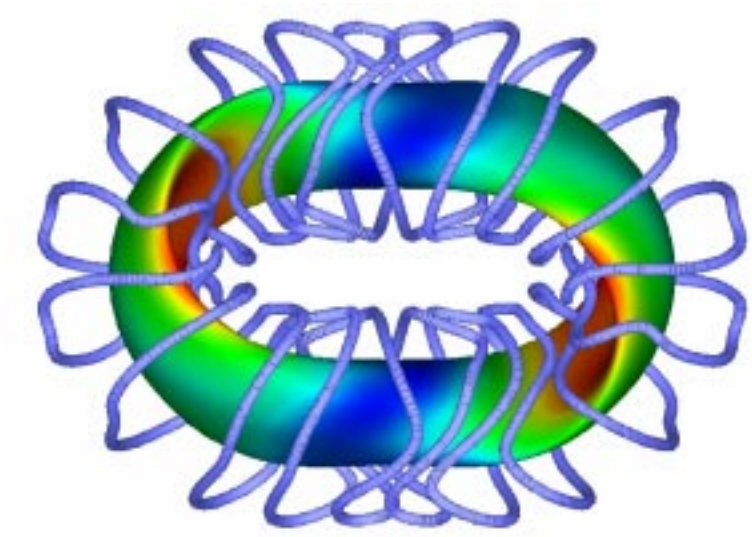
Overview of the QPS Experiment



J.F. Lyon for the QPS Team

International Stellarator Workshop

Canberra, Australia March 1, 2002

Multi-Laboratory QPS Design Team

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- **U. Texas at Austin – W.H. Miner, jr., P.M. Valanju**
- **U. Montana – A.J. Deisher, D. Heskett, A.S. Ware**
- **PPPL – A. Brooks, G.Y. Fu, S. Hudson, D. Mikkelsen, D.A. Monticello, N. Pomphrey**
- **Universidad Carlos III de Madrid, Spain – R. Sanchez**
- **U. Tennessee – T. Shannon**

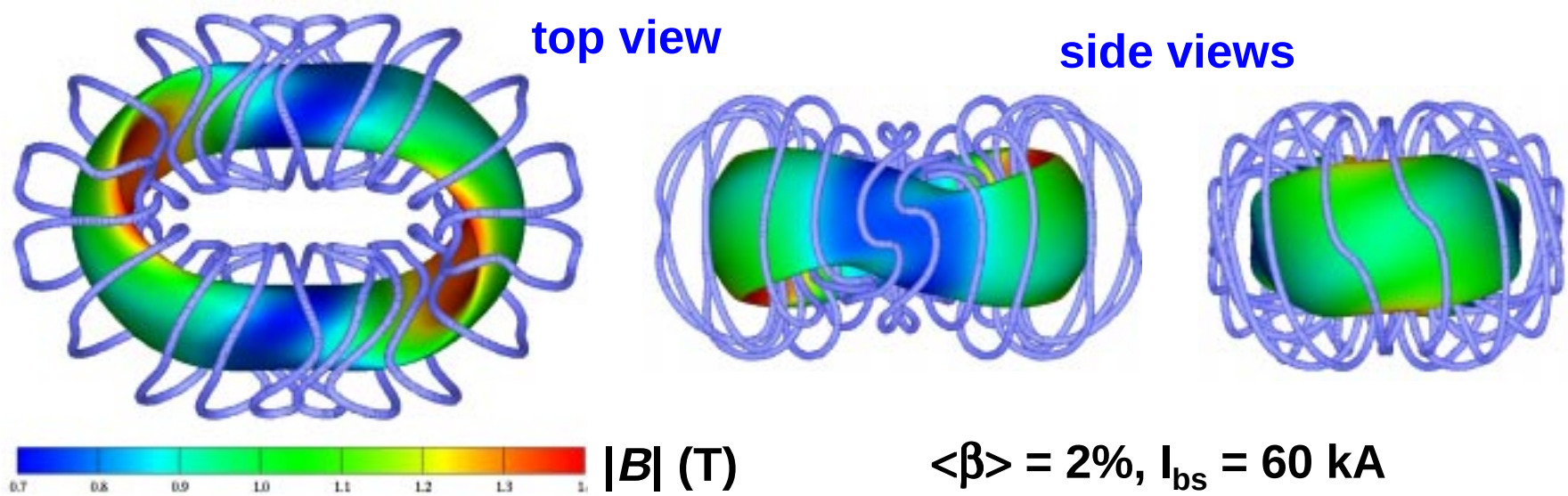
Over the past 6 years we have worked on development of a low-aspect-ratio stellarator that incorporates the bootstrap current in its optimization.

This has resulted in QPS -- a quasi-poloidal stellarator that has very low aspect ratio, excellent neoclassical confinement, good MHD properties, and a high-β reactor approach.

Topics

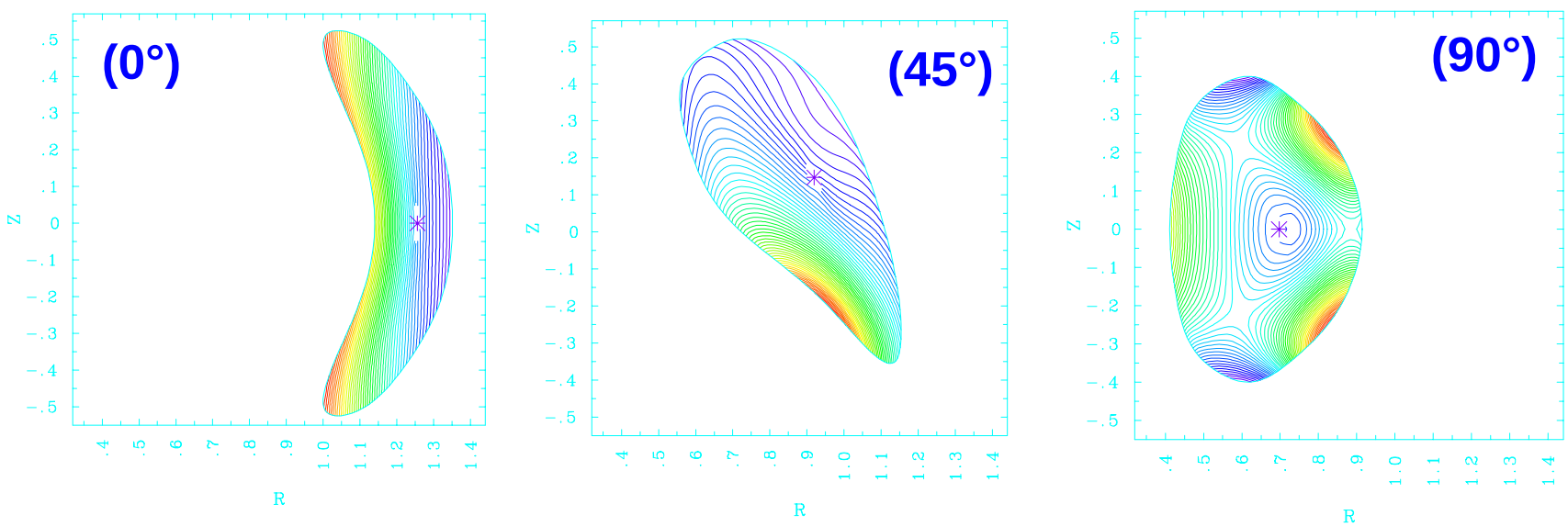
- Flux surface and coil geometry
- Quasi-poloidal symmetry
- Confinement properties
- MHD stability
- Engineering design
- Experimental objectives
- Status/Plans

QPS Magnetic Configuration



$|B|$ (T)

$\langle\beta\rangle = 2\%$, $I_{bs} = 60$ kA



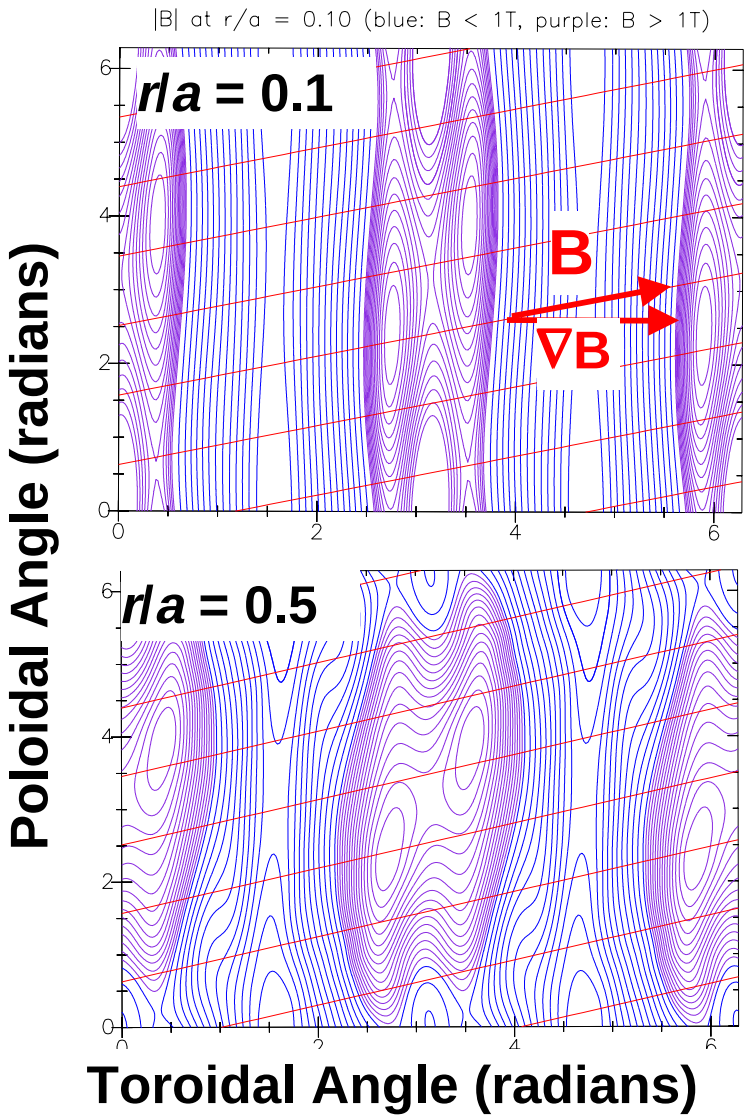
Quasi-Poloidal Symmetry Reduces Neoclassical Transport

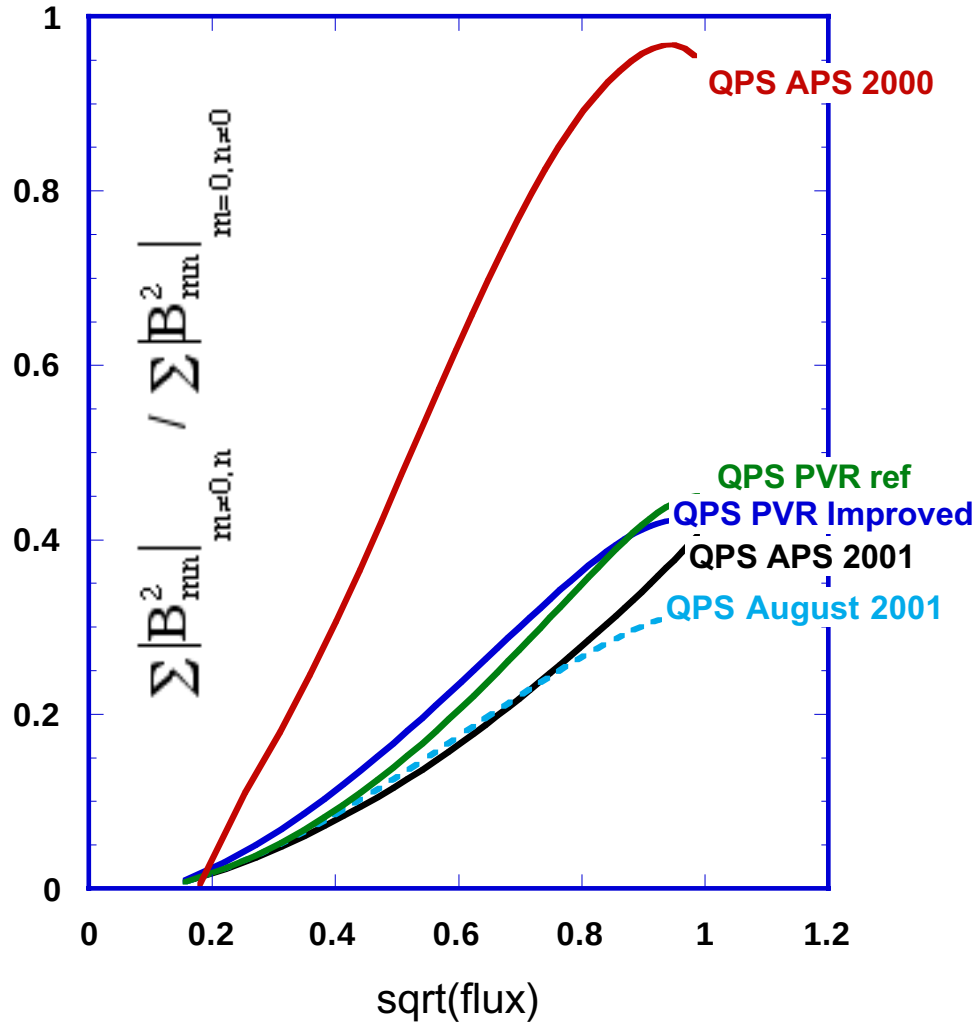
- For exact poloidal (θ) symmetry, p_θ is conserved
  - orbit excursions are limited to $\rho_{Tor} << \rho_{pol}$ (banana width)
  - no flow damping in the poloidal direction
  - the bootstrap current is reduced by $\sim\iota/N$
- However, it is not possible to have perfect symmetry on all flux surfaces in a stellarator $\Rightarrow$ "quasi-poloidal symmetry"

Unique Features of Quasi-Poloidally (QP) Symmetric Stellarators

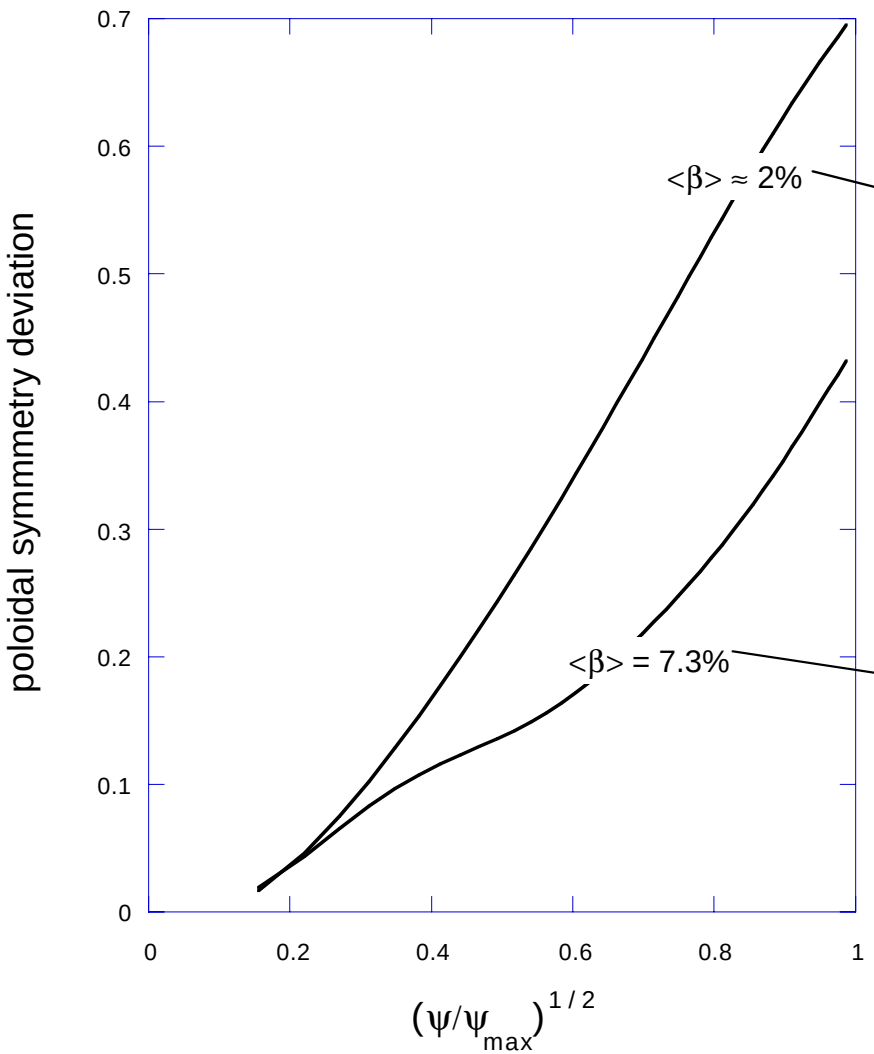
- Closer alignment of B and ∇B than is possible with other forms of symmetry - reduces radial drift and banana width
- Minimum flow damping in the direction of $E_r \times B$
  - flow shear could be self-sustained through E_r driven by ambipolar diffusion or externally produced
- Trapped particles are localized in low curvature regions
  - could improve dissipative trapped electron mode stability
- Properties improve with increasing β
  - access to a second stability region
  - omnigeneity, thermal and fast ion confinement
  - configuration becomes relatively insensitive to increasing β
  - bootstrap current is nearly independent of β at higher β

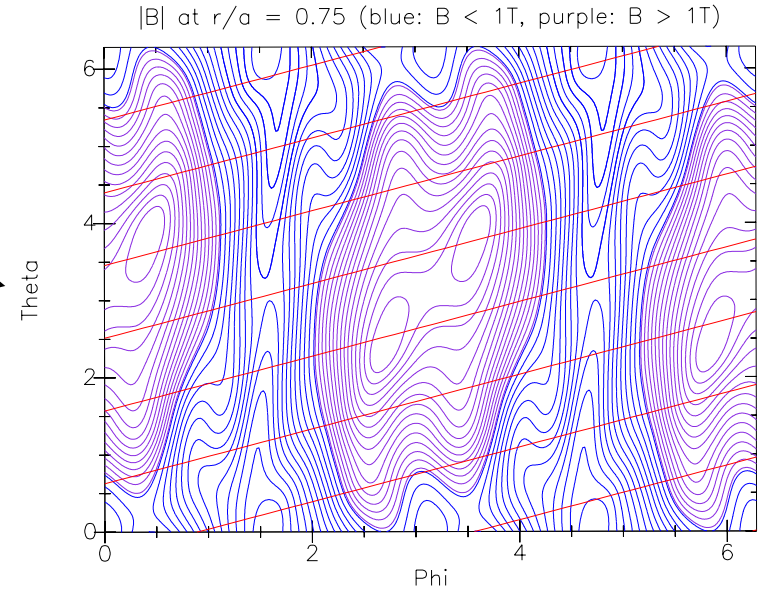
Quasi-Poloidal |B| Structure Varies with Radius

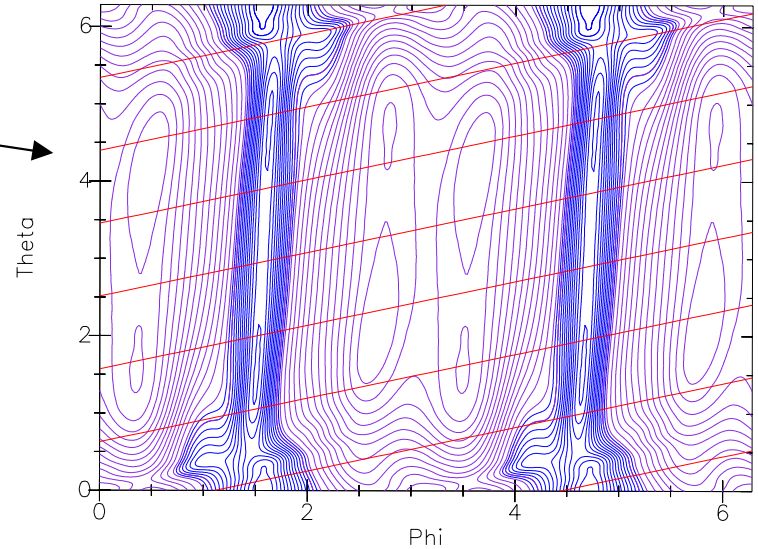




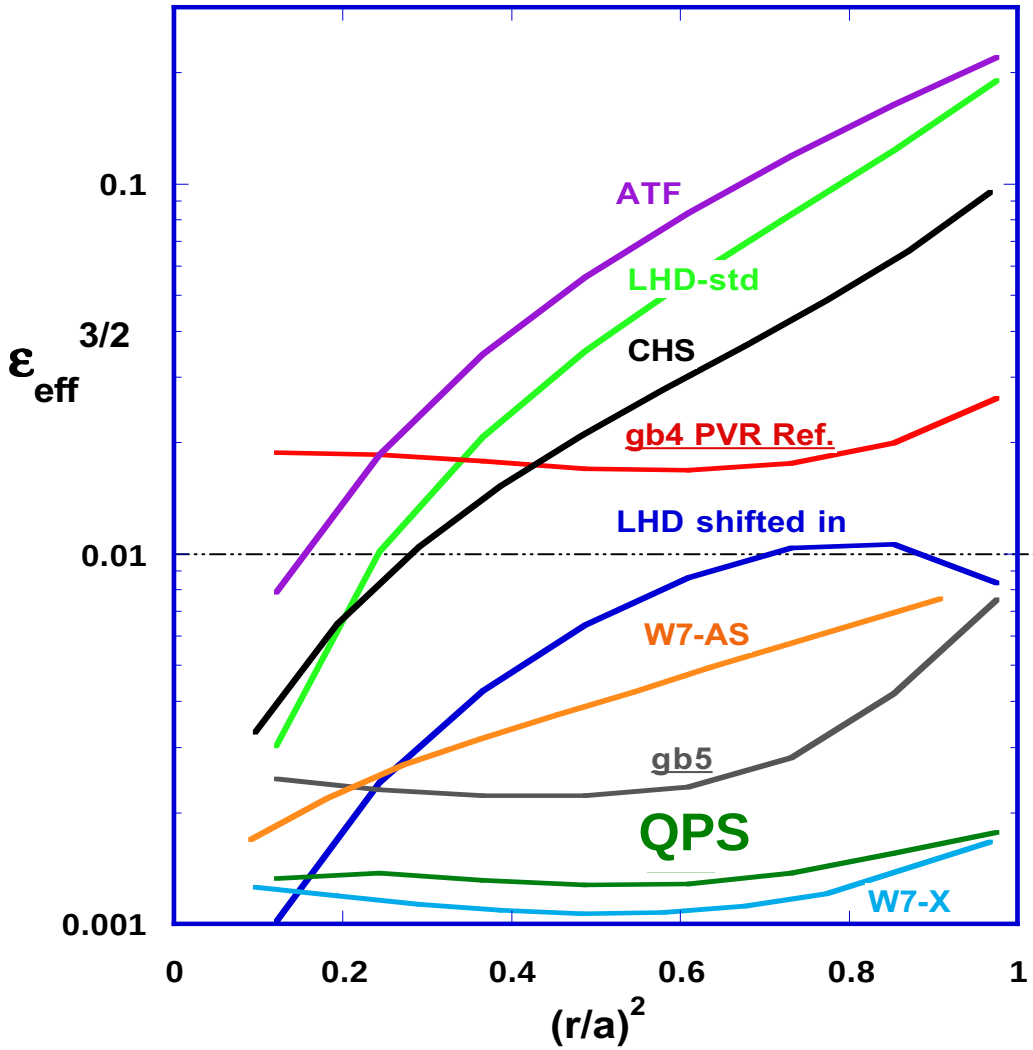
Finite-β Modifications of |B| Improve the Quasi-Poloidal Symmetry







QPS Configurations Have Small Neoclassical Transport



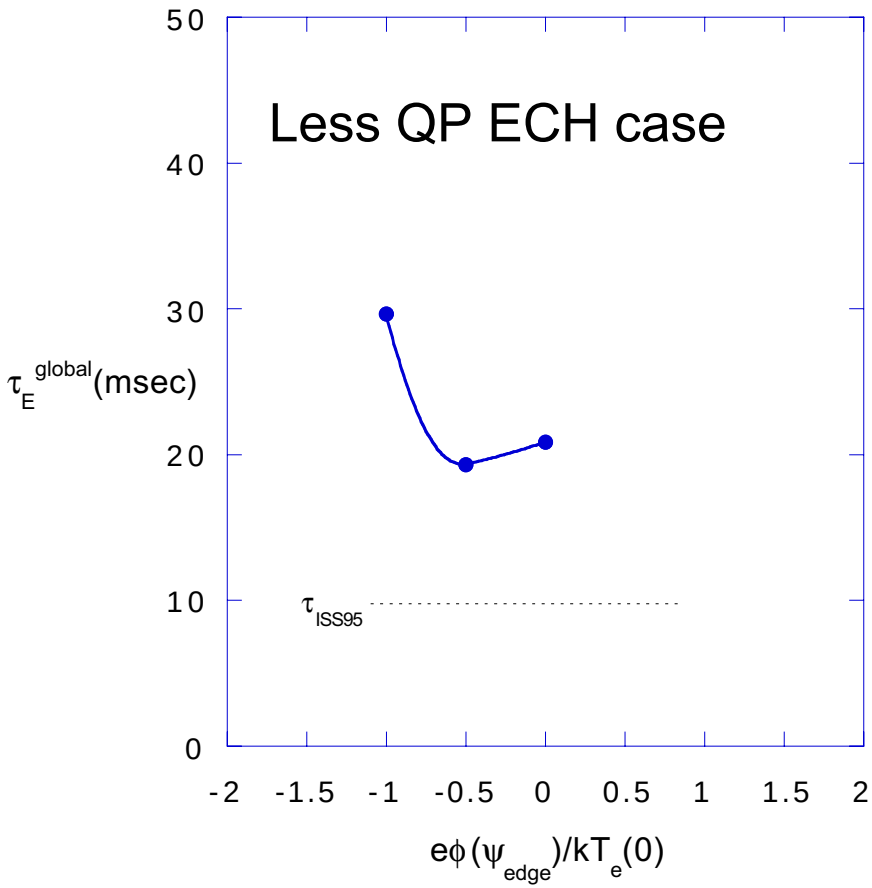
$\chi \propto \varepsilon_{eff}^{3/2}$

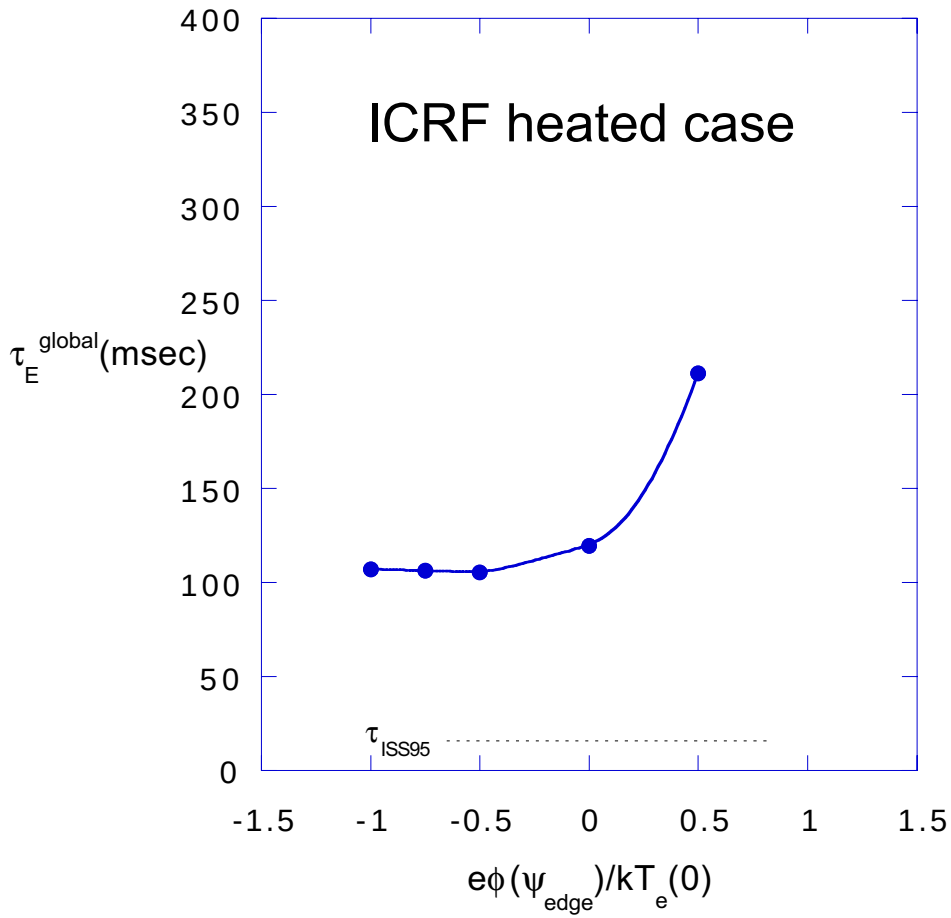
$1/\nu$ regime

ripple losses important at low collisionality

anomalous losses dominate over ripple losses at low collisionality, further improvement is not needed

ISS-95 Confinement Dominates over Neoclassical Confinement

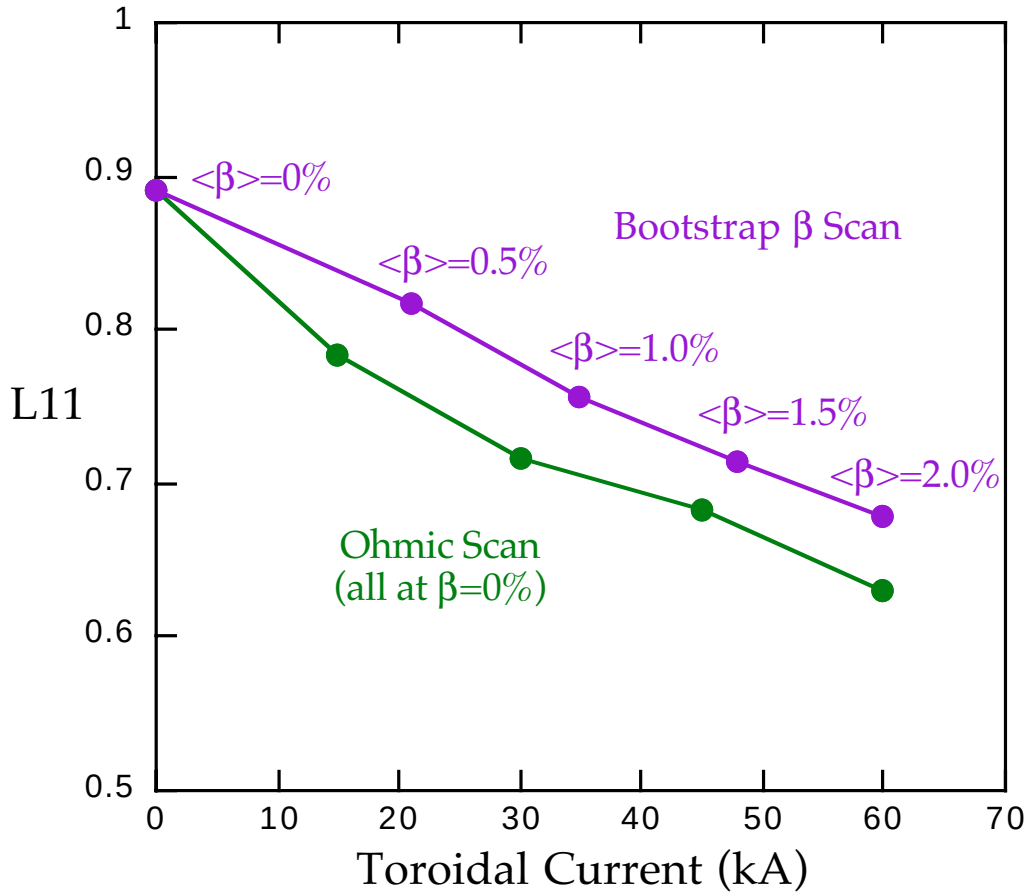




An older QPS configuration is shown here

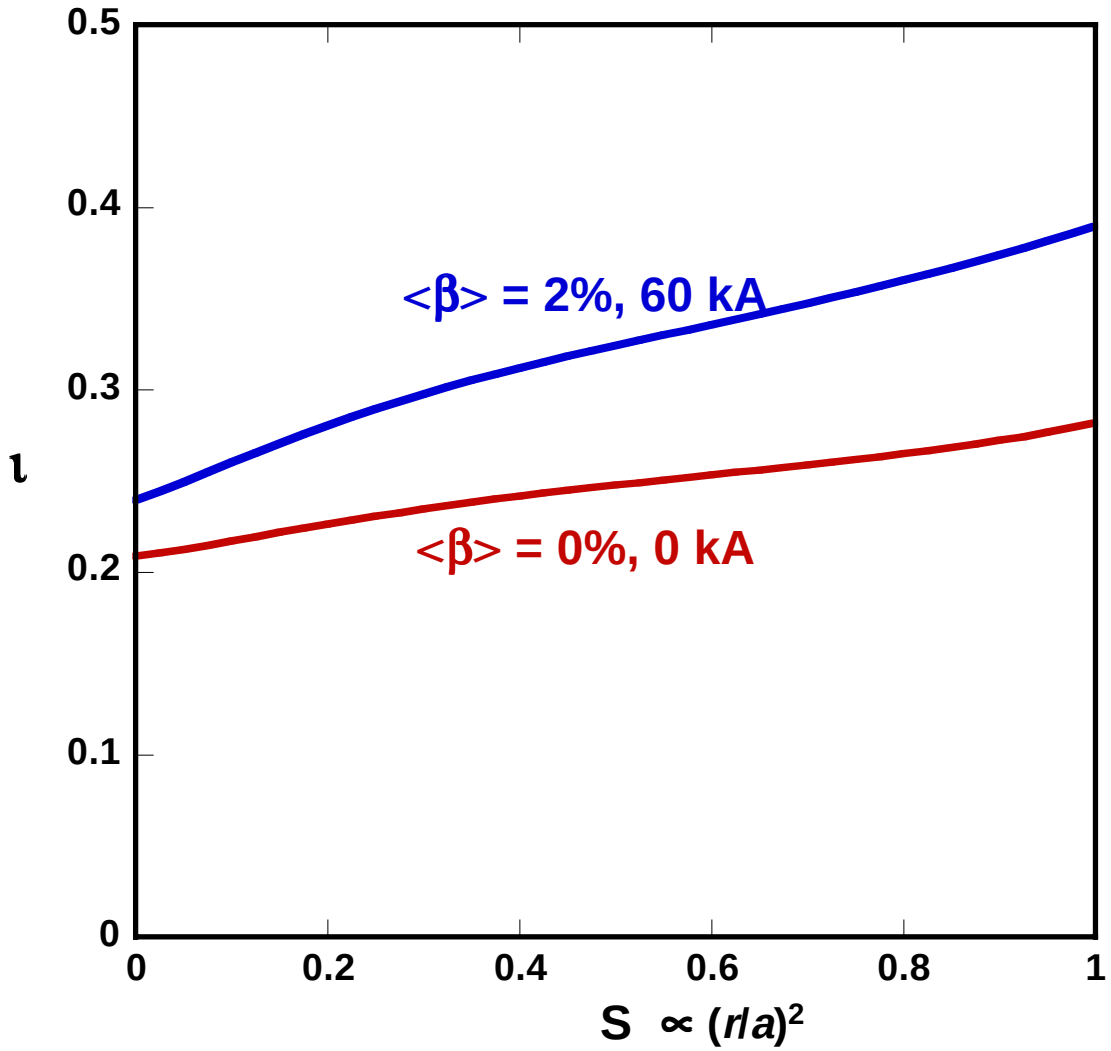
Confinement Improves with ⟨β⟩

- **Same trend seen up to ⟨β⟩ = 23% in quasi-poloidal reactor configuration**
- **Can be simulated by Ohmic current in QPS**

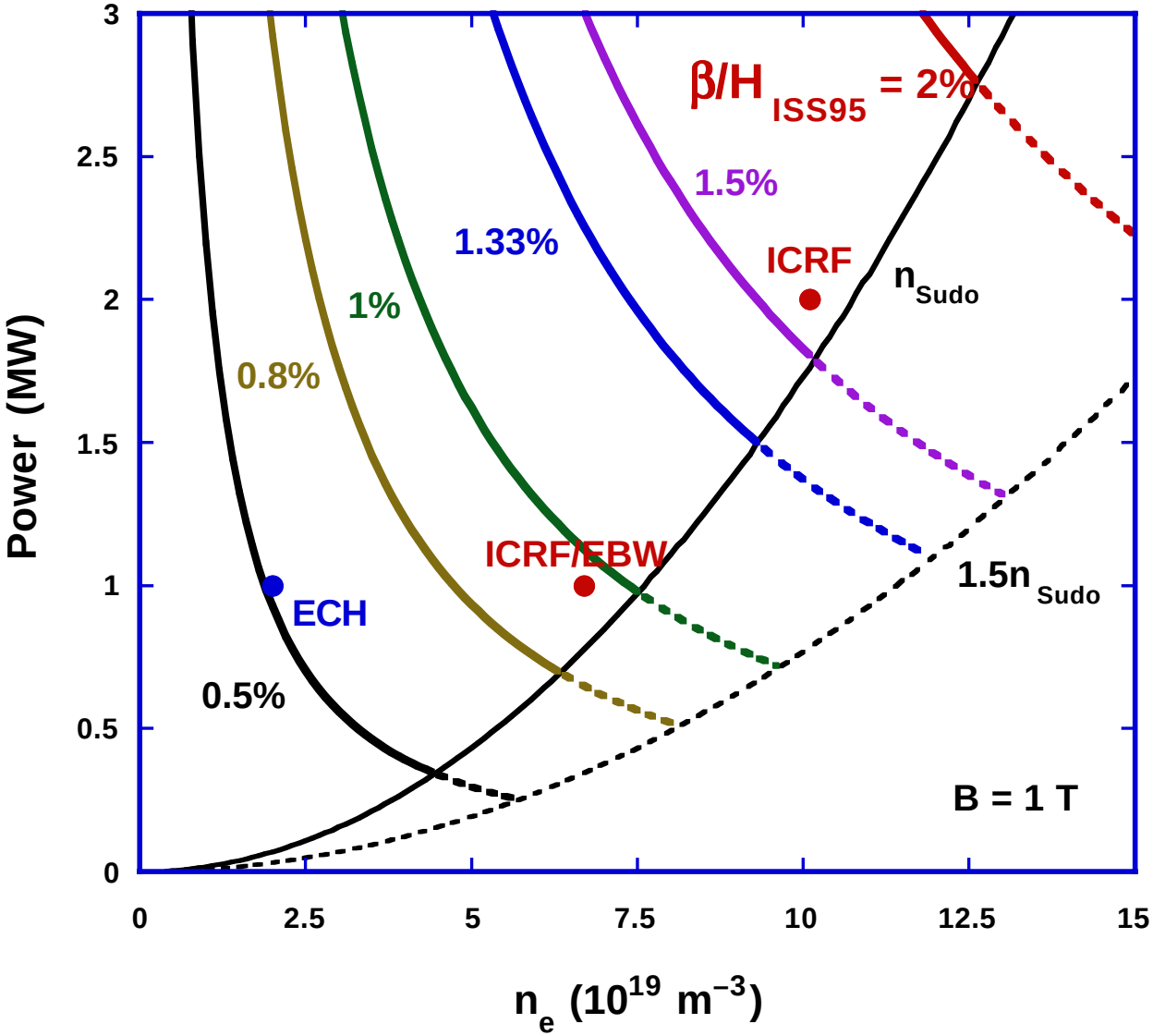


Radial transport coefficients on r/a = 0.84 surface

Part of the Rotational Transform Is Due to the Bootstrap Current



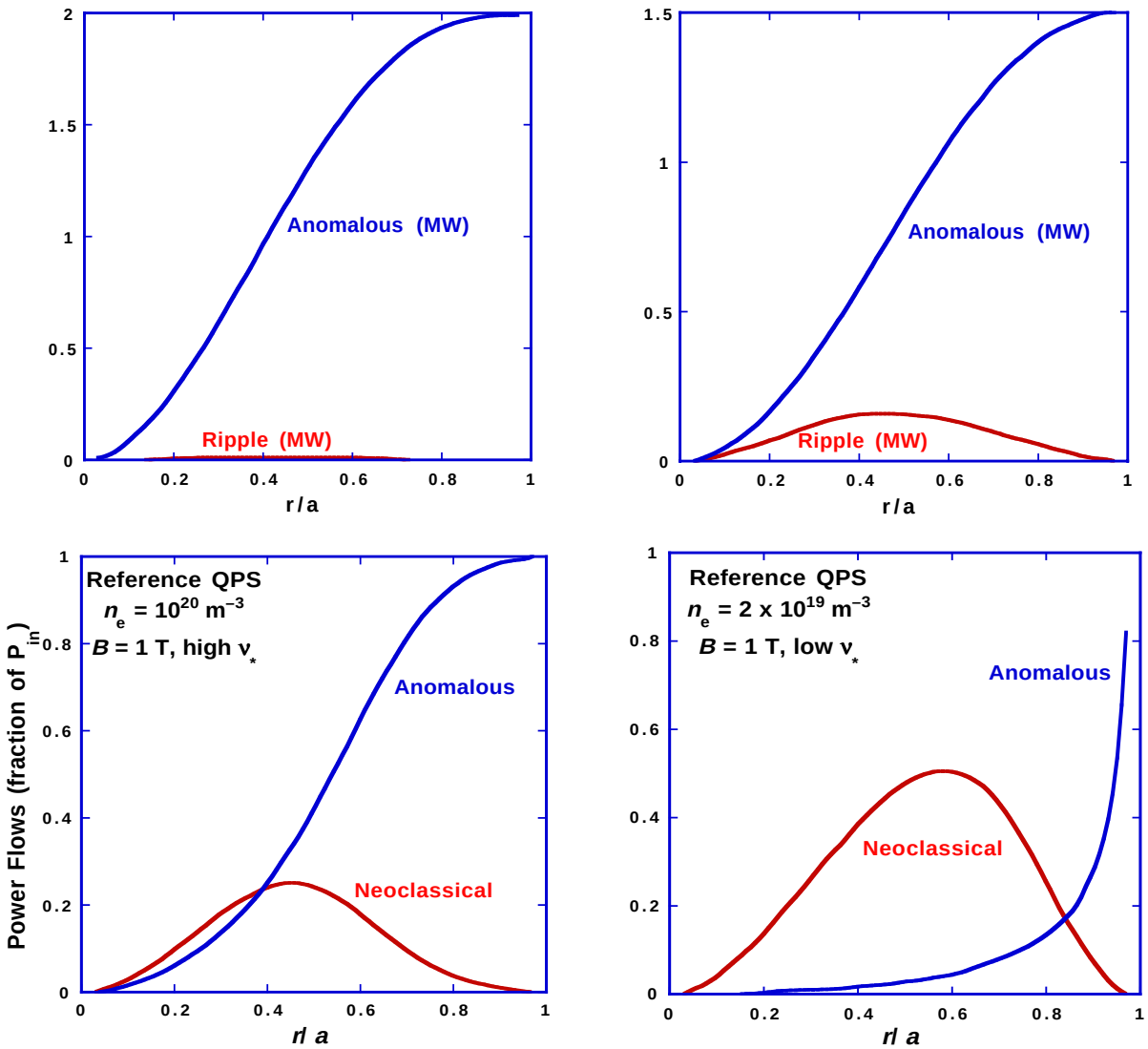
P = 1-3 MW Gives the Parameters Needed for the QPS Objectives



Multiply contour values by H_{ISS95} (= 1-2.5 in experiments)

QPS parameter space for *B* = 1 T

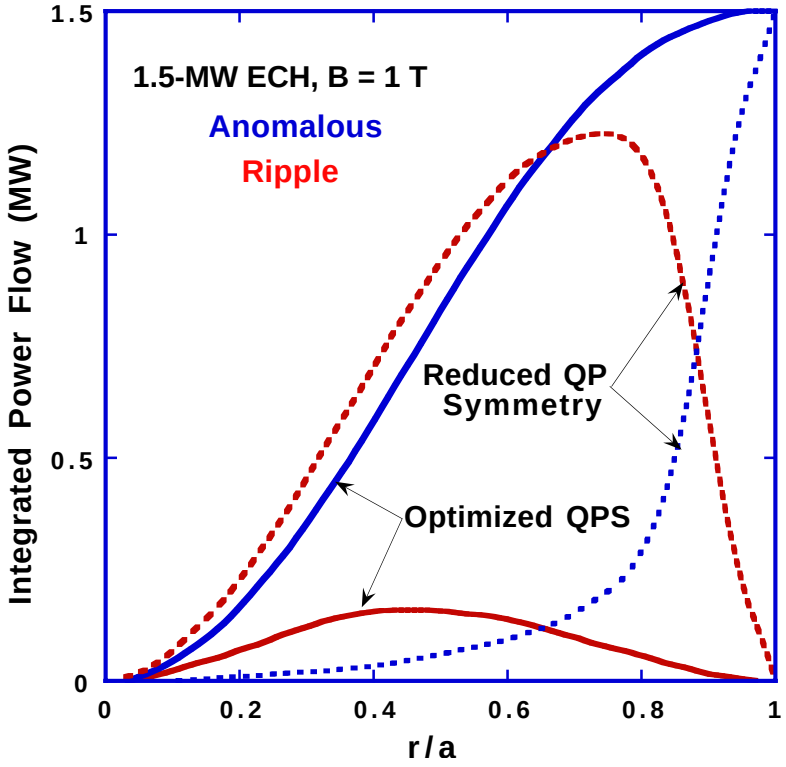
Anomalous and Neoclassical Loss Channels Can Be Separated through Choice of Density and Spoiling the Quasi-Poloidal Symmetry

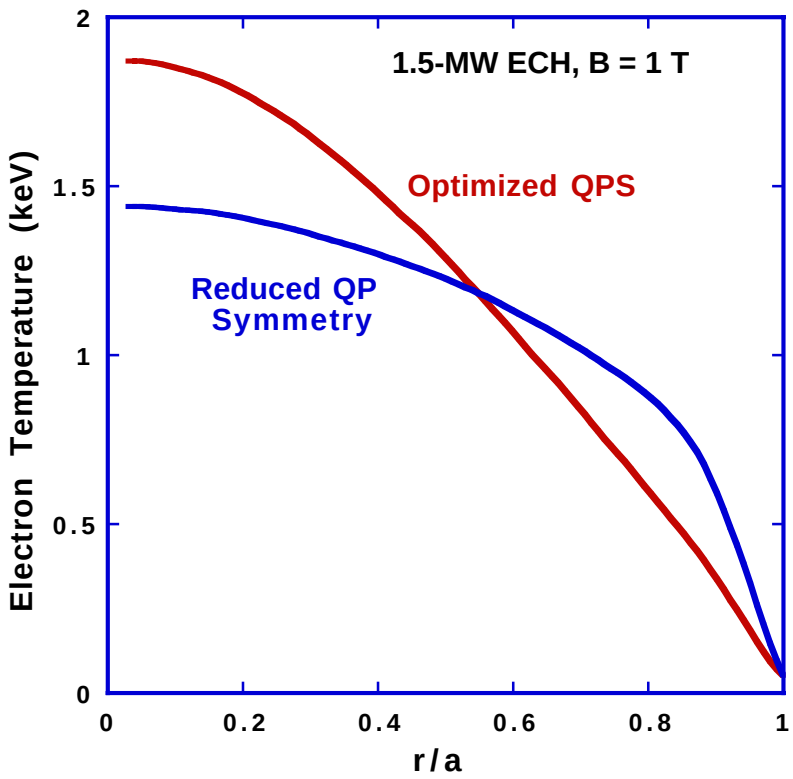


Optimized QPS configuration

QPS configuration with less quasi-poloidal symmetry

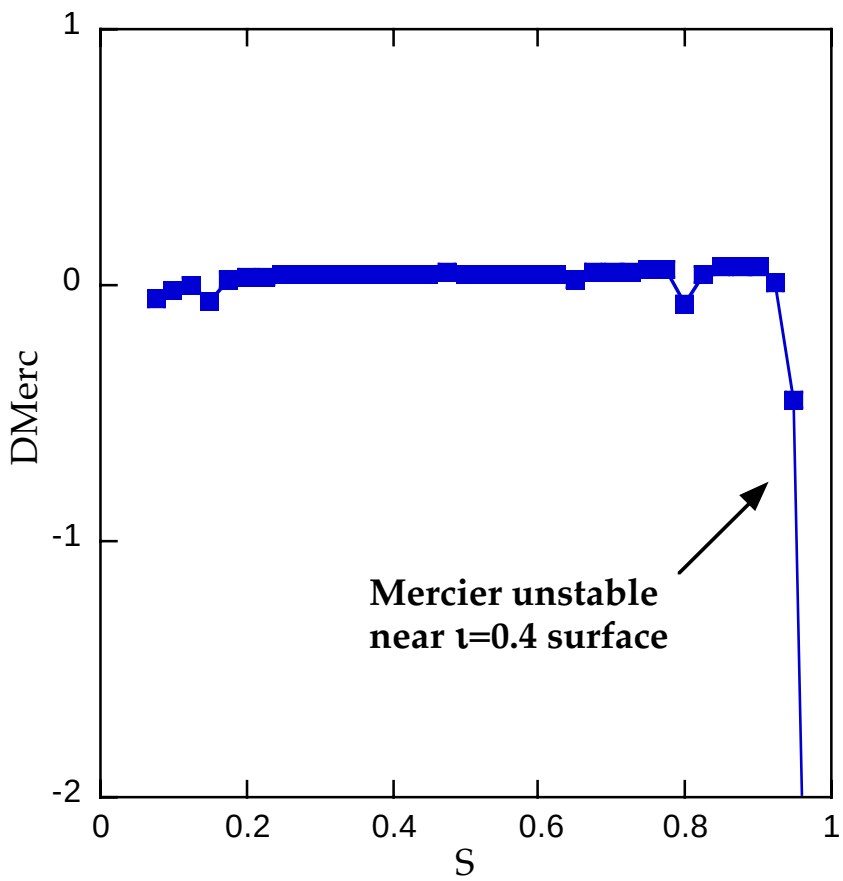
Spoiling the Quasi-Poloidal Symmetry Can Be Used to Enhance the Neoclassical Loss Channel

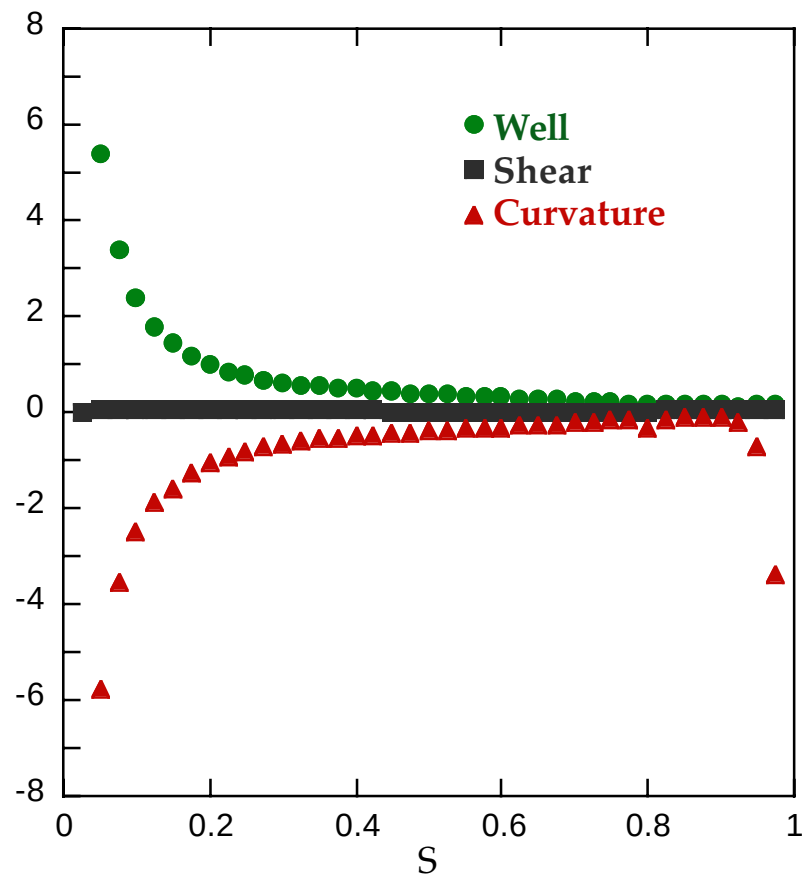




Mercier Stability: a Magnetic Well Provides Stability Except at Isolated Resonances

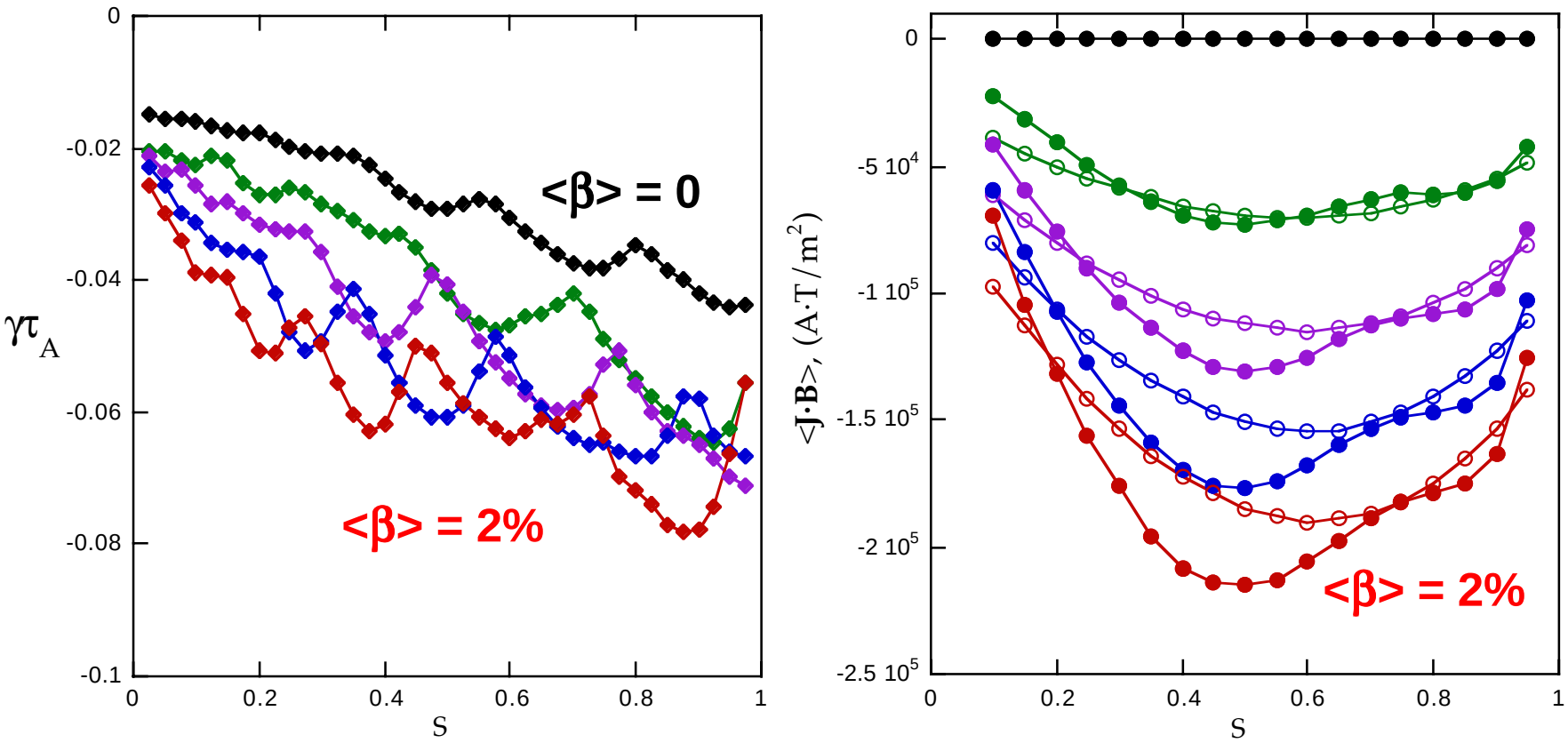
- Mercier stability criteria for fixed boundary at <β> = 2.5%
- However, these limits are exceeded in stellarator experiments





Ballooning Stability: Free Boundary Scan, Stable & Bootstrap Consistent to β = 2.3 %

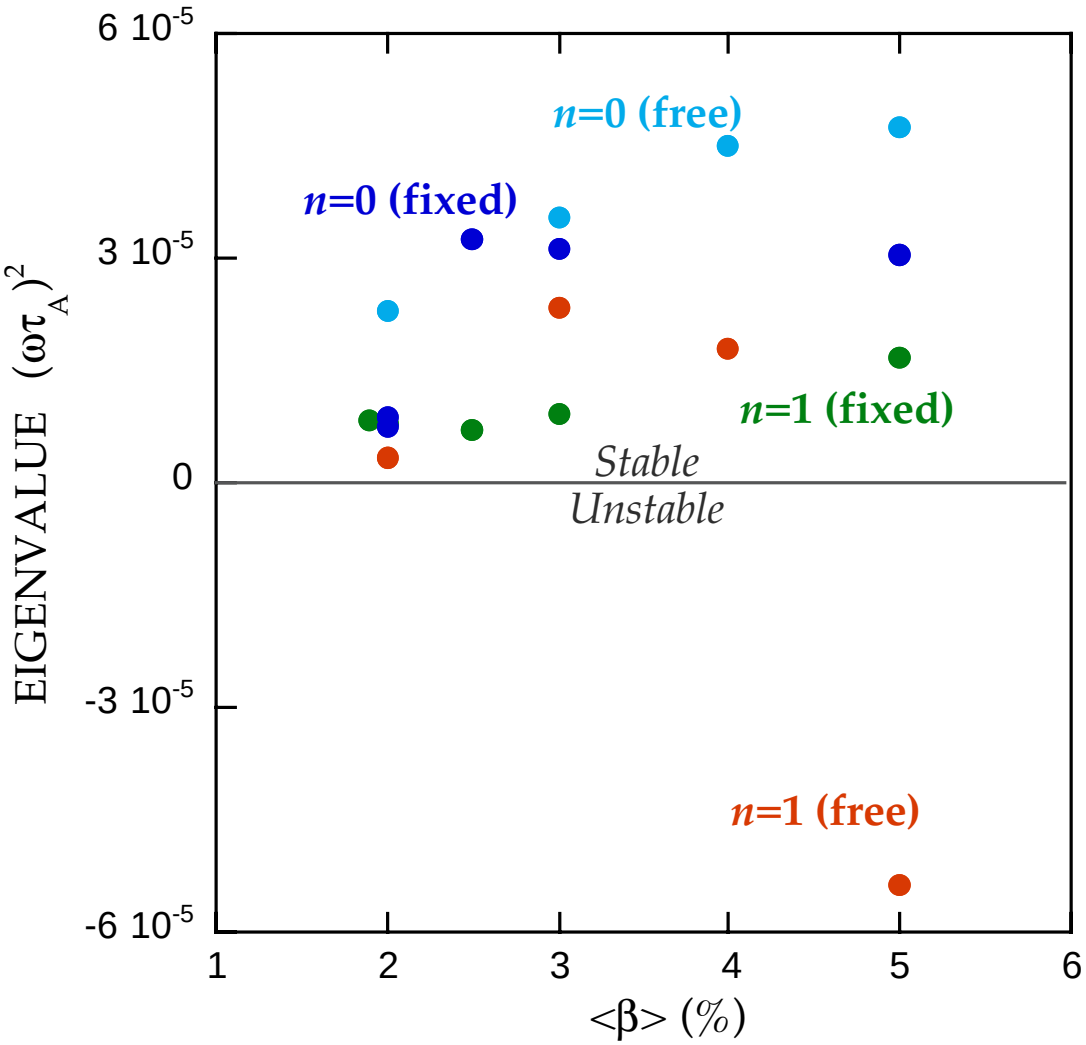
- **Ballooning growth rate & parallel current, free boundary β scan**



Second stability region occurs at higher beta

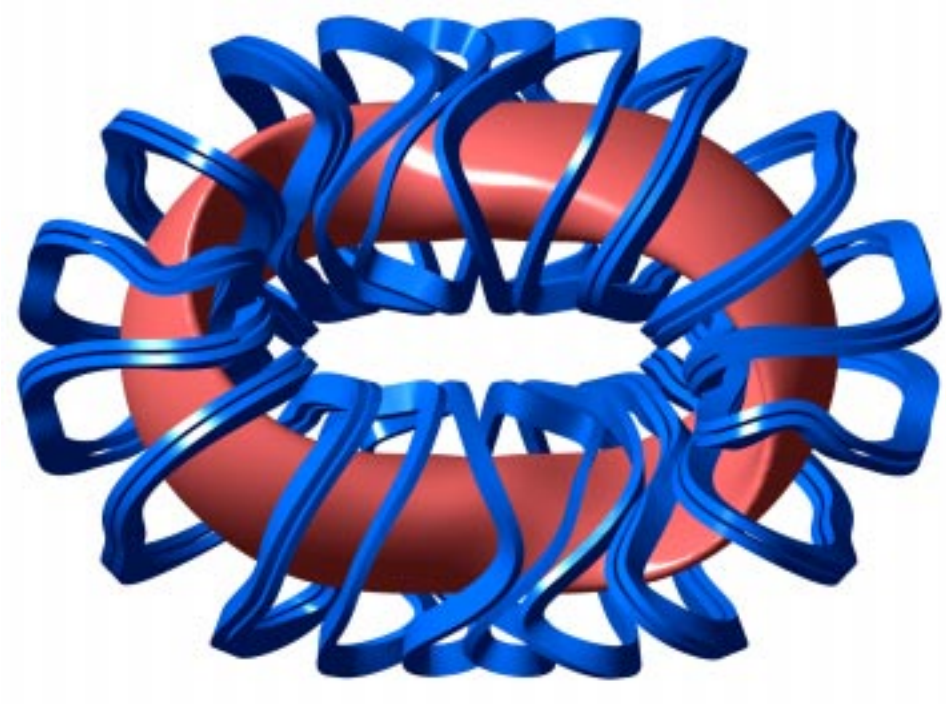
QPS configuration is kink/vertical stable for <β> up to 5%

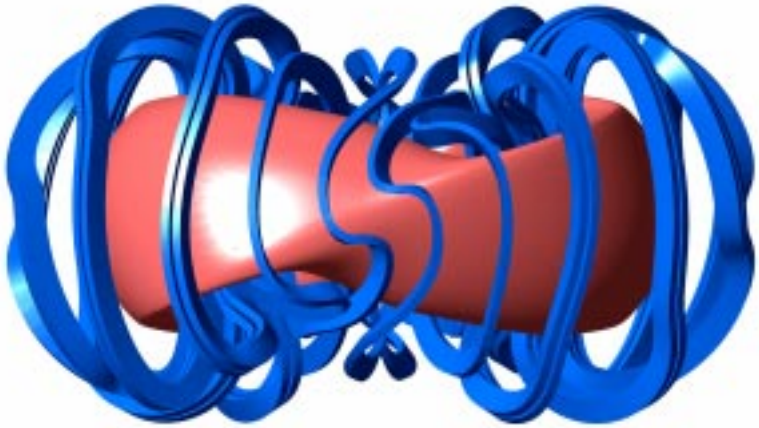
Kink & Vertical Stability: QPS configuration is kink/vertical stable for <β> up to 5%

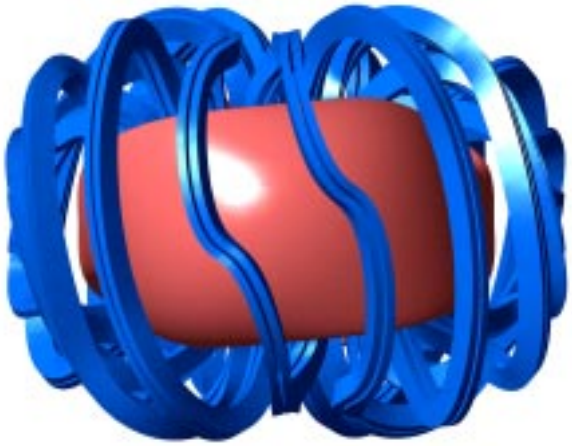


- n = 0 and n = 1 eigenvalues

The QPS Modular Coil Set Has Been Optimized to Create the Desired Magnetic Configuration



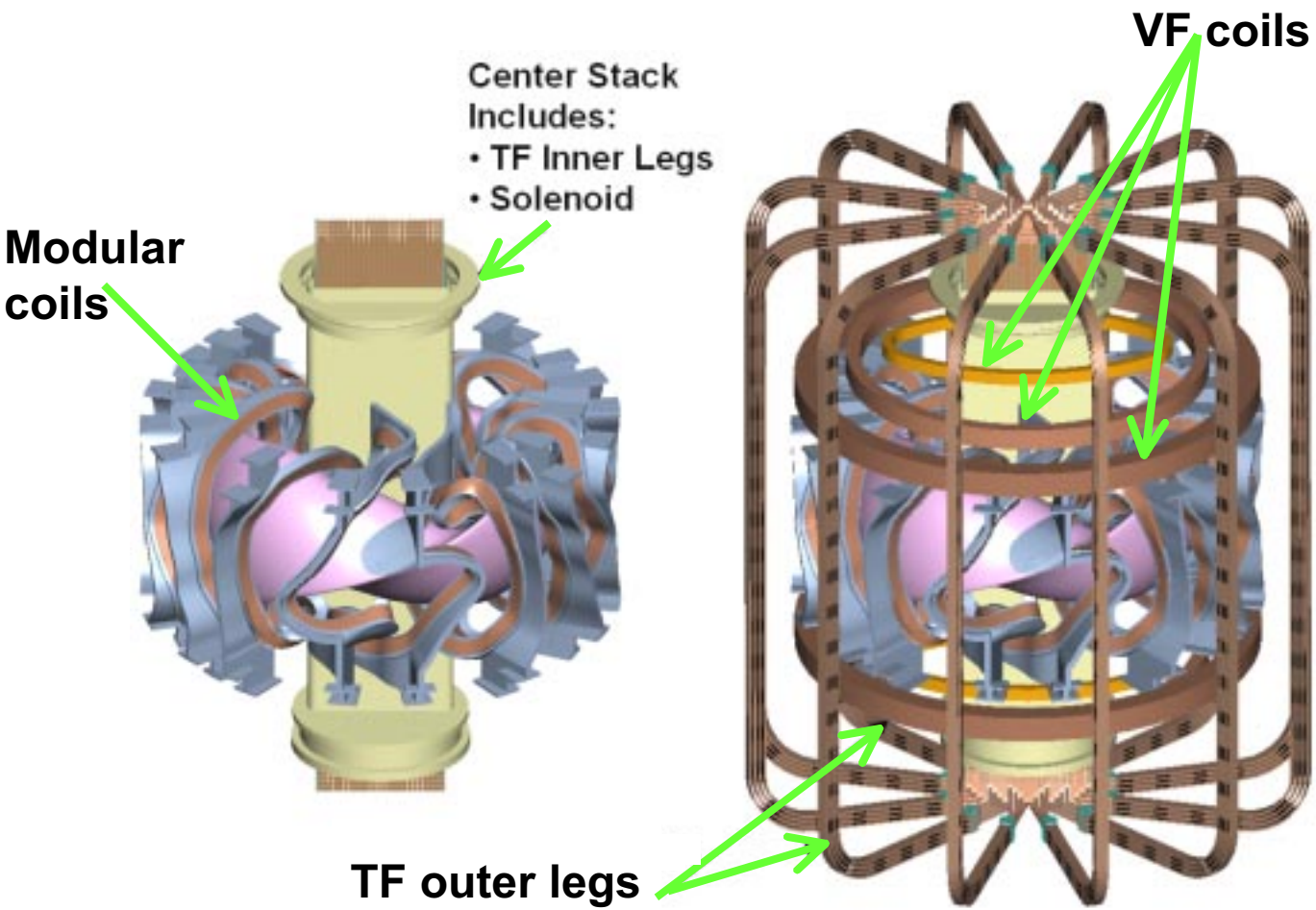




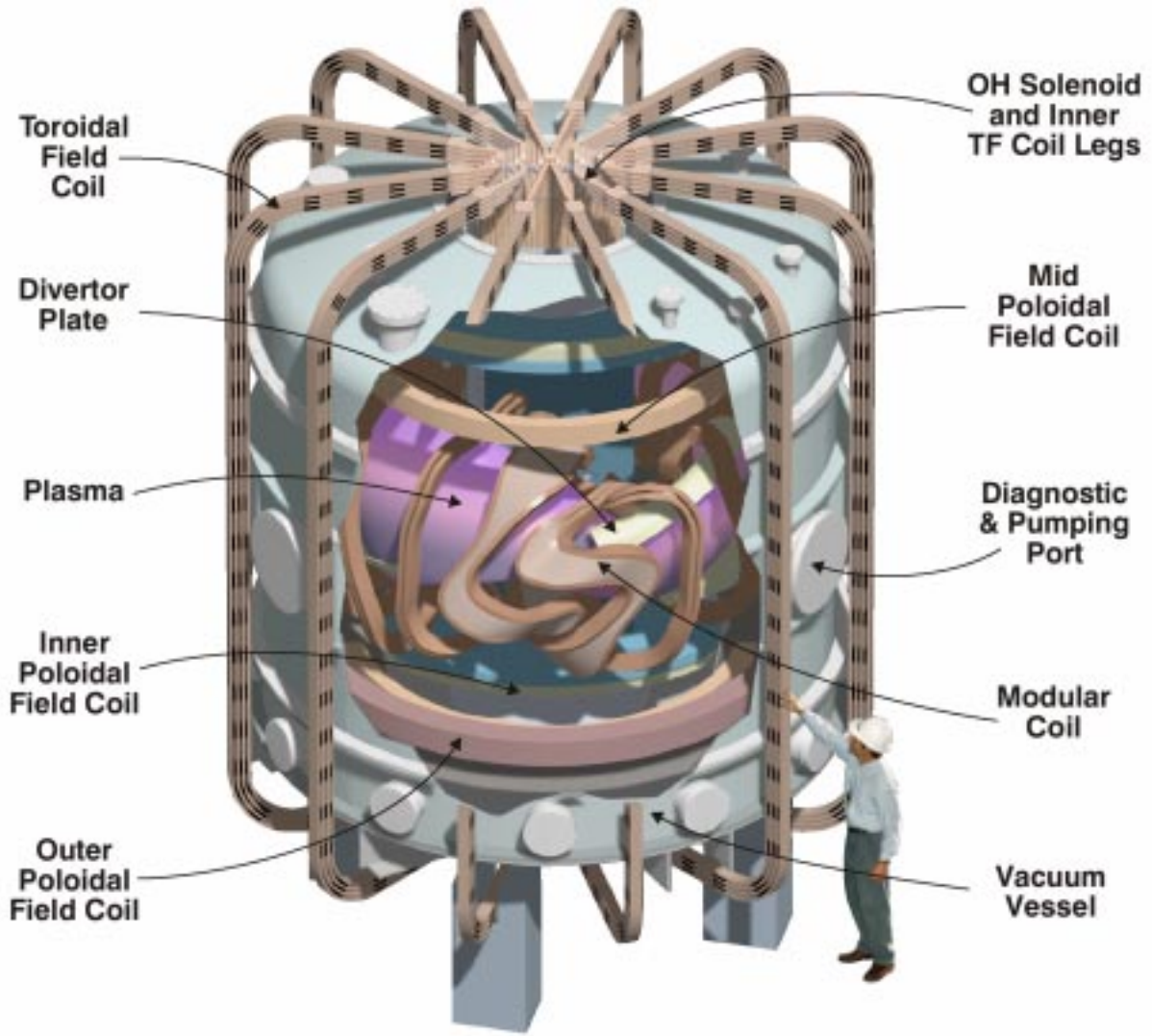
- 16 coils of 4 different types
- Adequate coil-coil spacing, plasma-coil spacing, minimum bend radius
- Good access between coils for heating and diagnostics
- Room in center for TF coil legs and OH solenoid

QPS Has Additional Coils to Change Transform, Shear, and Magnetic Configuration for Physics Studies

- $\Delta B_T = \pm 0.2$ T, PF coils for shifting and shaping the plasma
- ±150 kA Ohmic current allows changing transform and shear



Quasi-Poloidal Stellarator



- $\langle R \rangle = 0.9$ m
- $\langle a \rangle = 0.33$ m
- $\langle R \rangle / \langle a \rangle = 2.7$
- $V_{plasma} = 2\ m^3$
- 61-cm dia. ports
- No interior vacuum vessel
- $\iota_0 = 0.21$, $\iota_a = 0.32$
- $B_{mod} = 1$ T (1 s)
- $B_T = \pm 0.2$ T
- $I_p \leq 150$ kA
- $P_{ECH} = 0.6\text{-}1.2$ MW
- $P_{ICRF} = 1\text{-}3$ MW

QPS will Study Stellarator Issues for Quasi-Poloidal Symmetry and Very Low *R*/*a*

- **Reduction of neoclassical transport due to near alignment of *B* and ∇B**
- **Anomalous transport scaling, internal transport barriers, poloidal flow shear**
- **Impact of poloidal flows on enhanced confinement**
- **Equilibrium quality (islands, ergodic regions) for β up to ~2%**
- **Dependence of the bootstrap current on configuration properties**
- **Ballooning instability character and β limits**

Status and Plans

- **Passed physics and project reviews in 2001**
- **Next steps**
  - **Further improve the plasma and coil configuration**
  - **Complete assessment of QPS physics properties**
  - **Assess flexibility with VF, TF, and OH solenoid**
  - **Improve engineering design and cost/schedule estimates**
  - **Design, cost & schedule review in early 2003**
- **2003-2007: R&D, design and construction**
- **Mid-2007: first plasma**

Summary

- **QPS is a compact stellarator that has excellent neoclassical confinement, good MHD properties, and connection with a high-β reactor approach**
- **New element: use of reduced bootstrap current and quasi-poloidal symmetry at very low *R*/*a***
  - **alignment of B and ∇B reduces radial drift and banana width**
  - **reduced flow damping in poloidal direction**
  - **potential for second stability regime**
- **QPS design satisfies physics requirements and engineering constraints; now in conceptual design**