QPS Physics Studies

J. F. Lyon, ORNL

for the QPS Team

General Atomics April 23, 2004

Multi-Institution QPS Team

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- ORNL/GA/Auburn collaboration on equilibrium reconstruction

Topics

- Stellarator Experiments & Quasi-symmetry
- The QPS Magnetic Configuration
- Configuration Flexibility
- Transport Studies & RF Heating
- MHD Equilibrium and Stability
- Project Schedule and Status

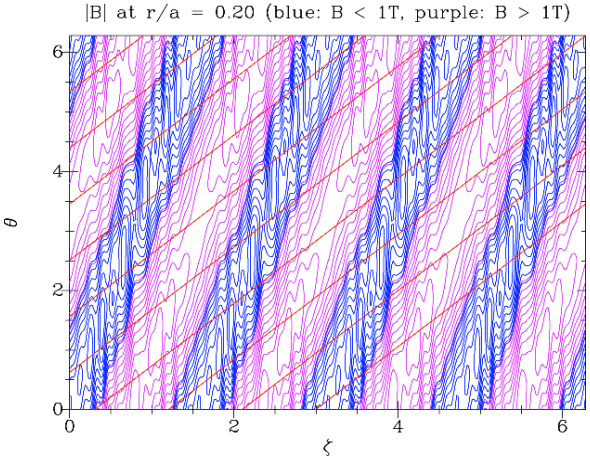
Direction of Stellarator Experiments

- **Extension of currentless stellarators to larger size, higher power, steady-state operation outside US**
  - Large-*R*/*a* (~12) modular stellarators: W 7-AS ==> W 7-X
  - Medium-*R*/*a* (~6) torsatrons: CHS ==> LHD
- **US exploiting quasi-symmetry and the bootstrap current for compactness**
  - low-*R*/*a* (4.4) quasi-toroidal (tokamak-like) symmetry: NCSX
  - very-low-*R*/*a* (2.7) quasi-poloidal (linked mirror) symmetry: QPS
- **Optimization of compact systems is difficult: helical/toroidal/mirror effects tightly coupled**
  - a solution is to produce some fraction of the rotational transform ($\iota = 1/q$) from plasma (bootstrap) current
  - less kinky coils, less demand on shaping to produce transform

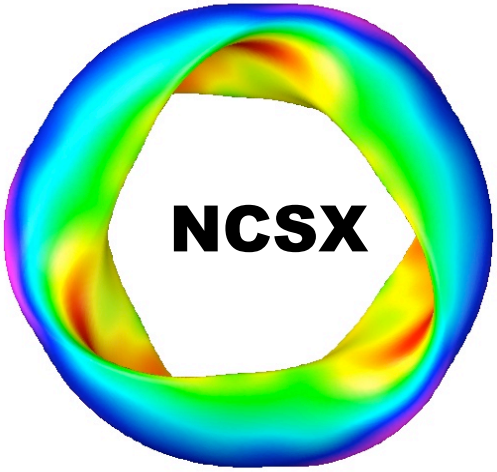
3 Possible Forms of Quasi-Symmetry

***R/a* = 8**

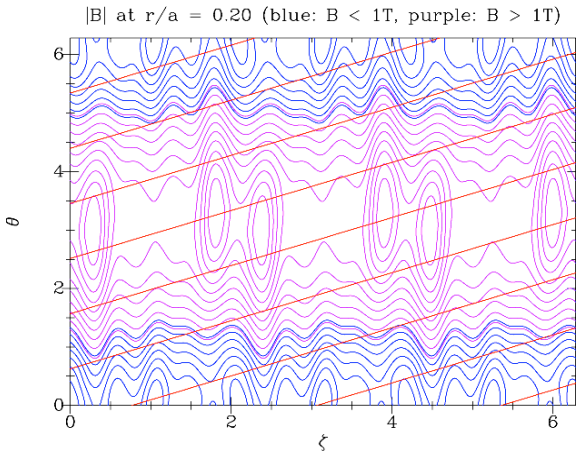
Univ. of Wisconsin



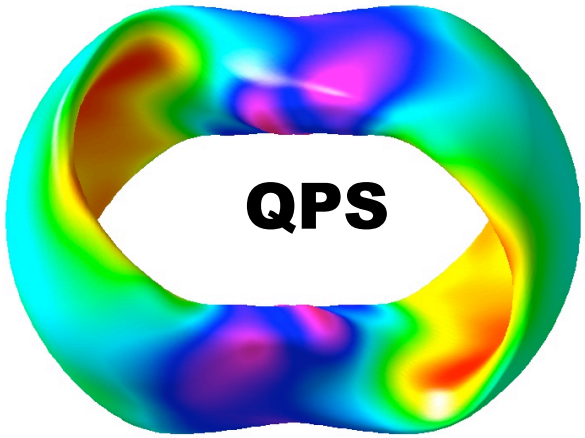
***R/a* = 4.4**



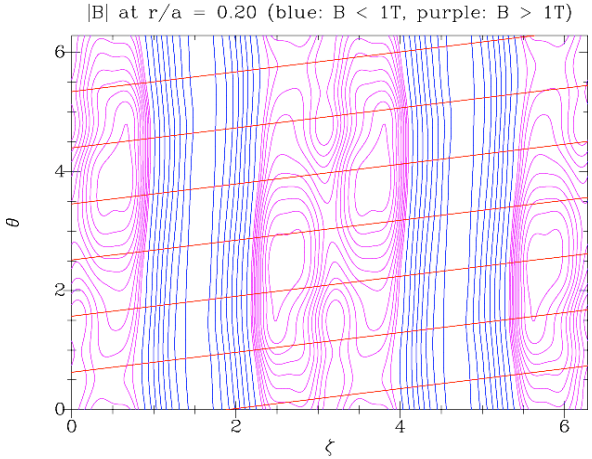
Princeton Plasma Physics Lab.



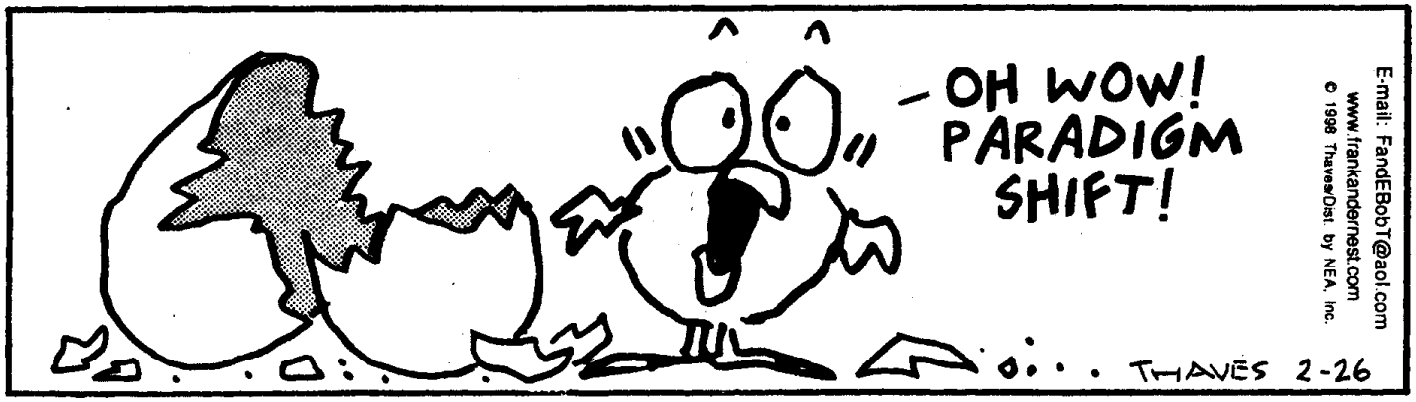
***R/a* = 2.7**



Oak Ridge National Lab.



Quasi-Poloidal Symmetry

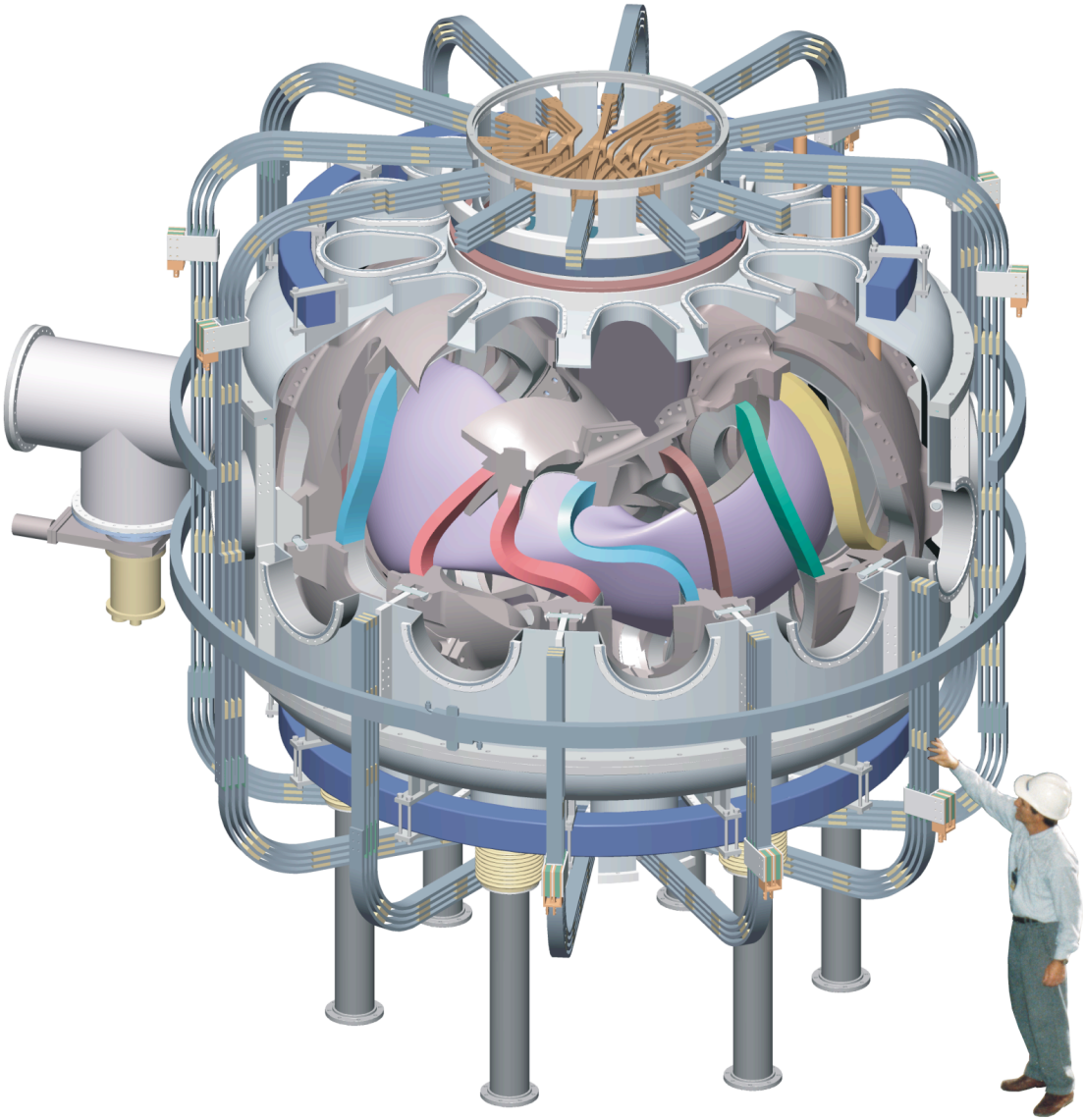


- **Most experiments rely on toroidal symmetry**
  - **tokamaks, spherical torus, RFPs, NCSX**
- **QPS is the only experiment that relies on poloidal symmetry**
  - **has a closer connection to toroidally linked mirrors**
- **It will explore a new physics regime using quasi-poloidal symmetry at very low aspect ratio**
  - **very low damping for poloidal flows: improved confinement?**
  - **reduced neoclassical transport, bootstrap current, sensitivity to β, second stability threshold**

QPS Program

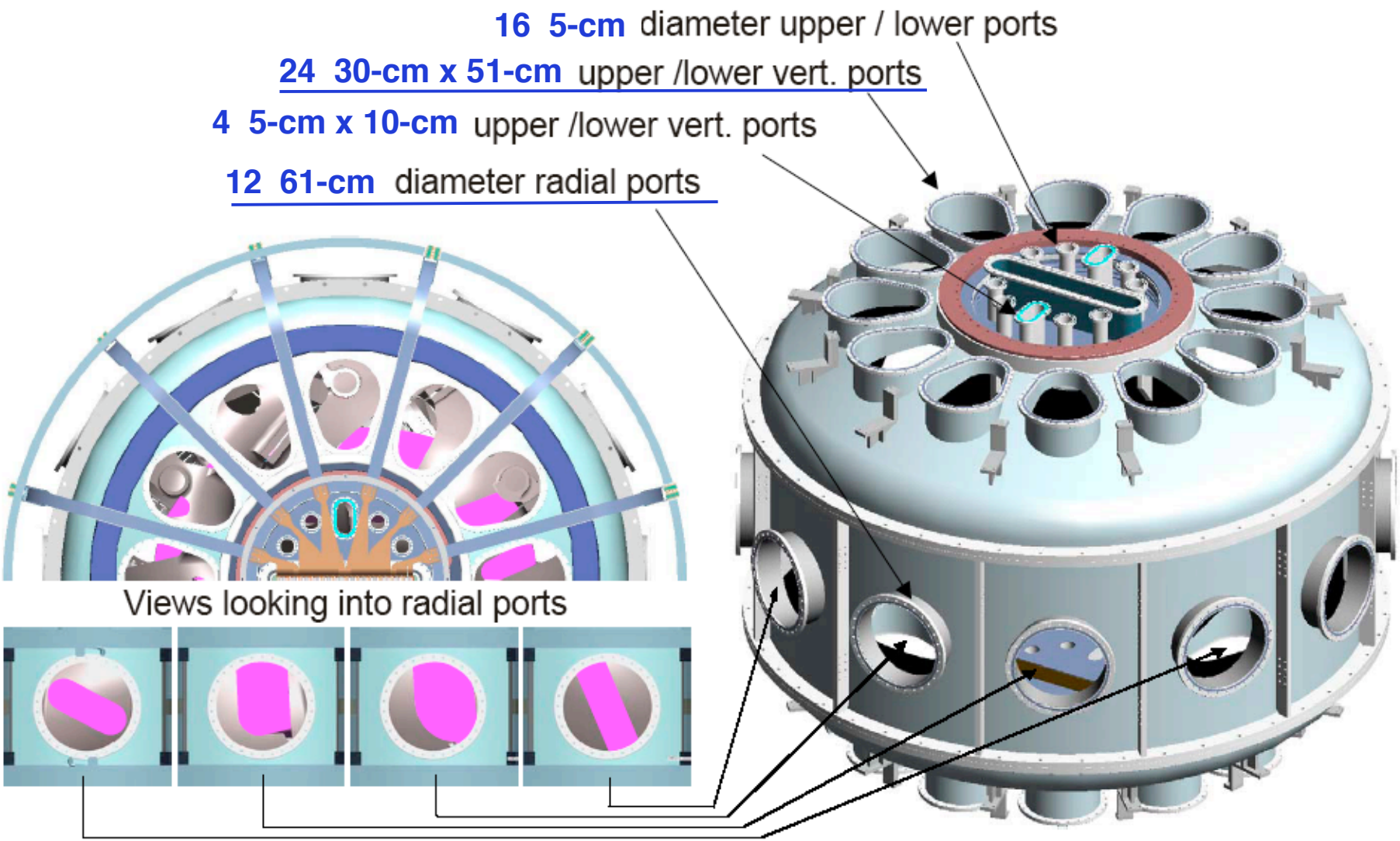
- **Main focus of the QPS program is use of quasi-poloidal geometry to explore toroidal physics issues at low *R/a***
  - **flux surface robustness at *R/a* > 2.5 and sensitivity to β with strong toroidal/helical coupling**
  - **reduction of neoclassical and anomalous transport**
  - **variation of effective ripple, trapped particle fraction, stellarator or tokamak shear, quasi-poloidal symmetry, poloidal viscosity and poloidal flow shear, ambipolar electric field & internal transport barriers, bootstrap vs. Ohmic current, magnetic island size, magnetic beach ICRF and EBW heating**
- **A secondary component is study of β limits and the character of MHD instabilities**
- **Benchmarking and improvement of 3-D theory**

The Quasi-Poloidal Stellarator -- QPS

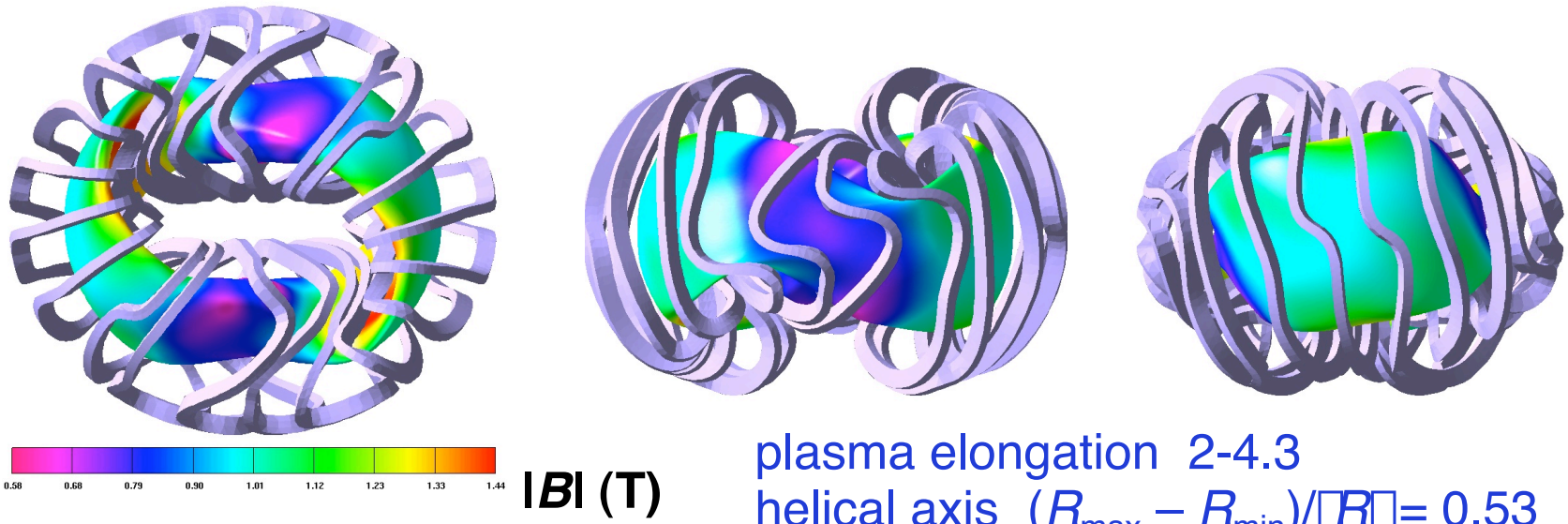


- $\langle R_{pl} \rangle$ = 0.95–1 m
- $\langle a_{pl} \rangle$ = 0.3–0.4 m
- V_{pl} = 2–3 m^3
- B_{mod} = 1 T (1.5 s)
- B_T = ± 0.15 T
- I_{plasma} < 50 kA
- 1-2 MW ECH/EBW
- 2-3.5 MW ICRF

QPS Has Excellent Diagnostic Access



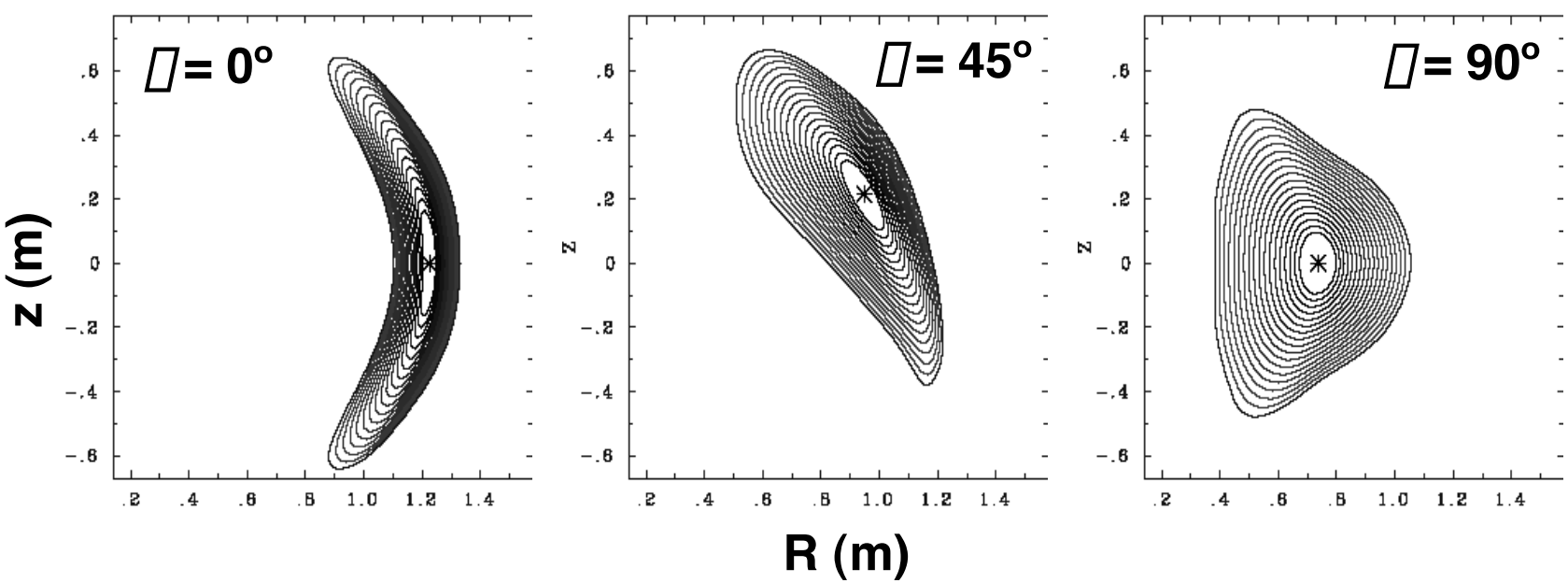
QPS Plasma and Coil Geometry



plasma elongation 2-4.3

helical axis $(R_{max} - R_{min})/\langle R \rangle = 0.53$

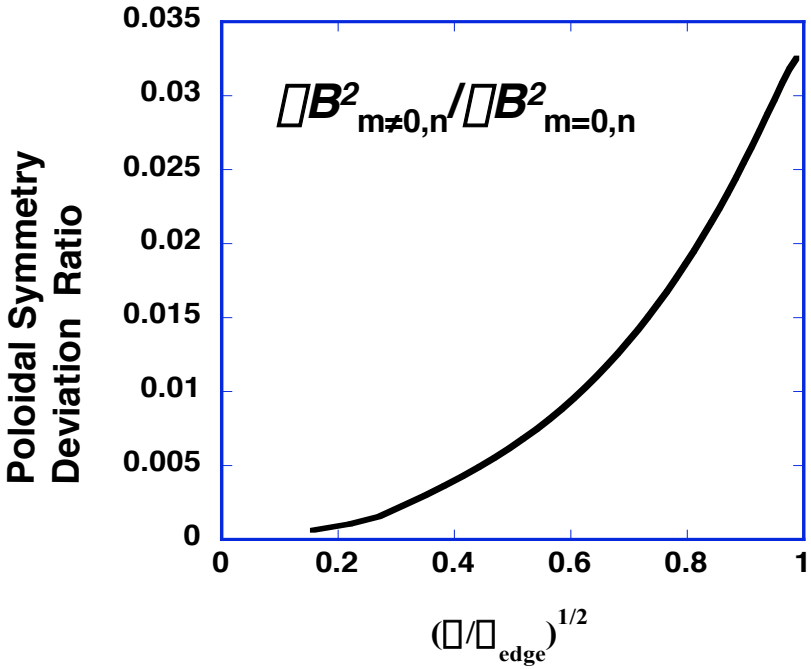
$(z_{max} - z_{min})/\langle R \rangle = 0.45$

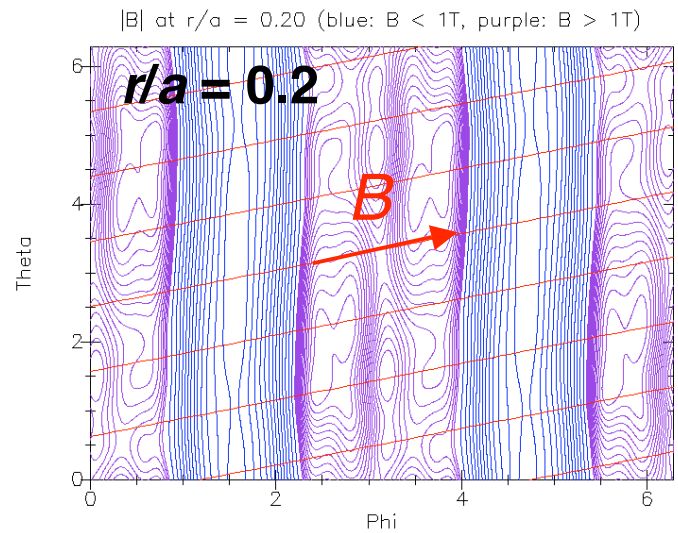


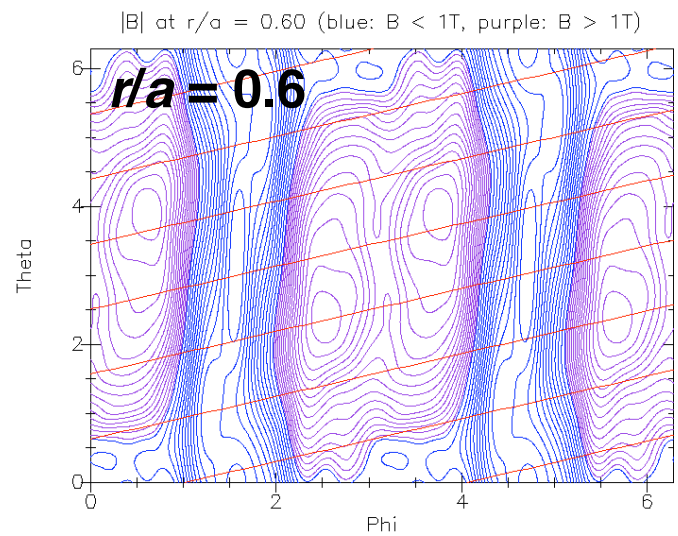
Quasi-Poloidal Symmetry

- $|B| = \sum B_{mn}(\psi) \cos(m\theta - n\zeta)$; m = 0 for poloidal symmetry

  ψ, θ and ζ in Boozer (field line) coordinates ==> circular torus



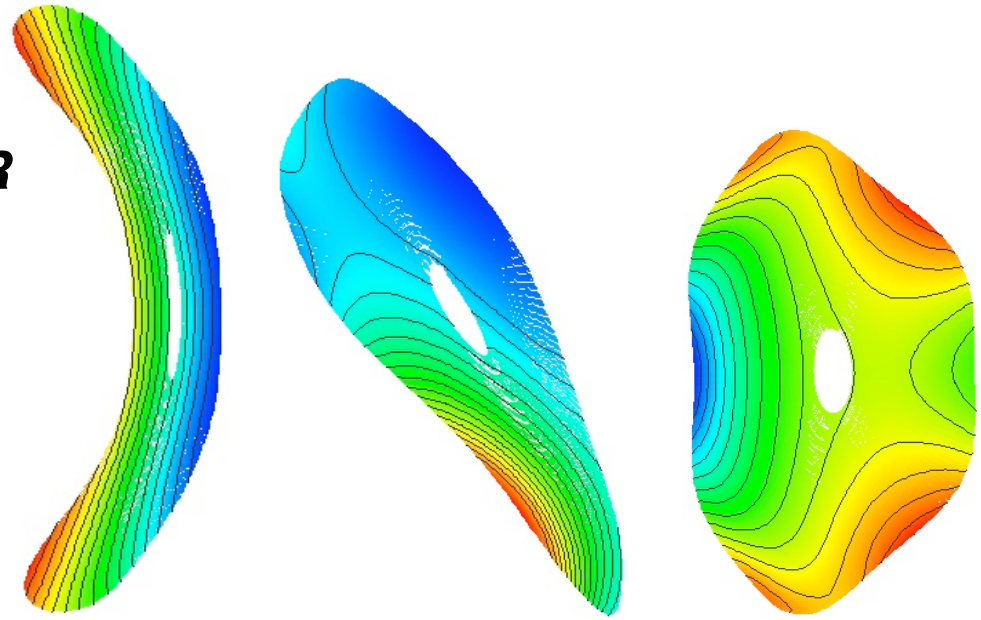




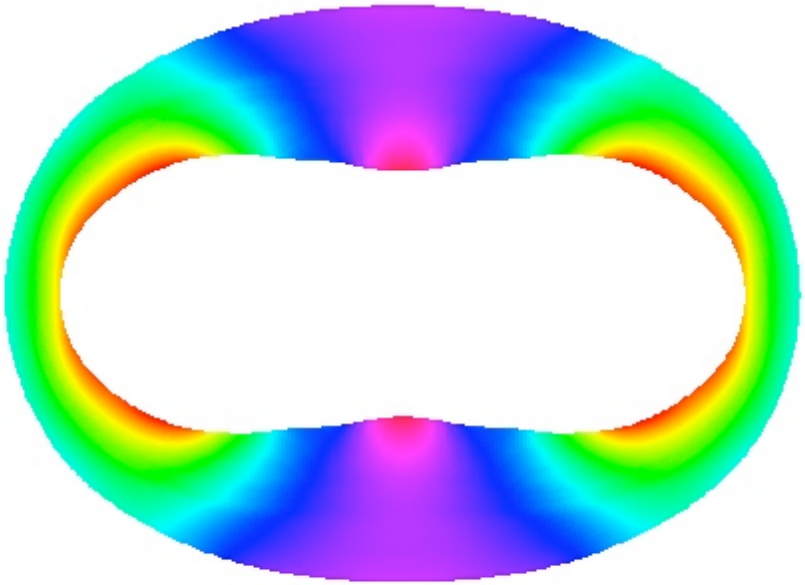
- **Electron beam mapping measures flux surface topology and deviation from QP symmetry**

QPS |B| Geometry at $\langle\beta\rangle$ = 2%

- |B| contours vary from 1/*R* (tokamak-like) in bean-shaped section to quadrupolar in the D-shaped section
  - blue low B, red high B

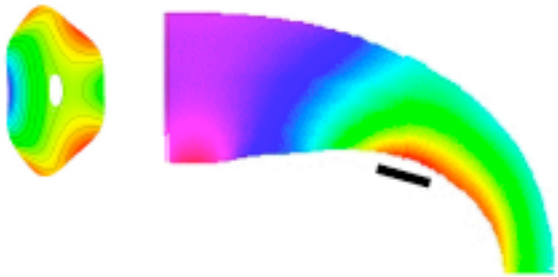


- Cut in midplane illustrates 2:1 mirror ratio
  - magenta low B, red high B



Configuration-Dependent RF Heating

ICRF propagates to
lower field "beach" region

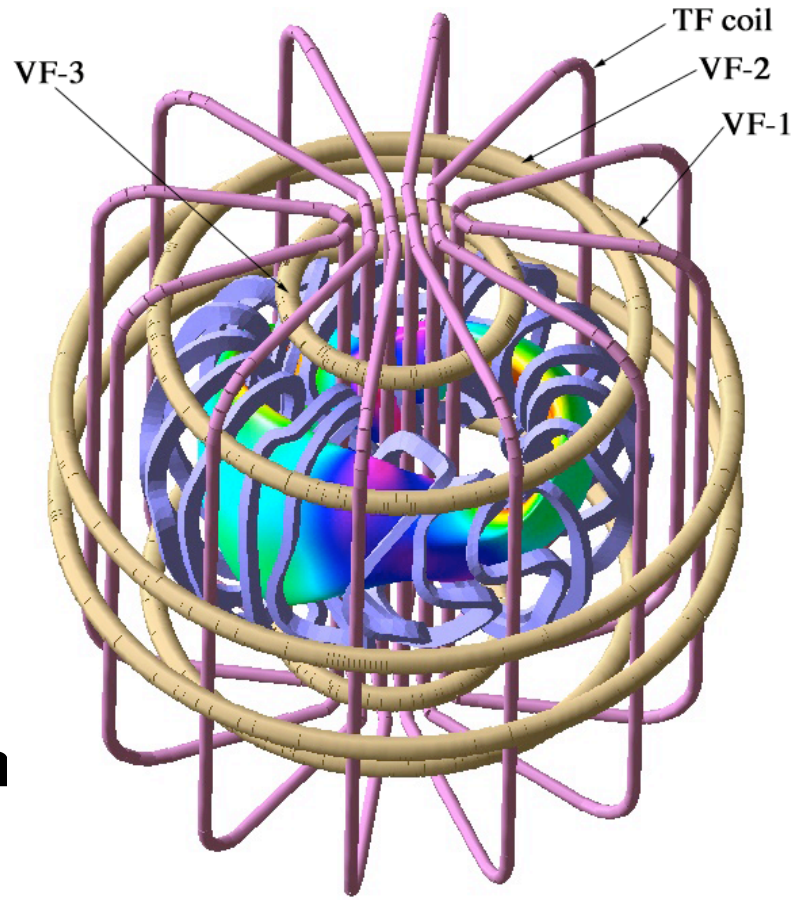


- **Exploration of magnetic beach heating**
  - IBI varies toroidally in QPS, similar to that in a toroidally linked mirror geometry
  - the mirror ratio can be varied for exploration of magnetic beach heating
- **Electron Bernstein wave heating**
  - ECH can transition directly to EBW in stellarator plasmas; no cutoff density gap
  - QPS can explore the physics of this transition at high power

Configuration Flexibility

QPS Allows Wide Variation in Plasma Properties

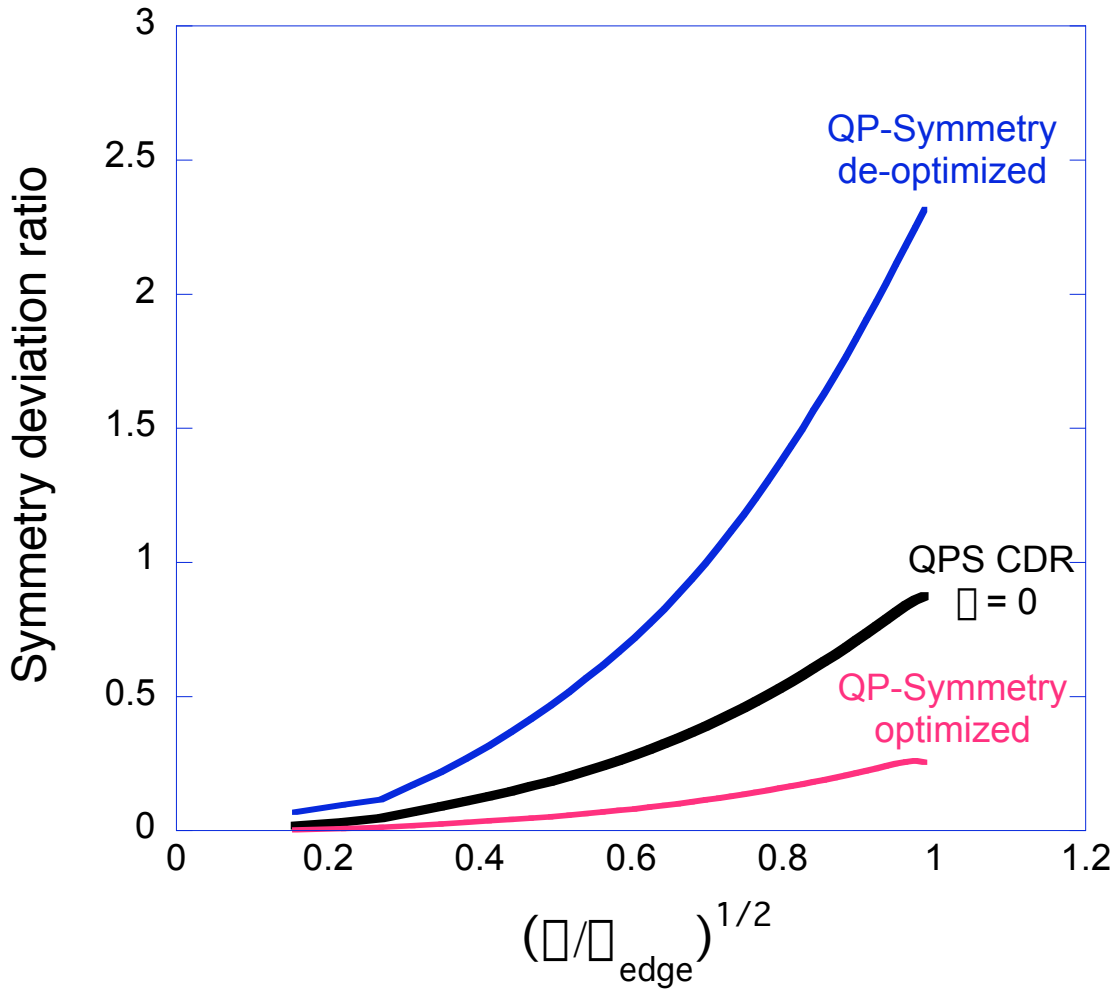
- **9 independent coil currents allow varying amount of**
  - **rotational transform (1/*q*)**
  - **stellarator or tokamak shear**
  - **helical axis excursion**
  - **magnetic field ripple**
  - **toroidal mirror ratio**
  - **helical vs. toroidal field components**
  - **plasma aspect ratio**
  - **ellipticity and triangularity**



- **This allows large variation in**
  - **neoclassical heat diffusivity**
  - **degree of quasi-poloidal symmetry**
  - **poloidal viscosity and flow damping**
  - **β limits**

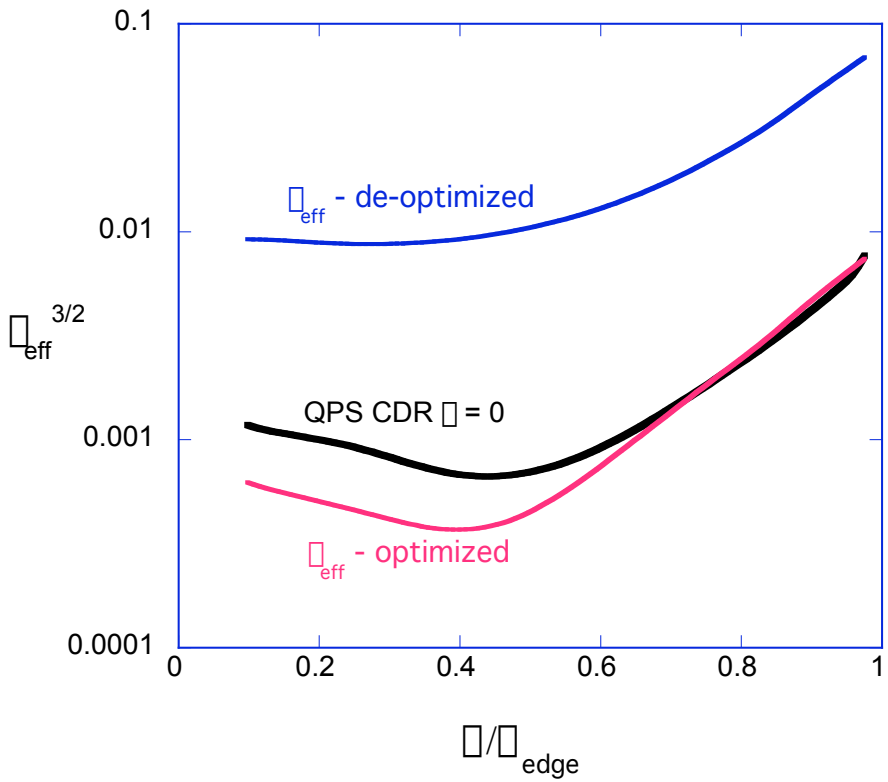
Variation in Quasi-Poloidal Symmetry

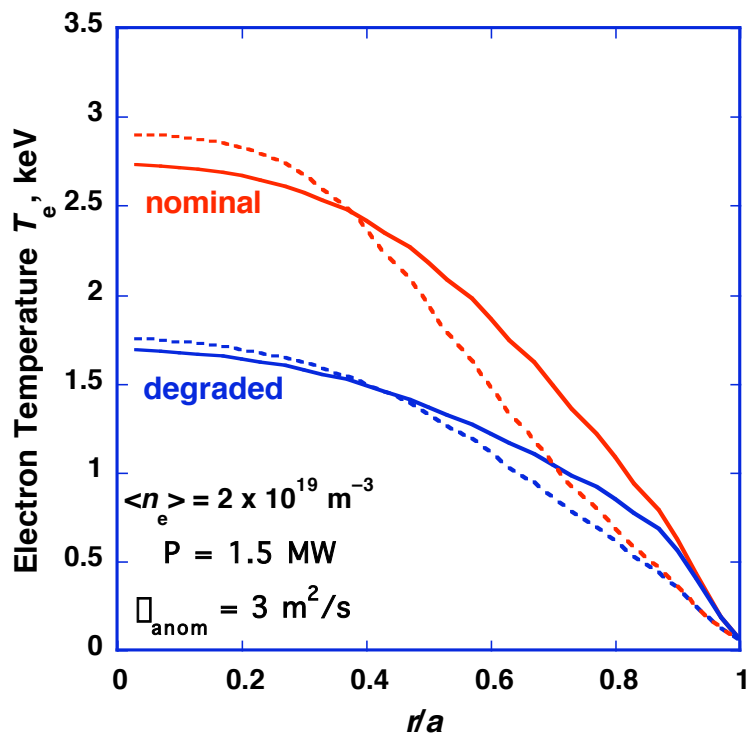
- **Changes in coil currents allow a factor ~10 variation in the deviation from quasi-poloidal symmetry**



Variation in Neoclassical Transport

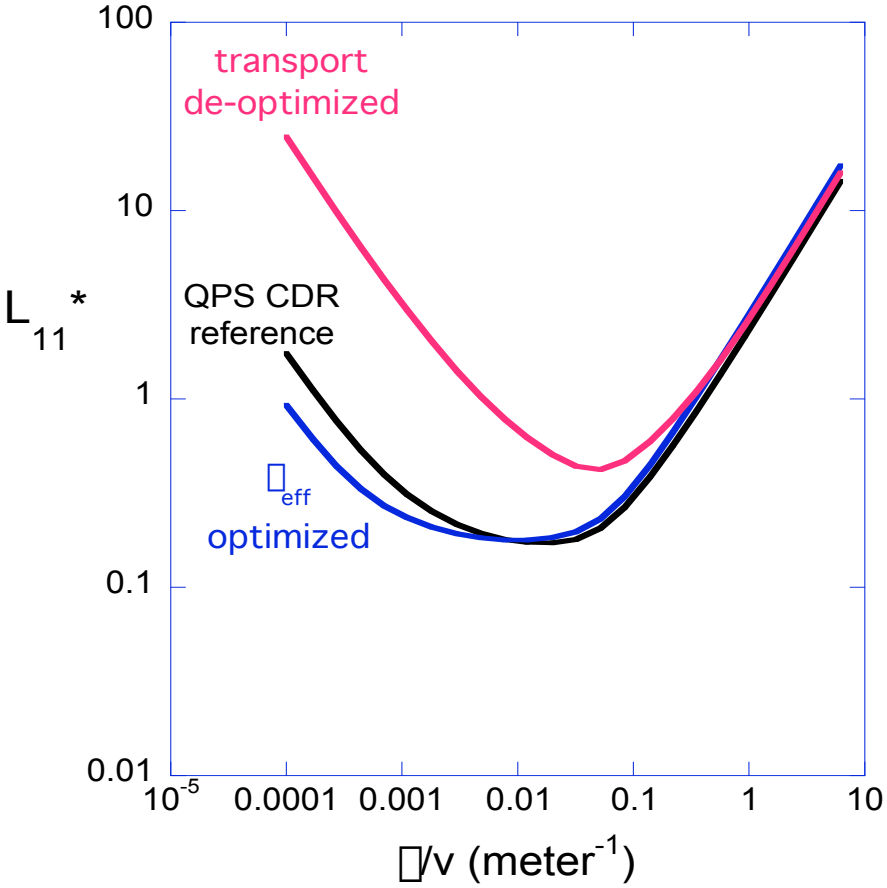
- **Changes in coil currents allow a factor ~25 variation in neoclassical χ ($\varepsilon_{eff}^{3/2}$)**
- **Produces a measurable difference in $T_e(r)$**

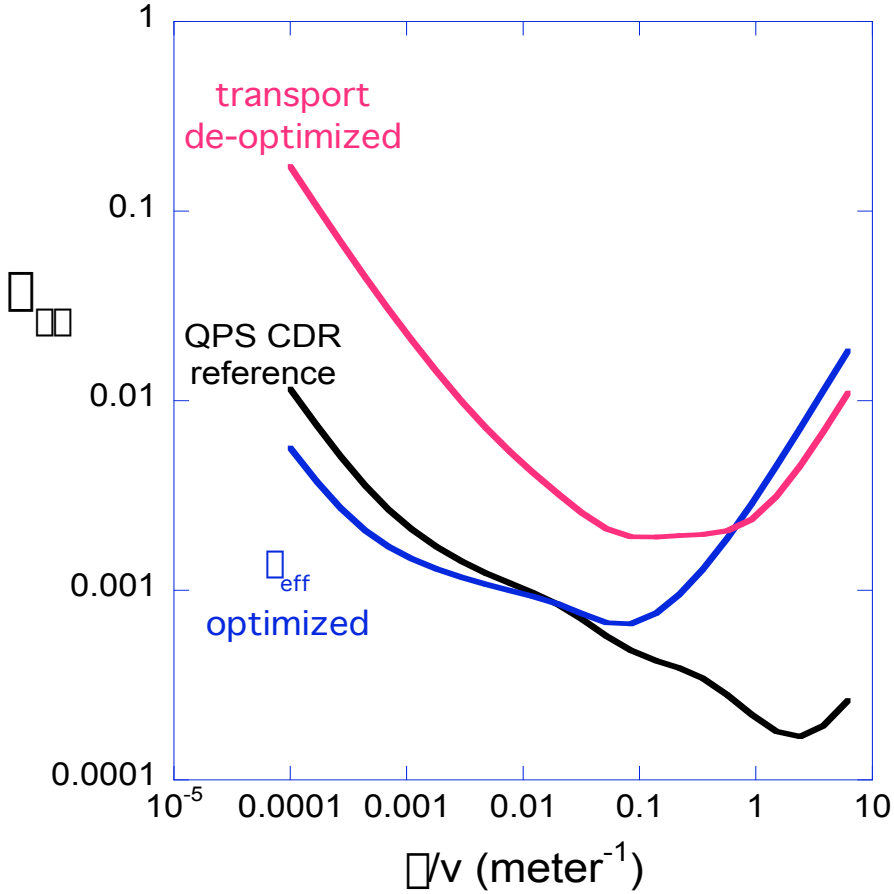




D. Mikkelsen

Factors of ~25 Variation in Transport and 5-30 Variation in Poloidal Viscosities for □≤□ Plateau Regime



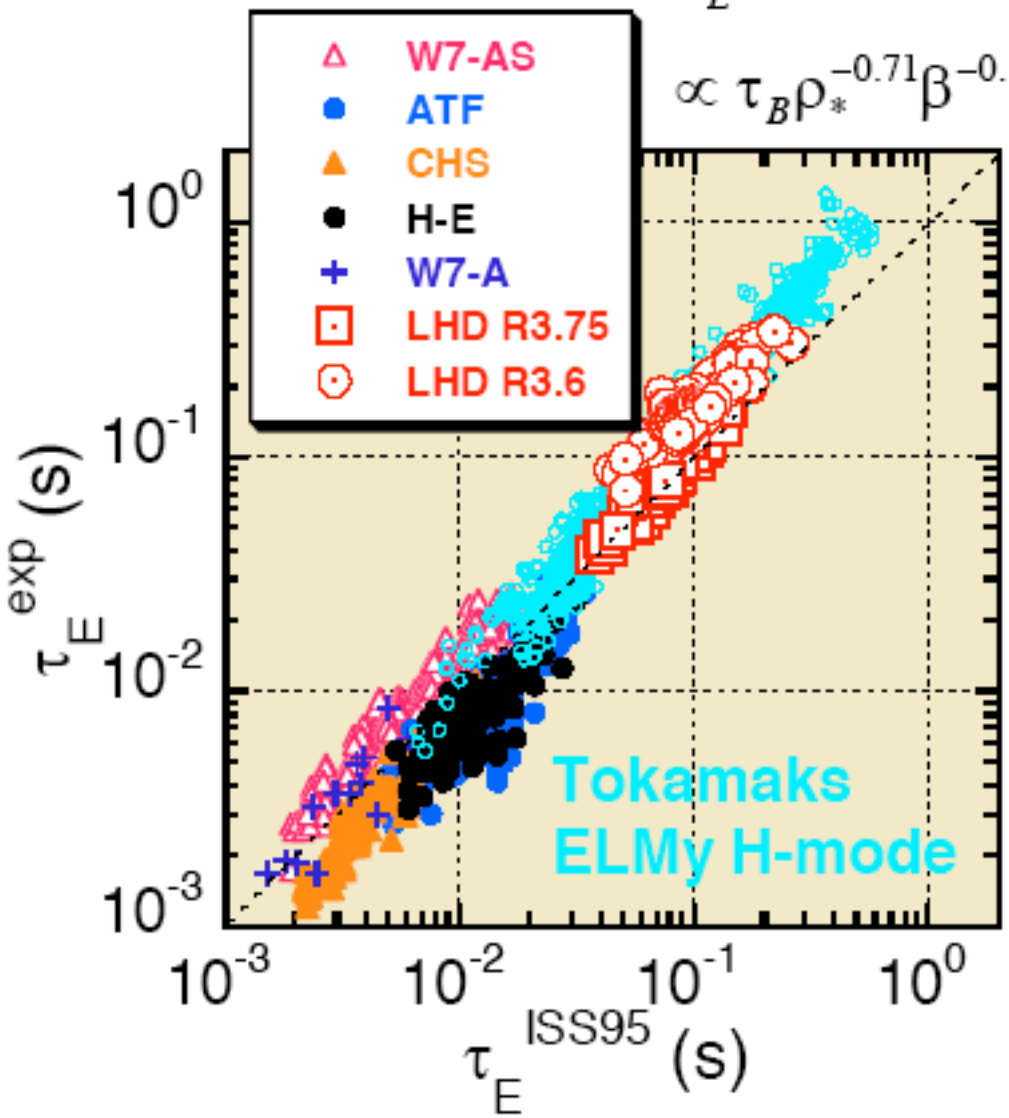


Transport Studies

Confinement Comparable to ELMy H-Mode

$$\tau_E^{ISS95} = 0.26 B^{0.80} P^{-0.59} \overline{n}_e^{0.51} R^{0.65} a^{2.21} q_{2/3}^{-0.40}$$

$$\propto \tau_B \rho_*^{-0.71} \beta^{-0.16} \nu_*^{-0.04}$$



Want to keep 1/□ neoclassical transport low and to reduce anomalous transport

H. Yamada

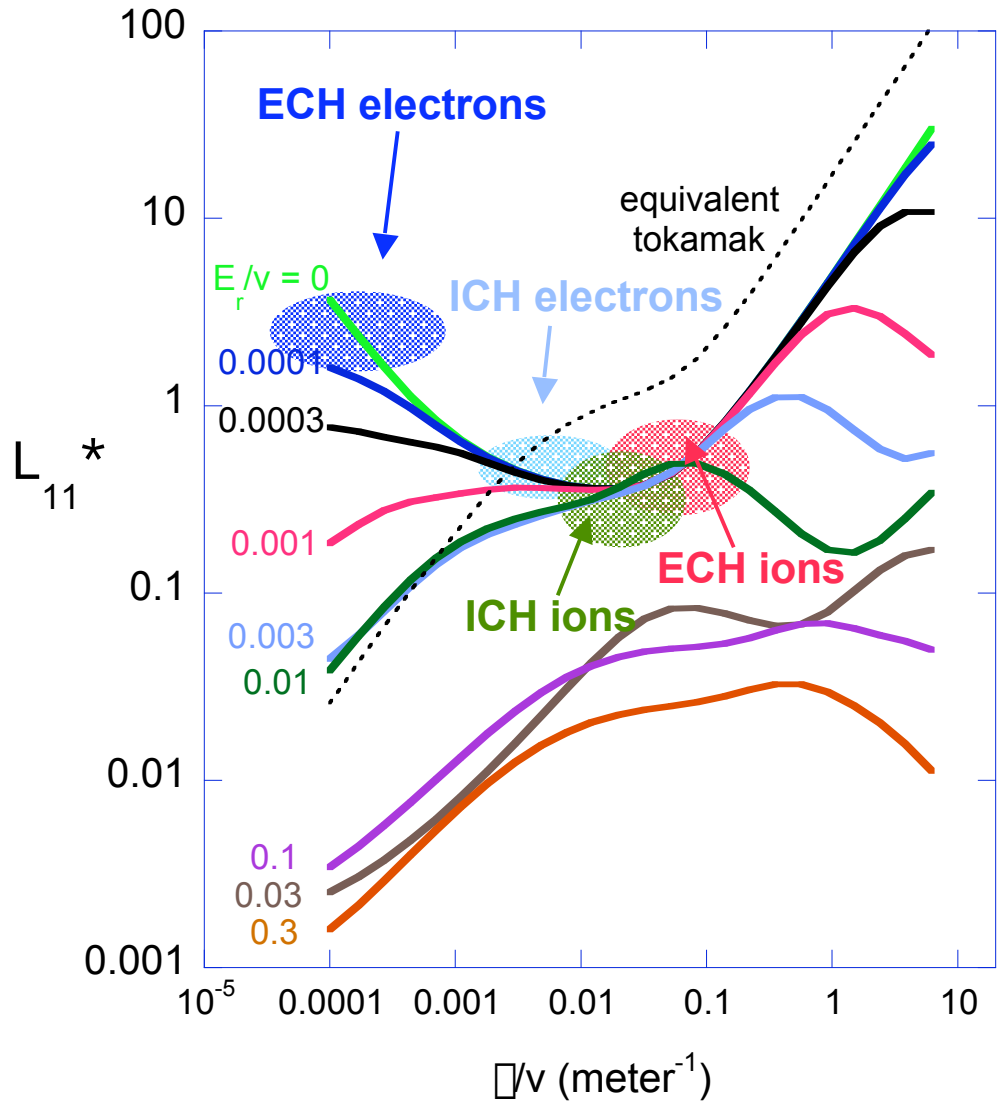
Plateau and 1/ν Regimes Can Be Studied

Neoclassical 1/ν transport at low ν* is reduced by reducing effective field ripple and by ambipolar electric field

Ignoring ambipolar electric field

ECH regime: $n = 1.8 \times 10^{19}$ m^{-3} T_{e0} = 1.4 keV, T_{i0} = 0.15 keV

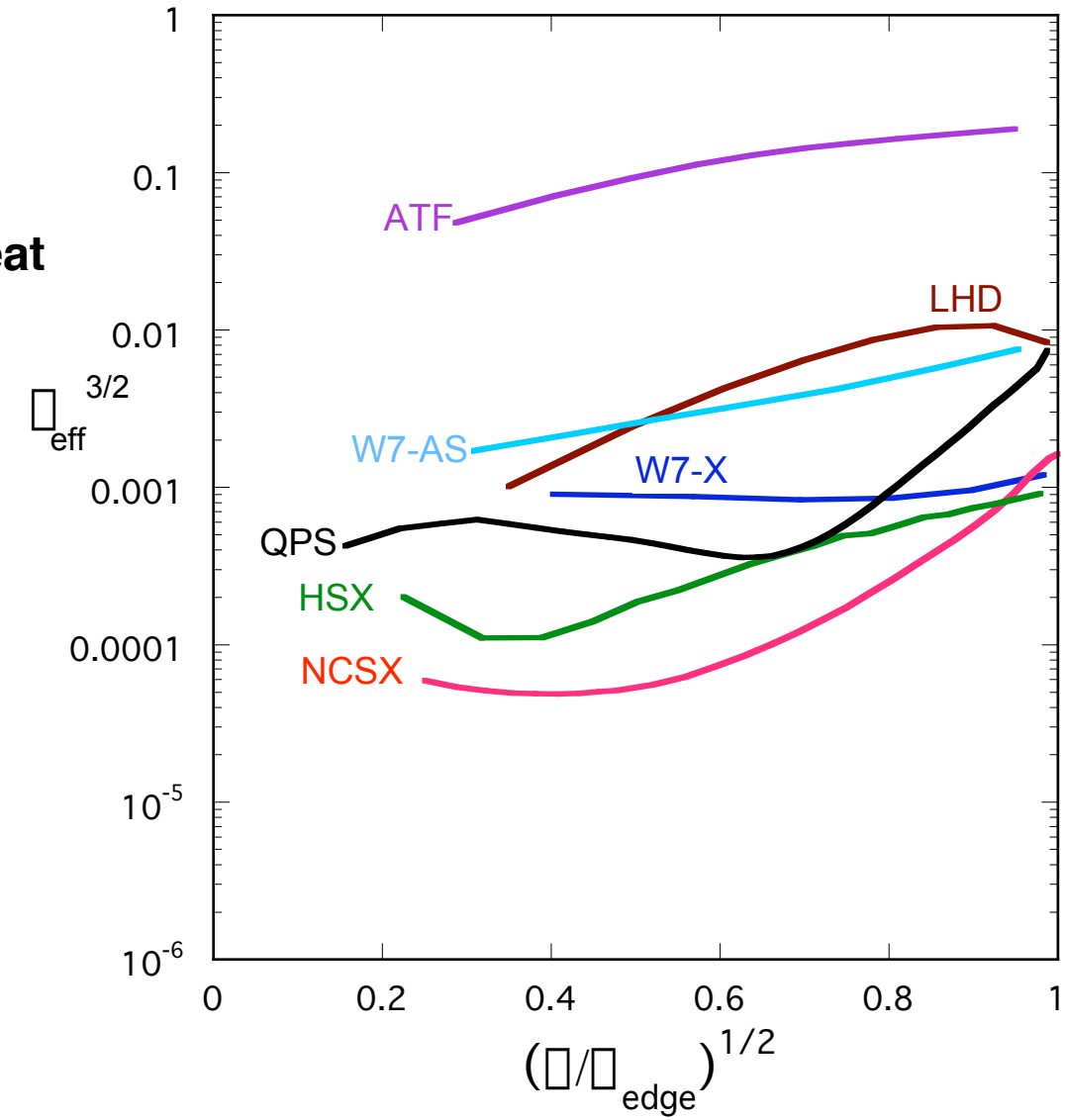
ICH regime: $n = 8.3 \times 10^{19}$ m^{-3} T_{e0} = 0.5 keV, T_{i0} = 0.5 keV



The Effective Ripple $\epsilon_{eff}^{3/2}$ in QPS Has Been Reduced to a Low Level

$\epsilon_{eff}^{3/2}$ is the coefficient of the neoclassical heat diffusivity in the $1/\nu$ regime with $E_r = 0$

$\epsilon_{eff}^{3/2}$ is similar to that for W 7-X, but at 1/4 the aspect ratio



1-D Transport Calculations Indicate Possible Range of QPS Parameters

Case	Net H-ISS95	χ_{anom} (m^2/s)	$\Delta\Delta$ (%)	$T_e(0)$ keV	$T_i(0)$ keV
1.5 MW	1	11.3	0.5	1.1	0.20
ECH	2	4.8	1.0	2.15	0.31
2×10^{19} m^{-3}	4	1.5	2.0	3.3	0.49
2 MW	1	7	1.3	0.36	0.30
EBW/ICRF	2	2.9	2.6	0.78	0.62
10^{20} m^{-3}	4	1.2	5.2	1.5	1.0
4 MW	1	10	1.7	0.53	0.38
EBW/ICRF	2	4.2	3.4	1.14	0.74
10^{20} m^{-3}	4	1.7	6.8	2.0	1.1

Requires improved confinement

D. Mikkelsen

Net H-ISS95 includes anomalous χ from ISS-95 scaling + neoclassical ripple-induced transport using calculated $\Delta_{eff}^{3/2}$ and self-consistent radial electric field

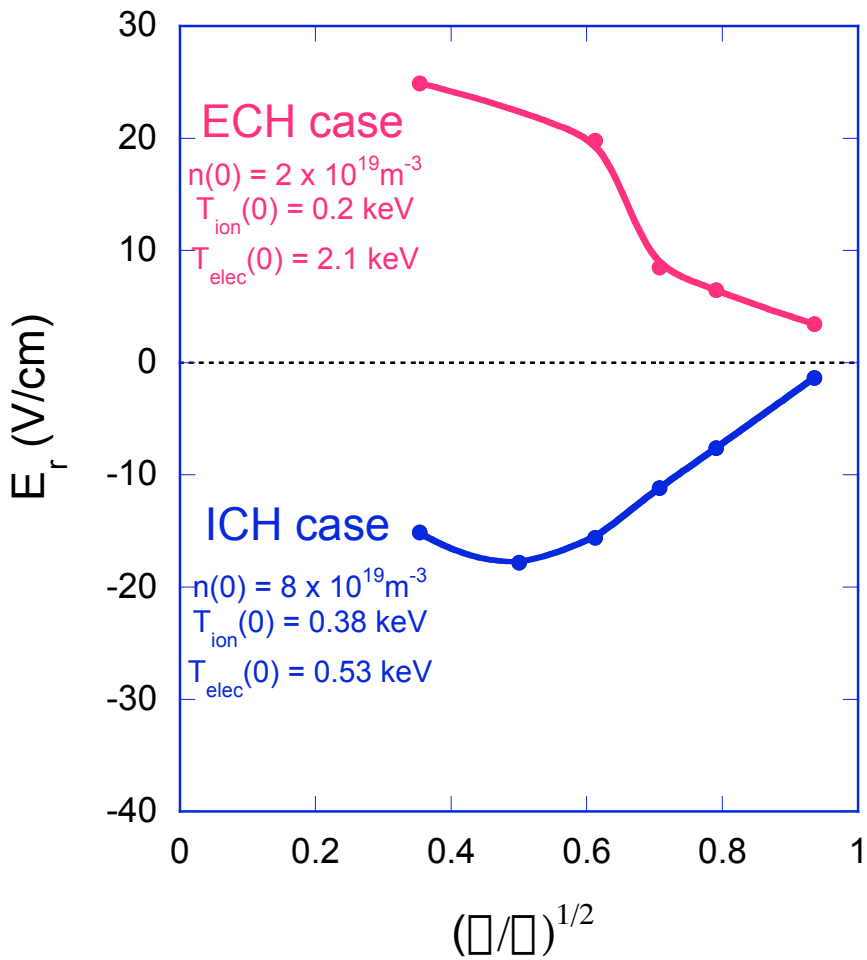
QPS Can Study the Effects of Quasi-Poloidal Symmetry on Anomalous Transport Suppression

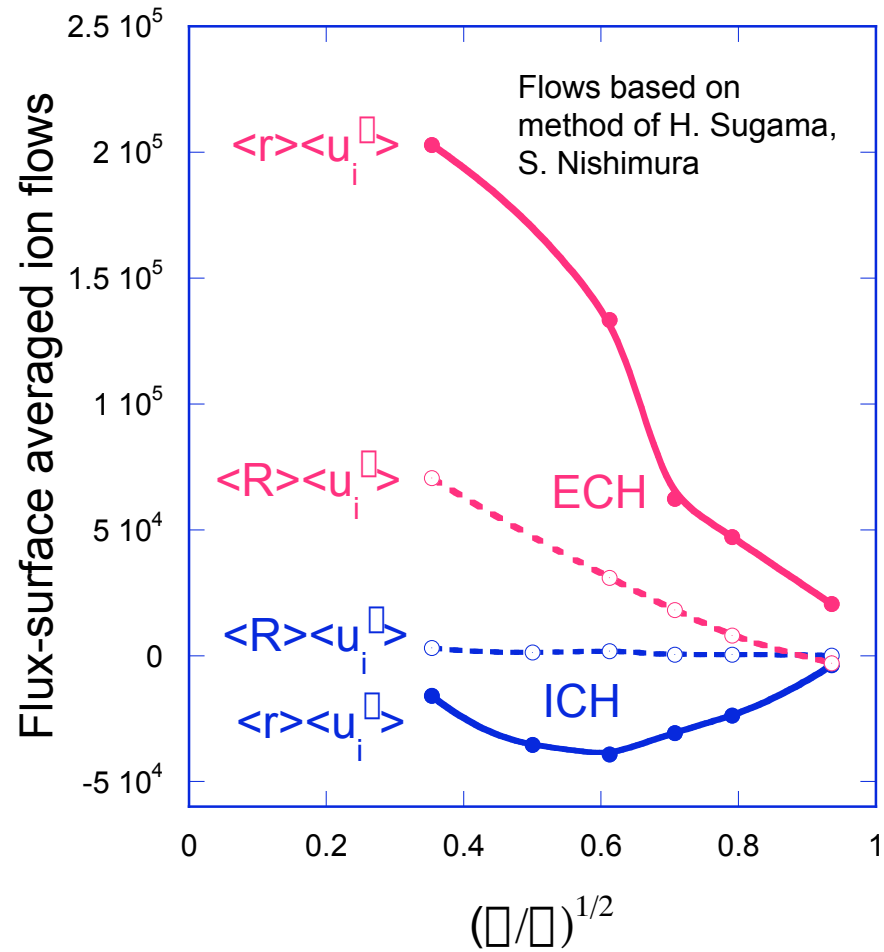
- **Enhanced confinement regimes attributed to electric field shear -- shredding of turbulent eddies**
- **This can be driven by a variety of sources**
  - **self-amplified background plasma flows**
  - **flows driven by external sources (biased plates, RF)**
  - **turbulence, pressure gradient drive**
- **QPS contributes to better understanding through**
  - **damping in the poloidal (symmetry) direction is weak in QPS, allowing self-generated and externally-driven poloidal flows**
  - **reduction of anomalous transport by poloidal flow shear and electric fields**
  - **sheared poloidal flows could be more effective than sheared toroidal flows**
  - **is there anomalous poloidal flow damping?**

Ambipolar Electric Field Is a Source for Self-Generated Poloidal Flows >> Toroidal Flows

QPS can access both positive and negative E_r values

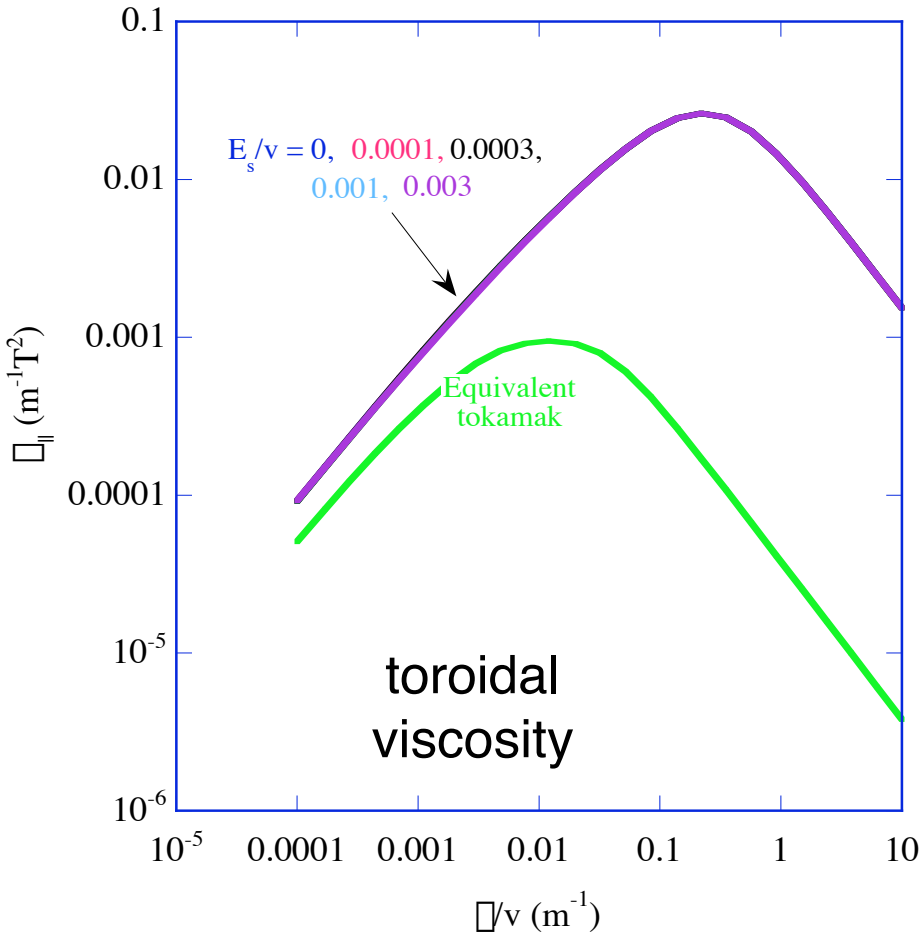
For fixed $v_{||}$, QP device enhances E_r by $(B_t/B_p)^2$

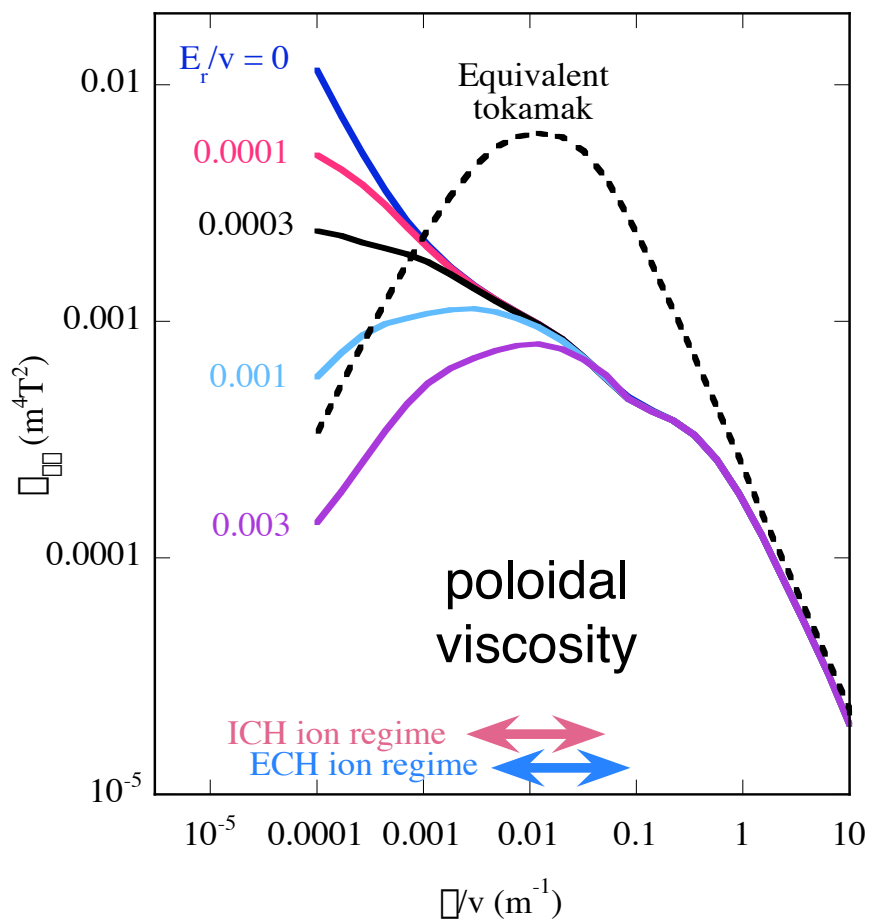




Ambipolar Electric Fields Further Reduce Poloidal Viscosity but not Toroidal Viscosity

Viscosity analysis based on method of H. Sugama, S. Nishimura, Phys. Plasmas 9, 4637 (2002)





Other Transport Studies

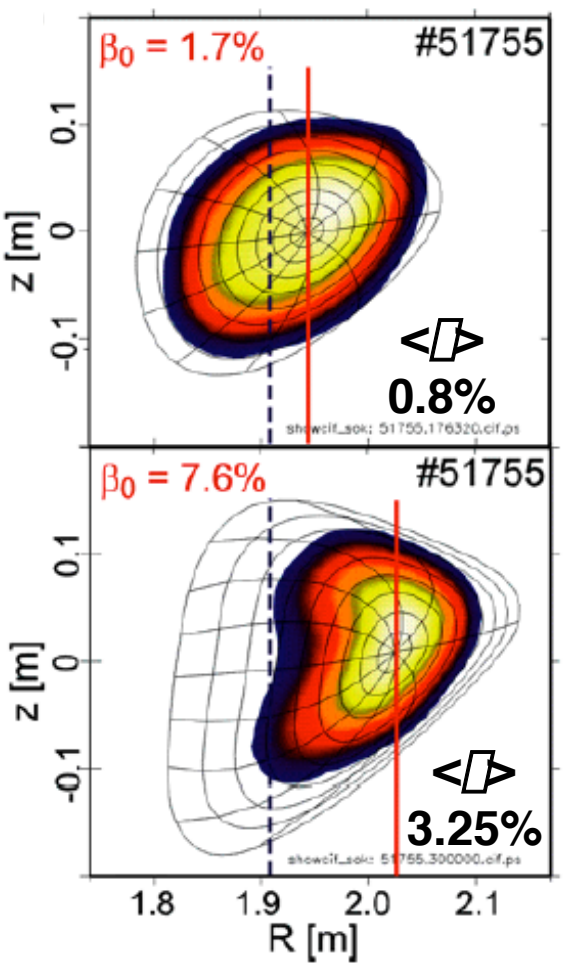
- **Transport scaling**
  - test the validity of International Stellarator Scaling and extend to R/a = 2.5-5
- **Degree of internal plasma contribution to confinement**
  - varying currents in external coils allows separating the effects of the plasma current from the magnetic confinement geometry and more external control over internal processes
- **Transport barrier formation**
  - study the impact of poloidal flows on electric fields and enhanced confinement as well as the level of helical ripple that can be tolerated at very low plasma aspect ratio
- **Blob mass transport controlled by radial E_{pol} x B_{tor} transport**
  - E_{pol} could be weaker in a quasi-poloidally symmetric system and studied by varying the degree of quasi-poloidally symmetry
- **Width of the scrapeoff region**
  - determined by balance between perpendicular and parallel transport
  - parallel transport is determined by the connection length, which can be varied

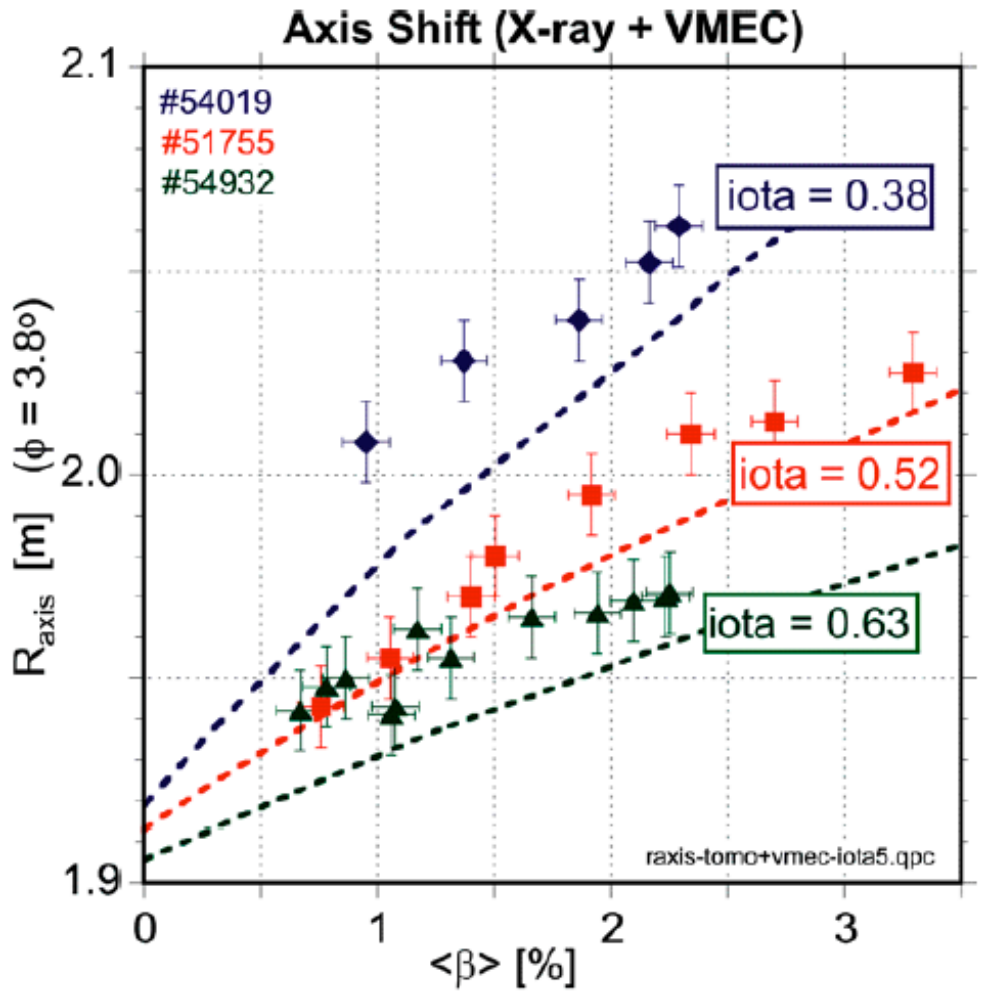
MHD Equilibrium

Magnetic Islands

Bootstrap Current

3-D MHD Equilibrium Calculations Agree with Experiment (W 7-AS)



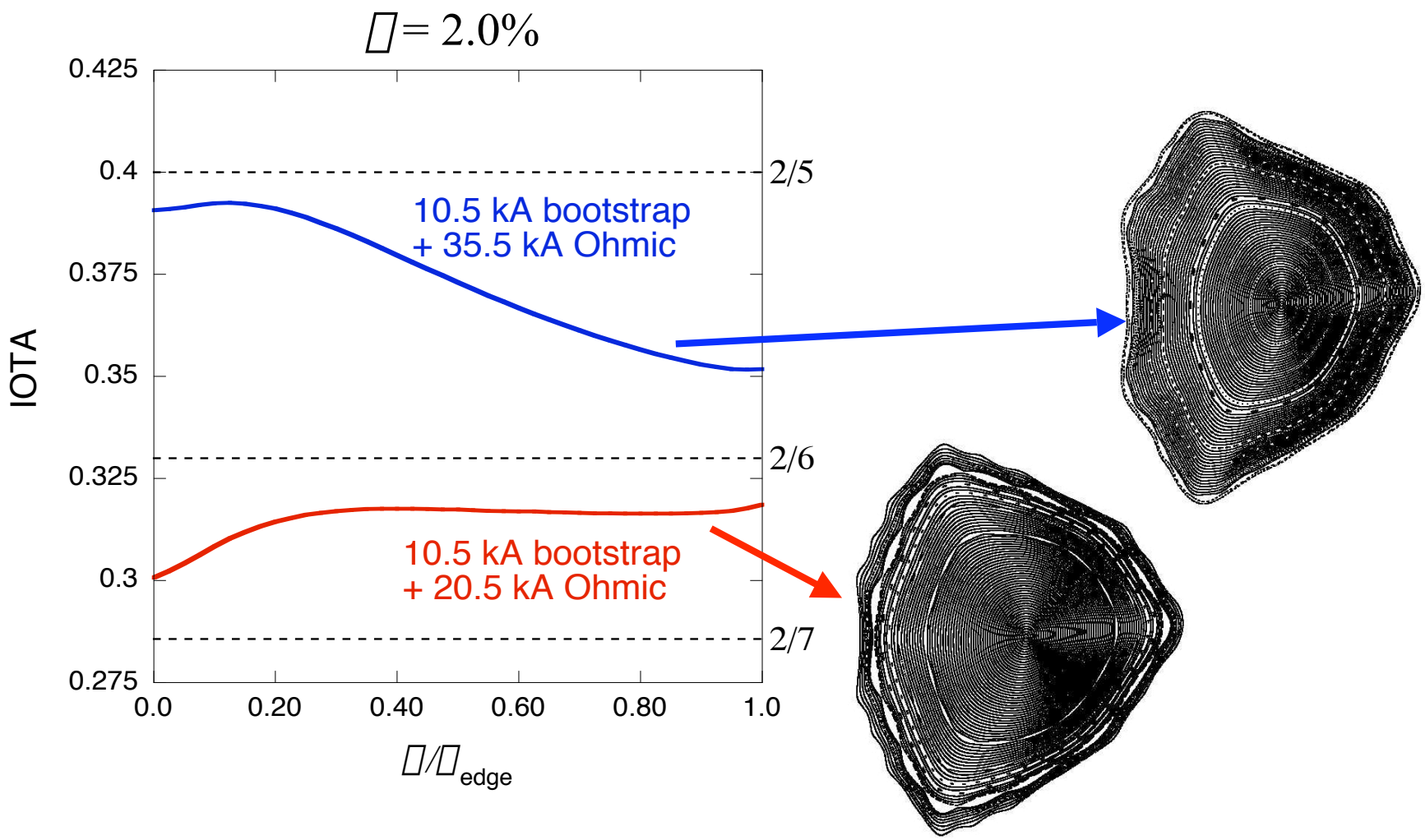


A. Weller

QPS Extends 3-D Equilibrium Studies to Very Low *R/a*

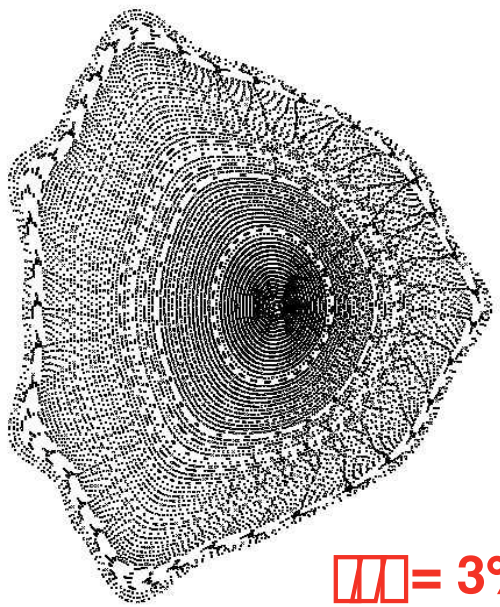
- **Coils allow external coil of magnetic islands, plasma shaping, rotational transform profile, and magnetic shear**
- **QPS can study the effect of equilibrium quality, magnetic islands and ergodic regions on plasma performance**

Good Flux Surfaces Obtained Using Ohmic Current to Avoid Low-Order Resonances

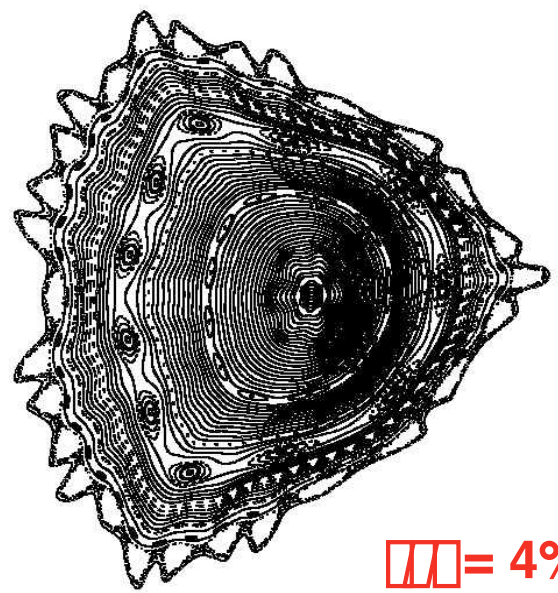


D. Monticello

MHD Equilibrium at β > 2%



β = 3%



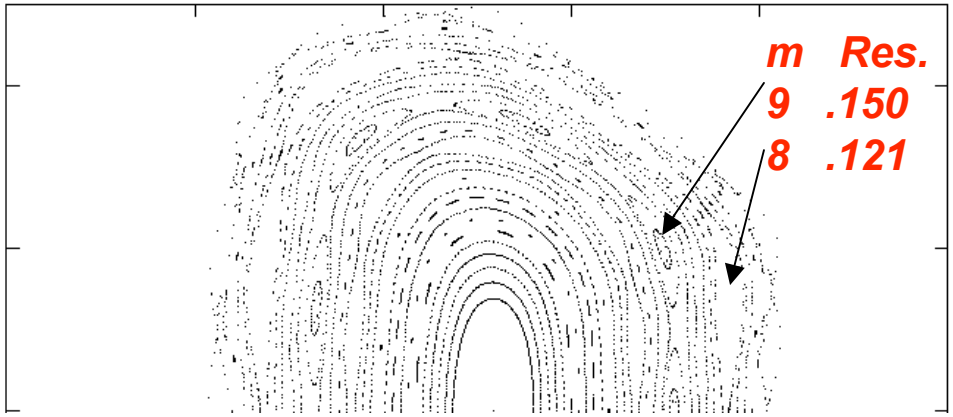
β = 4%

The bootstrap current and poloidal rotation can further reduce magnetic islands and their effects

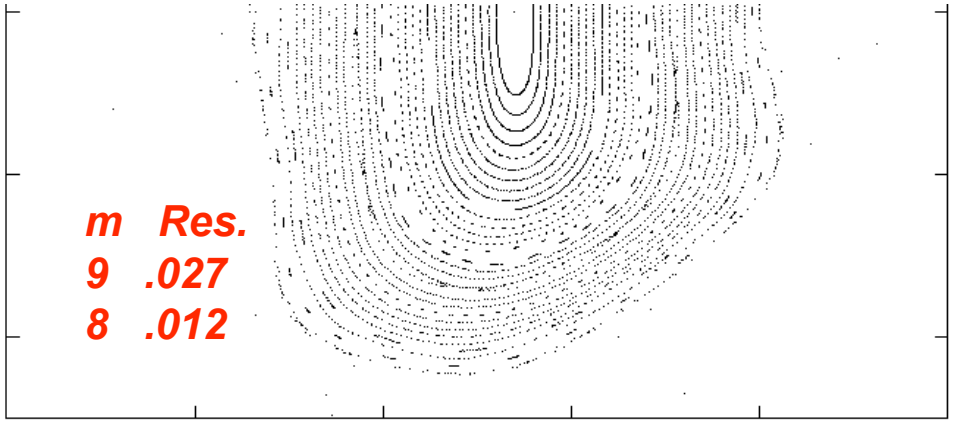
D. Monticello

Varying Coil Currents Reduces QPS Islands

QPS vacuum field - reference coil currents

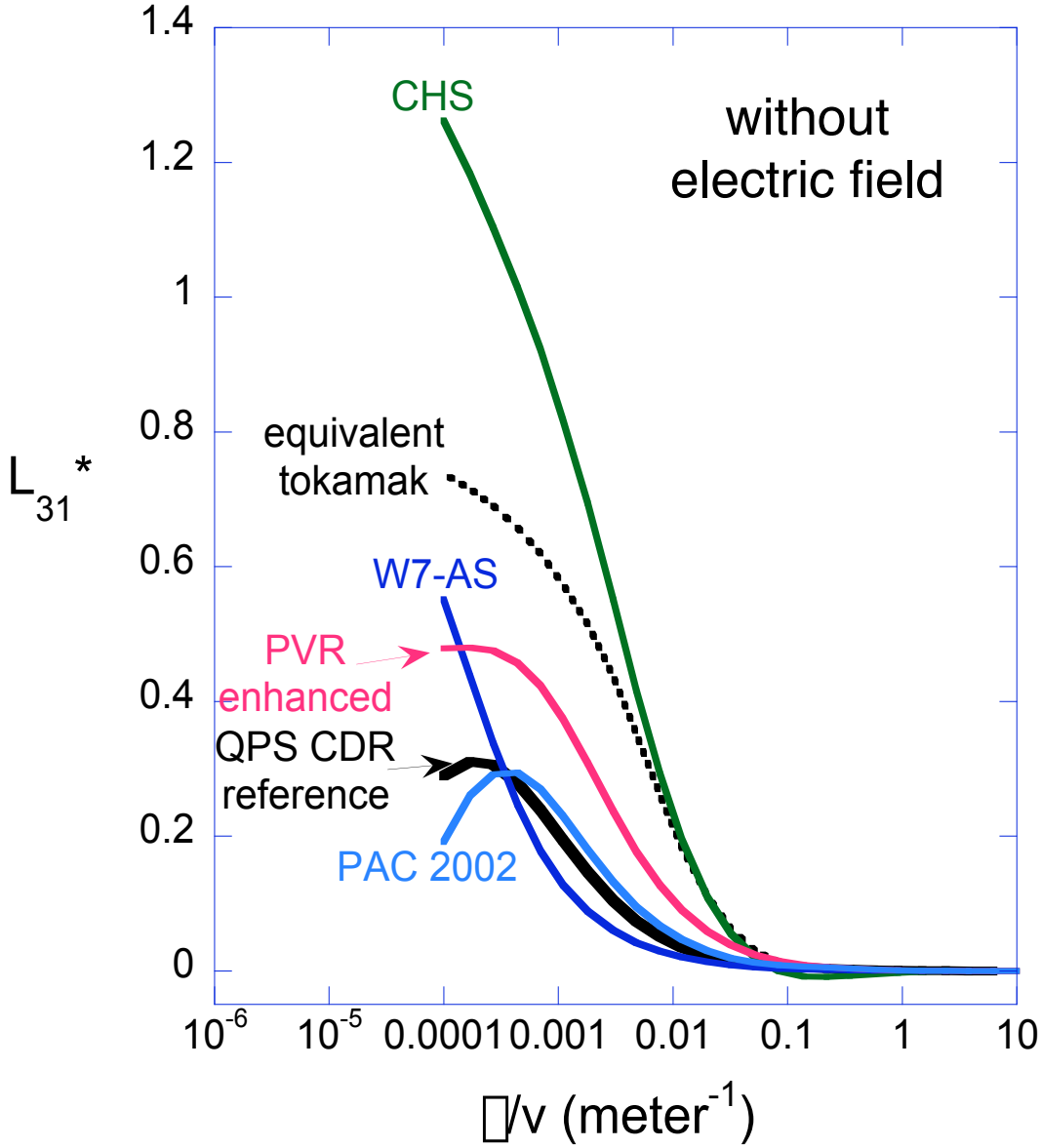


Final state - minimum residues



- an optimization technique based on Cary-Hanson method is used to minimize the residue of targeted magnetic islands
- coil currents are varied subject to constraints on currents and magnetic field
- also possible to use external island correction coils as in W 7-AS and LHD

Bootstrap Current Coefficient Lower In QPS

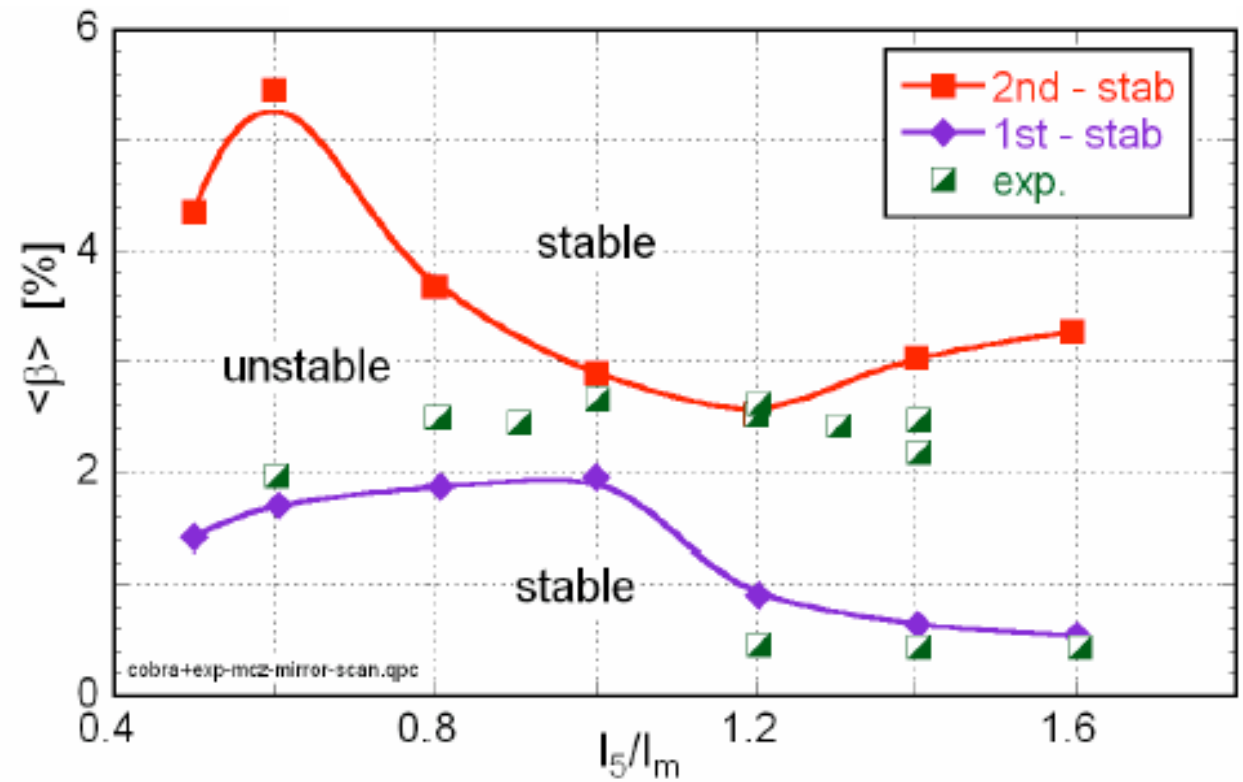


- **QPS extends I_{BS} configuration dependence to very low aspect ratio**
- **Direction of bootstrap current and the sign of shear should decrease the size of magnetic islands as the plasma pressure increases**

MHD Stability

High-*n* Ballooning Modes Do Not Predict Stellarator Operational Limits

- **High-*n* ballooning calculations are used as optimization targets and for comparing different stellarator configurations**
  - **ballooning modes are thought to be more dangerous than current-driven modes in stellarators**
- **However, ballooning instability are exceeded in W 7-AS (&LHD)**

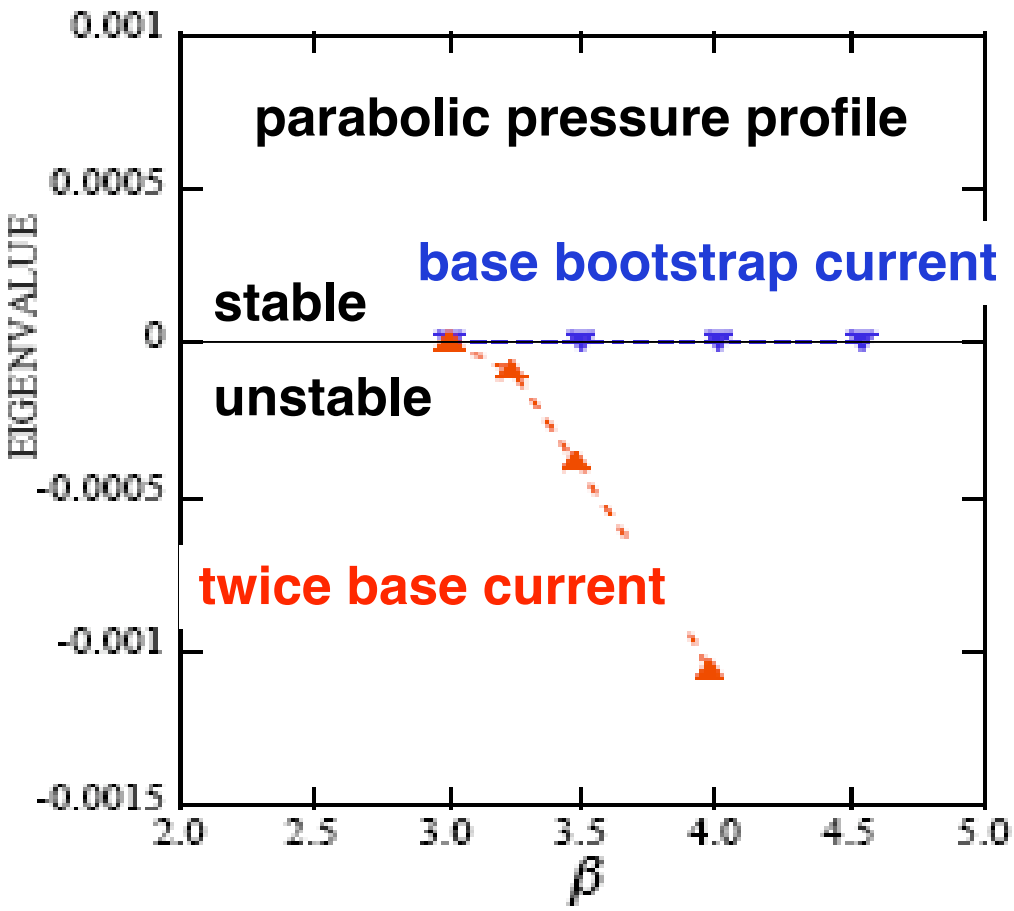


W 7-AS

Ballooning Instability Is Inherently Less Global (and Less Dangerous) in Stellarators

- **When a flux surface is ballooning unstable in tokamaks, all field lines on the surface go unstable simultaneously**
- **In 3-D systems, only a subset of the field lines on the surface may be unstable and each field line has a different growth rate**
- **A true global mode has not been found; if such a global mode could be constructed, it would possess significant mode coupling**
- **This will tend to increase the linear stability thresholds beyond those of the high-*n* theory (i.e., more bending energy required) and will also impact the nonlinear saturation of the mode**

Finite-*n* Ballooning Calculations Give Higher β Values



Varying the magnetic geometry allows study of ballooning modes

- **Is the structure of the mode different in a quasi-poloidal system?**
- **Localized particle and energy loss?**
- **Access to the QPS second stability region?**

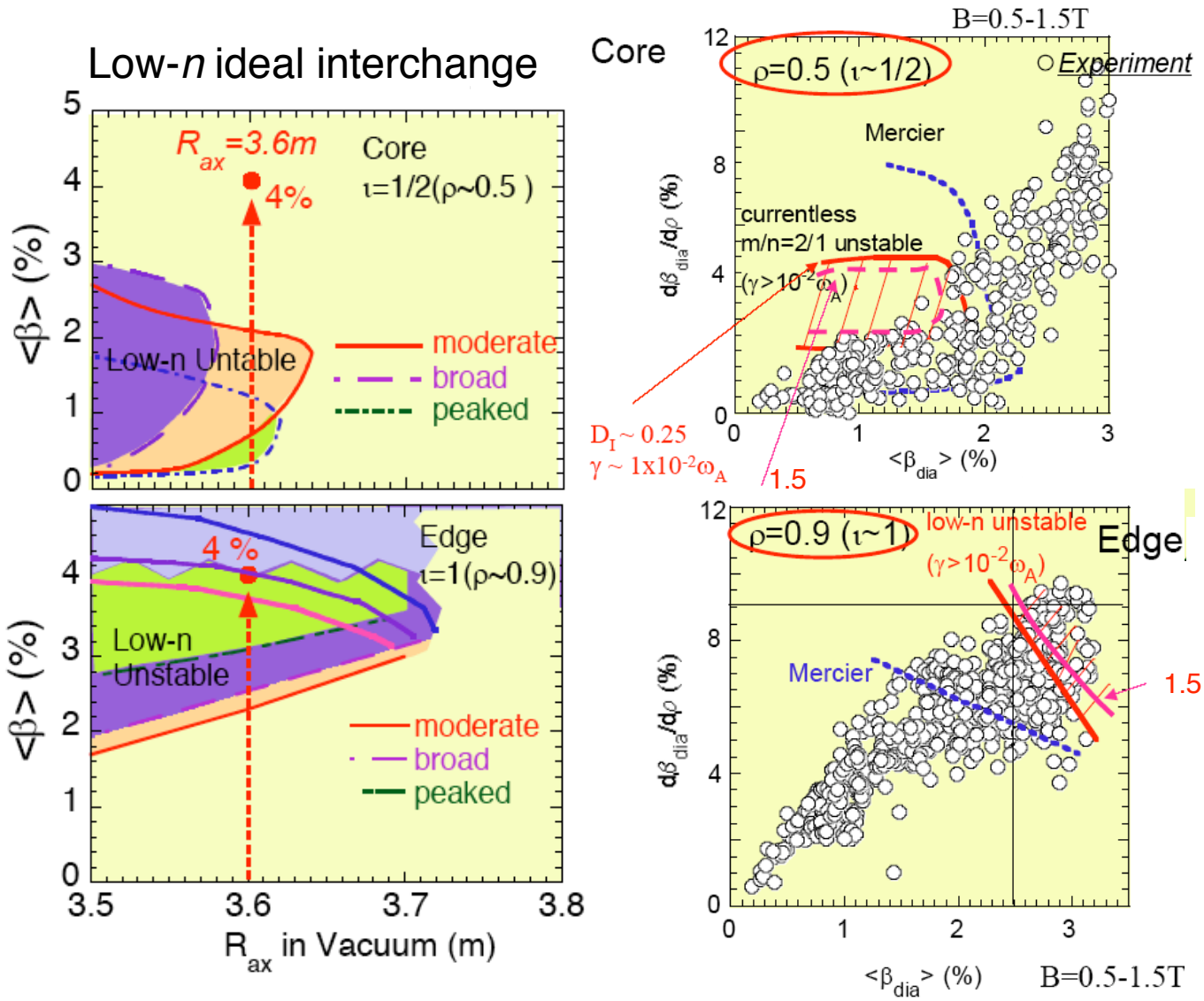
Low-*n* Stability Limits Exceeded in LHD

Core: stable for <β> above 2%, unstable regime avoided?

Edge: local flattening stabilizes plasma

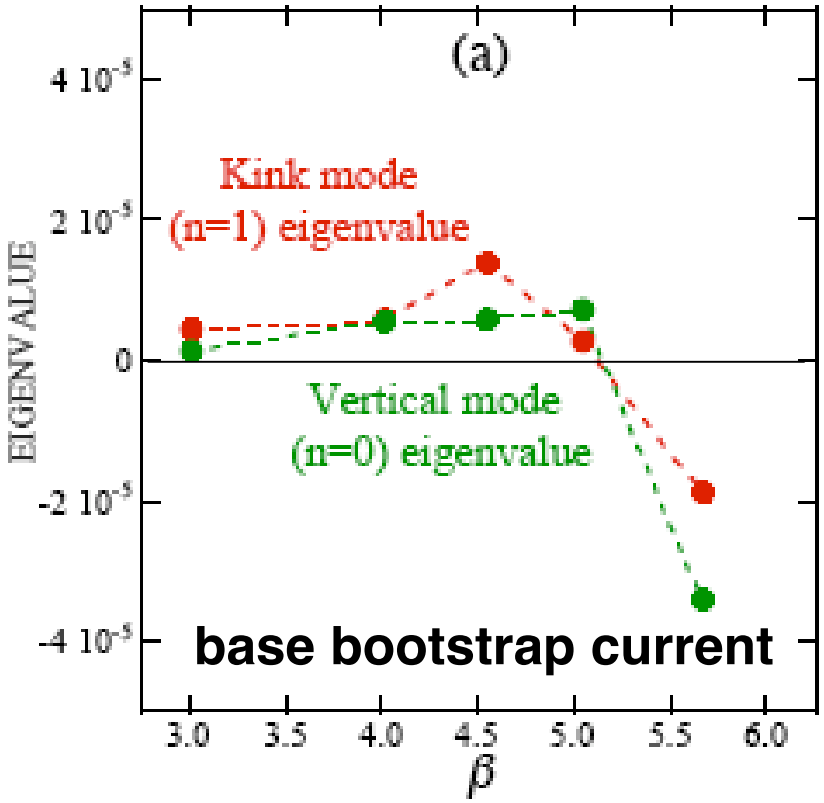
Mercier has no effect

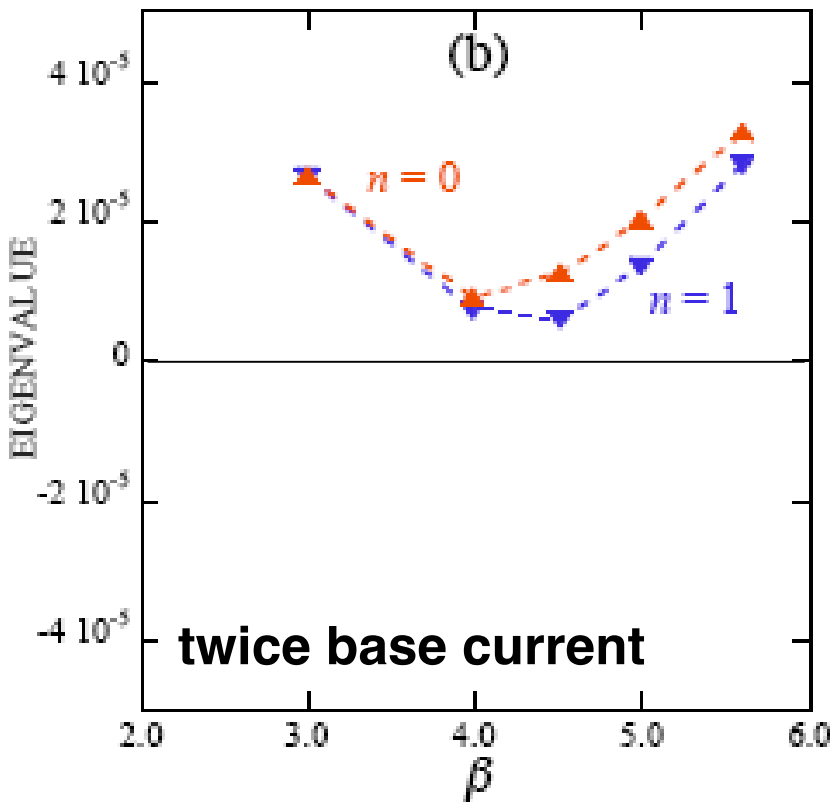
No deterioration up to <β> = 4%



H. Yamada

Vertical and Kink Stability in QPS

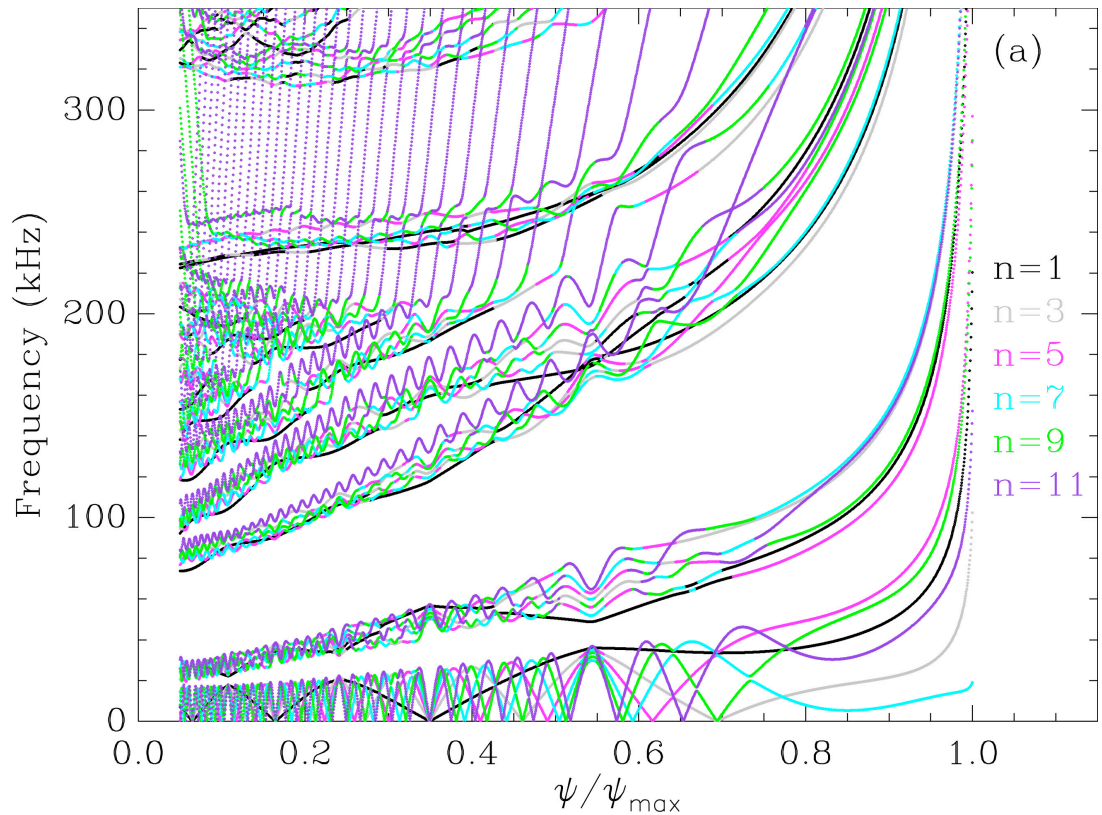




We Have Started to Analyze AE Gap Modes in Compact Stellarators

- **gap structure is sensitive to the magnetic geometry; wider at lower *R/a***
- **Coupling in toroidal as well as in poloidal direction**
- **AE gap modes can be excited by ECH tails or with external antennas or probes for more careful comparison with calculations**

QPS Alfvén continua from STELLGAP code
[D. Spong, et al., Phys. Plasmas **10** (2003) 3217]



Contributions to Other Stability Studies

- **Trapped-particle modes could be more stable than in axisymmetric devices**
  - trapped particles in long regions of low curvature
  - this can be studied by toroidally varying currents in the modular coils
- **Tearing modes**
  - shear can be changed from stellarator shear to tokamak shear
  - stellarator shear suppresses neoclassical tearing modes
  - different than in tokamaks due to low rotational transform and 3-D nature of the equilibrium?

QPS Project Status

- Successful DOE reviews completed
  - physics validation review ==> DOE mission need approval (CD-0), May 2001
  - project validation reviews, May 2001 and June 2002
  - conceptual design review June 2003 ==> DOE alternative selection and cost range approval (CD-1) this Spring
- The next steps are R&D and refining the design
  - casting a stainless steel winding form this year
  - winding, vacuum canning, and potting a prototype modular coil next year

Summary

- **Main focus of the QPS program is use of quasi-poloidal geometry to explore toroidal physics issues at low *R/a***
  - **flux surface robustness at *R/a* > 2.5 and sensitivity to β with strong toroidal/helical coupling**
  - **reduction of neoclassical and anomalous transport**
  - **variation of effective ripple, trapped particle fraction, stellarator or tokamak shear, quasi-poloidal symmetry, poloidal viscosity and poloidal flow shear, ambipolar electric field & internal transport barriers, bootstrap vs. Ohmic current, magnetic island size, magnetic beach ICRF and EBW heating**
- **A secondary component is study of β limits and the character of MHD instabilities**

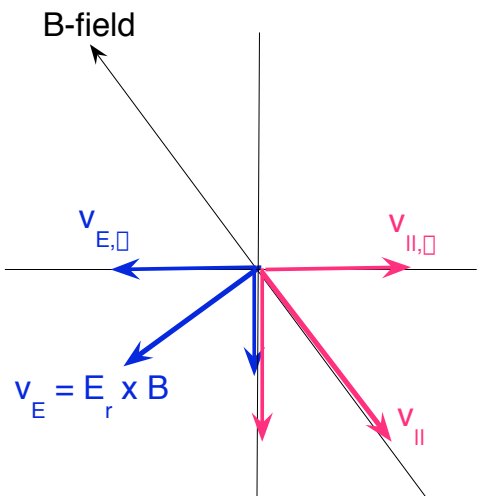
QPS Allows Flow Damping to Access Enhanced Confinement Regimes

Tok. QPS

$u_p \neq 0 \quad u_t \neq 0$

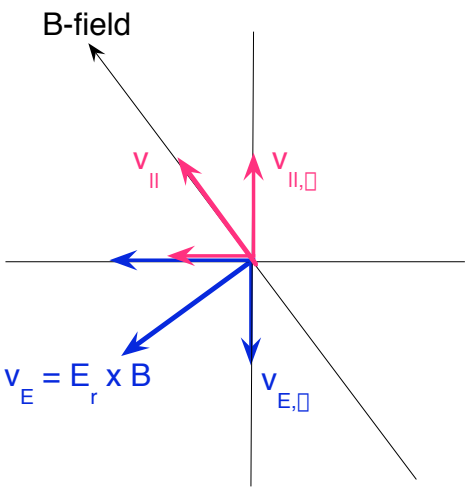
Lowest order flow equilibrium: $\left\langle \vec{B} \cdot \left(\vec{\nabla} \cdot \vec{\Pi} \right) \right\rangle = \Pi_{pp} u_p + \Pi_{tt} u_t = 0$

Tokamak: exact symmetry



$$\frac{E_r B_t}{B^2} = v_\parallel \frac{B_p}{B} \Rightarrow v_\parallel \propto \frac{E_r}{B_p} \quad \text{or } E_r = \frac{B_p}{B_t} B v_\parallel$$

QPS: exact symmetry



$$\frac{E_r B_p}{B^2} = v_\parallel \frac{B_t}{B} \Rightarrow v_\parallel = \frac{E_r}{B_t} \frac{B_p}{B} \quad \text{or } E_r = \frac{B_t}{B_p} B v_\parallel$$

For fixed $v_\parallel$, QP device enhances E_r by $(B_t/B_p)^2$