QPS Plasma and Coil Optimization

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+ Valuable collaboration with the NCSX project: M. Zarnstorff[3], H. Mynick, L.-P. Ku[3], et al.

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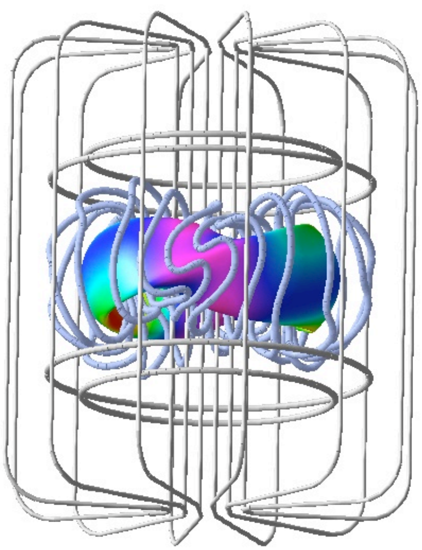

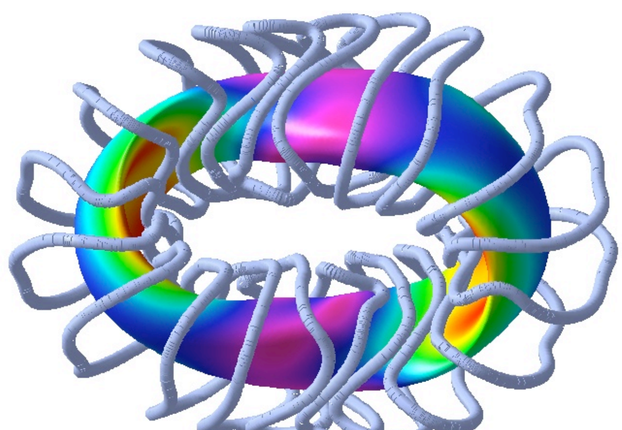

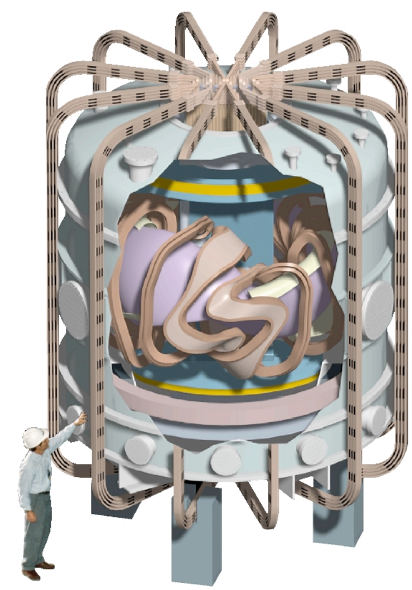

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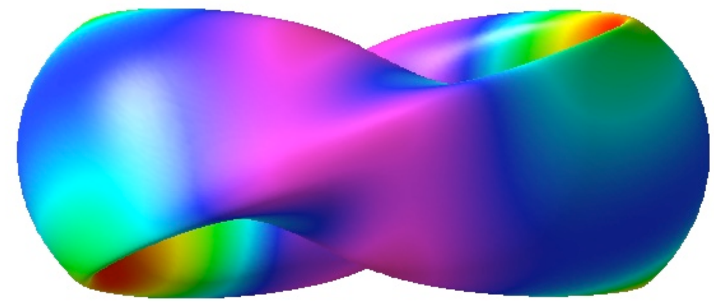
Goals of quasi-poloidally (QP) symmetric stellarators

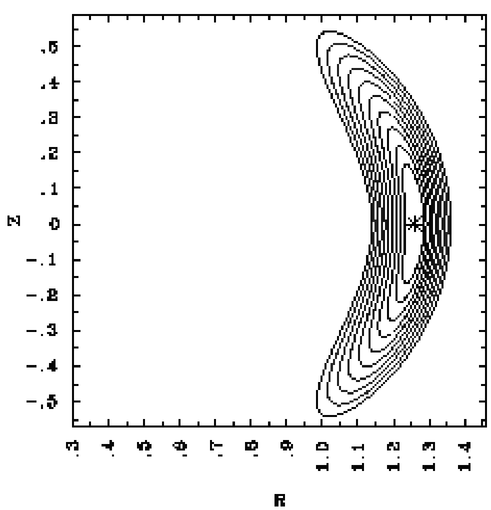
- Closer **B** and ∇**B** alignment than with other forms of symmetry
  - For exact QP symmetry, P_θ is constant of the motion rather than P_ϕ
  - reduces radial drift; banana thickness ~ $\rho_{toroidal}$ rather than $\rho_{poloidal}$
- Minimum flow damping in the direction of $\mathbf{E}_r$ x **B**
  - 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

  (Next talk by Andrew Ware)
- 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)]

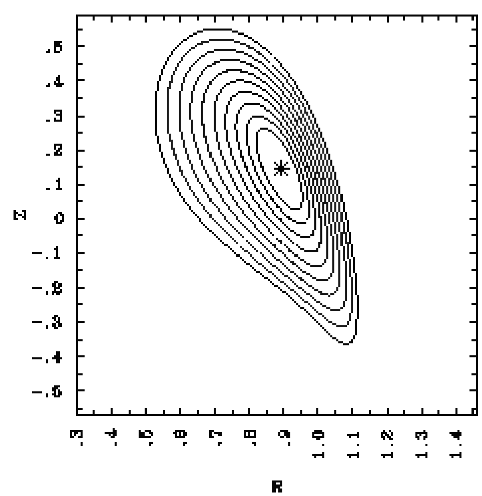
Properties of quasi-poloidally symmetric configurations

– 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: □~ 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 <□> in the 1.5 to 2% range
  - Stable to neoclassical tearing modes

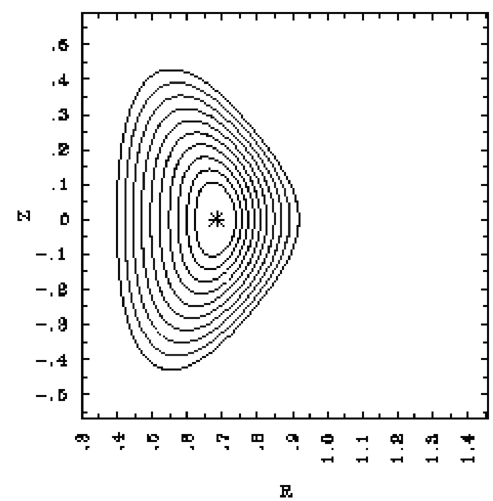




N_{fp}□ = 0°



N_{fp}□ = 90°



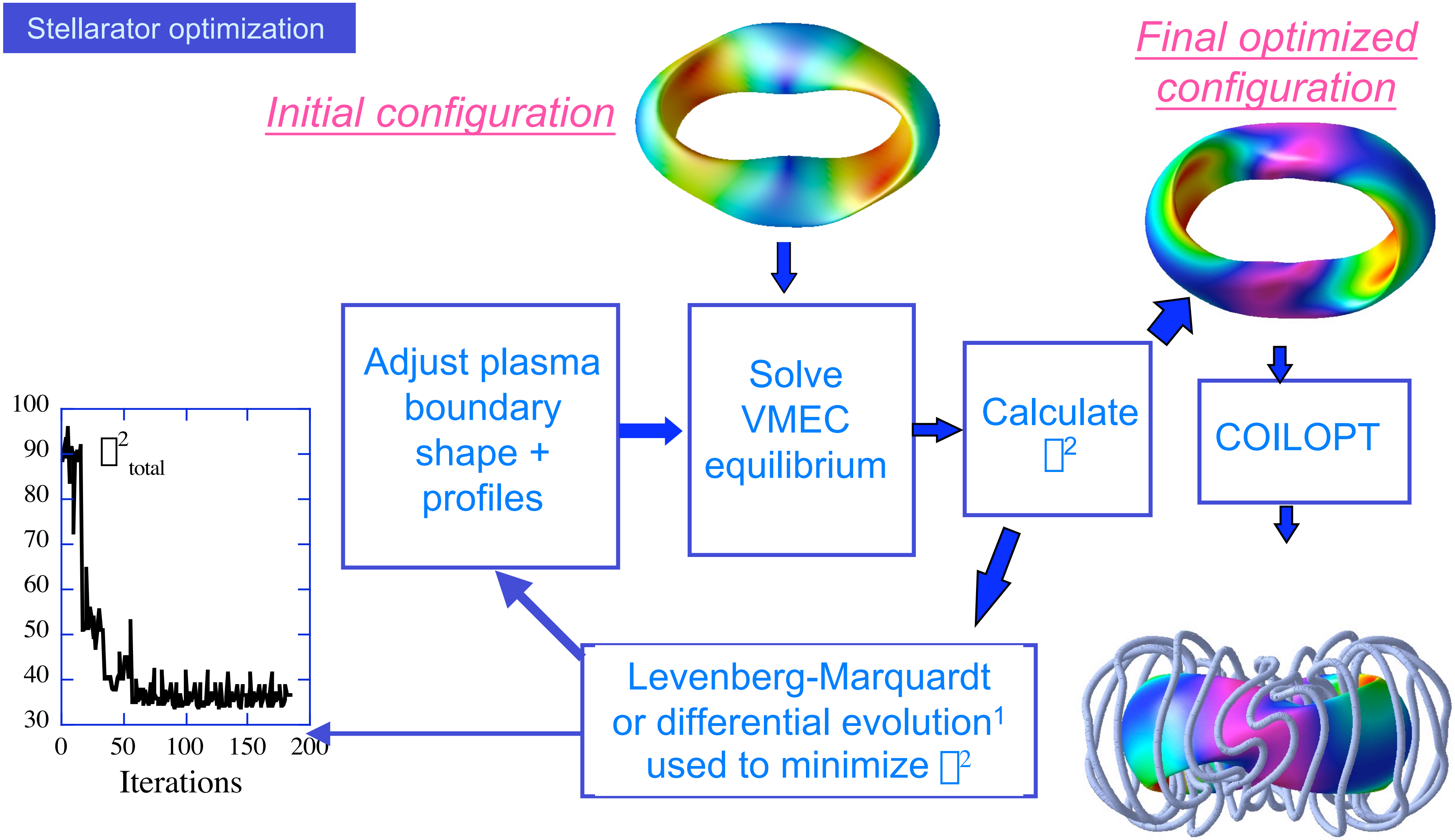
N_{fp}□ = 180°

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

[1]see poster by H. Mynick, et al. on differential evolution

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	$J = J(□)$ $B_{min} = B_{min}(□)$ $B_{max} = B_{max}(□)$
Nearby quasi-symmetries	Collisionless confinement of all orbit topologies	Minimize B_{mn} if $m \neq 0$ (QP) Or if $n \neq 0$ (QA)
Collisional transport coefficients	Neoclassical transport	L_{11} coefficient from DKES at $□^* \sim 1$
Effective ripple $□_{eff}$	1/□ neoclassical transport regime	$□_{eff}^{3/2}$ from NEO[1] code
Large orbit effects	Energetic particle confinement	Reduced Monte Carlo model for alphas

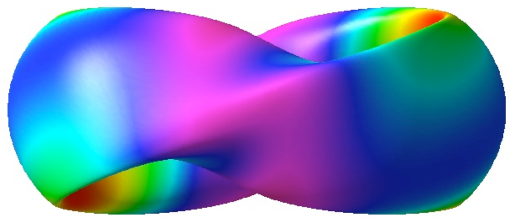
Currently existing (rows 1–4)

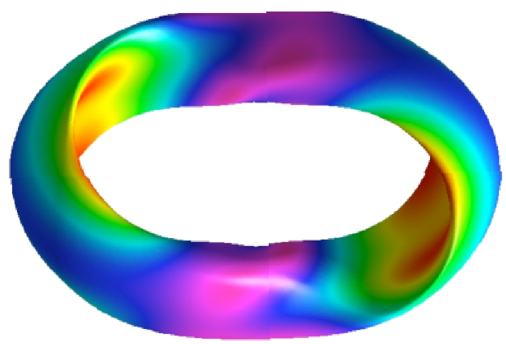
Future (row 5)

[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:

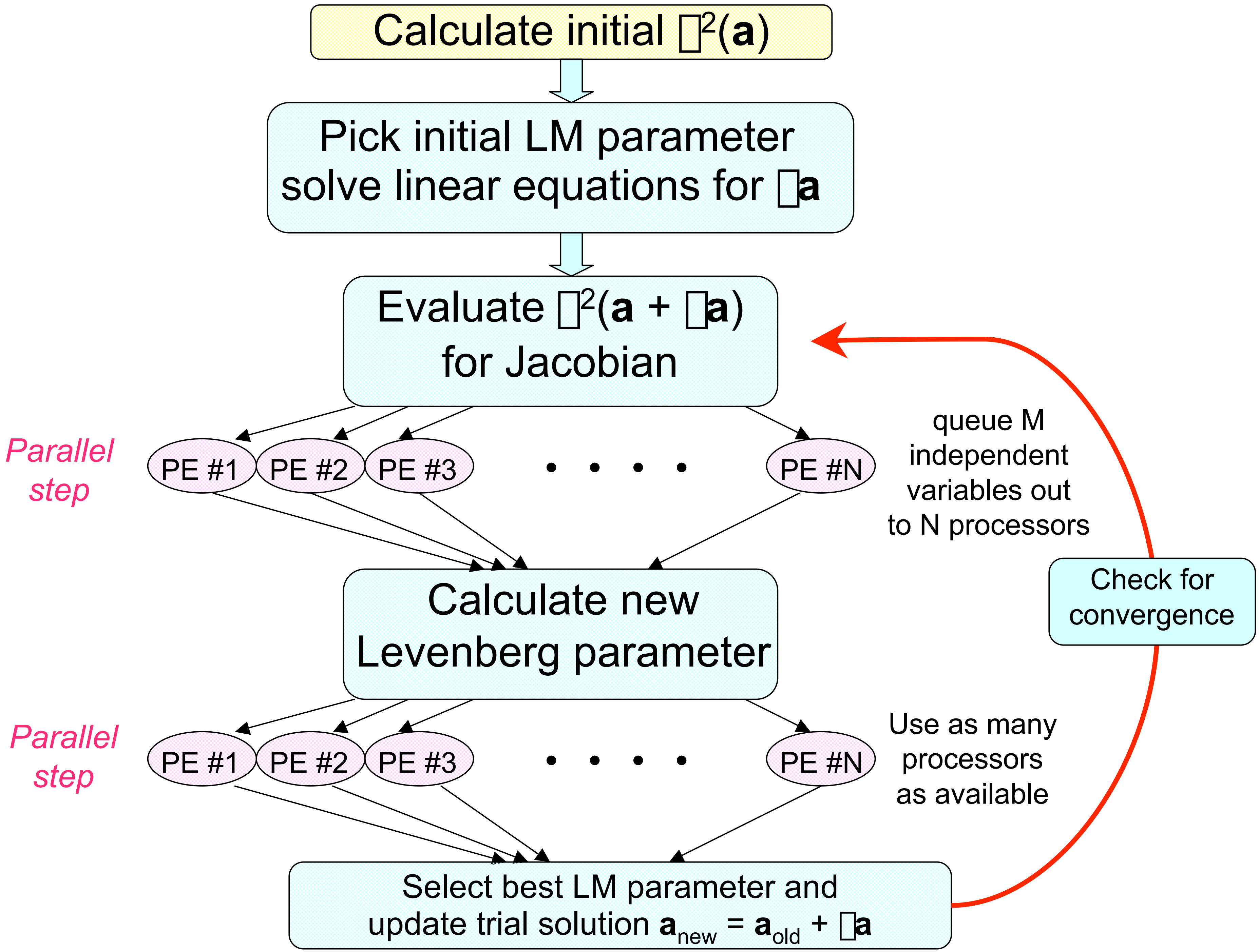
<u>**Targets**</u> **(Physics/Engineering)**	**Example**
Transport Measures	See previous slide
Current profile	self-consistent I_{BS}, I(□) goes to 0 at edge
Limit maximum plasma current	e.g., I_{max} < 60 kAmps at <□> ~ 2%
Iota profile	*i*(□) = 0.2 (□=0) 0.3 (□=1)
Magnetic Well, Mercier	V" < 0, D_M > 0 over cross section
Ballooning stability	<□> ~ 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

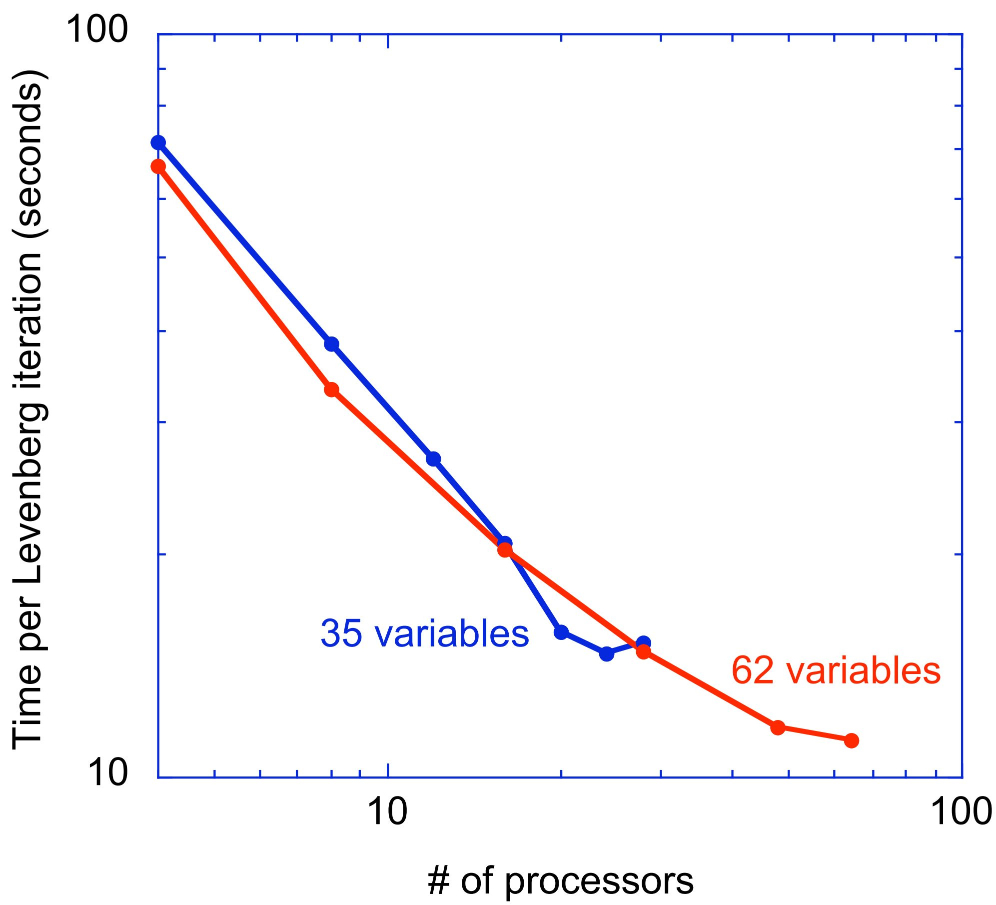
- Uses a global, coarse-grained parallelization over the 30 - 60 independent variables (i.e., shape and profile coefficients)
  - done over the periodic Jacobian evaluations and in the estimation of the Levenberg parameter
  - this simplifies the development of modules used to calculate the target functions (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 χ2(a)
Pick initial LM parameter
solve linear equations for Δa
Evaluate χ2(a + Δa)
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 anew = aold + Δa

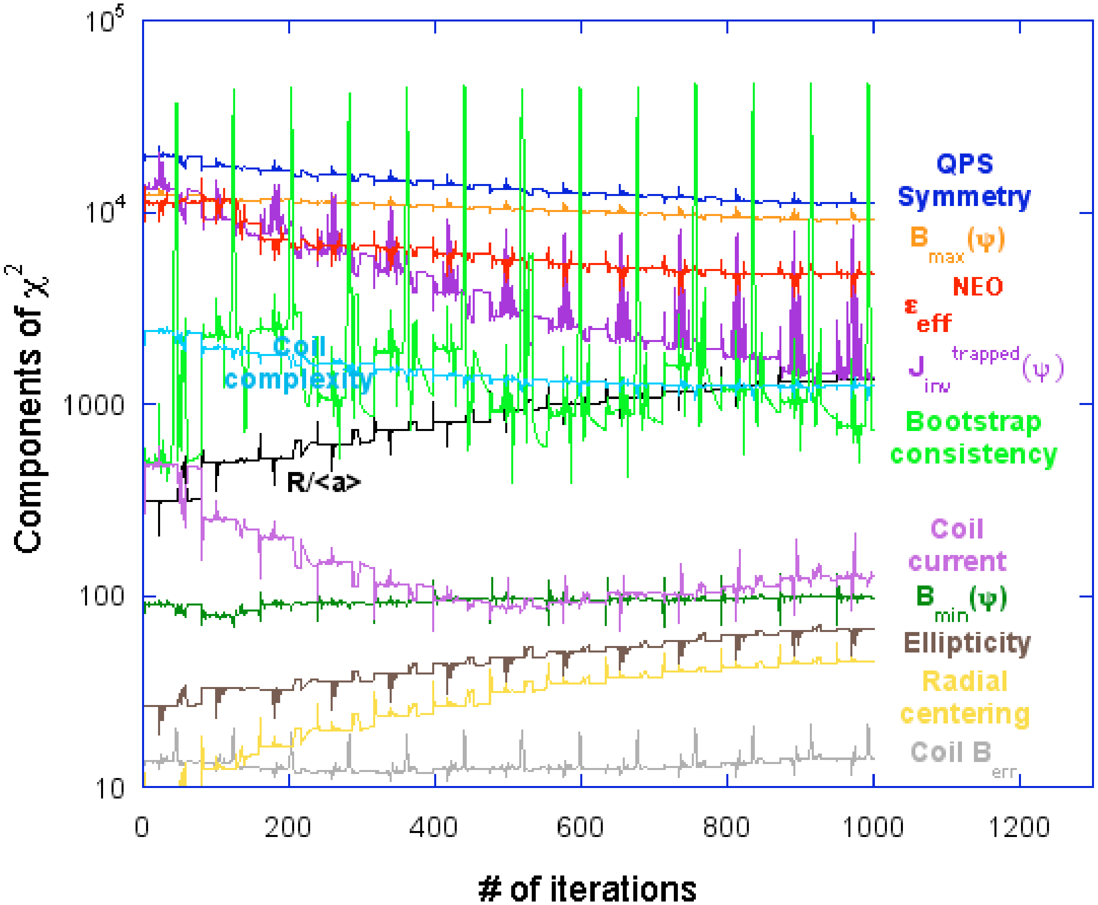
Parallelization has made our stellarator optimization significantly faster.

- 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

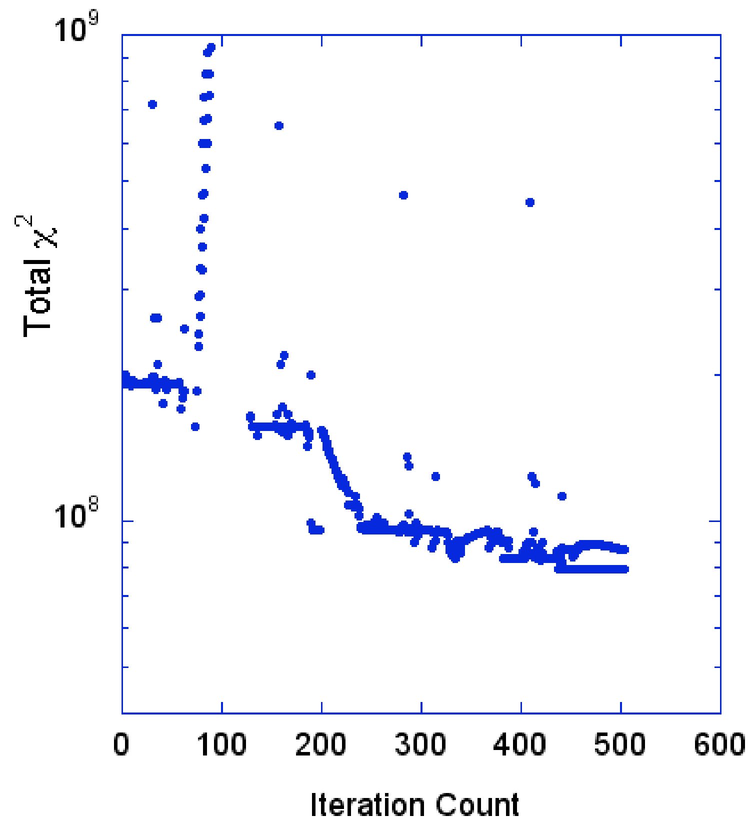


Reduction in target functions with iterations

Individual targets

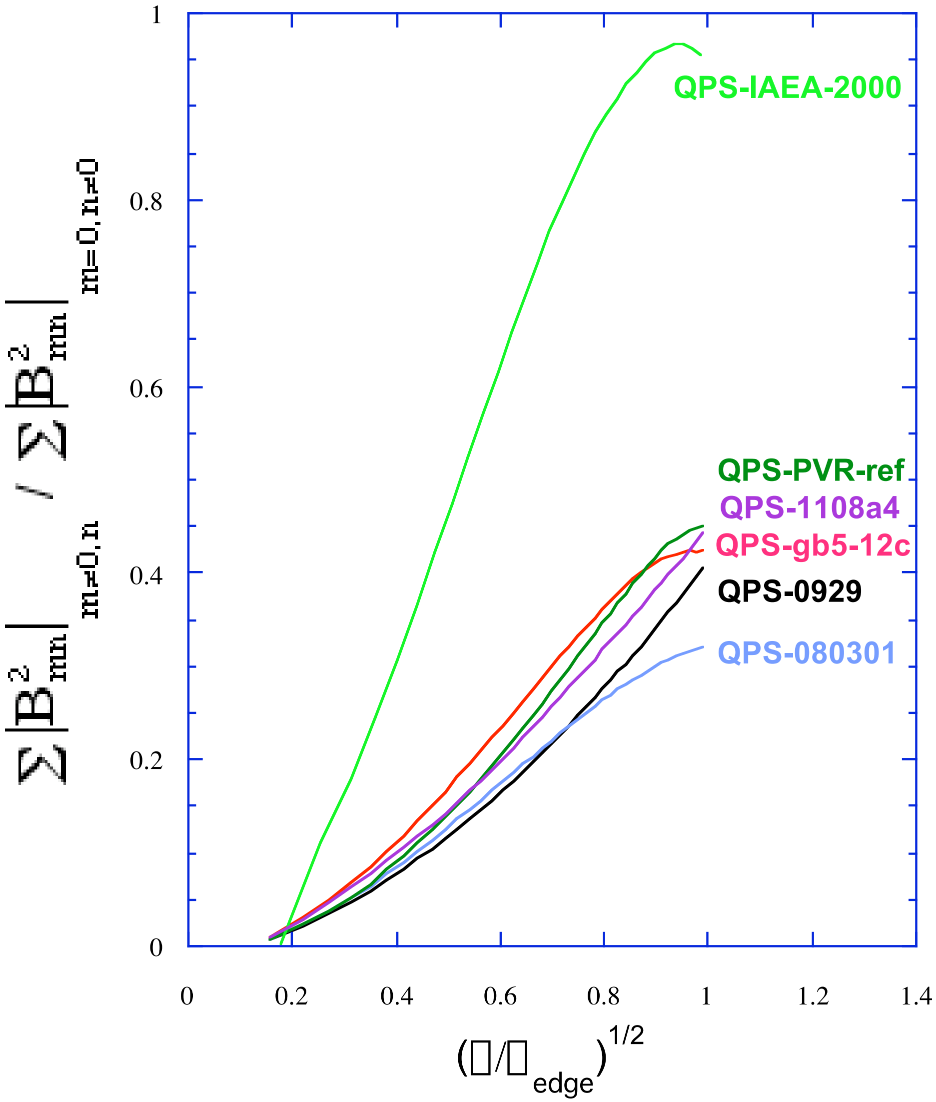


Overall χ^2

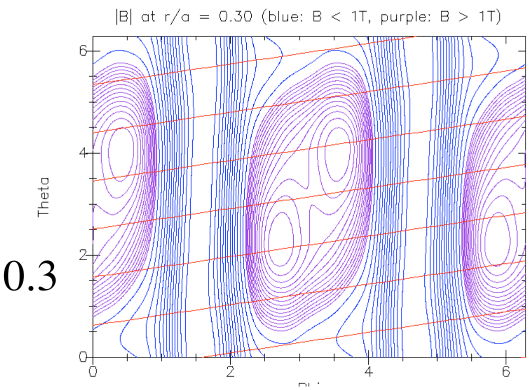


Our optimizations have resulted in increased poloidal symmetry from the initial QPS-IAEA-2000 device

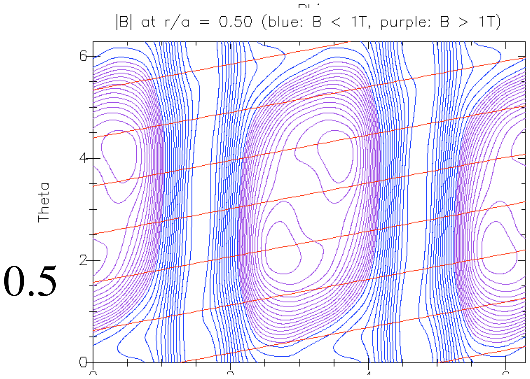
(shown here as the ratio of the magnetic energy in the non-poloidally symmetric modes to that in the poloidally symmetric modes)



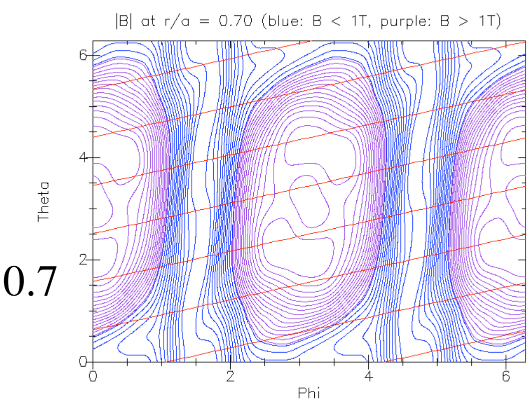
$\sqrt{\square/\square_{edge}} = 0.3$



$\sqrt{\square/\square_{edge}} = 0.5$

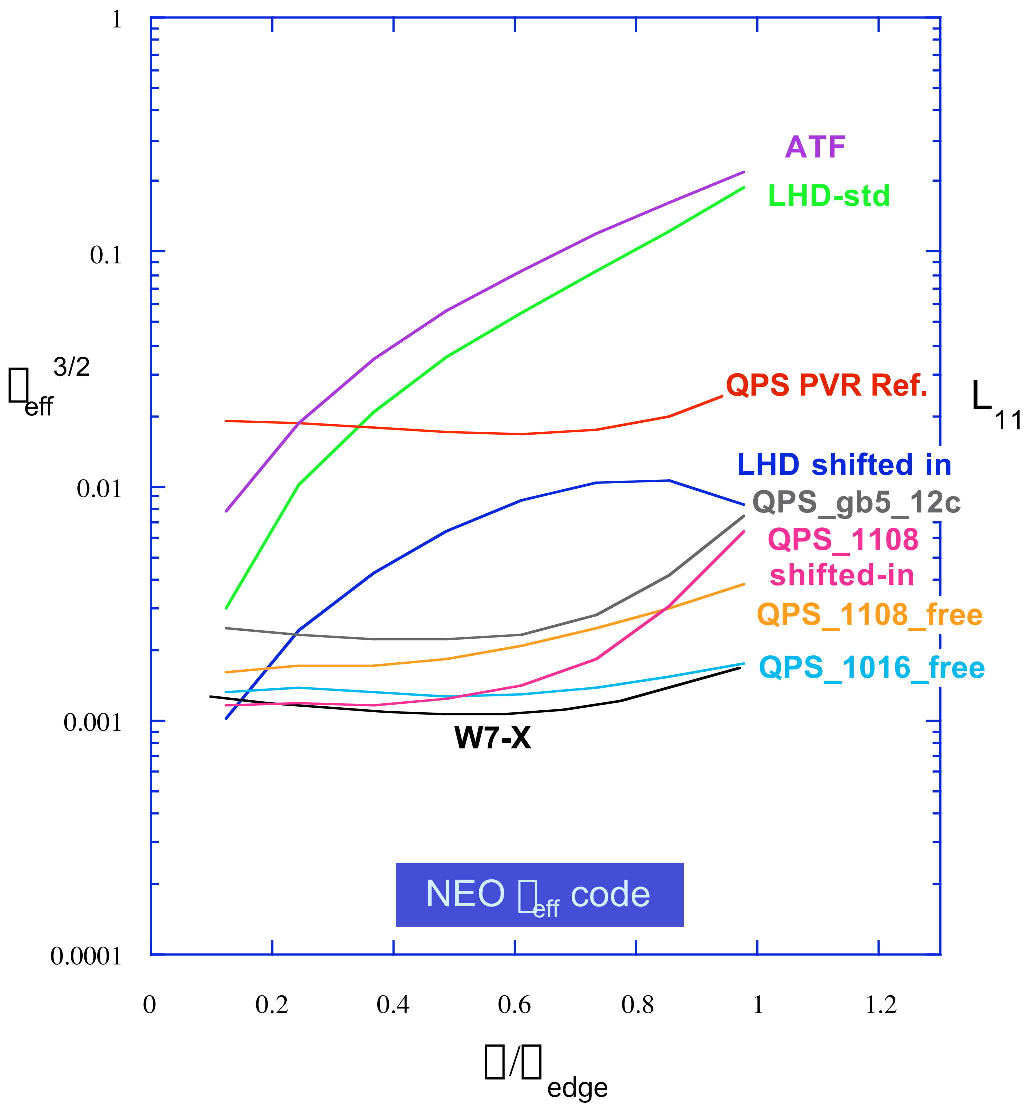


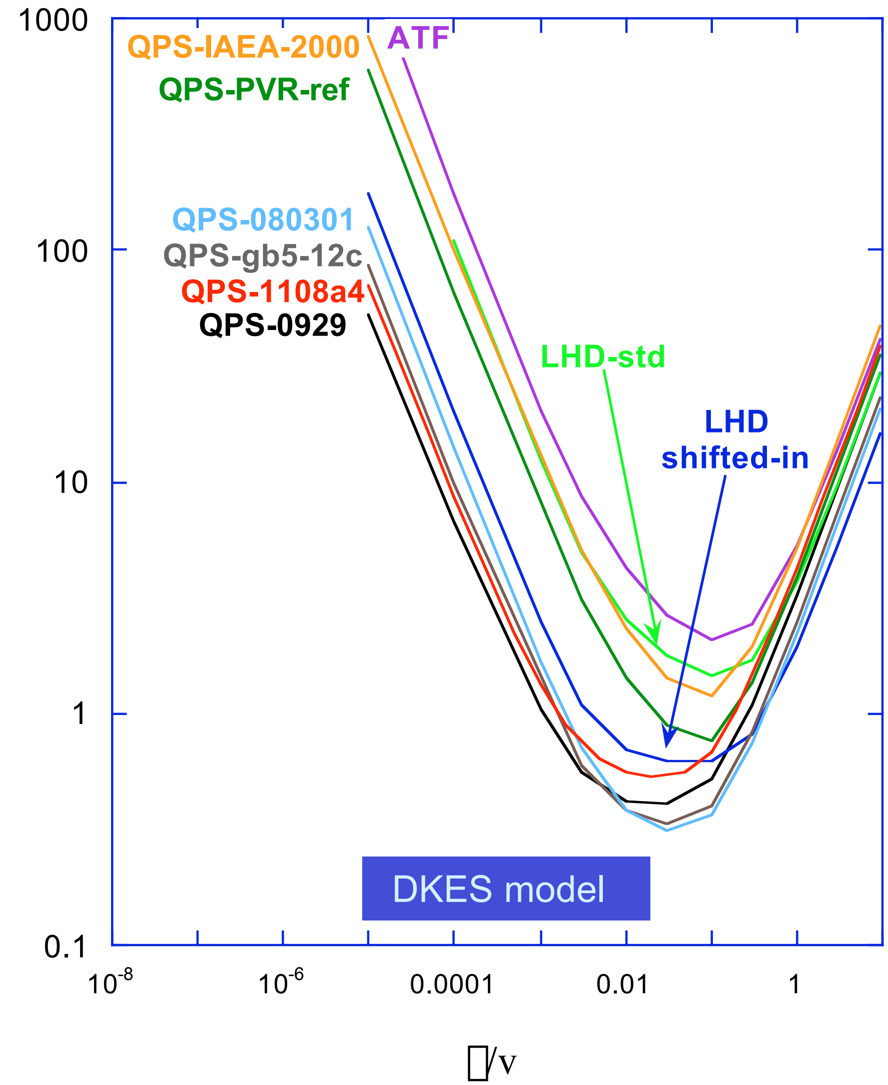
$\sqrt{\square/\square_{edge}} = 0.7$



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

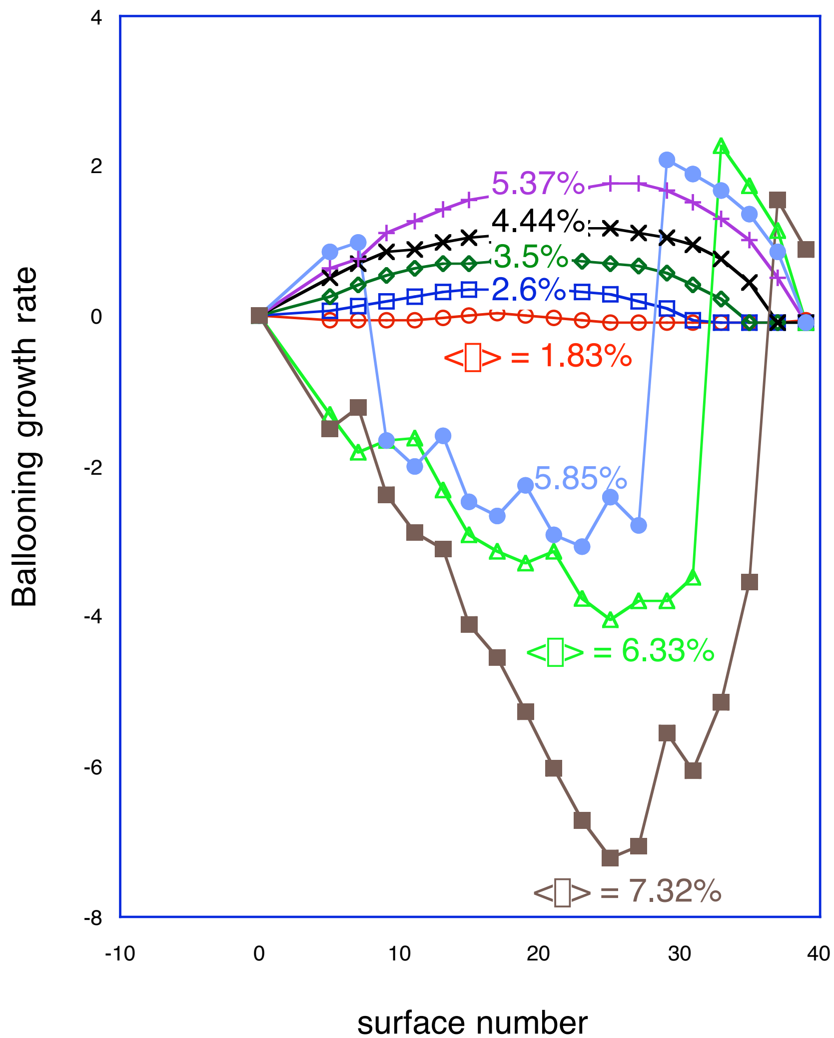
[1]Nemov, V. V., Kernbichler, W., et al., Phys. Plasmas **6**, 4622 (1999).

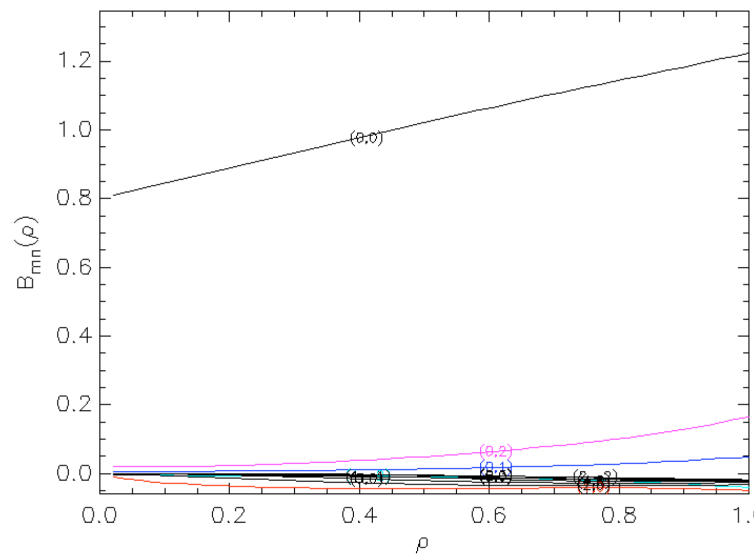


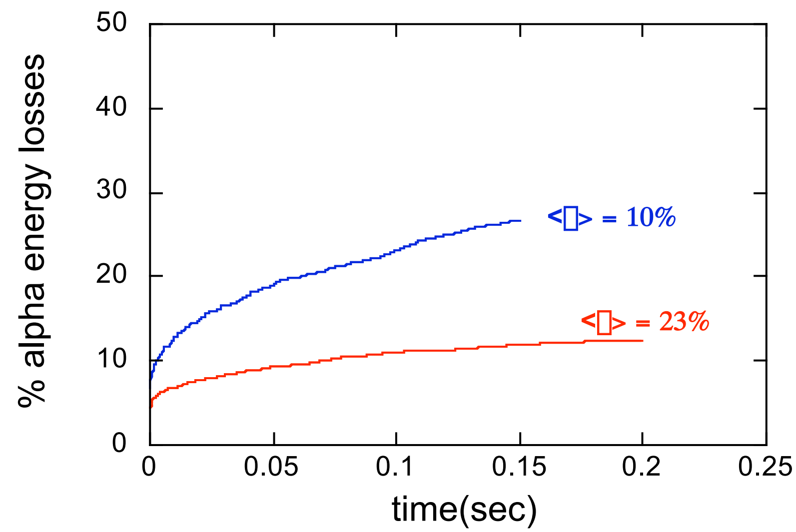


QPS configurations have second stability regimes

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

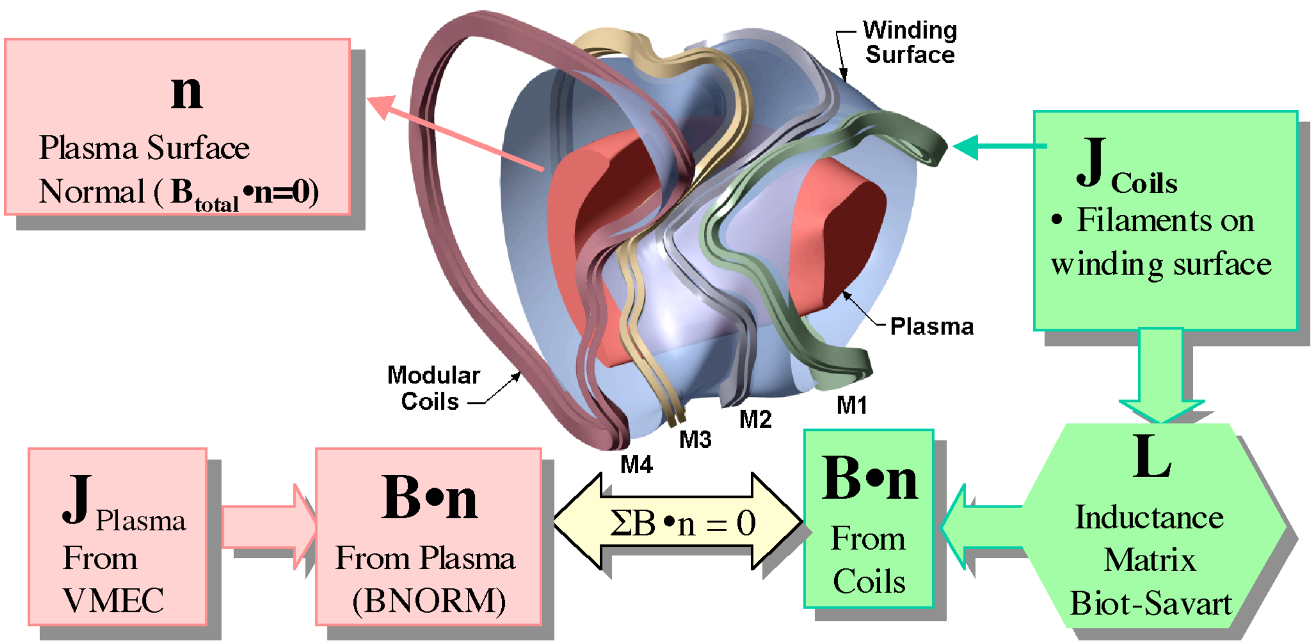






Coils to produce the physics optimized shape are “reverse–engineered”:

Coil Design Process



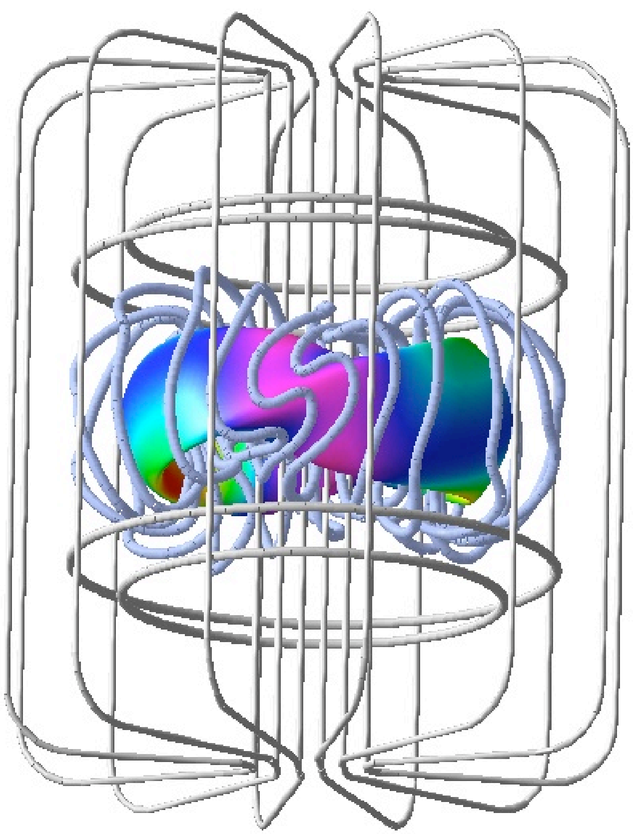
Vary “L” until $L \bullet J_{Coils} = B \bullet n(\text{Coils}) \approx -B \bullet n(\text{Plasma})$

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

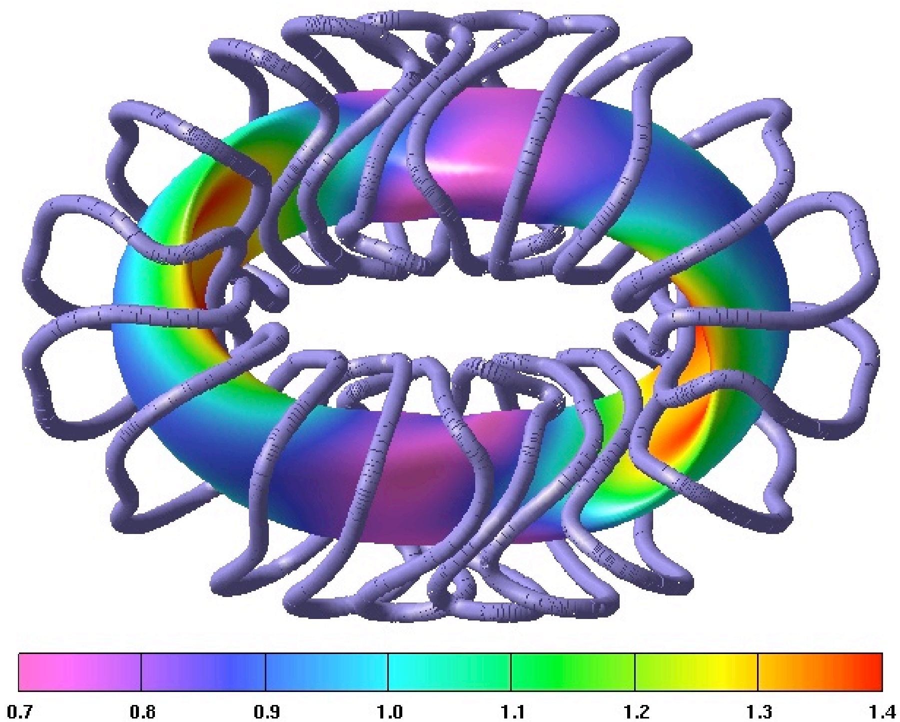
– Can find neighboring equilibria

- With similar physics, but coils that are easier to build
- Smoother flux surfaces than those reconstructed from original coils

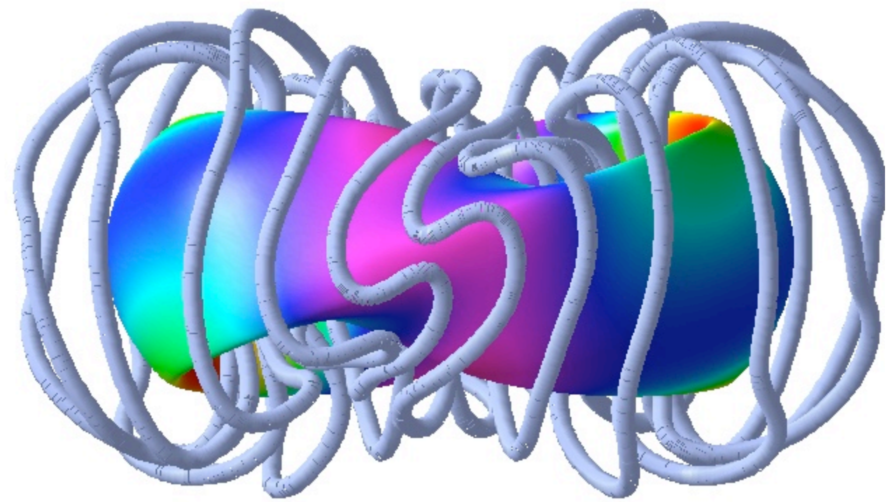
QPS Coil Design Choices

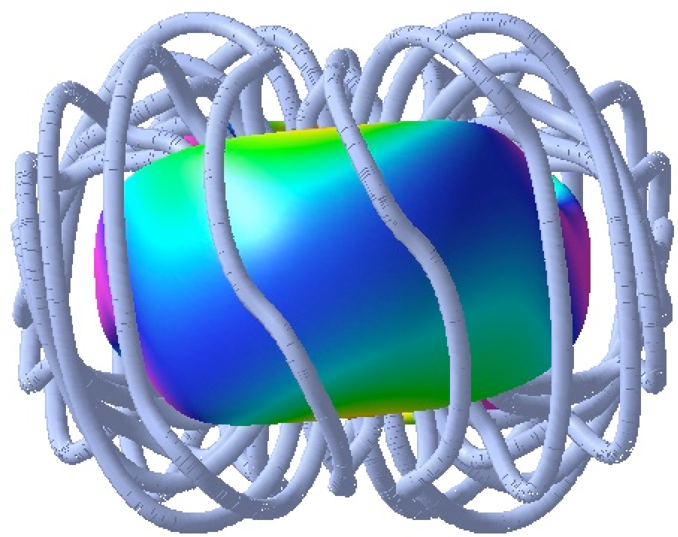
- For QPS we have found the following choices to work well:
  - 8 coils per field period (center two are split coils)
  - no coils on the symmetry planes
  - uniform modular coil currents
  - a pair of vertical field coils with fixed position and variable current
  - inclusion of a small background toroidal field (TF)   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 $\langle \square B_{normal} \rangle$ ~ 0.8% 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



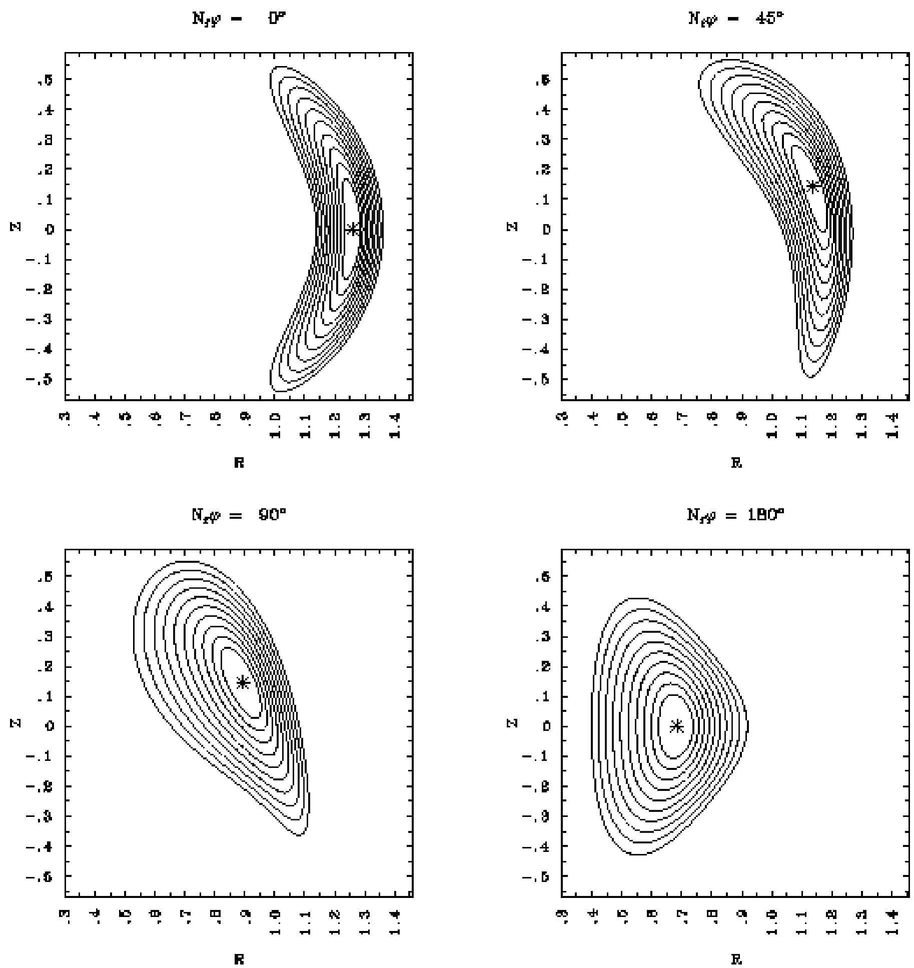
|B| in Tesla



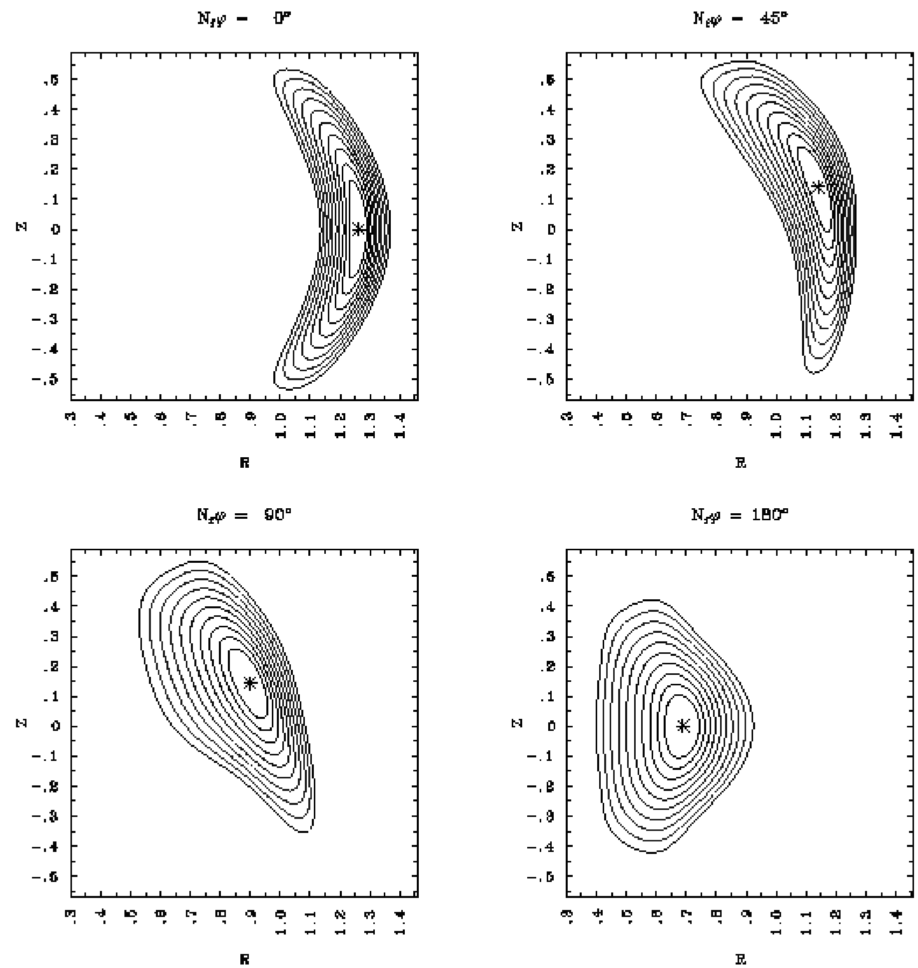


These coils preserve the flux surface shape between fixed and free boundary equilibrium solutions:

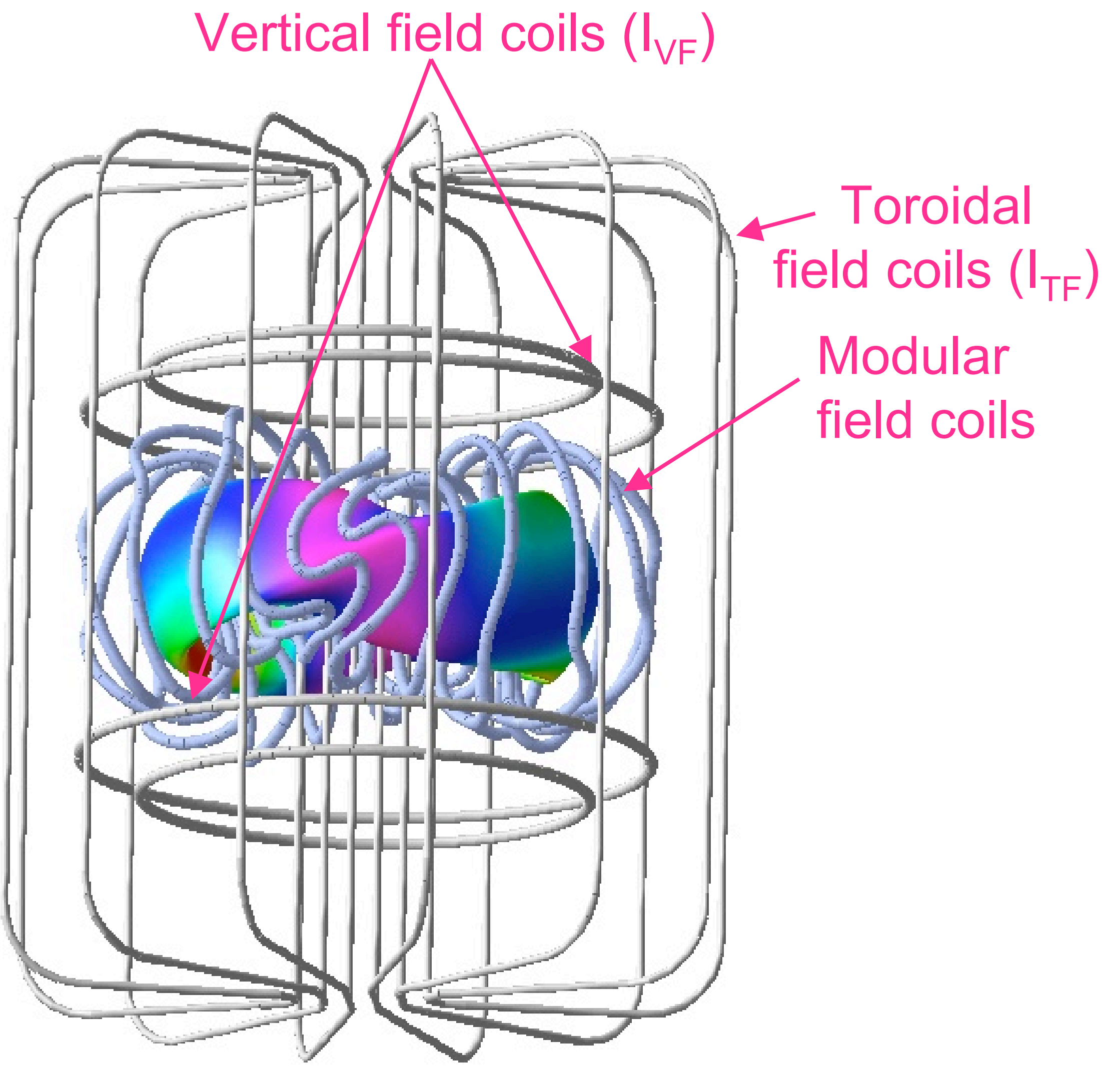
QPS_{1108a4} fixed boundary



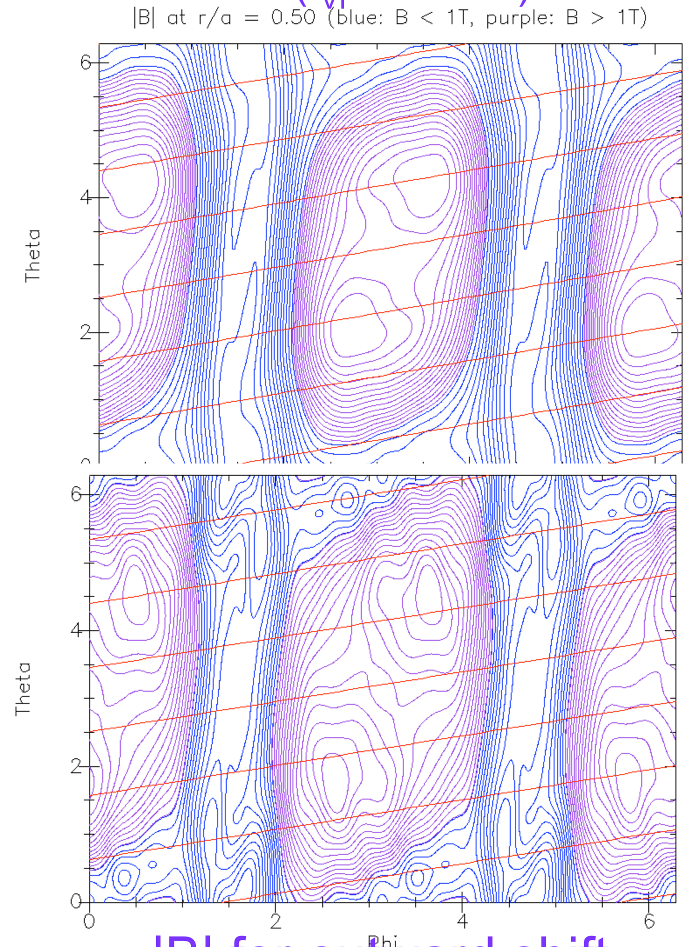
QPS_{1108a4} free boundary



Flexibility is provided in QPS by 3 main coilsets. By changing these coil currents, different configurations are possible.

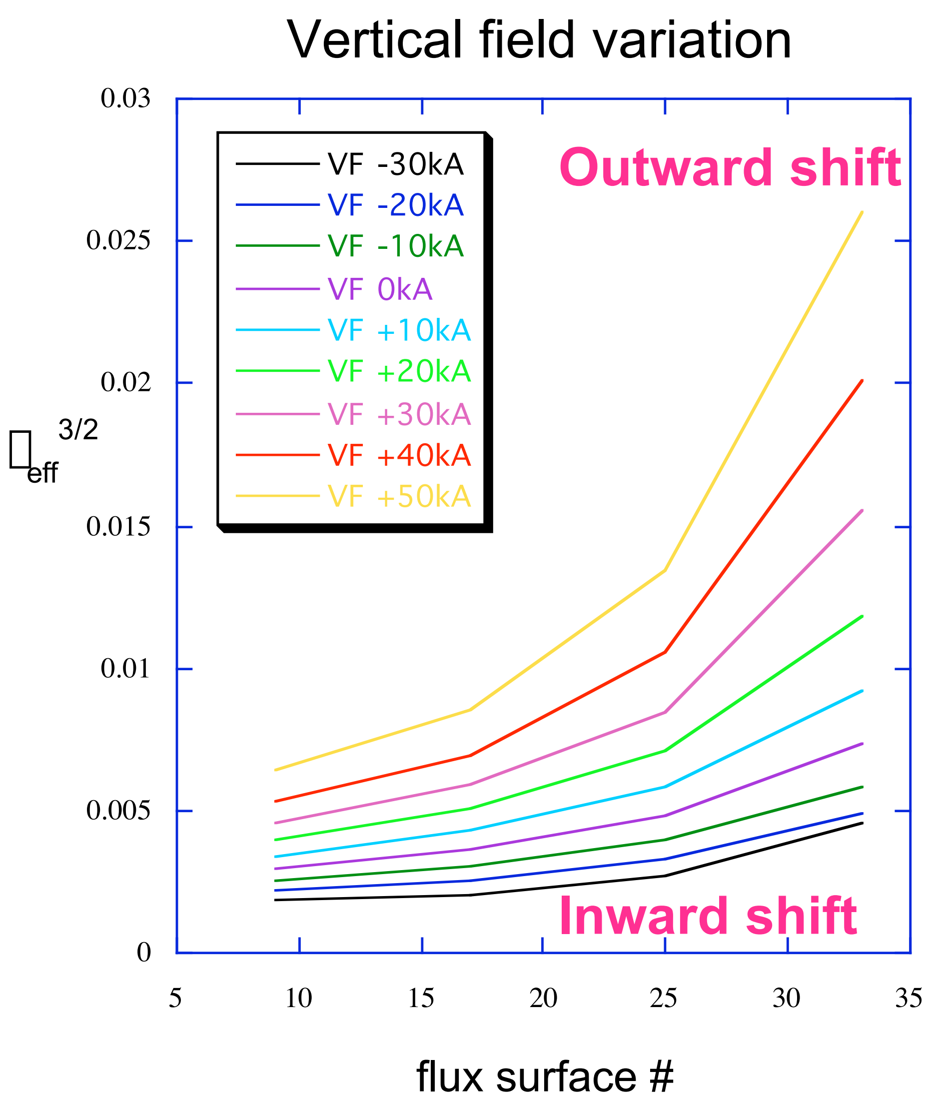


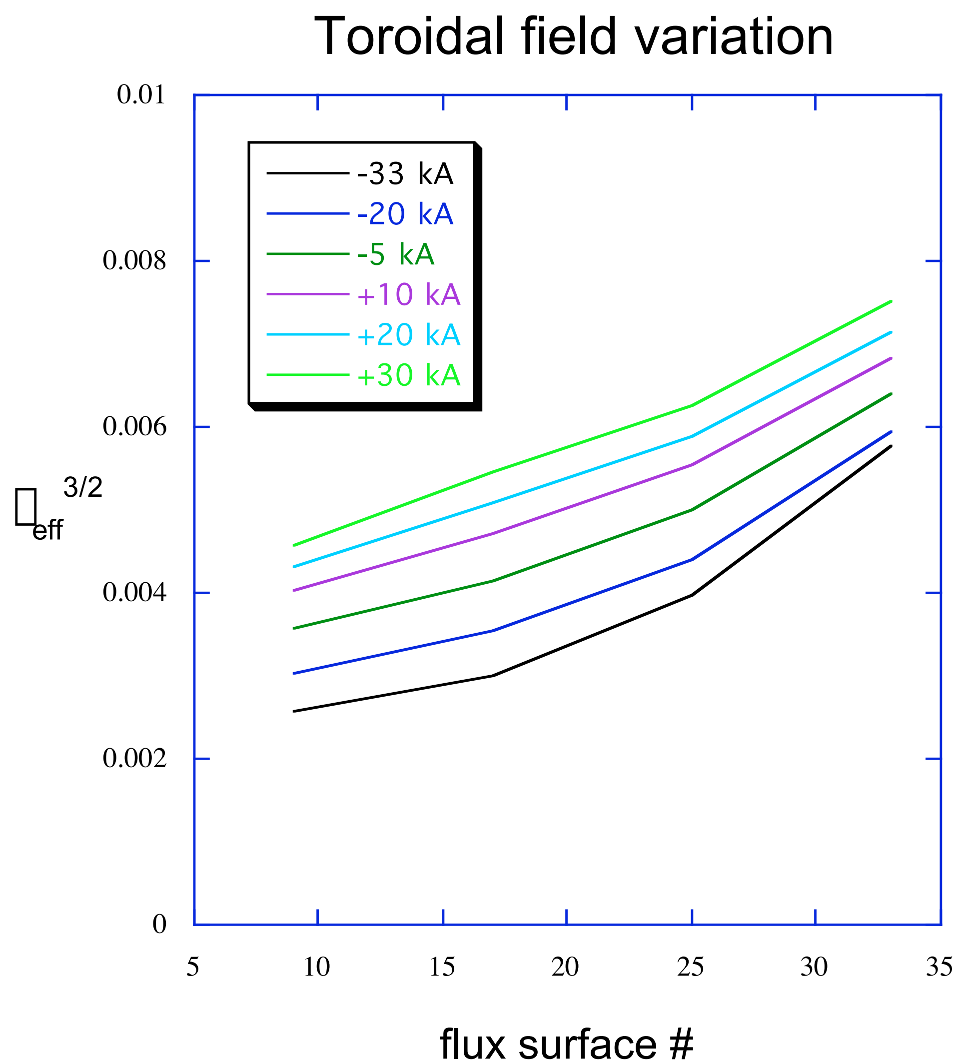
|B| for inward shift
(I_{VF} = -30kA)



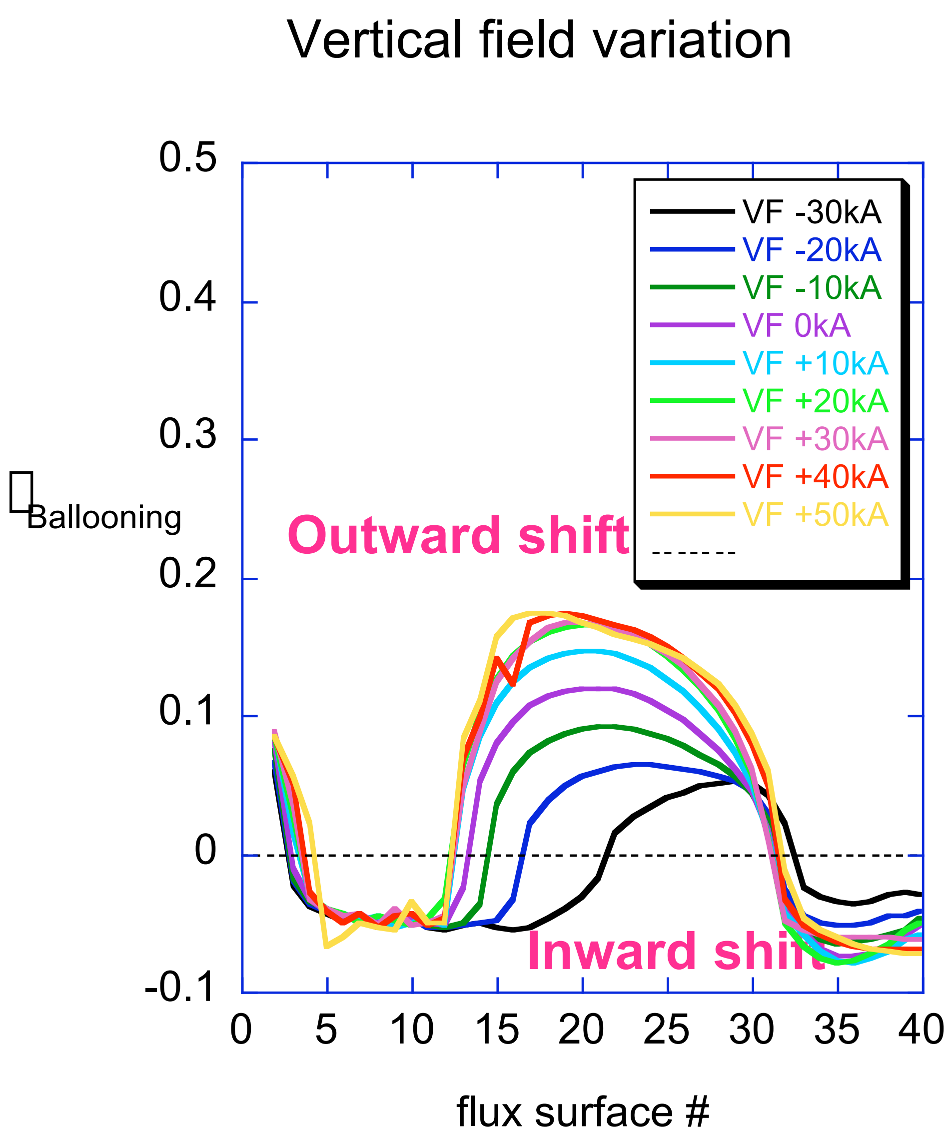
|B| for outward shift
(I_{VF} = +50kA)

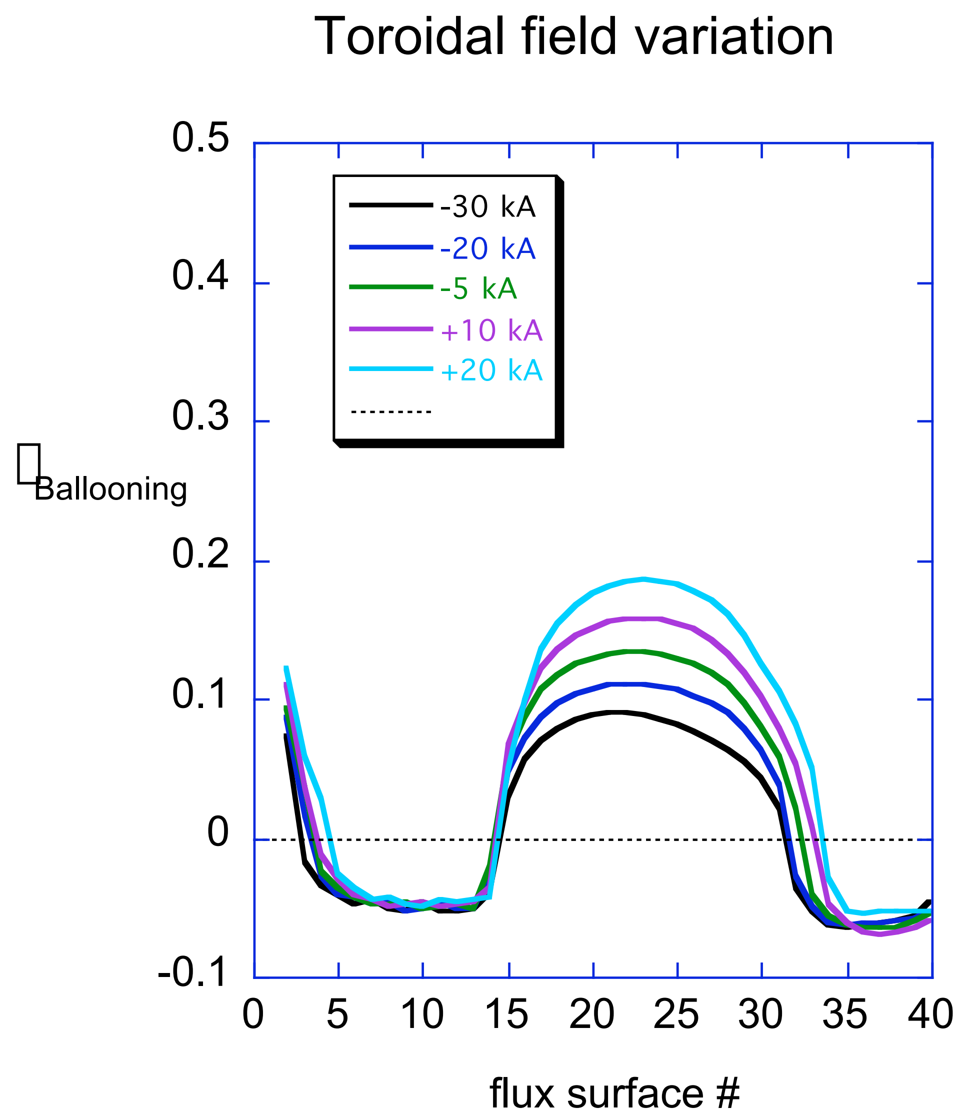
Transport properties can be influenced either by varying the vertical or toroidal fields.





Ballooning stability can also be influenced through vertical or toroidal field variation.





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 <□> = 2%, second stability up to <□> = 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 - differential evolution algorithm[1]
  - Poloidal viscosity minimization
  - Alfven mode suppression --> would like AE continua to be vertical rather than horizontal --> maximize $|d\square_{AE}/d\square|$
- 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

[1]see poster by H. Mynick, et al. on differential evolution