Plasma Equilibrium Flux Surfaces and Healing

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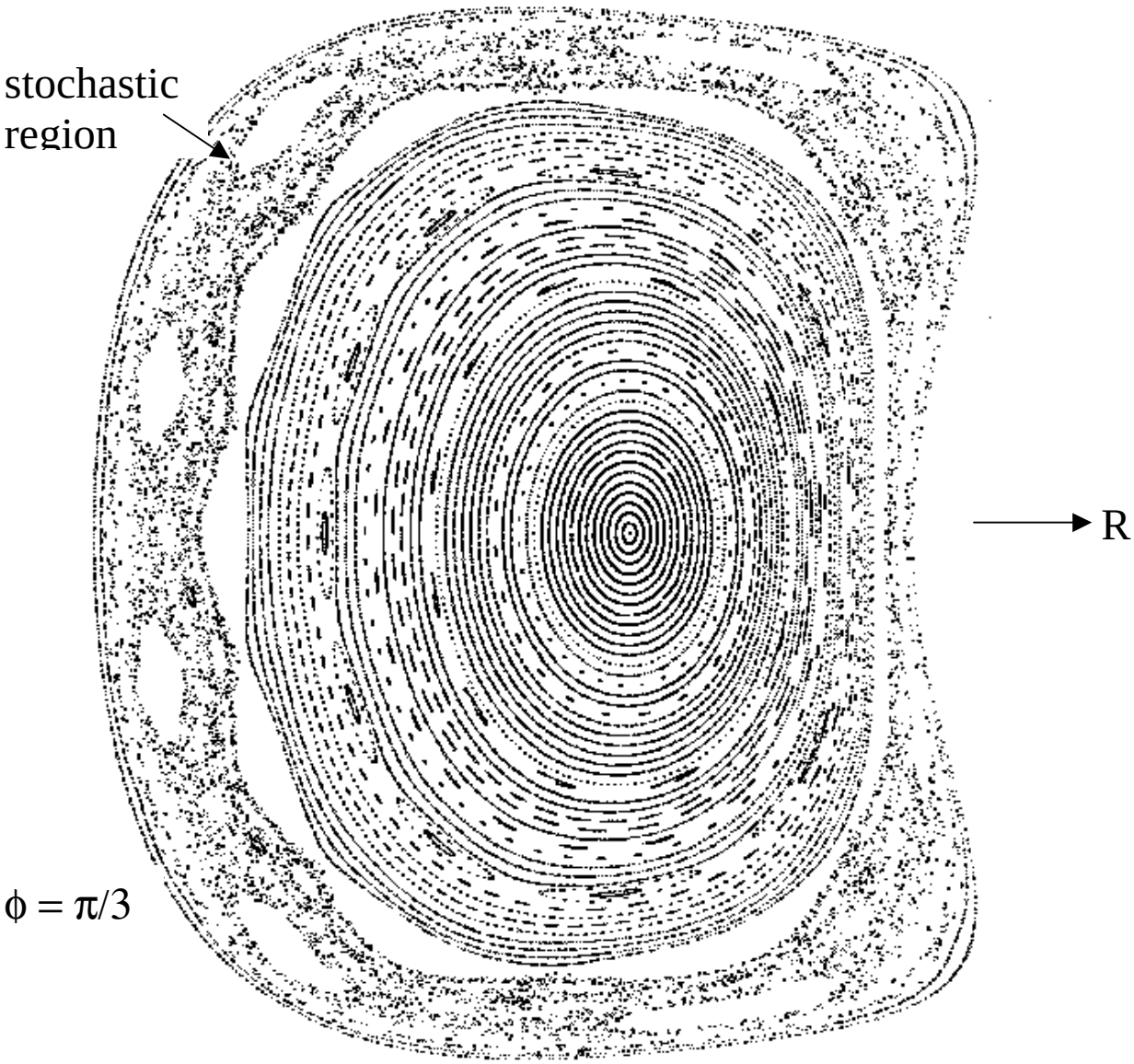
As of PAC-4, had found configurations with improved fixed boundary flux surfaces.

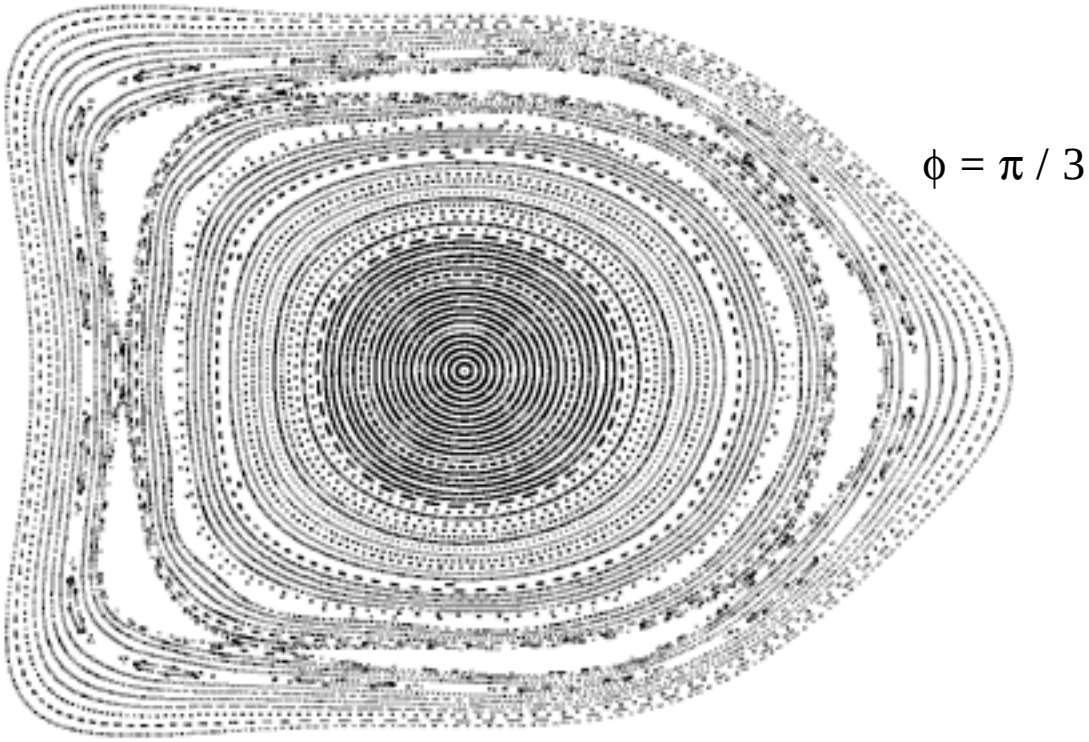
Configuration C82 (earlier reference configuration) has poor flux surfaces.



Fixed boundary PIES calculation. $\beta = 3\%$.
Not converged. Continues to deteriorate with iteration.

Calculations do not include neoclassical effect.

Configuration LI383 Has Intrinsically Better Flux Surfaces



fixed boundary, fully converged PIES calculation

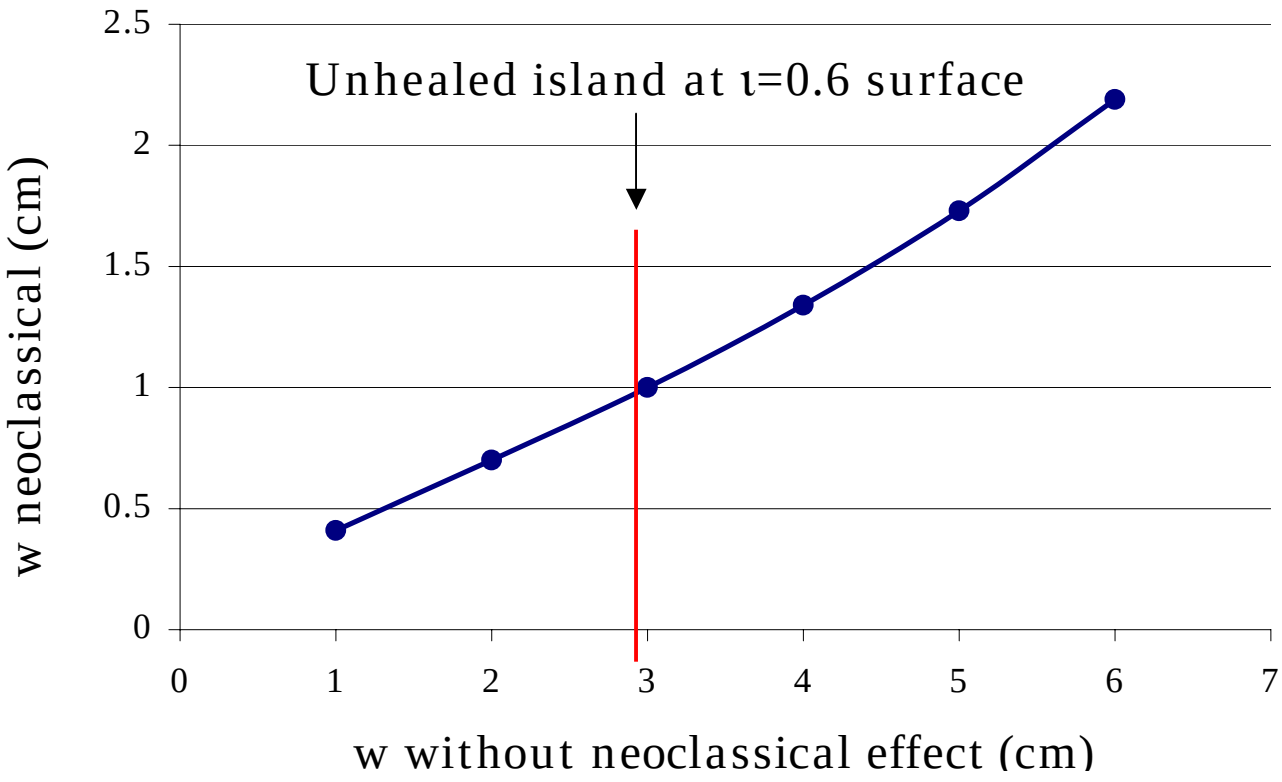
- Output from optimizer has islands across ≈ 15% of minor radius. (Configuration optimizer does not target flux surfaces.)
- Difference due to magnetic well? shear? to be investigated.
- Islands can be removed, with little effect on physics, by adjusting resonant Fourier components of boundary shape.
- In practice, design coils around unhealed LI383, and then modify coils to heal flux surfaces.

Neoclassical Effect on Island Widths

- Perturbed bootstrap current gives neoclassical tearing mode in tokamaks ($\iota' < 0$).
- For $\iota' > 0$, the effect predicted to reduce NCSX island widths. (Hegna & Callen)
- Effect estimated for island at $\iota = 0.6$ surface in LI383. Analytic calculation in cylinder.

  Estimate $\Delta' = -2\ m / r$.

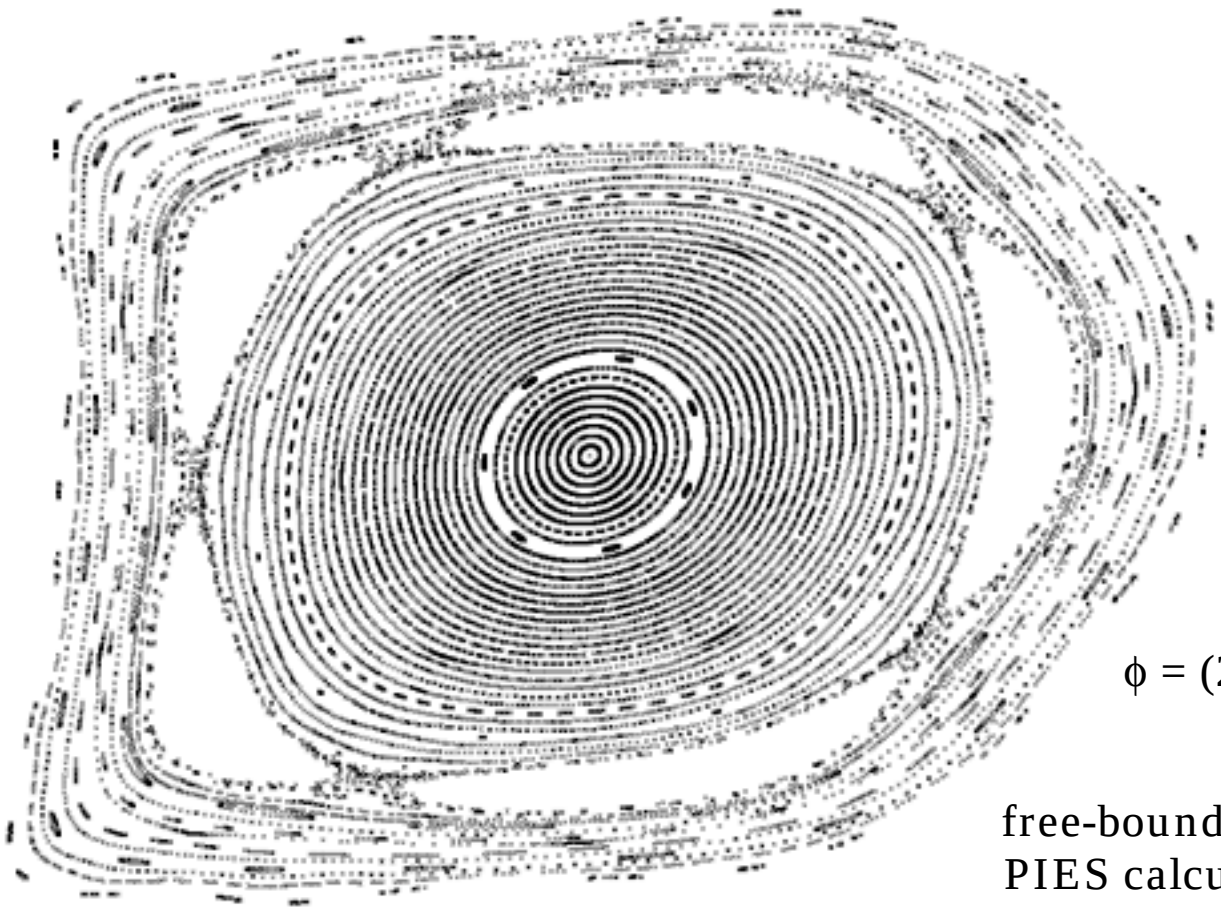
  Take $\beta = 4.2\%$, $B = 1.2$ T, $\langle n_e \rangle = 5.8 \times 10^{19}\ m^{-3}$.



Reduces island width from 9% to 3% of minor radius.

Discrete Coils Further Break Flux Surfaces

- Free-boundary PIES calculation for unhealed version of an early modular coil design (0907 coils).
  Coil design optimizer does not target islands.
- PIES run not converged. Equilibrium continues to deteriorate with iteration.



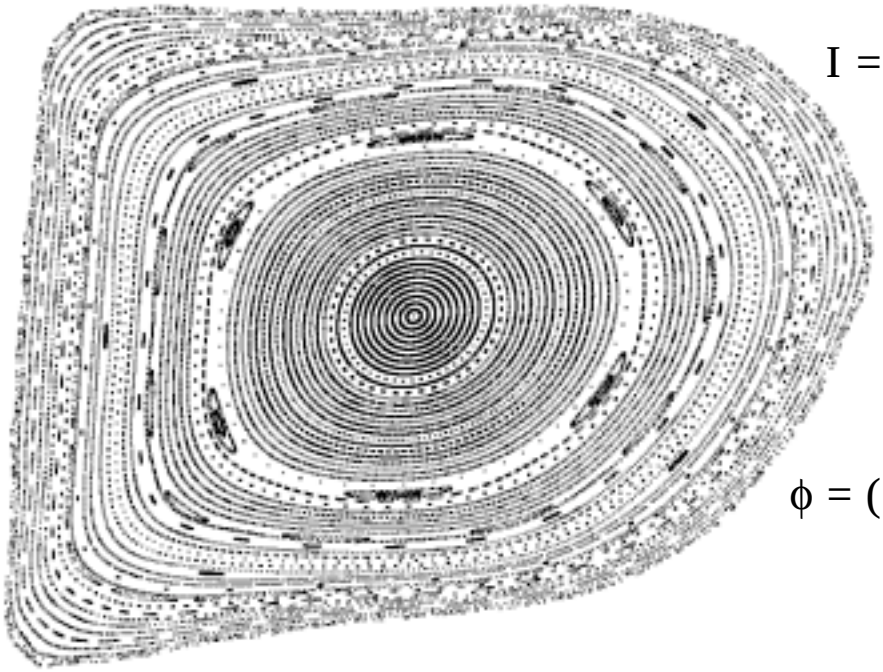
$\phi = (20/19)\ (\pi/3)$

free-boundary
PIES calculation

Healing of Flux Surfaces

(Hudson et al)

- Series of incompletely converged PIES runs (~20 iterations) measure effect of coil perturbations.
- Response matrix determines desired boundary shape. Adjust 21 Fourier coefficients in coil winding law.
- Maximum final coil perturbation ~ 1.7 cm (0907 coils).



$I = 125$ kA, $\beta = 4\%$

$\phi = (20/19)\,(\pi/3)$

free boundary PIES calculation, fully converged

- Method works well for these coils, but not always successful because it relies on incompletely converged PIES calculations.

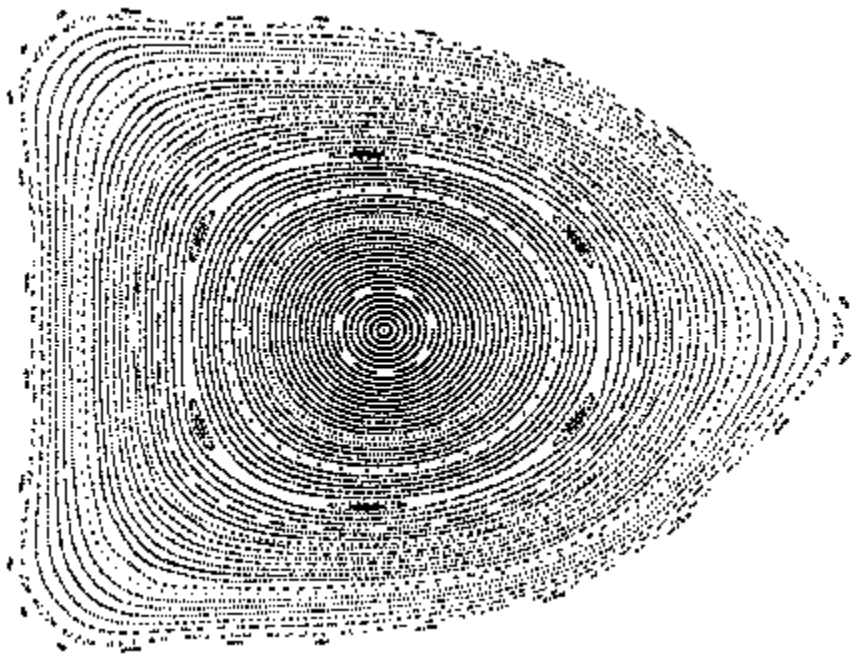
Good flux surfaces maintained for a range of β and I.

Healed 0907 coils

$\beta = 3\%$, $I = 83$ kA (3/4 full β, 2/3 full current)

Currents in coils adjusted to maintain stability and quasi-symmetry

free-boundary,
fully converged
PIES calculation



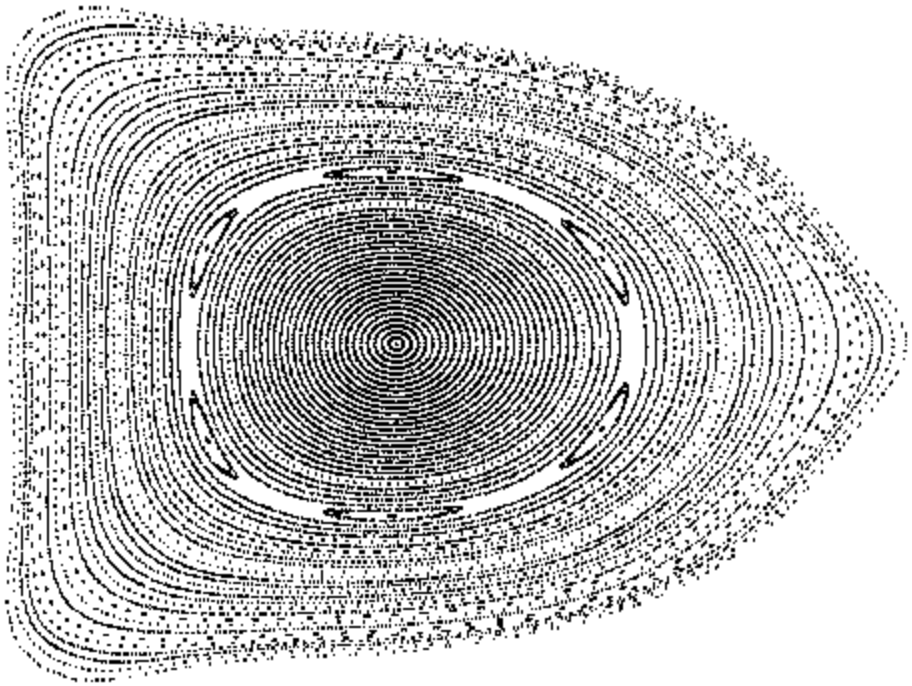
Good flux surfaces maintained for a range of β and I.

Modified 0907 coils

$\beta = 2\%$, $I = 83$ kA (1/2 full β, 2/3 full current)

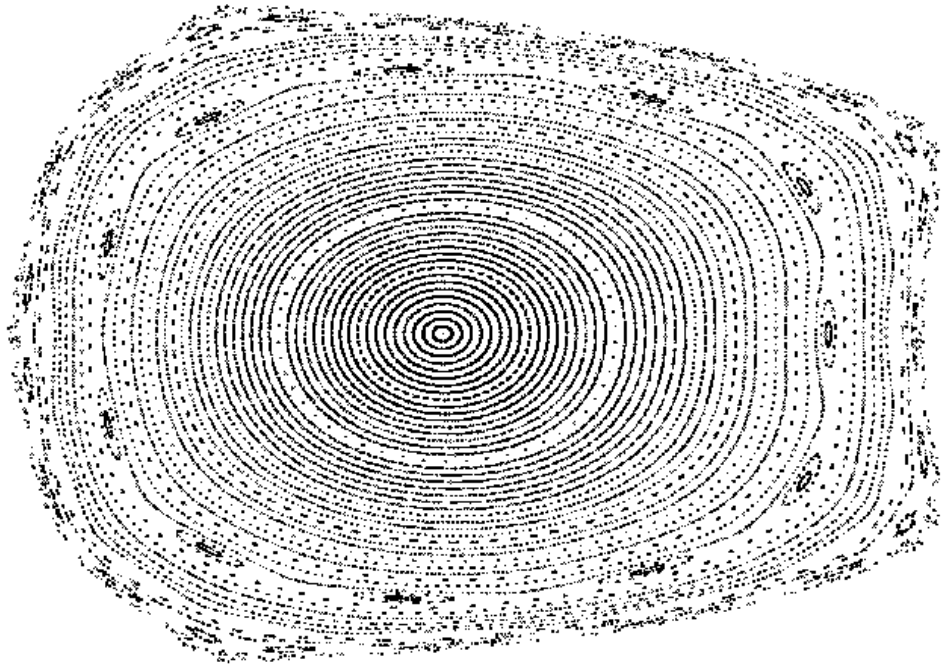
Currents in coils adjusted to maintain stability and quasi-symmetry.

free-boundary,
fully converged
PIES calculation



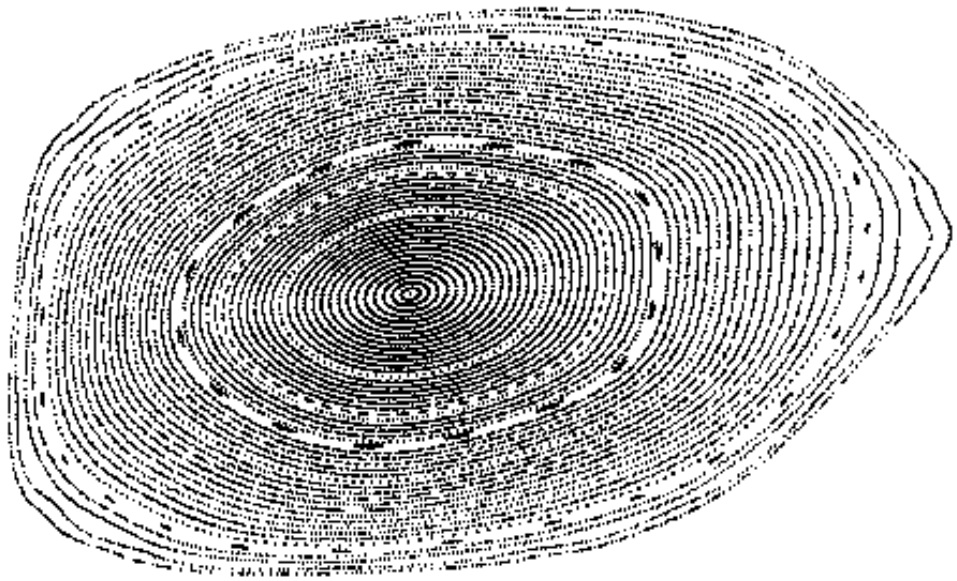
Equilibrium from Discharge Modeling (E. Lazarus)

60 ms into shot: I= 43 kA (about 40% of maximum), $\beta = 0.3\%$



Vacuum Flux Surfaces

Minor radius is 83% that of LI383.



A new "dynamical healing" algorithm adjusts the coils in each PIES iteration to suppress islands.

Coils lie on a winding surface given by

$$R = \sum_{m,n} r_{mn} \cos(m\theta + nN\varphi),$$

$$Z = \sum_{m,n} z_{mn} \sin(m\theta + nN\varphi).$$

Each coil has toroidal variation given by

$$\varphi_i = \varphi_{i0} + \sum_k \left[\varphi_{i,k,c} \cos(k\theta') + \varphi_{i,k,s} \sin(k\theta')\right],$$

$$\theta' = \theta + \sum_j \theta'_j \sin(j\theta).$$

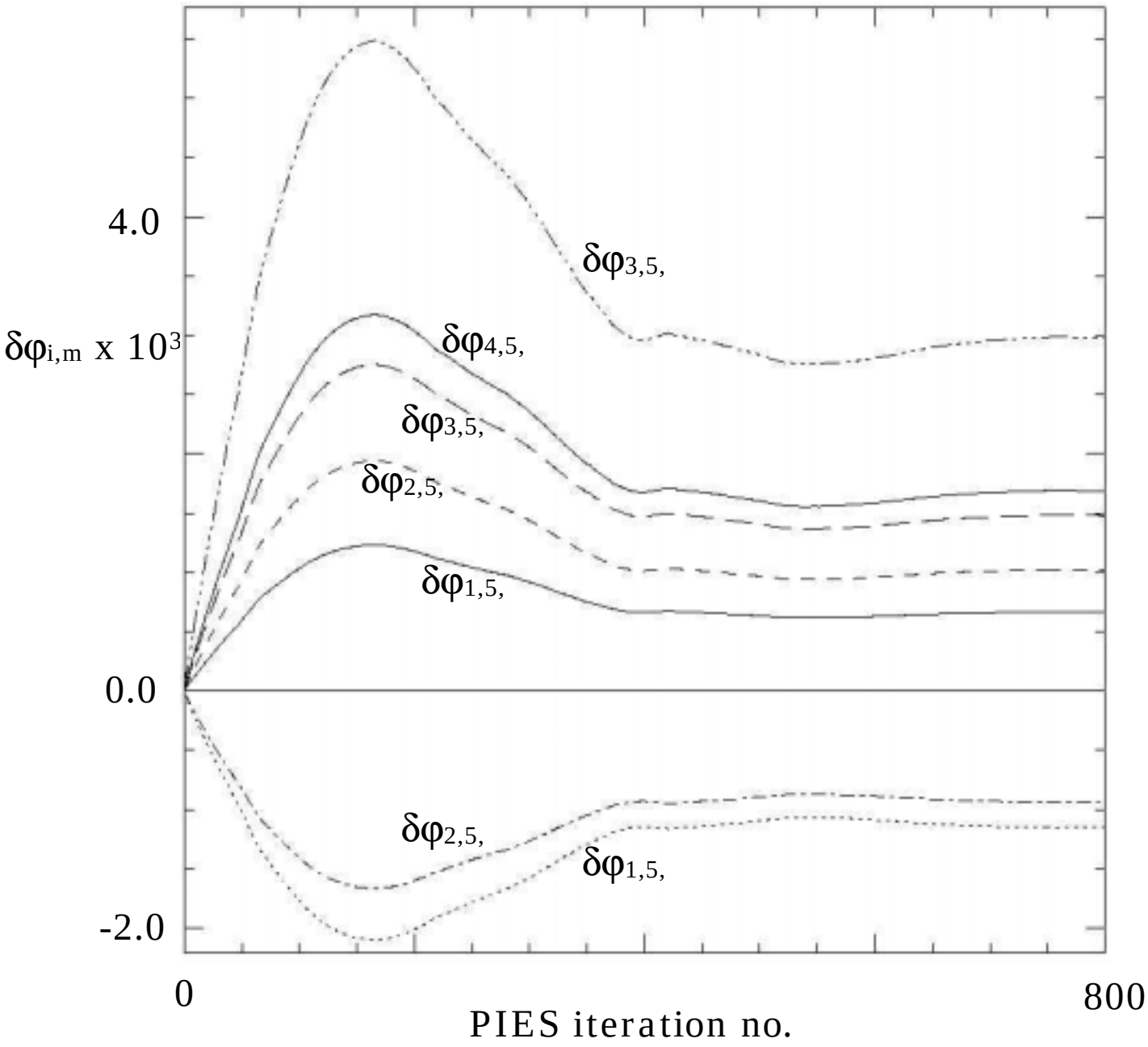
- Changes in resonant harmonics of field at rational surfaces related to changes in $\varphi_{i,k,c}, \varphi_{i,k,s}$ via coupling matrix $\mathbf{C}$:

$$\mathbf{B}(\mathbf{r}_0 + \delta\mathbf{r}) = \mathbf{B}(\mathbf{r}_0) + \mathbf{C} \cdot \delta\mathbf{r} + \ldots \qquad .$$

- Newton procedure + SVD adjusts $\varphi_{i,k}$ at each iteration to suppress targeted islands.

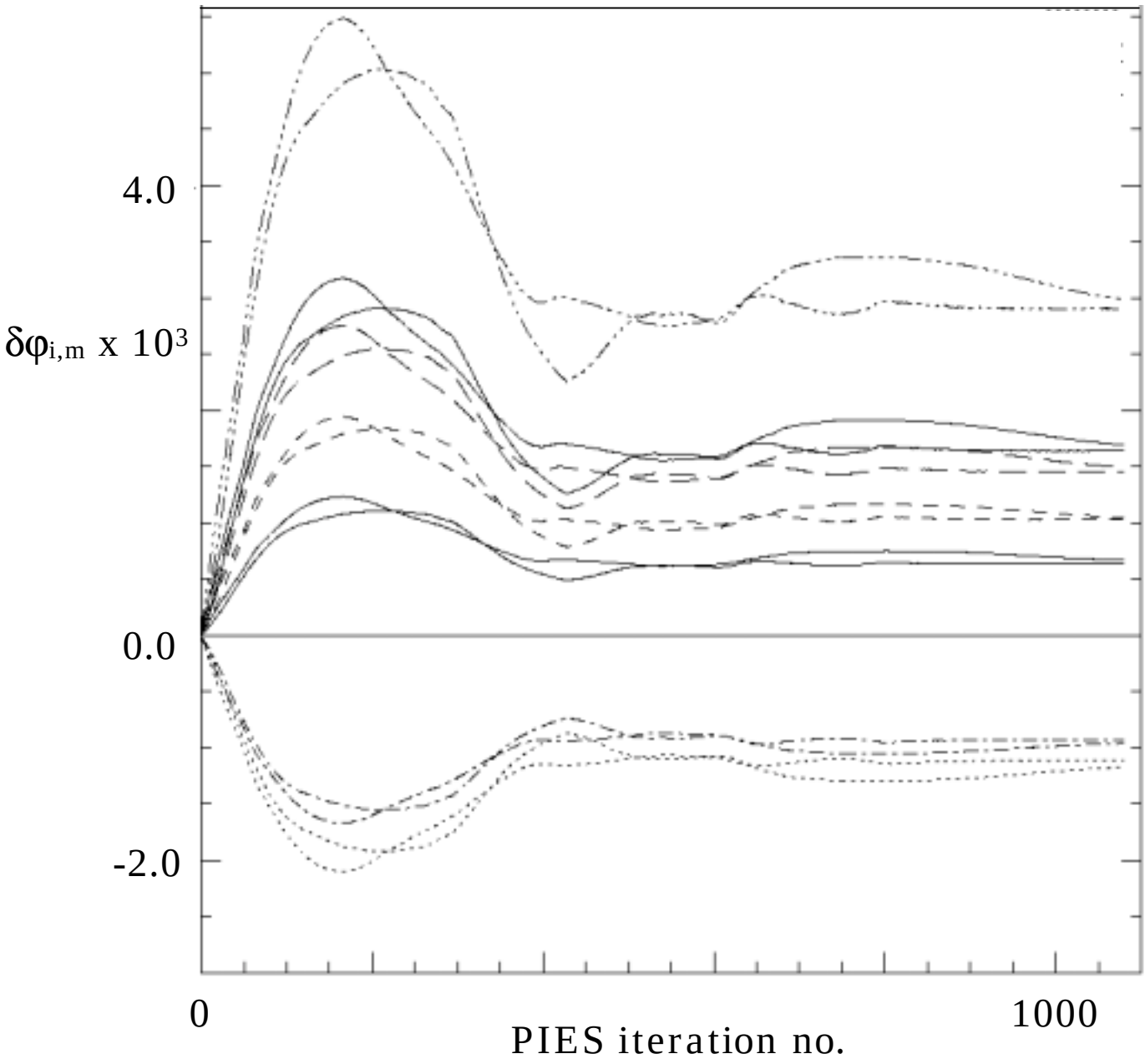
Dynamical Healing Does Converge

Integrated change in coil parameters vs. PIES iteration no.
M12 coils (best 21 coil design).
Only n=3, m=5 island targeted.



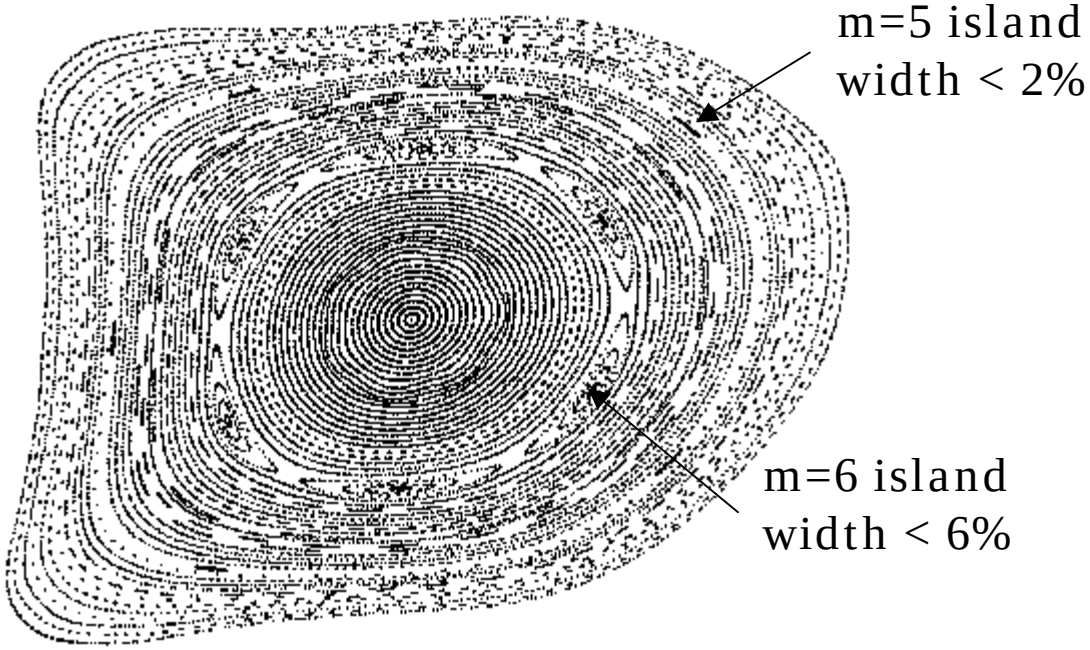
When coils stop changing, have converged PIES equilibrium with m=5 island suppressed.

A 2nd healing calculation for the M12 coils, initialized with a different magnetic field, arrives at essentially the same set of coil modifications.



SVD used in these calculations to choose coil modifications that optimally target n=3, m=5 island width.

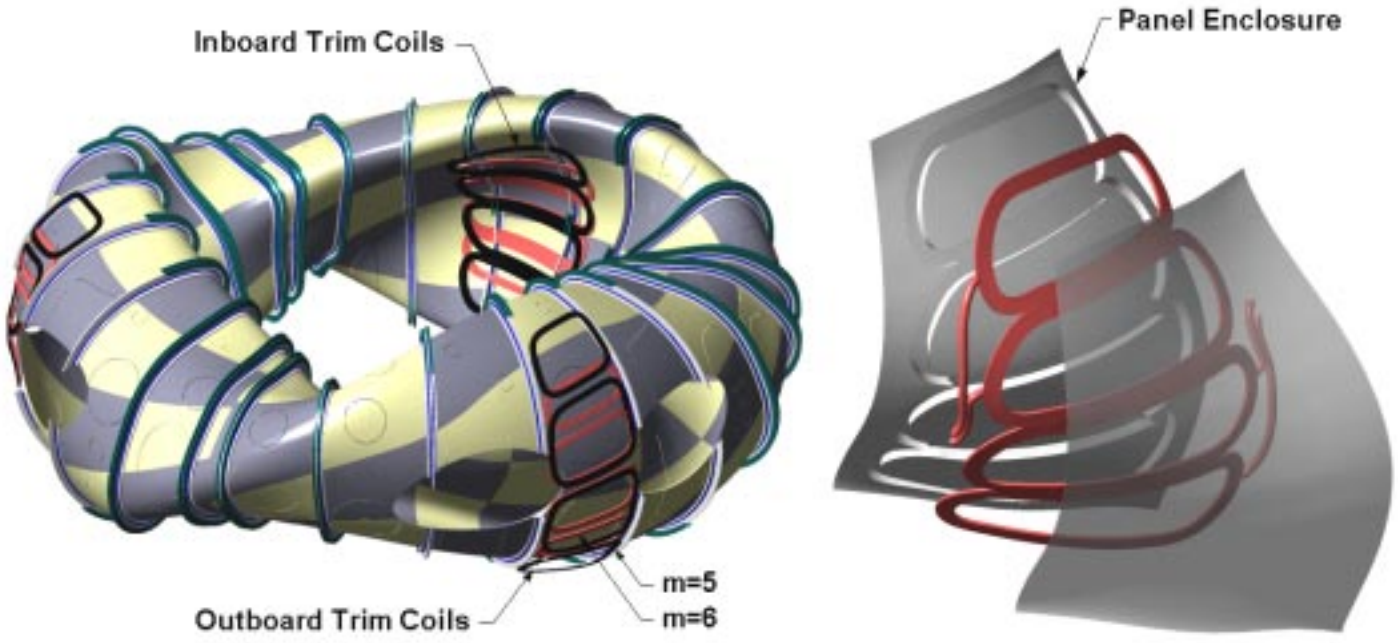
After Dynamical Healing, the m=5 Island is Suppressed



- Only small changes in island widths when coils frozen and PIES run continued.
- PIES calculation with healed coils does not converge to this equilibrium if reinitialized with field that is sufficiently different. e.g. VMEC solution for unhealed coils.
- Further improvement in equilibrium flux surfaces possible by targeting also m=6 island.

Trim coils

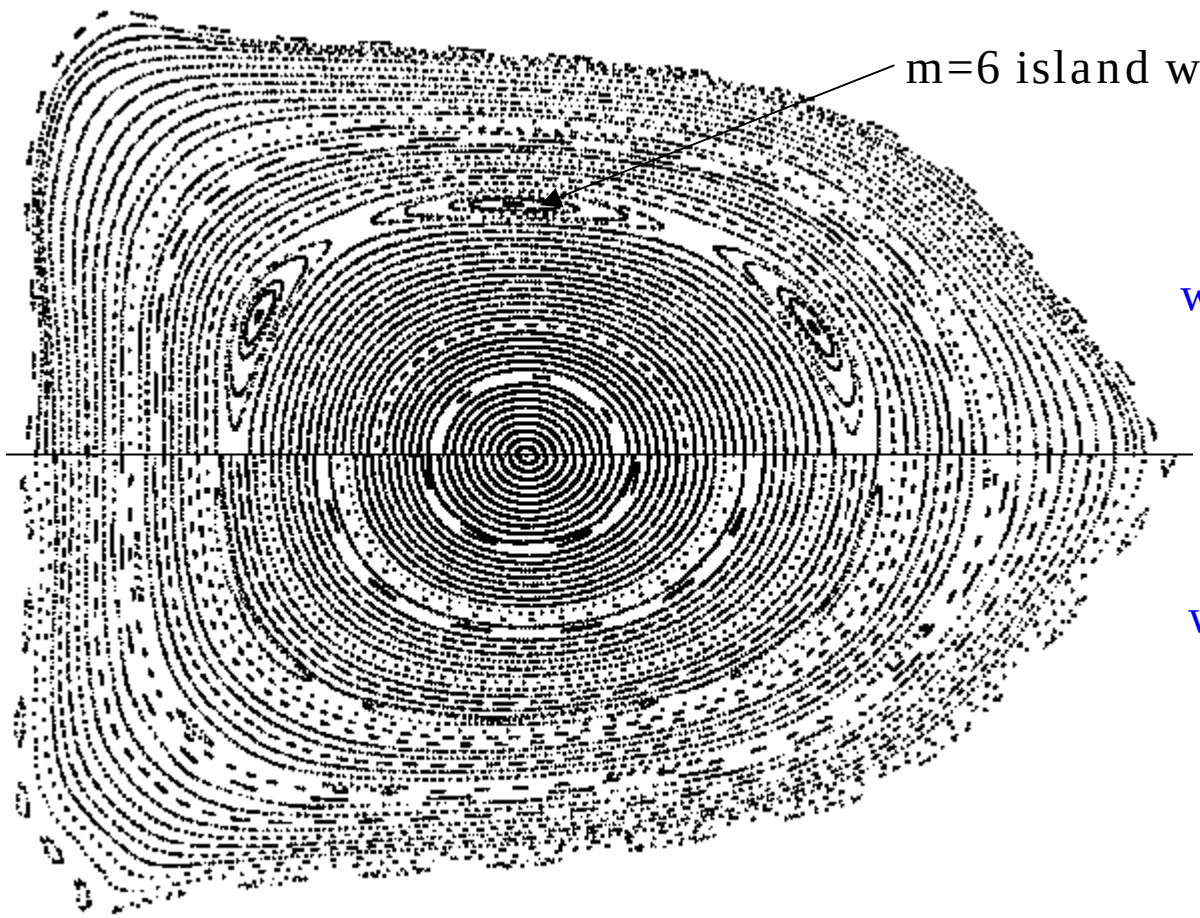
- Provided to mitigate field errors on m=5 and m=6 resonant surfaces
- Located close to inboard and outboard midplane at v=0 cross-section
- Mounted off vacuum vessel, behind liner
- Canned for vacuum compatibility



The Trim Coils Can Suppress Islands

β = 3%, I = 83 kA

Island suppressed by 0.6 kA current in m=6 trim coil.



without trim coils

with trim coils

Plans

- Heal new coils.

  New coil representation incorporated in healing code.
- Study sensitivity of flux surfaces to perturbations.

  Calibrate quasi-analytic model for field error effects.
- Flux surfaces for a range of current and pressure profiles.

  Startup scenario.
- Finite build coils.

Summary

- Two approaches to healing coils developed:
  - Earlier “static” approach used incompletely converged PIES runs to measure response to coil perturbation;
  - Recent “dynamic approach” modifies coils to maintain good flux surfaces at each iteration of the code.
- Dynamic approach converges even in cases where static approach fails.
- Dynamic healing of M12 (best 21 coil set) found to yield same coils for different initializations of magnetic field.
- Calculations with healed 0907 coil set (early modulars) found good flux surfaces maintained for a range of β and I.
- Healing calculations proceeding for recently developed coils.