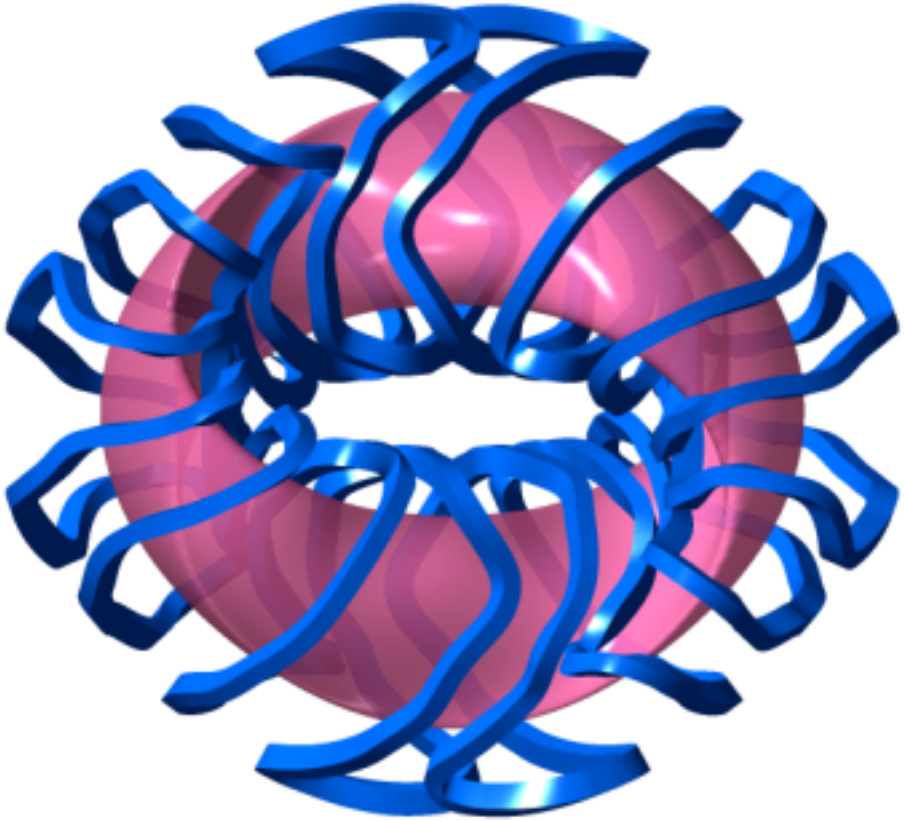
QPS Overview



J.F. Lyon for the QPS Team

Multi-Laboratory QPS Design Team

- **ORNL – D.B. Batchelor, L.A. Berry, M.J. Cole, R.H. Fowler, P. Goranson, E.F. Jaeger, S.P. Hirshman, J.F. Lyon, P.K. Mioduszewski, B.E. Nelson, D.A. Rasmussen, D.A. Spong, D.J. Strickler, J.C. Whitson, D.E. Williamson**
- **U. Texas at Austin – W.H. Miner, jr., P.M. Valanju**
- **U. Montana – A. 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**

Tools & experience developed by NCSX-QPS team applied to QPS

Over the past 5 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 CE-level stellarator that has very low aspect ratio, excellent neoclassical confinement, good MHD properties, and a high-β reactor vision.

Topics

- Programmatic role
- Quasi-poloidal symmetry
- General description of QPS
- Choice of QPS parameters
- Highlights of the presentations

QPS Would Make Unique Contributions to Fusion Research in Three Areas

- **Explore physics issues of very low *R/a* and quasi-poloidal symmetry for compact stellarators**
- **Explore key issues pertinent to a high-β ($\langle\beta\rangle$ > 10%) low-*R/a* (2.7) compact stellarator reactor vision**
- **Expand database on toroidal confinement physics**

Compact Stellarators Are a New Element in the World Program

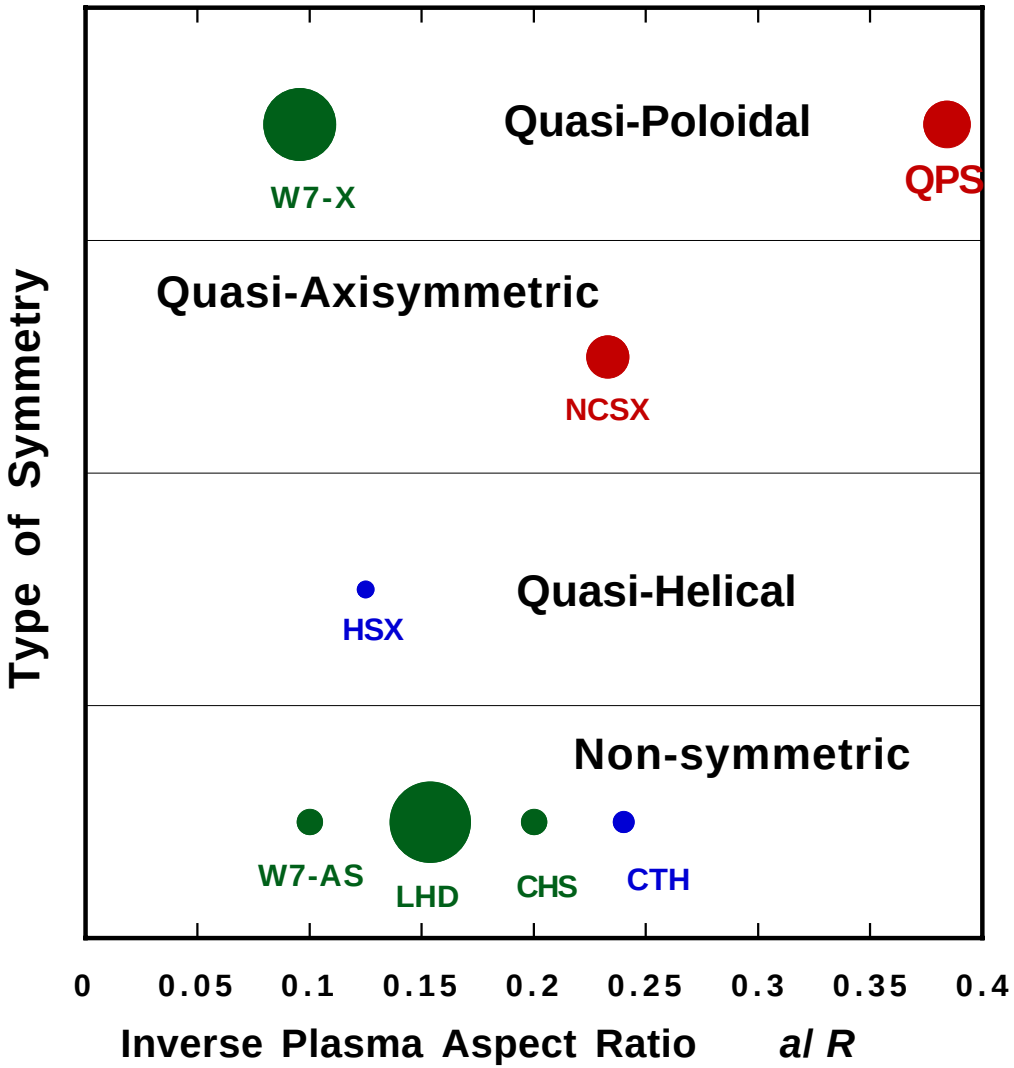
- **Compact stellarators have the potential for combining the best features of tokamaks and stellarators**
- **<u>The U.S. stellarator community proposed an integrated CS PoP program</u> in 1998 and 1999**
  - **two complementary low-*R*/*a* experiments**
    - **NCSX PoP-level experiment: conservative approach, low aspect ratio, quasi-axisymmetric configuration**
    - **QPS CE-level experiment: aggressive approach, very low aspect ratio, quasi-poloidal configuration**
  - **support of CE experiments HSX & CAT-U/CTH**
  - **increased support of stellarator theory**
  - **international collaboration & systems studies**

Compact Stellarators Allow the U.S. to Fill a Gap in the World Program

- **Large world program focused on high-aspect-ratio currentless stellarators**
- **U.S. CE stellarators focus on unique physics**
  - **HSX: high-*R/a* quasi-helical stellarator with high effective ι**
  - **CTH: stabilization & study of current-driven modes**
- **<u>Missing element</u>: optimization of stellarators at low *R/a* that could lead to a more attractive reactor than advanced tokamaks or currentless stellarators**
  - **NCSX and QPS are proposed to explore this route**
- **Information is needed to meet 10-year goals**
  - **FESAC US program objective to assess compact stellarators**
  - **decision on the next step after LHD & W 7-X**

QPS Fills a Unique Niche in the World Stellarator Program

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



QPS Supports and Complements NCSX

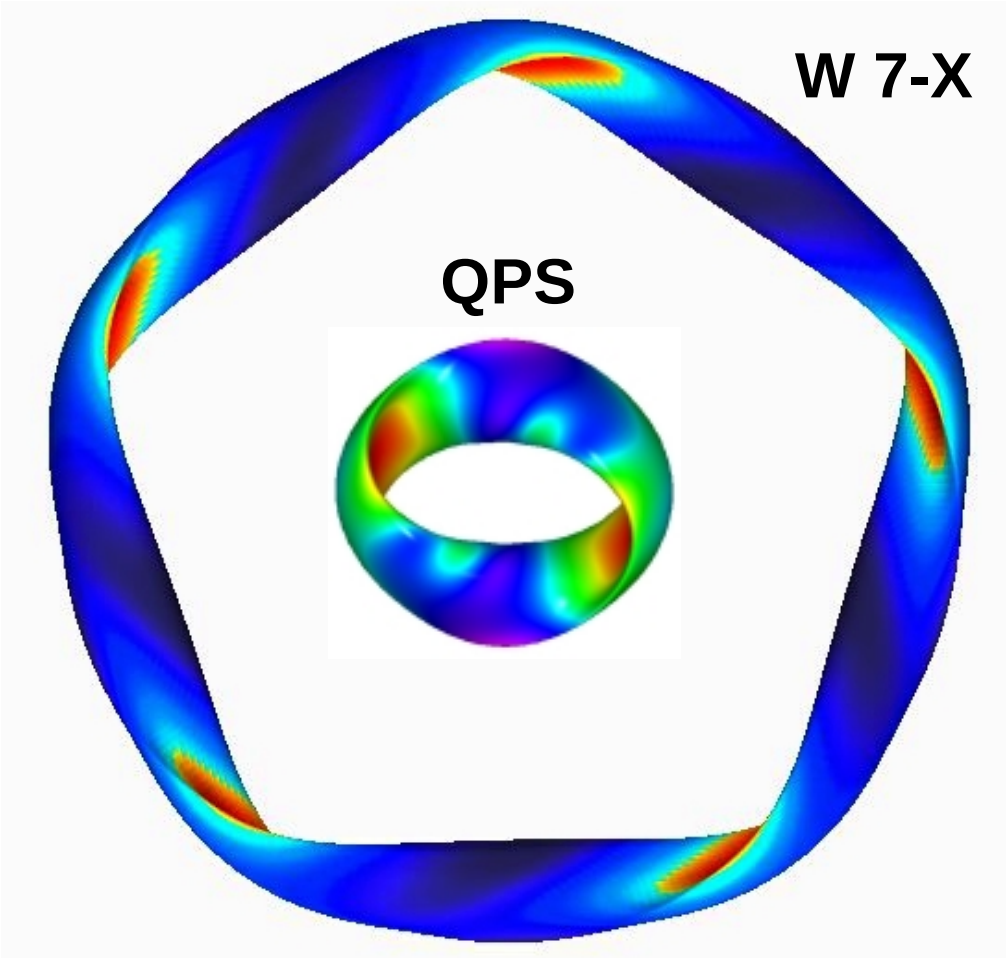
- **QPS complements NCSX by exploring the low-*R*/*a*, quasi-poloidally-symmetric (*qps*) approach to compact stellarator optimization**
  - **this requires understanding equilibrium, confinement, and stability of low-*R*/*a* *qps* configurations and their relation to the low-*R*/*a* *qps* high-β reactor vision**
- **QPS supports the NCSX program by providing knowledge needed to extend the NCSX quasi-axisymmetric (*qa*) approach to lower *R*/*a* for a more attractive *qa* reactor**

QPS Supports and Complements NCSX in the Compact Stellarator Program

Feature	NCSX	QPS
R, a, B, $P_{heating}$	1.4 m, 0.33 m, 2 T, 6-12 MW	0.9 m, 0.35 m, 1 T, 1-3 MW
Magnetic Symmetry	Quasi-Axial	Quasi-Poloidal
Aspect Ratio R/a	4.3	2.6
Key physics issue	High-β stability and disruption immunity	Low-R/$\langle a \rangle$: strong toroidal effects on equilibrium, stability & transport
Enhanced Confinement Route	Tokamak-like drift orbits, flow-shear stabilization	Small $B \times \nabla B$ radial drift, reduced poloidal viscosity

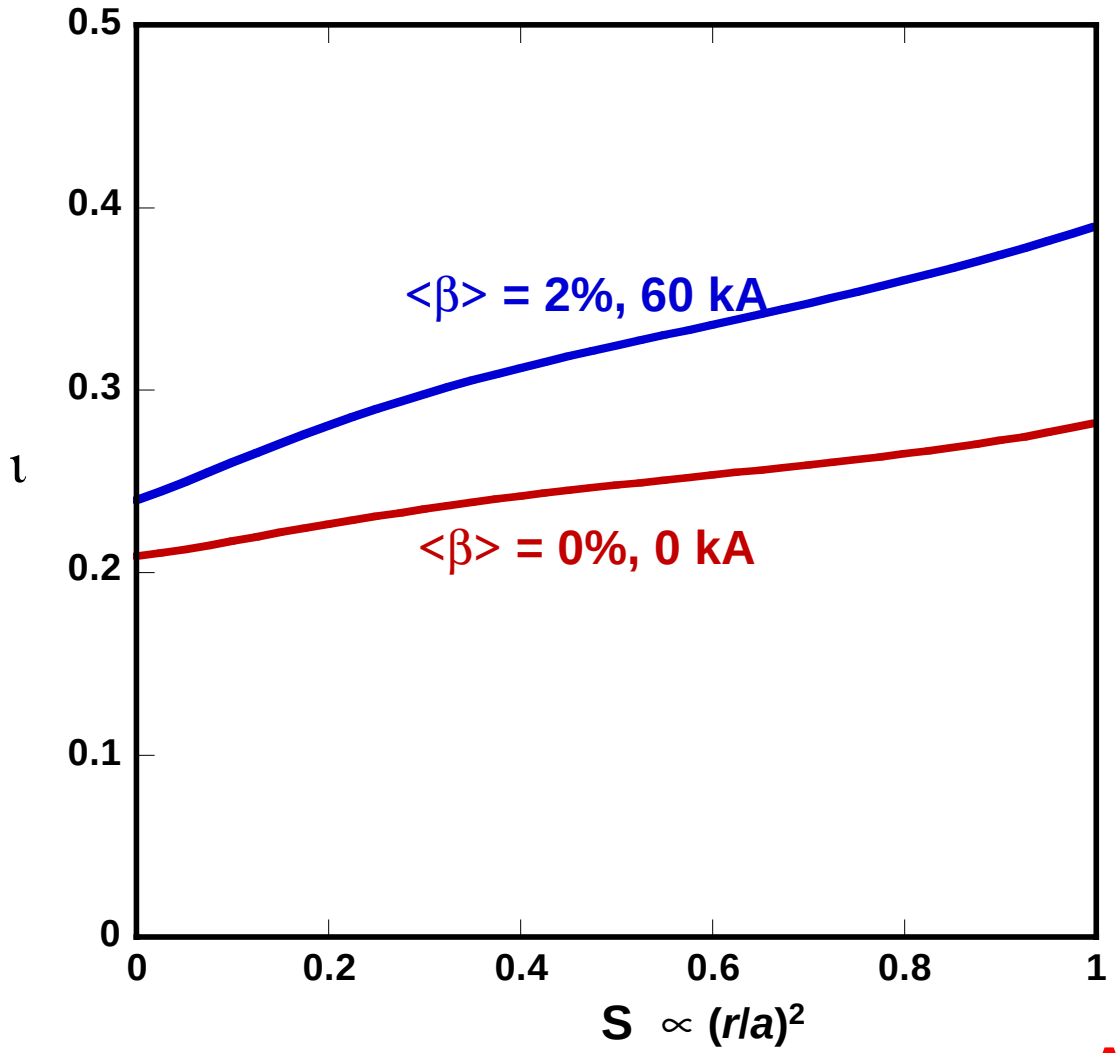
- **Reactor visions have similar range of aspect ratios (R/a ~ 2.7-4.3) but different β ranges (4-6% vs 10-15%) with different physics optimizations**

QPS Complements W 7-X by Extending Knowledge on the *qps* Approach to Stellarator Optimization by a Factor of 4 Lower in Aspect Ratio



- **Normalized to the same average plasma radius**

Part of the Rotational Transform Is Due to the Bootstrap Current in QPS

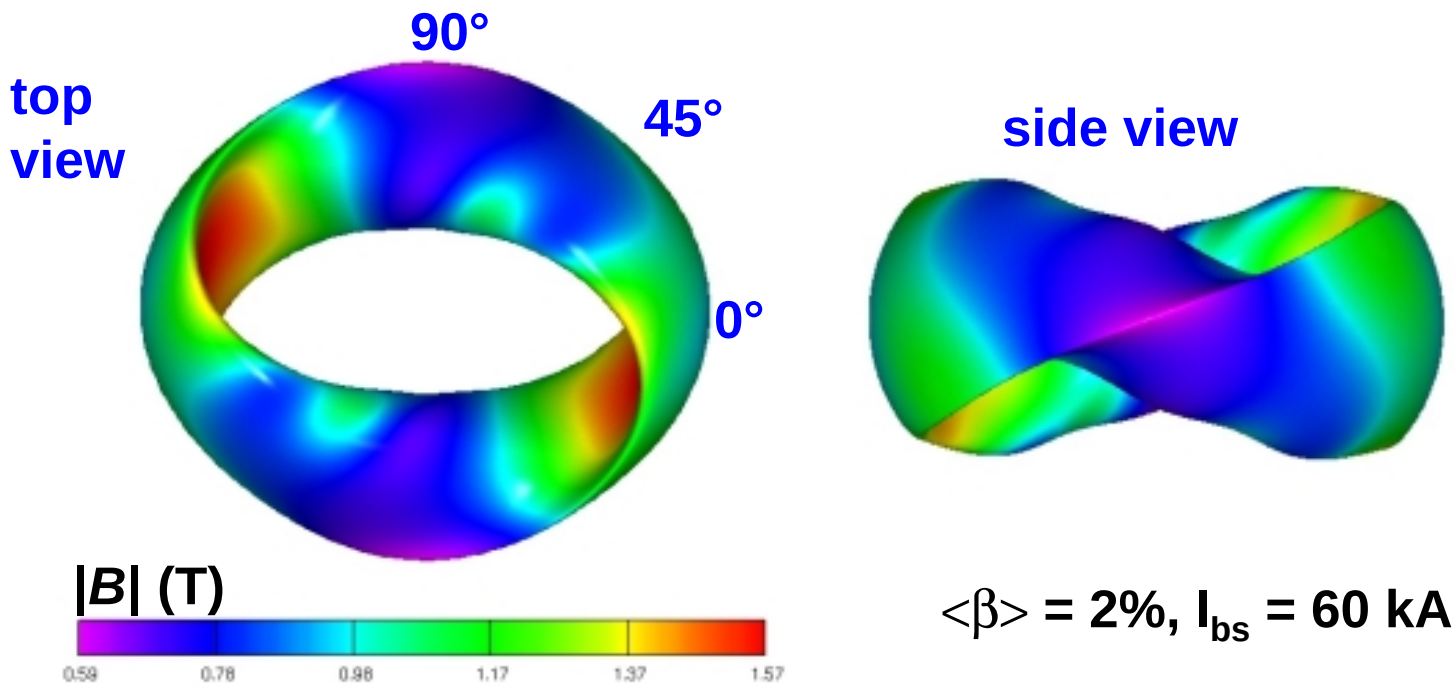


A. Ware

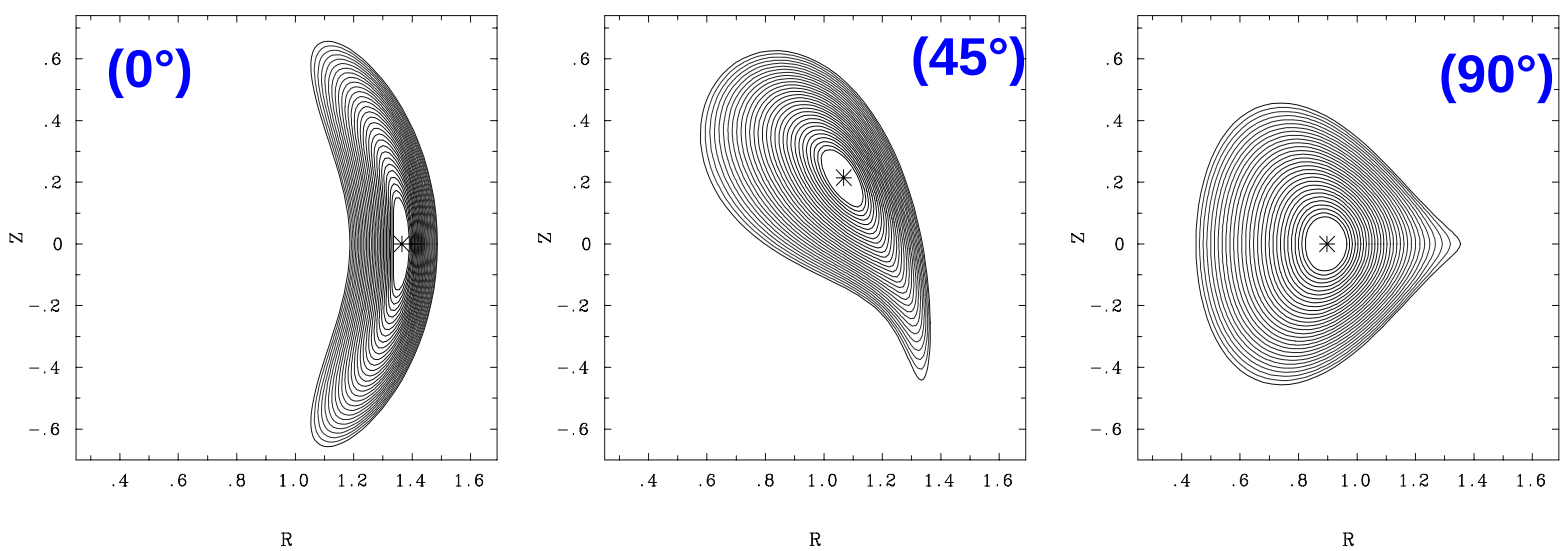
QPS Complements W 7-X

- **Both explore the quasi-poloidally-symmetric approach to stellarator optimization, but at very different aspect ratios**
  - ***R/a* = 2.6 for QPS and 10.6 for W 7-X; the role of toroidal effects is very different**
- **QPS uses the bootstrap current to obtain low aspect ratio and W 7-X minimizes it**
- **Neoclassical confinement improvement is due to alignment of drift and flux surfaces in W 7-X and due to alignment of *B* and grad *B* in QPS at lower ι**
- **<|B|> decreases towards the center in QPS; improves superbanana orbit confinement**

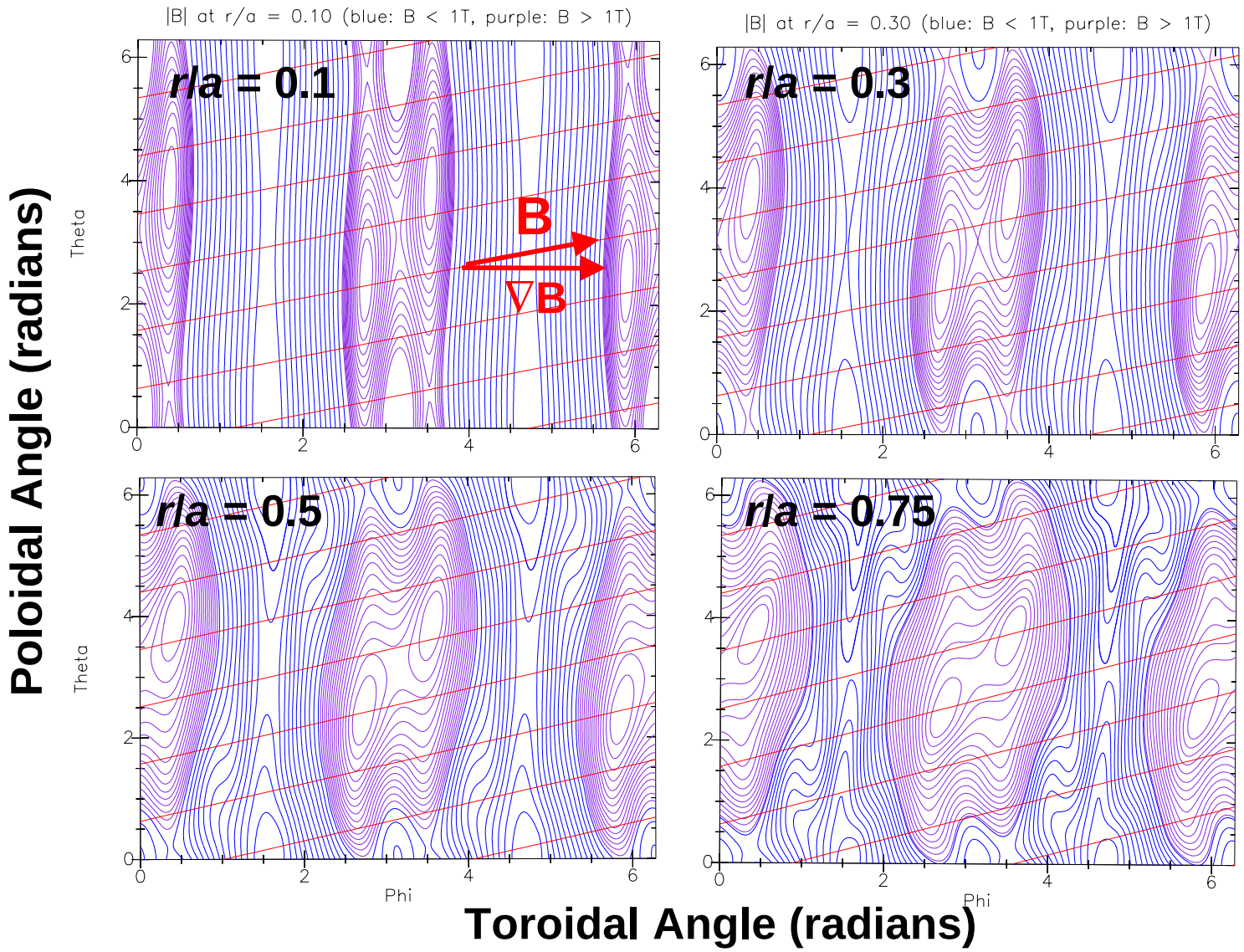
QPS Magnetic Configuration



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

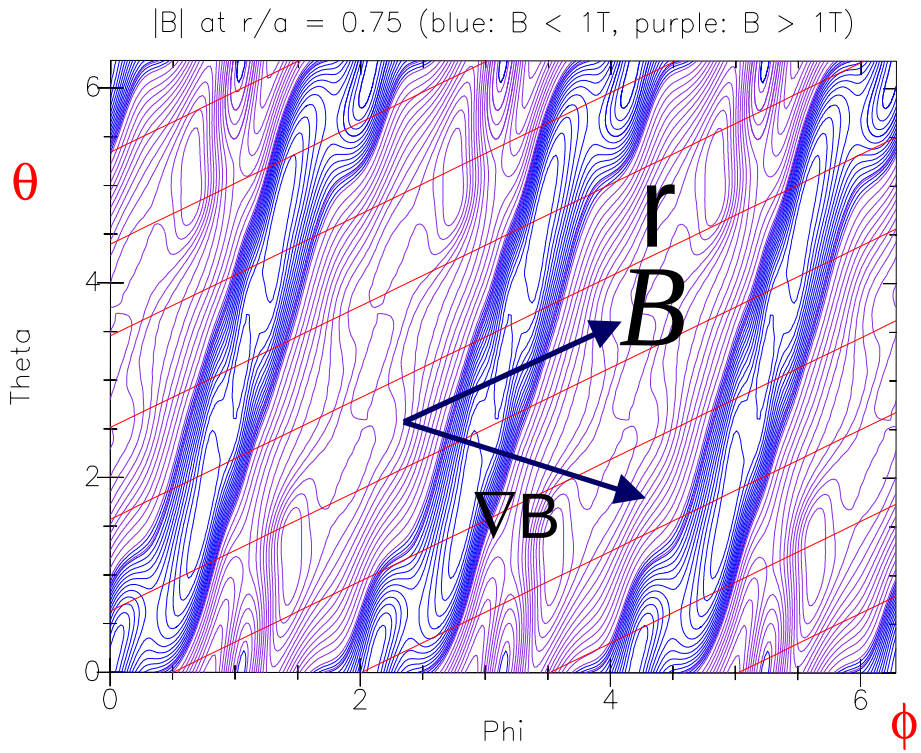


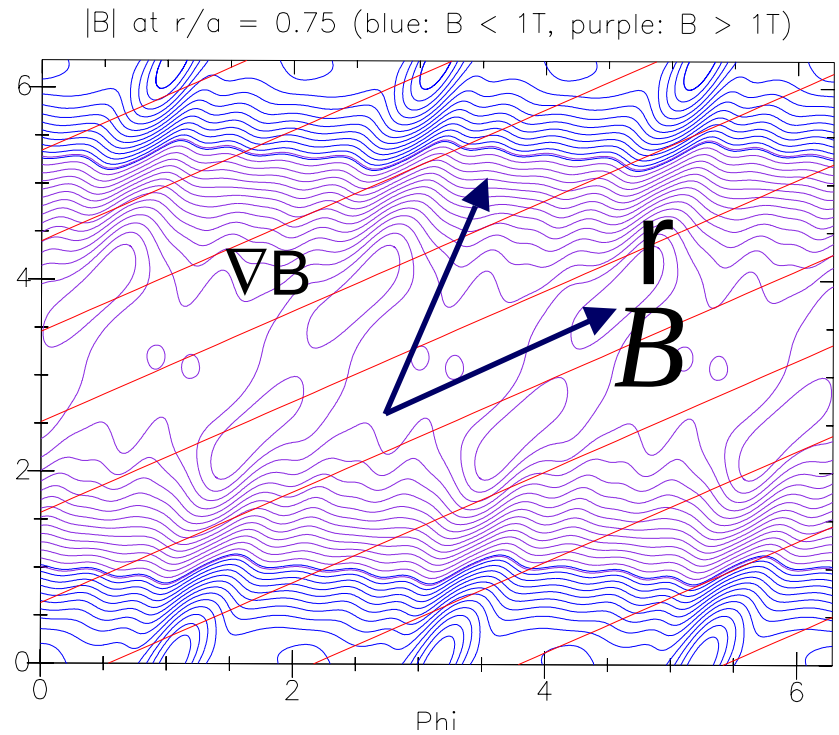
Quasi-Poloidal |B| Structure Varies with Radius



- **The *B* x ∇B drift can be made very small in this approach.**

QPS Complements Quasi-Symmetry in Other Stellarators



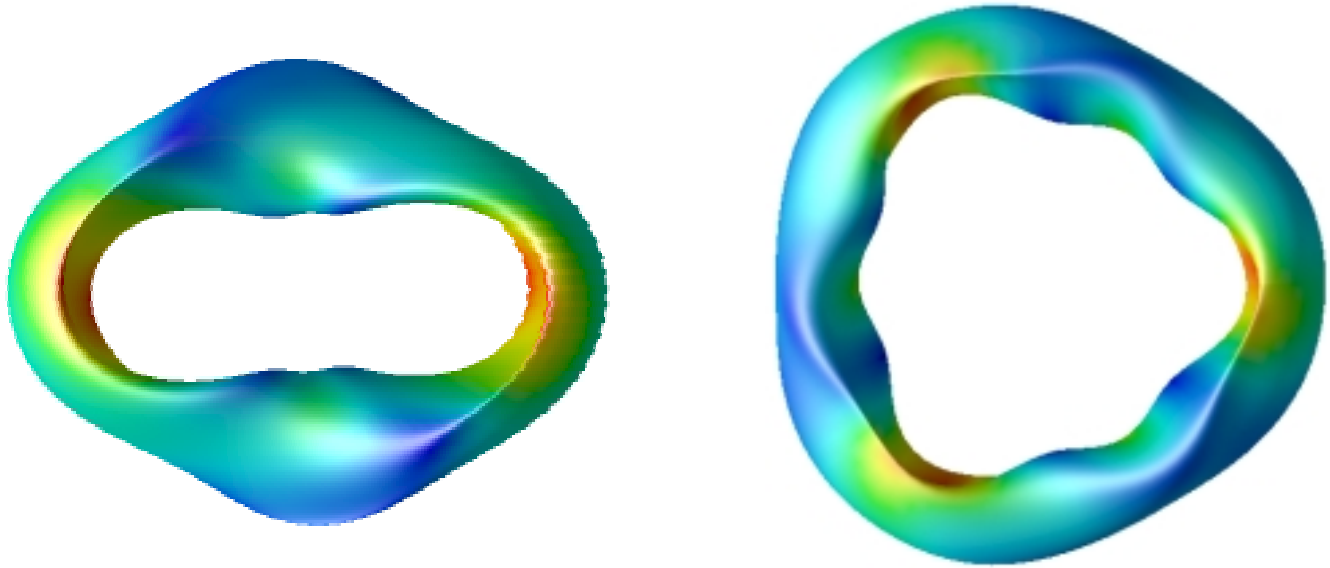


- **Quasi-helical**: |B| like large *R*/*a* stellarator.
  HSX (*R*/*a* = 8) will test this concept.
- **Quasi-axisymmetric**: |B| like tokamak.
  NCSX (*R*/*a* = 4.3) would test this concept.

S. Hirshman

High-β Quasi-Poloidal Reactor Vision

- **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**



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

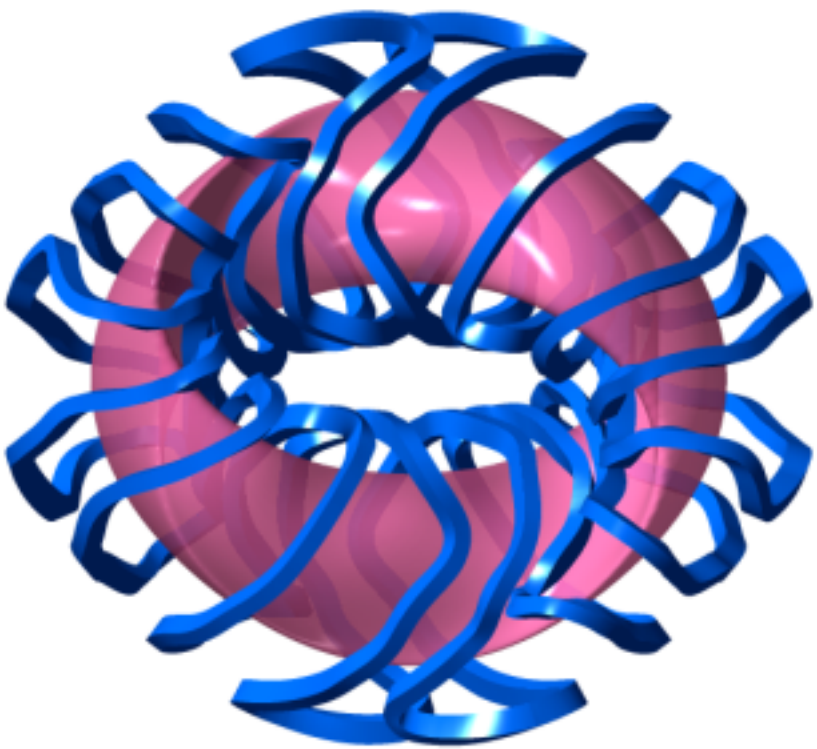
QPS CE-level Experiment Would Contribute to Understanding the High-β Reactor Vision

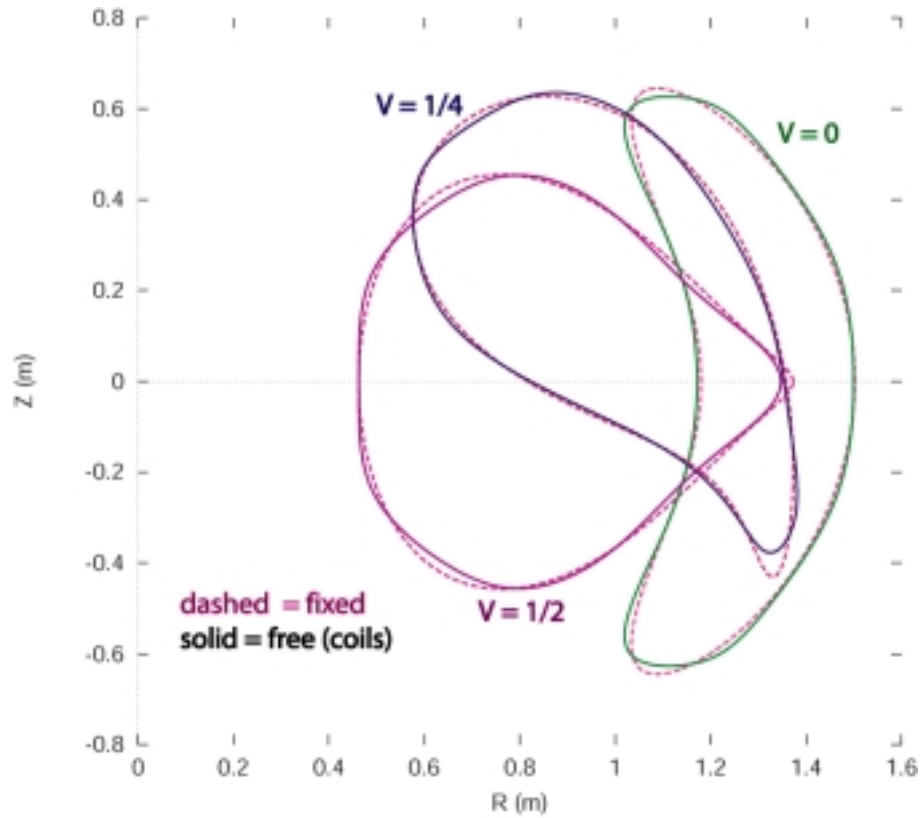
- **Role of quasi-poloidal symmetry on neoclassical and anomalous confinement improvement at lower β**
  - **For high-β *qps*, confinement increases with β, becomes more quasi-poloidally symmetric**
- **Configuration dependence and β dependence of the bootstrap current at low *R/a***
  - **For high-β *qps*, bootstrap current relatively independent of β $\Rightarrow$ configuration invariance with β**
- **MHD stability at $<\beta>$ 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 (NTM's)**
  - **For high-β *qps*, shear is opposite to that in QPS (*without* I_{OH})**

QPS Would Broaden our Understanding of Toroidal Confinement to Very Low *R/a*

- **Flux surface robustness at $<\beta>$ up to 2-3% in the presence of strong toroidal/helical coupling**
- **The dependence of the bootstrap current on configuration properties**
- **Validity of stellarator confinement scaling and anomalous transport**
- **The physics of neoclassical confinement improvement at very low aspect ratio**
- **The electric field, poloidal flows, and their influence on transport barriers and enhanced confinement regimes**

The Reference Coil Set Is Buildable and Able to Reproduce the Original Optimized Plasma Configuration



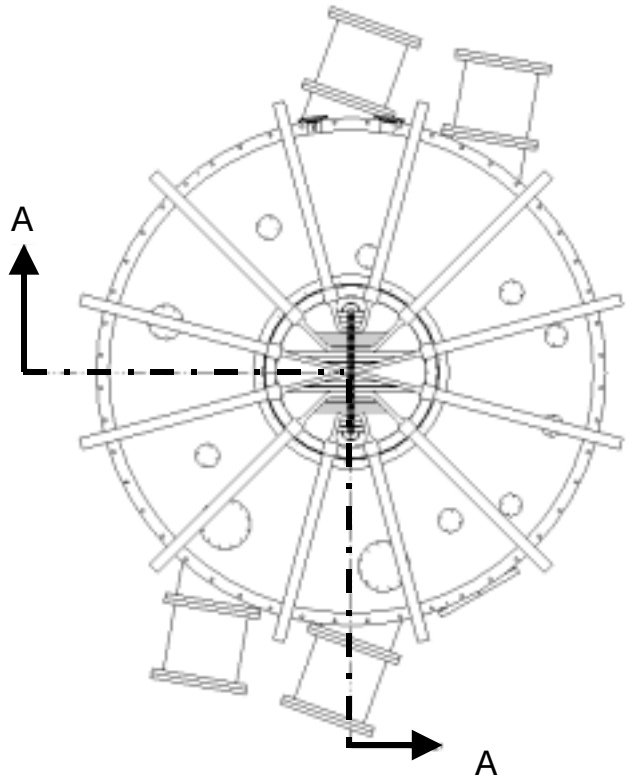


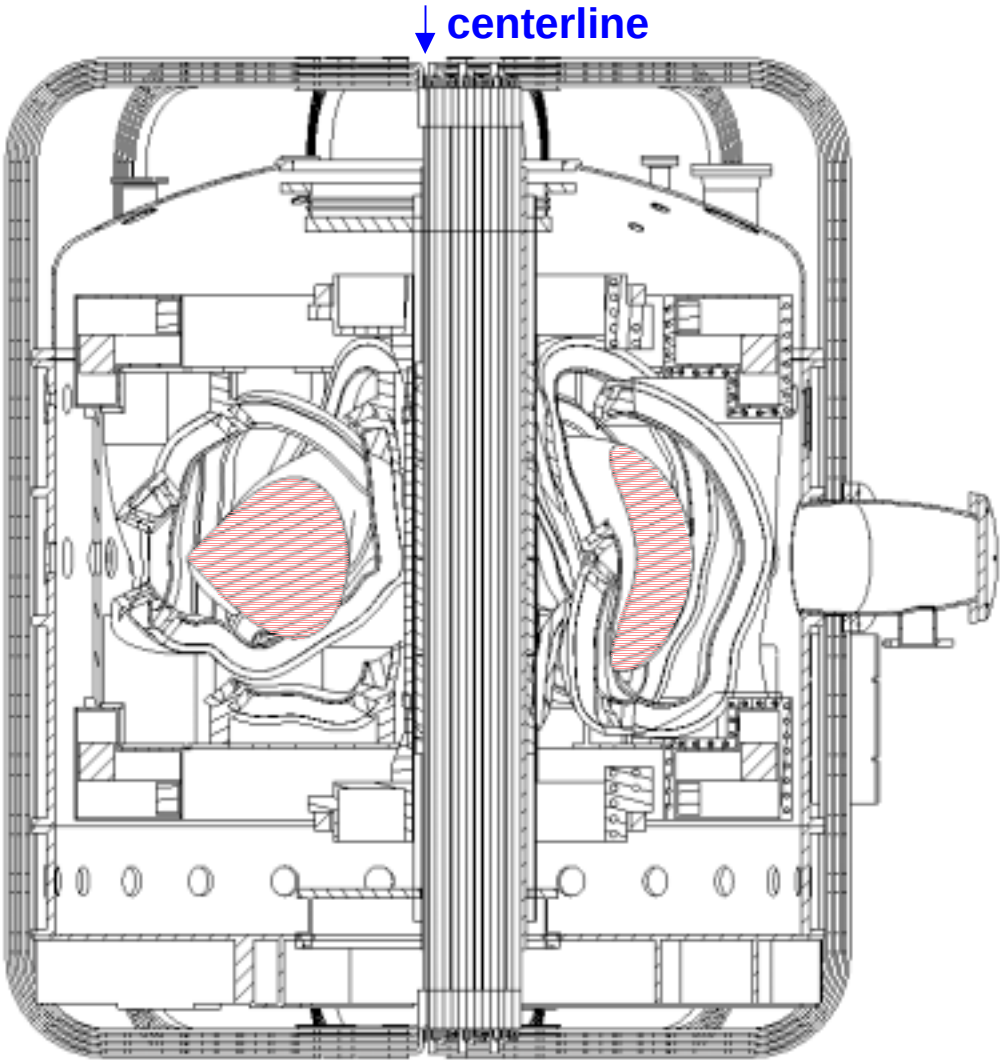
Engineering coil set and plasma boundary

Plasma boundary at at three toroidal angles

L. Berry

Cutaway View of QPS



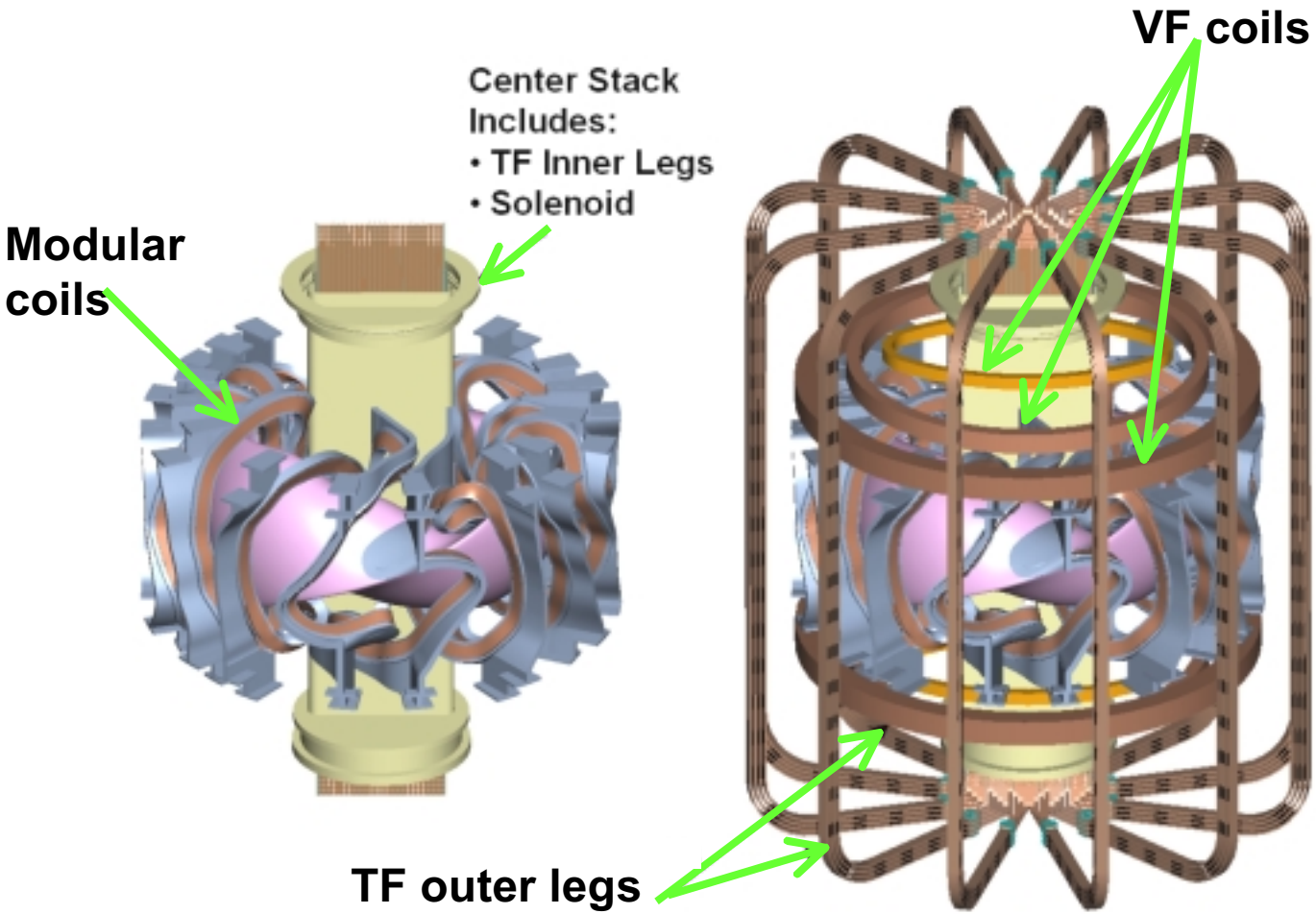


Section A-A

B. Nelson

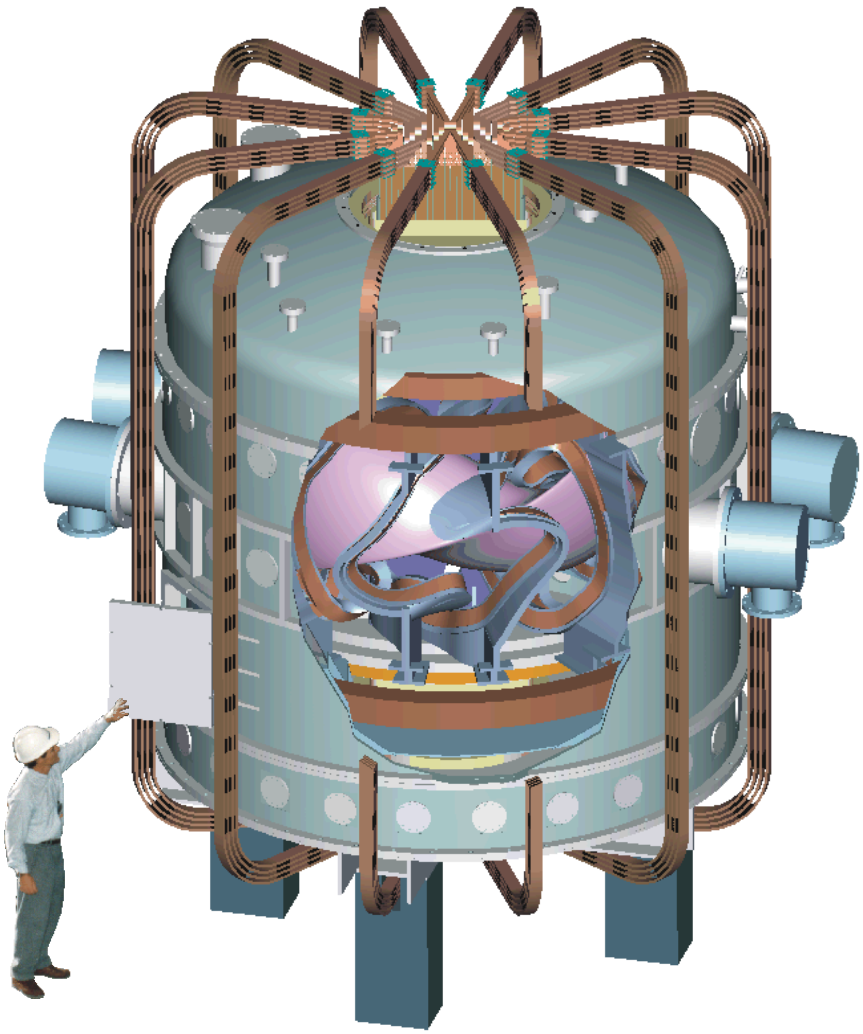
Auxiliary Coils Allow Changing Transform, Shear, and Magnetic Configuration for Physics Studies

- $\Delta B_T = \pm 0.15$ T, PF coils for shifting and shaping the plasma
- Ohmic current also allows changing the transform and shear



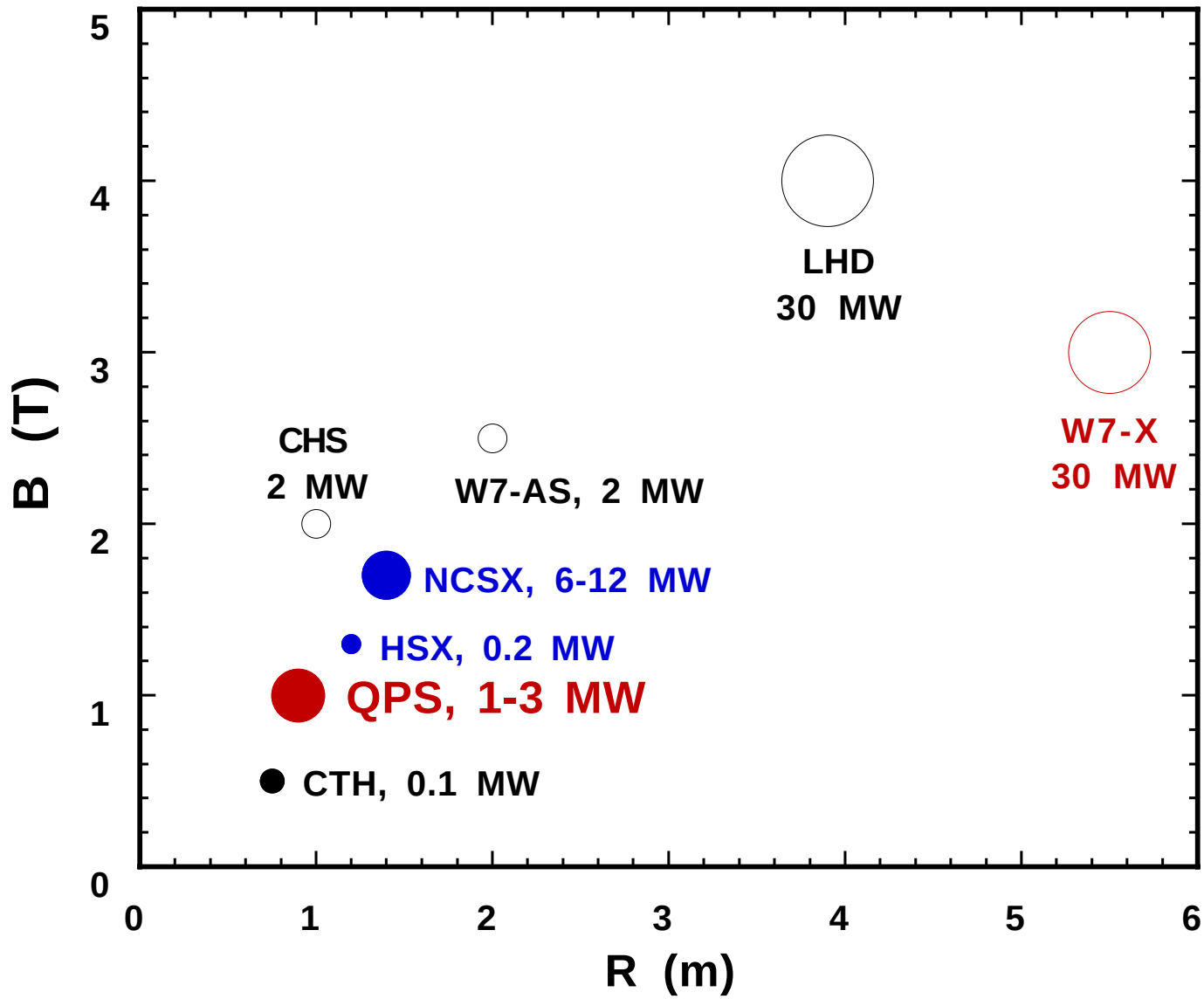
QPS

a Low- R/a Quasi-Poloidal Stellarator



- $\langle R \rangle = 0.9$ m
- $\langle a \rangle = 0.35$ m
- $\langle R \rangle / \langle a \rangle = 2.6$
- $V_{pl} = 2.1$ m^3
- $\iota_0 = 0.26$, $\iota_a = 0.39$
- $B_{mod} = 1$ T (0.5 s)
- $B_T = \pm 0.15$ T
- $I_p \leq 70$ kA
- $P_{ECH} = 0.6\text{-}1.2$ MW
- $P_{ICRF} = 1\text{-}3$ MW

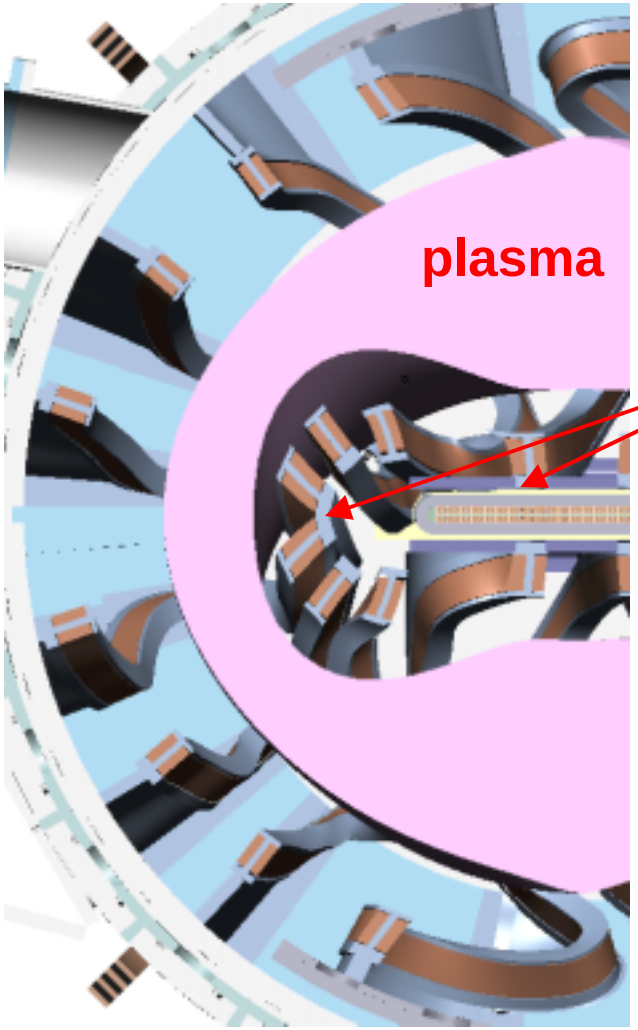
Although *R* (0.9 m) and *B* (1 T) Is Small, Plasma Radius (35 cm) Is Not Small Due to the Low Aspect Ratio



B = 1 T, R = 0.9 m Is Set by QPS Mission Needs

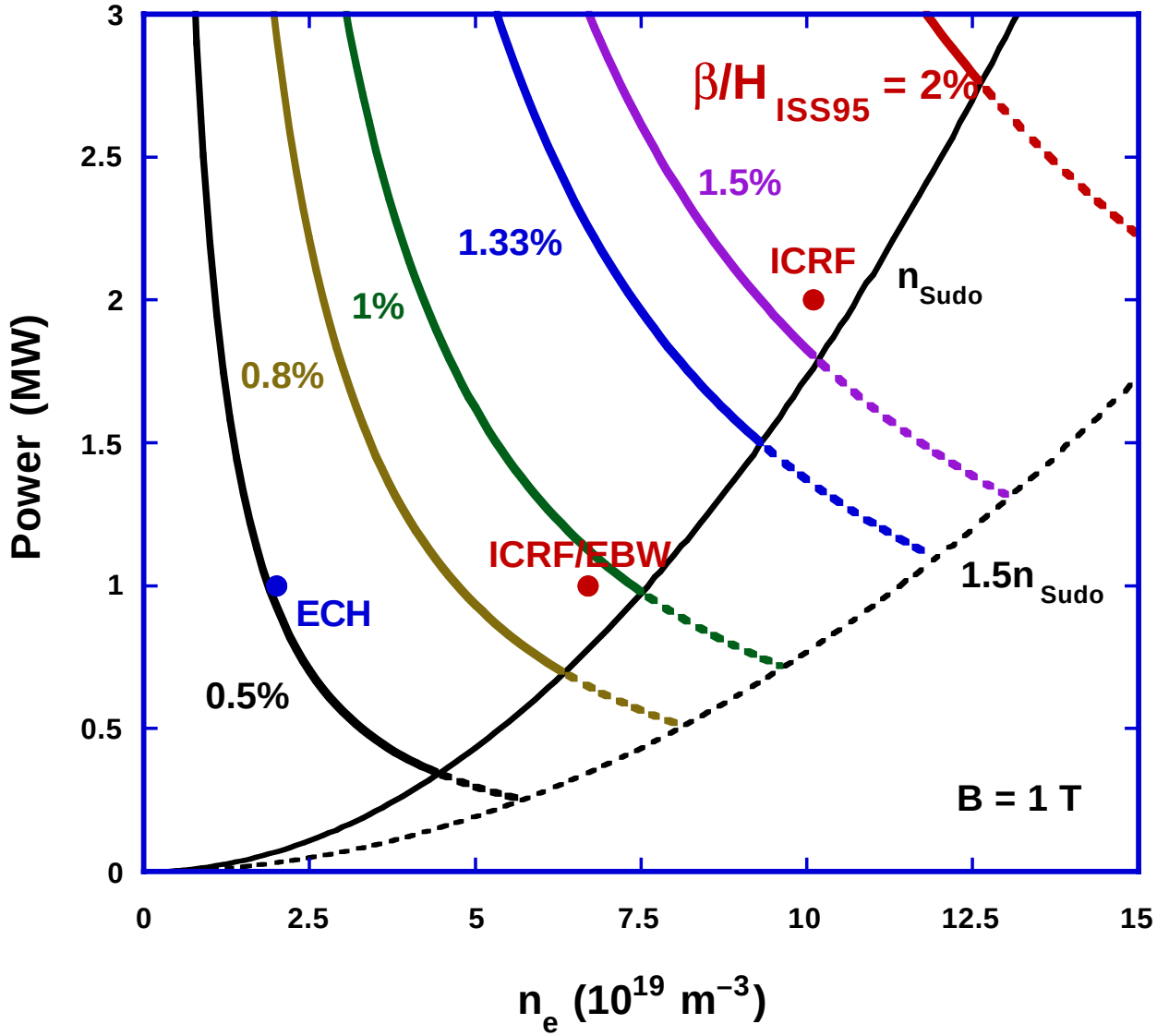
- **Adequate beta for study of equilibrium quality and ballooning limits: $\langle\beta\rangle$ ~ 2% $\Rightarrow$ P = 1-3 MW**
  - **available ECH and ICRF heating $\Rightarrow$ B = 1 T**
- **Low collisionality for study of neoclassical losses in $1/\nu$ regime: $\nu^* \propto 1/B^{3.7}$ $\Rightarrow$ B = 1 T for $\nu_{e*} << 1$**
- **Neoclassical confinement time larger than anomalous (ISS95) confinement time $\Rightarrow$ B = 1 T, R = 0.9 m**
- **Plasma density not dominated by atomic physics**
  - **smallest plasma dimension > ~25 cm $\Rightarrow$ R = 0.9 m**
  - **for ECH, $n_e = 2 \times 10^{19}$ m^{-3} $\Rightarrow$ B = 1 T**
- **Room-temperature coils with feasible current density (j ~ 8 kA/cm^2) that do not intersect $\Rightarrow$ R = 0.9 m**

Minimum *R* Set by Coil-Coil Spacing, Current Density, Power Supply, and Cooling Constraints



- $R_{min} \propto 1/(\Delta_{coil\text{-}coil}/R)^2 j$
- $\Delta_{coil\text{-}coil}/R$ set by plasma and coil optimization geometry
- Coil-coil spacing already very tight
- Higher *j* leads to higher cost by requiring
  - cryogenic cooling of the coils
  - thermal insulation
  - additional structure
  - an interior vacuum vessel
  - larger plasma-coil spacing to slide coils over vacuum vessel

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



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

D. Spong

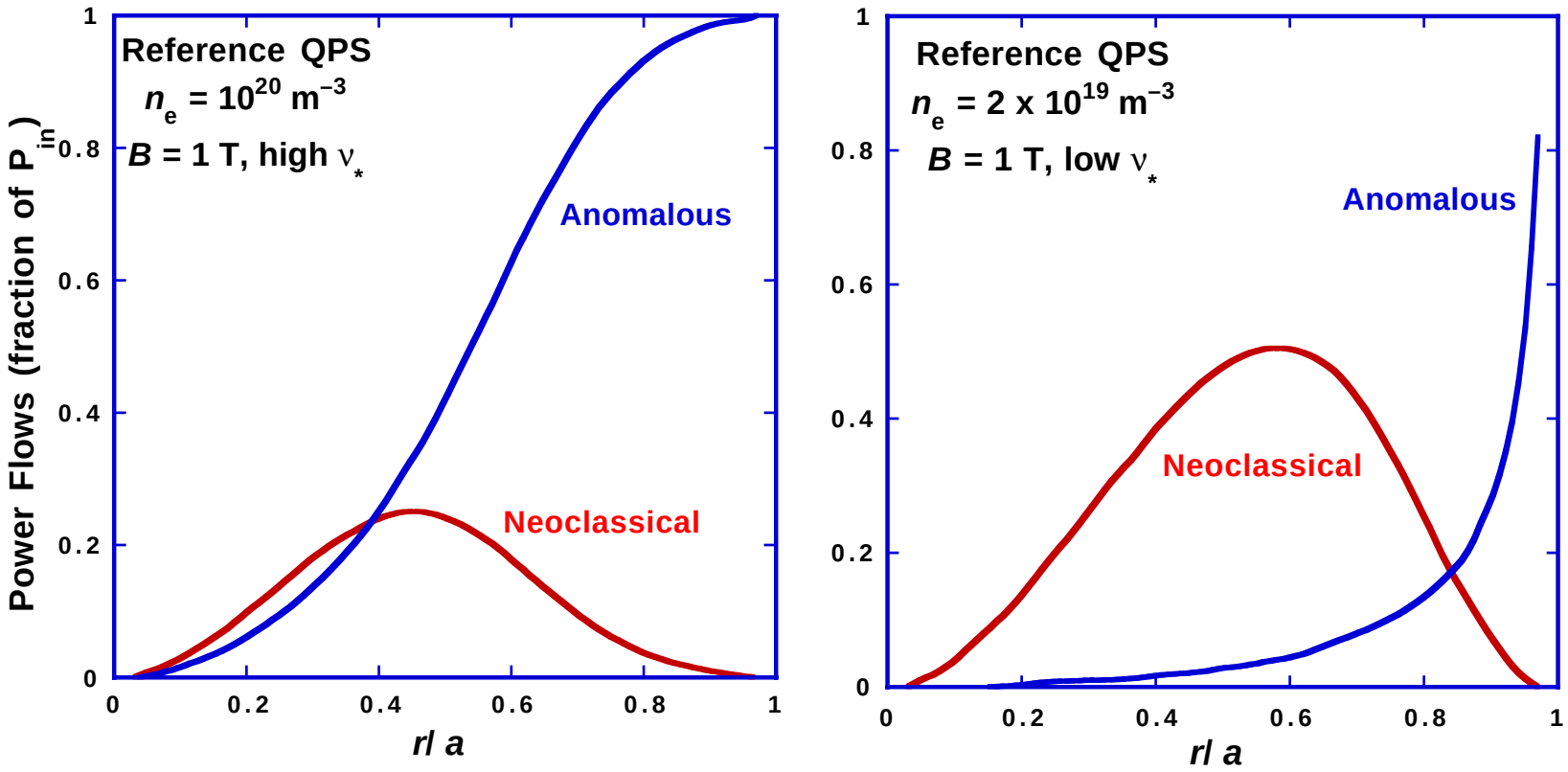
QPS parameter space for *B* = 1 T

Parameters Needed for the QPS Objectives Are Accessible with the Available Power

- **1-D transport calculations using ambipolar neoclassical transport from the NEO code and $\tau_E = 1.5\tau_E^{ISS95}$ where $\tau_E^{ISS95} = 0.079 a_p^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{-0.4}$**

B T	P MW	n_e, n_{Sudo} 10^{19} m^{-3}	T_e keV	T_i keV	τ_E ms	$\langle\beta\rangle$ %	ν_e*	ν_i*
0.5	1	5.0, 5.3	0.43	0.31	9.0	**2.77**	0.55	1.0
1	1	6.7, 7.5	0.64	0.48	18.3	**1.41**	0.33	0.56
1	2	10.1, 10.6	0.72	0.55	15.1	**2.32**	0.40	0.64
0.5	1	0.5	1.52	0.11	2.8	0.86	**0.0044**	0.79
1	1	2.0	1.21	0.23	10.0	0.77	**0.028**	0.73

Anomalous and Neoclassical Loss Channels Can Be Separated through Choice of Density



Substantial RF Heating Is Available for QPS

Type of RF Heating	Power and Frequency Range
ECH/EBW	1.2 MW at 28 GHz 0.6 MW at 53.2 GHz
ICRF	2 MW at 6-20 MHz, 1.5 MW at 40-80 MHz

D. Rasmussen

QPS Experimental Program

- **As an experiment exploring a new confinement approach, QPS would address the range of physics issues outlined by FESAC and the IPPA**
  - **MHD equilibrium and stability**
  - **confinement and transport**
  - **plasma heating**
  - **particle and power handling**
- **As a CE-level experiment, QPS must focus on a few areas for in-depth physics studies**
  - **equilibrium quality and energy confinement at very low *R/a***

L. Berry

QPS Presentation Highlights

- **Steve Hirshman -- Design of the QPS Reference Configuration**

  A low-aspect-ratio QPS reference configuration has been designed with
  - **low collisionality transport nearly as good as in much higher *R/a* devices (HSX, W 7-X)**
  - **predicted ballooning β limits (~2-2.5%) comparable to best existing stellarators**

- **Lee Berry -- QPS Coil Design**
  - **the reference coil set meets engineering constraints and reproduces the fixed-boundary physics**
  - **the PF coil design can provide the required configuration flexibility and Ohmic heating flux**

QPS Presentation HIghlights

- **Andrew Ware -- Equilibrium and MHD Stability for QPS**
  - **bootstrap-consistent equilibria for $\langle\beta\rangle$ = 0 to 2%**
  - **ballooning stability sets the stability β-limits for QPS: $\langle\beta\rangle$ = 2.5% fixed boundary; $\langle\beta\rangle$ = 2.2% free boundary; other limits $\geq$ 5%**
- **Don Spong -- Confinement and Transport for QPS**
  - **ISS95 scaling + neoclassical transport (0-D and 1-D) calculations predict $\langle\beta\rangle$ = 1 - 3%, τ_E ~ 20 ms at high ν_{e*}**
  - **neoclassical transport can be studied at low ν_{e*}**
- **Brad Nelson -- QPS Engineering Design**
  - **preconceptual design of all QPS components has been developed**
- **Peter Mioduszewski -- Power and Particle Control for QPS**
  - **needed for optimum QPS operation: connection lengths in the scrapeoff region are long enough for effective island divertor operation**

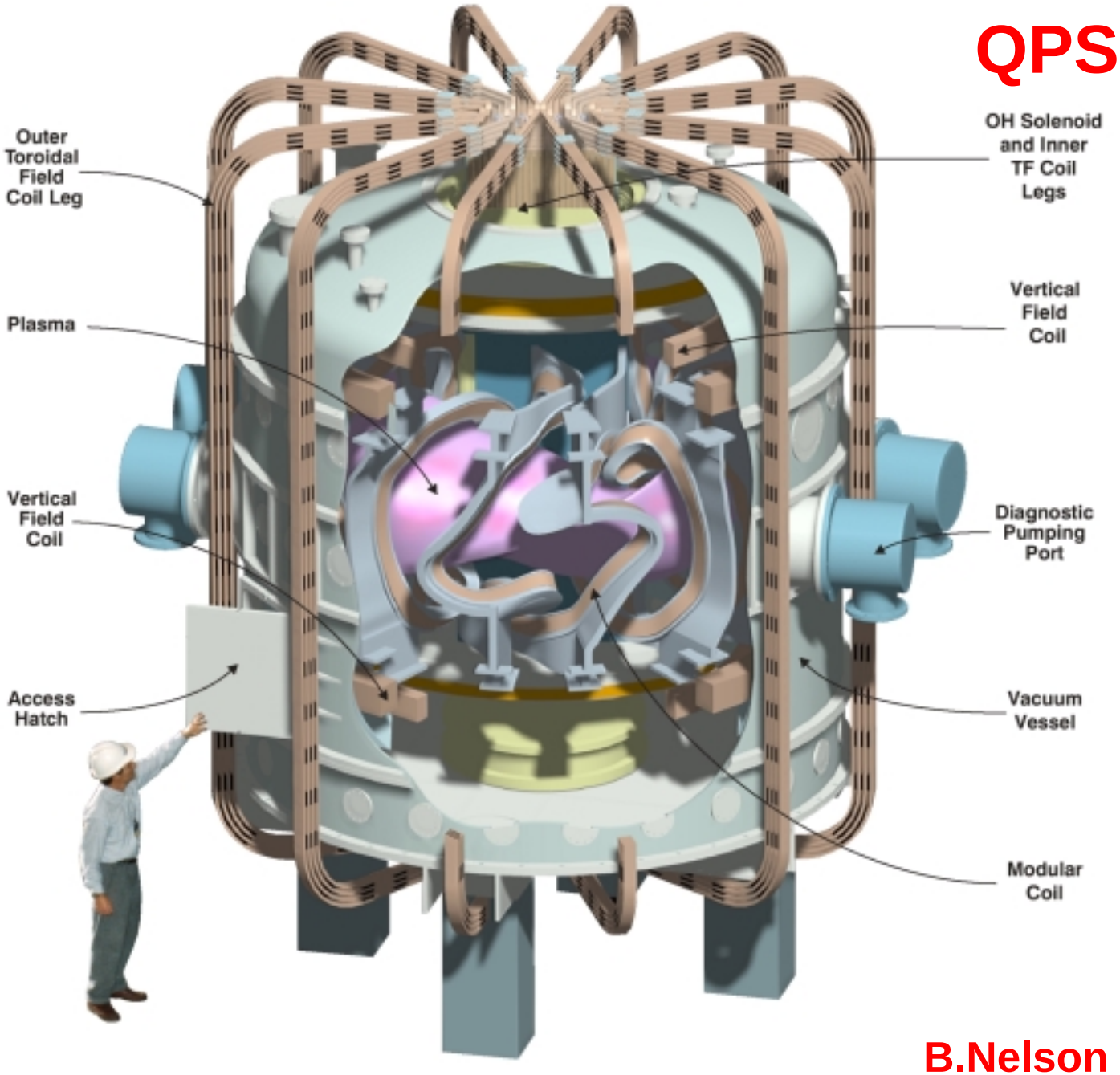
QPS Presentation Highlights

- **Dave Rasmussen -- RF Heating for QPS**
  - **practical ECH/EBW and ICRF heating options exist for QPS**
- **Lee Berry -- QPS Experimental Program**
  - **staged program on broad topics with emphasis on low-*R*/*a* equilibrium/stability and confinement with appropriate diagnostics**
- **Jim Lyon -- General Project Issues**
  - **project schedule and CDR preparation**
  - **project cost estimate**
  - **infrastructure**
  - **program staffing and management**

SUMMARY

- **QPS is the logical first step in understanding transport and stability for quasi-poloidal stellarators at low aspect ratio**
- **This information is not available from any other experiment and is needed to have confidence in a high-β compact stellarator reactor vision that has potential advantages over advanced tokamaks and conventional stellarators**
- **The QPS design satisfies all physics requirements and engineering constraints for this first step**

QPS


Outer Toroidal Field Coil Leg
Plasma
Vertical Field Coil
Access Hatch
OH Solenoid and Inner TF Coil Legs
Vertical Field Coil
Diagnostic Pumping Port
Vacuum Vessel
Modular Coil

B.Nelson