Aries-CS
Physics Issues & Optimization Code

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PPPL

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Outline

- Overview: stellarator design & opportunities
- Issues, assumptions, and design goals
- Tools
- Experience
- Summary & Next steps

Stellarator Advances

- Understanding of how to design for orbit confinement, good flux surfaces
- Numerical design to obtain desired physics properties
- Experience in accurately constructing experiments at a range of scales (CE -> PE), with good confinement and stability

Allows effective use of Stellarator Advantages:

- Steady-state compatible, lack of need for external current drive
- Disruptions typically not observed, can be avoided by design.
- 3D Shaping, to obtain desired physics properties:
  high-beta stability, good confinement

Two strategies for Orbit Confinement in 3D

3D shape of standard stellarators $\Rightarrow$

field lines and particle orbits can have resonant perturbations,

become stochastic $\Rightarrow$ lost

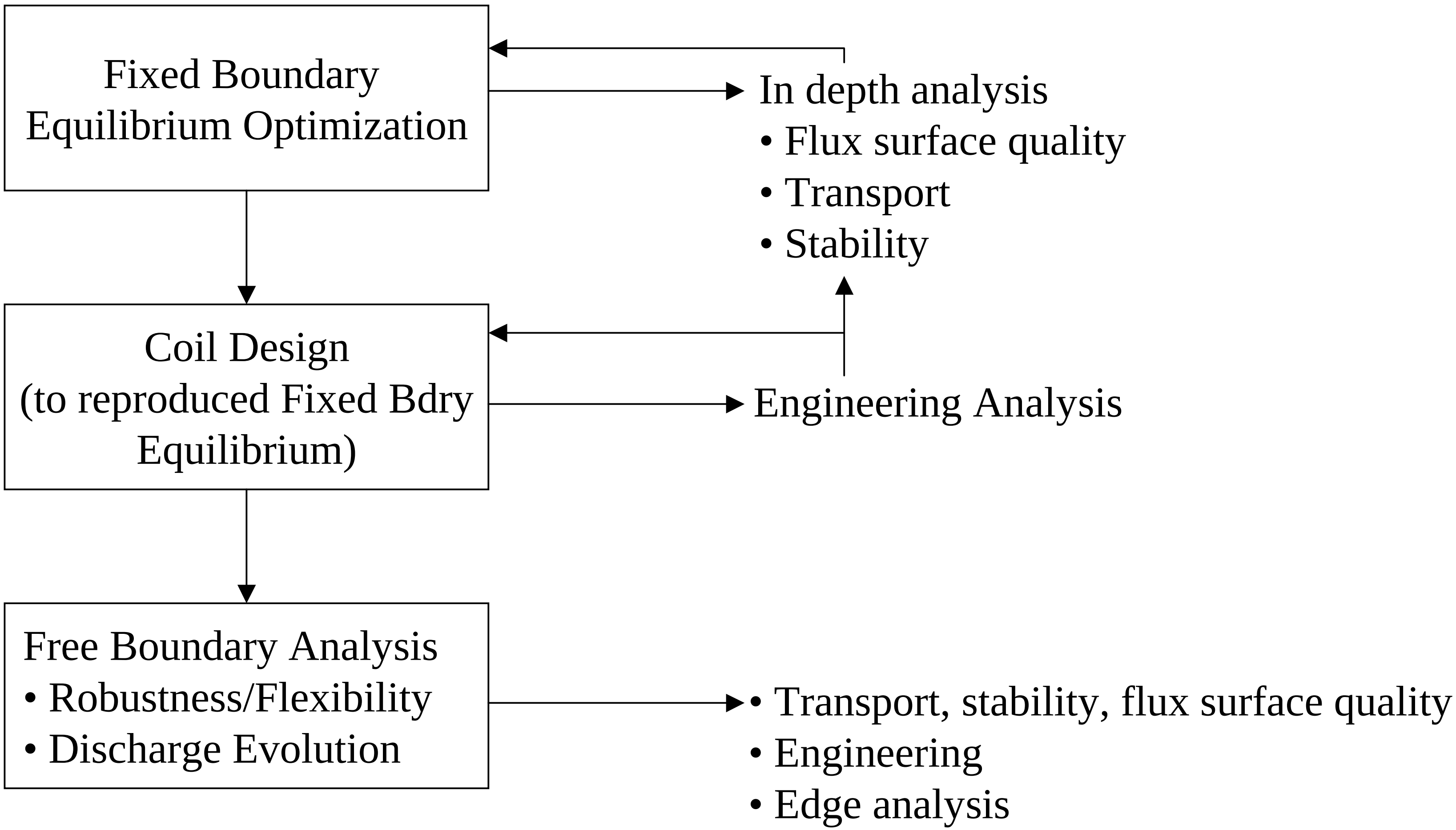
B is bumpy every direction $\Rightarrow$ rotation is strongly damped

- 'quasi-symmetry'
  - Boozer (1983) Drift orbits & neoclassical transport depends on variation of |B| within flux surface, not the vector components of B !
  - If |B| is symmetric in "Boozer" coordinates, get confined orbits like tokamak

  $\Rightarrow$ neoclassical transport very similar to tokamaks, undamped rotation

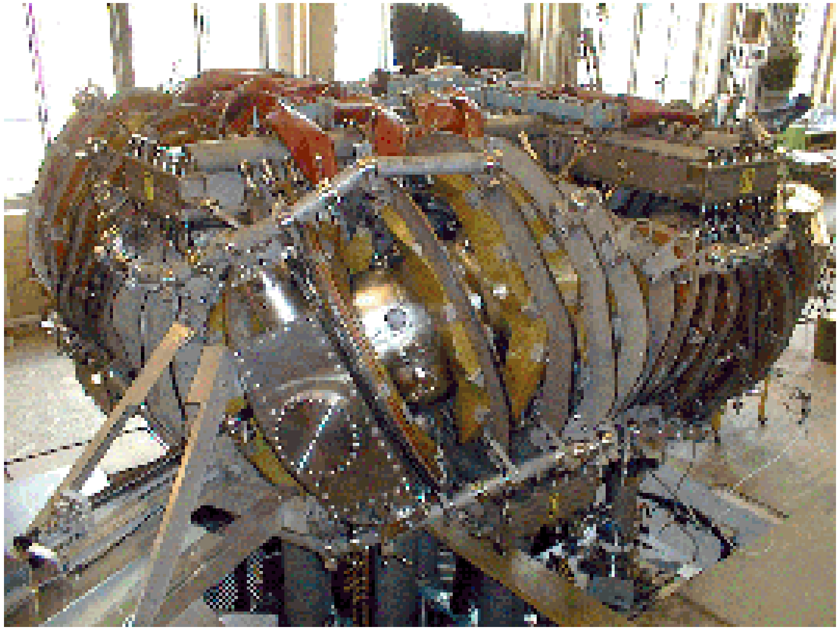
- Quasi-poloidal, Non-symmetric drift-orbit omnigeneity, linked mirrors…
  - Toroidal and helical drifts cancel; align drift orbit with flux surface
  - If could be done perfectly, would result in |B| independent of poloidal angle
  - Principle of W-7X, new German superconducting experiment (A=11)
  - Principle of QPS design

Optimized Stellarator Design Process



- Process as first developed for W7-X, used on HSX
  - – has been extended to address finite β, current, and low A for NCSX & QPS

Helically Symmetric Experiment (HSX): Neoclassical Transport Reduction via Quasi-Helical Symmetry



R=1.2 m, B=1 T, 4 periods,
R/⟨a⟩ = 8

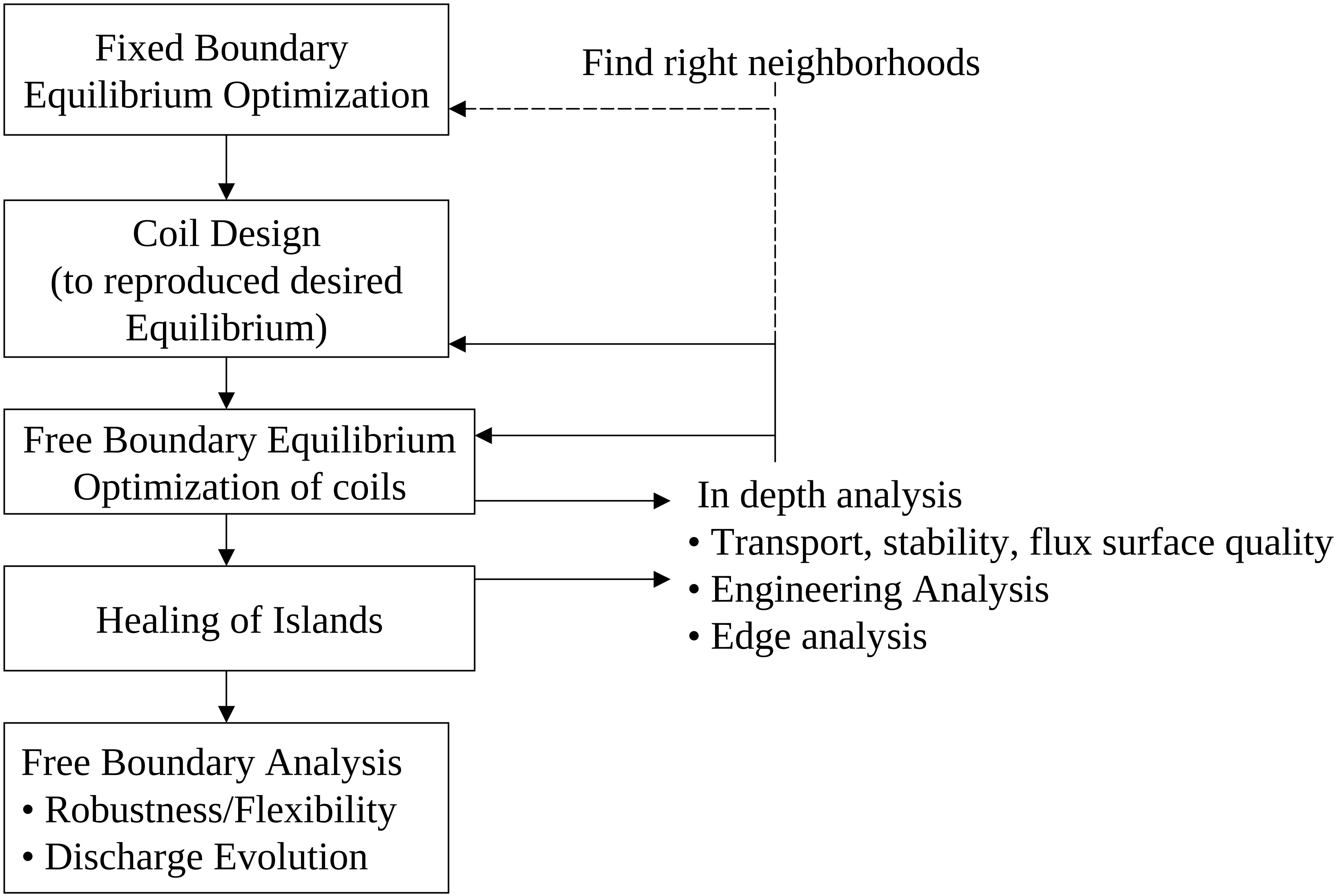
Univ. of Wisconsin

In Boozer coordinates, magnetic field looks like straight helix

First test of quasi-symmetry

started operation in 2000

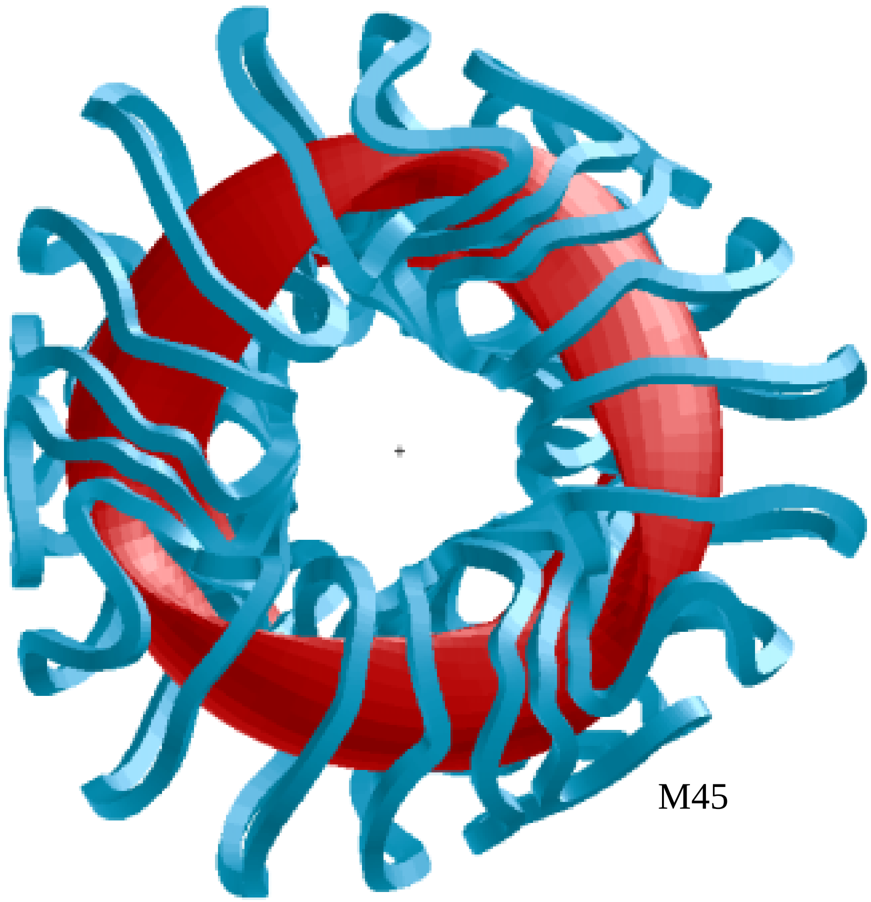
New Design Process (NCSX, QPS)



- Only possible due to availability of parallel high-speed computers

NCSX Plasma Configuration Has Attractive Physics

- 3 periods, R/⟨a⟩=4.4, ⟨κ⟩~1.8
- Quasi-axisymmetric: low helical ripple transport, low flow damping
- Passively stable at β=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes; without conducting walls or feedback systems.
- Steady state without current-drive
- 18 modular-coils (3 shapes)
  Full coil set includes PF coils & weak T
- Coils meet engineering criteria



Using Advances in Theory and Numerical modeling; parallel computing (NERSC, ACL/LANL, Princeton/PPPL)

Choices, Choices

Stellarators provide very large configuration space

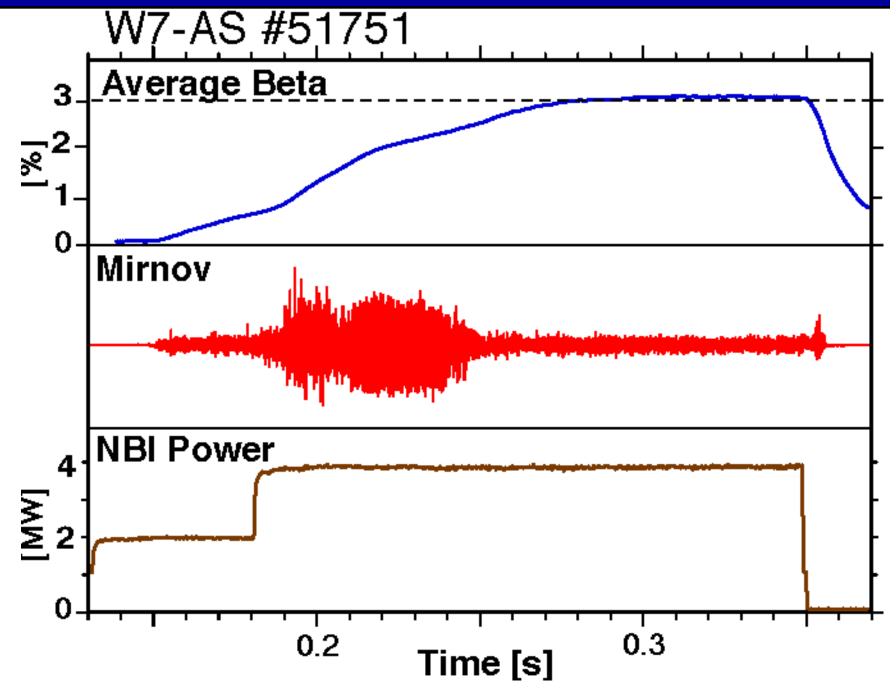
Need to identify

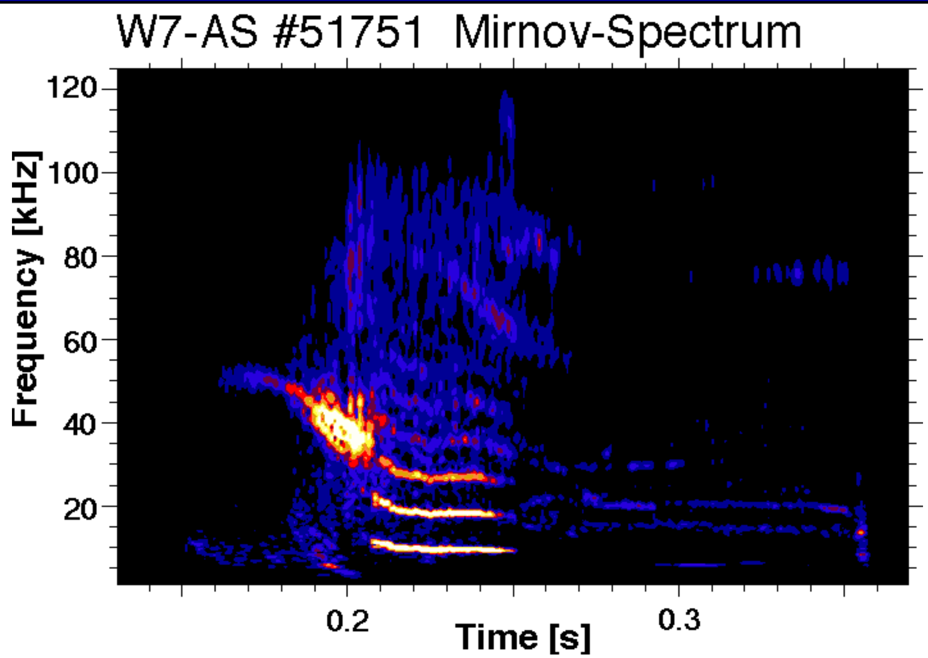
- Standard characteristics: size, B, A, adequate confinement, stability,
  coil-plasma separation for blankets & shield
- Number of field periods
- Orbit optimization strategy
- Rotational transform from coils
- Adequate alpha-particle confinement
  - What loss level is tolerable? Useful?
- Number & topology of coils, limit on bend radii &c.

Stellarators are different, offer different possible choices

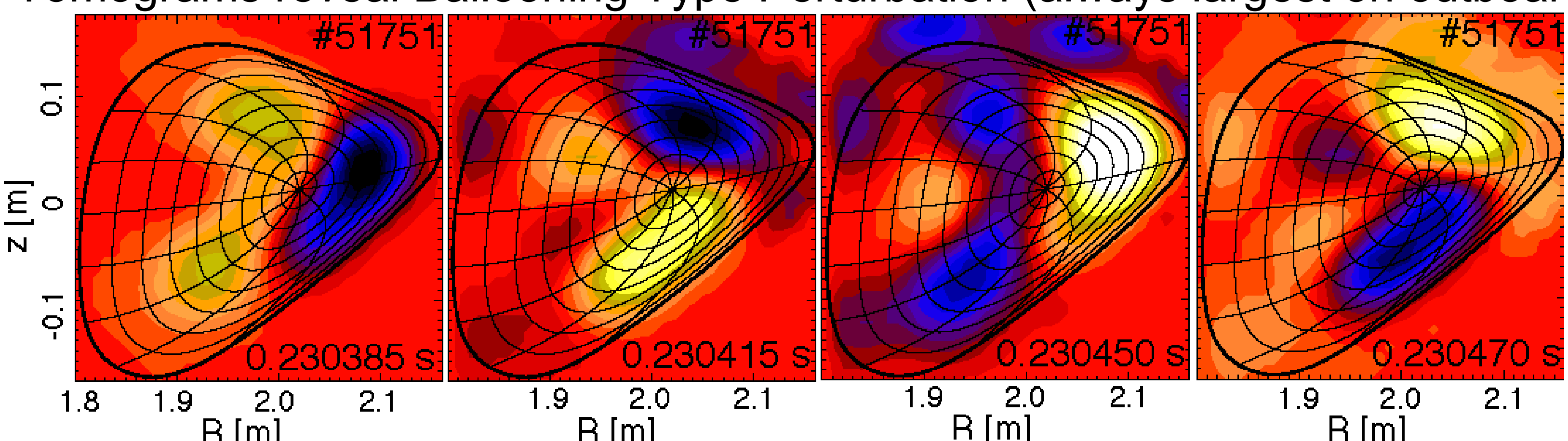
e.g. is MHD marginal stability necessary?

Global Modes appear at intermediate β-Values
Pressure driven (m,n) = (2,1) Modes around iota = 1/2

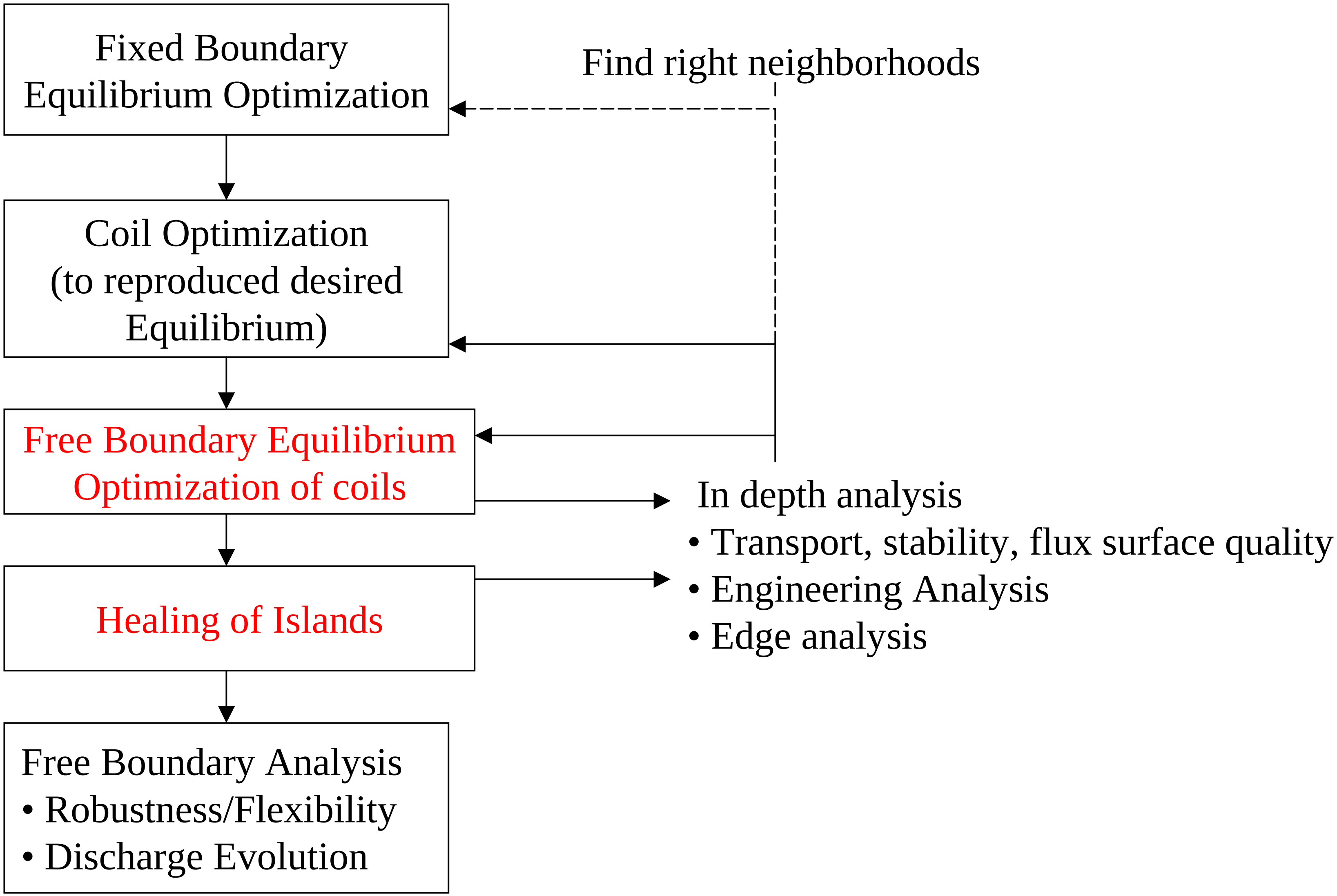




X-Ray Tomograms reveal Ballooning Type Perturbation (always largest on outboard side)



New Design Process



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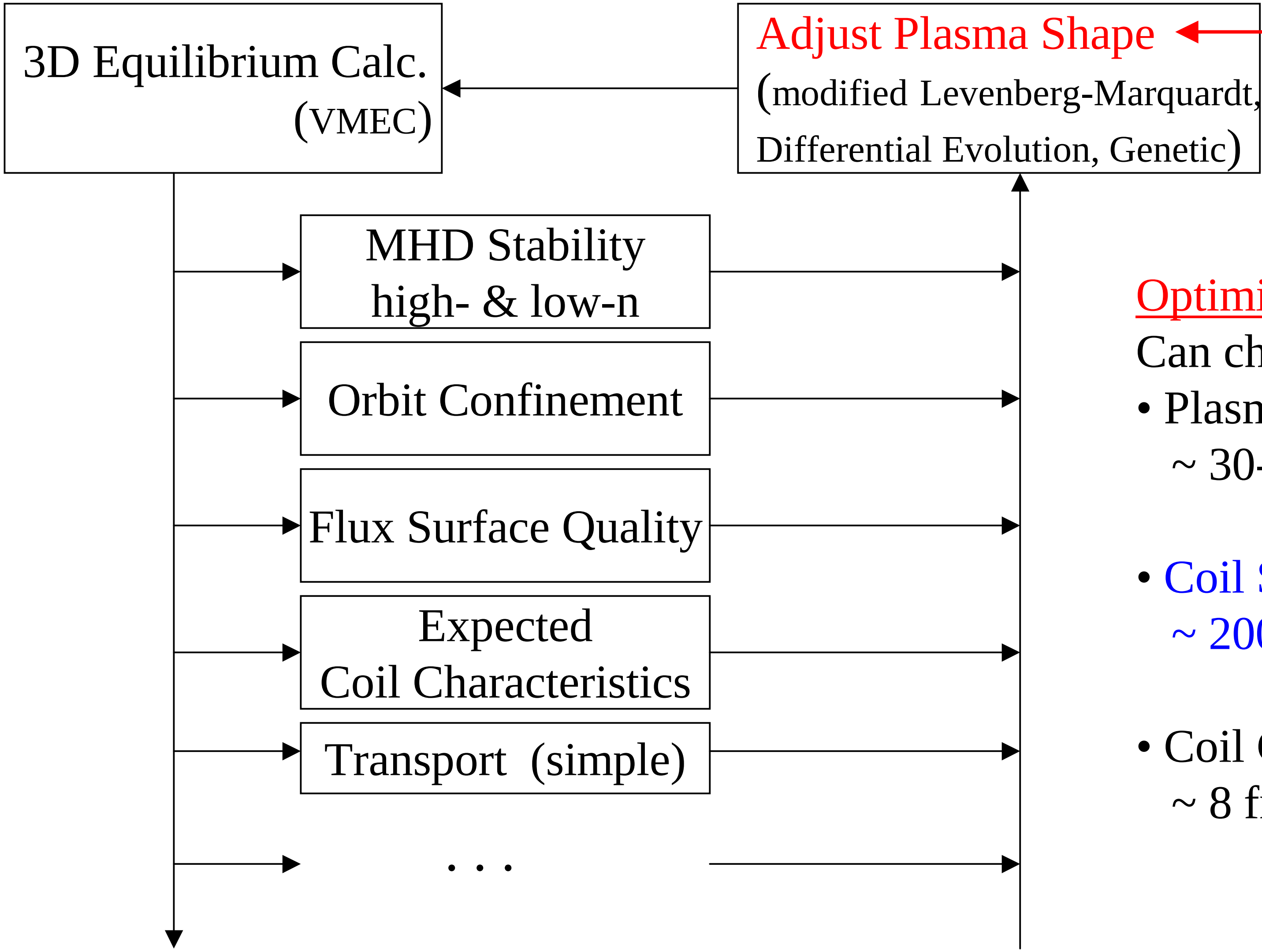
Primary Tool: Numerical Optimization

STELLOPT (ORNL & PPPL)



<u>Optimization Variables</u>

Can choose to vary:

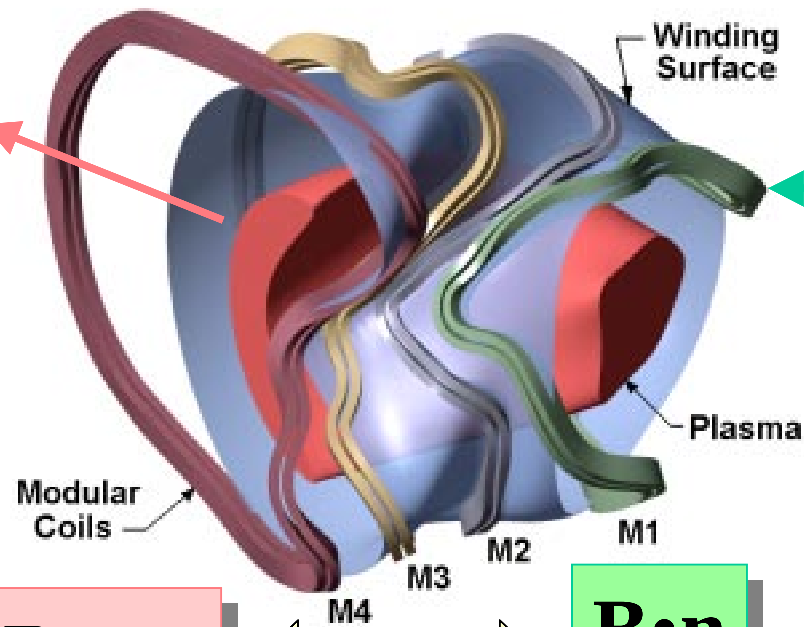
- Plasma Shape
  ~ 30-70 free parameters

- Coil Shapes
  ~ 200 – 400 f.parameters

- Coil Currents
  ~ 8 free parameters

Coil Design Process

n
Plasma Surface Normal ($B_{total} \bullet n = 0$)



J_{Coils}
- Filaments on winding surface

J_{Plasma}
From VMEC

B•n
From Plasma (BNORM)

$\Sigma B \bullet n = 0$

B•n
From Coils

L
Inductance Matrix
Biot-Savart

Vary "L" until $L \bullet J_{Coils} = B \bullet n(\text{Coils}) \approx -B \bullet n(\text{Plasma})$

COILOPT – flexible Coil Optimization Tool

(D. Strickler, L. Berry, S. Hirshman, ORNL)

- Varies filament coil shapes within a winding surface
- Varies winding surface shape
- Can vary coil current. Can deal with different coil topologies (modular, saddle, PF)

For fixed number of coils, targets:

– Bnormal mismatch

– Engineering criteria: bend radius, separation

– Coil-plasma separation

Established Equilibrium Codes Used

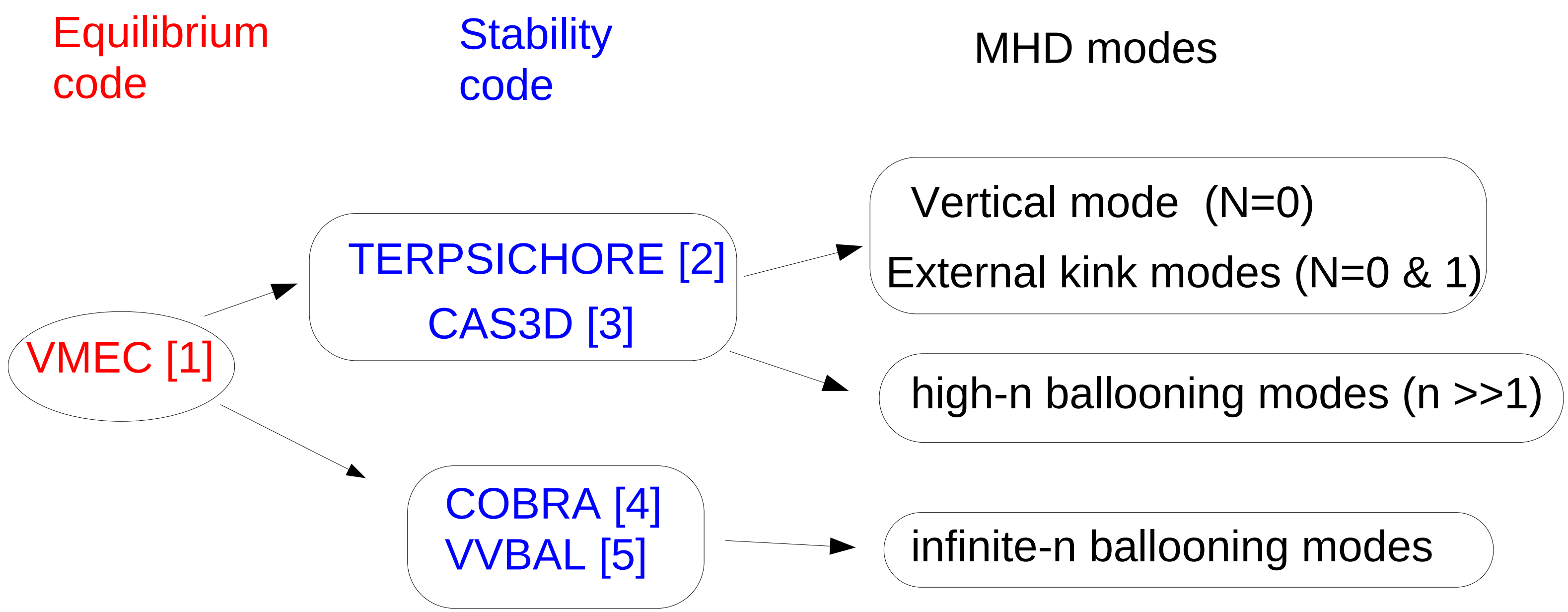
- VMEC - an 'inverse' equilibrium solver, which solves directly for the shape of the flux surfaces. Representation presumes that the flux surfaces are simply connected, without islands or stochastic regions. (Hirshman, ORNL)
- PIES - is a 'forward' equilibrium solver, directly calculating the 3D magnetic field and current distribution, including simulating the effect of islands and stochastic regions by flattening ∇p. Flux surface topology and shape determined by integrating the field-line orbits. (Reiman, Monticello, et al, PPPL)

— Both well benchmarked against 2D equilibrium codes, each other, and against available other 3D equilibrium codes.

— VMEC compares well with SXR tomography on W7-AS.

— VMEC used for physics optimization,
PIES used for island analysis and healing

Stability Codes and Their Validation



[1] Hirshman S. P. and Whitson, J. C., Phys. Fluids **26** (1983) 3553.

[2] Anderson, D. V. *et al.*, Scient. Comp. Supercomputer II, (1990) 159.

[3] Nüehrenberg, C., Phys. Plas. **3**, (1996) 2401.

[4] Sanchez, R. *et al.*, J. Comp. Physics **161**, (2000) 576.

[5] Cooper, W. A., Phys. Plasmas **3**, 275(1996)

Ballooning Codes: Terpsichore-VVBAL and Cobra

- Cobra solves the ideal ballooning mode equation for eigenvalue γ^2:

$$\rho\gamma^2\frac{\mathbf{k}_\perp^2}{B^2}\Phi - \mathbf{B}\cdot\nabla\frac{\mathbf{k}_\perp^2}{B^2}\mathbf{B}\cdot\nabla\Phi - \frac{p'}{B^2}(\mathbf{k}_\perp\times\mathbf{B})\cdot\kappa\Phi = 0 \quad (1)$$

  where $\mathbf{k}_\perp = \nabla\phi - q(\psi)\nabla\theta - q'(\theta-\theta_k)\nabla\psi$.

- Terpsichore-VVBAL solves a modified ballooning mode equation for eigenvalue λ:

$$\mathbf{B}\cdot\nabla\frac{\mathbf{k}_\perp^2}{B^2}\mathbf{B}\cdot\nabla\Phi + (1-\lambda)\frac{p'}{B^2}(\mathbf{k}_\perp\times\mathbf{B})\cdot\kappa\Phi = 0 \quad (2)$$

  where $(1-\lambda)$ is an artificial multiplier to the pressure-gradient term and $\lambda > 0$ for instability.

- Note that the eigenvalues are defined differently in two codes but the marginal stability points are the same.

- $\gamma = \gamma(s, \theta_k, \alpha)$ with s being flux label, θ_k being the radial wave number and α being the field line variable.

- The Terpsichore and CAS3D are 3D ideal MHD stability codes that determine stability by minimizing the plasma potential energy:

$$\delta W_p = \frac{1}{2}\int d^3x[\delta\mathbf{B}_\perp{}^2 + (\delta\mathbf{B}_\parallel - \mathbf{B}\frac{\xi\cdot\nabla p}{B^2})^2 + \mathbf{j}_\parallel\cdot\xi\times\delta\mathbf{B} - 2\xi\cdot\nabla p\ \xi\cdot\kappa]$$

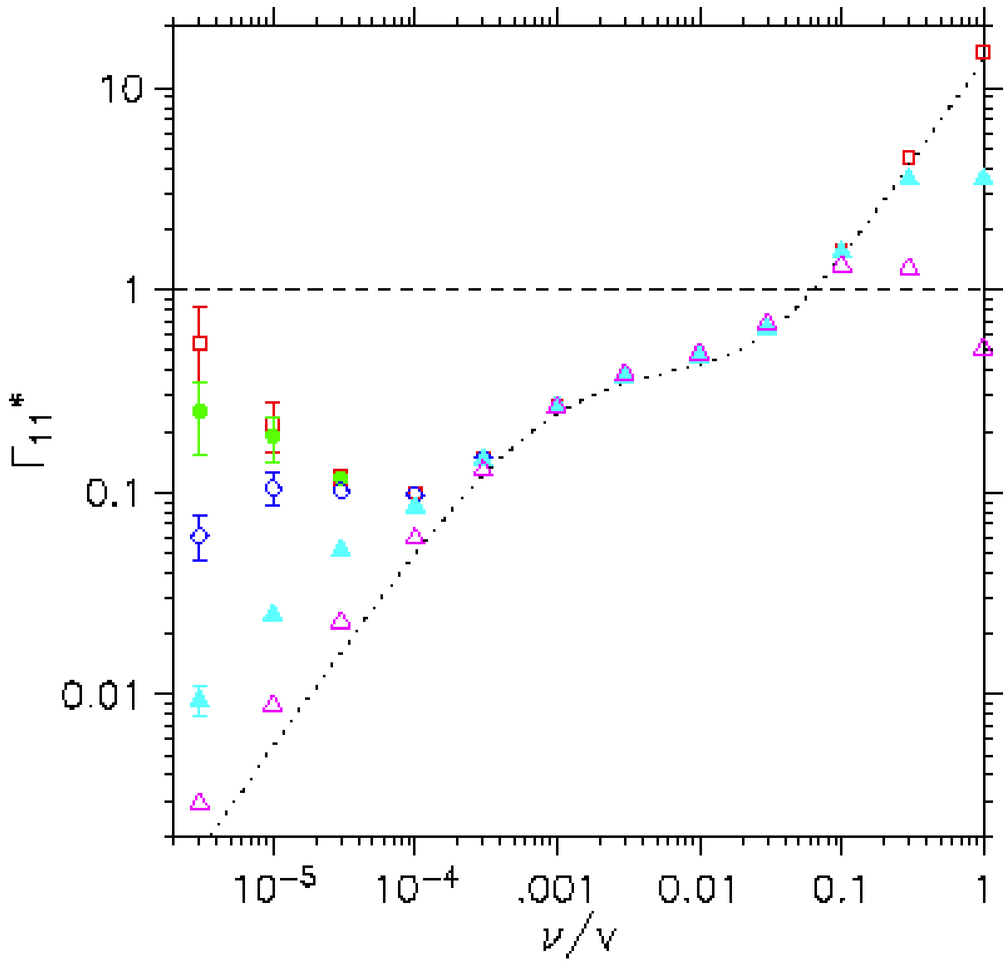
- Both codes use a finite element method for radial discretization and Fourier decomposition in poloidal and toroidal angles.
- The Terpsichore treats vaccum as a pseudo-plasma. The CAS3D uses Green's function method to solve the vacuum problem and thus can evaluate stability without a conducting wall.
- The Terpsichore code is used in the optimizer for sake of speed.

Thermal Confinement

- In Stellopt, have several targets available:
  * NEO calculations of effective-helical ripple (ε_{eff})
  – DKES diffusion coefficient for a single particle energy
  – RMS-sum of undesired B-harmonics
  – "Pseudo-symmetry" – secondary magnetic wells
  – J contour allignment
- For detailed analysis, use:
  – Global scaling laws
    - ISS95 from a diverse set of stellarators
    - Equivalent-ITER97P, for quasi-axisymmetric stellarators
  – DKES calculations for full distribution function
  – Monte-Carlo simulations of neoclassical transport
  – Turbulence simulations almost available

DKES Monoenergetic Transport for NCSX (li383)

DKES code (Hirshman) predictions confirmed by W7-AS (Maaßberg).
Monoenergetic diffusivities are strongly reduced by E_r; and asymptotically approach the axisymmetric result.
With the ambipolar E_r the neoclassical ripple transport is negligible.



E_r/Bv= 0
1x10-4
3x10-4
1x10-3
3x10-3

Fast Ion Orbit Confinement

Is not the same as thermal confinement, due to very low collisionality, large orbit displacements. Losses often due to stochastic orbits.

- Do not have fully adequate Stellopt target
  - Thermal confinement targets
  - J contour confinement & allignment
  - restricted Monte-Carlo simulation (v. expensive)
- For detailed analysis, use:
  - Monte-Carlo simulations of neoclassical transport

Flux-Surface Quality

- 3D Configurations typically have islands, stochastic regions
- So far, have not succeeded in developing useful target for Stellopt for targeting island
- Depend on removing resonant fields (and thus islands) as second optimization step

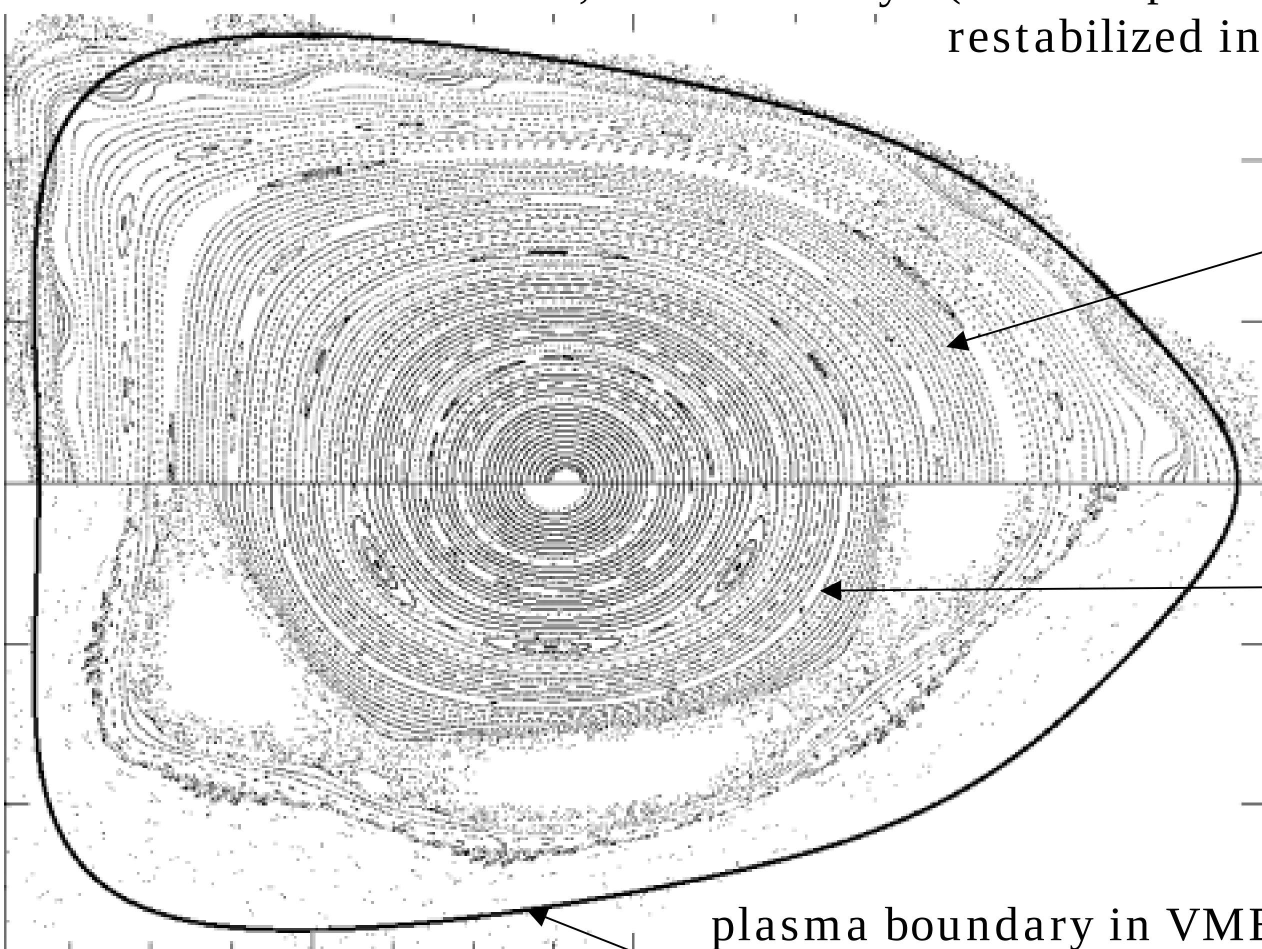
Island Removal Method

- Calculate coupling between plasma boundary shape and island widths by perturbation, using PIES
- Invert coupling matrix to find (small) shape modification to remove islands

(S. Hudson, D. Monticello, A. Reiman)

Coil Design Has Been Modified to Produce Good Surfaces

- “Dynamic healing” algorithm modifies coils in each PIES iteration to suppress targeted islands.
- Preserves engineering and physics constraints on coil curvature, minimum distance between coils, kink stability. (Stable up to n=45. Ballooning restabilized in startup scenario.)



Converged, free-boundary PIES calculation with healed coils. Sum of effective island widths < 1%.

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

plasma boundary in VMEC calculation with unhealed coils.

NCSX Design Experience

- Parameter space is very large. Many local minima.
- Optimization process is an exploration.
- We went through several stages, exploring and developing tools
  - Fixed boundary plasma
  - Coil designs
  - Optimized coil designs

  $\rightarrow$ For NCSX, each stage took more than a year. Generated many competing designs. Requires enormous amounts of computer time.
- It is important to identify goals, then explore for them directly
  - Best if the optimizer can directly target desired properties

Summary and Work to be Done

We have made enormous progress in developing a toolset for designing optimized stellarators. We can simultaneously target goals that were not approachable ~5 years ago.

To develop an optimized Stellarator reactor, we need to target some new goals

- Alpha-particle confinement
- COE – measure of reactor attractiveness
- Flux surface quality (if possible)

We should expect to spend some time exploring the landscape

- Need to make sure we have adequate computer resources