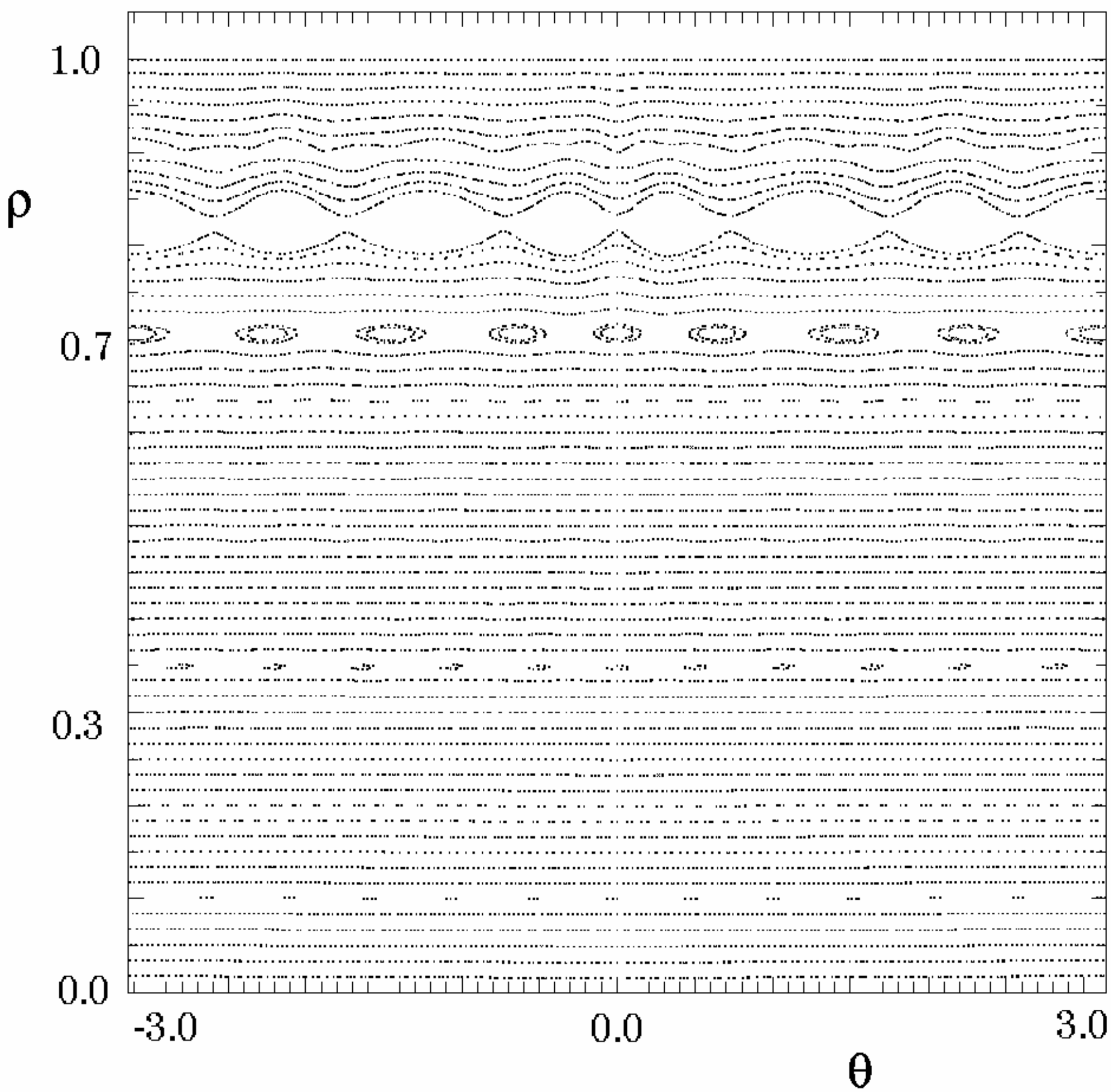
Note: Stabilizing neoclassical effect not included in calculations.

PIES Calculations for NCSX: 1. Identification of Fixed Boundary Equilibria with Intrinsically Good Flux Surfaces



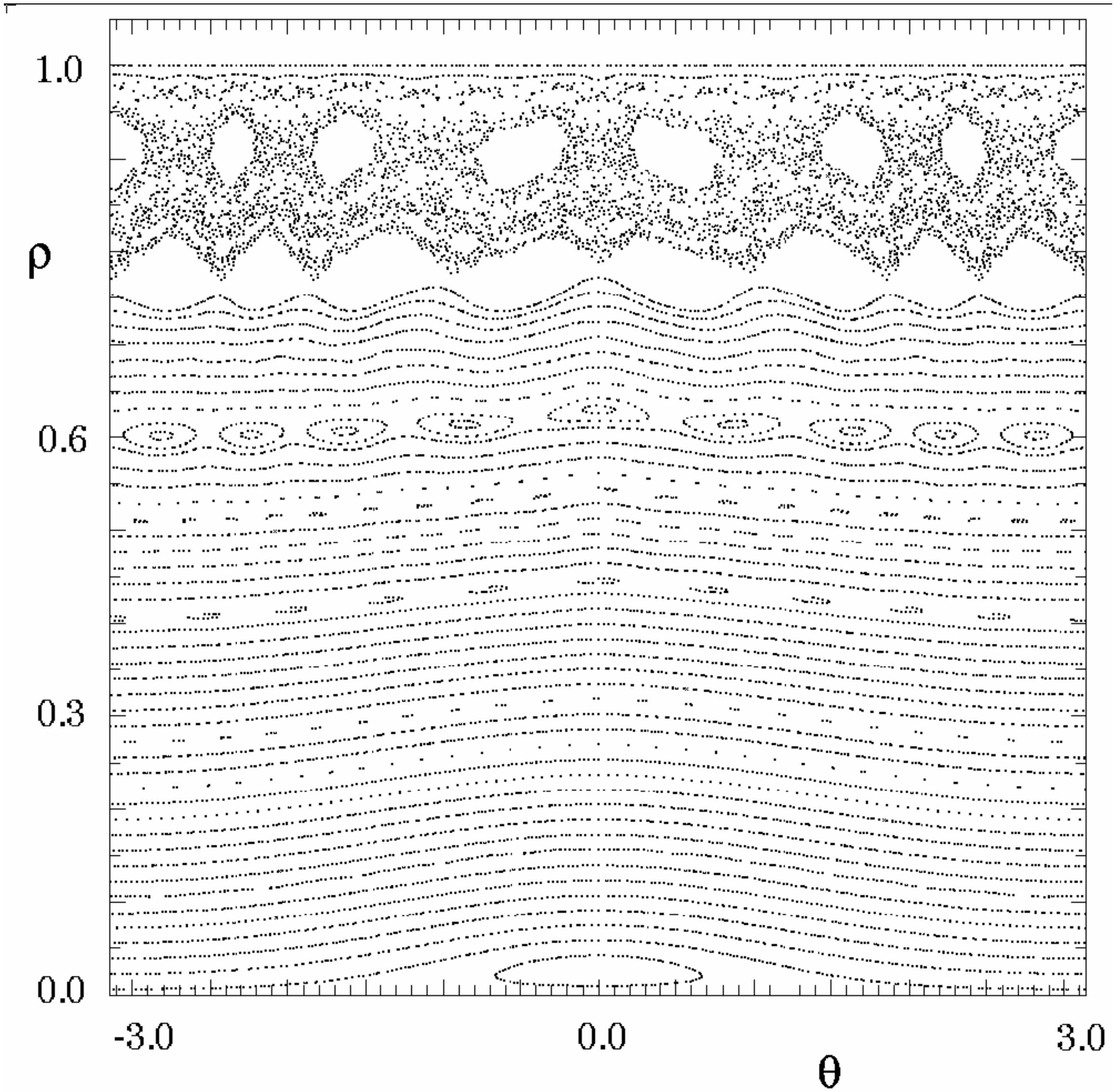
Poincare plot for an early candidate configuration, C82, at full current, $\beta = 0$. The shape of the boundary has been specified ("fixed-boundary" equilibrium).

C82



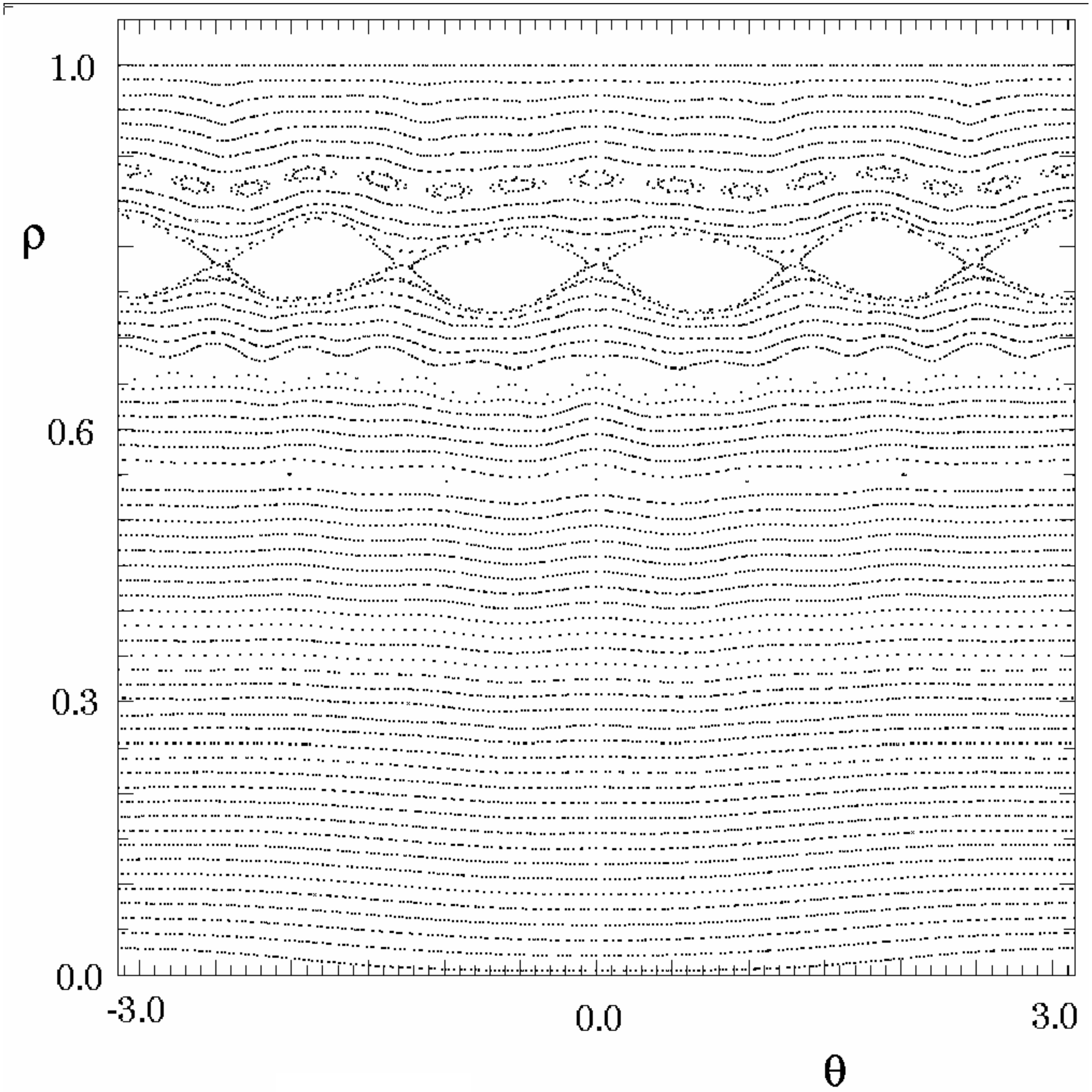
C82

Plotting the same data in a polar (ρ, θ) coordinate system makes the islands more readily visible. Here, the coordinate ρ is taken to be constant on VMEC flux surfaces, and to measure the distance of the VMEC flux surface from the magnetic axis along the θ = 0, ϕ = 0 line. The angular coordinate θ is identical to the VMEC angular coordinate. When plotted in these coordinates, the Poincare plot gives straight lines when the VMEC and PIES solutions coincide.



C82

When β is raised to 3%, the PIES calculations find that a substantial fraction of the flux surfaces are lost. The magnetic field used for this plot does not correspond to a converged equilibrium. With the pressure profile flattened in the stochastic region, the outer surfaces continue to deteriorate as the calculation progresses, so that further computation is of limited interest. (Note that, in addition to flattening the pressure profile in the stochastic region, the calculation

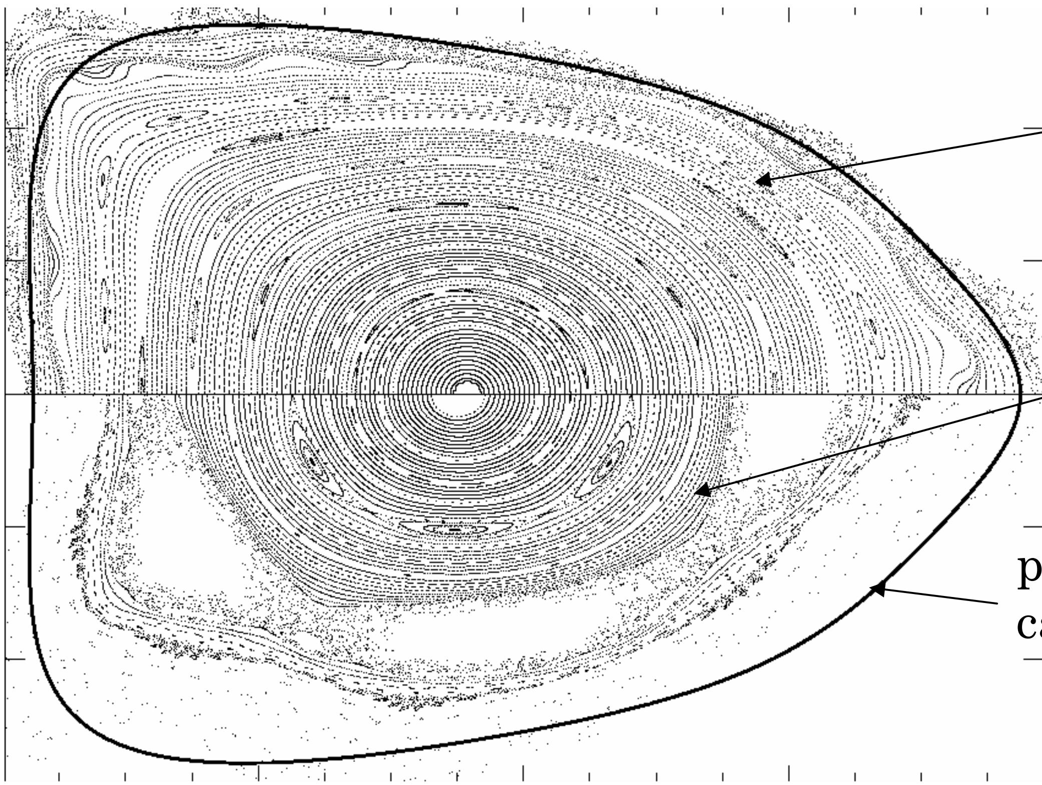


LI383

PIES calculation for configuration LI383, as originally generated by the optimizer, at full current, $\beta = 4.2\%$. The flux surfaces are intrinsically better than those of configuration C82. The width of the island chain at $\rho \approx 0.8$ can be greatly reduced by adjusting the amplitude of the corresponding resonant Fourier mode in the specification of the boundary shape.

PIES Calculations for NCSX: 2. Design of Coils to Preserve Flux Surfaces

An optimizer has been built around the PIES code to modify the coil design to heal islands while preserving desired physics and engineering properties.

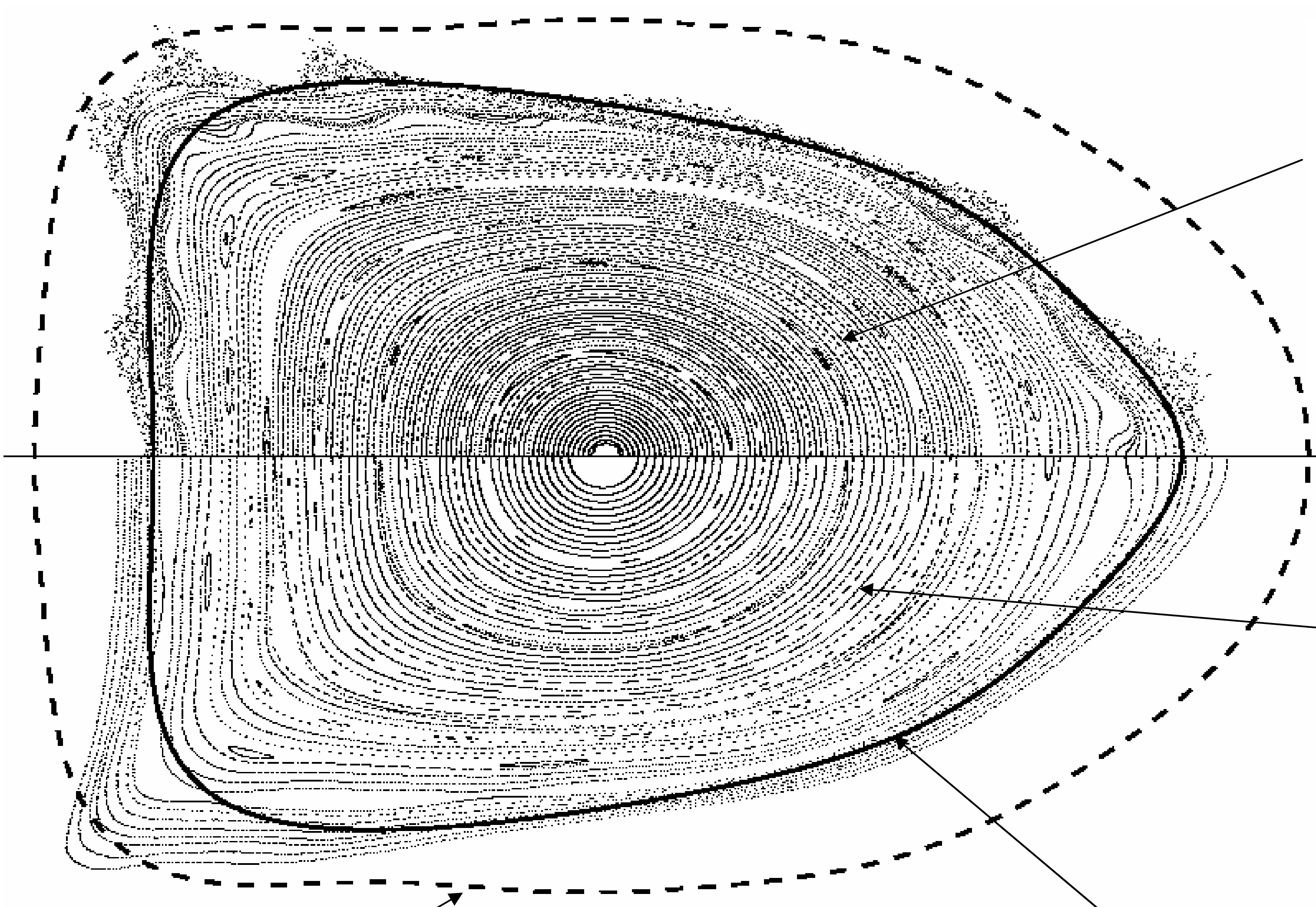


Converged, free-boundary PIES calculation with healed coils.

PIES calculation with original coils. Continues to deteriorate as iteration proceeds.

plasma boundary in VMEC calculation with unhealed coils.

Multi-Filament Model Improves Flux Surfaces



Summary and Conclusions

- Divertor control coil influences achievable β in W7AS stellarator.
- Control coil designed to influence resonant field near plasma edge, with little effect on ι (= 1/ q) or on Shafranov shift.
- Effect of control coil on vacuum field does not provide adequate guide to effect at finite β.
- PIES calculations consistent with experimental observations.
  More detailed comparison being pursued, and improved model of Pfirsch-Schlüter currents being implemented.
- Experiment and calculations consistent with soft β limit on W7AS due to flux surface degradation.
- Rule of thumb that assumes that equilibrium β limit corresponds to magnetic axis shift of approximately ½ minor radius does not adequately characterize observations.
- NCSX designed to have good flux surfaces up to β > 4%.