Progress on the Physics of Low *A* Quasi-Poloidal Stellarators[1]

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on behalf of the QPS Design Team

University of Wisconsin - Dec. 5, 2001

[1]QPS

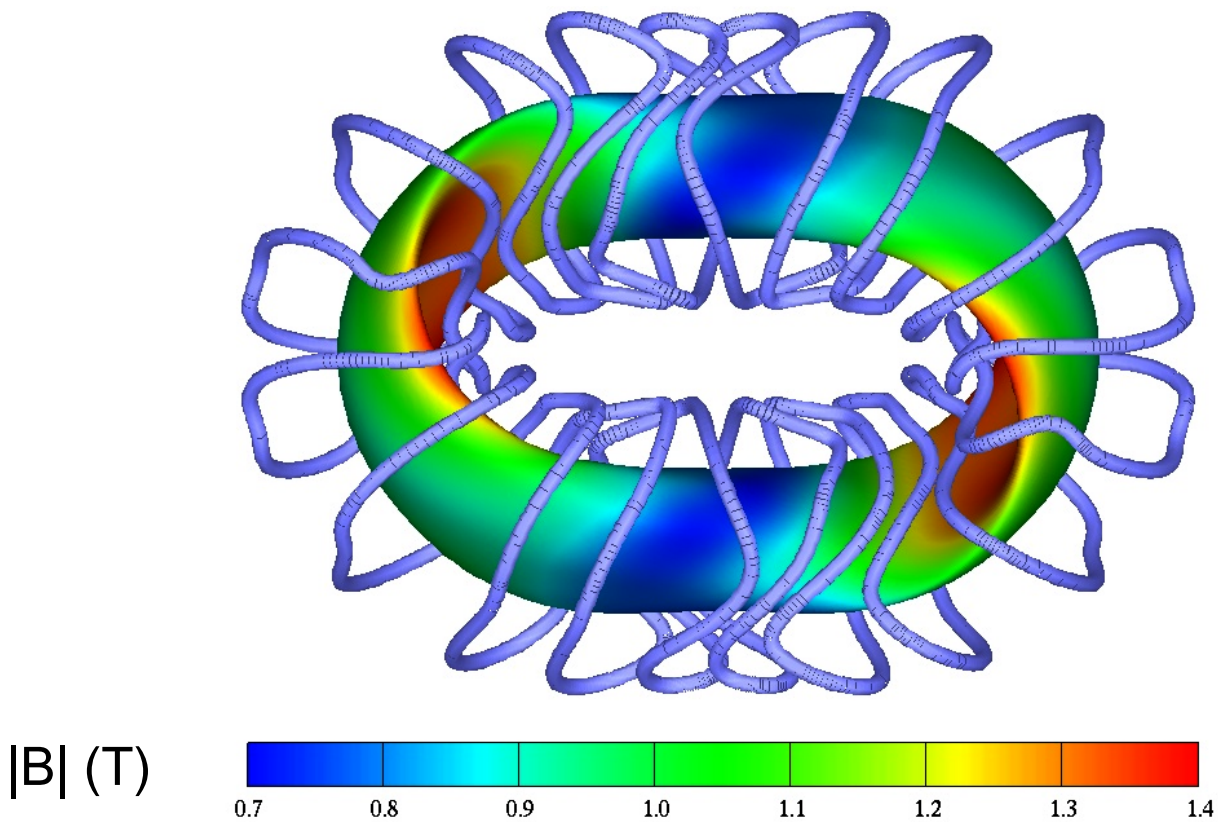
QPS: Compact Stellarator Physics

- To minimize ripple losses due to 3D effects, traditional stellarators are large aspect ratio (*A*)
  - Scales to large reactors (W7X -> 24m reactor)
- To reduce stellarator size (lower *A*), the QPS design
  - Uses unique US super-computing capabilities to perform advanced non-linear optimizations aimed at improving ripple transport through quasi-poloidal symmetry
  - Allows finite bootstrap current to ease coil design *and* increase β limits

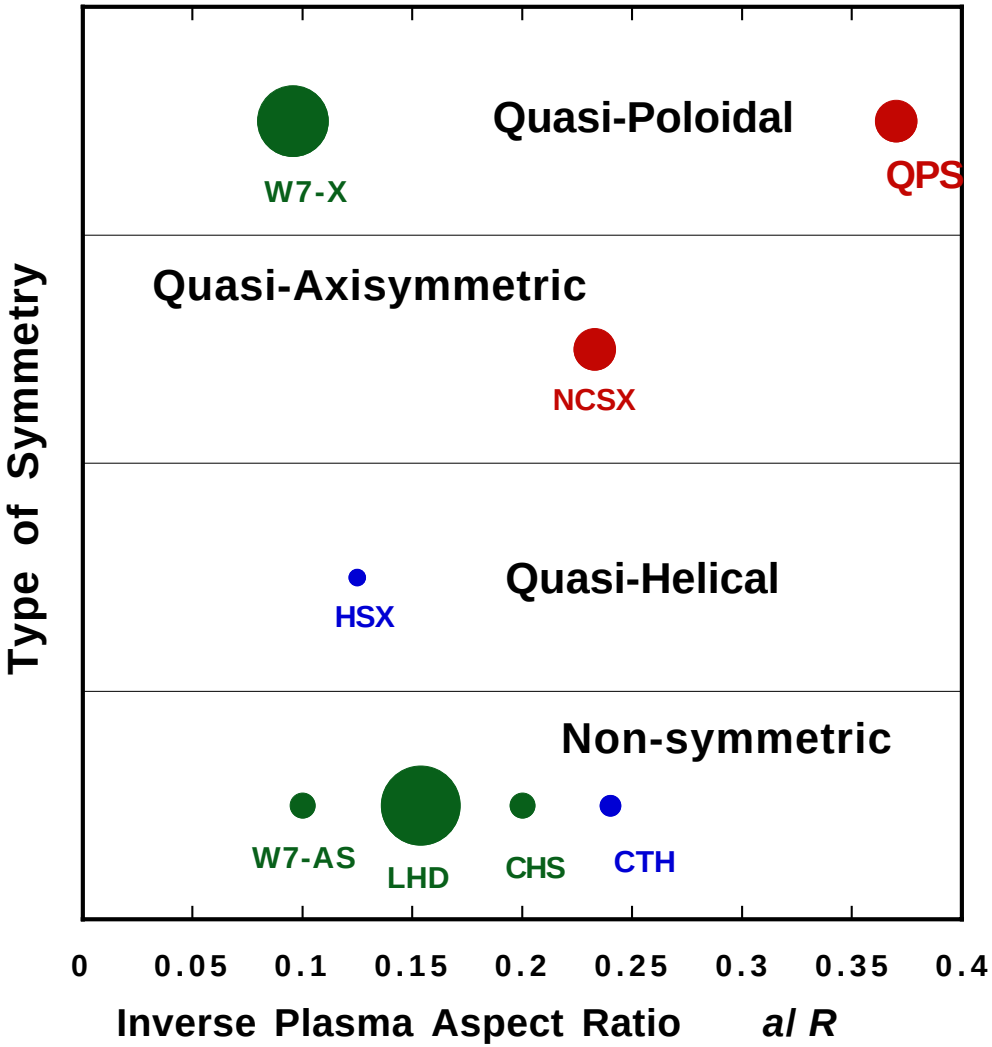
Status Report on Exciting QPS Developments Since the PVR (4/01)

- **At time of PVR, we had designed a low aspect ratio QPS configuration (GB5) with adequate neoclassical confinement, but with no coils**
- **Present QPS has *both* better transport (local diffusivity comparable to W7-X, but at 25% the aspect ratio!) *and* buildable coils with acceptable reconstruction that preserves designed physics properties of plasma**

QPS: Linked Mirror (Magnetically), Racetrack- Drakon (Topologically), Compact *A=R/<a>* ~ *2.75*



QPS Will Explore a New Region of Configuration Space: Low Aspect Ratio



MOTIVATION:

Compact Stellarators May Lead to Smaller (Attractive) Reactor Designs

Radius of circles Is proportional to the average plasma radius

Symmetry of |B| Limits Ripple (1/ν) Losses Due to 3D in Advanced Stellarators

- **Different types of symmetry lead to different approaches to improving low collisionality transport**
  - **Quasi-axisymmetry (NCSX): tokamak-like $|B|=|B|(\psi,\theta)$**
  - **Quasi-helical (HSX): $|B|=|B|(\psi,m\theta - n\varphi)$**
  - **Quasi-poloidal (W7-X, QPS): $|B|=|B|(\psi,\varphi)$**

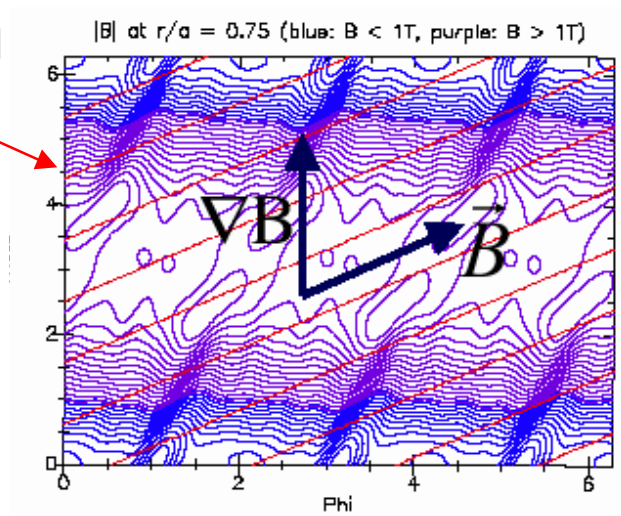
Quasi-Poloidal (and Quasi-Helical) Symmetry Reduces BX∇|B| Drifts

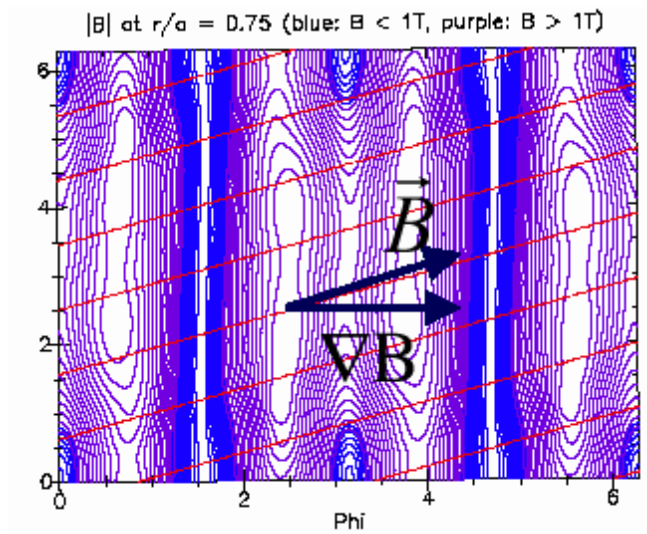
Increased alignment of **B** with ∇|B| reduces heat transport and bootstrap currents

Quasi-axisymmetric

Quasi-poloidal

Magnetic Field Lines



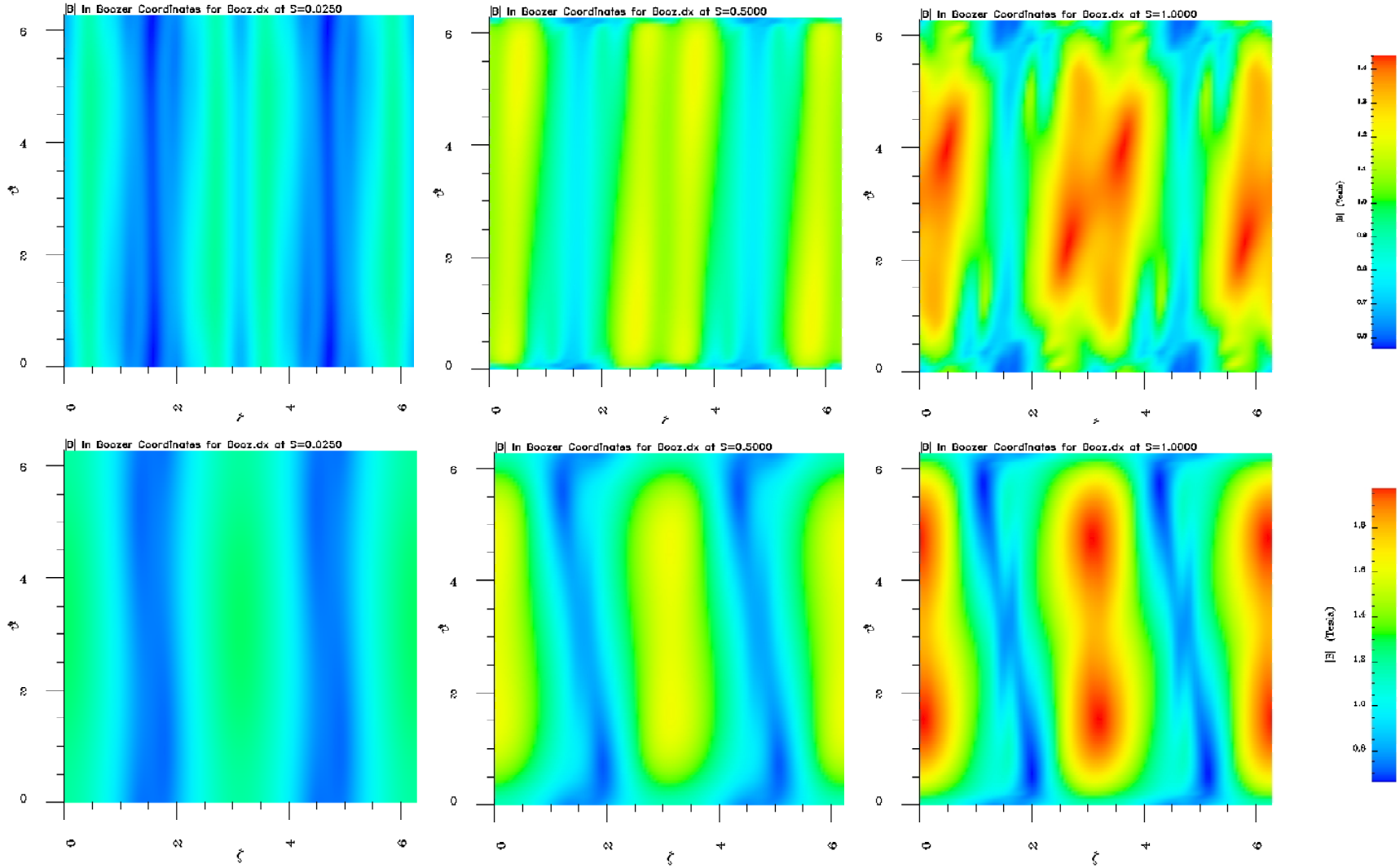


QPS Has Similar Symmetry in Boozer Space to Recent High β Hybrid

S = 0.025 S = 0.5 S = 1.0

QPS

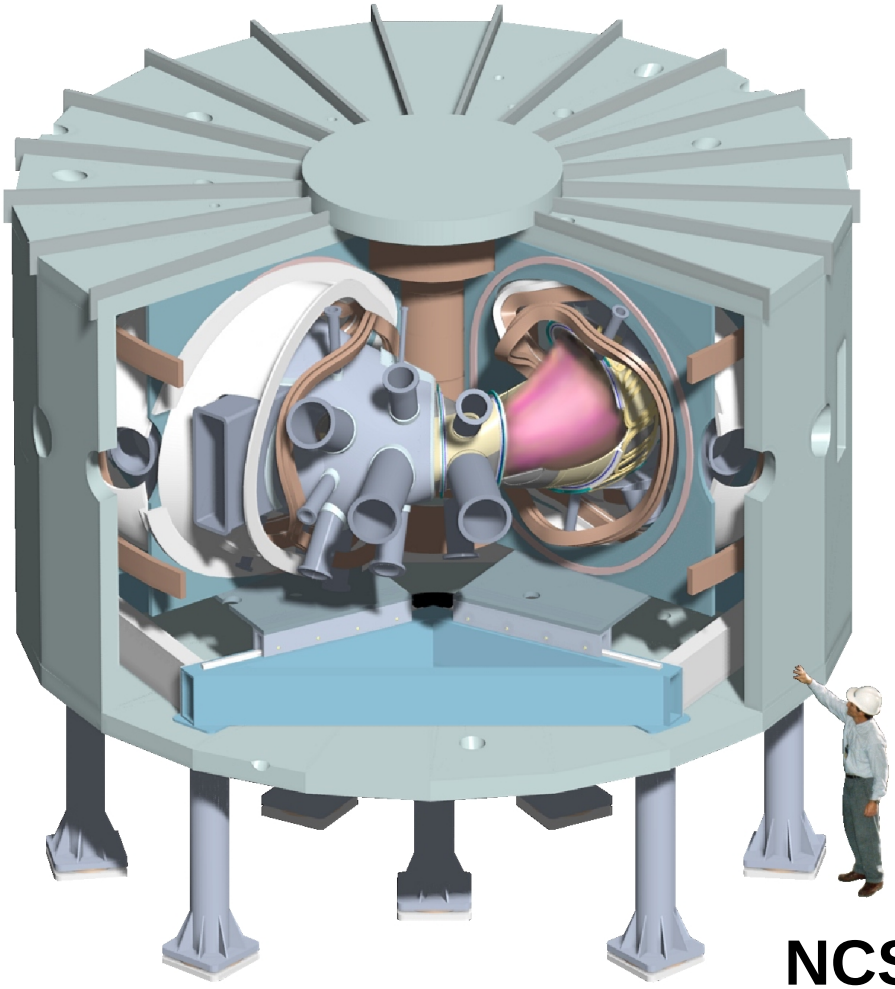
Hybrid



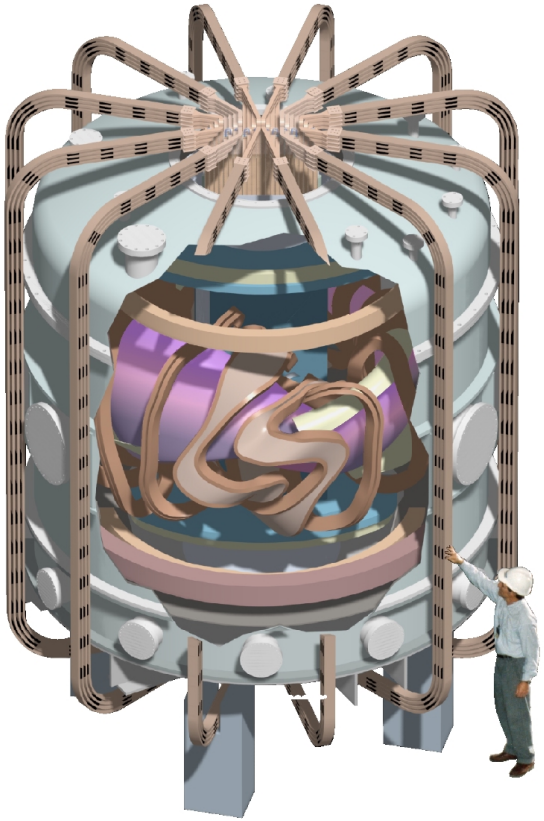
Key Features of QPS

- **Very low (for stellarator) $A \sim 2.75$**
  - $A \equiv \langle R \rangle / \langle a \rangle$, where $\langle a \rangle \equiv \langle ab \rangle^{0.5} \sim \langle a \rangle_{tok} \iota^{0.5}$
- **Optimized $1/\nu$ transport by aligning of B and $\nabla|B|$ (qp-symmetry:smaller drifts)**
  - **Low viscosity in poloidal direction (EXB flow) : transport barriers at reasonable power levels**
- **Small (but finite) bootstrap current compared with tokamak ($I_{bs} \sim I_{tok}/3$)**
  - **Kink, vertical stability up to $\beta \sim 4\%$**
- **Trapped particles localized in low κ (curvature) regions: DTE mode stability**

NCSX: cryogenic coils, *interior* vacuum vessel
QPS : room-temperature (gas cooled) coils, *exterior* vacuum vessel



NCSX



QPS

QPS Post PVR Progress: Better Physics *and* Better Coils

Importance of tool development

Overview of stellarator optimization

Ripple transport reduction at low *A*

Coil design and plasma reconstruction for optimized configurations

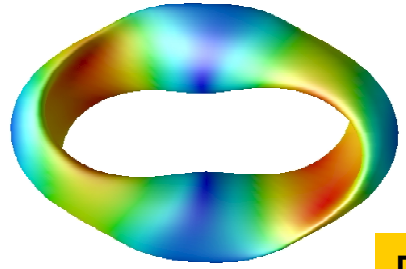
Physics Progress Enabled by Numerical Tool Developments

- **STELLOPT (stellarator optimizer code)**
  - **Merged NEO, COILOPT: improve physics (stability, transport,), also directly from coils. Collaboration with PPPL**
- **COILOPT (coil optimization code)**
  - **Introduced flexible basis set option (Fourier/Spline): design coils with lower $B_\perp$ errors satisfying engineering constraints (coil bend radii, access for neutral beams)**
- **DKES (drift-kinetic equation solver)**
  - **ORNL seed money: resolved ill-conditioning at low ($1/\nu$ regime) collisionalities: convergent solutions obtained**

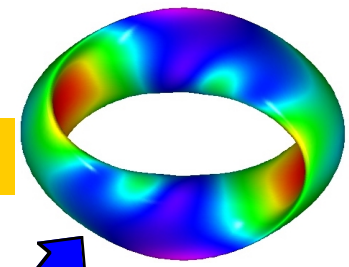
Stellarator Optimization Design Philosophy

Stellarator optimization

Initial configuration



Final optimized configuration



PHYSICS

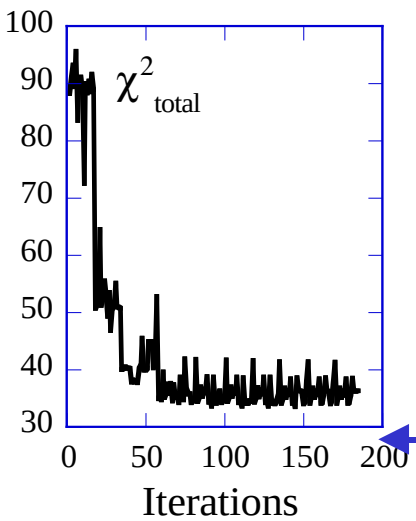
Adjust plasma boundary shape + profiles

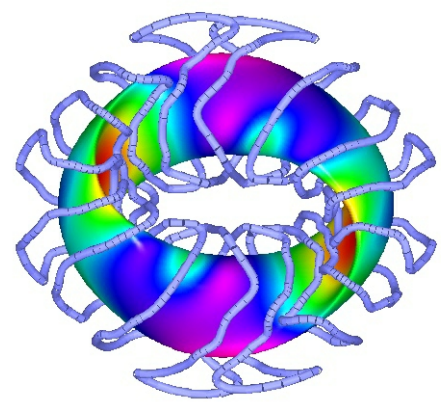
Solve VMEC equilibrium

Calculate χ^2

COILOPT

Levenberg-Marquardt Minimize χ^2

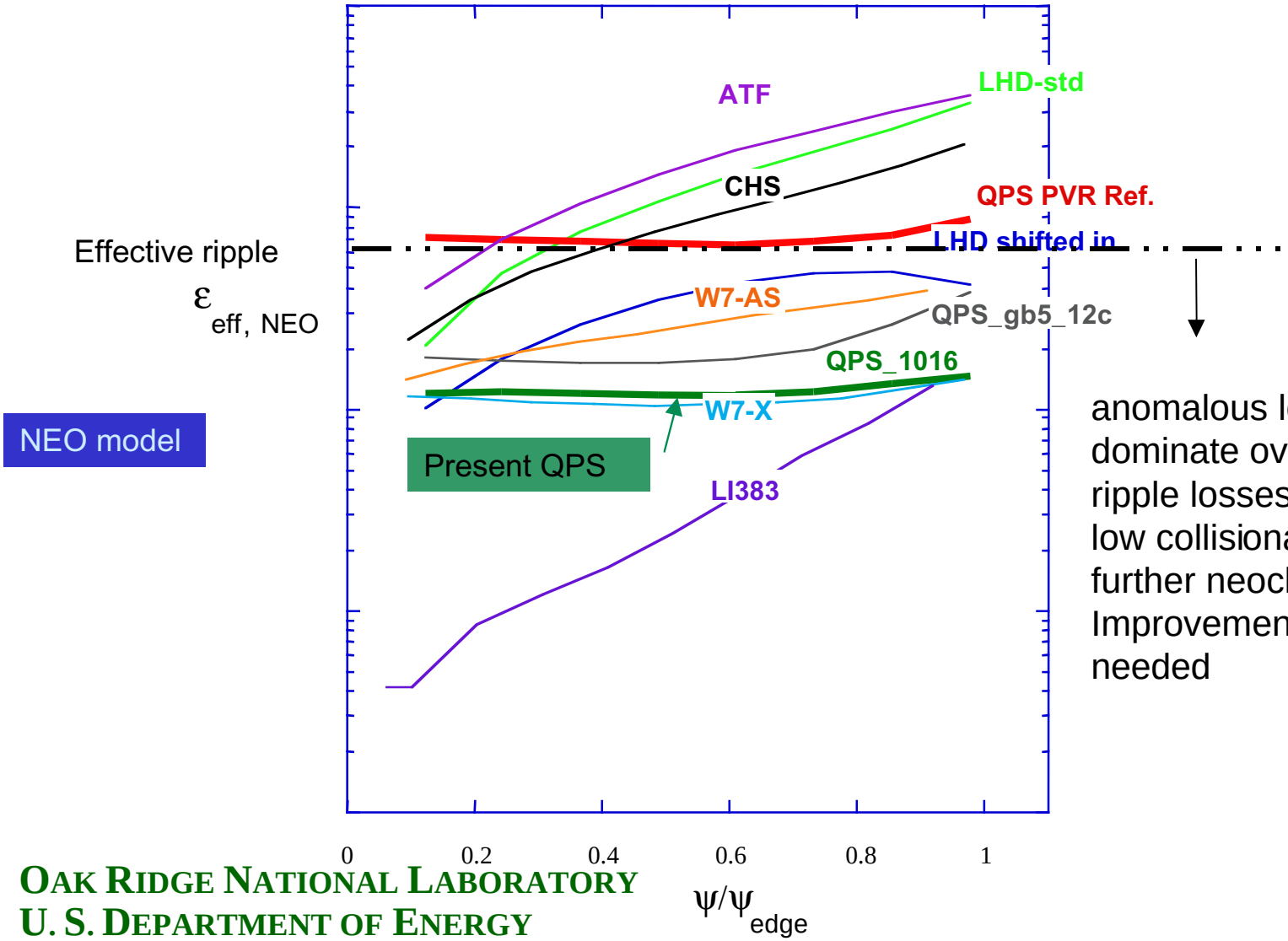




Reduced Ripple Loss in QPS Obtained Using NEO/DKES Codes in Optimizer

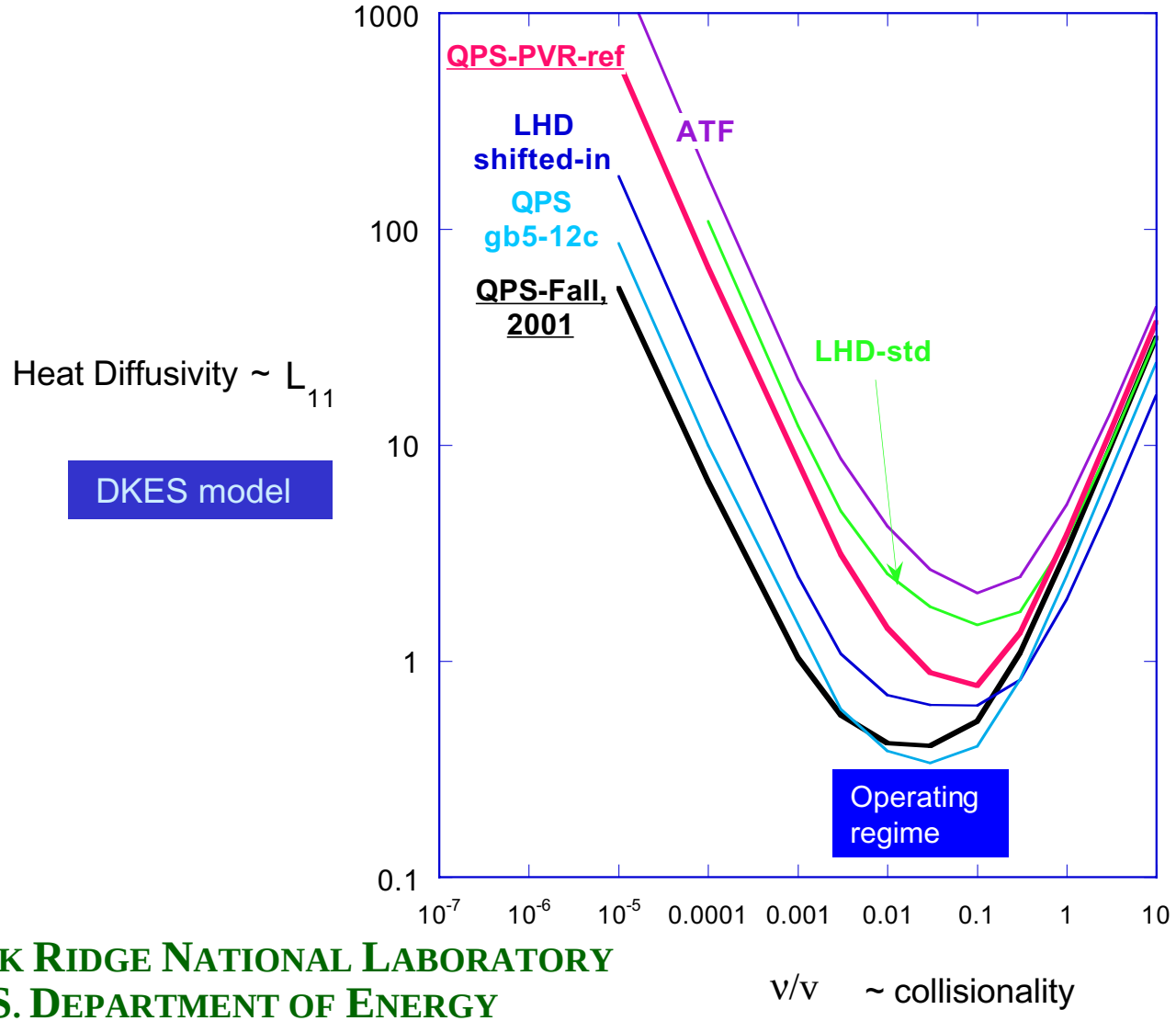
- **NEO**
  - Developed by Austrian collaborators Kernbichler and Nemov; computes $1/\nu$ transport
  - Fast method for evaluating trapped particle J-invariants and effective neoclassical ripple ε_{eff}, where $\chi_{heat} \sim (\varepsilon_{eff})^{3/2}$.
- **DKES**
  - Used both in optimizer and standalone to verify neoclassical transport over a range of collision frequencies corresponding to experimental T,n profiles

Ripple Transport ($\sim\varepsilon_{eff}^{3/2}$) Reduced in Present QPS Design

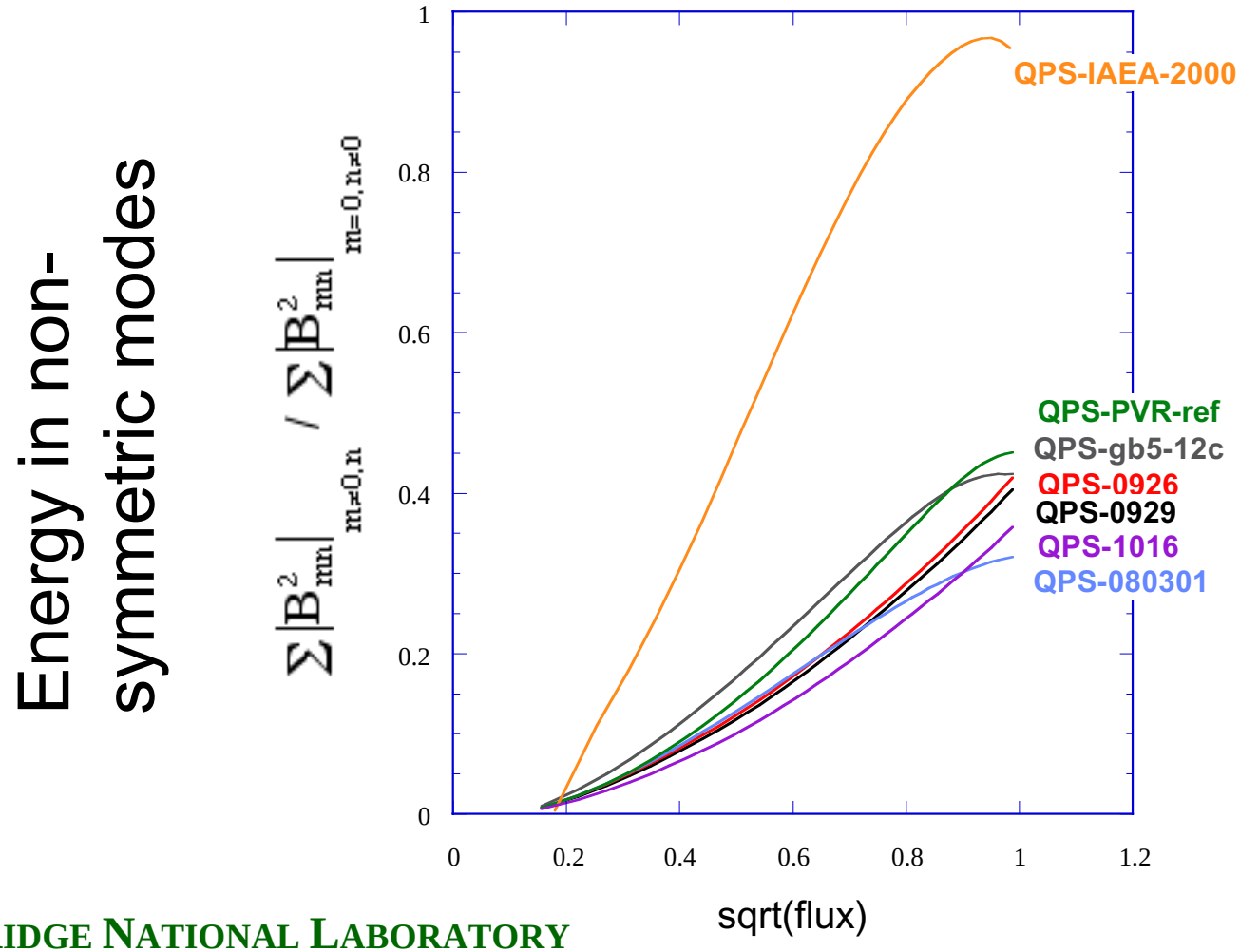


anomalous losses dominate over ripple losses at low collisionality, further neoclassical Improvement is not needed

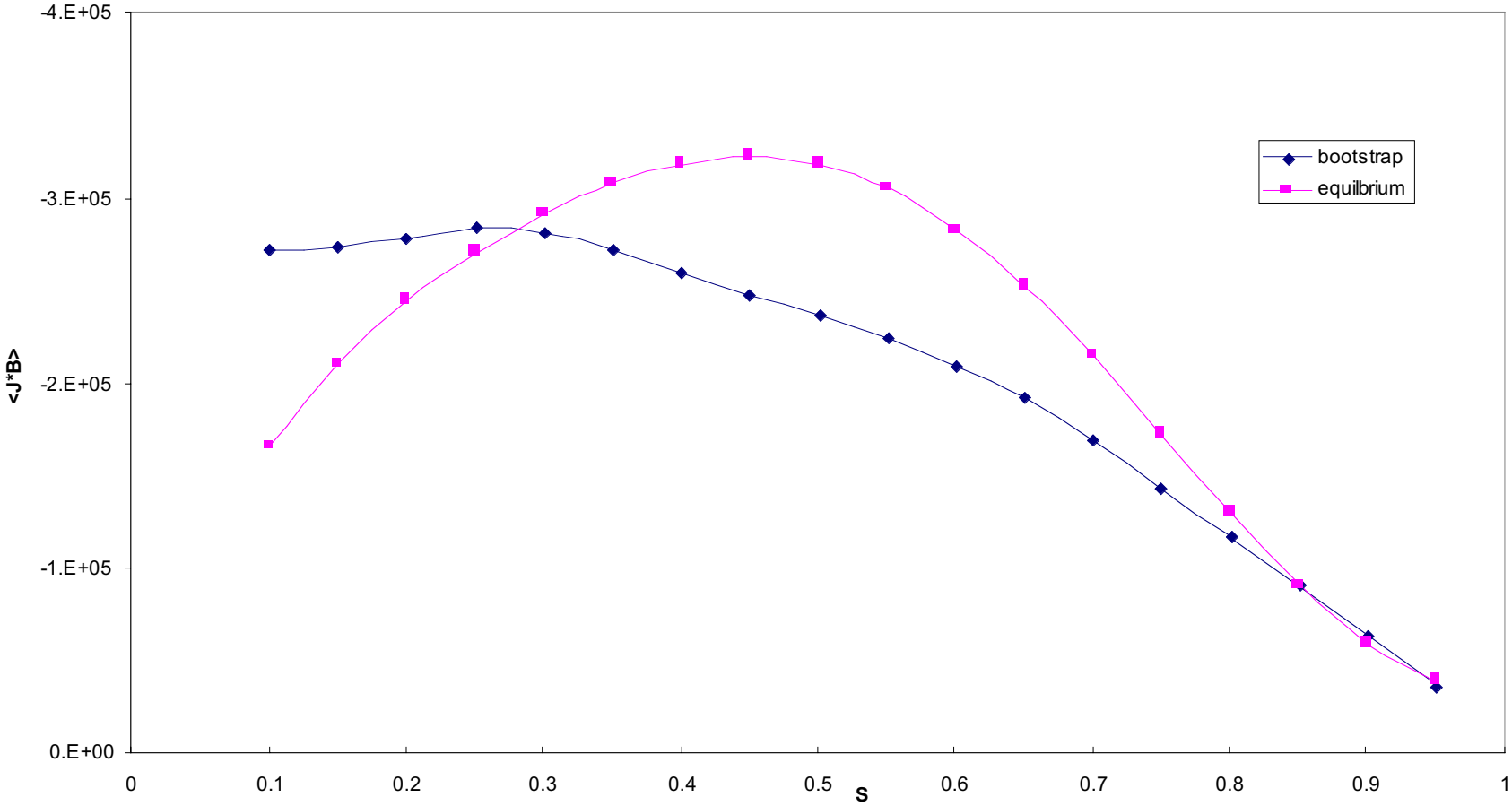
Heat Diffusivity at Higher ν Follows 1/ν Trends



Latest Configurations Have Improved Poloidal Symmetry



Bootstrap Current Alignment Is Good



Ideal MHD Stability for QPS

- **Ballooning**
  - **COBRA code (Sanchez, et. al.) included in optimization**
    - **Infinite n ballooning modes set QPS pressure limit at $\beta \geq 2\%$ (actually higher - FLR, etc.?)**
- **Mercier**
  - **Only isolated surfaces are unstable**
    - **not expected to be an issue**
- **Kink/Vertical Modes**
  - **QPS stable to vertical/kink modes for $\beta \geq 4\%$**

Coil Design at Low *A* is a Challenge Met by the COILOPT Code

- COILOPT (D. Strickler, et. al., to be published)
  - Workhorse code for both QPS and NCSX designs
    - Matches $B_{normal} = 0$ at plasma boundary, using VMEC and BNORM (P. Merkel) input
  - Uses general representation for coil winding law
    - incorporates either Fourier harmonics or B-splines as basis functions
  - Engineering constraints imposed on coils to guarantee accessibility (ports, injection) and practical realization (can be built!)

Flexible Description of Coils

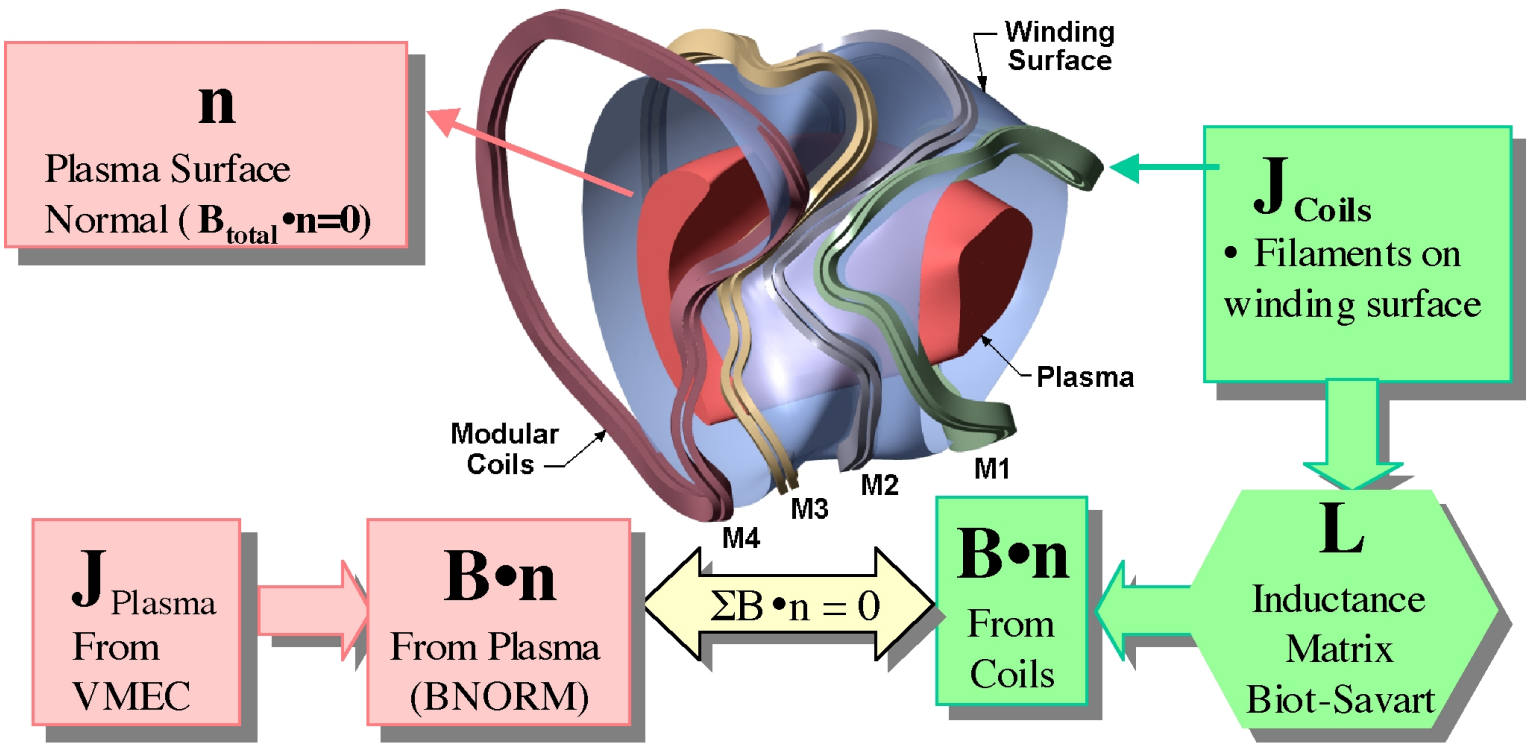
- **Toroidal winding surface (Γ) : (u,v) angles**

$$R = \Sigma\, r_{mn} \cos(2\pi(mu + nv))$$
$$Z = \Sigma\, z_{mn} \sin(2\pi(mu + nv))$$
$$\phi = 2\pi v/N$$

Stellarator symmetry: $R(u,v) = R(-u,-v)$; $Z(u,v) = -Z(-u,-v)$

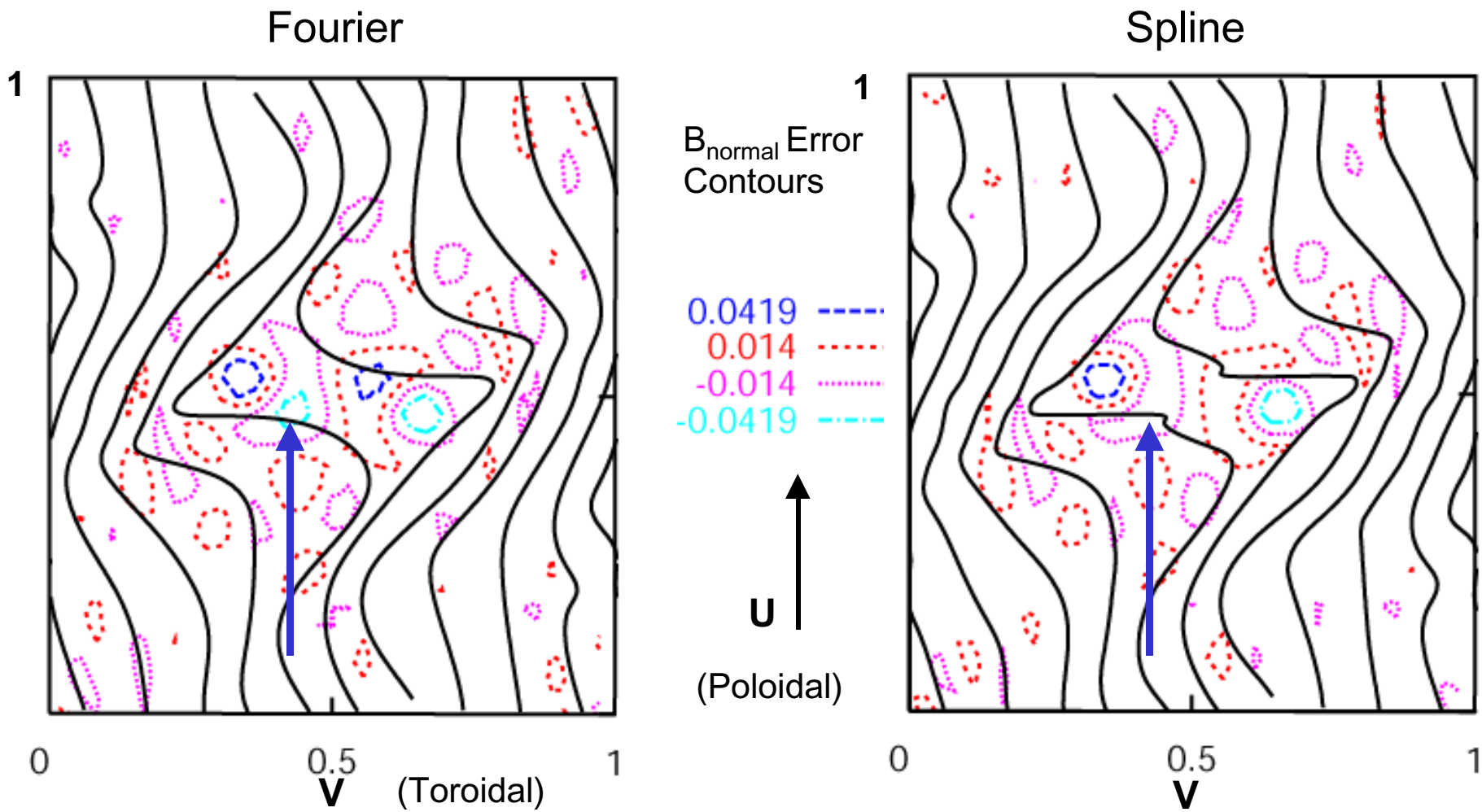
- ***Either*** **Fourier or B-spline basis for modular coils on Γ in terms of arclength $0 < s < 1$**
  - ***u(s) = s + U(s)*** ***U periodic: U(0) = U(1)***
  - ***V(s) = V(s)*** ***V periodic***
    - **U(s), V(s) expanded in basis set, coefficients varied to match magnetic, engineering constraints**

Coil Design Process

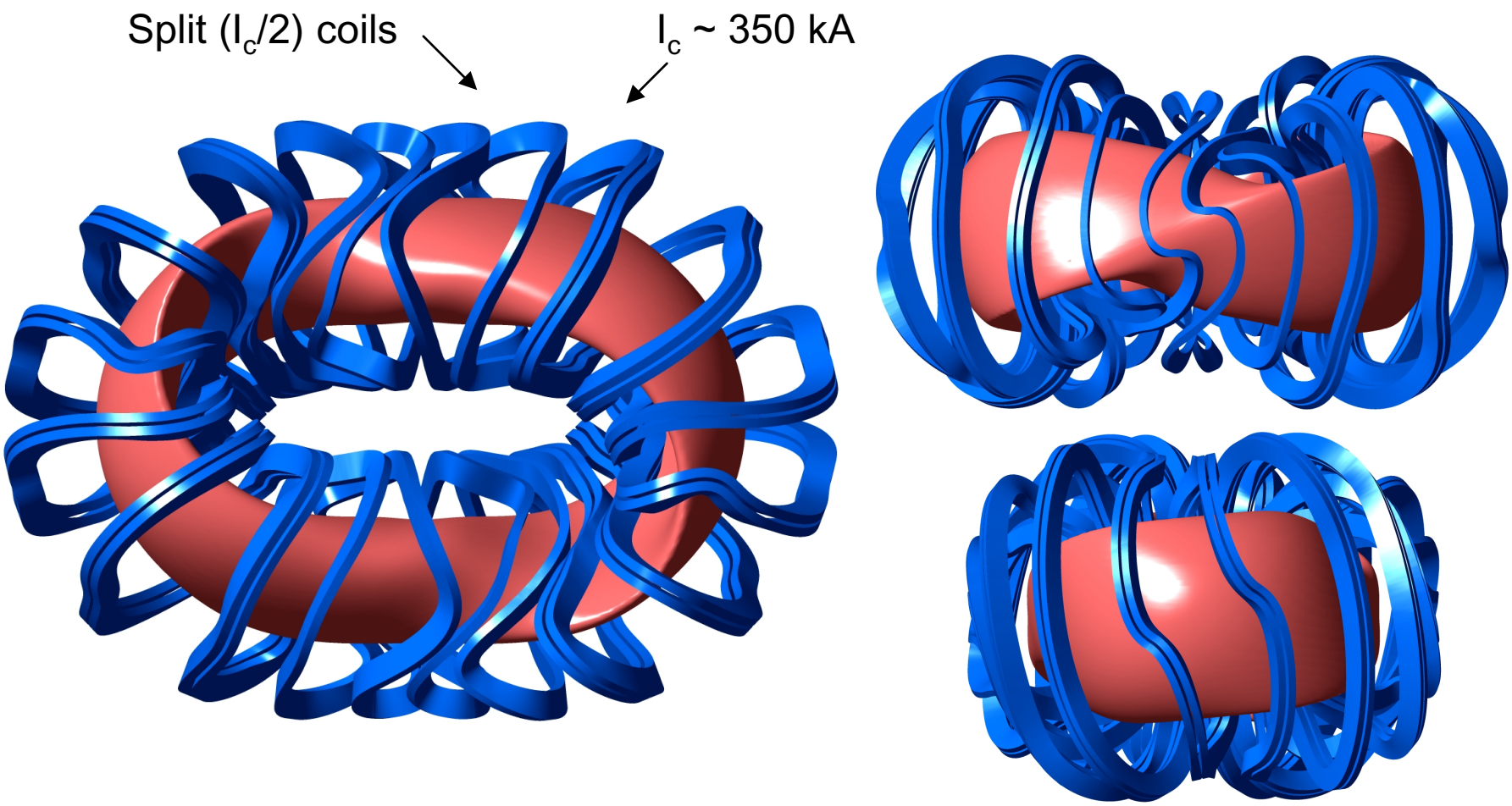


Vary "L" until L• J_{Coils} = B•n(Coils) ≈ -B•n(Plasma)

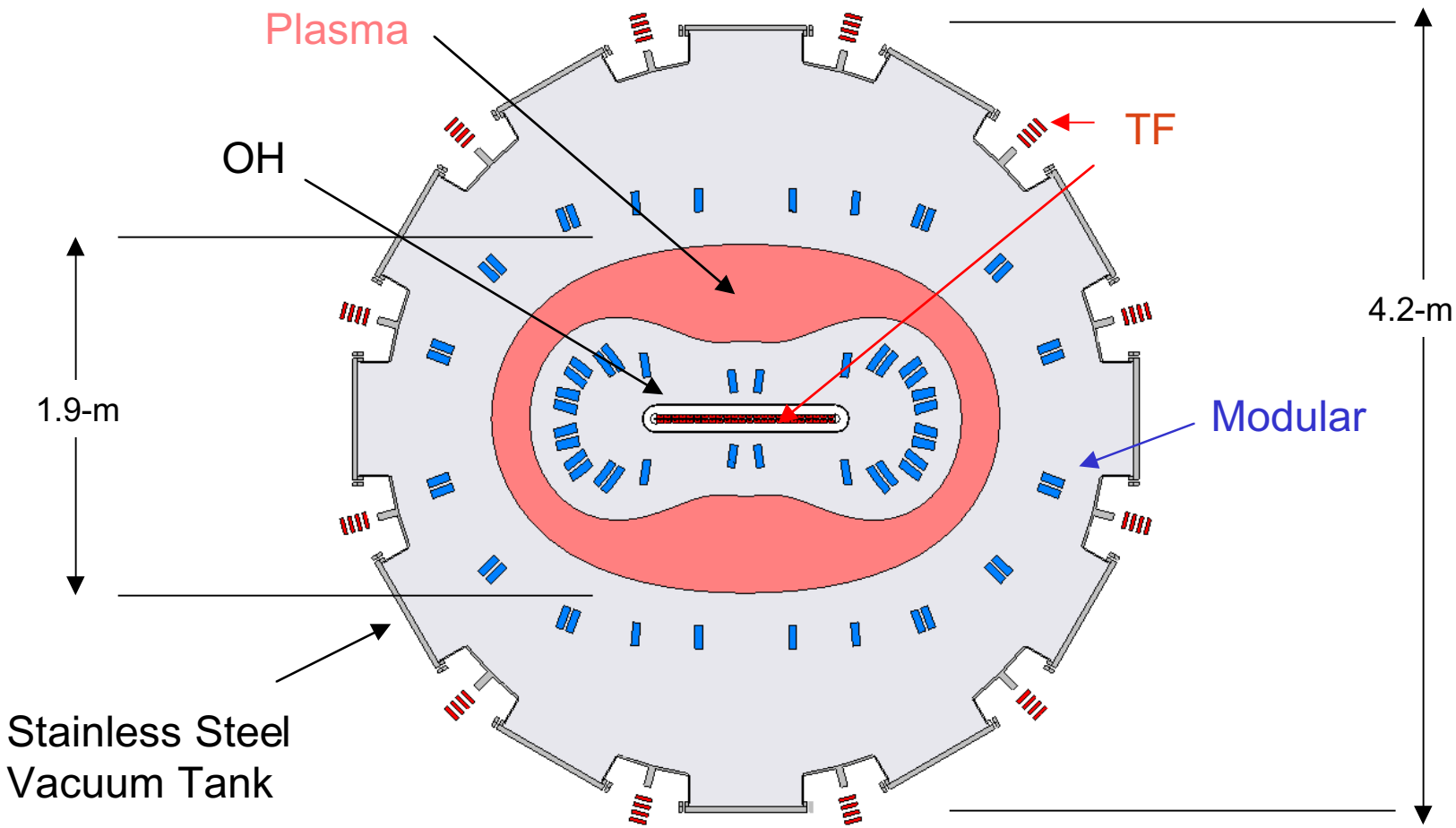
Spline Representation of Winding Law in COILOPT Can Remove *Local* Errors



Coils For Present QPS Design Use Innovative Split Coil Feature



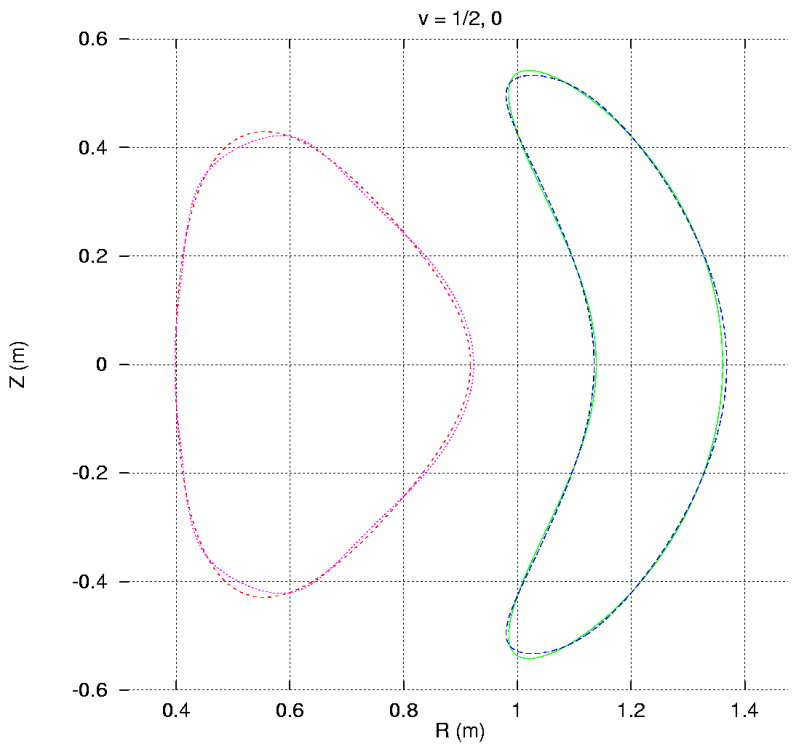
Present QPS Design Satisfies Geometric Constraints for Coils

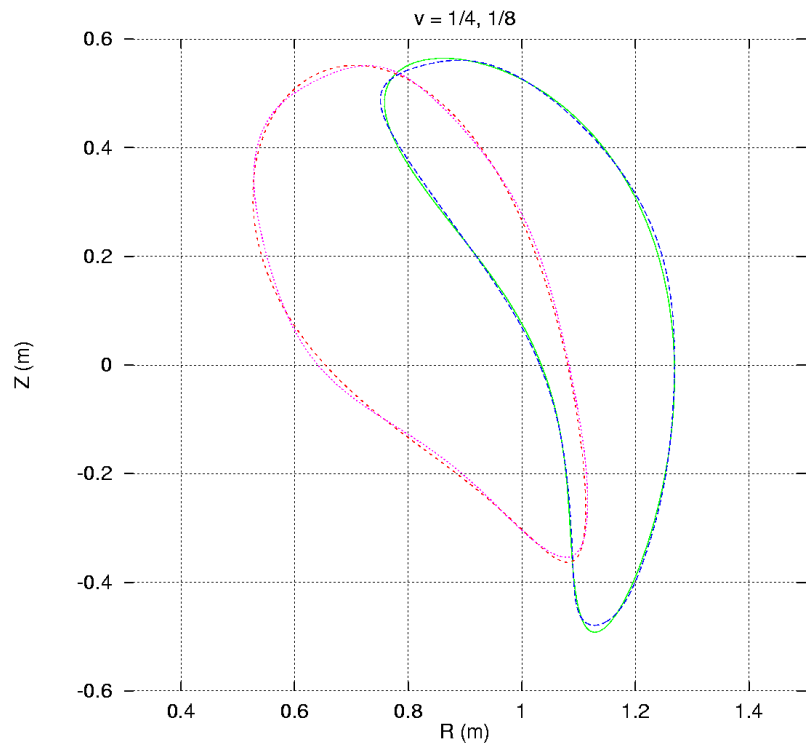


Reconstruction from Coils Preserves QPS Physics

$\langle B_{error} \rangle$ = .75% B_{error}(max) = 7%

(1%, 12% for PVR configurations with inferior physics)



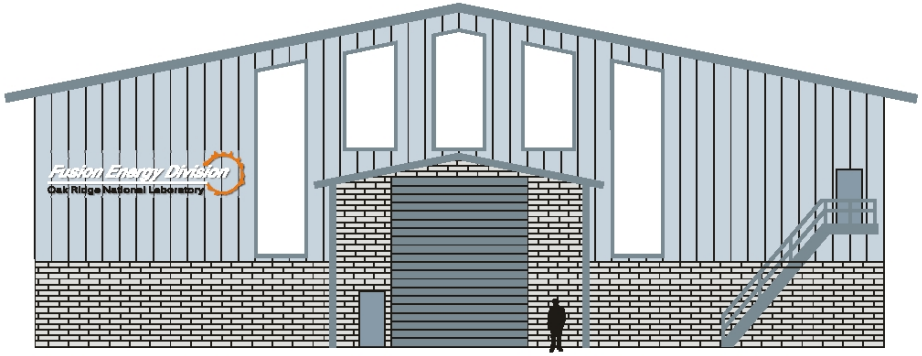


ORNL (UT-Battelle) Recognition for QPS Science

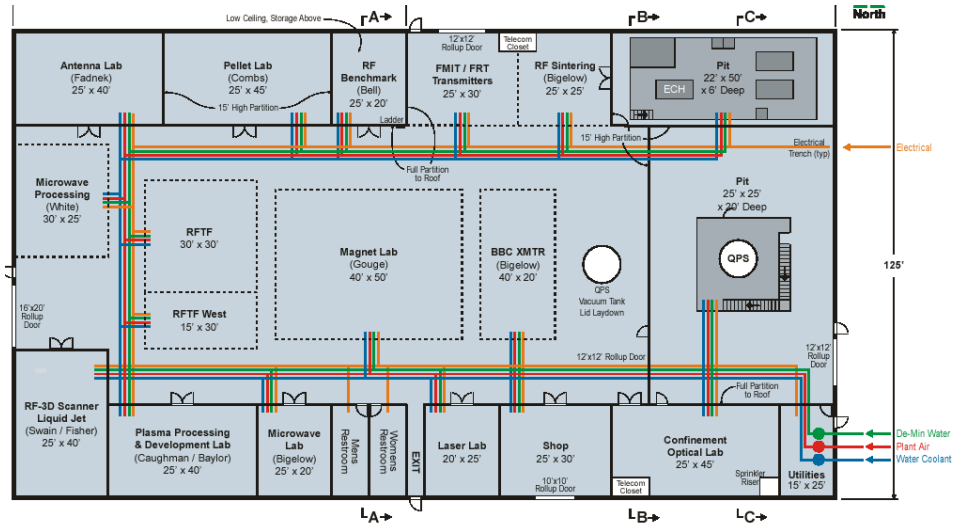
- **Award for Scientific Research by a Team**
  - **10 ORNL members, 8 collaborators**
  - **For research on the physics of plasma confinement in three-dimensional systems, leading to the development of the QPS Stellarator concept**
- **Finalist for R&D Leadership by a front-line manager**
  - **J. Lyon, QPS project manager**
- **Finalist for Distinguished Engineer**
  - **B. Nelson, lead QPS engineer**

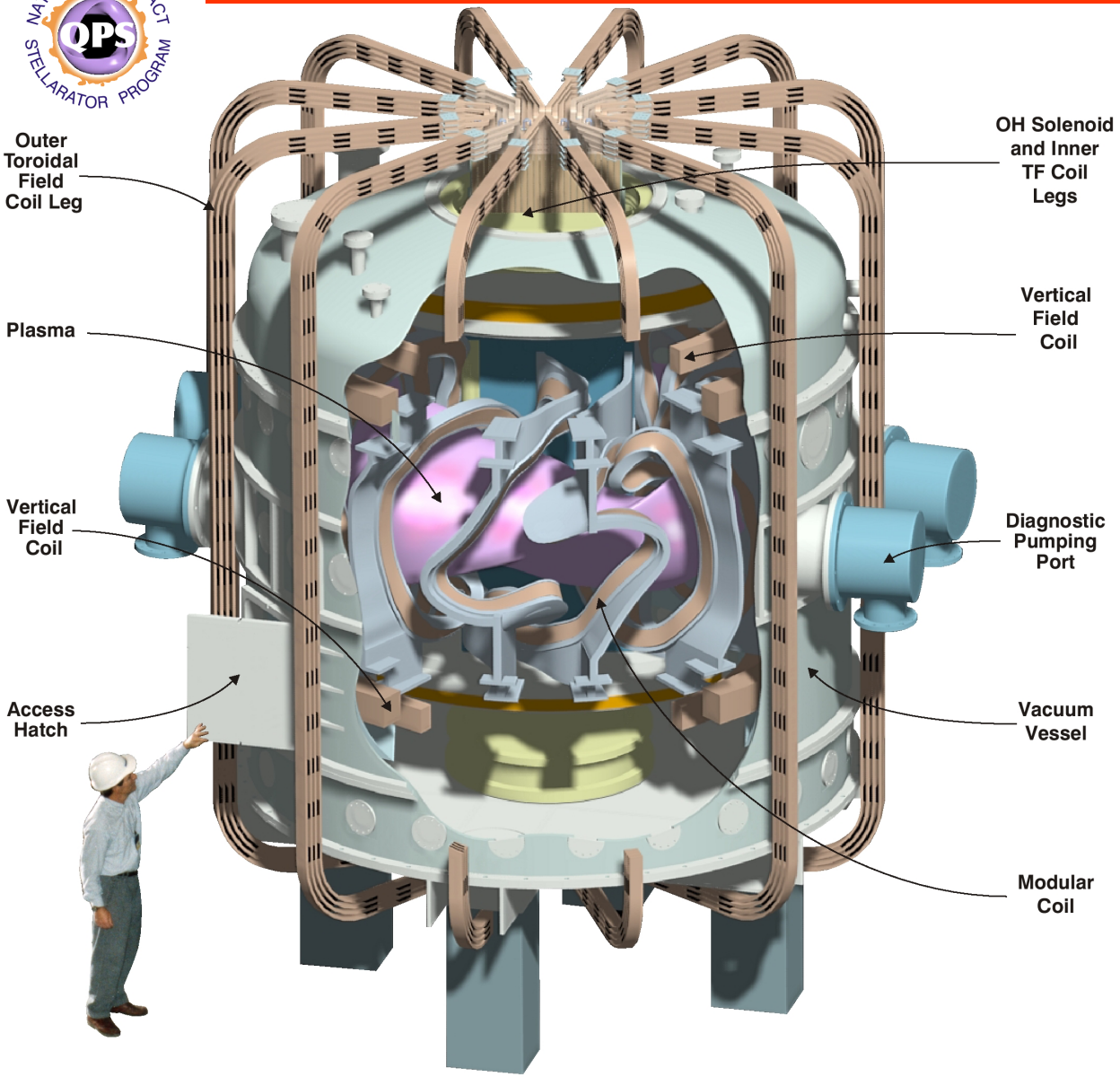
The Laboratory Intends to Invest Substantially in the Future of Fusion at ORNL

- 27, 500 sq. ft multi-purpose research facility at new site (65% Fusion)
- 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



End view looking eastward





- $\langle R \rangle = 0.9$ 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)
- $B_T = -0.2$ T
- I_p † 60 kA
- $P_{ECH} = 0.6\text{-}1.2$ MW
- $P_{ICRF} = 1\text{-}3$ MW

Project Status & Proposed Schedule

- QPS is now in the conceptual design phase after a successful Physics Validation Review in April, and a Project Validation Review in May
- Conceptual design, cost and schedule review planned for May 2002
- The design will continue to evolve through the Conceptual Design Review to account for improvements in the coil design and vendor input / participation
- 4-year design and construction period required after that
- Open issues
  - Reducing construction cost for modular coils
  - Optimum design for coil support structure
  - Maximum baking temperature & divertor plate geometry

Summary

- **Substantial progress has been made in designing a QPS device to test physics of compact stellarator (low *A*)**
  - **Better physics and better coils**
  - **A design exists - with coils - that is suitable basis for CDR**
- **Future activities in support of the CDR will include:**
  - **Island analysis and suppression — trim oils**
  - **Energetic particle heating and confinement**
  - **Development of detailed experimental program**

Future Activities (cont d)

- **Further improvements of coils**
  - **Remove *localized* regions of small bend radii on inboard side**
  - **Analyze effects of finite coil thickness**
- **Continue investigation of high-β QPS design and its relation to proposed experiment**
  - **Second stable plasma for $\beta > 6\%$**
  - **Investigate paths to second stability**
    - **work with C. Hegna and A. Ware**

Comparison of QPS With NCSX

Feature	NCSX	QPS
R, a, B, $P_{heating}$	1.4m, 0.33m, 2T, 6-12MW	0.9m, 0.33m, 1T, 1-3MW (ECH, EBW, ICH)
Magnetic Symmetry	Quasi-axisymmetric	Quasi-poloidal
Aspect Ratio, Field Periods, Modular Coils	A = 4.3, N = 3, N_c = 18	A = 2.7, N = 2, N_c =16
Key Physics Issues	Proof-of-principle: High-β stability	Concept exploration Low A equilibrium and transport
Enhanced Confinement	Reduced toroidal viscosity	Reduced poloidal viscosity