Overview of the ORNL Quasi-Poloidal Stellarator (QPS)

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representing the QPS Team

Univ. of Maryland, Jan. 25, 2002

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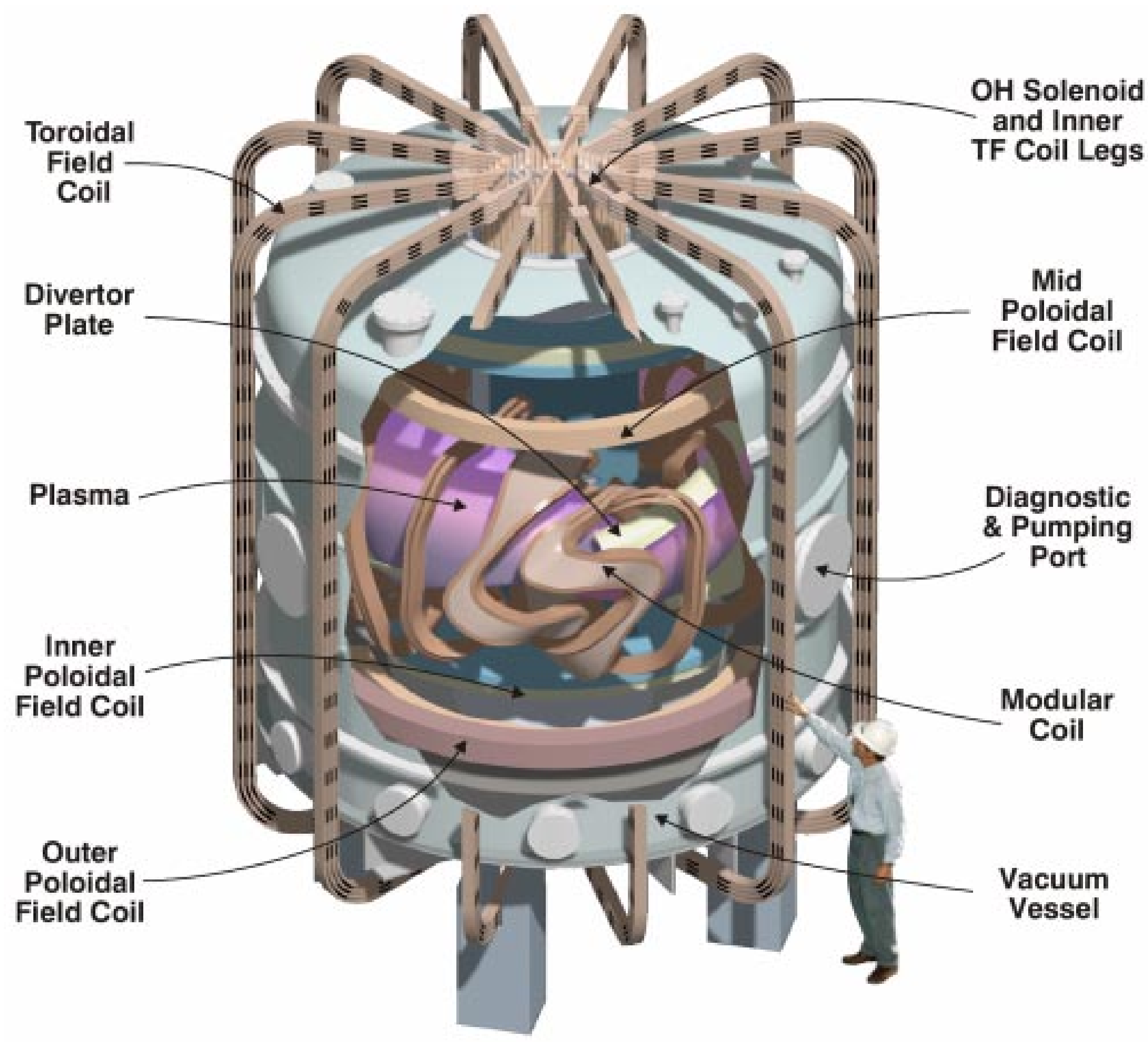
Over the past 5 years ORNL has worked on development of a low-aspect-ratio stellarator that incorporates the bootstrap current in its optimization.

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 path.

Although the basic QPS configuration has not changed in the last year, there have been substantial design improvements.

Quasi-Poloidal Stellarator



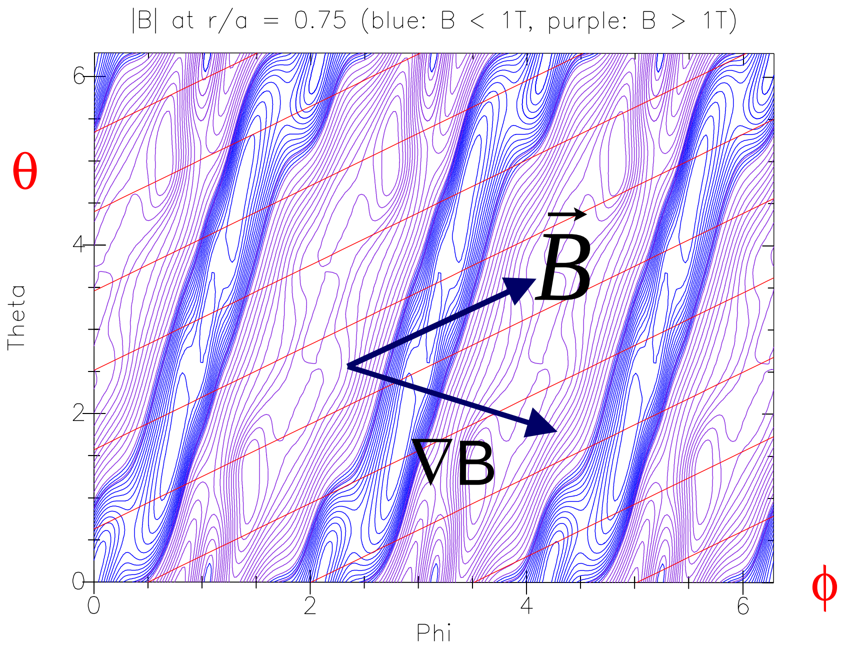
Topics

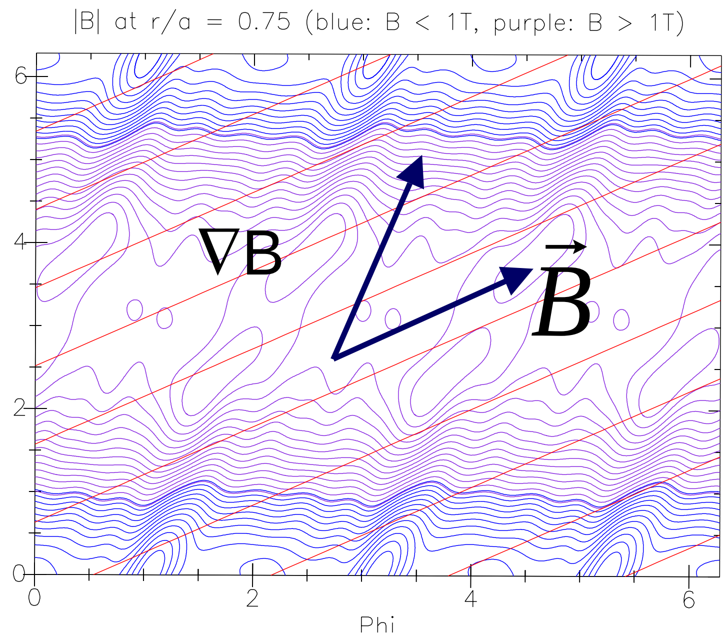
- **Compact stellarators and quasi-symmetry**
- **The QPS experiment**
  - **magnetic configuration**
  - **confinement properties**
  - **MHD equilibrium and stability**
  - **engineering design**
  - **experimental objectives**
- **High-beta exploration**
- **Plans**

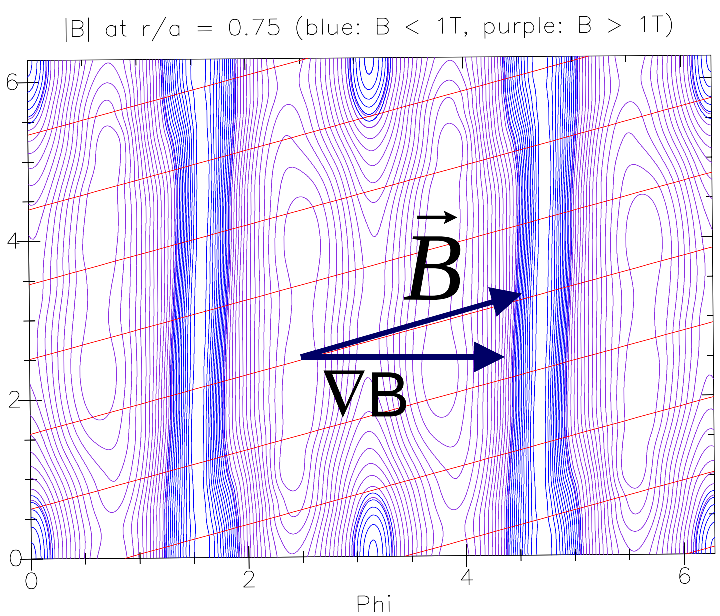
Compact Stellarators Could Combine the Best Features of Advanced Tokamaks and Currentless Stellarators

- **Currentless stellarators have significant advantages**
  - **no current-driven disruptions, kink modes or vertical instability, or need for current drive or feedback stabilization**
  - $\Rightarrow$ **inherently steady-state**
- **Conventional stellarators also have some serious drawbacks**
  - **large plasma aspect ratio $\Rightarrow$ large reactor size (HSR *R* = 22-24 m)**
    - ***R*/*a* = 6(LHD) to 11(W 7-X) $\Rightarrow$ *R*/*a* = 2.7(QPS) & 4.3 (NCSX)**
  - **large neoclassical transport at low collisionality: $\chi \propto 1/\nu$**
    - **quasi-symmetry reduces this ripple-induced transport**
  - **low beta limits**
    - **quasi-poloidal stellarators have potential for high beta**
- **New element: use of a *reduced* bootstrap current and quasi-symmetry in a low *R*/*a* stellarator**
- **QPS explores quasi-poloidal symmetry and very low *R*/*a* (2.7) and creates basis for high-β compact stellarators**

US Stellarator Approach Features Quasi-Symmetry

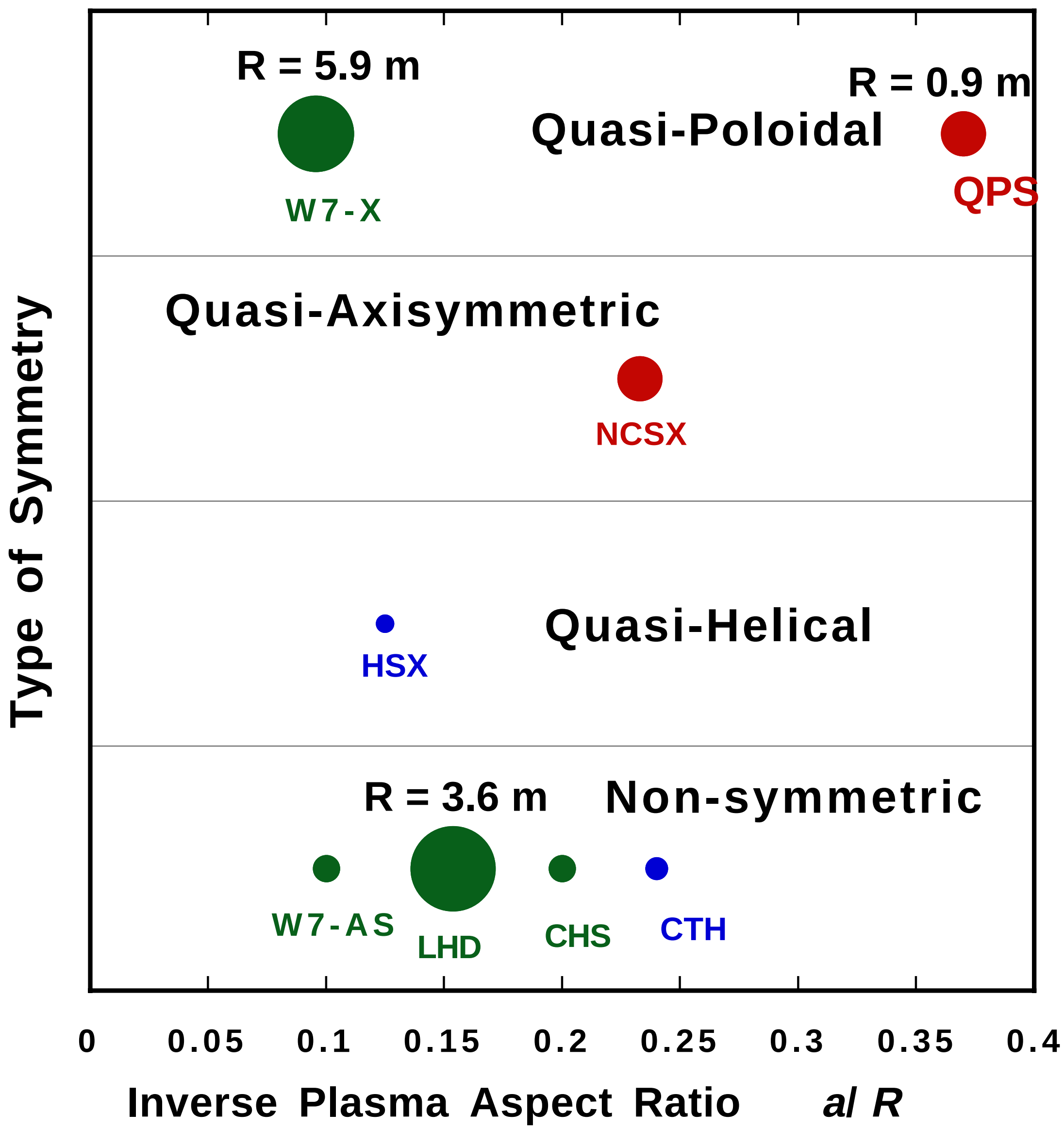






- **Quasi-helical**: |B| like large *R*/*a* stellarator. HSX (*R*/*a* = 8) will test this concept.
- **Quasi-axisymmetric**: |B| like a tokamak. NCSX (*R*/*a* = 4.3) would test this concept.
- **Quasi-poloidal: |B| like toroidally linked mirrors *with* transform. The *B* x ∇B drift can be made very small in this approach. QPS (*R*/*a* = 2.7) would test this concept.**

QPS Complements Other World Stellarators



⇐ **Low aspect ratio and quasi-poloidal symmetry**

Radius of circles Is proportional to the average plasma radius

Quasi-Symmetry Reduces Neoclassical Transport

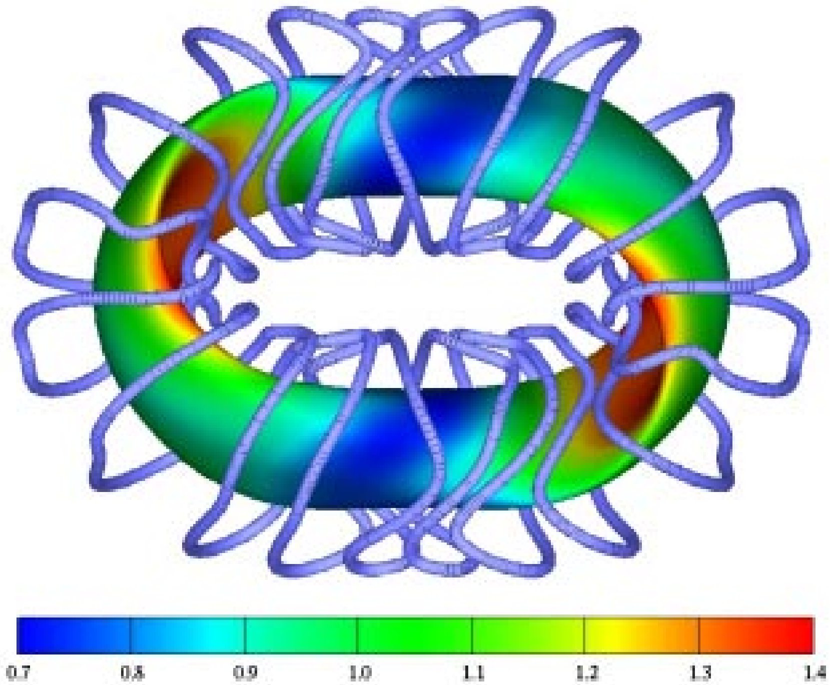
- **For exact poloidal (θ) symmetry, p_θ is conserved**
  - **orbit excursions are limited to $\rho_{Tor} << \rho_{pol}$ (banana width)**
  - **no flow damping in the poloidal direction**
  - **the bootstrap current is reduced by $\sim\iota/N$**

- **However, it is not possible to have perfect symmetry on all flux surfaces in a stellarator $\Rightarrow$ "quasi-symmetry"**
  - ***B* x grad B can be small $\Rightarrow$ small drift away from magnetic surfaces**
  - **trapped particles are localized in low curvature regions**

Unique Features of Quasi-Poloidally (QP) Symmetric Stellarators

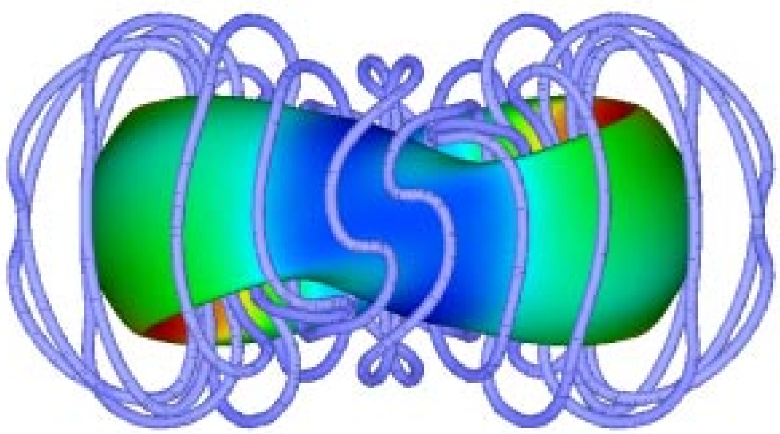
- **Closer alignment of B and ∇B than is possible with other forms of symmetry - reduces radial drift and banana thickness**
- **Minimum flow damping in the direction of E_r x B**
  - ***tokamaks*** **have minimum flow damping in toroidal direction - flow shear requires weak driving force (e.g., beams, RF)**
  - ***QP stellarators*** **have minimum flow damping in poloidal direction - flow shear is potentially self-sustained through internally generated E_r driven by plasma ambipolar diffusion**
- **Trapped particles are localized in low curvature regions**
  - **potential improvements to dissipative trapped electron mode stability**
- **Properties improve with increasing β**
  - **access to a second stability region**
  - **omnigeneity, thermal and fast ion confinement**
  - **configuration relatively insensitive to increasing β**
  - **bootstrap current relatively independent of β**

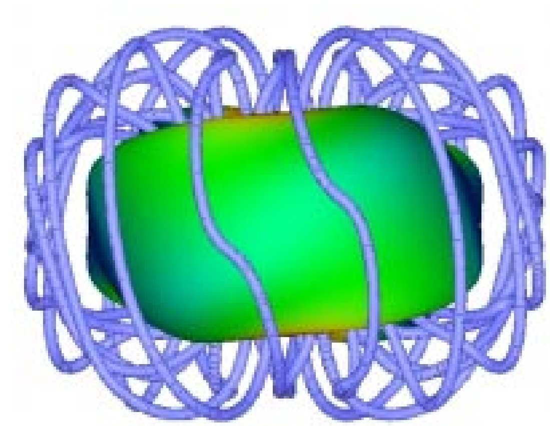
The QPS Plasma and Modular Coil Configuration



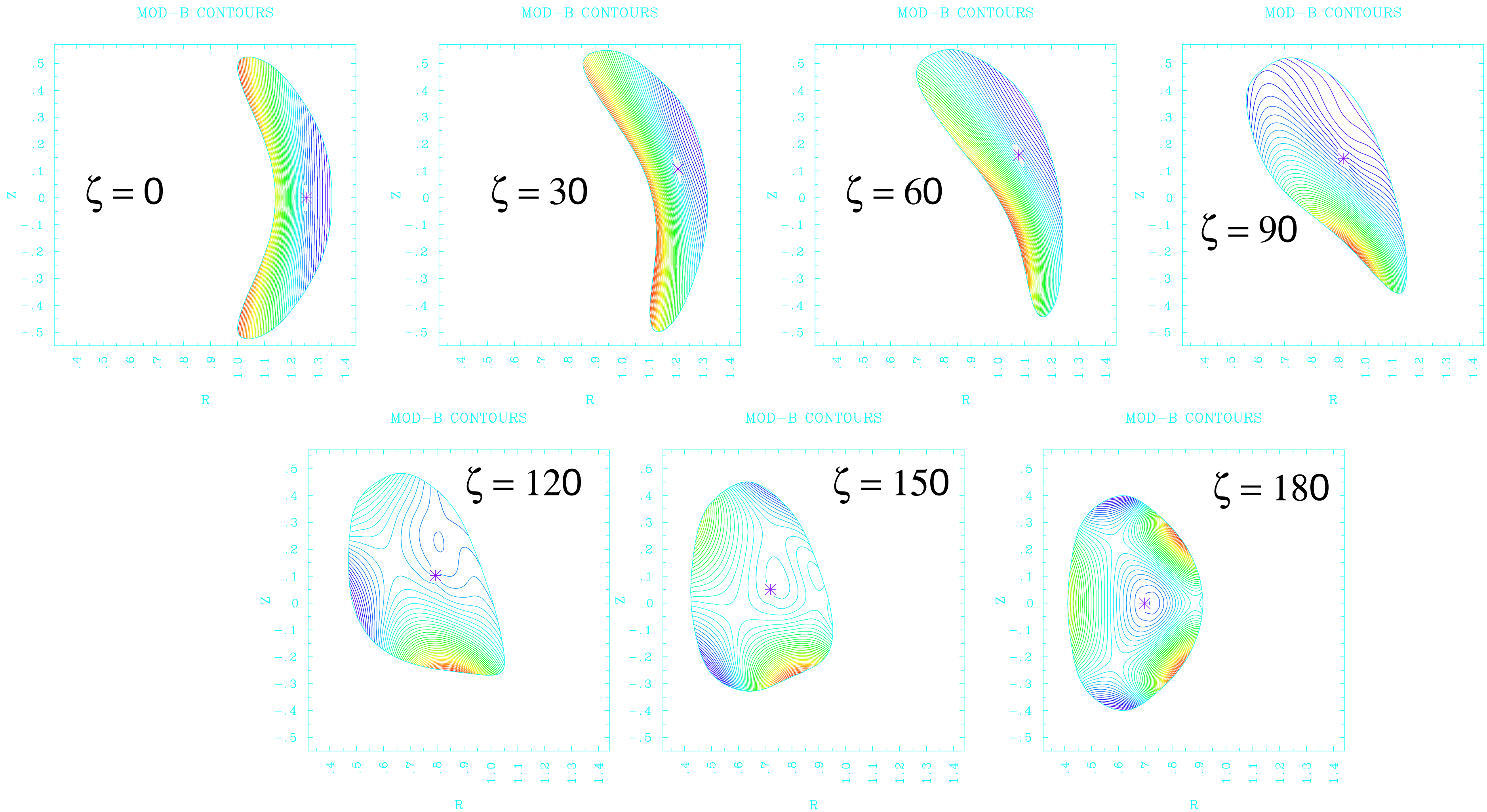
|B| in T

- **QPS has two field periods**
- **These coils produce the plasma configuration shown**
- **The colors indicate the value of |B| on the last closed flux surface**

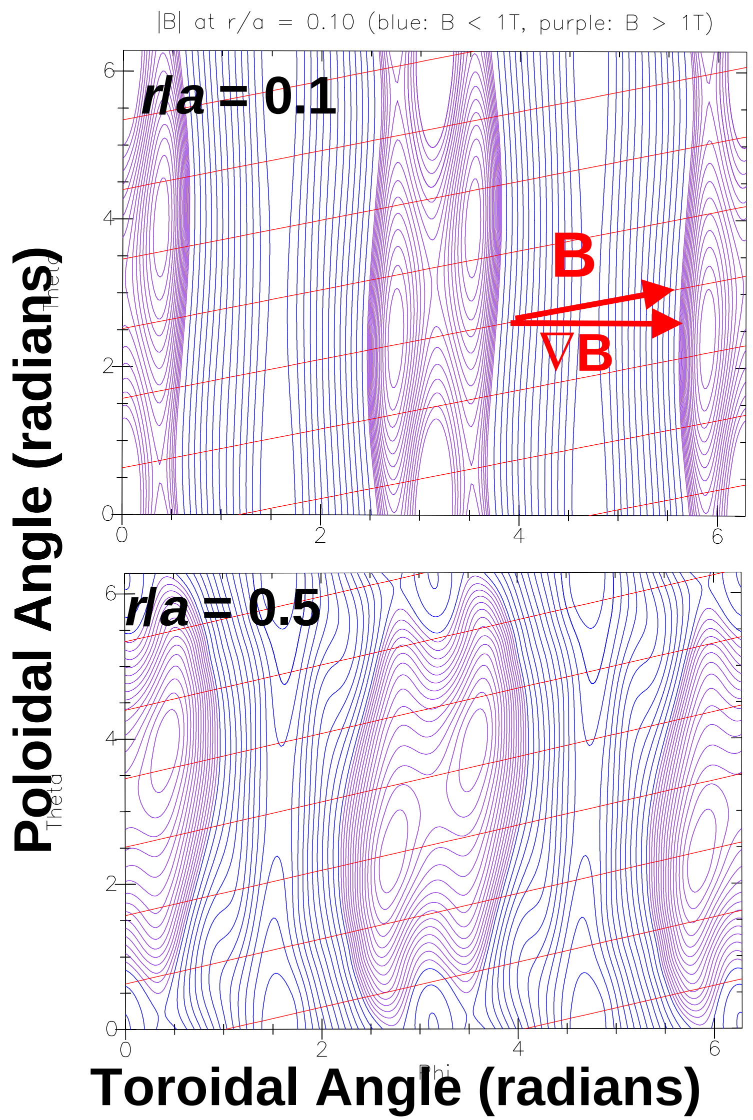


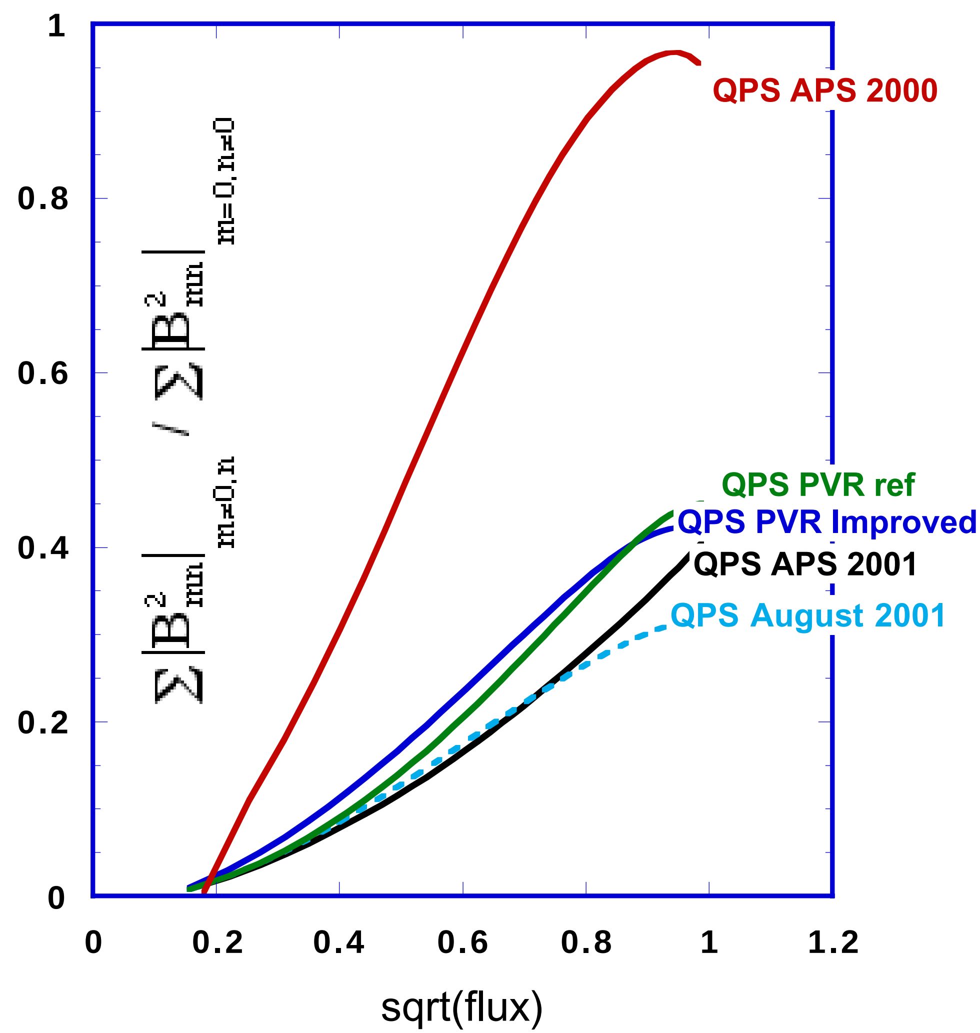


QPS Plasma Cross Sections and |B| Contours



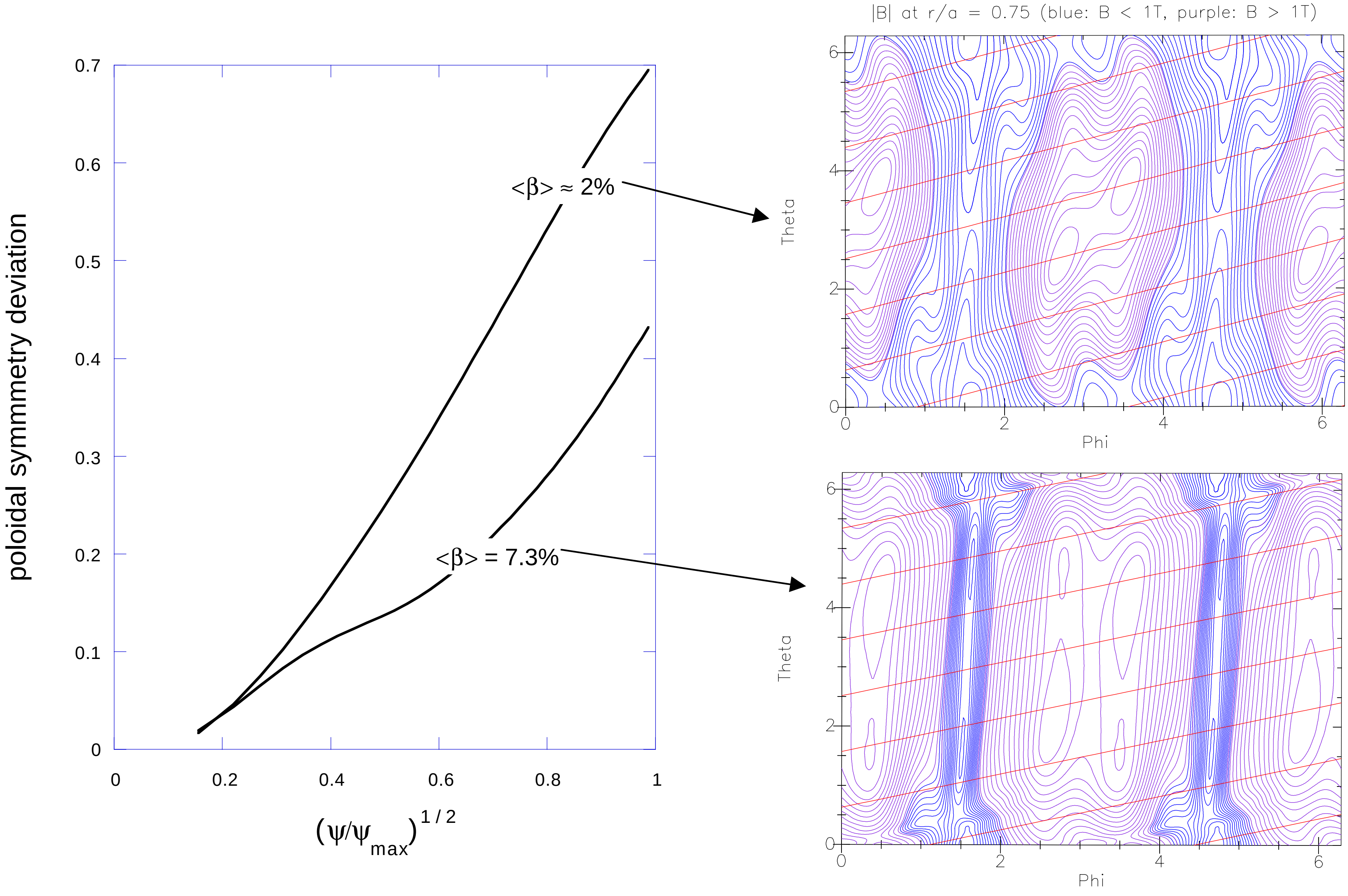
Quasi-Poloidal |B| Structure Varies with Radius



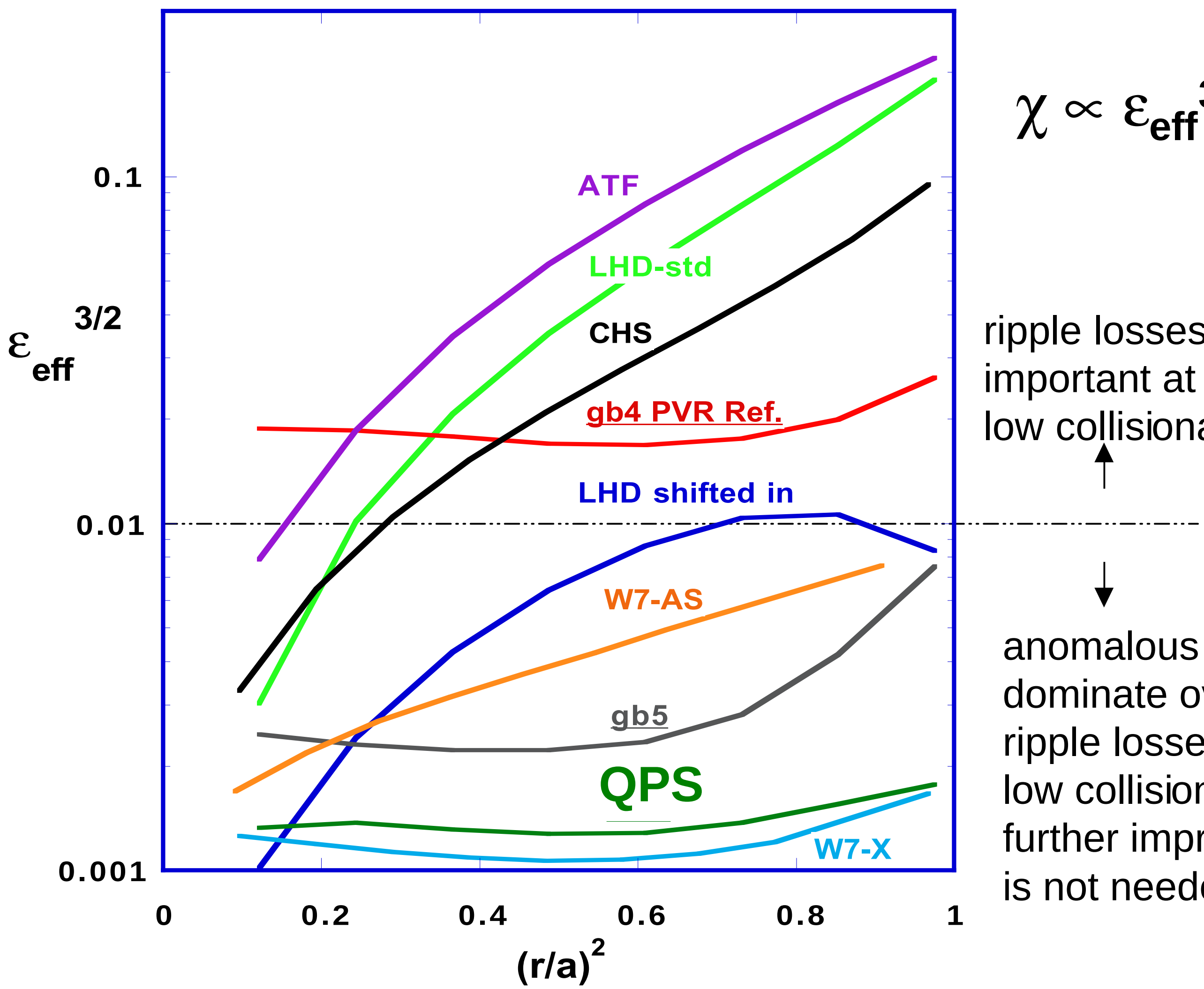


- **The *B* x ∇B drift can be made very small in this approach**
- **Configuration becomes more quasi-poloidal as β increases**

Finite-β Modifications of |B| Lead to Improved Quasi-Poloidal Symmetry



QPS Configurations Have Small Neoclassical Transport

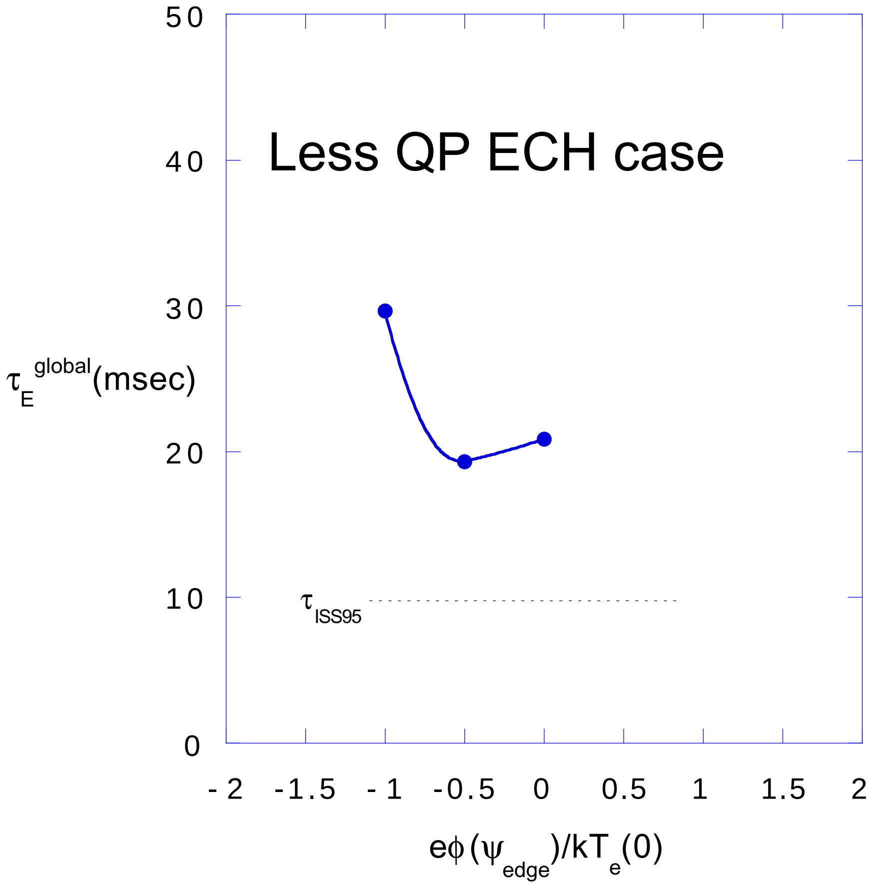


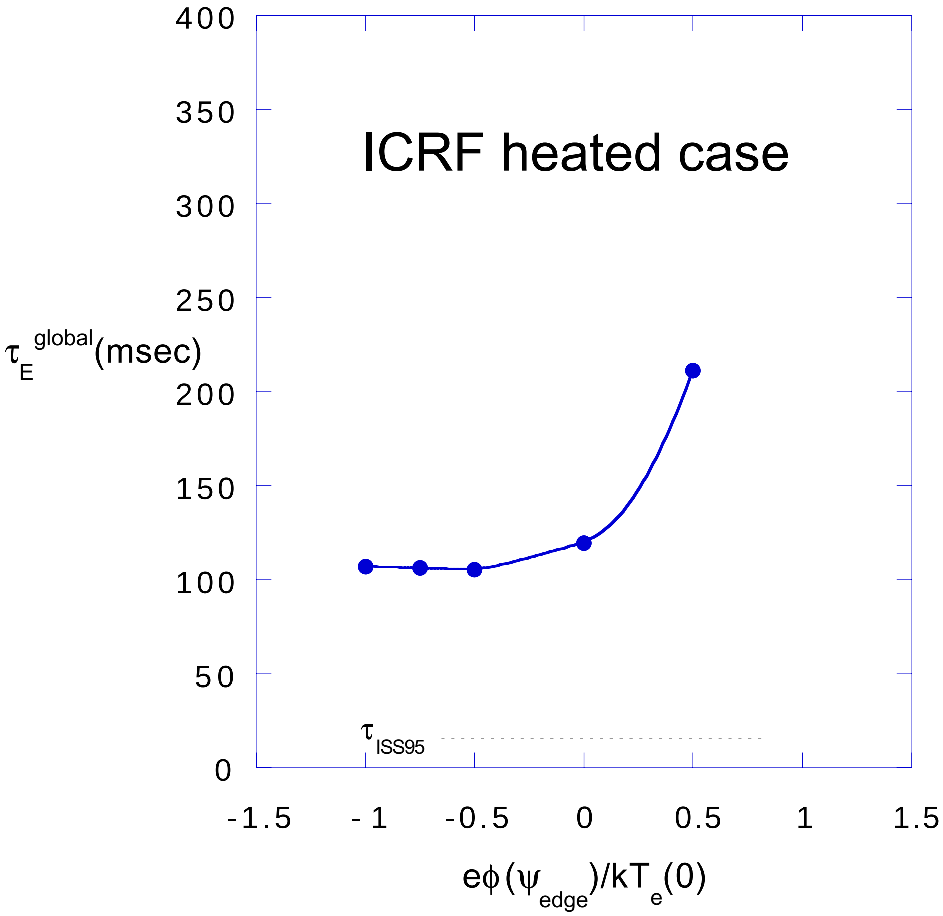
$\chi \propto \varepsilon_{eff}^{3/2}$

ripple losses important at low collisionality

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

ISS-95 Confinement Dominates Neoclassical Confinement

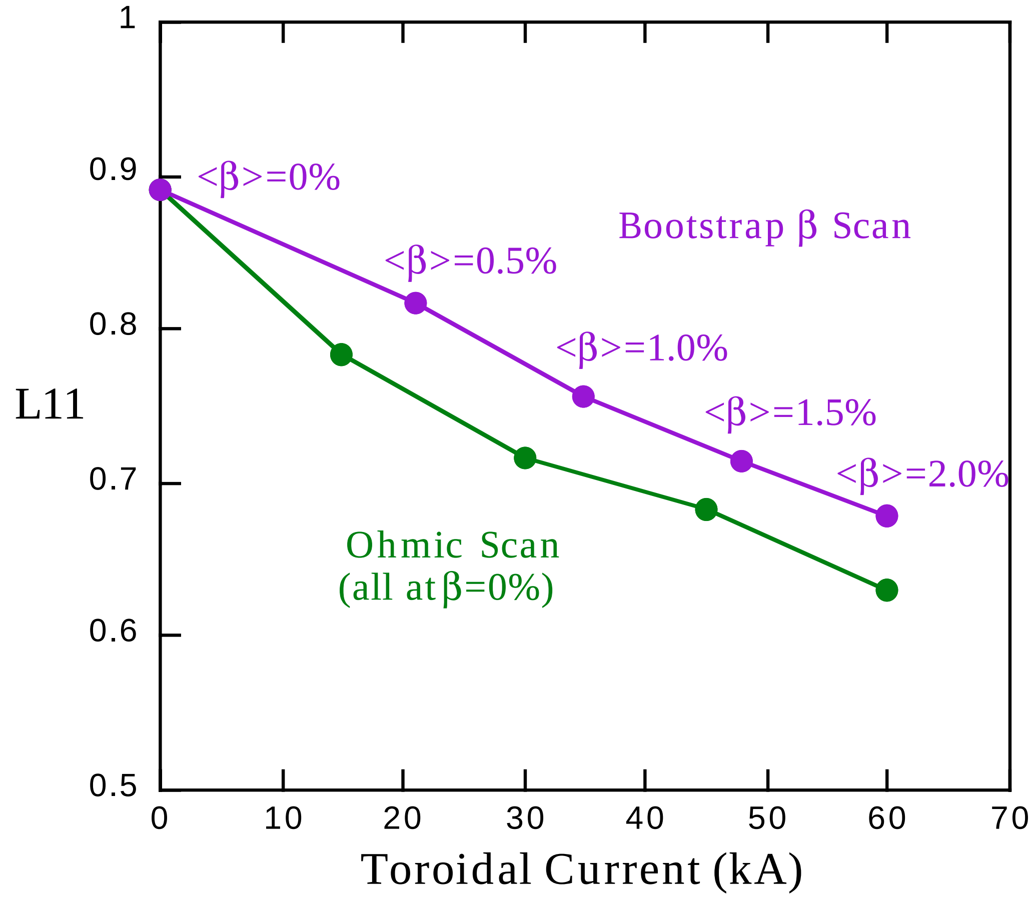




Older (PVR) configuration shown here; the present QPS configurationhas very much improved neoclassical confinement

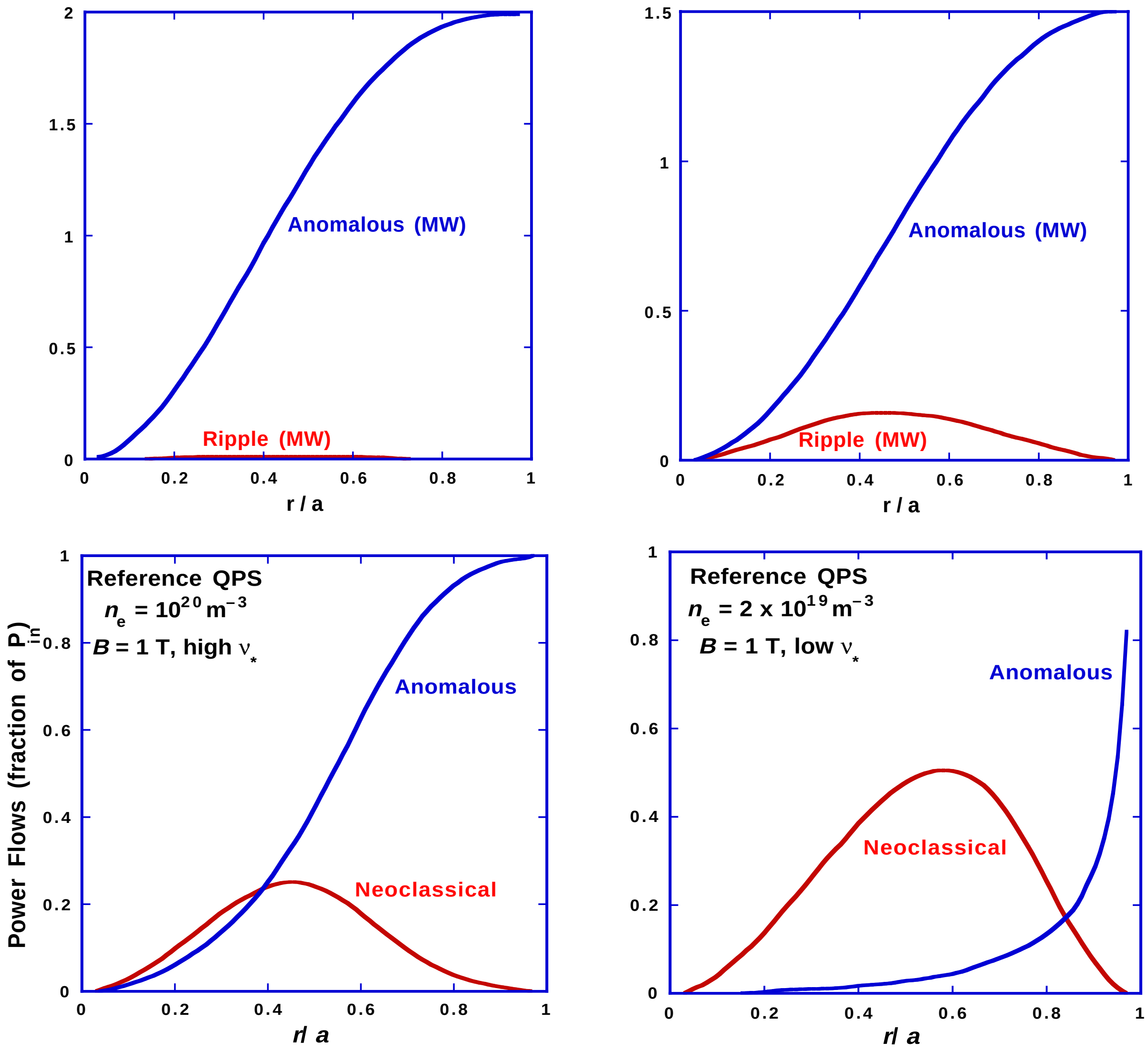
Confinement Improves with ⟨β⟩

- **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

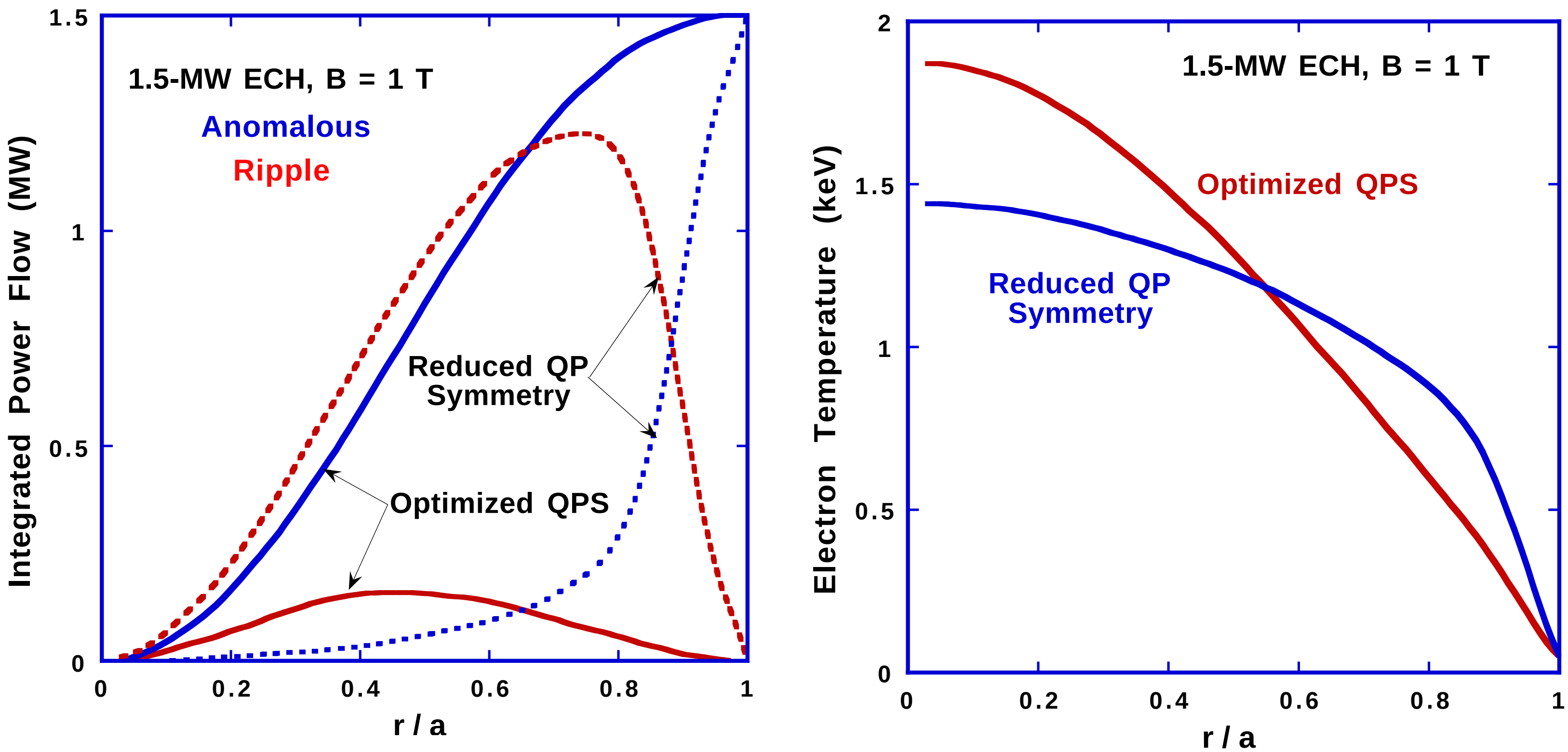
Anomalous and Neoclassical Loss Channels Can Be Separated through Choice of Density and Spoiling the Quasi-Poloidal Symmetry



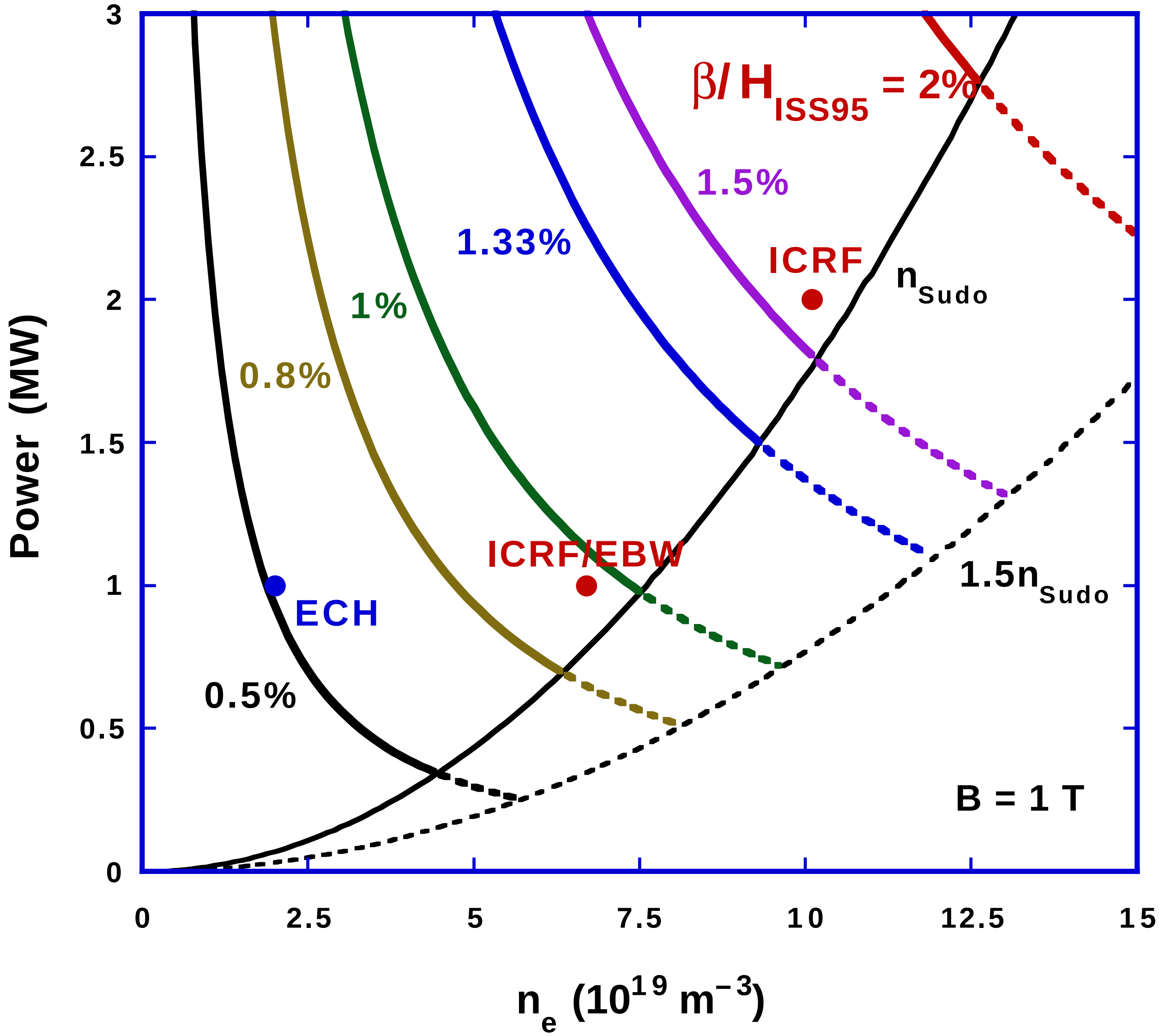
Optimized QPS configuration

QPS configuration with less quasi-poloidal symmetry

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



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

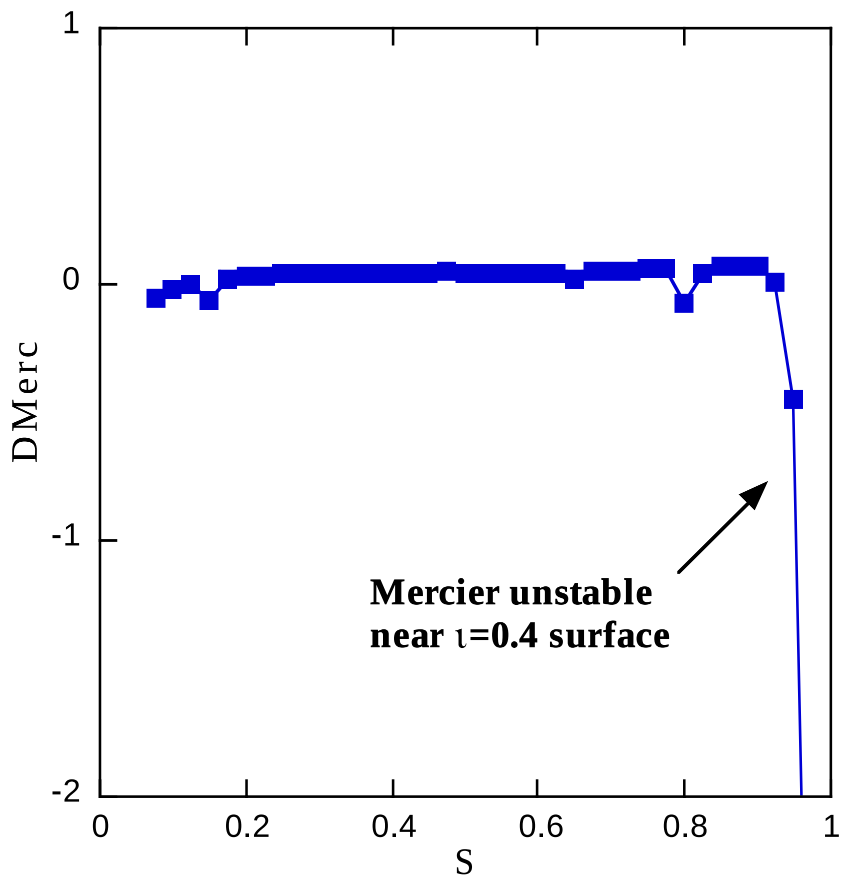


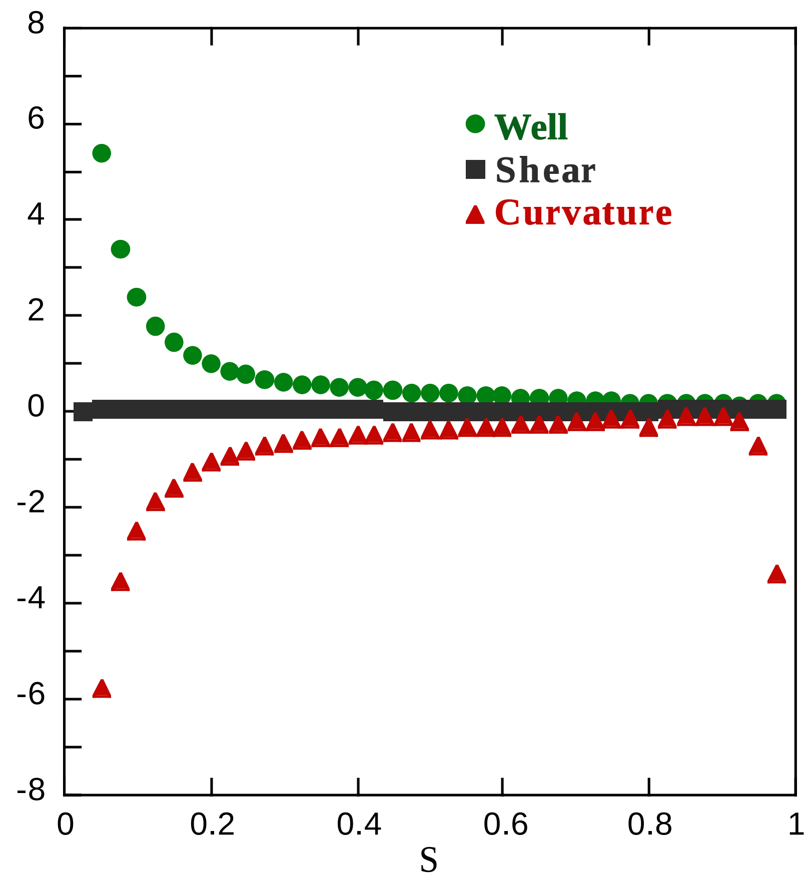
Multiply contour values by H_{ISS95} (= 1-2.5 in experiments)

QPS parameter space for *B* = 1 T

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

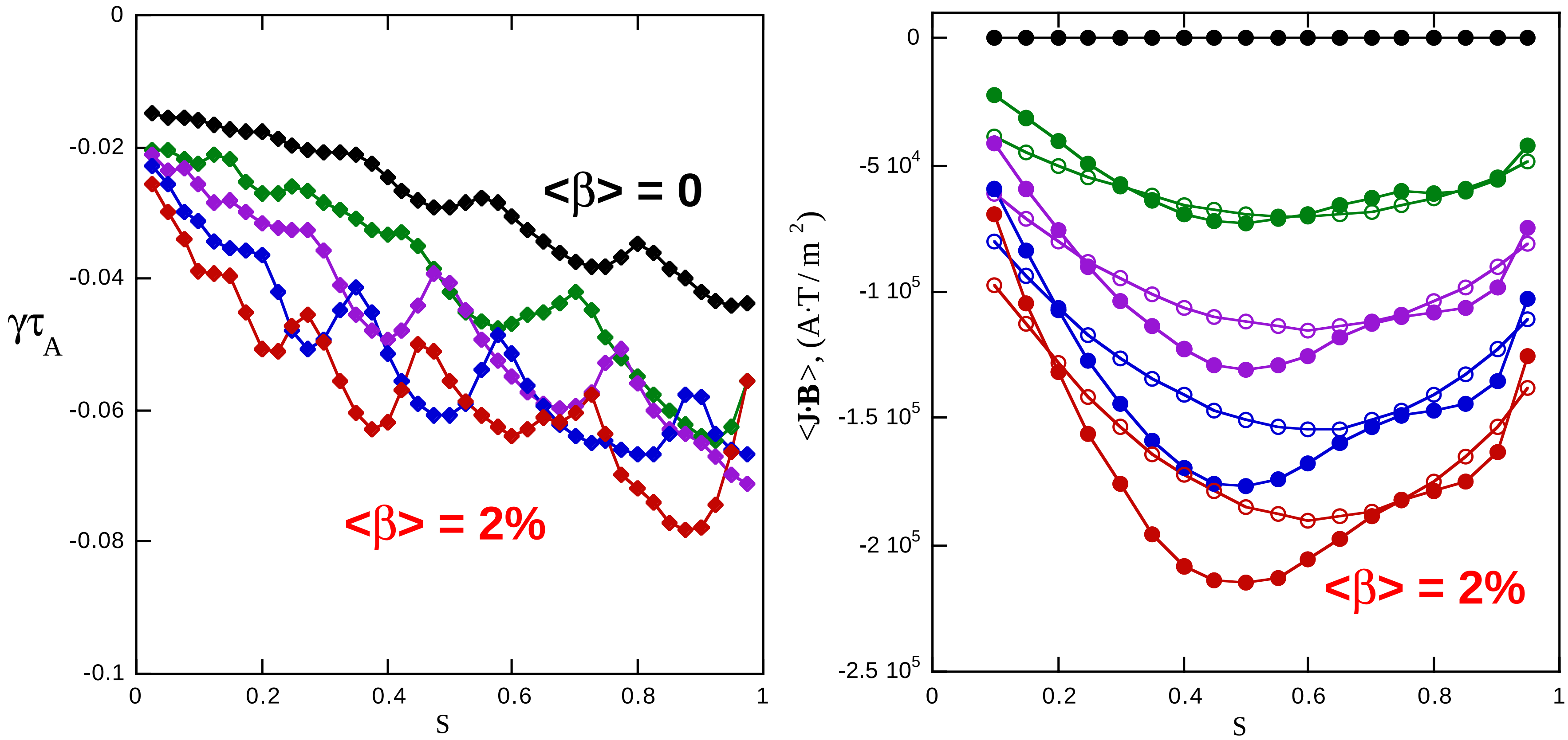
- Mercier stability criteria for fixed boundary at <β> = 2.5%
- However, these limits are exceeded in stellarator experiments





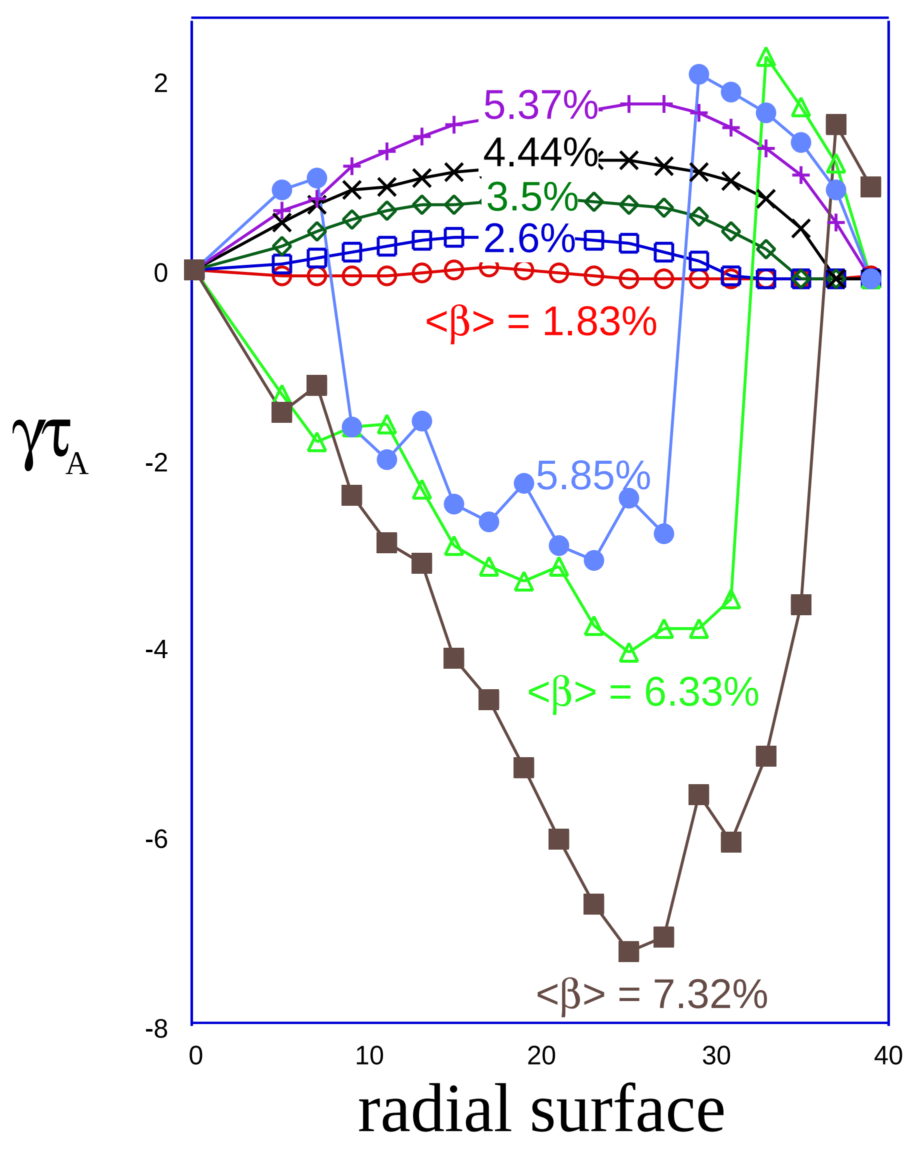
Ballooning Stability: Free Boundary Scan, Stable & Bootstrap Consistent to β = 2.3 %

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

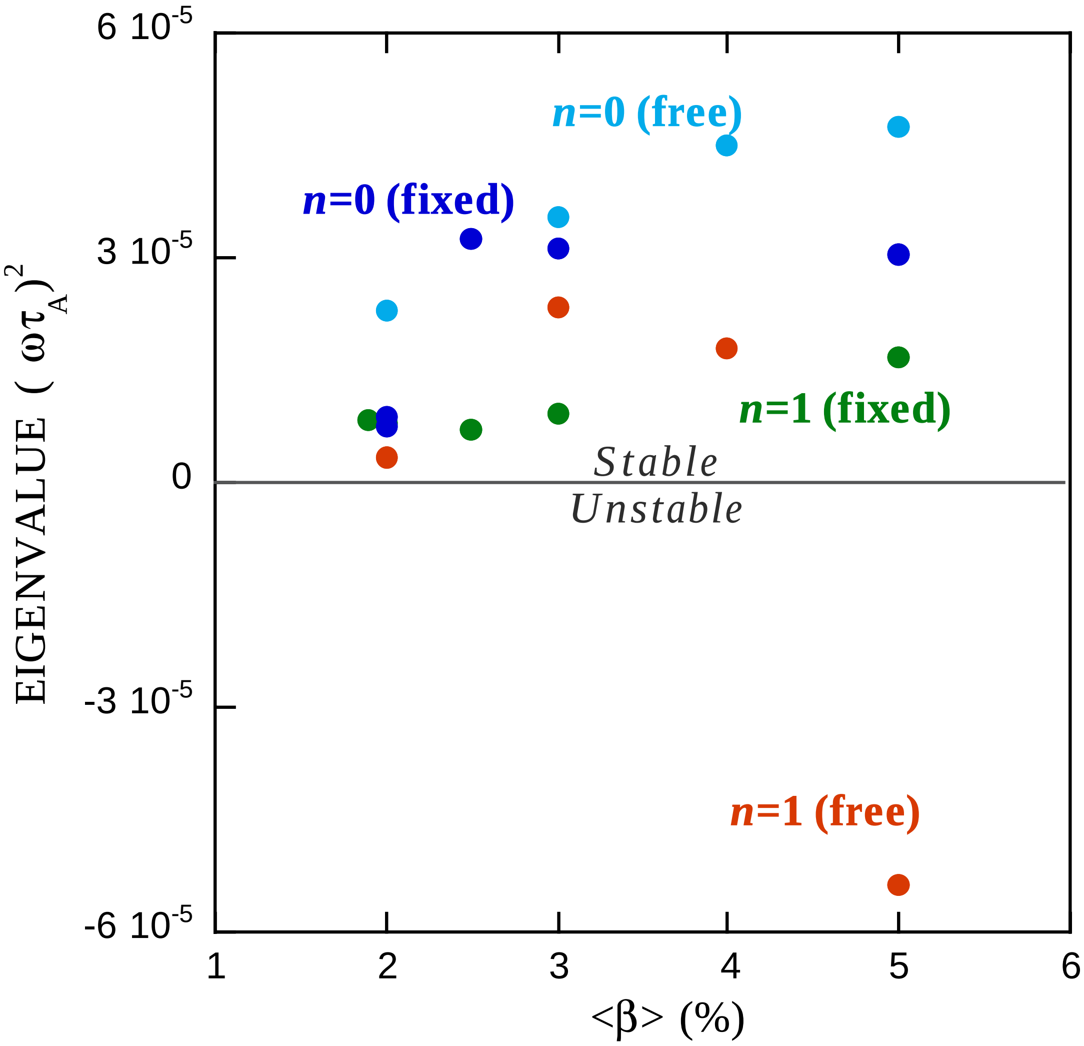


Theoretically these modes should determine the β limit, but these "β limits" are exceeded in stellarator experiments

Second Stability Regime Exists in QPS at Higher Beta

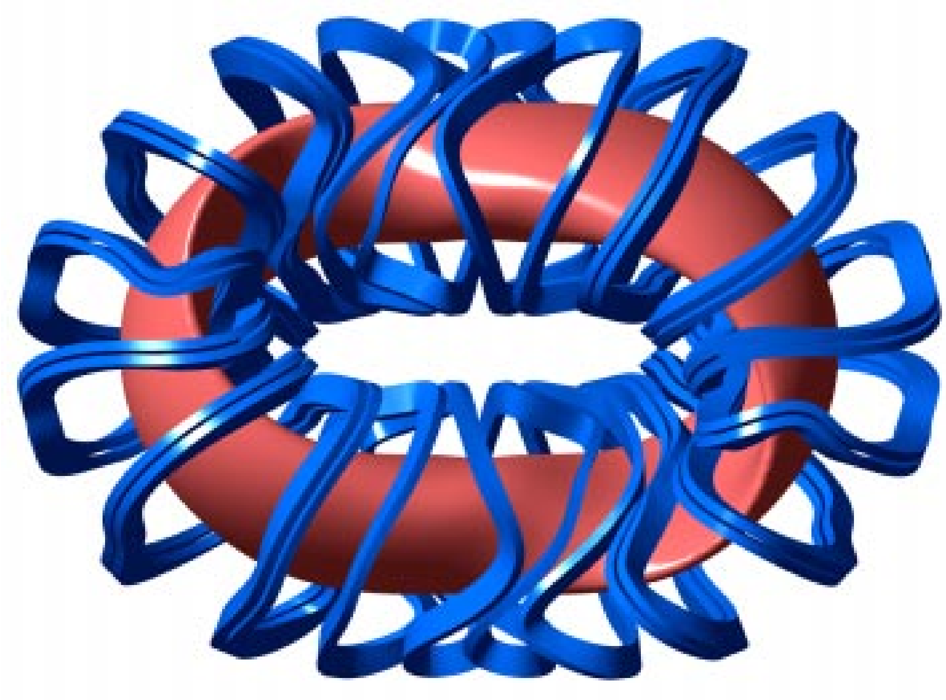


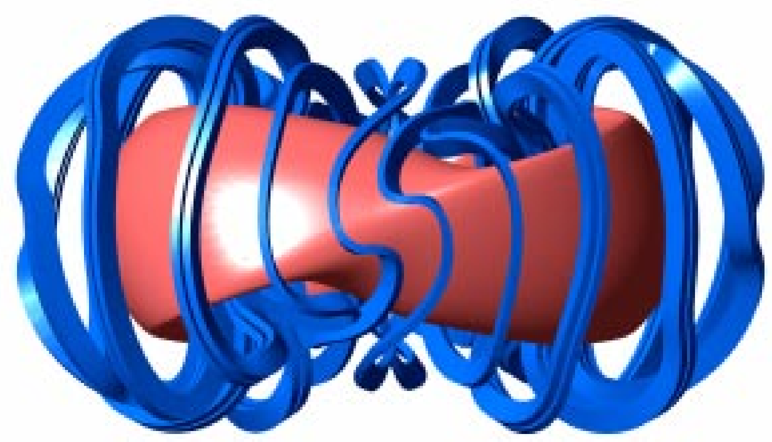
Kink & Vertical Stability: QPS configuration is kink/vertical stable for <β> up to 5%



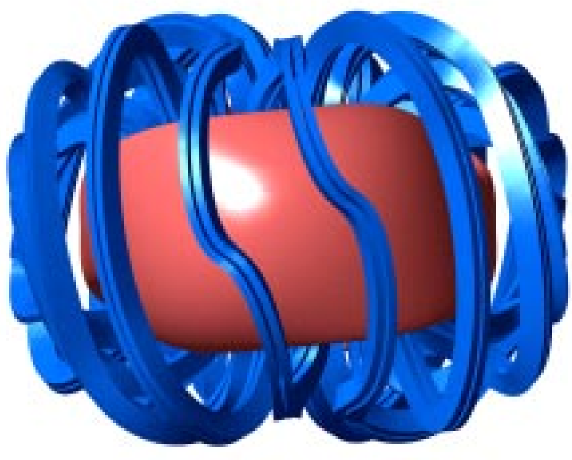
- $n = 0$ and $n = 1$ eigenvalues

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



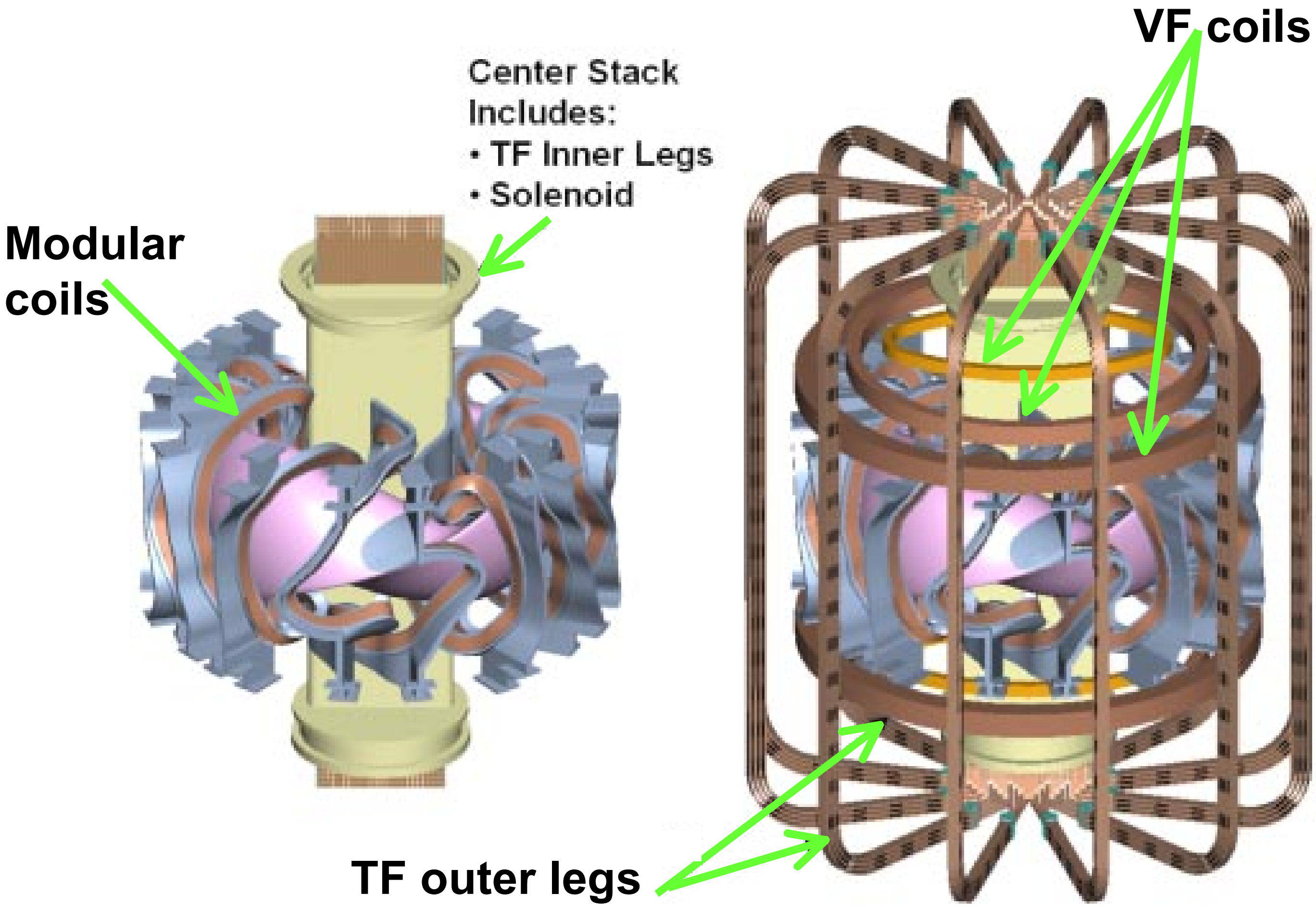


- 16 coils of 4 different types
- Adequate coil-coil spacing, plasma-coil spacing, minimum bend radius
- Good access between coils for heating and diagnostics
- Room in center for TF coil legs and OH solenoid

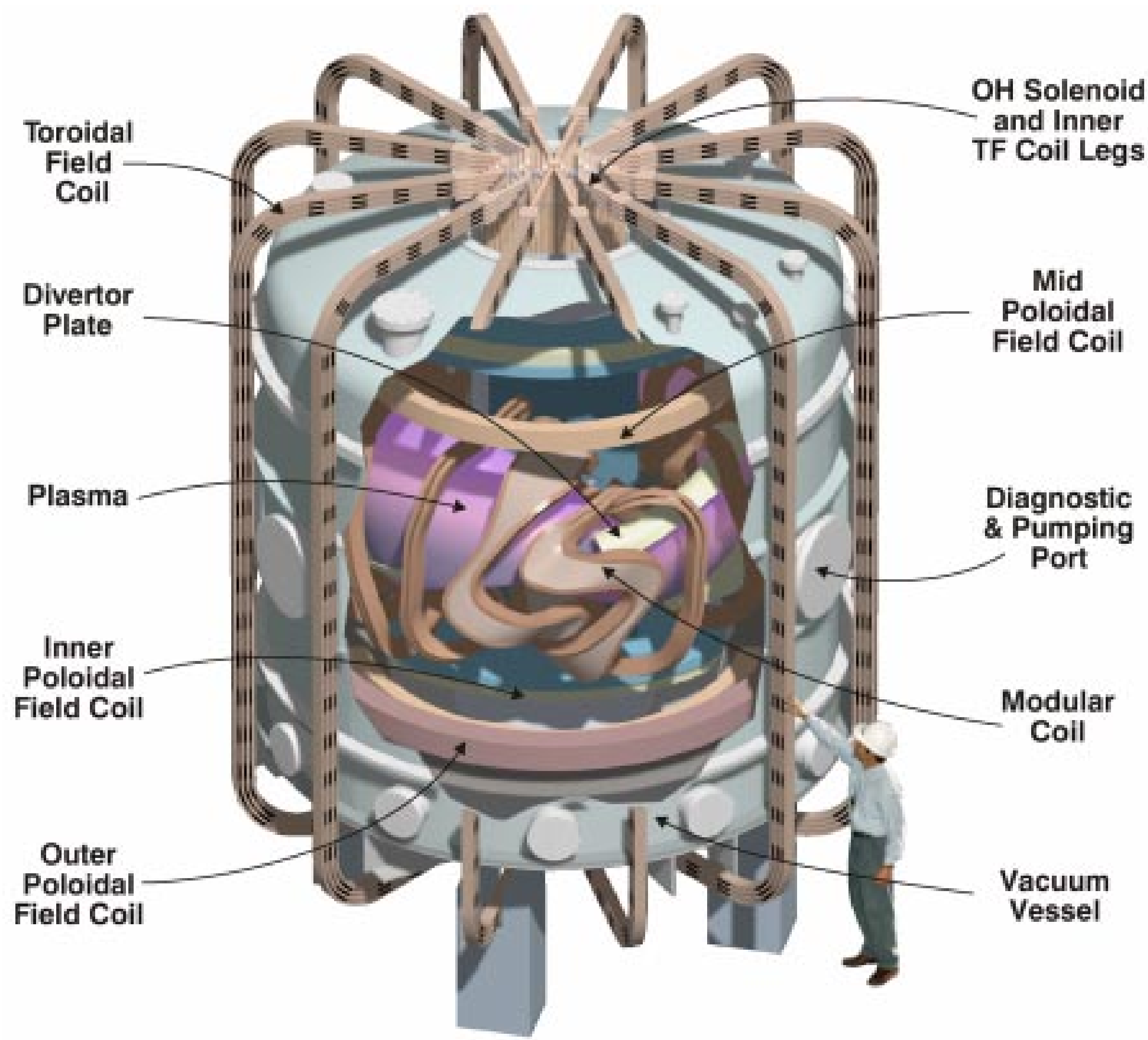


QPS Has Additional Coils to Change Transform, Shear, and Magnetic Configuration for Physics Studies

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



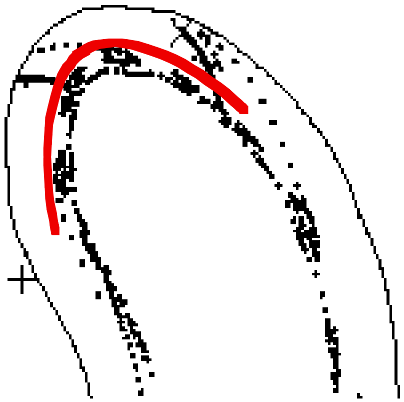
Quasi-Poloidal Stellarator



- $<R> = 0.9$ m
- $<a> = 0.33$ m
- $<R>/<a> = 2.7$
- $V_{plasma} = 2\ m^3$
- 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
- $P_{ECH} = 0.6$-1.2 MW
- $P_{ICRF} = 1$-3 MW

Control of Neutrals

1. The build-up of neutral pressure in the vessel will be minimized through local concentration of recycling
   - Poincaré plots (and experiments on W7-AS) indicate that field lines (particles) leave the plasma predominantly at the top and bottom of the bean shape.



   - Here, recycling neutrals will be confined mechanically by baffles and then have a finite probability of re-ionization by the boundary plasma.
   - Mechanical baffling and local recycling with re-ionization can lead to high-recycling divertor operation with low electron temperatures at the plate.
   - Connection lengths in the scrapeoff region are long enough for effective island divertor operation

2. Additional neutrals control will be achieved by surface pumping
   - Boronization *(line-of-sight of plasma)*
   - Large area titanium (or cryo-) pumping *(top or bottom, behind baffles)*

QPS Research Topics

- **Anomalous transport, internal transport barriers, and flow shear in low-*R*/*a* configurations with quasi-poloidal symmetry**
- **Reduction of neoclassical transport due to near alignment of *B* and ∇B**
- **Impact of poloidal flows on enhanced confinement**
- **Equilibrium quality (islands, ergodic regions) and its repair at *R*/*a* ~ 2.7**
- **Flux surface robustness with β and dependence of bootstrap current on configuration properties**
- **Ballooning β character and limits for quasi-poloidally symmetric configurations at very low *R*/*a***

QPS Physics Areas and Diagnostics

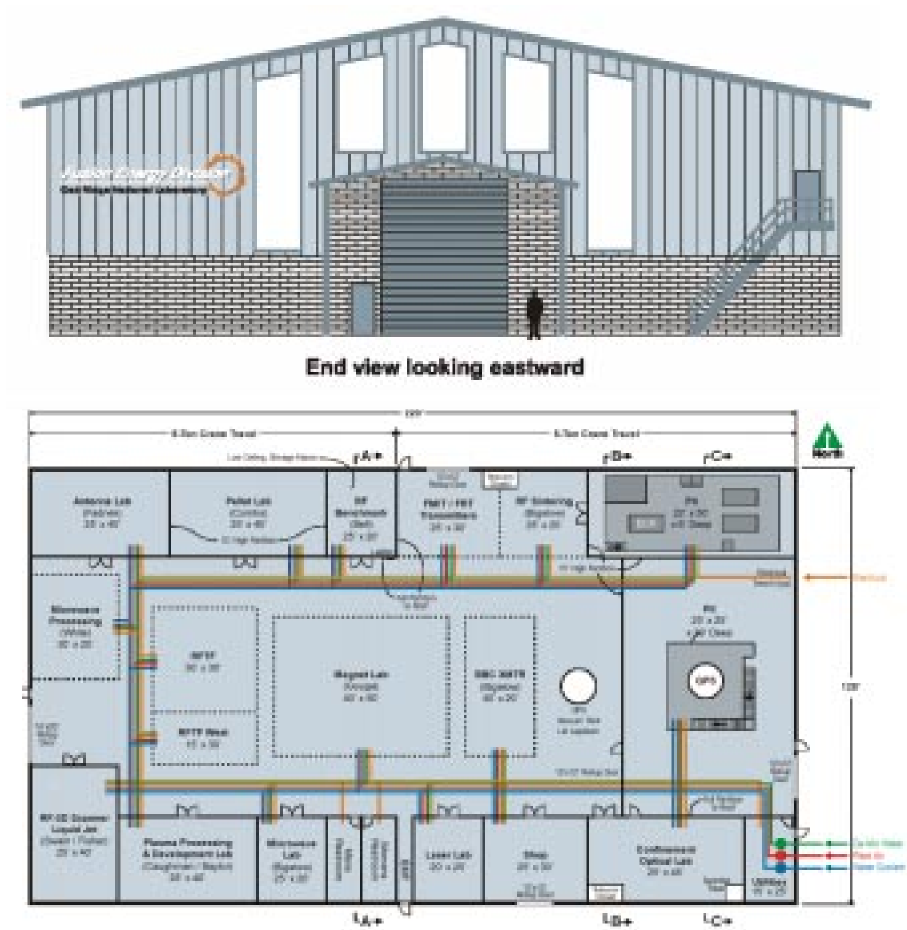
PROGRAM AREA	PHYSICS ISSUES	DIAGNOSTIC (Program Phase)
VACUUM MAGNETIC GEOMETRY, FLEXIBILITY	starting/low beta geometry: dominant |B|components, ergodic regions, islands, aspect ratio, ellipticity, triangularity, helical axis, etc.	electron beam with fluorescent screen or rods **(1)** and CCD camera **(0)**: low energy -- flux surfaces; high energy -- lowest |B| components and energetic orbits.
MHD EQUILIBRIUM, ROBUSTNESS OF FLUX SURFACES	finite-beta geometry: flux surfaces, magnetic axis shift, interior ergodic regions and magnetic islands	Soft X-ray diode arrays **(2, 3)** YAG Thomson scattering **(5)**
BOOTSTRAP CURRENT	variation (reduction) with coil currents, effect on magnetic islands, ergodization of flux surfaces, and tearing modes	Rogowski coils **(2)**, magnetic loops **(2)**
POWER BALANCE	power deposition power losses	fast diamagnetic loop **(0)**, YAG Thomson scattering **(3?)**, reflectometer **(3)** bolometers **(2)**, spectroscopy **(2)** fast ion loss cups **(3)**
TRANSPORT	electron density electron temperature profile ion temperature profile electric field	2-mm/FIR multi-channel interferometer **(0, 2)** ECE **(3)**, Thomson scattering **(3?, 5)** spectroscopy (2), charge-exchange **(3)** probes **(2)**, spectroscopy **(2)**, HIBP **(collab?)**
MHD INSTABILITY	frequency spectrum, mode structure, correlations	high frequency magnetic probes **(5)** soft X-ray array **(5)**
PLASMA EDGE, DIVERTOR GEOMETRY	limiting aspect ratio, edge magnetic structure and islands, diverted flux bundle	Langmuir probes **(4)**, filtered CCD cameras **(4)**, edge interferometer **(4)**, IR camera **(4)**, bias on divertor plates **(4)**

QPS Features

- A low-aspect-ratio QPS configuration with
  - low-collisionality transport as low as in the high-*R*/*a* W 7-X, much lower than anomalous (ISS-95) losses
  - ISS95 scaling + neoclassical transport (0-D and 1-D) calculations predict $\langle\beta\rangle$ = 1 - 3%, τ_E ~ 20 ms at high collisionality
  - connection lengths in the scrapeoff region are long enough for effective island divertor operation
  - ballooning β limits (~2.5%) comparable to best existing stellarators
- A coil set that meets all engineering constraints and reproduces the fixed-boundary physics
- An experimental program with
  - adequate ECH/EBW and ICRF heating for QPS goals
  - staged approach on broad topics with emphasis on low-*R*/*a* equilibrium/stability and confinement with appropriate diagnostics

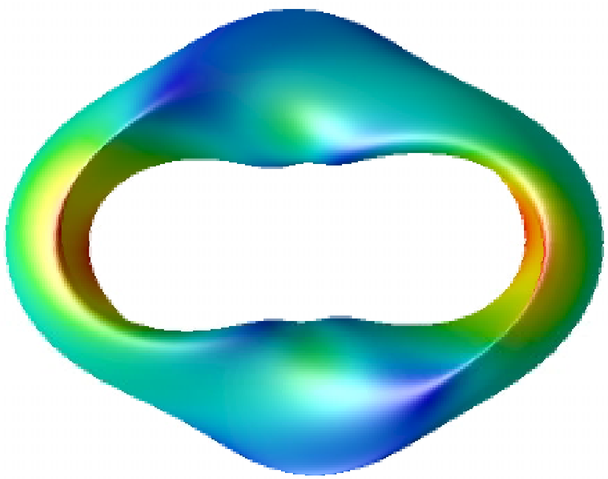
ORNL Is Providing New Facilities for QPS

- **27, 500 sq. ft multi-purpose research facility at new site**
- **Infrastructure is configured for the QPS requirements**
  - **all coil power supplies; ECH & ICRF heating; bus work; cooling water; etc.**
- **60 office spaces in a new office complex in the main campus**
- **Additional offices at the QPS site**

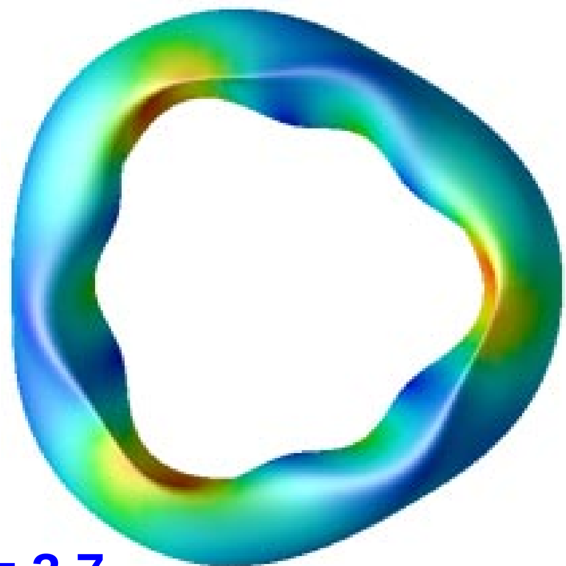


High-β Quasi-Poloidal Configurations

- **Ballooning/Mercier stable at $\langle\beta\rangle$ > 20%, kink/vertical stable at $\langle\beta\rangle$ ~ 11%**
- **Tokamak-like shear but avoids *q* = 1 and *q* = 2 surfaces, bootstrap current a factor of 3-5 less than for a tokamak**
- **Degree of quasi-poloidal symmetry increases as β increases, more quasi-poloidal than QPS**



$\langle R\rangle/\langle a\rangle$ = 2.7
$\langle\beta\rangle_{limit}$ = 10%



$\langle R\rangle/\langle a\rangle$ = 3.7
$\langle\beta\rangle_{limit}$ = 15%

QPS will provide the first experimental basis needed for extrapolation to high β

QPS Can Contribute to Understanding the High-β Quasi-Poloidal Reactor Vision

- **Role of quasi-poloidal symmetry on neoclassical and anomalous confinement improvement at lower β**
  - **For high-β *qps*, confinement increases with β, becomes more quasi-poloidally symmetric**
- **Configuration dependence and β dependence of the bootstrap current at low *R*/*a***
  - **For high-β *qps*, bootstrap current relatively independent of β ⇒ configuration invariance with β**
- **MHD stability at <β> up to 2-3%**
  - **For high-β *qps*, transition from first to second ballooning stability region occurs at low β**
- **Effect of bootstrap current on flux surface integrity for low-*R*/*a* stellarators (neoclassical tearing modes)**
  - **For high-β *qps*, shear is opposite to that in QPS (*without* I_{OH})**

Status and Plans

- Successful Physics and Project Validation reviews were held by DOE in April and May
- Further improve the plasma and coil configuration
- Complete assessment of QPS physics properties
- Assess flexibility obtained with VF, TF, and OH solenoid
- Improve engineering design and cost/schedule estimates
- June 2002: Project Validation Review
- FY 2003: Design, Cost & Schedule Review
- 2003-2007: R&D, design and construction
- March 2007: first plasma

Summary

- **QPS is a compact stellarator that has excellent neoclassical confinement, good MHD properties, and a high-β reactor path**
- **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 thickness**
  - **reduced flow damping in poloidal direction**
  - **potential for second stability**
- **The QPS design satisfies physics requirements and engineering constraints; now in conceptual design**