

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

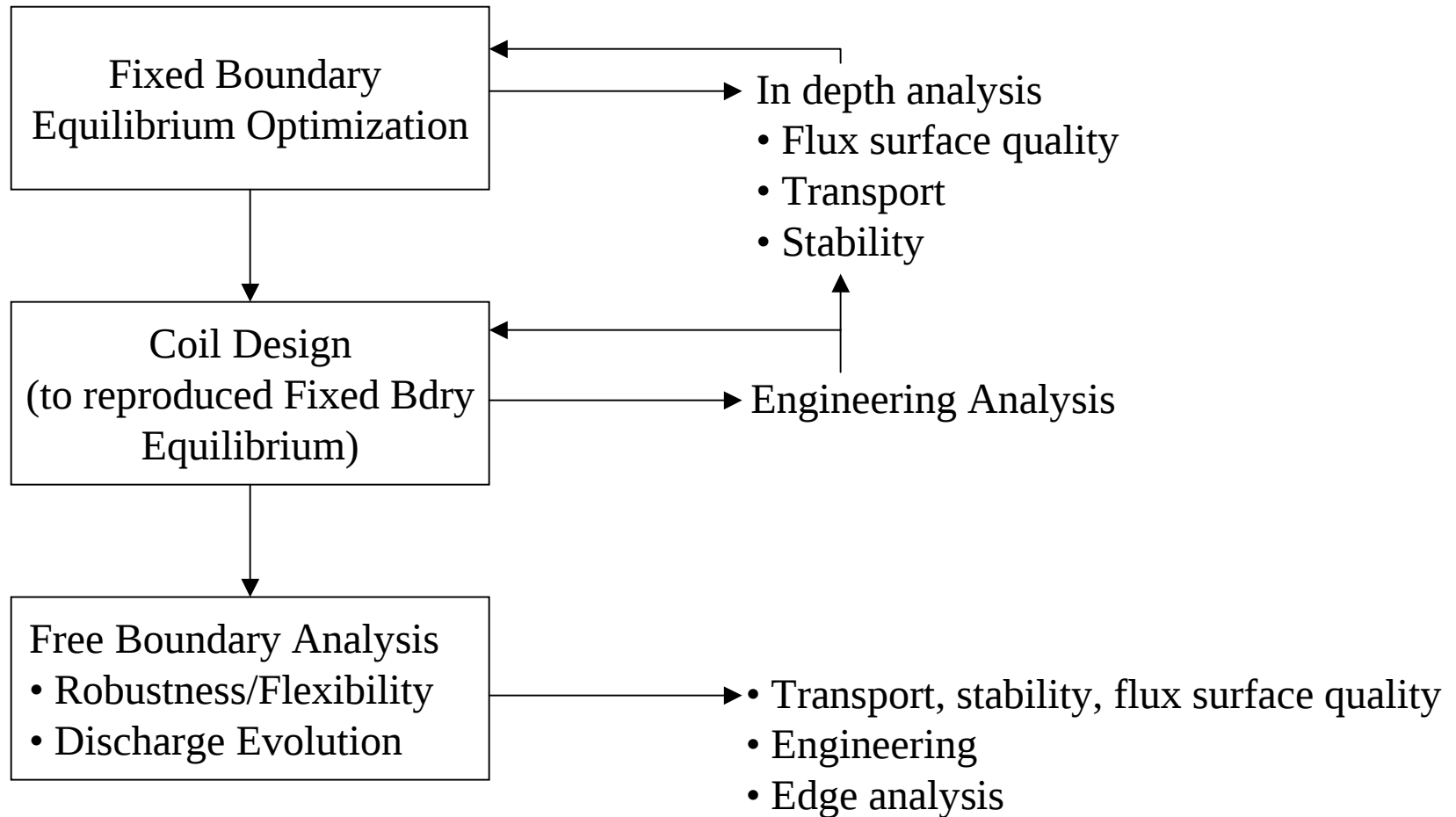
- 'quasi-symmetry'

- 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...

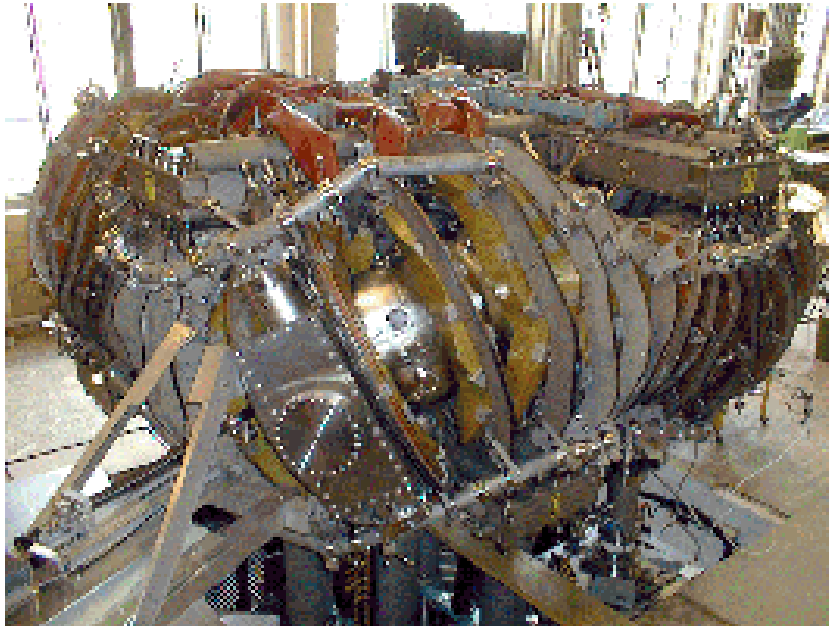
- Toroidal and helical drifts cancel; align drift orbit with flux surface
- If could be done perfectly, would result in $|B|$ independent of poloidal angle
- Principle of W-7X, new German superconducting experiment (A=11)
- Principle of QPS design

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



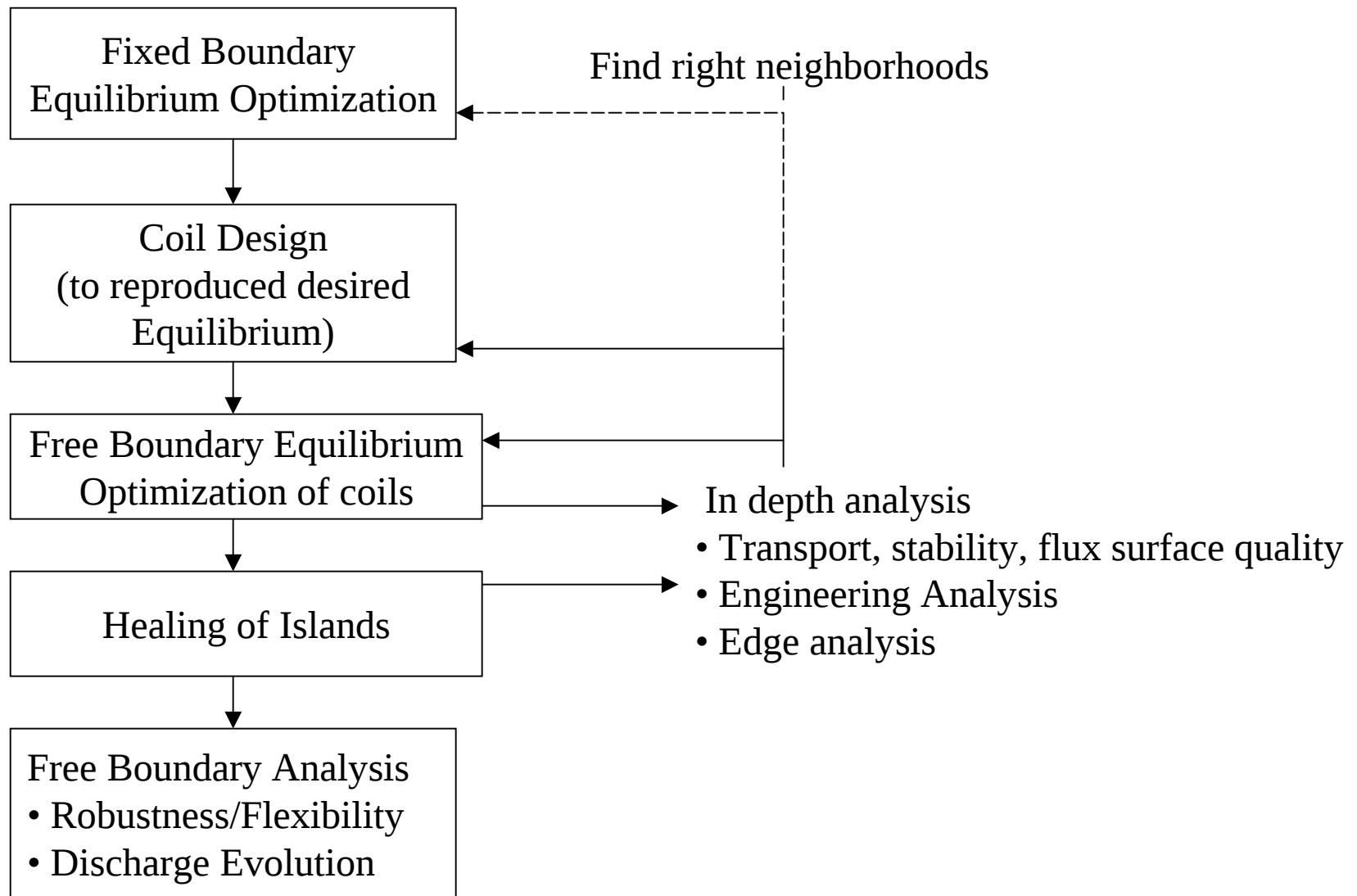
In Boozer coordinates,
magnetic field looks like
straight helix

First test of quasi-symmetry
started operation in 2000

$R=1.2$ m, $B=1$ T, 4 periods,
 $R/\langle a \rangle = 8$

Univ. of Wisconsin

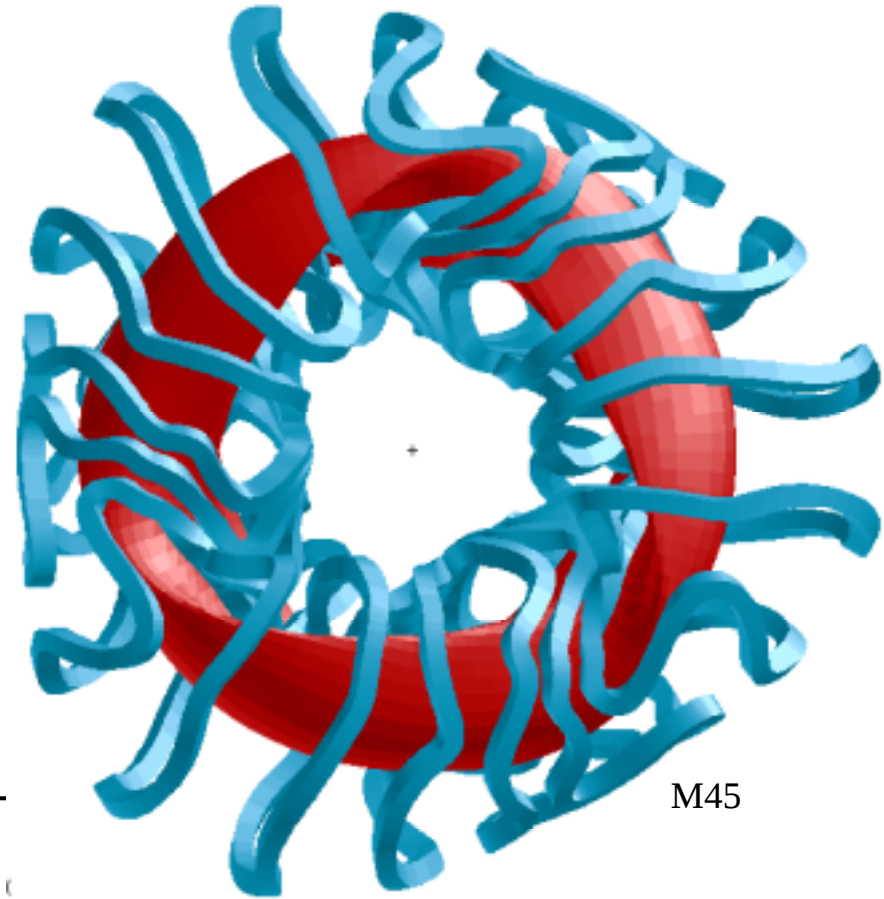
New Design Process (NCSX, QPS)



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

NCSX Plasma Configuration Has Attractive Physics

- 3 periods, $R/\langle a \rangle = 4.4$, $\langle \kappa \rangle \sim 1.8$
- Quasi-axisymmetric: low helical ripple transport, low flow damping
- Passively stable at $\beta = 4.1\%$ 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?

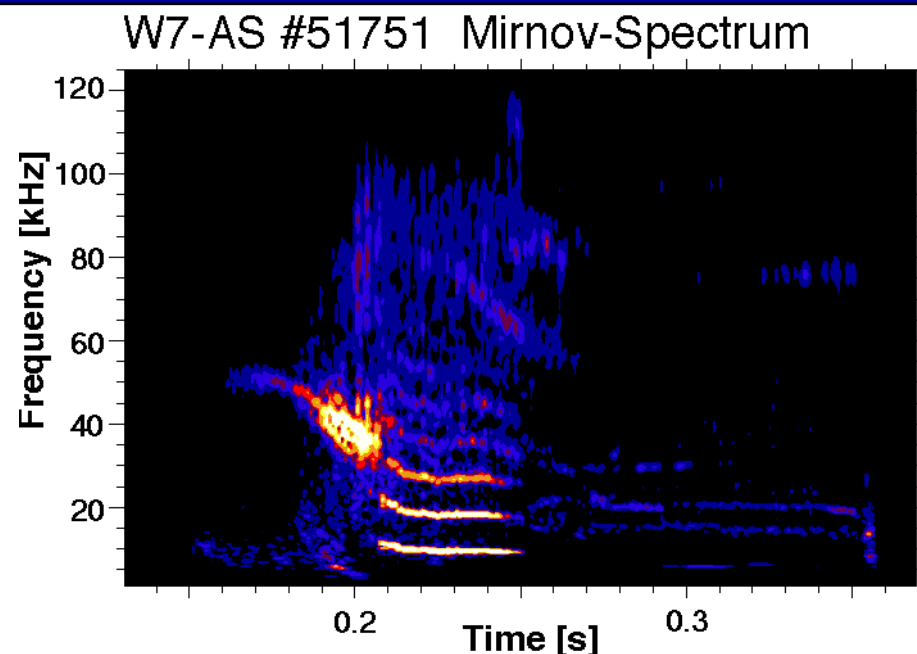
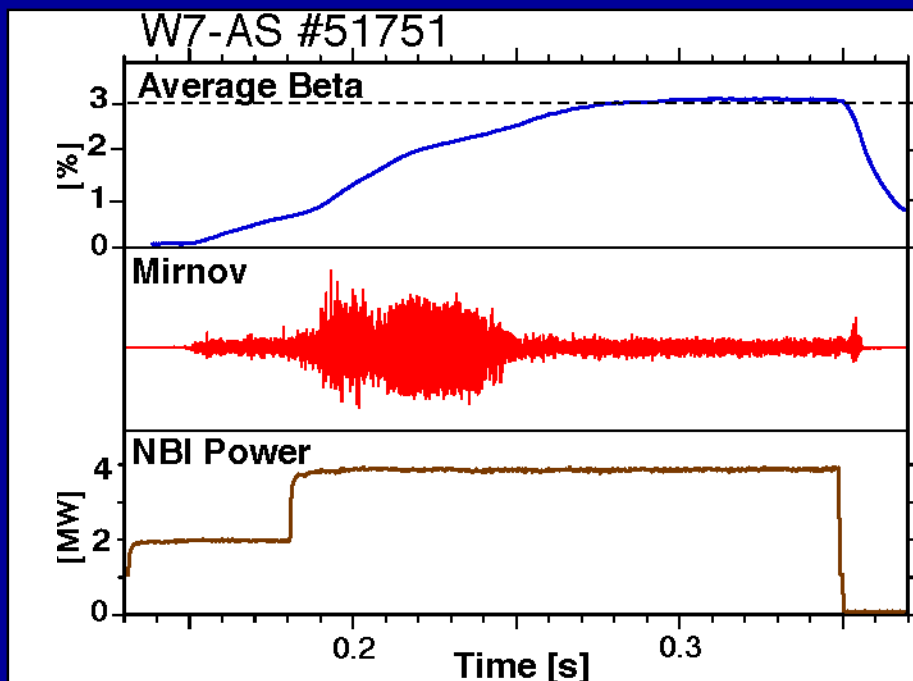


WENDELSTEIN 7-AS

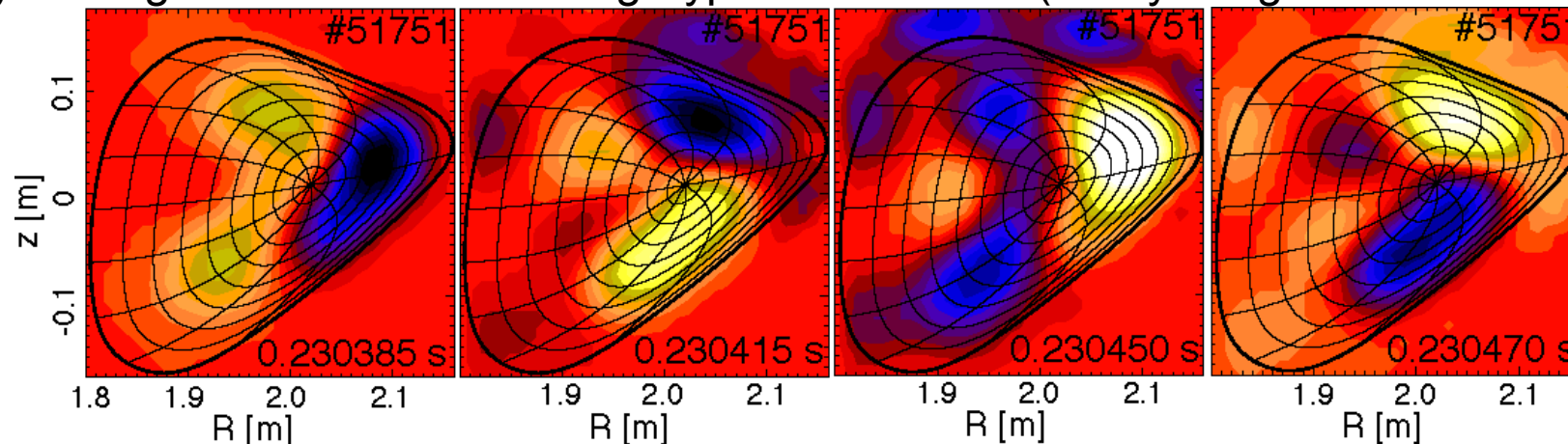
Global Modes appear at intermediate β -Values

Pressure driven $(m,n) = (2,1)$ Modes around $iota = 1/2$

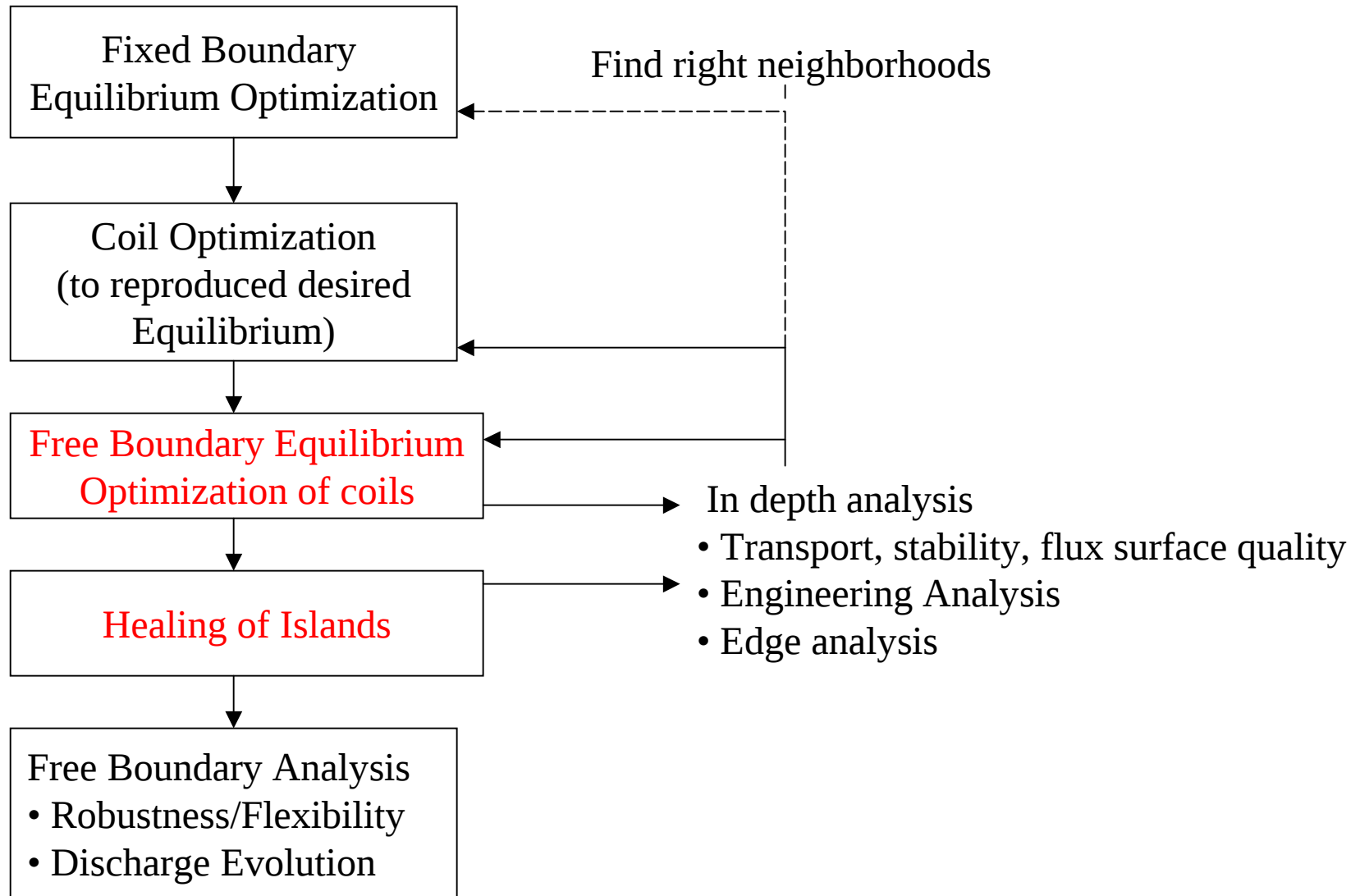
IPP



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



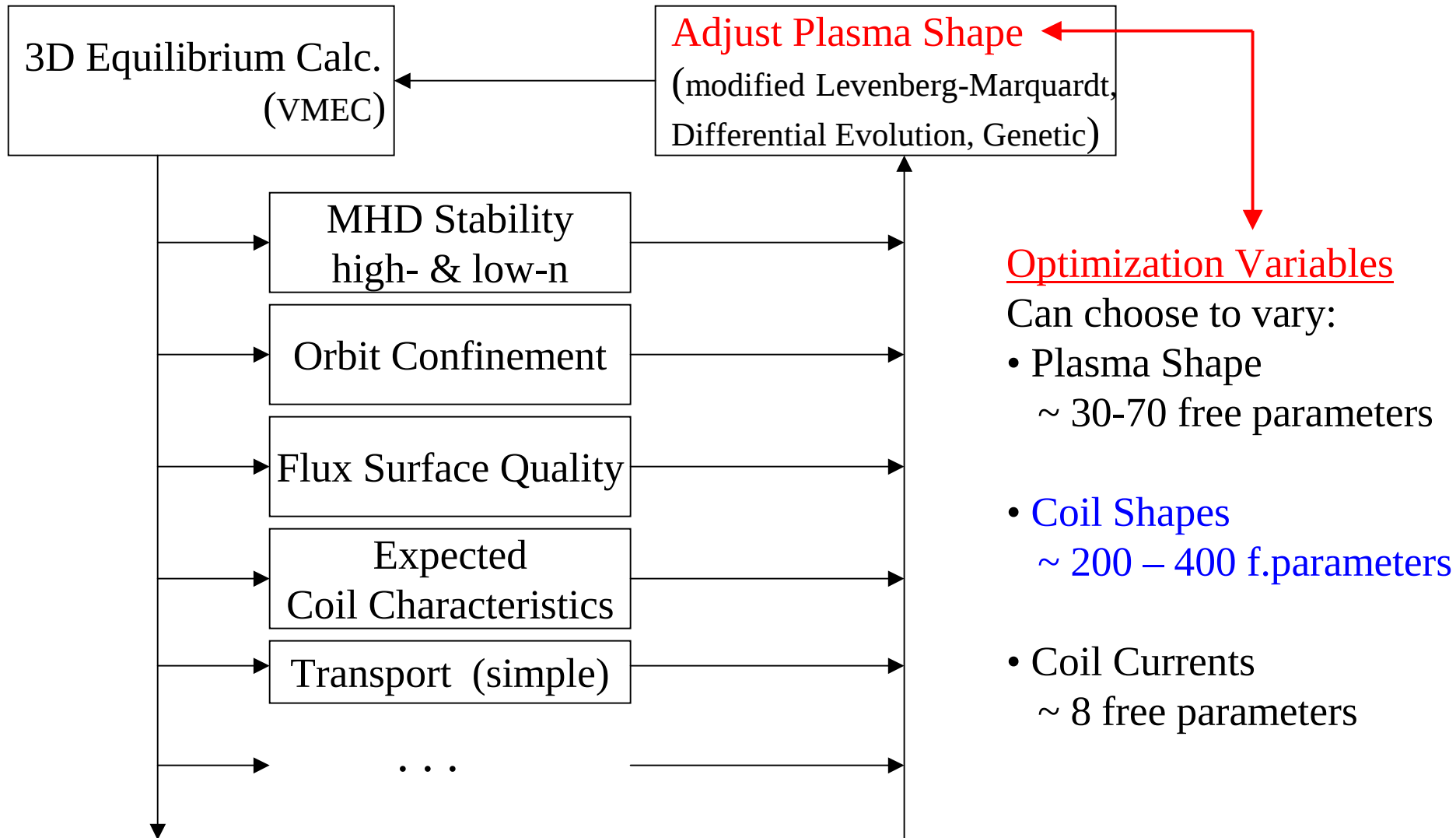
New Design Process



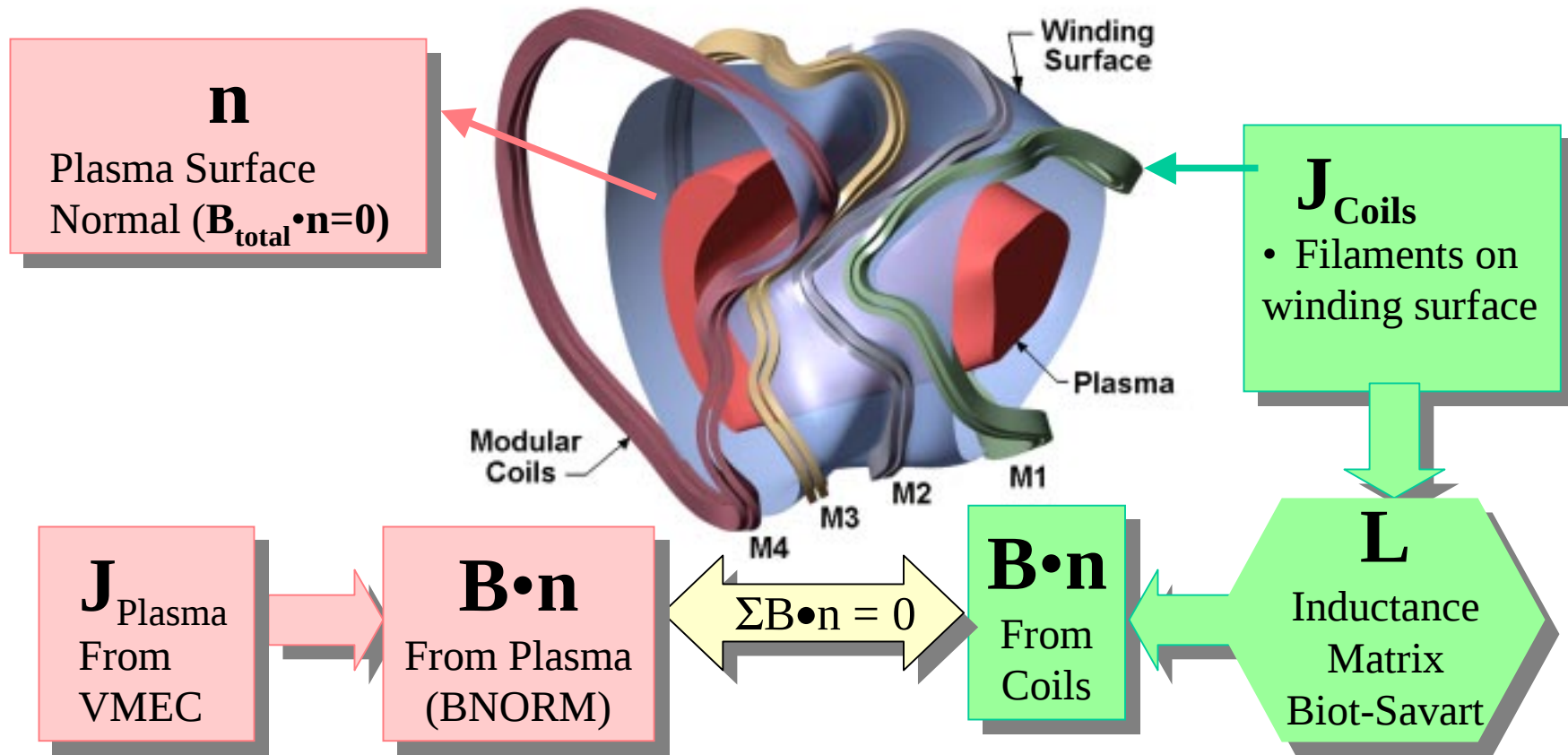
- Only possible due to availability of parallel high-speed computers

Primary Tool: Numerical Optimization

STELLOPT (ORNL & PPPL)



Coil Design Process



Vary “L” until $\mathbf{L} \cdot \mathbf{J}_{\text{Coils}} = \mathbf{B} \cdot \mathbf{n}(\text{Coils}) \approx -\mathbf{B} \cdot \mathbf{n}(\text{Plasma})$

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:

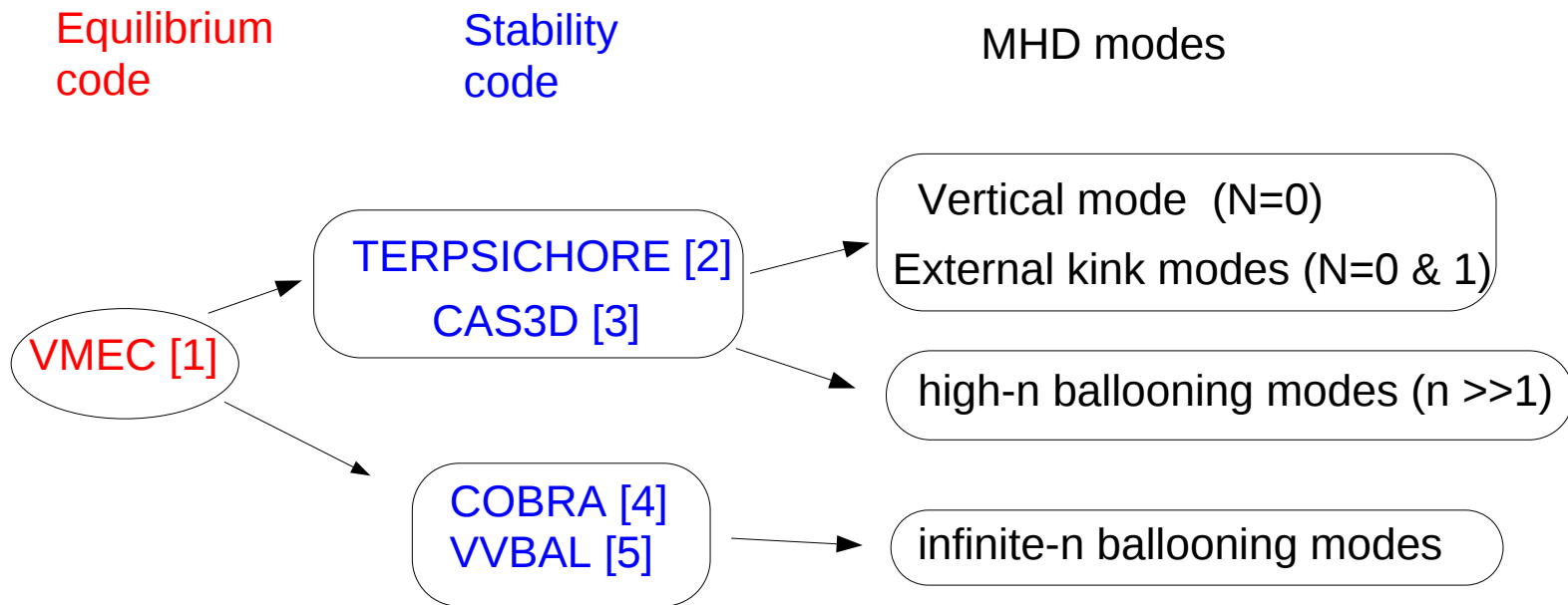
- Bnormal mismatch
- Engineering criteria: bend radius, separation
- Coil-plasma separation

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

PPPL



[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)

- 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.

Global Stability Codes: Terpsichore and CAS3D

PPPL

- 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 vacuum 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

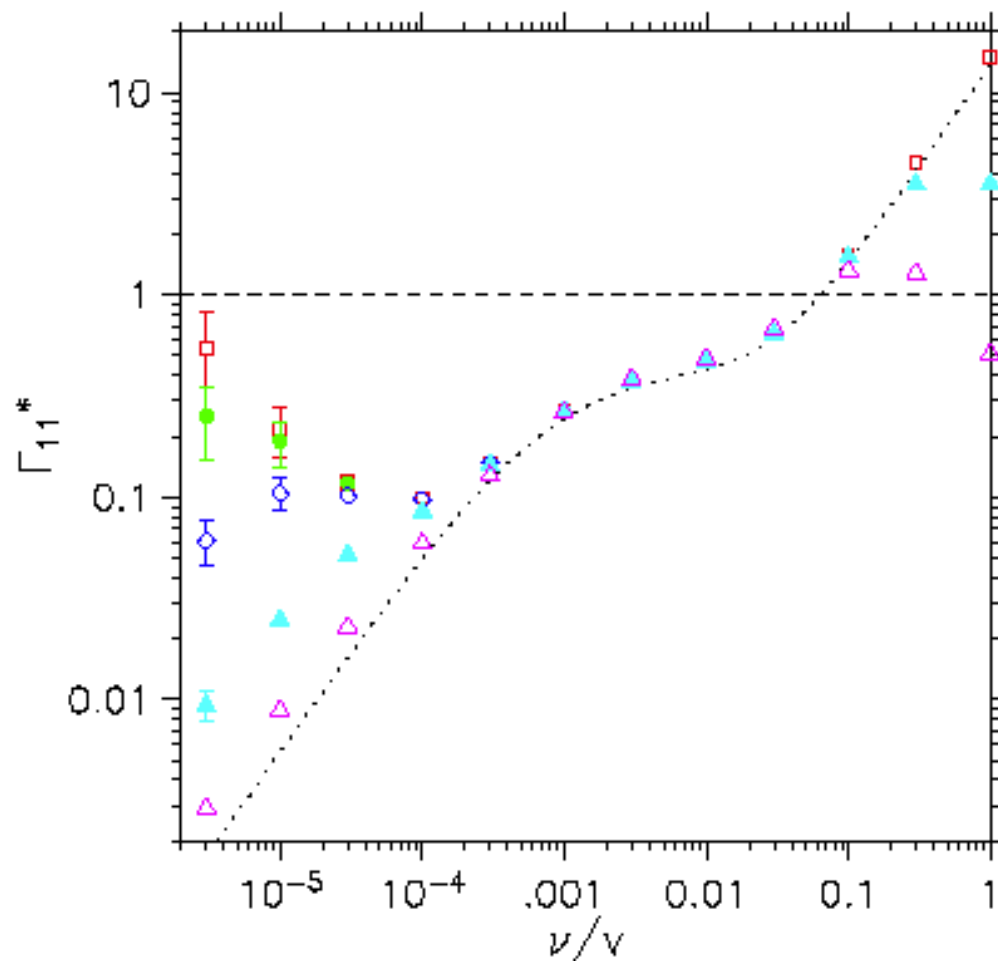
- In Stellopt, have several targets available:
 - * NEO calculations of effective-helical ripple (ϵ_{eff})
 - DKES diffusion coefficient for a single particle energy
 - RMS-sum of undesired B-harmonics
 - “Pseudo-symmetry” – secondary magnetic wells
 - J contour alignment
- For detailed analysis, use:
 - 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 (Ii383)

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.



$E_r/Bv = 0$
 1×10^{-4}
 3×10^{-4}
 1×10^{-3}
 3×10^{-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 & alignment
 - 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

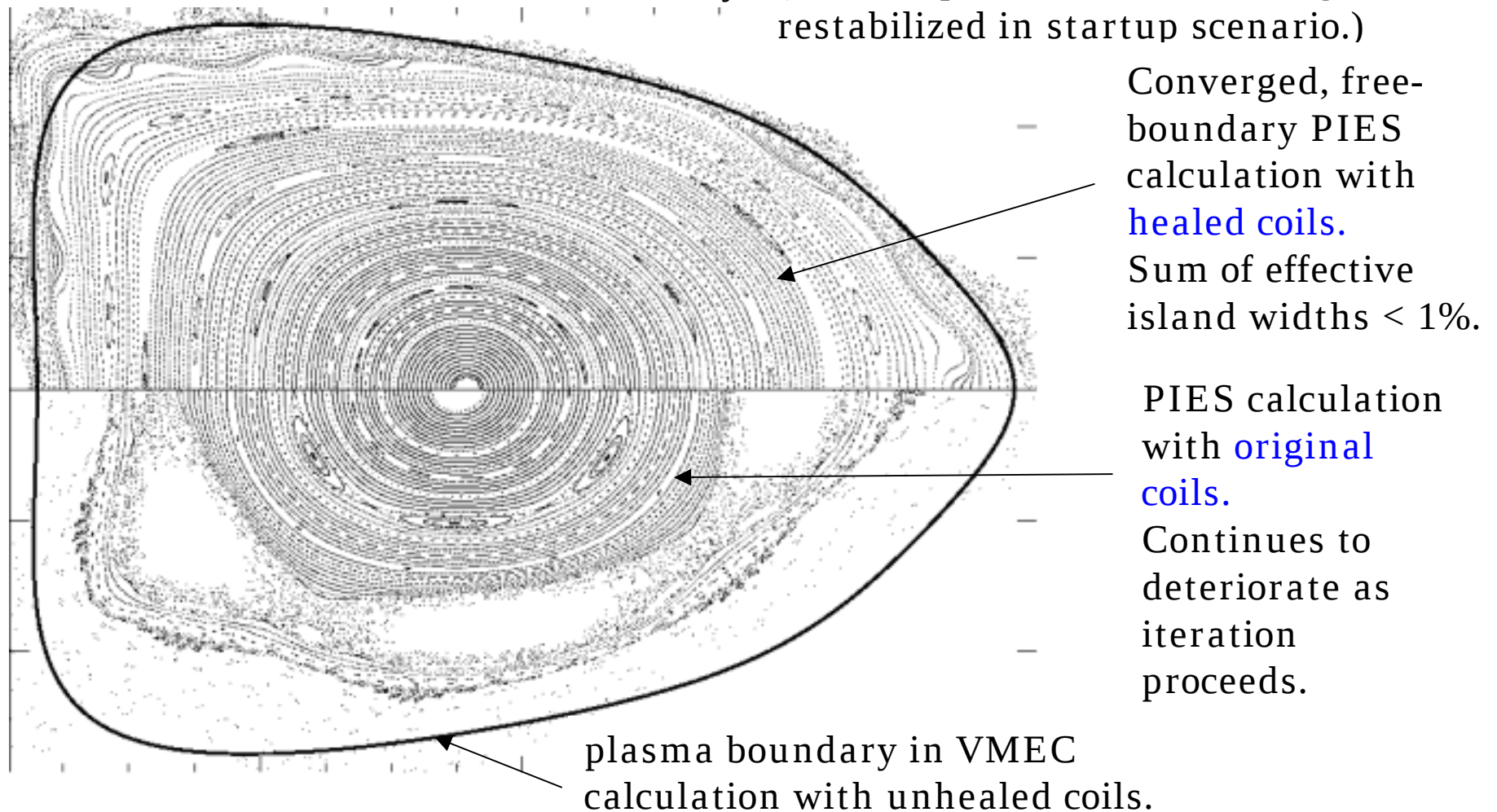


- Calculate coupling between plasma boundary shape and island widths by perturbation, using PIES
- Invert coupling matrix to find (small) shape modification to remove islands

(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.)



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
- 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

