Overview of the ORNL QPS Compact Stellarator Experiment

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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.

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**

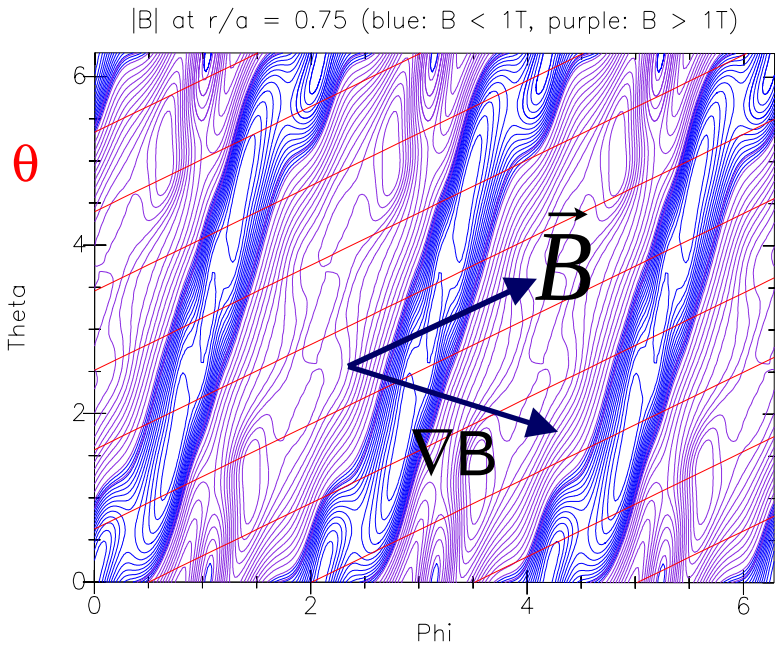
Topics

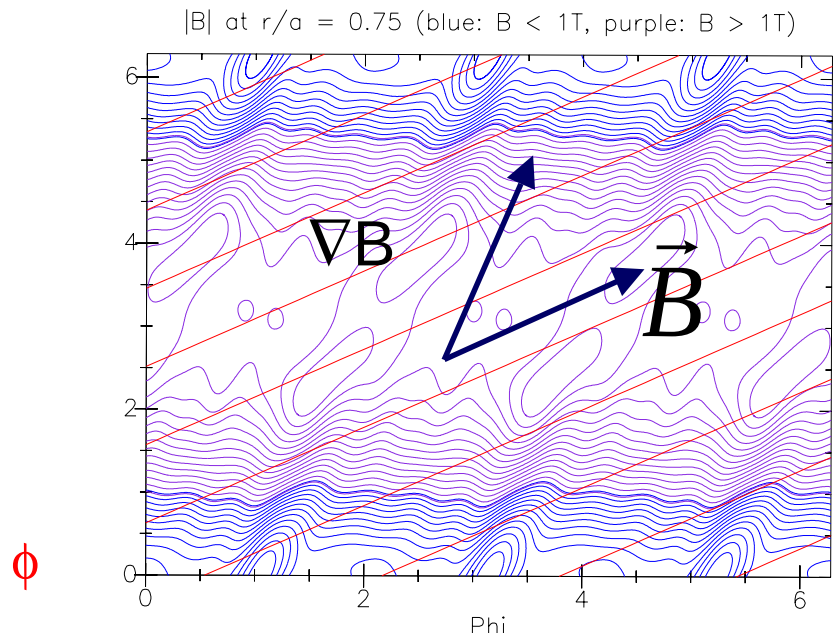
- Role of compact stellarators and QPS in the US and world programs
- Physics of quasi-poloidal configurations
- QPS plasma and device optimization
- The QPS experiment
  - confinement properties
  - MHD equilibrium and stability
  - engineering design
  - experimental objectives
- High-beta reactor vision
- Plans

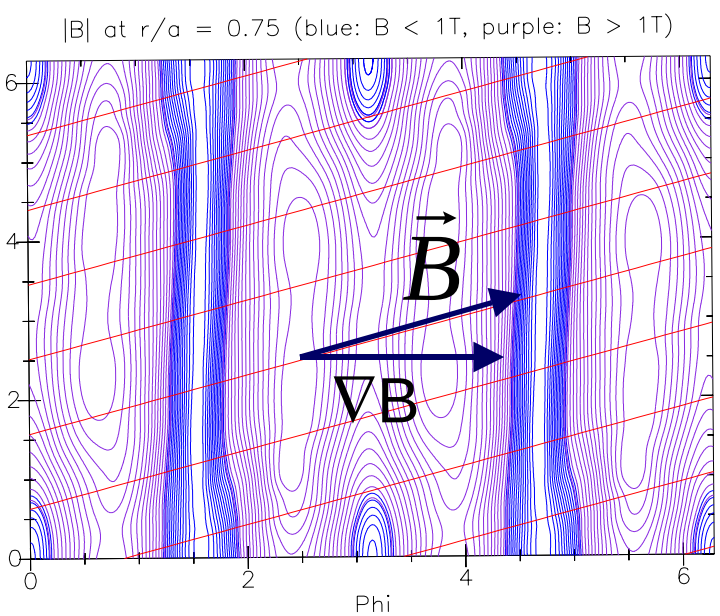
Compact Stellarators Are a New Element in the World Program

- **Low *R*/*a* stellarators could combine the best features of advanced tokamaks and currentless stellarators**
  - **good confinement and MHD stability *without* current-driven disruptions, kink modes or vertical instability, or need for current drive or feedback stabilization**
- **New element: use of a *reduced* bootstrap current and quasi-symmetry in a low *R*/*a* stellarator**
- **NCSX & QPS would allow the U.S. to be competitive in the world stellarator program at minimum cost**
  - **PoP-level NCSX explores quasi-axisymmetry and low *R*/*a* (4.3), complements tokamaks (hybrid configuration)**
  - **CE-level QPS explores quasi-poloidal symmetry and very low *R*/*a* (2.7), complements high-*R*/*a* (10.6) currentless W 7-X, and creates basis for high-β compact stellarators**

US Stellarator Approach Features Quasi-Symmetry





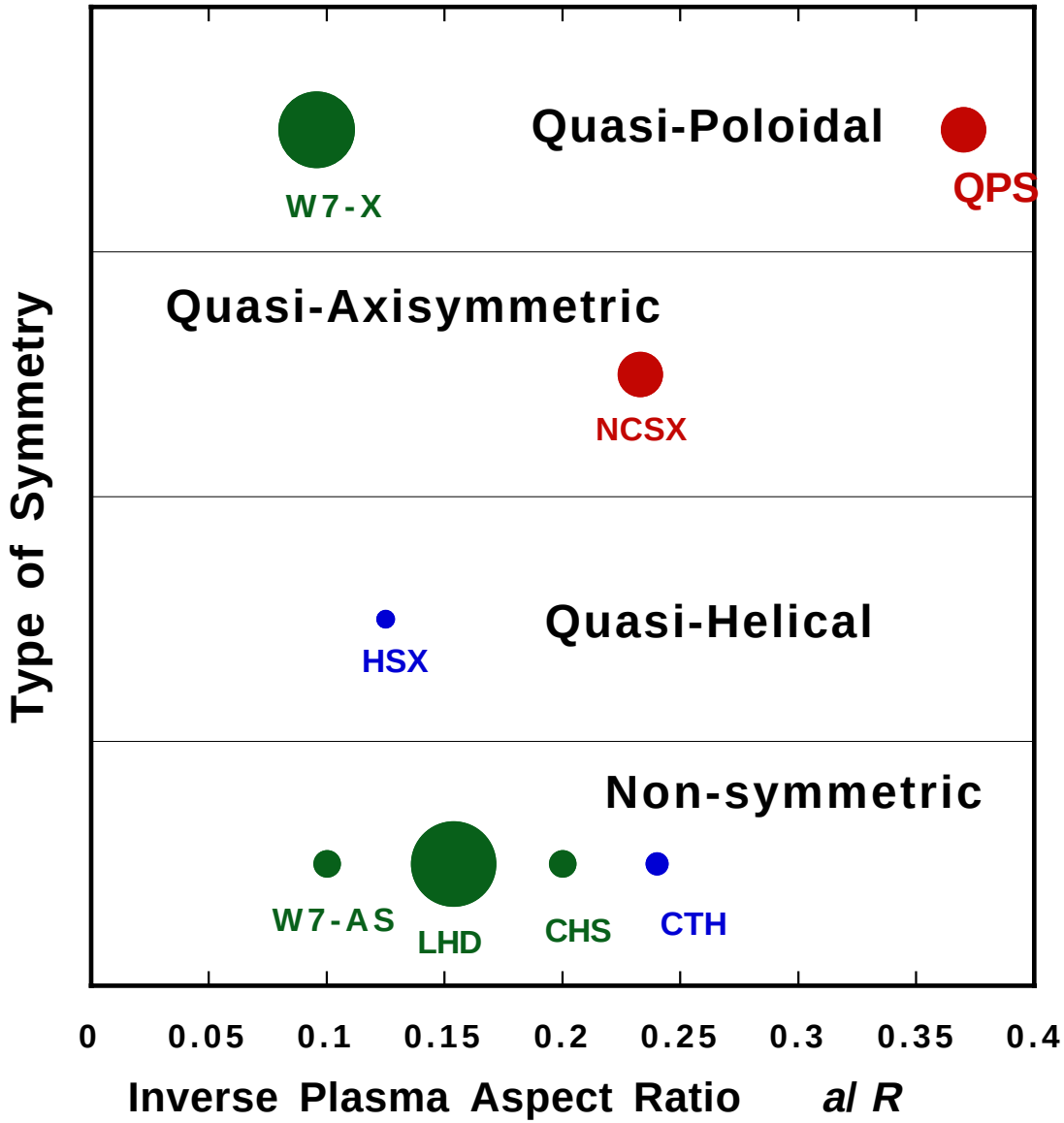


- **Quasi-helical**: |B| like large *R*/*a* stellarator.
  HSX (*R*/*a* = 8) will test this concept.
- **Quasi-axisymmetric**: |B| like a tokamak.
  NCSX (*R*/*a* = 4.3) would test this concept.
- **Quasi-poloidal**: **|B| like toroidally linked mirrors. The *B* x ∇B drift can be made very small in this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

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**

QPS Complements Other World Stellarators



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

Radius of circles
Is proportional to
the average plasma
radius

QPS Differs from W 7-X

- **Both explore the quasi-poloidally-symmetric approach to stellarator optimization, but at very different aspect ratios**
  - ***R*/*a* = 2.7 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**

$\Rightarrow$ **Present theory can not be used to extrapolate from W 7-X to QPS**

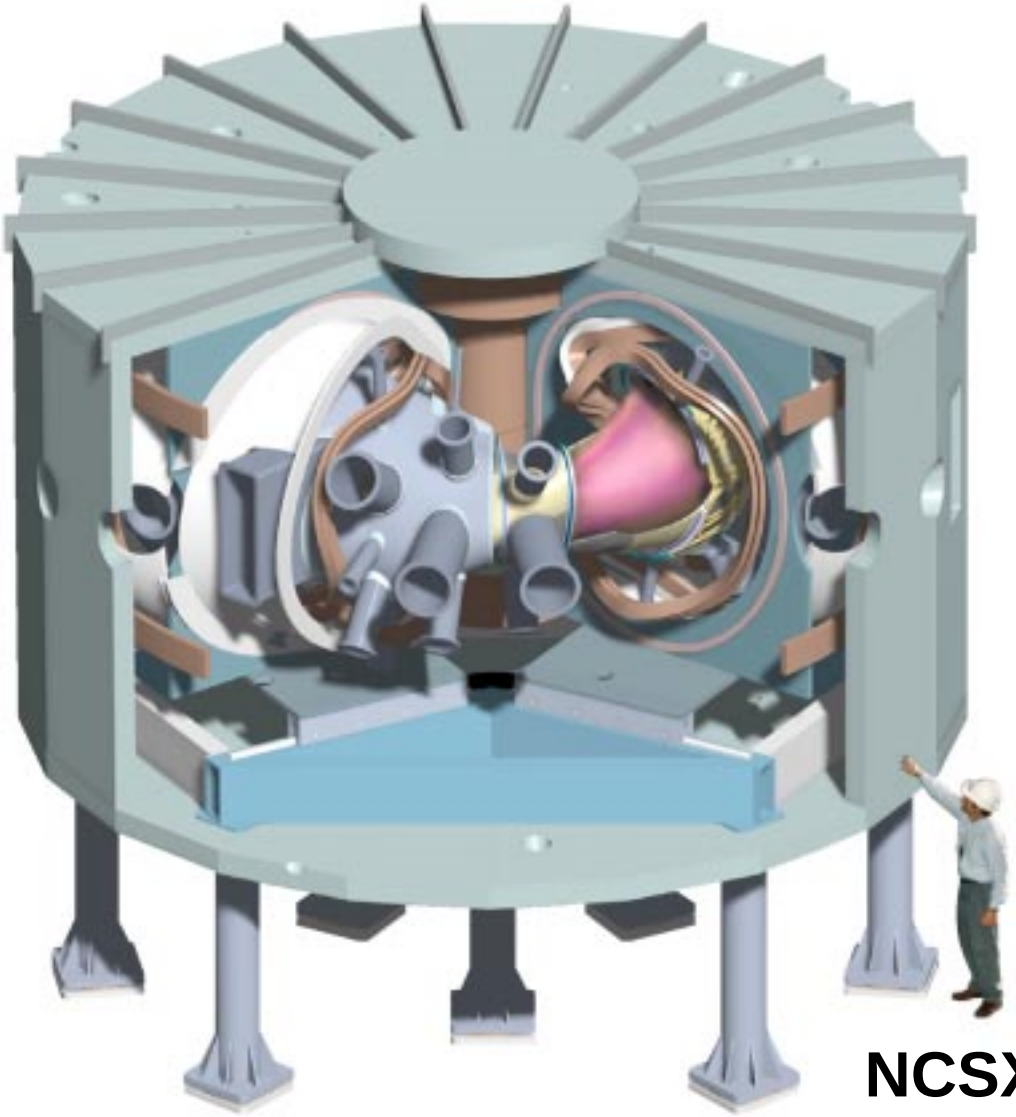
QP S Differs from NCSX

Feature	NCSX	QPS
R, a, B, $P_{heating}$	1.4 m, 0.33 m, 2 T, 6-12 MW	0.9 m, 0.33 m, 1 T, 1-3 MW
Magnetic Symmetry	Quasi-Axial	Quasi-Poloidal
Aspect Ratio R/a	4.3	2.7
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

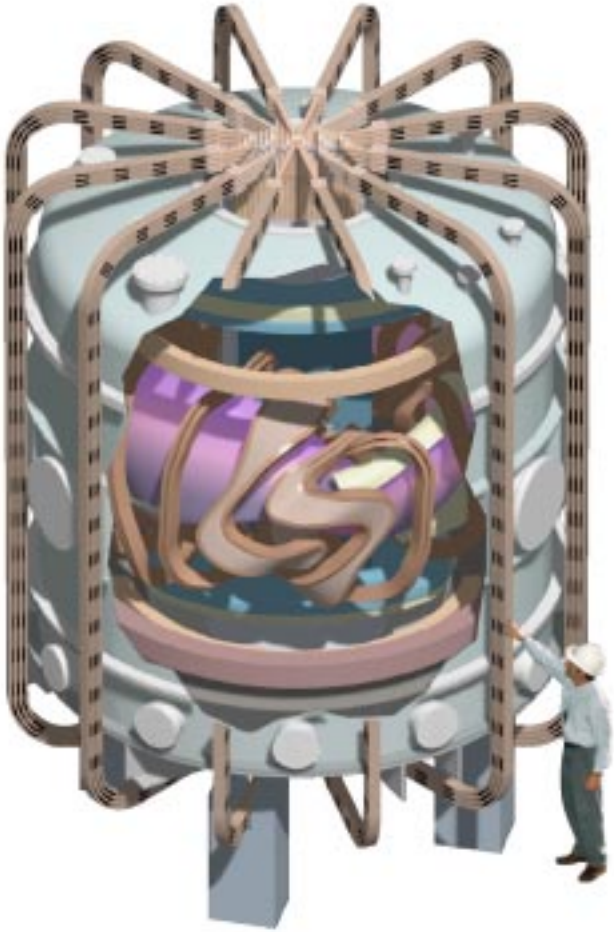
- Two orthogonal approaches exist for compact stellarators
- quasi-axisymmetric tokamak-like configuration: $69M NCSX is a proof-of-principle-level experiment to test this approach
- quasi-poloidal linked-mirror-like configuration: $14M QPS is a concept-exploration-level experiment to test this approach

NCSX and QPS Use Different Design Approaches

QPS does not use cryogenic coils or an interior vacuum vessel



NCSX



QPS

QPS Extends Stellarator/Toroidal Physics Understanding to Very Low *R*/*a* and Quasi-Poloidal Symmetry

- **Flux surface robustness at $\langle\beta\rangle$ up to ~2.5% in the presence of strong toroidal/helical coupling**
- **The dependence of the bootstrap current on magnetic configuration properties**
- **Validity of stellarator confinement scaling and anomalous transport at a factor of 2 lower *R*/*a***
- **The physics of neoclassical confinement improvement at very low aspect ratio: reduced B x ∇B drift out of a flux surface**
- **The electric field, poloidal flows, and their influence on transport barriers and enhanced confinement regimes**

Status

- **Both NCSX and QPS have had successful Physics and Project Validation reviews this year by DOE**
- **Next step is Conceptual Design, Cost and Schedule Reviews and Project Reviews in April and May, 2002**
- **Work on NCSX could start first with start of operation for both in March 2007**

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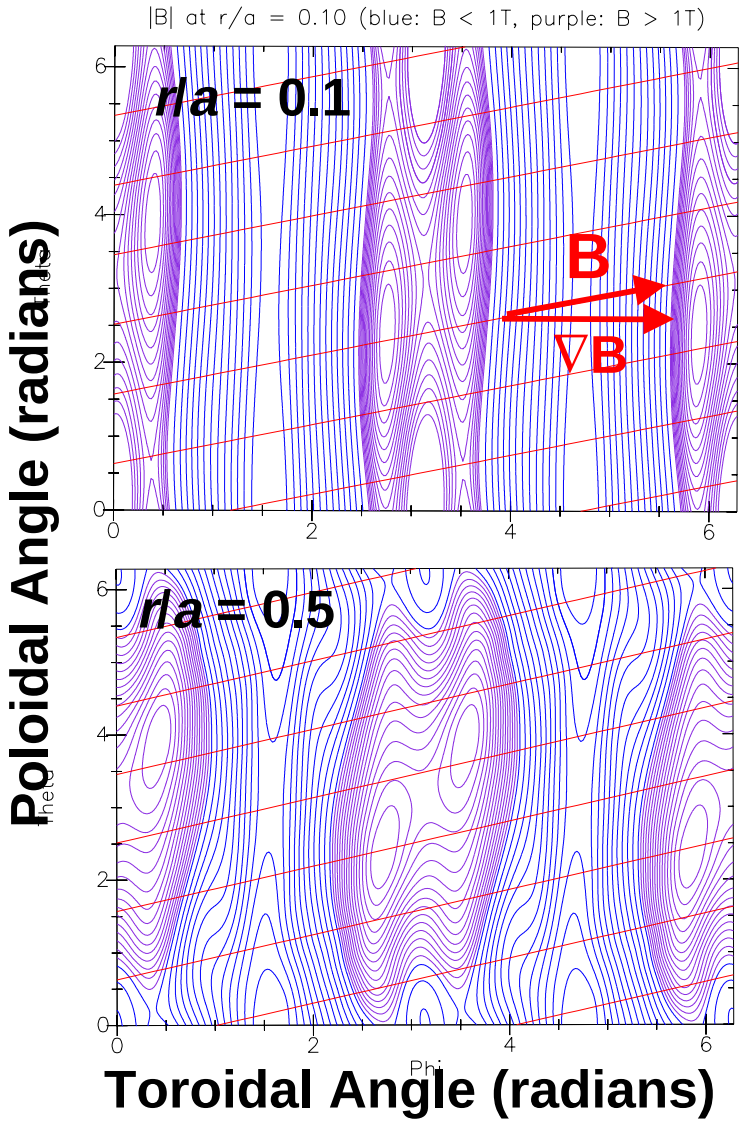
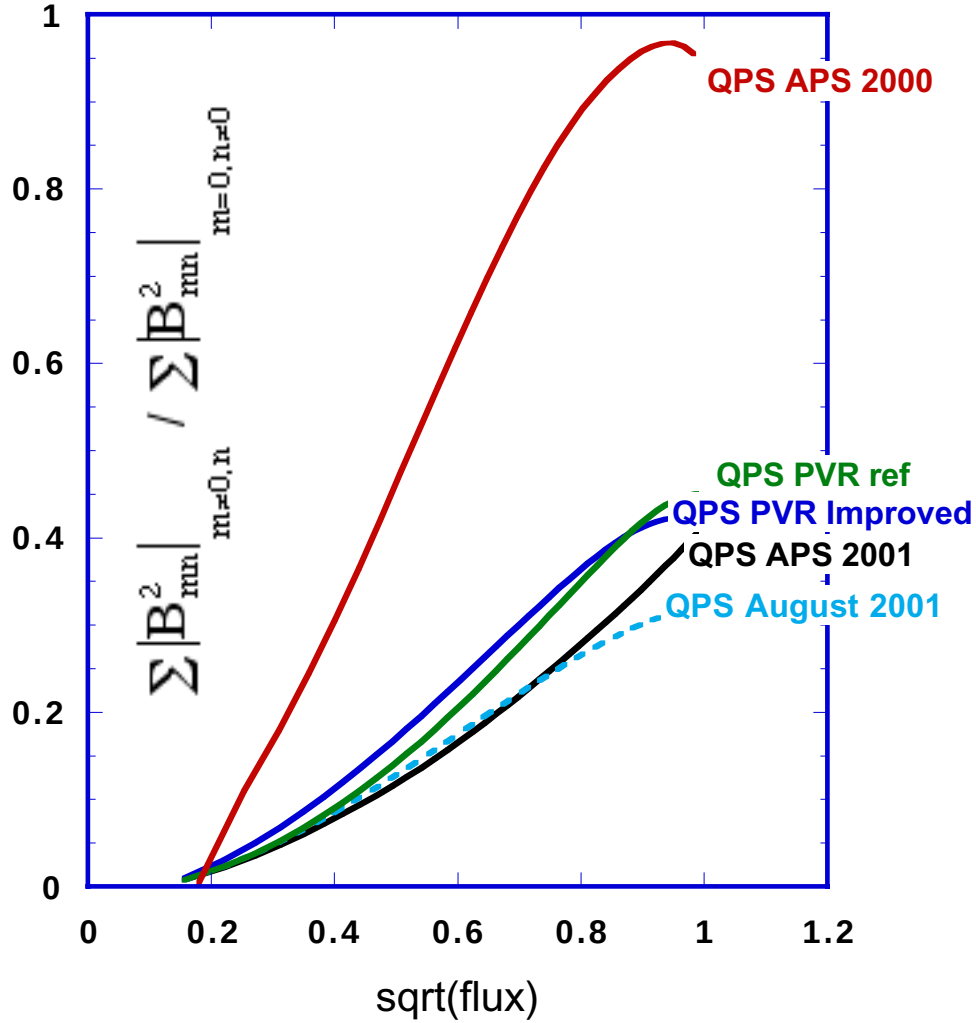
Quasi-Poloidal |B| Structure Varies with Radius





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

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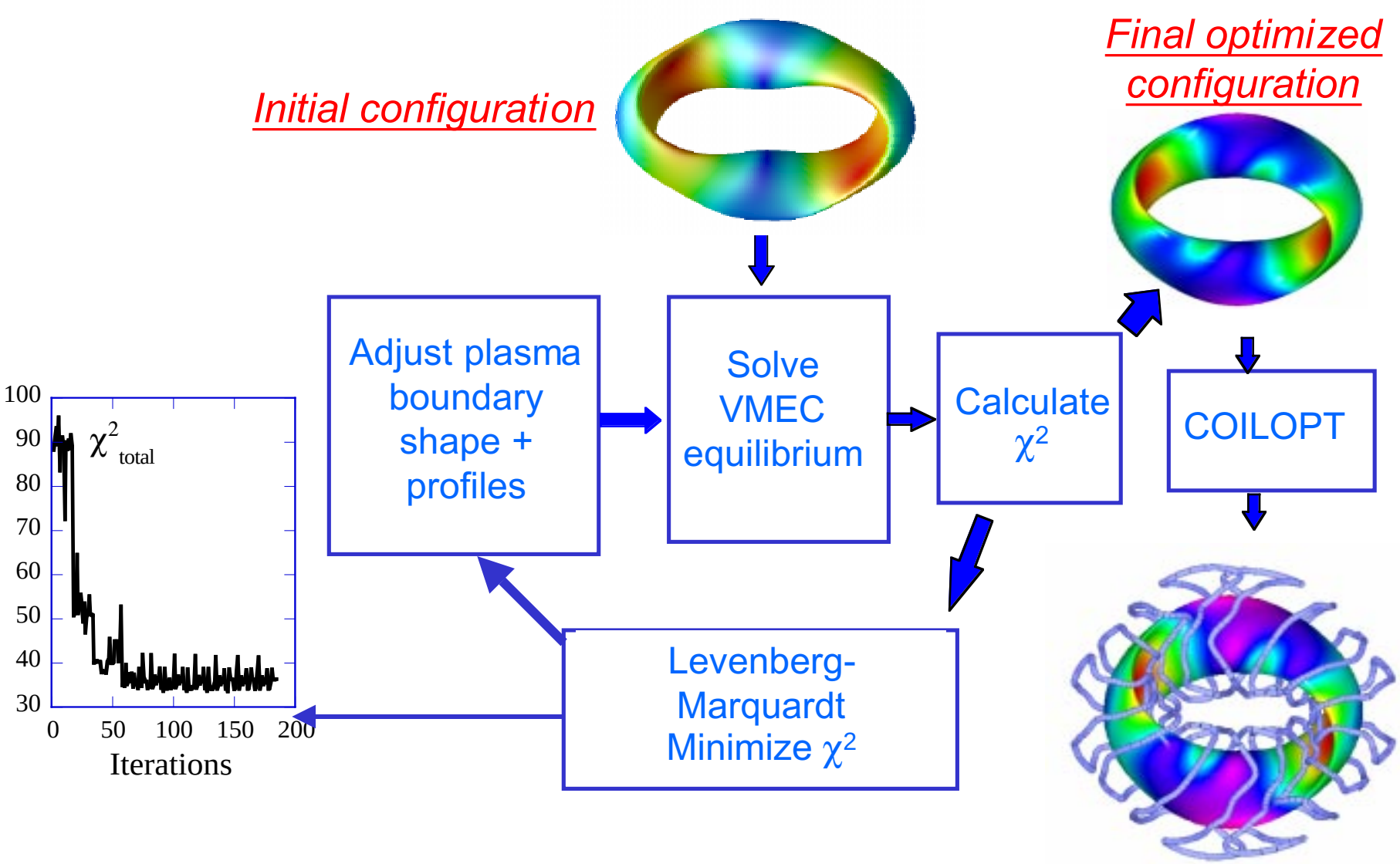
Compact Stellarator Optimization Procedure



Plasma boundary is characterized by 30-40 Fourier harmonics

Rapidly Evaluated Measures of Transport Are Important within the Optimization Loop

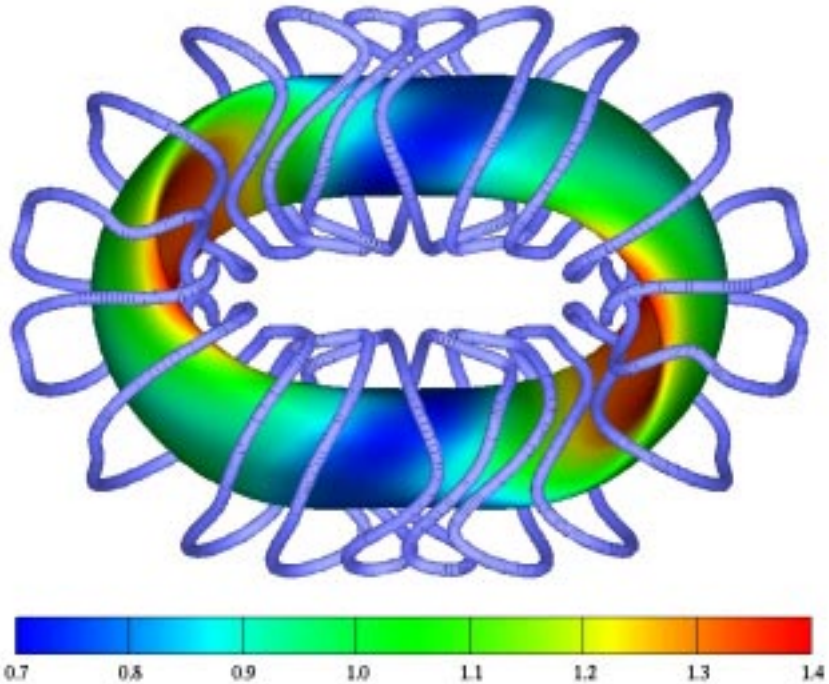
- **Conventional stellarators have large ripple-induced ($1/\nu^*$) transport at low collisionality**

TARGET	IMPROVES:	EXAMPLE	
Bounce-averaged omnigeneity	Collisionless trapped/transitional particle confinement	$J = J(\psi)$ $B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$	Currently existing
Nearby quasi-symmetries	Collisionless confinement of all orbit topologies	Minimize B_{mn} if $m \neq 0$ (QP) Or if $n \neq 0$ (QA)	Currently existing
Collisional transport coefficients	Neoclassical transport	L_{11} coefficient from DKES at $\nu^* \sim 1$	Currently existing
Effective ripple ε_{eff}	$1/\nu$ neoclassical transport regime	$\varepsilon_{eff}^{3/2}$ from NEO code	Currently existing
Large orbit effects	Energetic particle confinement	Reduced Monte Carlo model for alphas	Future

These Transport Measures Are in Addition to Stability, Configuration and Engineering Targets

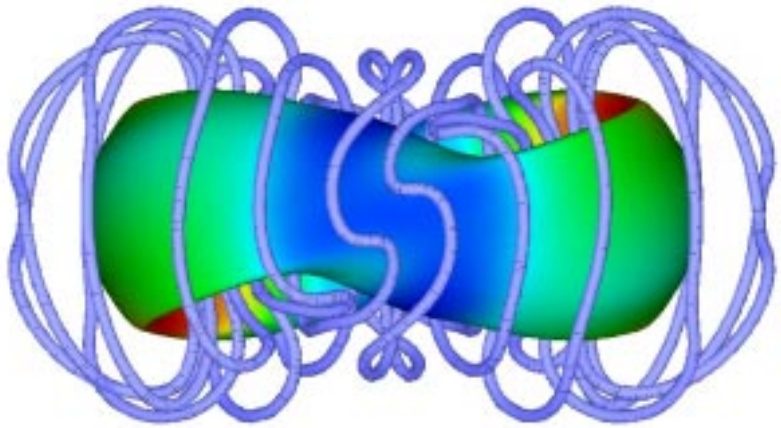
Targets (Physics/Engineering)	**Example**
Transport Measures	See previous slide
Current profile	self-consistent I_{BS}, $I(\psi)$ goes to 0 at edge
Limit maximum plasma current	e.g., I_{max} < 80 kAmps
Iota profile	$i(\psi)$ = 0.25 (ψ=0) 0.4 (ψ=1)
Magnetic Well, Mercier	V < 0, D_M > 0 over cross section
Ballooning stability	$\langle\beta\rangle$ ~ 2-4%
Aspect ratio	R_0/a ¯ 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

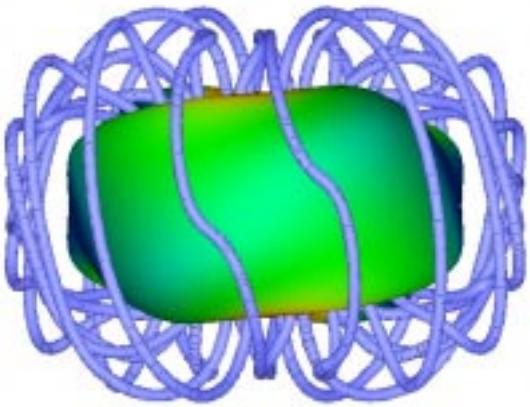
The QPS Plasma and Modular Coil Configuration



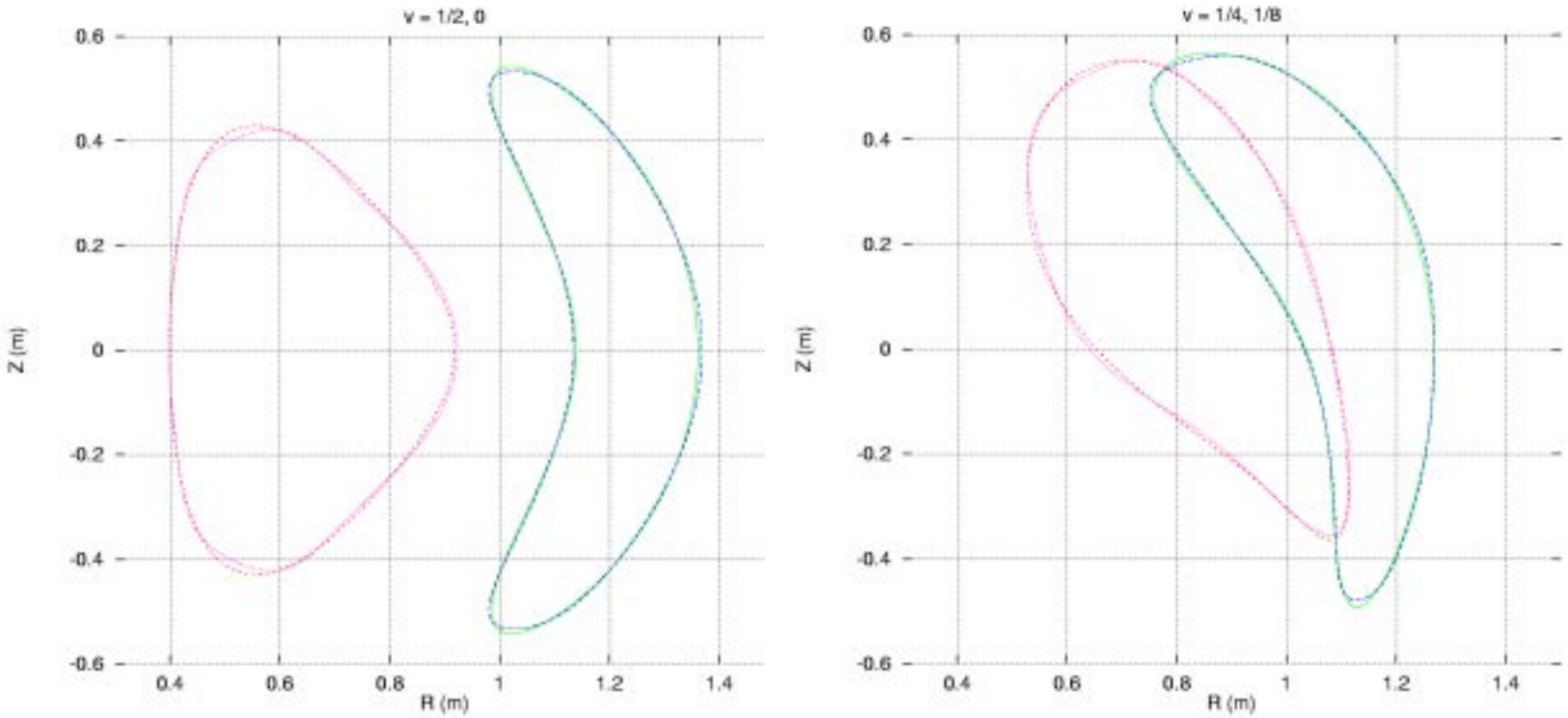
|B| in T

- **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**

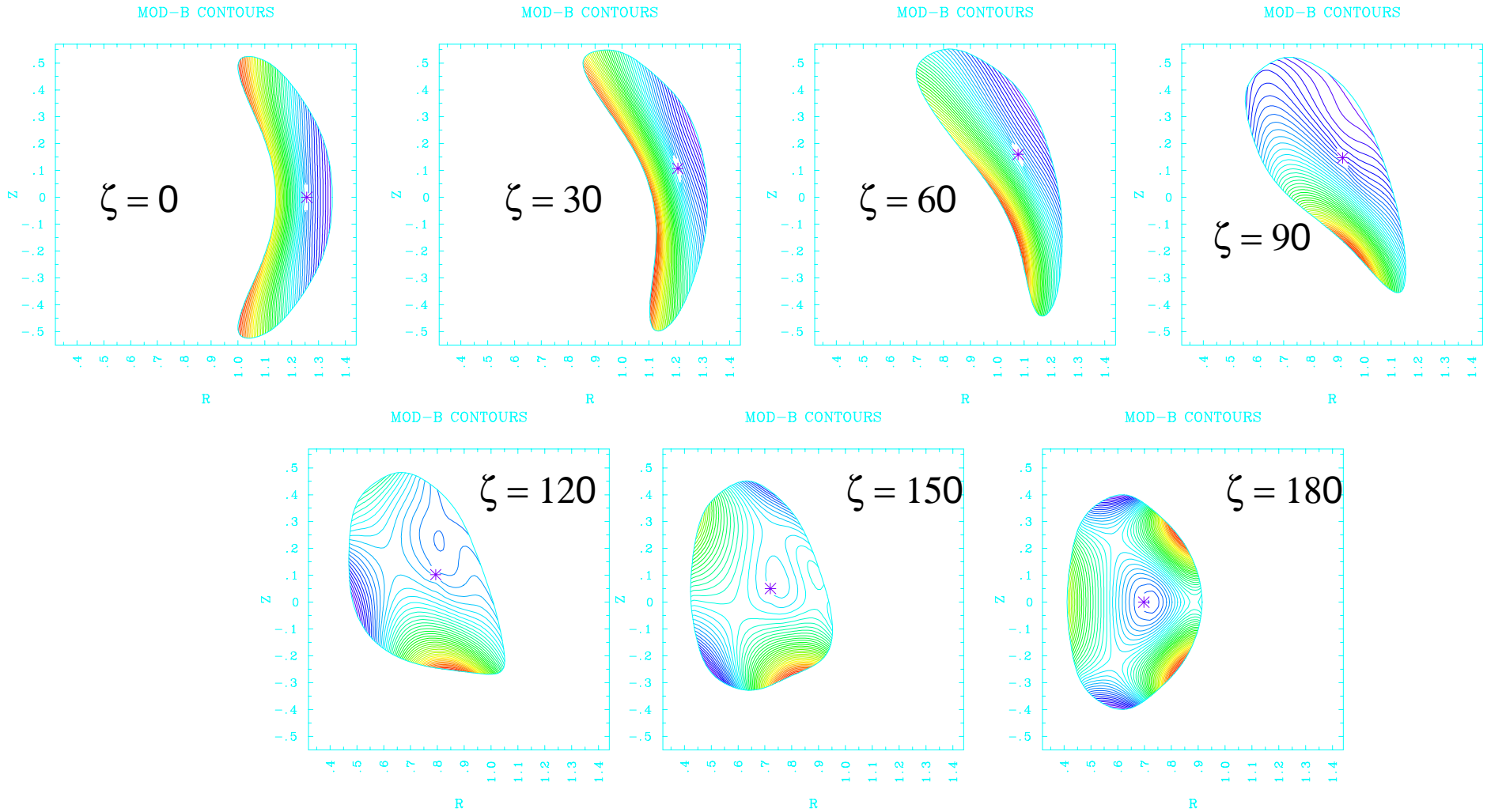




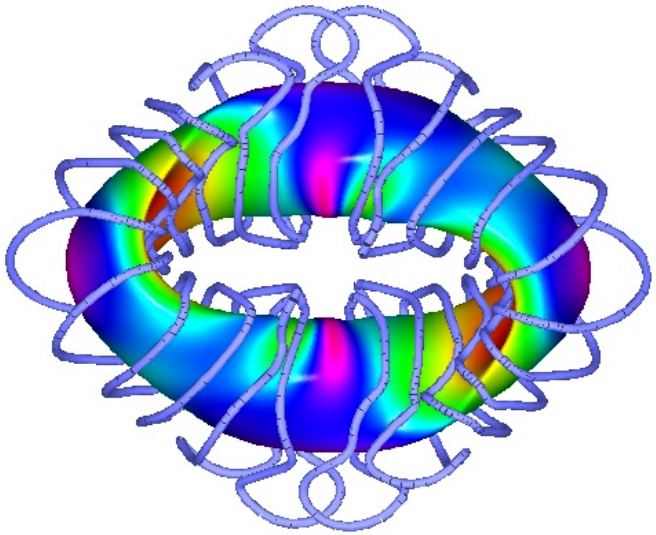
Reconstruction from Coils Reproduces Optimized Fixed-Boundary Configuration



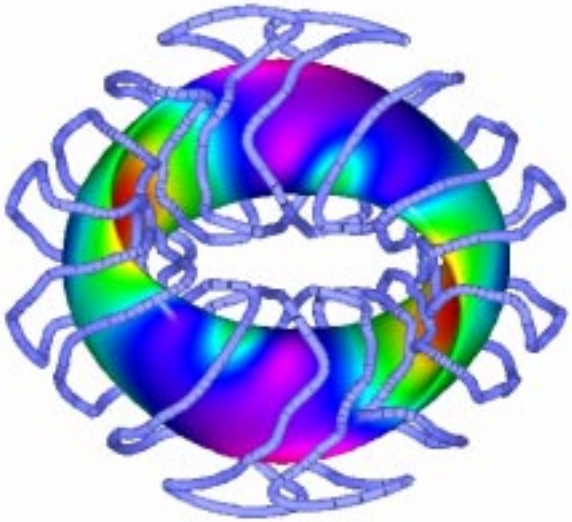
QPS Plasma Cross Sections and |B| Contours



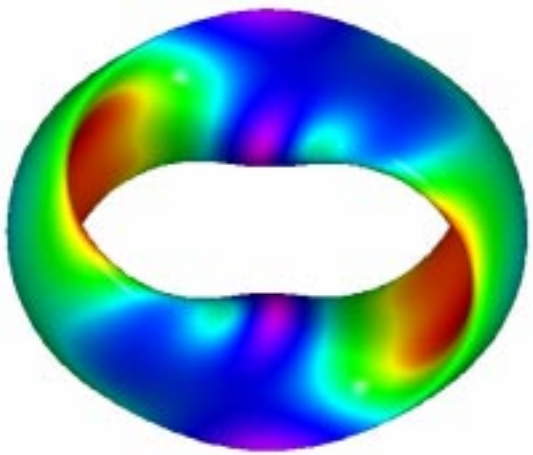
Improvements Have Been Made to the Basic QPS Plasma & Coil Configuration This Year



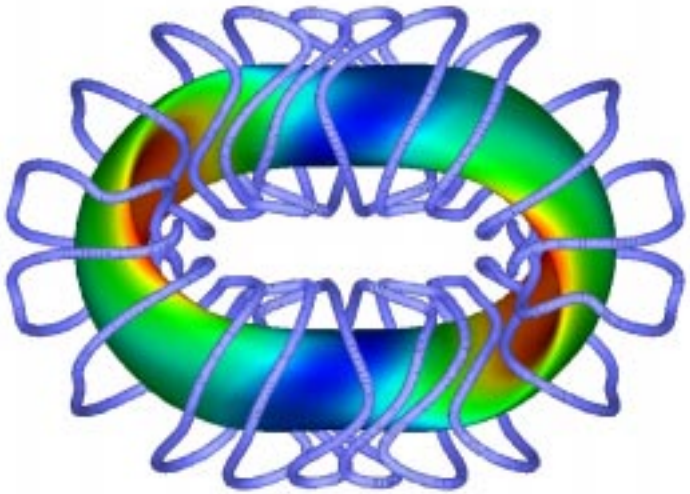
APS 2000 configuration



April 2000 PVR Config.



Improved PVR Config.

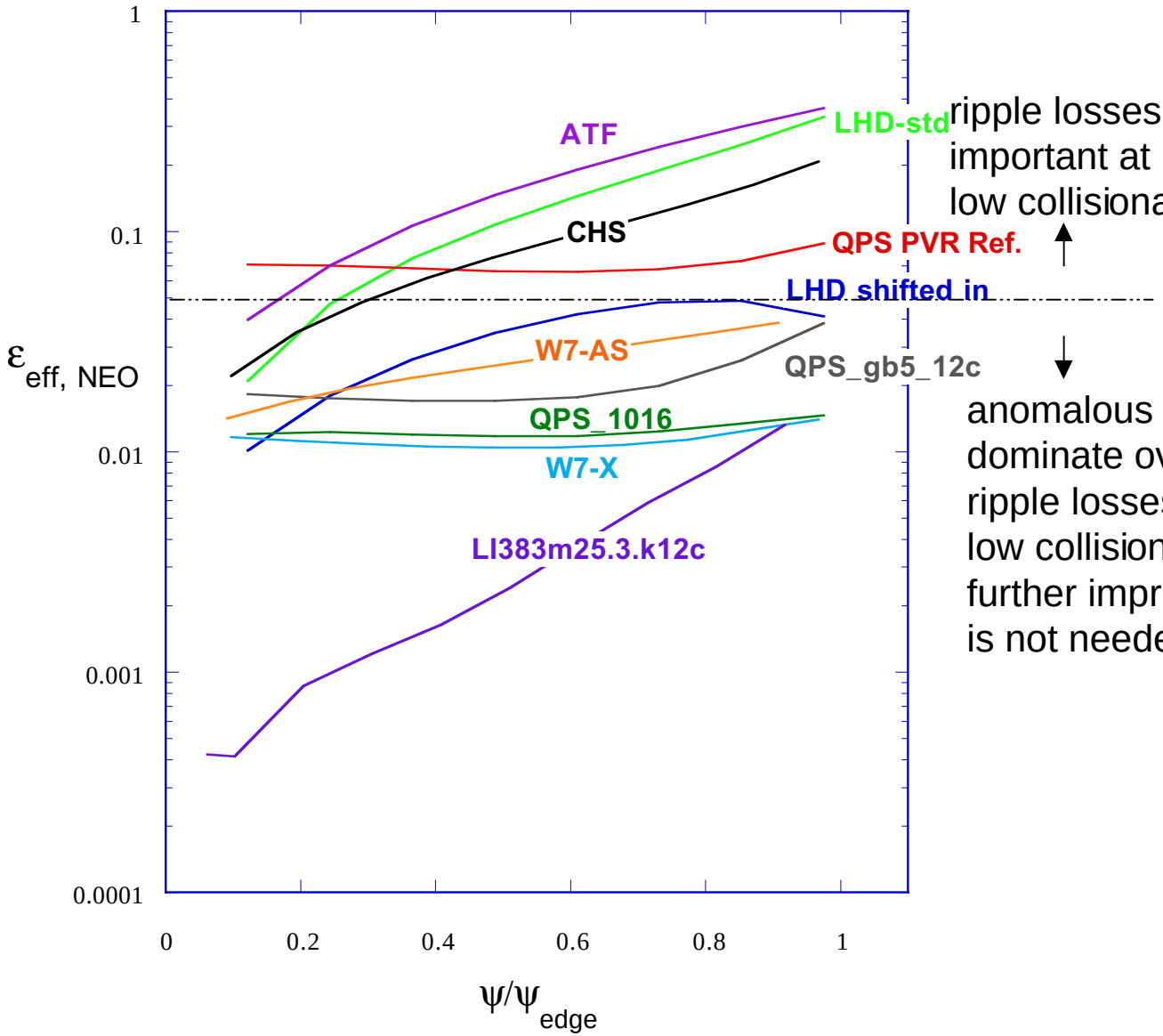


Present Configuration

Consequences of QPS Improvements

- Neoclassical losses reduced by factor ~20, now at same level as in W 7-X with 4 x *R*/*a* of QPS
- Departure from quasi-poloidal symmetry has been reduced by a factor 2.7
- Space in middle has been increased to accommodate TF coil legs and OH solenoid
- Increased plasma-coil and coil-coil spacings
- Modular coils have been modified to reduce errors in reconstructing the optimized field by factor 2.2
- Vacuum vessel has been modified to eliminate eddy currents induced by PF system

Newer QPS Configurations Have Much Smaller Neoclassical Transport



ripple losses important at low collisionality

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

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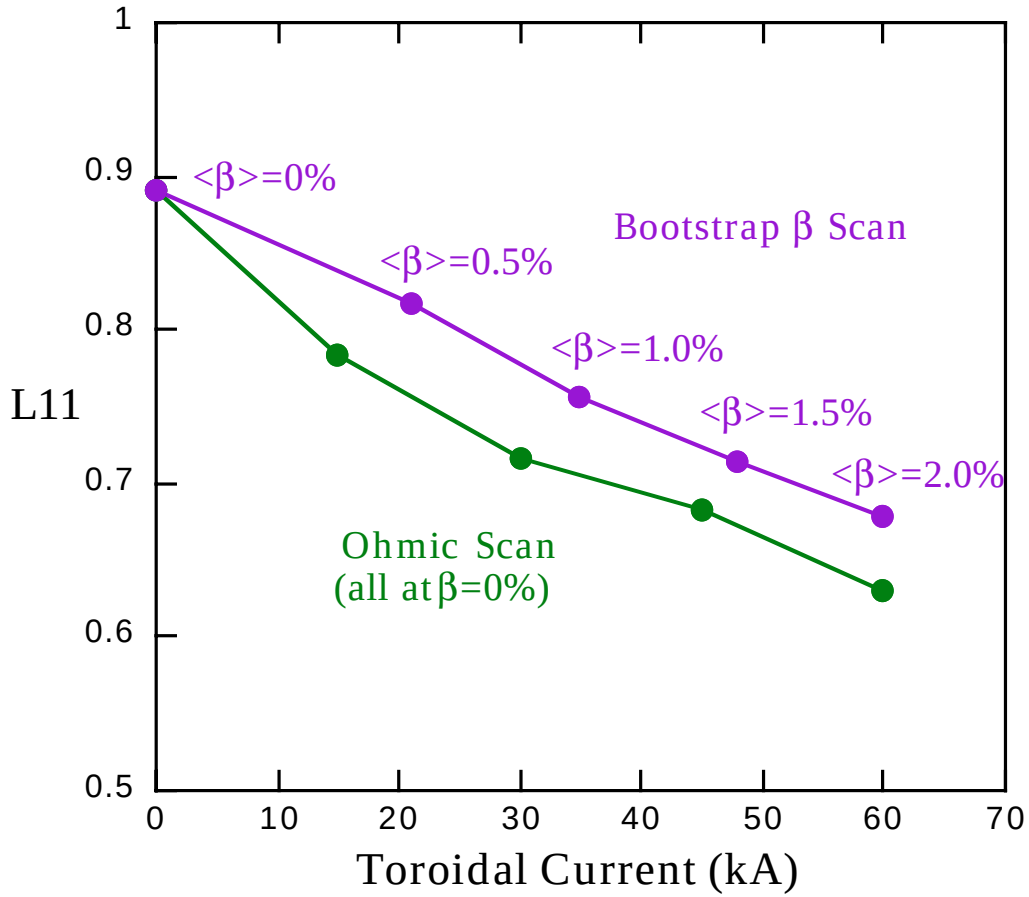
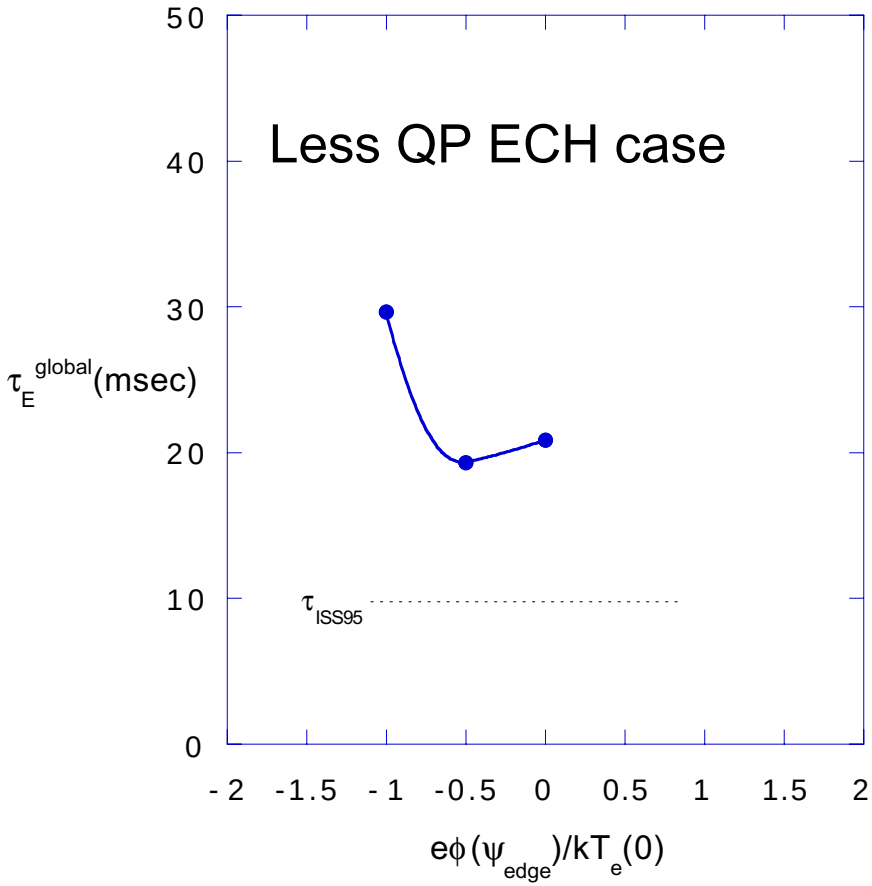
Confinement Improves with ⟨β⟩

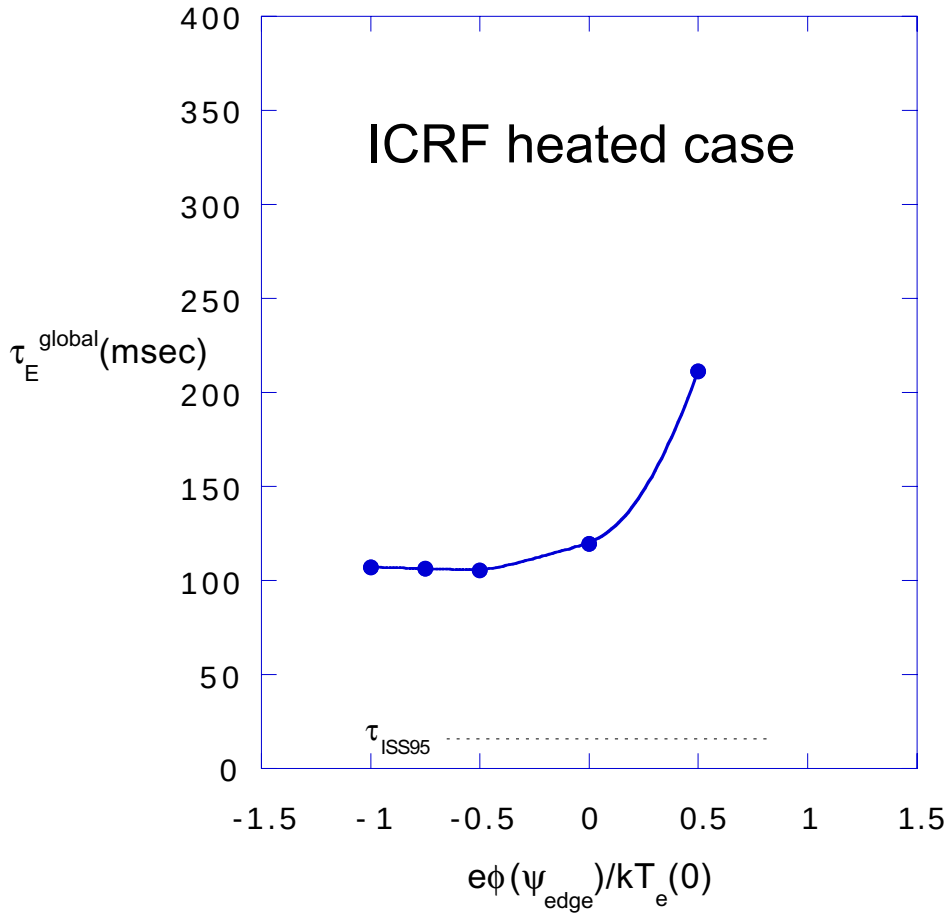
- **Same trend seen up to ⟨β⟩ = 23% in quasi-poloidal reactor configuration**
- **Can be simulated by Ohmic current in QPS**



- Radial transport coefficients on *r*/*a* = 0.84 surface

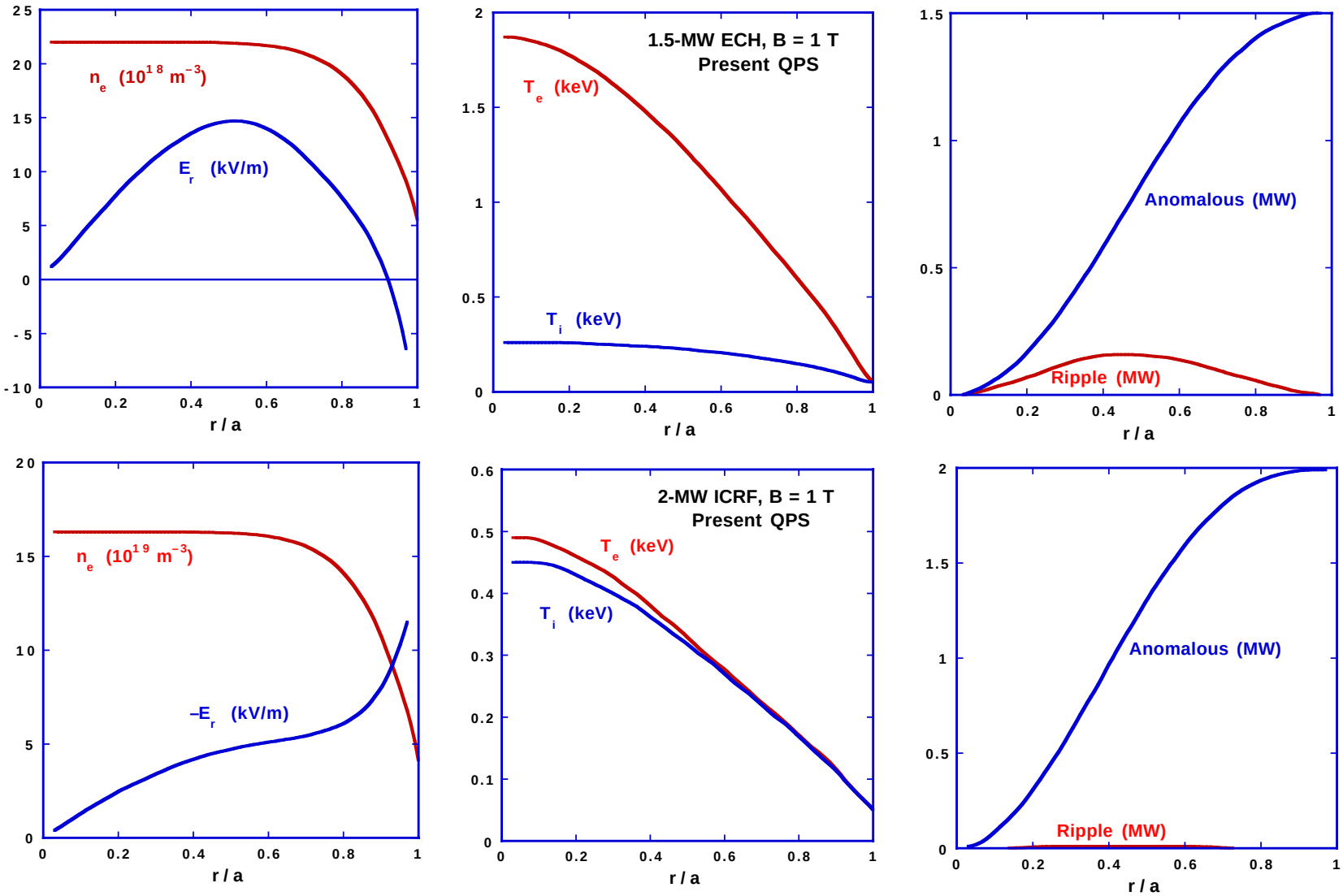
ISS-95 Confinement Dominates Neoclassical Confinement





PVR configuration shown here; the newer QPS configuration has very much improved neoclassical confinement

1-D Calculations Show Ripple-Induced Transport Small in *Optimized* QPS Plasma Configuration



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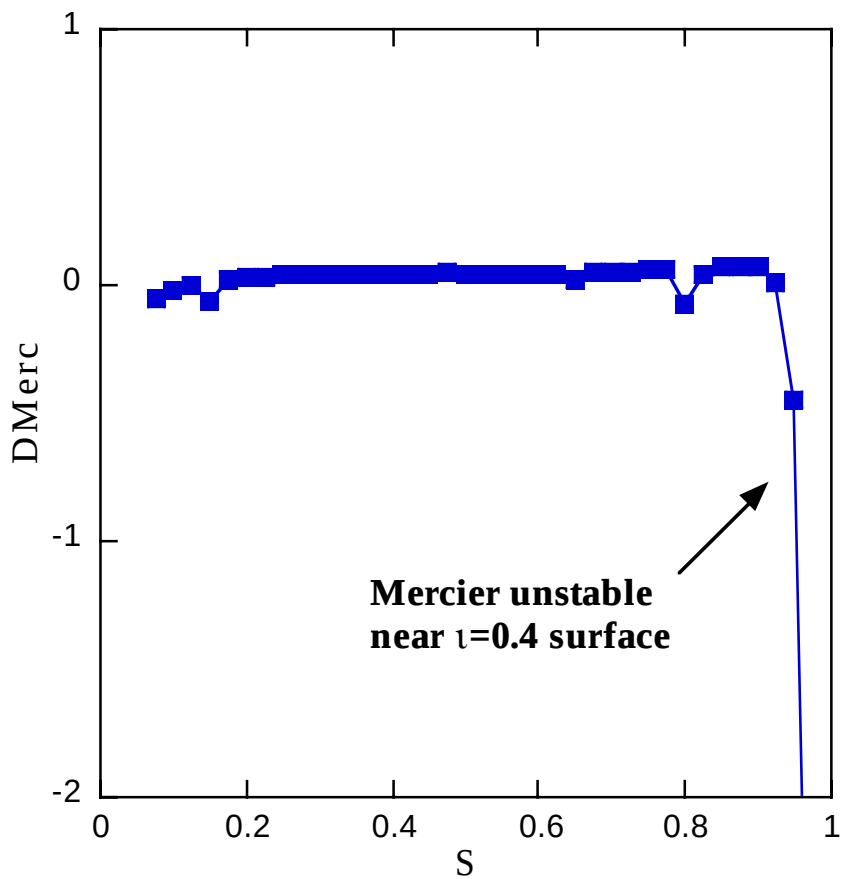
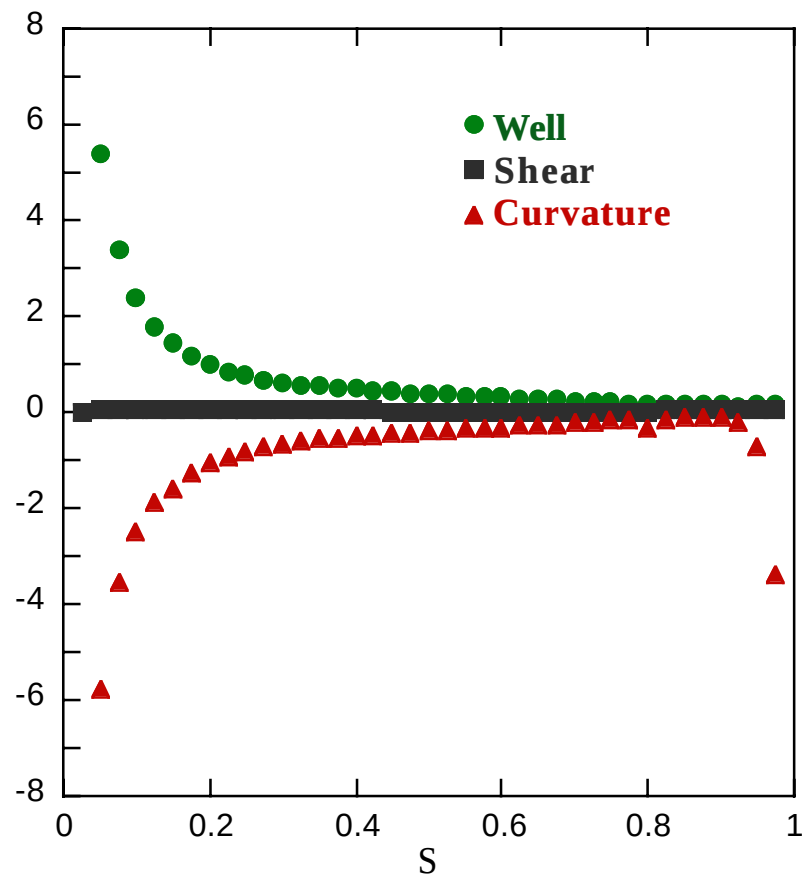
Mercier Stability: a Magnetic Well Provides Stability Except at Isolated Resonances

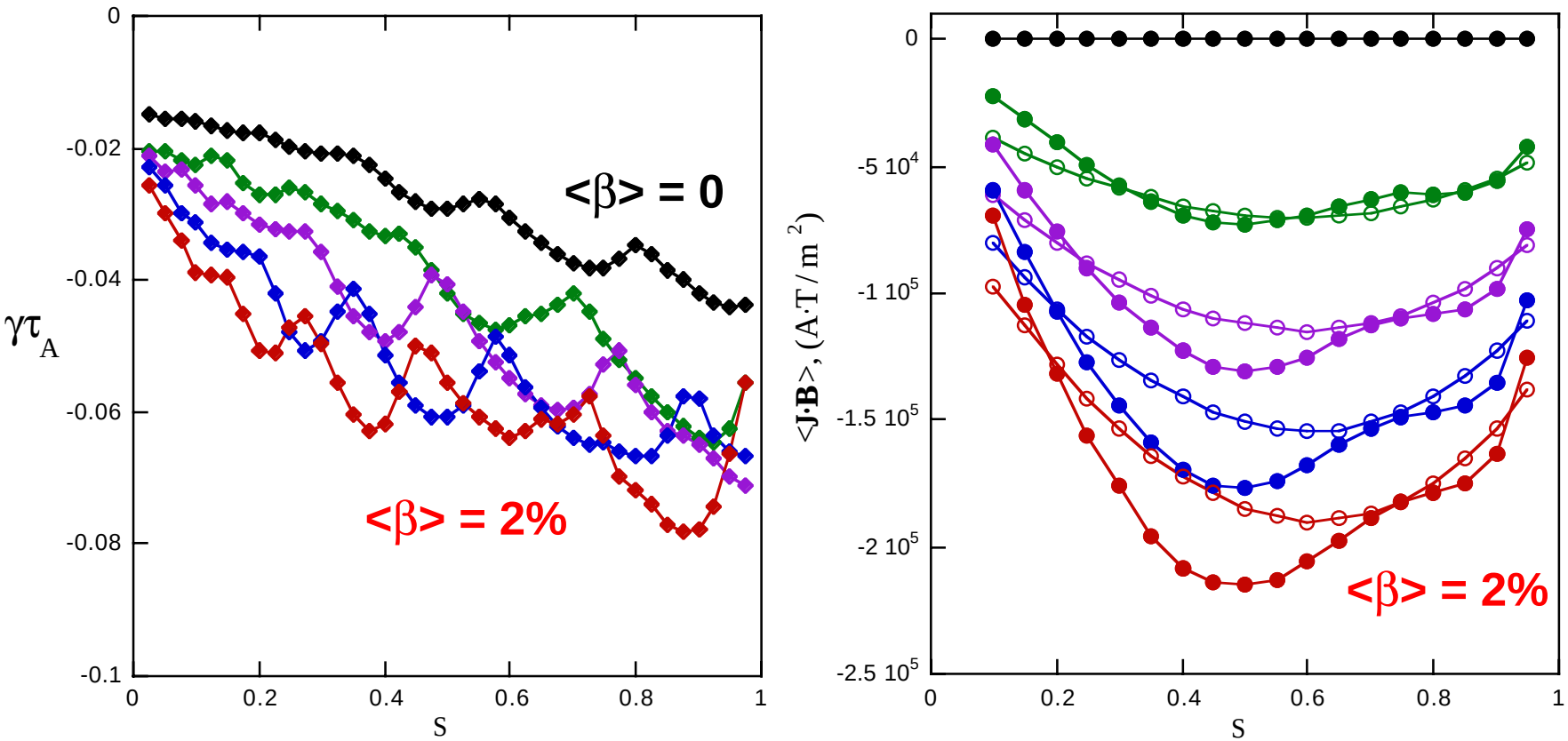
- Mercier stability criteria for fixed boundary at <β> = 2.5%
- However, these limits are exceeded in stellarator experiments





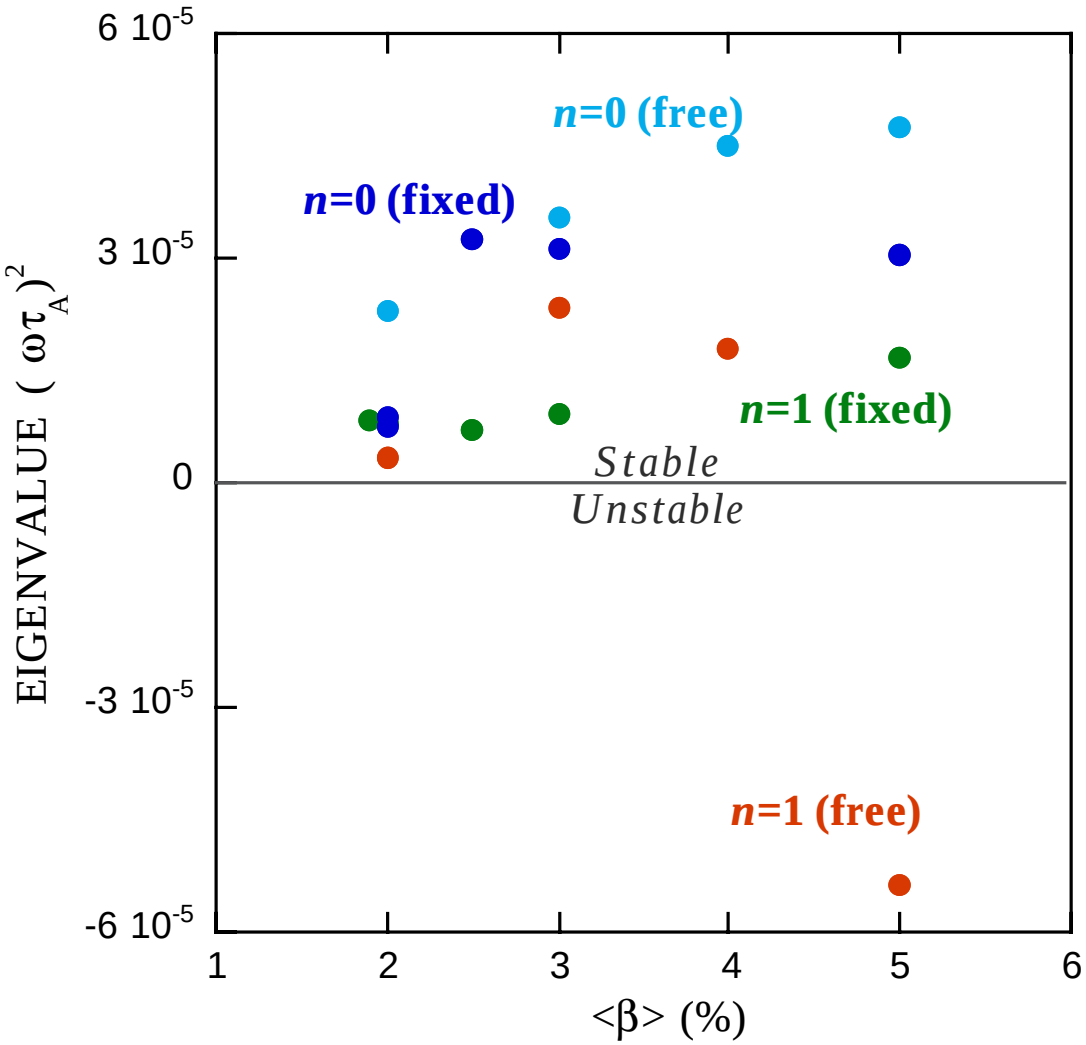
Ballooning Stability: Free Boundary Scan, Stable & Bootstrap Consistent to β = 2.3 %

- **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

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



- n = 0 and n = 1 eigenvalues

QPS Meets MHD Stability Goals

VMEC Equilibrium	Mercier Mode	High-n Ballooning Mode	External Kink/ Vertical Mode	Neoclassical Tearing Mode
Fixed Boundary	$\langle\beta\rangle$ > 2% [a]	$\langle\beta\rangle$ = 2.5%	$\langle\beta\rangle$ > 3%	stable [b]
Free Boundary	$\langle\beta\rangle$ > 2% [a]	$\langle\beta\rangle$ = 2.3%	$\langle\beta\rangle$ > 2%	stable [b]

(a) Stability from deep magnetic well, not shear; should be stable against resistive tearing modes

(b) $B \cdot j_{BS} \times \iota'/\iota > 0$

Experience in stellarators indicates that MHD stability is not a limiting factor

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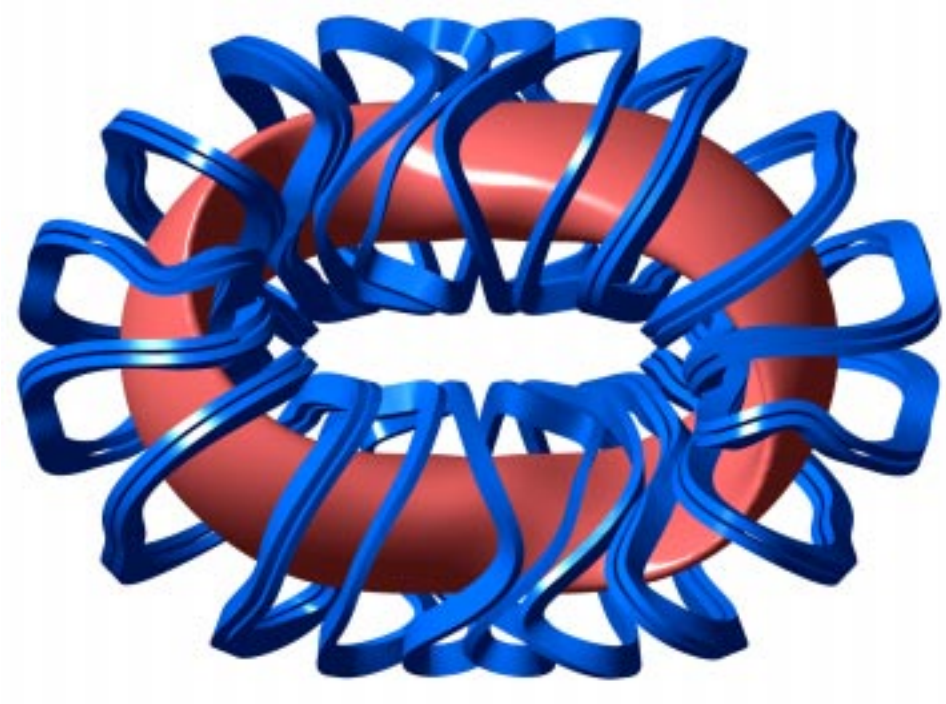
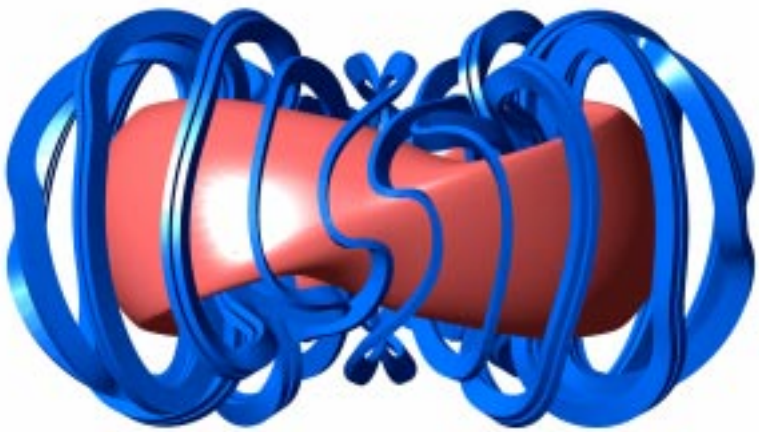
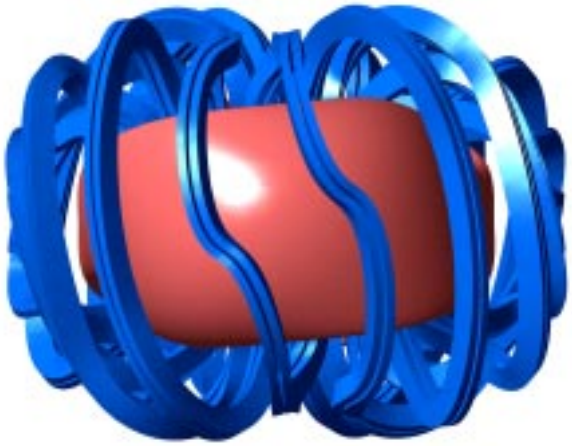
The QPS Modular Coil Set Has Been Optimized to Create the Desired Magnetic Configuration



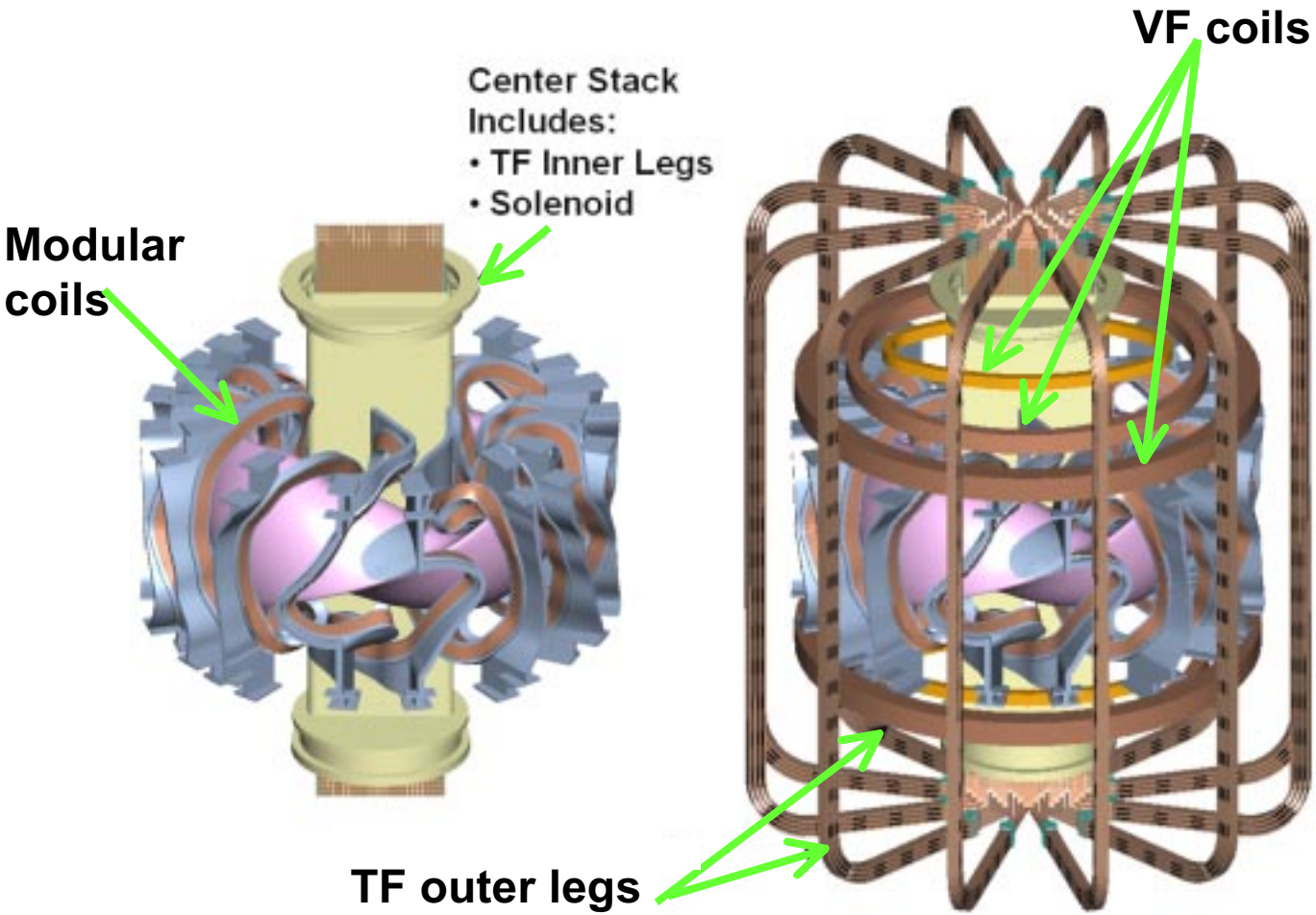


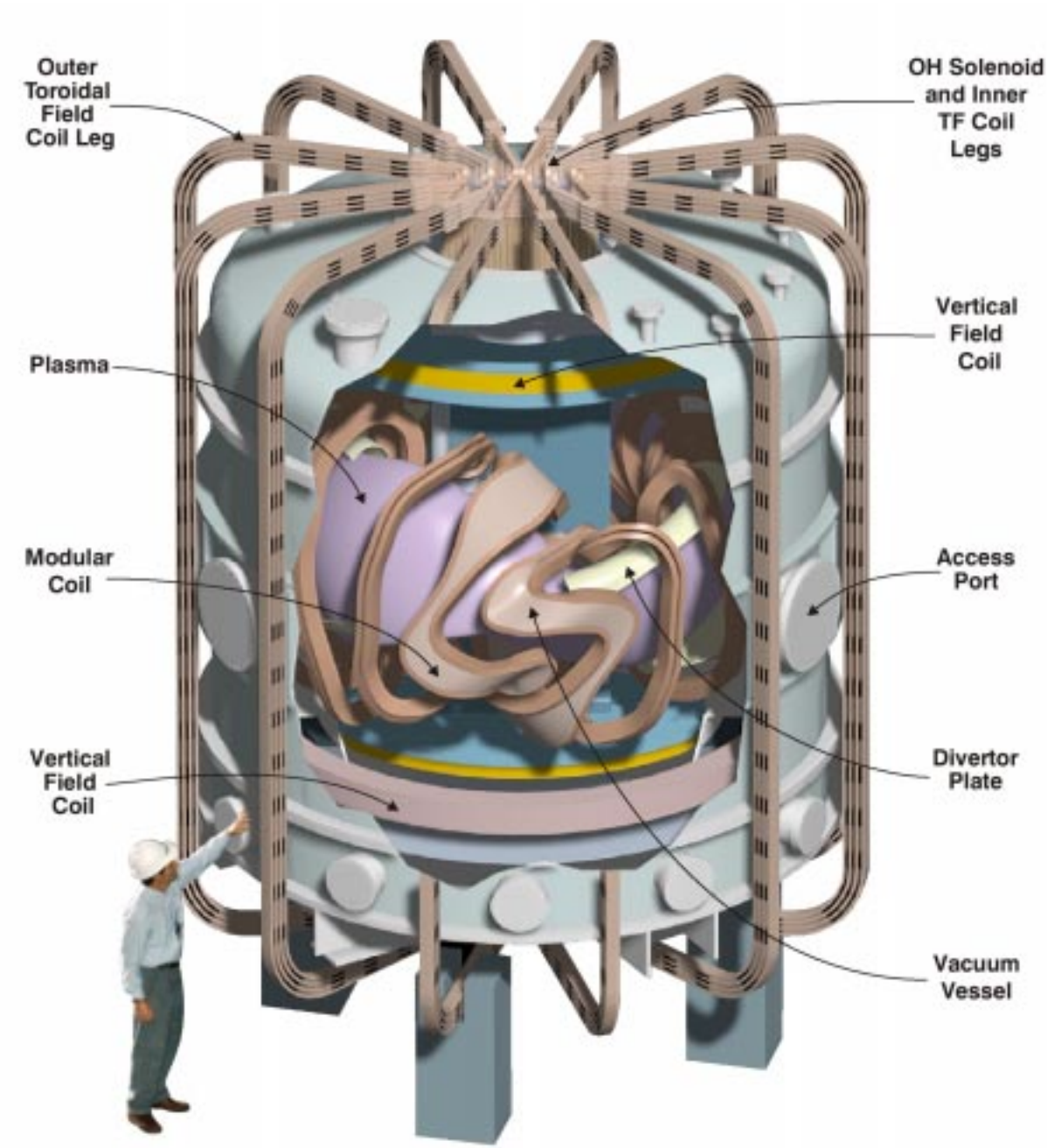


- 16 coils of 4 different types
- Adequate coil-coil spacing, plasma-coil spacing, minimum bend radius
- Good access between coils for heating and diagnostics
- Room in center for TF coil legs and OH solenoid

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





QPS

$\langle R \rangle = 0.9$ 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)

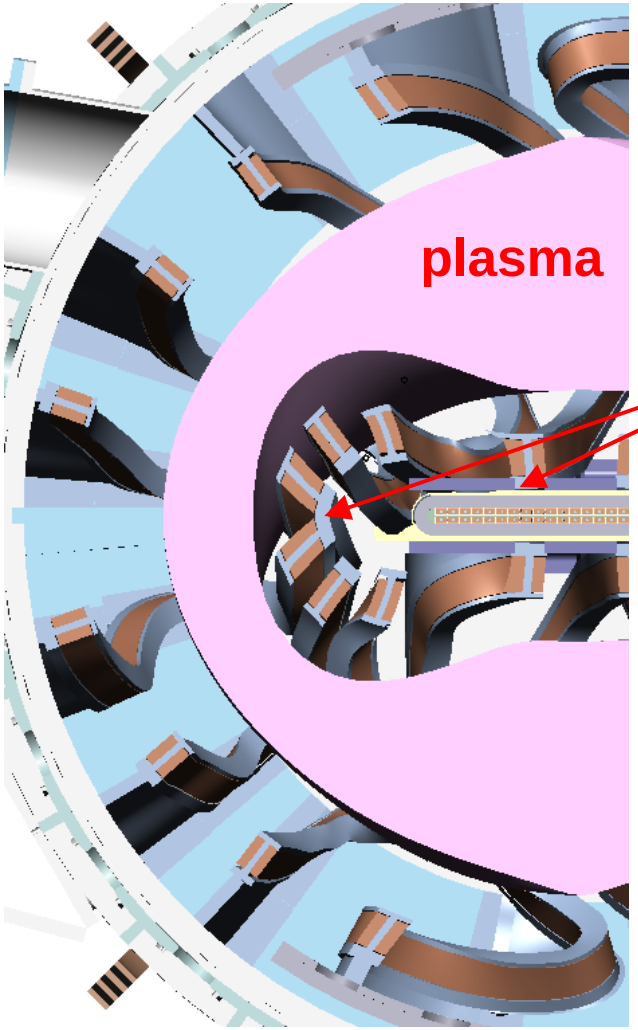
$B_T = \pm 0.2$ T

$I_p \leq 150$ kA

$P_{ECH} = 0.6$-1.2 MW

$P_{ICRF} = 1$-3 MW

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

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)***

Topics

- Rationale for QPS and compact stellarators in the US and world programs
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- The QPS experiment
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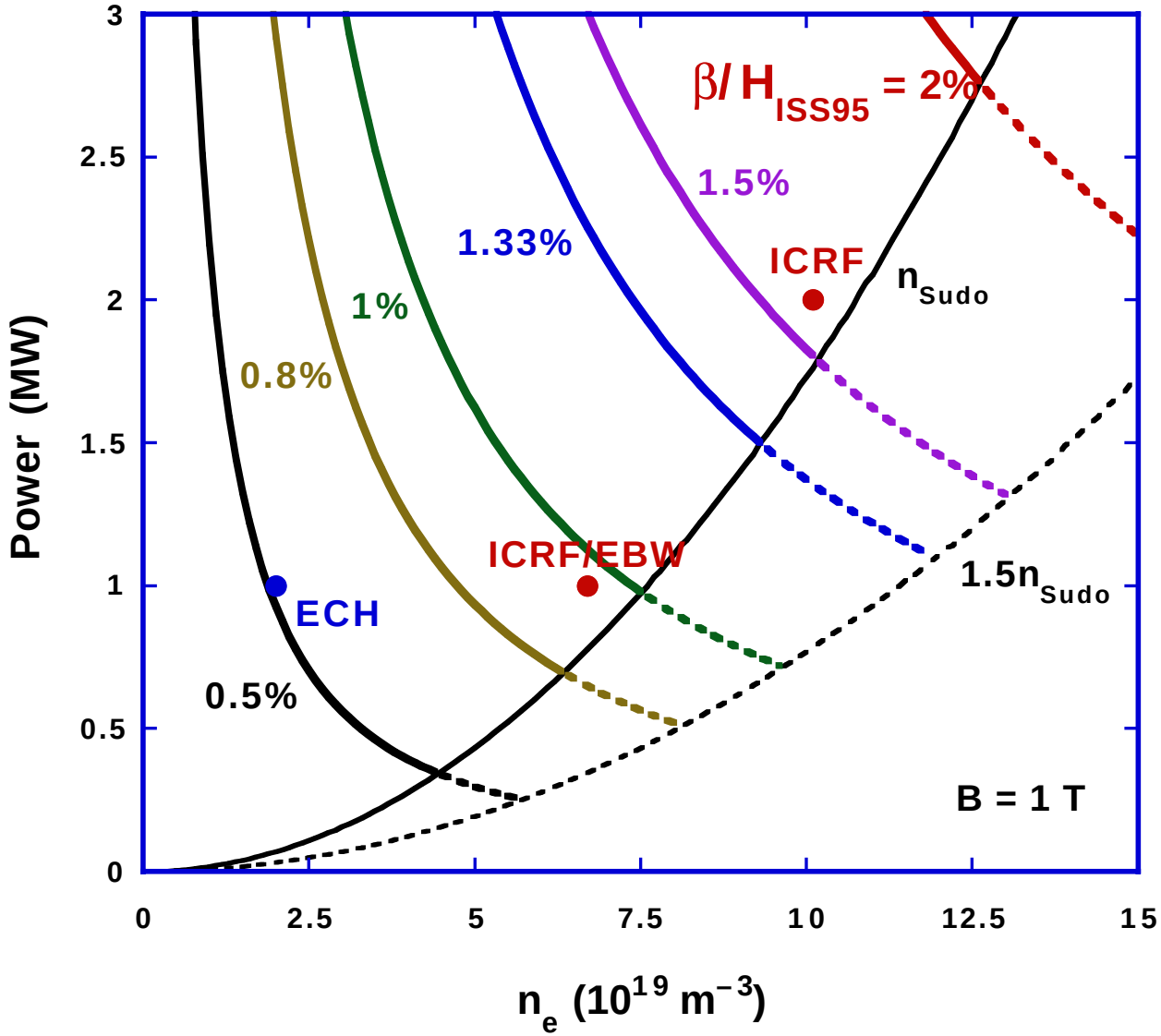
  - MHD equilibrium and stability
  - particle control
  - engineering design
  - **experimental objectives**
- High-beta reactor vision
- Plans

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



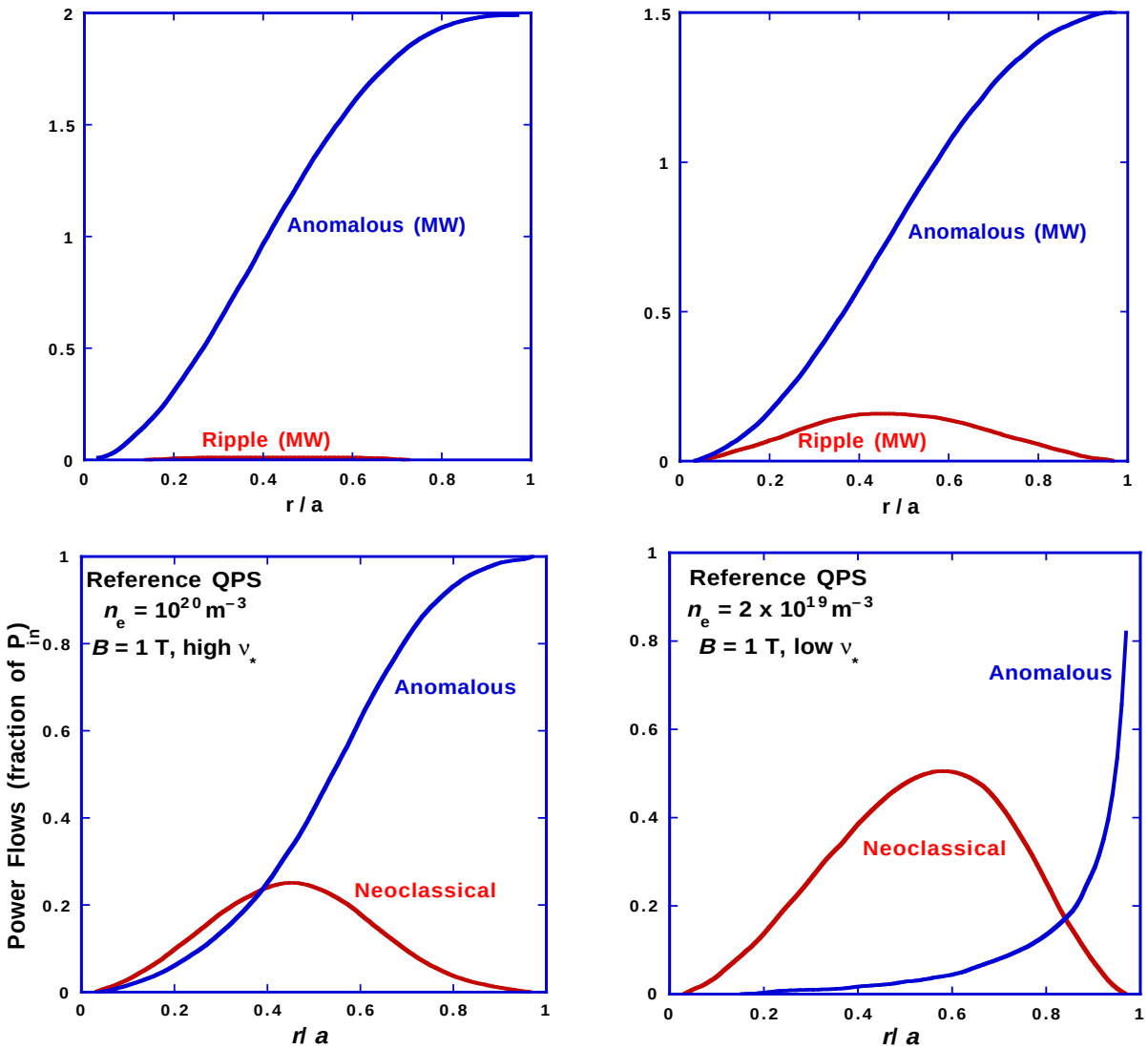
Multiply contour values by H_{ISS95} (= 1-2.5 in experiments)

QPS parameter space for *B* = 1 T

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

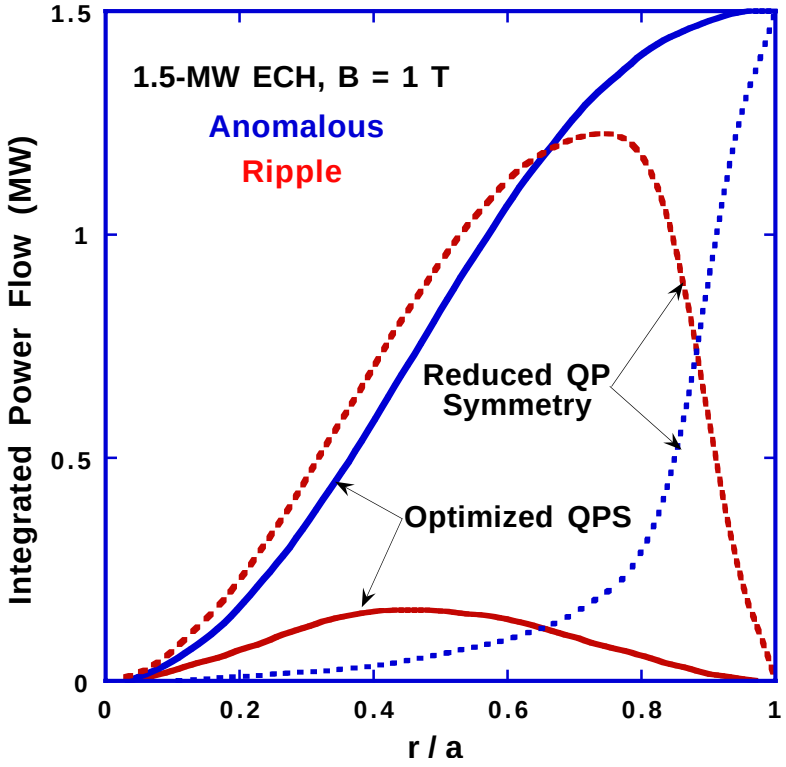
Anomalous and Neoclassical Loss Channels Can Be Separated through Choice of Density and Spoiling the Quasi-Poloidal Symmetry

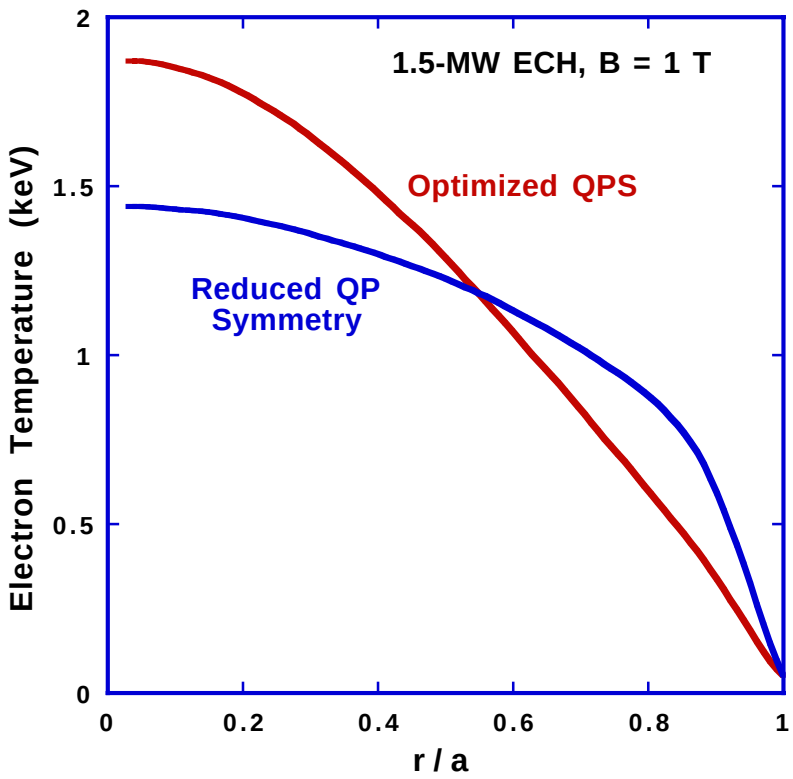


Optimized QPS configuration

QPS configuration with less quasi-poloidal symmetry

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





QPS Program Objectives

- **Extend confinement understanding to a new area**
  - **Extend study of anomalous transport, internal transport barriers, and flow shear to low-*R*/*a* configurations with quasi-poloidal symmetry**
  - **Study reduction of neoclassical transport due to near alignment of *B* and ∇B**
  - **Study impact of poloidal flows on enhanced confinement**
  - **Study equilibrium quality (islands, ergodic regions) and its repair at *R*/*a* ~ 2.7**
  - **Study robustness with β and dependence of the bootstrap current on magnetic configuration properties at low *R*/*a***
  - **Understand β limits and limiting mechanisms for quasi-poloidally symmetric configurations at very low *R*/*a***

QPS Program Objectives (cont.)

- **Explore physics not obtainable from very-high-R/a quasi-poloidal W 7-X or other experiments and theory**
  - **effect of strong toroidal coupling**
  - **significant bootstrap current in quasi-poloidal geometry**
  - **different neoclassical transport reduction mechanism**
- **Study fundamental issues common to low-β and high-β quasi-poloidal configurations**
  - **scaling of the bootstrap current with β**
  - **reduction of the H-mode power threshold**
  - **flux surface robustness as β increases due to reduced parallel bootstrap current**
  - **ballooning instability character and β limits**

QPS Diagnostic Plan

Resource/Phase	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Objective	**Commissioning**	**Vacuum configurations**	**Configuration characterization**	**Heating, confinement**	**Power, particle control**	**MHD limits**
Heating			**ECH 500 kW B = 0.5 T**	**ECH 1 MW B = 1.0 T**		**ECH + ICH 2 MW total**
CCD camera, H-alpha filter						
Fast diamagnetic loop						
2 mm interferometer						
Fluorescent screen/rods						
Soft X-ray arrays						
Spectroscopy						
Rogowski coils/magnetic loops						
Bolometers						
Probes						
Charge exchange						
YAG Thomson scattering						
Reflectometer						
Filtered CCD cameras						
Divertor probes						
IR camera						
Divertor bias plates						
Edge interferometer						
Heavy ion beam probe						
High frequency magnetic probes						
Fast X-ray array						
Vacuum surface quality						
Equilibrium, flux surface robustness						
Bootstrap current						
Power balance						
Transport						
MHD stability						
Plasma edge, divertor geometry						

Under discussion
Planned
Primary issue emphasis

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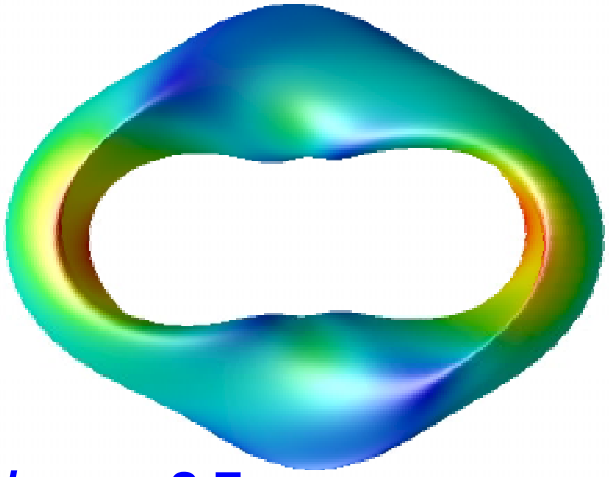
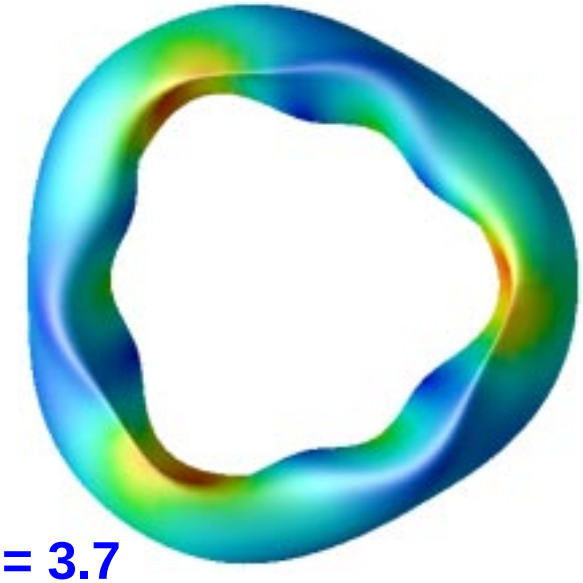
- **High-beta reactor vision**
- Plans

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%



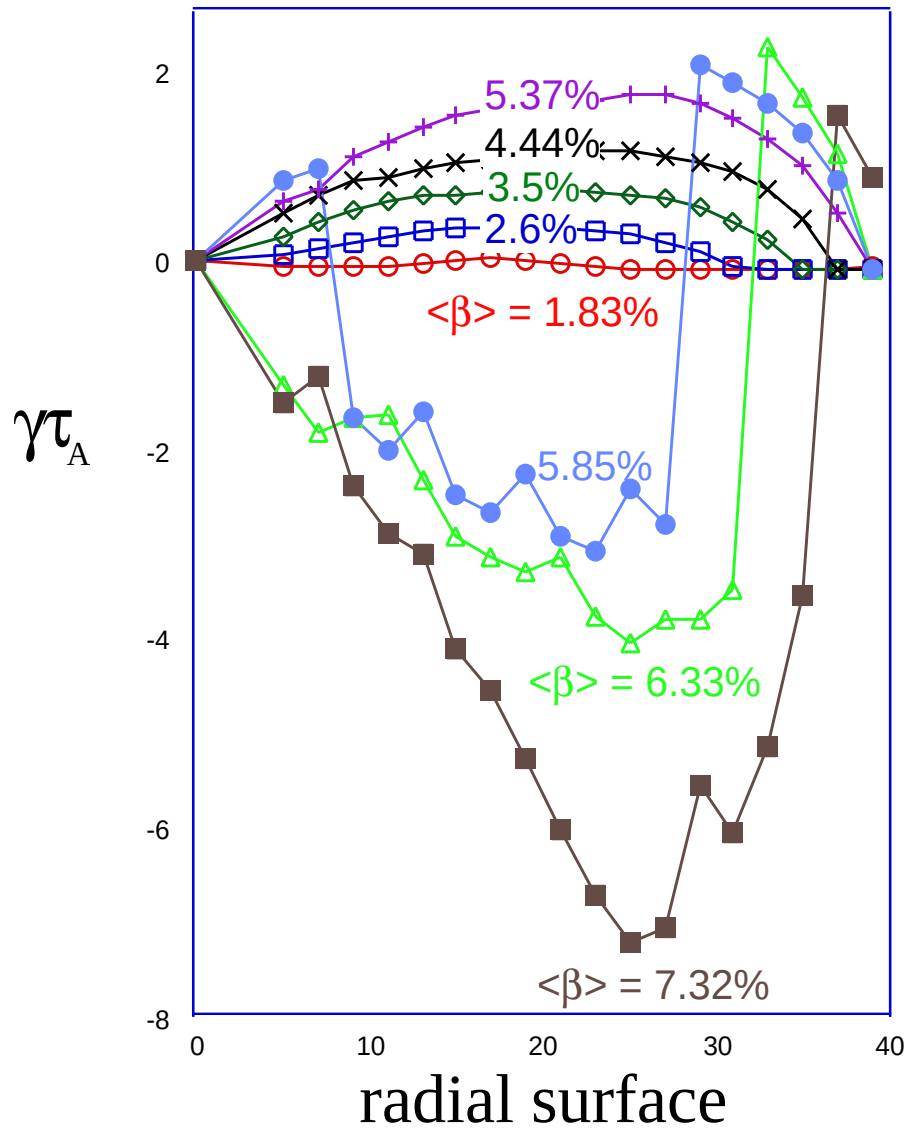
$\langle R\rangle/\langle a\rangle$ = 3.7
$\langle\beta\rangle_{limit}$ = 15%

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 $\Rightarrow$ configuration invariance with β**
- **MHD stability at $\langle\beta\rangle$ 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})**

Second Stability Regime Exists in QPS at Higher Beta



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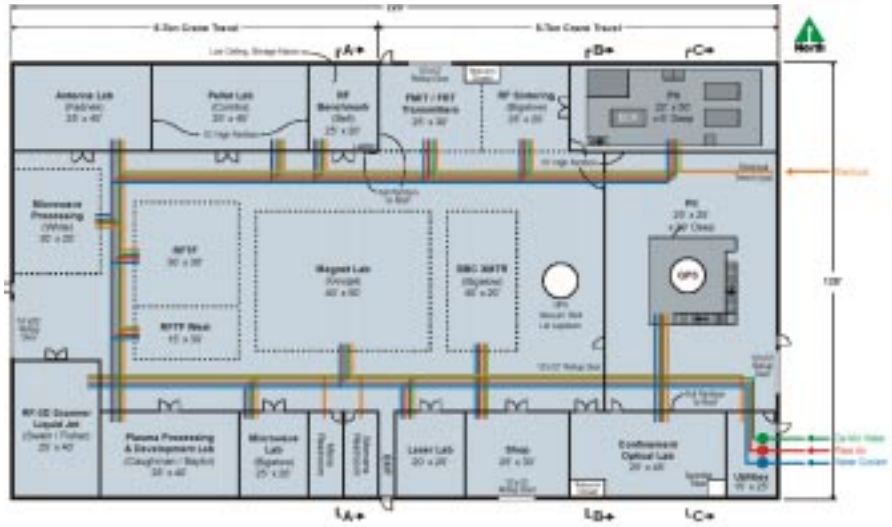
Status and Plans

- 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
- May 2002: Design, Cost & Schedule Review; Project Validation Review
- 2003-2007: R&D, design and construction
- March 2007: first plasma

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**

End view looking eastward



Technical Summary

- **A low-aspect-ratio QPS configuration has been designed 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**
- **The QPS coil set meets engineering constraints and reproduces the fixed-boundary physics**
- **QPS Experimental Program**
  - **adequate ECH/EBW and ICRF heating exists for QPS goals**
  - **staged program on broad topics with emphasis on low-*R*/*a* equilibrium/stability and confinement with appropriate diagnostics**

Programmatic 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**