QPS Plasma and Coil Optimization

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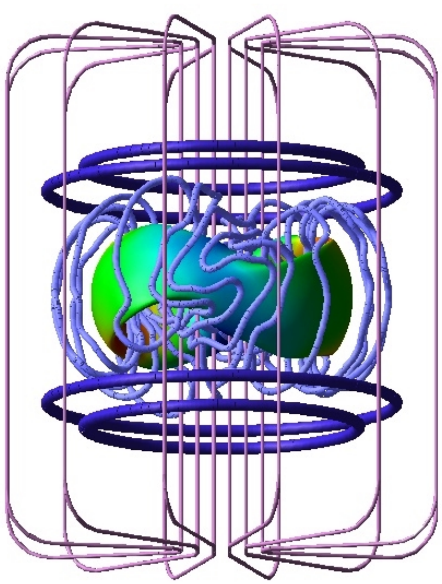

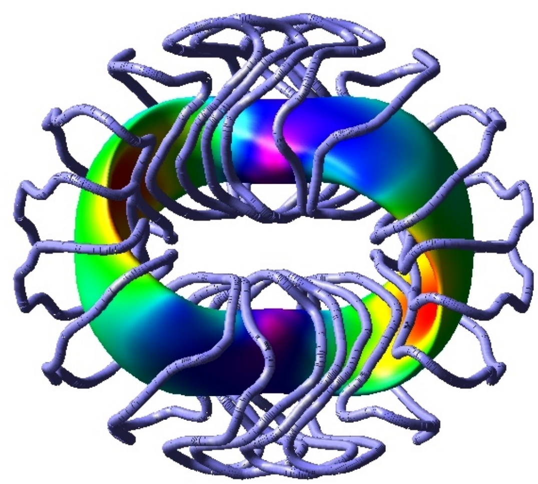

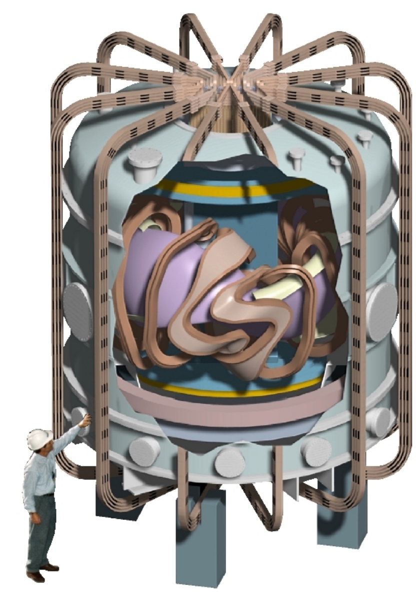

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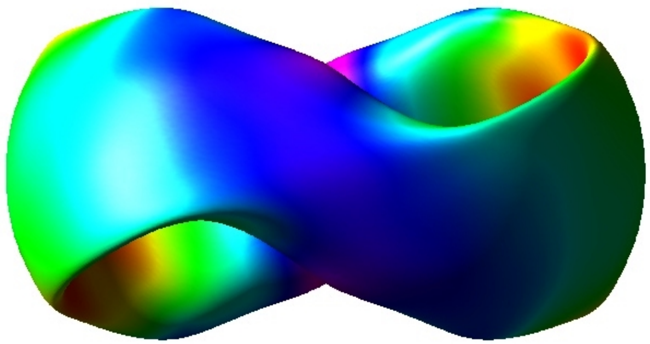
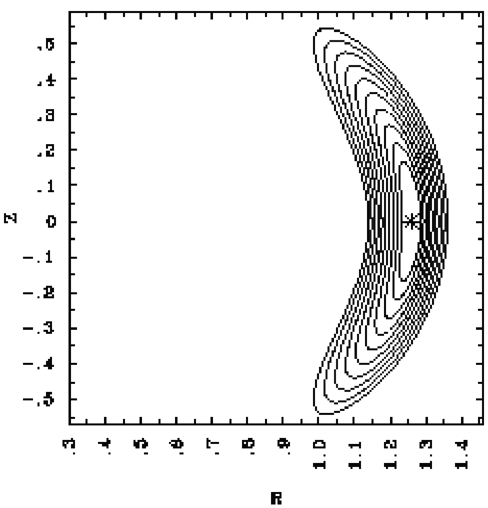
Goals of quasi-poloidally (QP) symmetric stellarators

- Closer **B** and **∇B** alignment than with other forms of symmetry
  - For exact QP symmetry, P_θ is constant of the motion rather than P_ϕ
  - reduces radial drift; banana thickness ~ $\rho_{toroidal}$ rather than $\rho_{poloidal}$
- Minimum flow damping in the direction of $\mathbf{E}_r$ x **B**
  - Flow shear potentially self-sustained
  - Via internally generated $\mathbf{E}_r$ driven by plasma ambipolar diffusion
- Second stability access and improved omnigeneity at high β
- Trapped particle localization in low curvature regions
  - potential improvements to DTEM (dissipative trapped electron mode) stability [e.g. see A. Kendl, H. Wobig, Plasma Physics 6, 4714 (1999)]

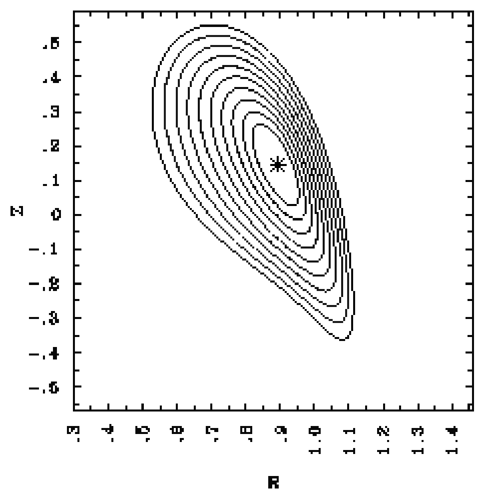
Properties of quasi-poloidally symmetric configurations

- Low aspect ratio: A ≈ 2.7
  - Have obtained configurations with aspect ratios in the range: A=2.1-3.0
- Rotational transform below 0.5: $\iota \sim 0.2$ - 0.3
  - Majority of the transform is from the coils, bootstrap current causes iota to increase
  - Max. Toroidal Currrent = 40 - 50 kA for $\langle\beta\rangle$ in the 1.5 to 2% range
  - Stable to neoclassical tearing modes

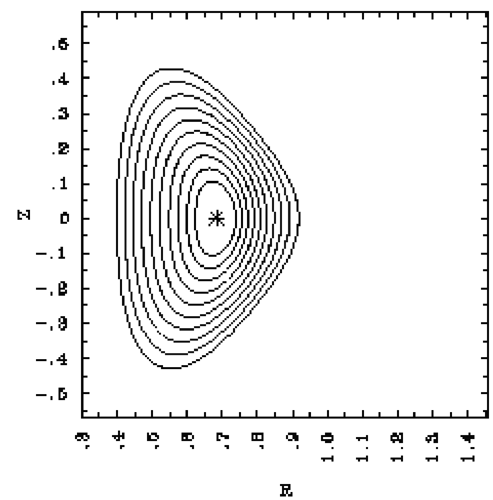




$N_{fp}\zeta = 0°$



$N_{fp}\zeta = 90°$



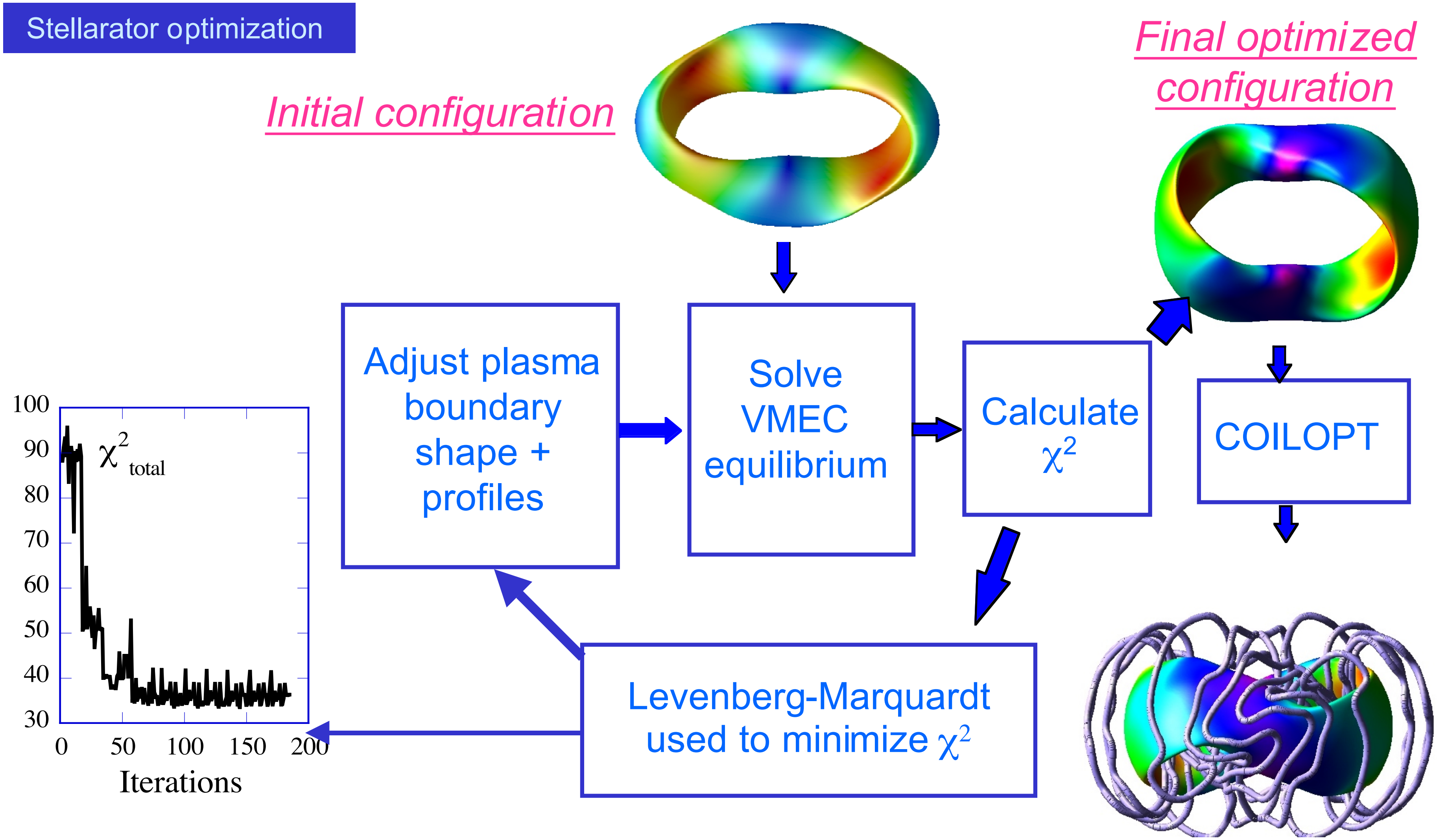
$N_{fp}\zeta = 180°$

Our current low aspect ratio stellarator optimization capabilities have been built on a series of past accomplishments:

- Identification of appropriate coordinate system where symmetries in |B| improve confinement
  - A. H. Boozer, Phys. Fluids **24,** 1999 (1981).
- Rapidly calculated 3D equilibria
  - S. P. Hirshman, J. C. Whitson, Phys. Fluids 26, 3553 (1983).
- Demonstration that numerical optimization of 3D systems can improve equilibrium/transport/stability
  - J. Nührenberg, A. Zille, Phys. Lett. A **114**, 129 (1986)
- Methods of numerical coil design to produce such 3D equilibria
  - P. Merkel, Nuclear Fusion 27, 867 (1987)
- Increasing availability of massively parallel (> 1 teraflop) computers and efficient algorithms to utilize them.

Stellarator optimization loop determines outer flux surface shape.

Stellarator optimization



Plasma boundary is characterized by 30-40 Fourier harmonics

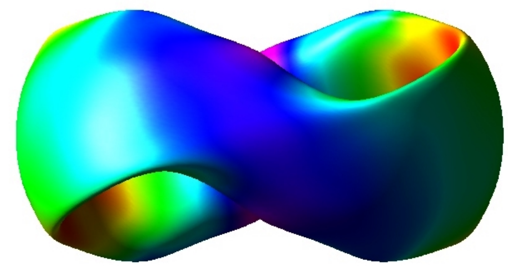
Reduced (rapidly evaluated) measures of transport have been used to optimize compact stellarator configurations:

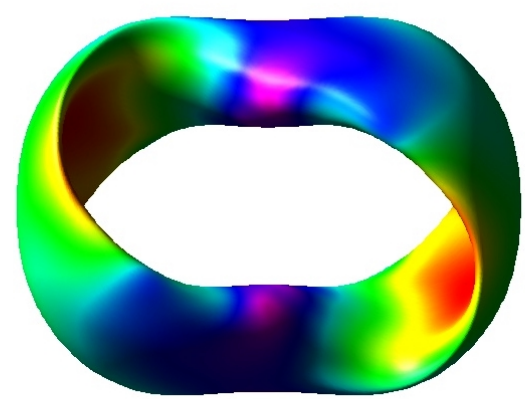
TARGET	IMPROVES:	EXAMPLE	
Bounce-averaged omnigeneity	Collisionless trapped/transitional particle confinement	$J = J(\psi)$ $B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$	Currently existing
Nearby quasi-symmetries	Collisionless confinement of all orbit topologies	Minimize B_{mn} if $m \neq 0$ (QP) Or if $n \neq 0$ (QA)	Currently existing
Collisional transport coefficients	Neoclassical transport	L_{11} coefficient from DKES at $\nu^* \sim 1$	Currently existing
Effective ripple ε_{eff}	$1/\nu$ neoclassical transport regime	$\varepsilon_{eff}^{3/2}$ from NEO[1] code	Currently existing
Large orbit effects	Energetic particle confinement	Reduced Monte Carlo model for alphas	Future

[1]Nemov, V. V., Kernbichler, W., et al., Phys. Plasmas **6**, 4622 (1999) + talk in next session

These transport measures are in addition to a set of stabiltity, configuration and engineering targets:

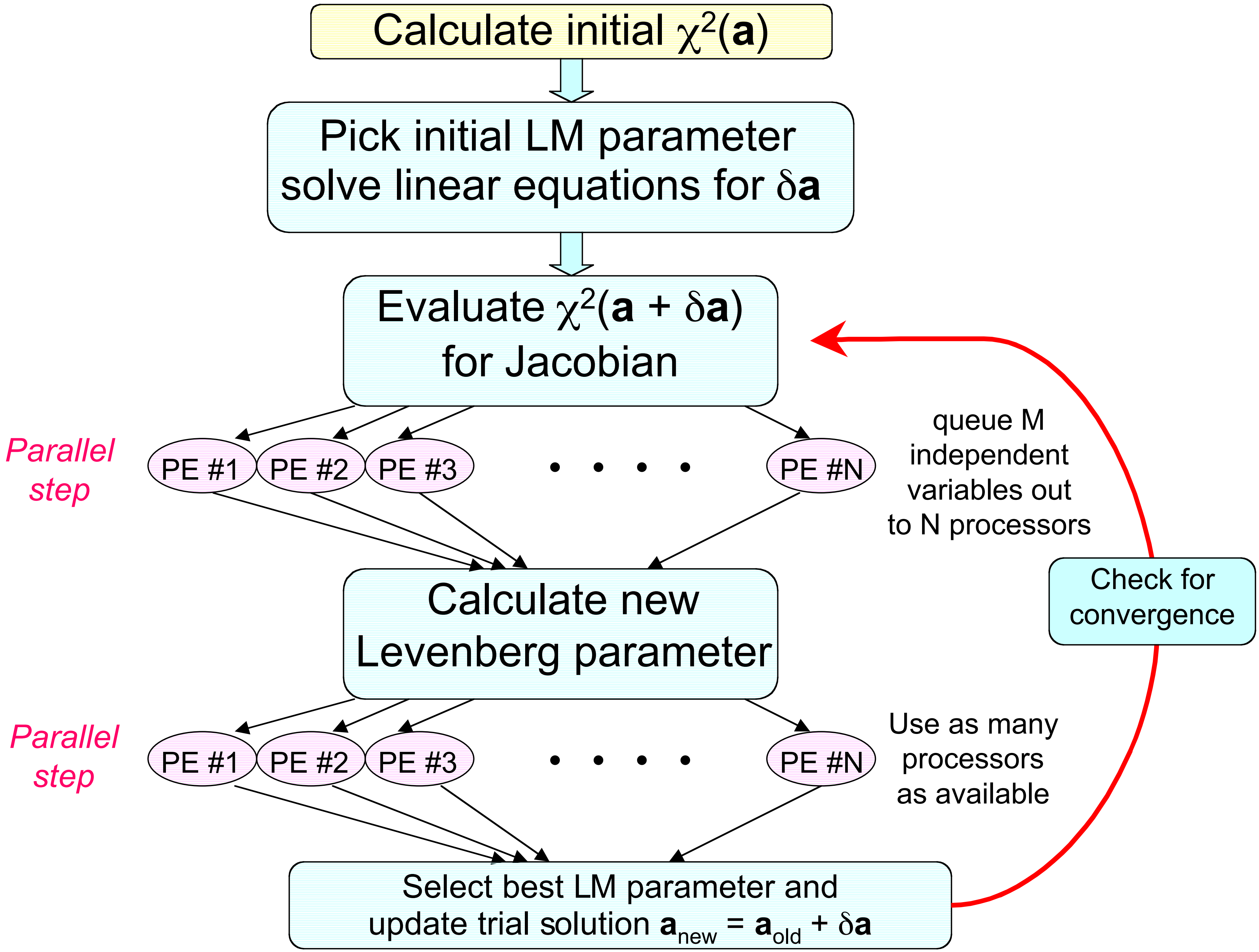
Targets (Physics/Engineering)	**Example**
Transport Measures	See previous slide
Current profile	self-consistent I_{BS}, $I(\psi)$ goes to 0 at edge
Limit maximum plasma current	e.g., I_{max} < 60 kAmps at $<\beta> \sim 2\%$
Iota profile	$i(\psi) = 0.2$ ($\psi=0$) 0.3 ($\psi=1$)
Magnetic Well, Mercier	$V'' < 0$, $D_M > 0$ over cross section
Ballooning stability	$<\beta> \sim$ 2-3%
Aspect ratio	$R_0/a \approx 2.5$ to 3.5
NESCOIL targets/feasible coil design	Complexity, B_{err}, Max. current density
Adequate shielding of neutrals	Minimum "waist" thickness
Fit within vacuum bell jar	R_{max} < 1.5 meter
Limit outer surface curvature	avoid strong elongation/cusps





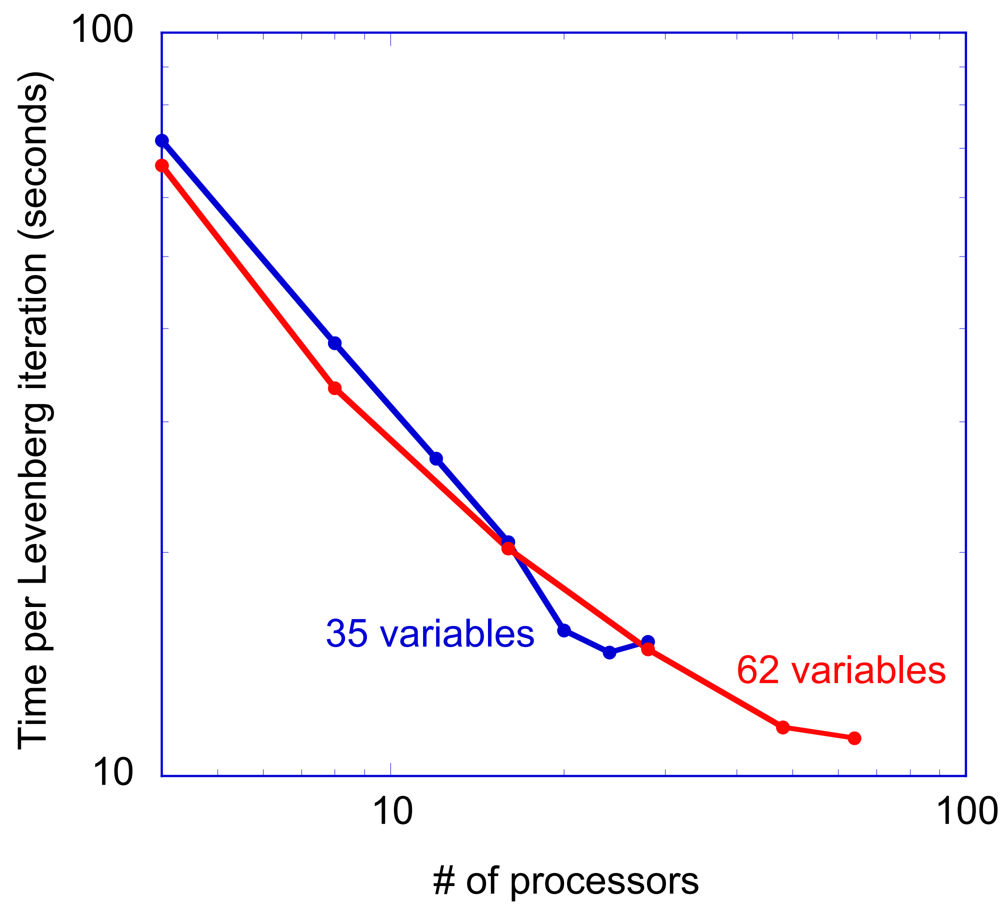
We have developed an MPI-based parallel version of the Levenberg-Marquardt optimizer

- Uses a global, coarse-grained parallelization over the 30 - 60 independent variables (i.e., shape and profile coefficients)
  - done over the periodic Jacobian evaluations and in the estimation of the Levenberg parameter
  - this simplifies the development of modules used to calculate the target functions (they are left as serial tasks)
- A bank-queuing algorithim is used to parcel out the computational tasks to the processors
  - this accommodates for the fact that they are generally of unequal computational length (e.g., VMEC may converge more rapidly for some shapes than others)

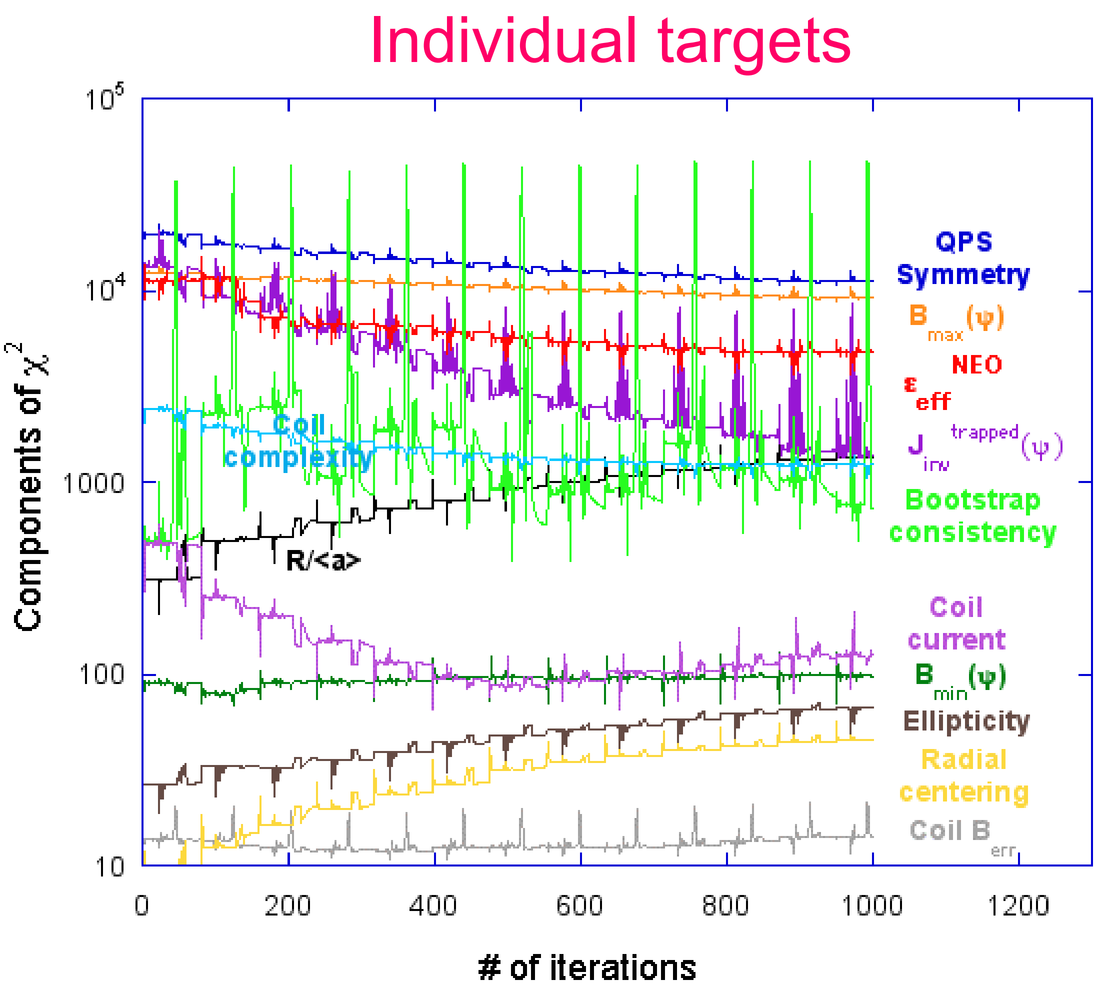

Calculate initial $\chi^2(\mathbf{a})$
Pick initial LM parameter
solve linear equations for $\delta\mathbf{a}$
Evaluate $\chi^2(\mathbf{a} + \delta\mathbf{a})$
for Jacobian
Parallel step
PE #1
PE #2
PE #3
• • • •
PE #N
queue M independent variables out to N processors
Calculate new Levenberg parameter
Check for convergence
Parallel step
PE #1
PE #2
PE #3
• • • •
PE #N
Use as many processors as available
Select best LM parameter and
update trial solution $\mathbf{a}_{new} = \mathbf{a}_{old} + \delta\mathbf{a}$

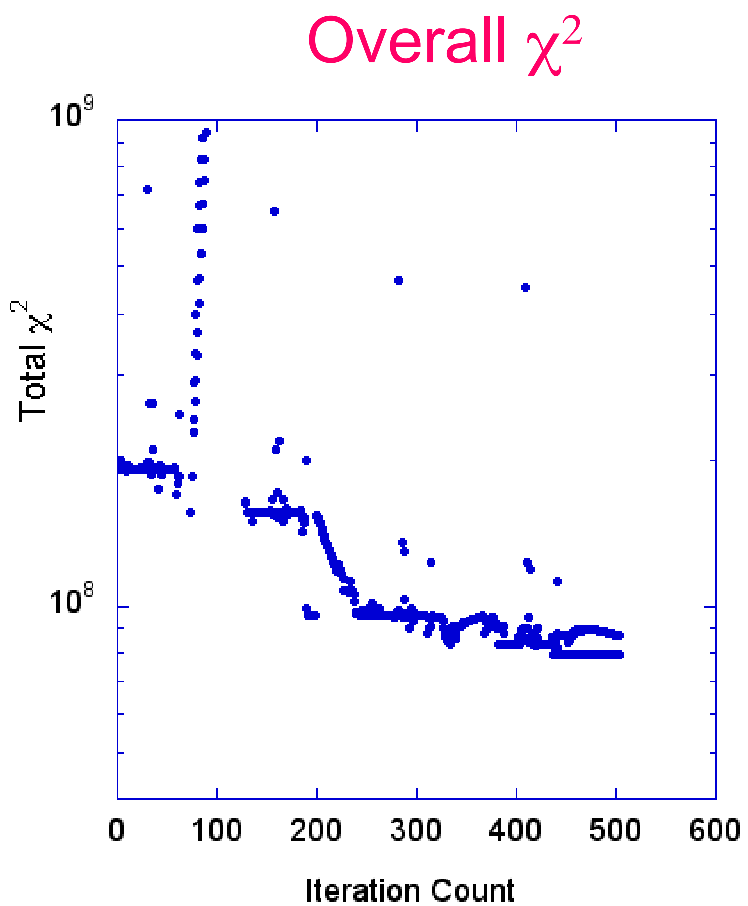
Parallelization has made our stellarator optimization significantly faster.

- Allows more physics targets to be included.
- Parallel speedup saturates
  - as processors ≥ (0.5 to 1) x(# of independent variables)
- # of parallel tasks = # of independent variables + 1
- Communication overhead



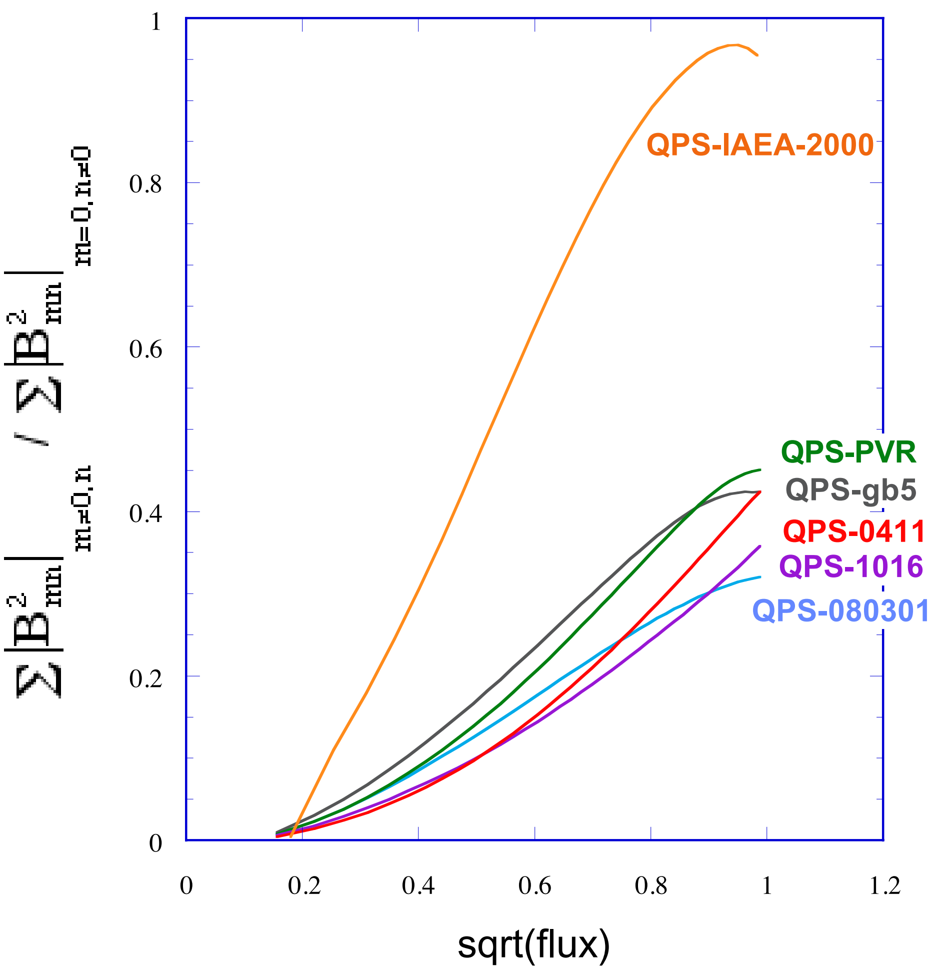
Reduction in target functions with iterations



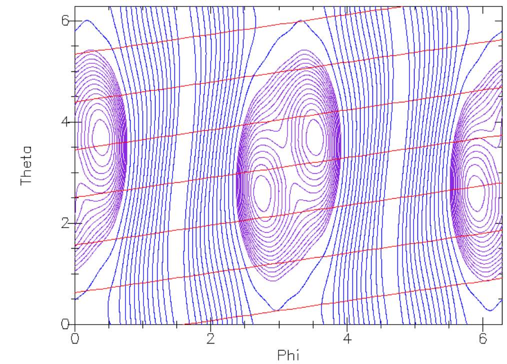


Our optimizations have resulted in increased poloidal symmetry from the initial QPS-IAEA-2000 device

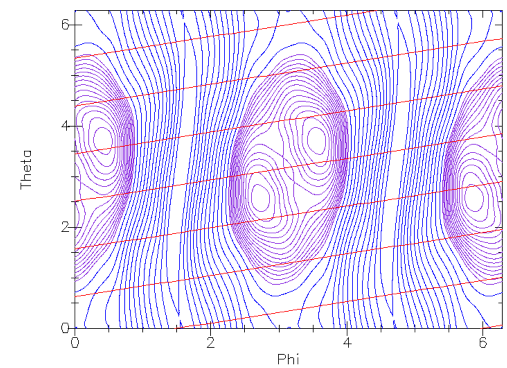
(shown here as the ratio of the magnetic energy in the non-poloidally symmetric modes to that in the poloidally symmetric modes)



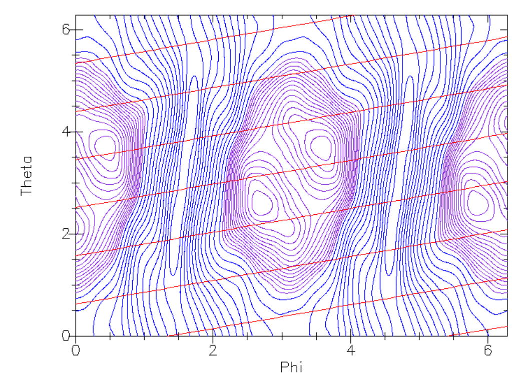
$$\sqrt{\psi/\psi_{edge}} = 0.3$$



$$\sqrt{\psi/\psi_{edge}} = 0.5$$

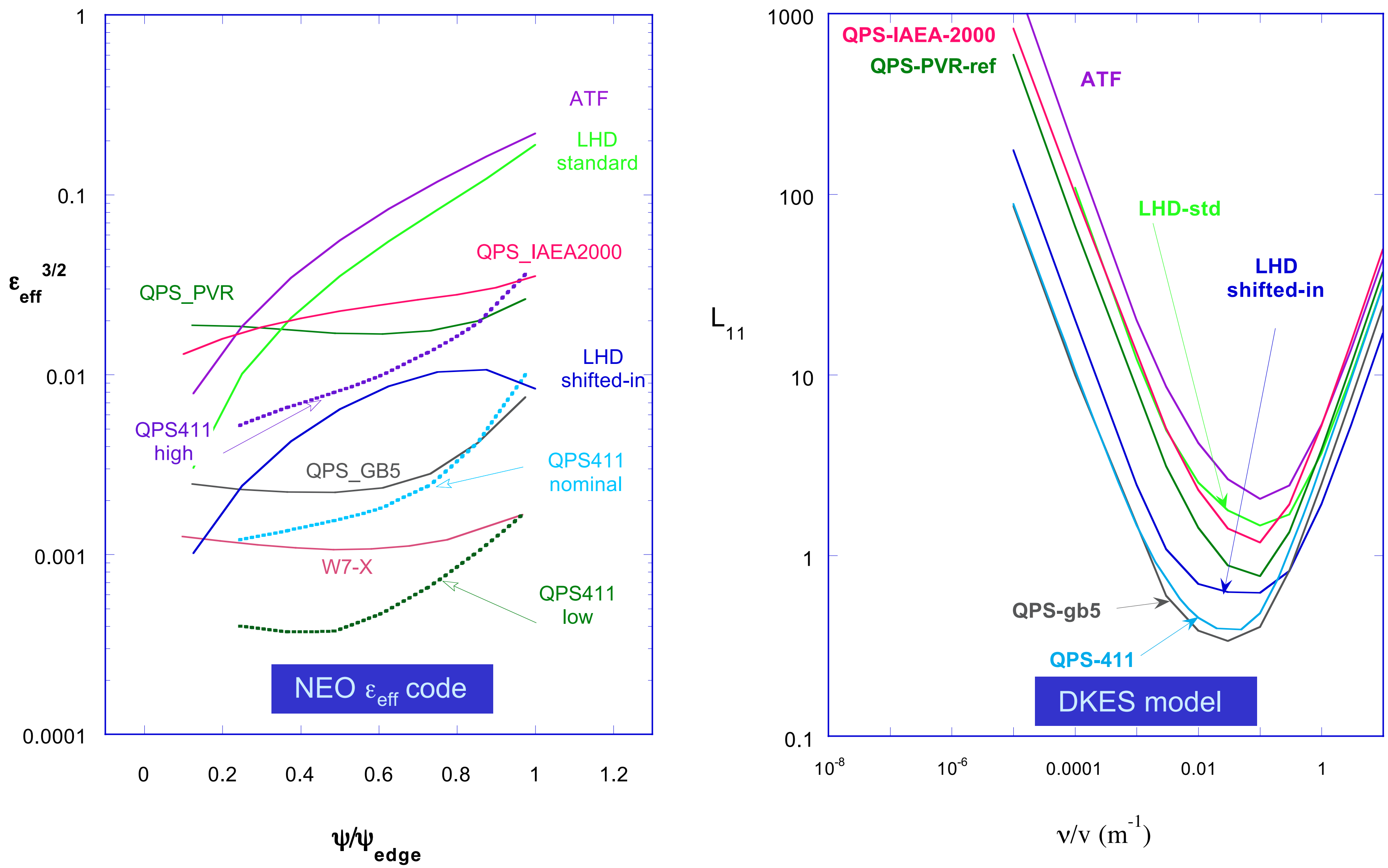


$$\sqrt{\psi/\psi_{edge}} = 0.7$$



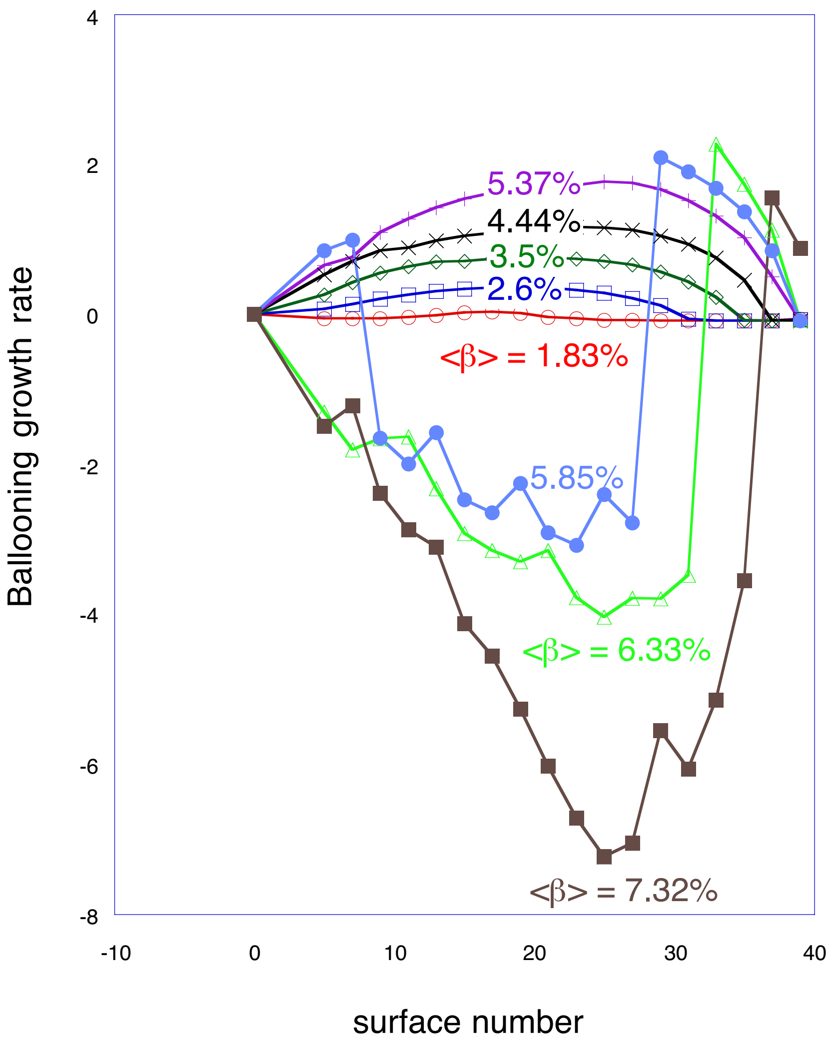
DKES L_{11} transport coefficients for $E_r = 0.0$ show similar trends at low collisionality as the NEO[1] $\varepsilon_{eff}^{3/2}$ coefficient

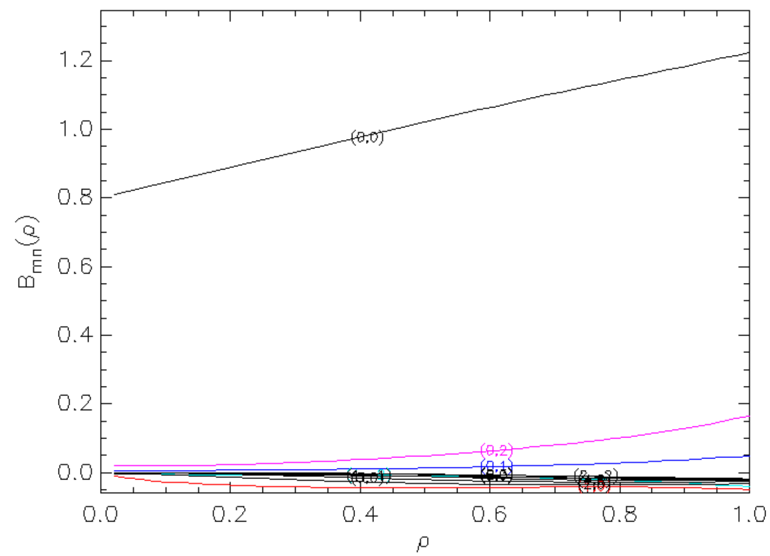
[1]Nemov, V. V., Kernbichler, W., et al., Phys. Plasmas **6**, 4622 (1999).

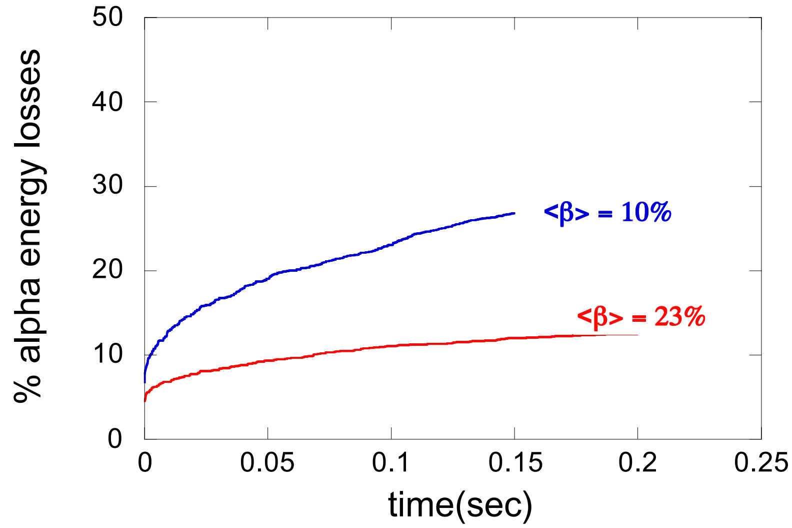


QPS configurations have second stability regimes

- Stellarator iota profiles: some bootstrap suppression required
- Tokamak iota profiles: bootstrap current can be self-consistent

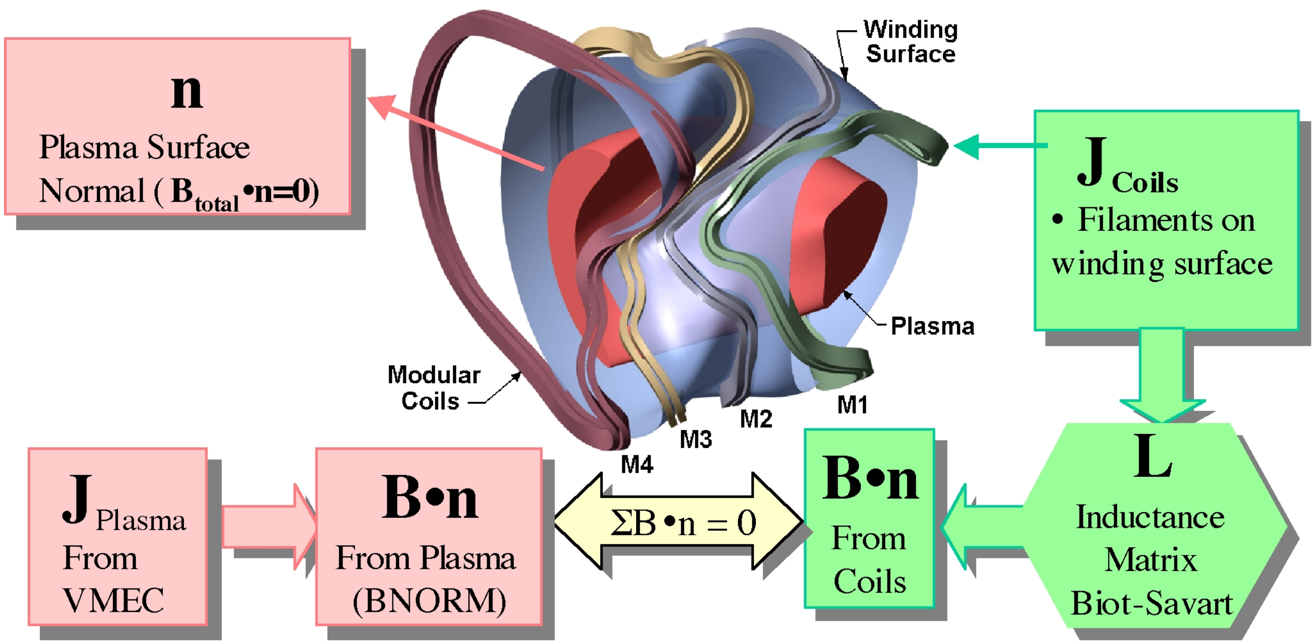






Coils to produce the physics optimized shape are "reverse–engineered":

Coil Design Process



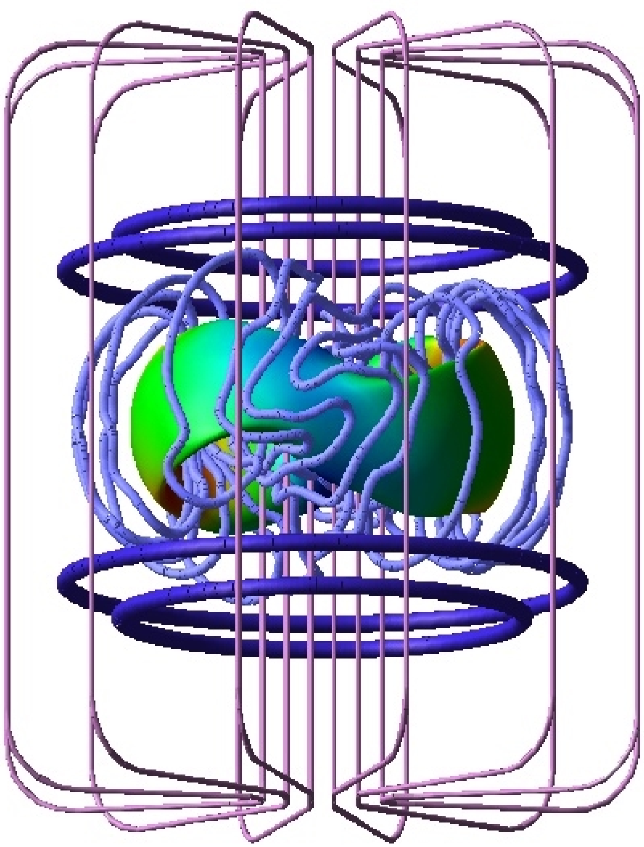
Vary "L" until L• J_{Coils} = B•n(Coils) ≈ -B•n(Plasma)

Coil design uses NESCOIL targets in physics optimization ⇨ COILOPT to synthesize discrete coils

STELLOPT Physics optimization

⇨ uses NESCOIL current sheet

–minimize coil complexity, current density, current density curvature and $B_{\perp}$



COILOPT varies coils on winding surface to minimize $B_{\perp}$

- incorporates modular, saddle, helical, toroidal, and vertical coil options
- variable winding surface shape
- engineering penalty targets: coil-coil and coil-plasma separation, coil current density and coil curvature

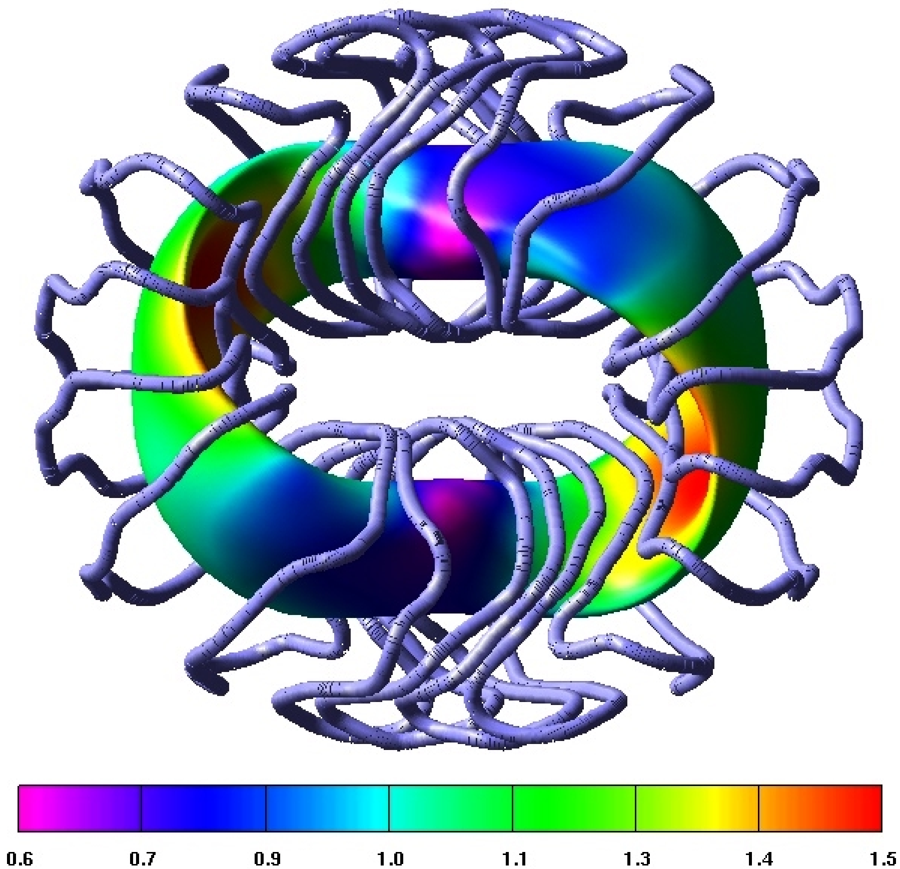
Merged STELLOPT/COILOPT

- Direct variation of coil geometry to minimize physics targets
- Can find neighboring equilibria
  - With similar physics, but coils that are easier to build
  - Smoother flux surfaces than those reconstructed from original coils

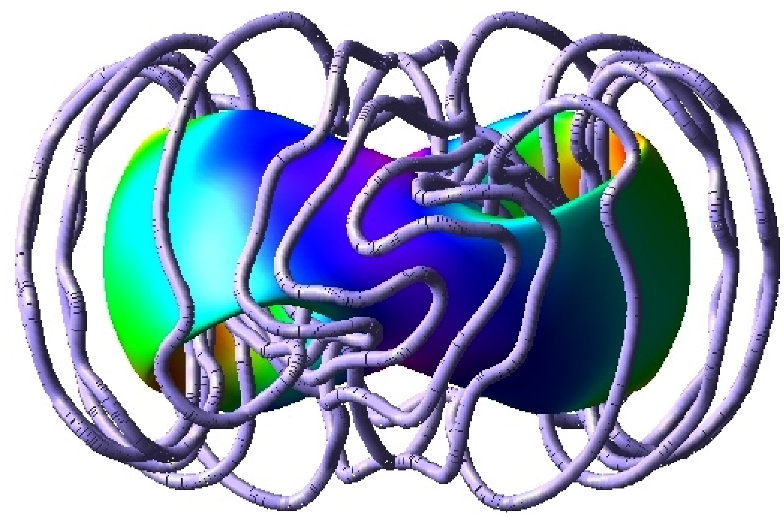
QPS Coil Design Choices

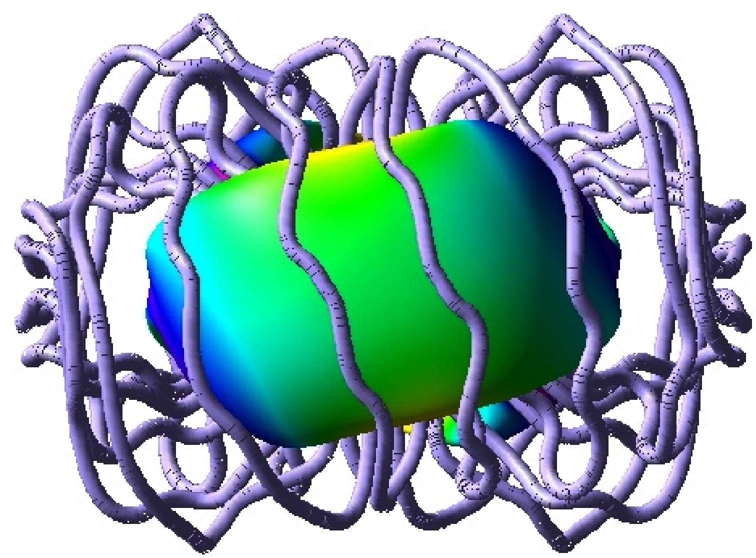
- For QPS we have found the following choices to work well:
  - 8 coils per field period (center two are split coils)
  - no coils on the symmetry planes
  - uniform modular coil currents
  - a pair of vertical field coils with fixed position and variable current
  - inclusion of a small background toroidal field (TF) $\propto$ 1/R
    - works best when TF field is in opposite direction to that produced by the modular coils
    - this increases modular coil currents, but reduces their toroidal variation -> improves coil-coil separation
- This has resulted in coil sets with $<\delta B_{normal}>$ ~ 0.58% that
  - provide good flux surface reconstruction
  - preserve physics properties of the original fixed boundary optimization

Views of the latest QPS configuration with modular filamentary coils

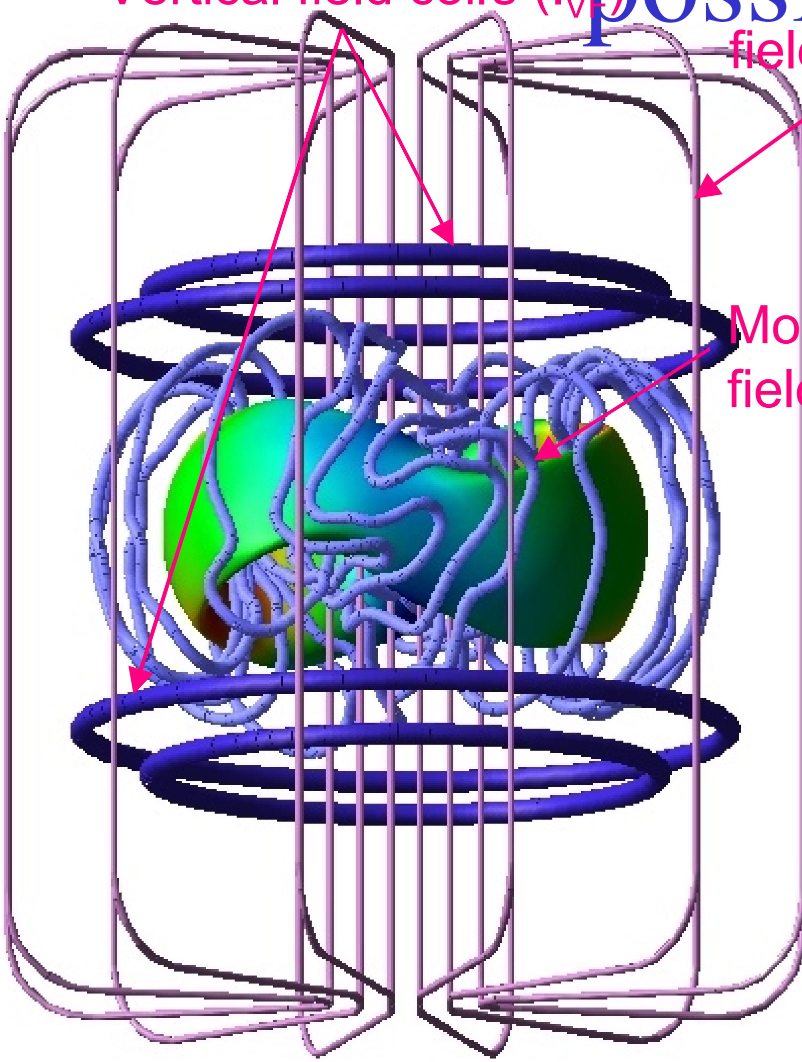


|B| in Tesla

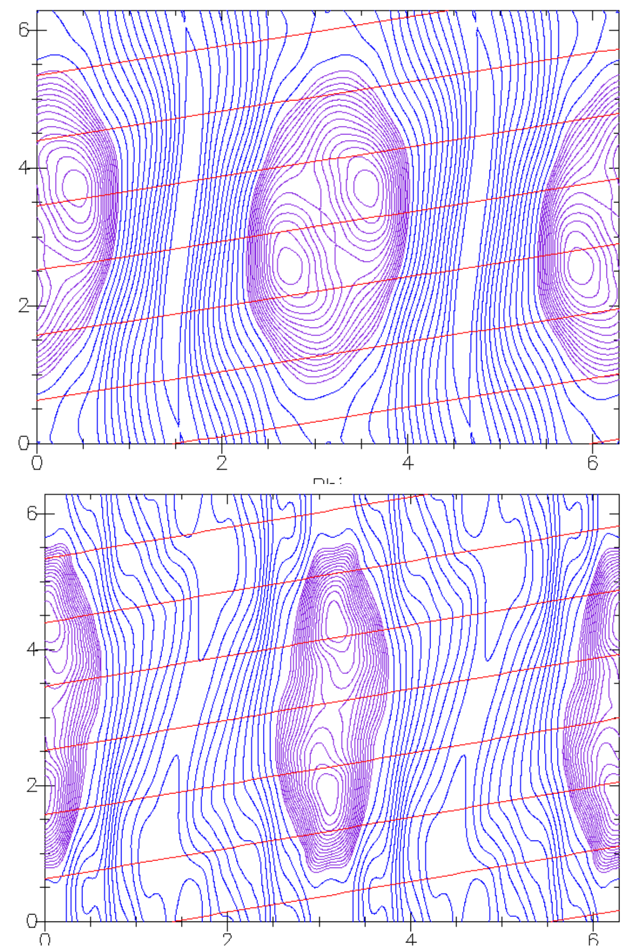




main coilsets. By changing these coil currents, different configurations are possible.



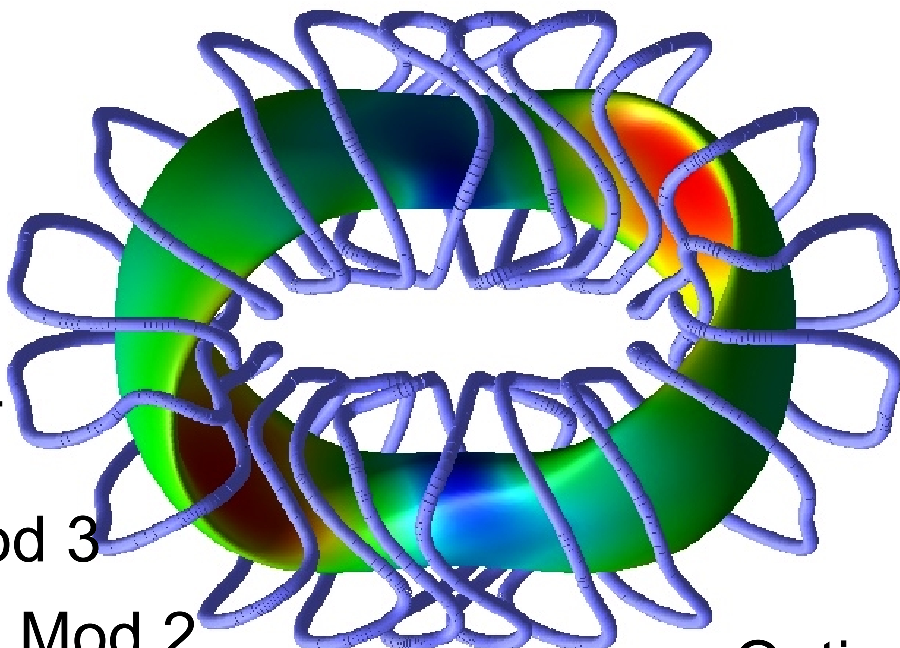
|B| for nominal case



|B| for high $\varepsilon_{eff}^{3/2}$ case

Transport properties can be influenced either by varying the vertical or toroidal fields.

We optimize, allowing currents to independently vary in the following modular coils + 2 circular VF coils + 1 elliptical VF + 1 set of planar TF coils



Mod 4

Mod 3

Mod 2

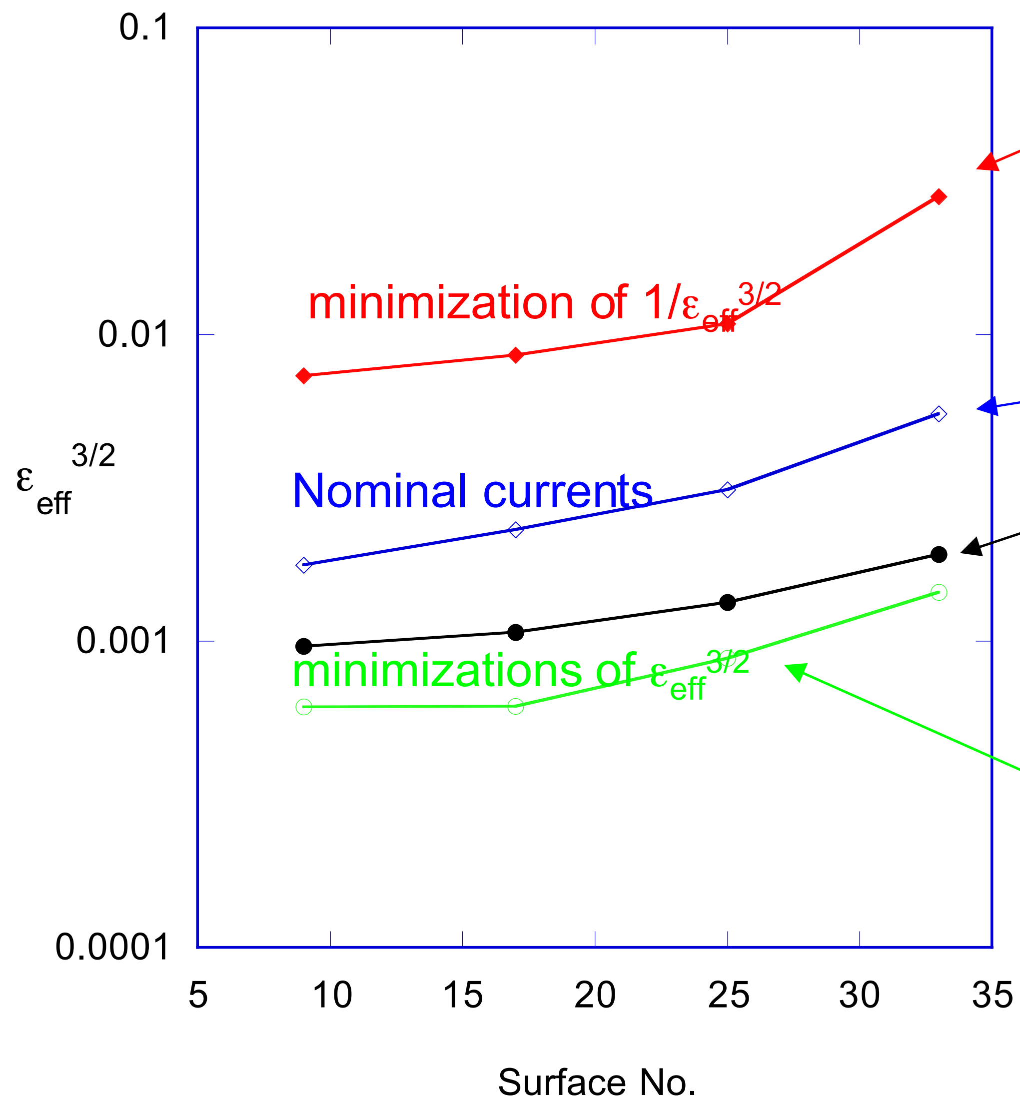
Mod 1
(split coils)

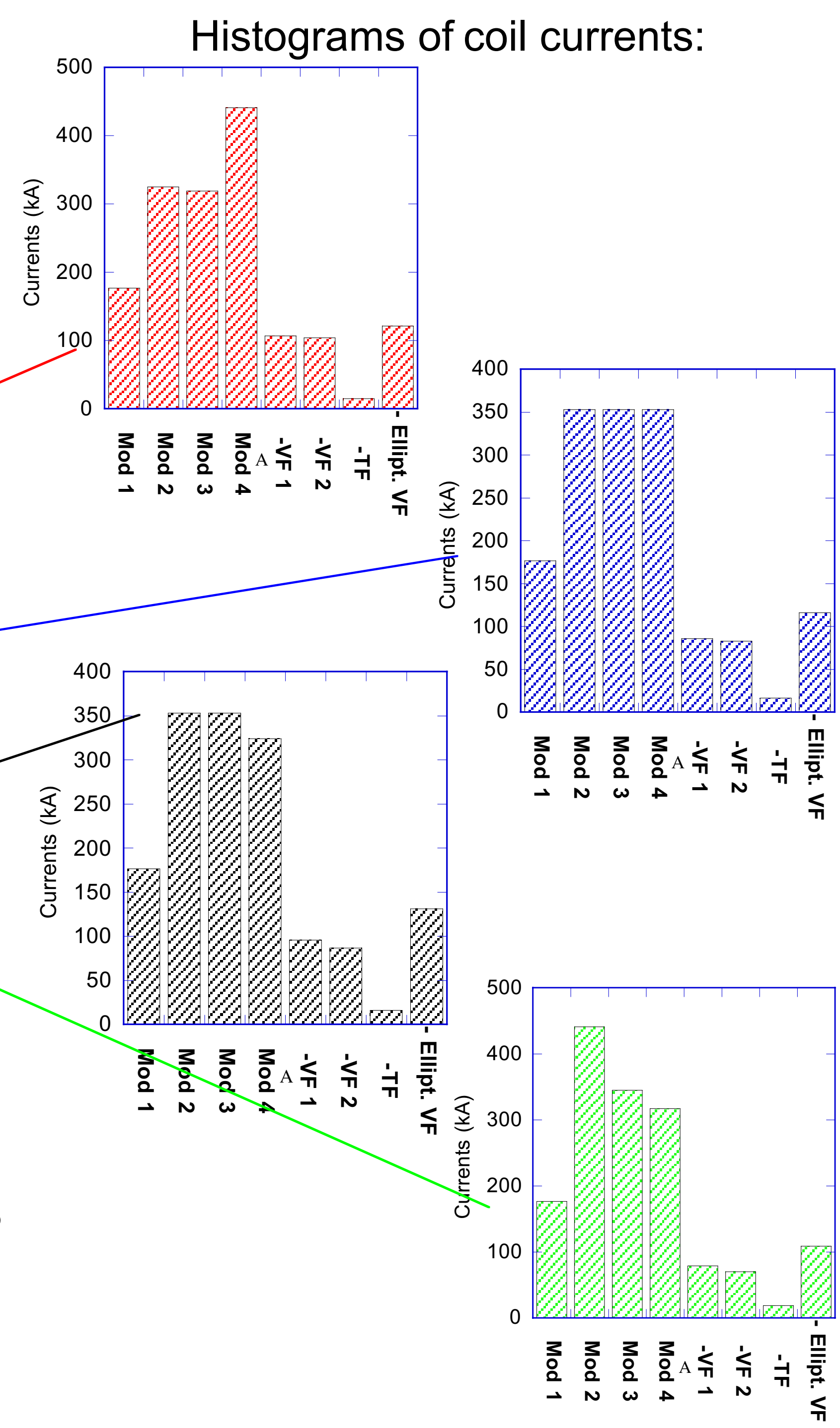
This results in 7 independent currents since the current in one coilset can be fixed as a normalization (we fix the Mod 1 currents for this study)

Optimizations have been done for:

- transport at $\beta = 0$, $I_{plasma}=0$
  (both best and worst cases)

Effective ripple vs. coil current distribution





Conclusions

- A systematic plasma optimization and modular coil synthesis procedure have been developed and used to design compact stellarators with Quasi-Poloidal symmetry (QPS)
  - both plasma and coil optimization codes take good advantage of parallel computing platforms and allow new targets to be easily incorporated
- This has led to the QPS device
  - A = 2.7, iota = 0.2 to 0.3
  - neoclassical transport subdominant to ISS95 (by a factor of 2 - 8)
  - first stability limits around $\langle\beta\rangle = 2\%$, second stability up to $\langle\beta\rangle = 15\%$
  - Modular coils have been developed that have good engineering feasibility, flux surface reconstruction, and preserve physics properties
- VF and TF coils provide flexibility to test transport/stability

Future Optimization Projects

- Although the QPS design is gradually becoming fixed, there will be further needs for optimization:
  - Adjustment of coil currents: modular(4), vertical(6), toroidal (12)
  - Location of magnetic loops and interpretation
  - Future devices
- Future target development
  - Monte Carlo fast ion confinement
  - Poloidal viscosity minimization
  - Alfven mode suppression --> would like AE continua to be vertical rather than horizontal --> maximize $|d\omega_{AE}/d\psi|$
- Computational improvements
  - Want to prepare for “fatter node” SMP (Symmetric Multi Processor) computers
  - Be able to use O(100) -> O(1000) processors
  - Requires two-level parallelism
    - OpenMP within individual functions (e.g. parallelize over flux surface loops)
    - MPI inter-node communication, one function evaluation per node