Overview of the QPS Experiment

J. F. Lyon for the QPS Team

International Stellarator Workshop

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Multi-Institution QPS Team

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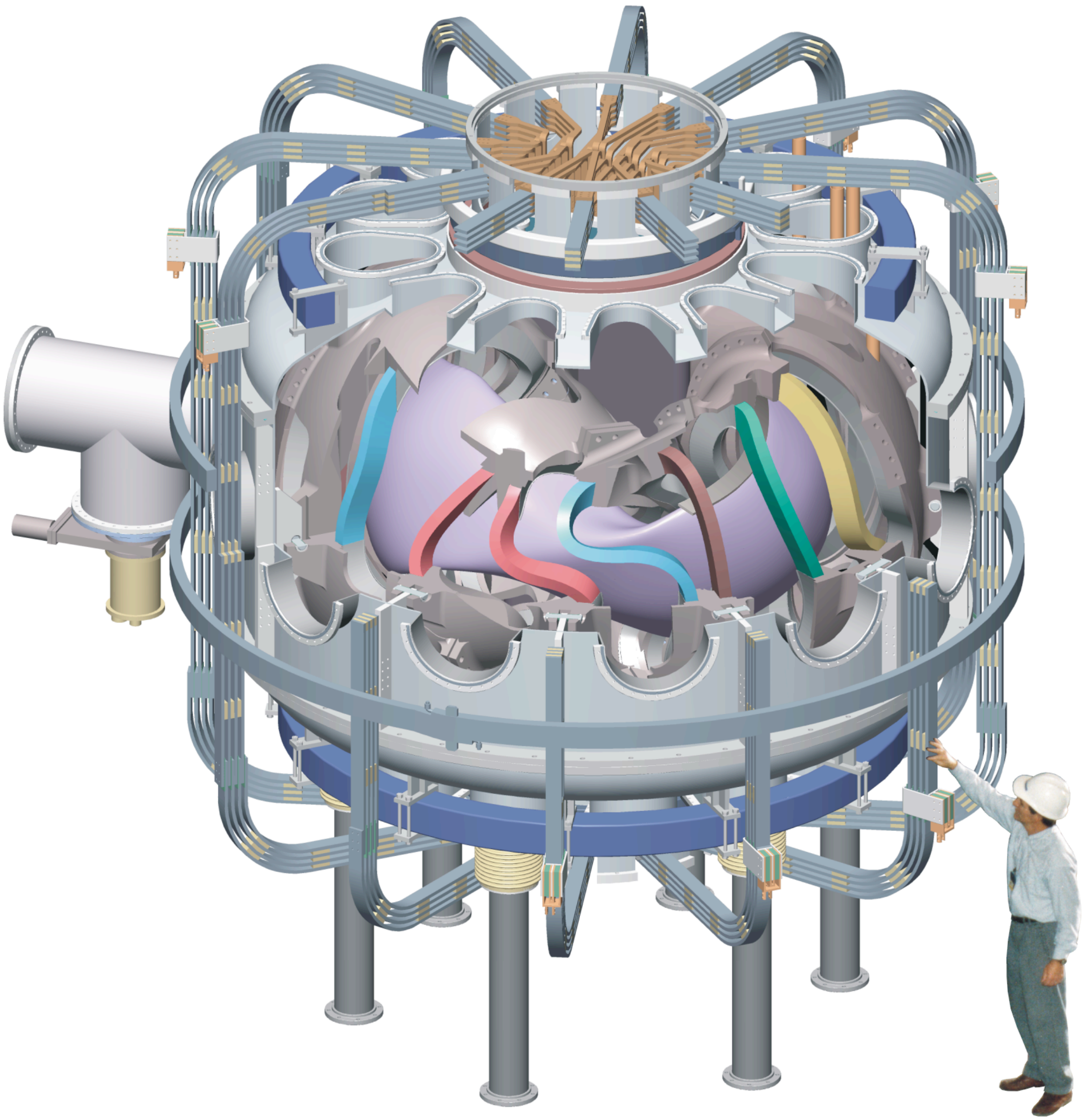
- **BWXT Y-12** – K. Freudenberg, P. Goranson, G. Jones
- **DevTech** – T. Hargrove
- **MK Technologies** – G. Lovett
- **PPPL** – G.Y. Fu, D. Mikkelsen, D.A. Monticello
- **U. Montana** – A.S. Ware, E. Barcikowski, S. Wang, D. Westerly
- **Universidad Carlos III de Madrid**, Spain – R. Sanchez
- **U. Tennessee** – T. Shannon, D. Irick, M. Madhukar, M. Parang
- ORNL/GA/Auburn collaboration on equilibrium reconstruction

Topics

- **The QPS experiment and program**
  - **plasma and coil geometry**
  - **quasi-poloidal symmetry**
- **MHD equilibrium and stability**
- **Confinement properties**
- **Configuration flexibility**

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
- P = 2–4 MW
  ECH/EBW + ICRF

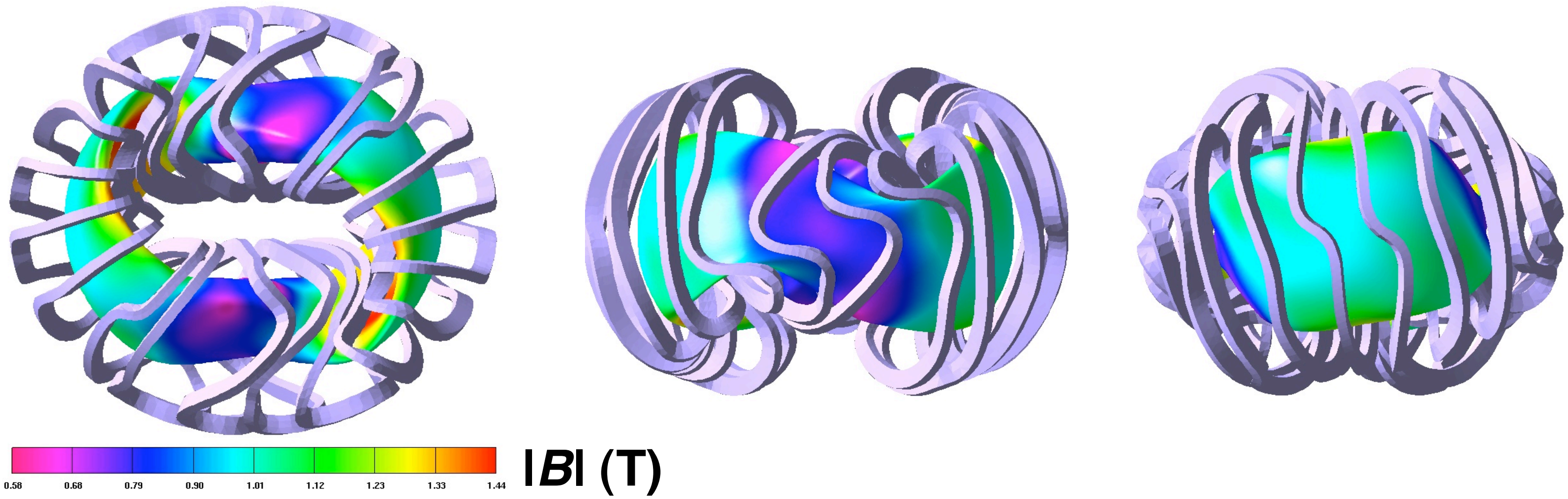
QPS Program

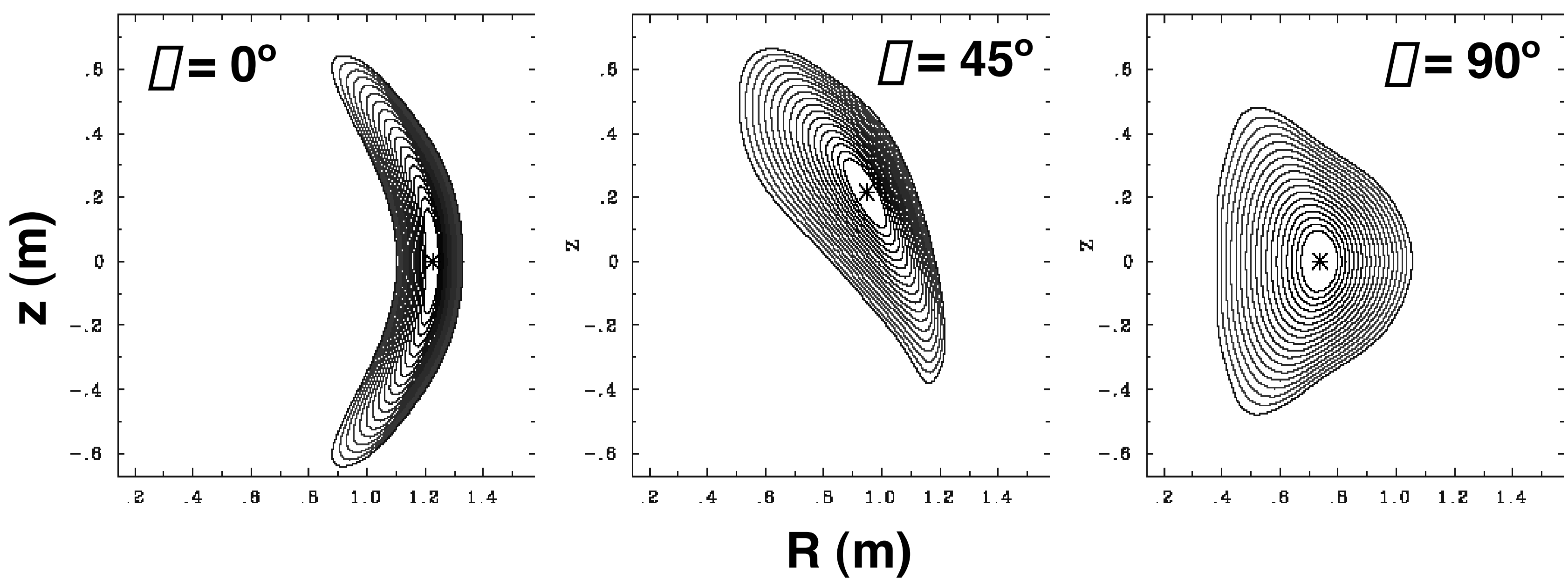
- **The main focus of the QPS program is the optimization of stellarator confinement at very low plasma aspect ratio**
  - **flux surface robustness at *R*/*a* > 2.5 and β up to 2-3% with strong toroidal/helical coupling**
  - **reduction of neoclassical transport**
  - **reduction of anomalous transport**
  - **role of reduced effective ripple, quasi-poloidal symmetry, poloidal viscosity and poloidal flows, ambipolar electric field and internal transport barriers, and fluctuations**
- **A secondary component is study of β limits and the character of MHD instabilities for a very low *R*/*a*, quasi-poloidal stellarator**
- **Benchmarking and improvement of 3-D theory**

QPS Design Requirements

- **Sufficient *B*, *n*, heating power, and confinement to reach the parameters needed for the physics studies**
- **A robust magnetic configuration and a path to relevant density and [illegible] values**
- **Ability to vary parameters (effective ripple, quasi-poloidal symmetry, poloidal viscosity, [illegible] limits) over wide range to reveal underlying physics**
- **Good access for plasma heating and diagnostics**

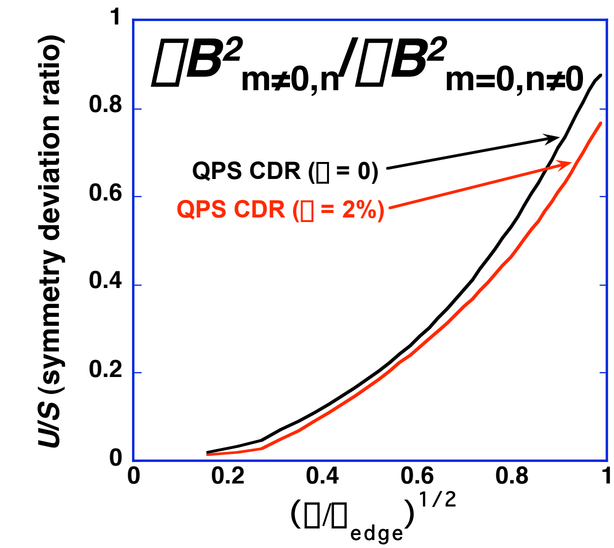
QPS Plasma and Coil Geometry

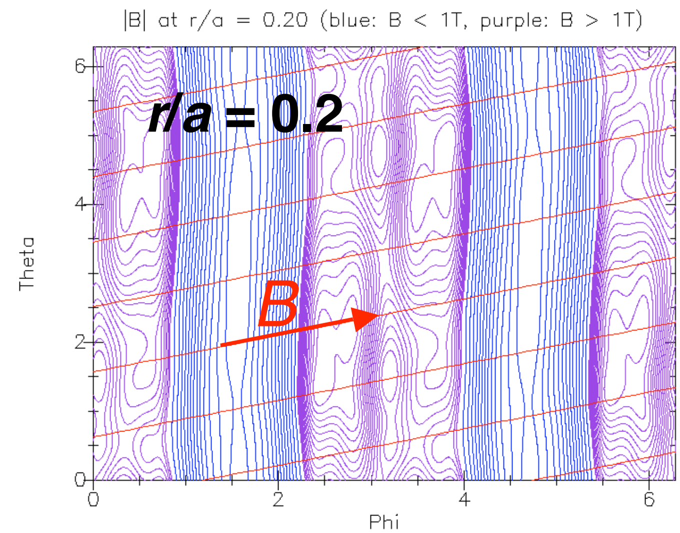


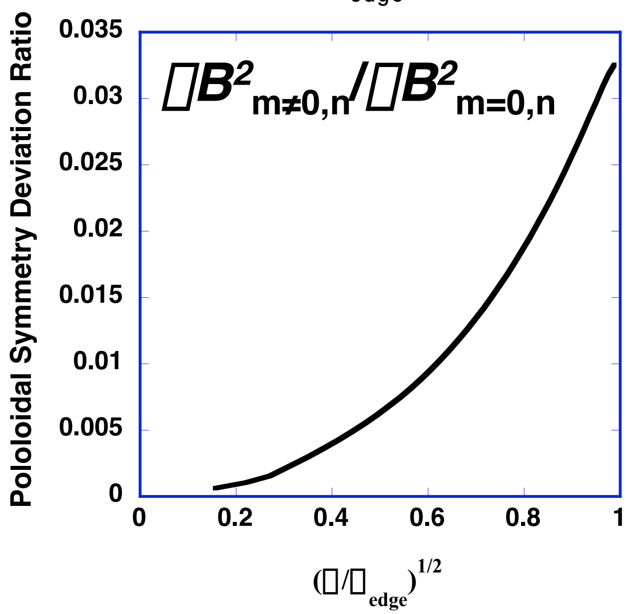


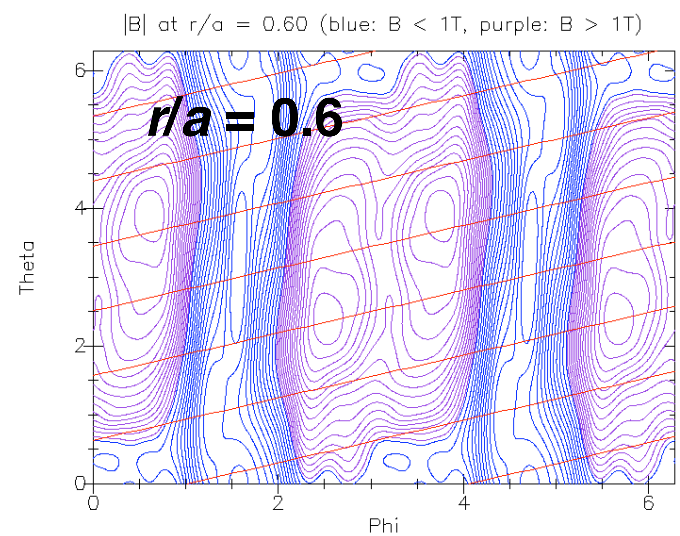
Quasi-Poloidal Symmetry

- **Reduces neoclassical transport, poloidal flow damping, bootstrap current, sensitivity to □, second stability threshold**









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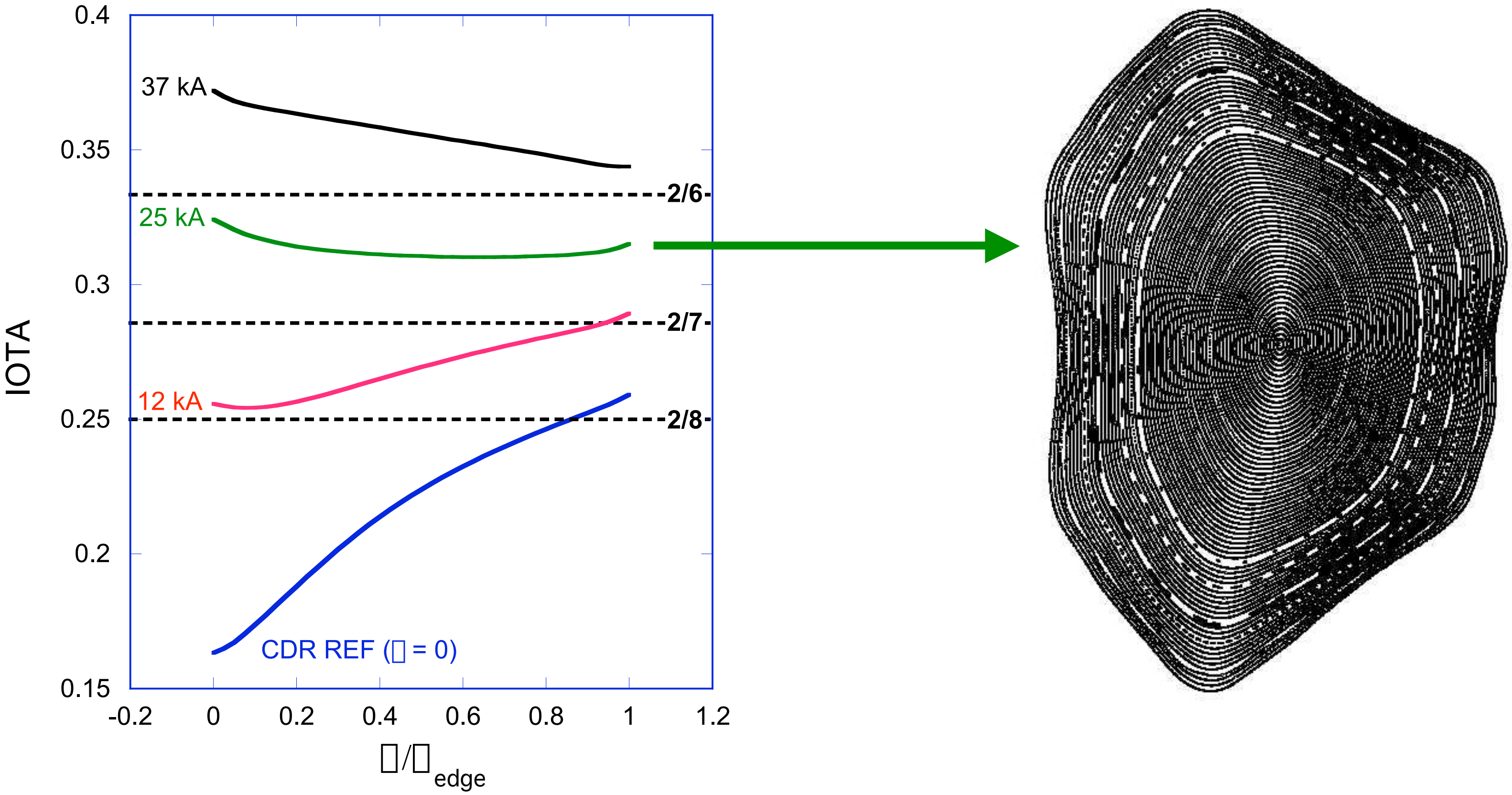
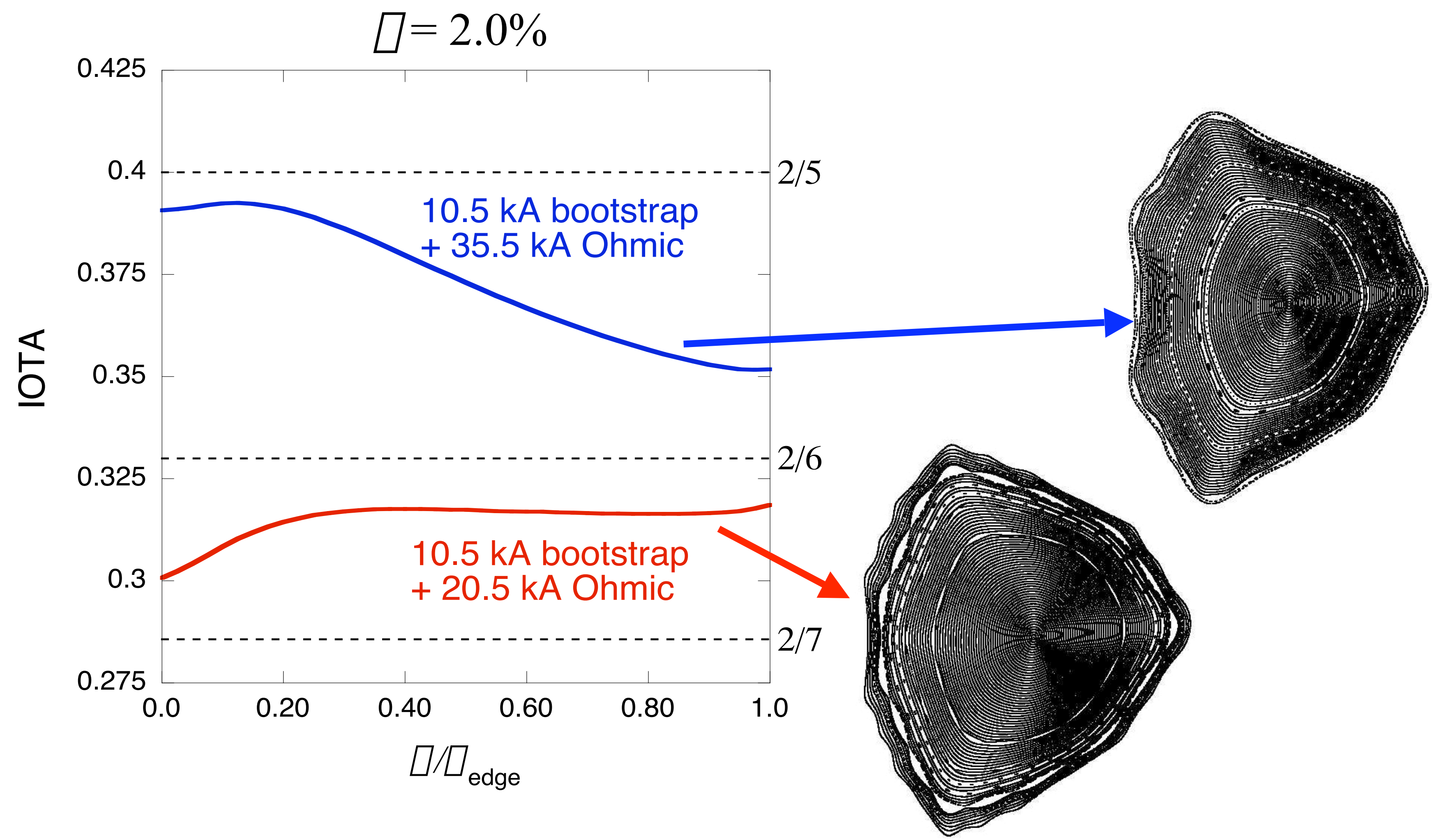
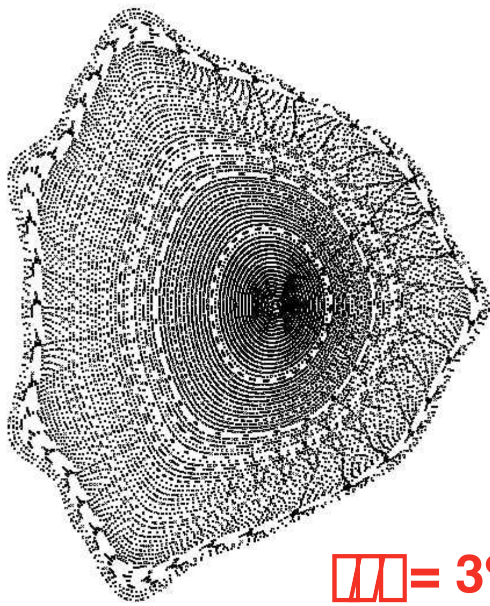
Coil Current Optimization + Ohmic Current Allow Avoiding Low-Order Resonant at Low



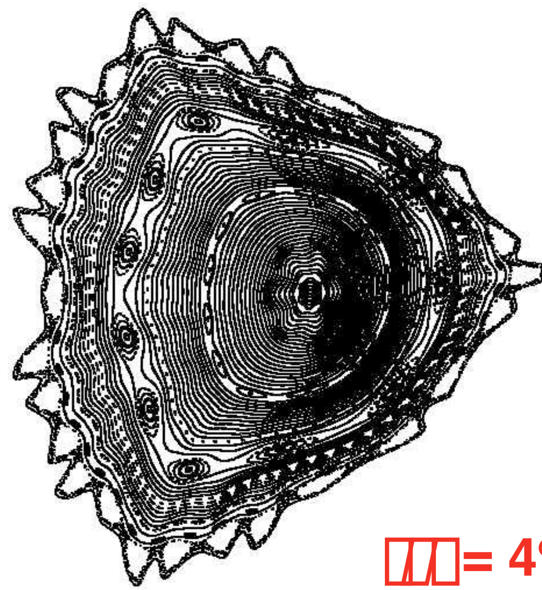
Good Flux Surfaces Obtained Using Ohmic Current to Avoid Low-Order Resonances



MHD Equilibrium at ▯/▯> 2%



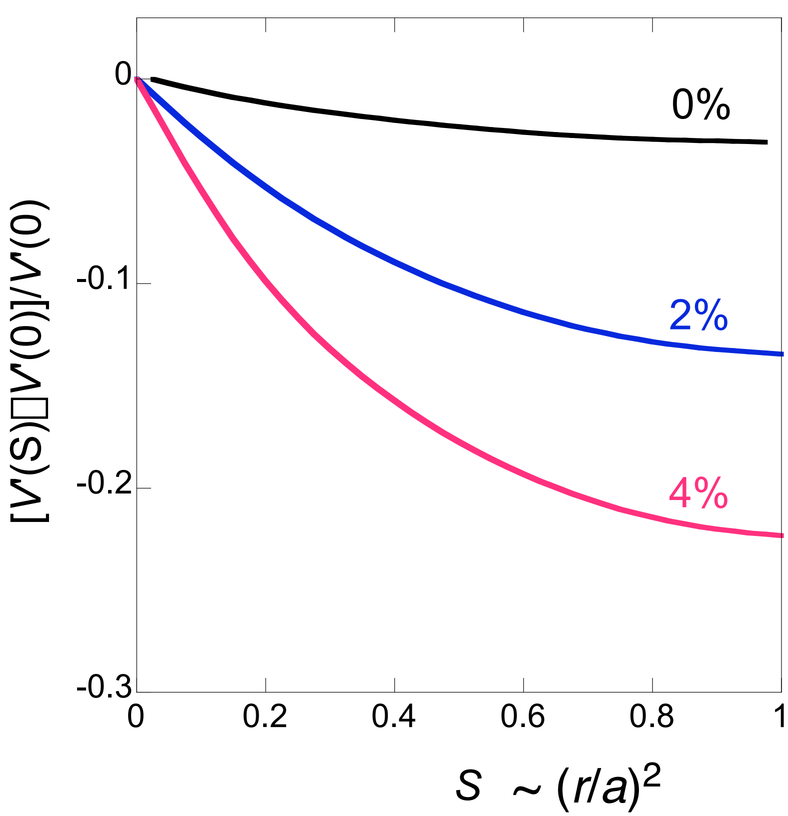
▯/▯= 3%

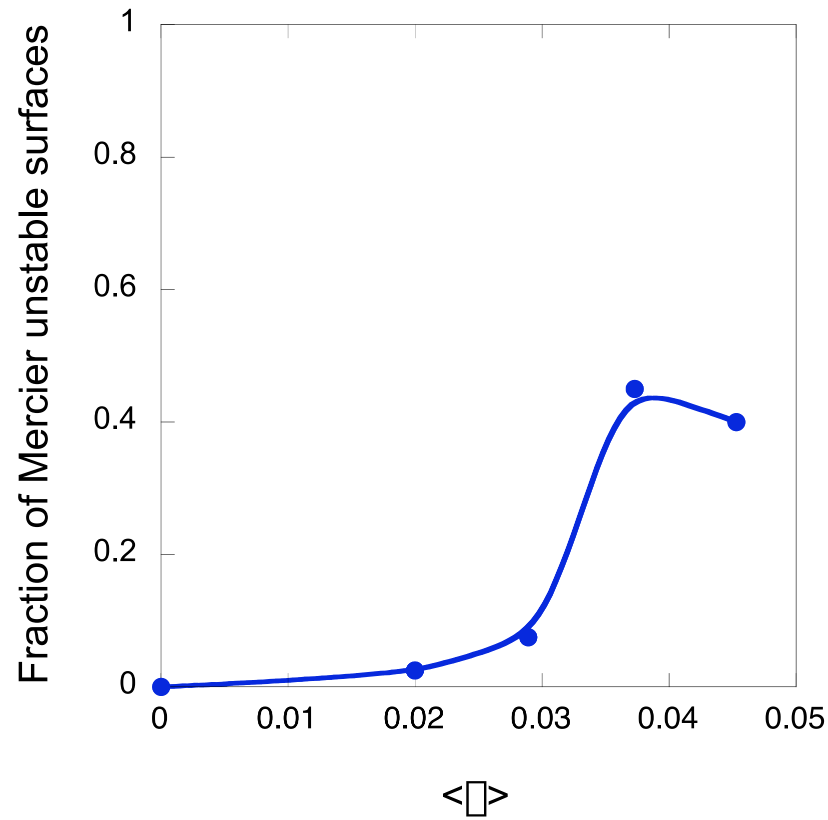


▯/▯= 4%

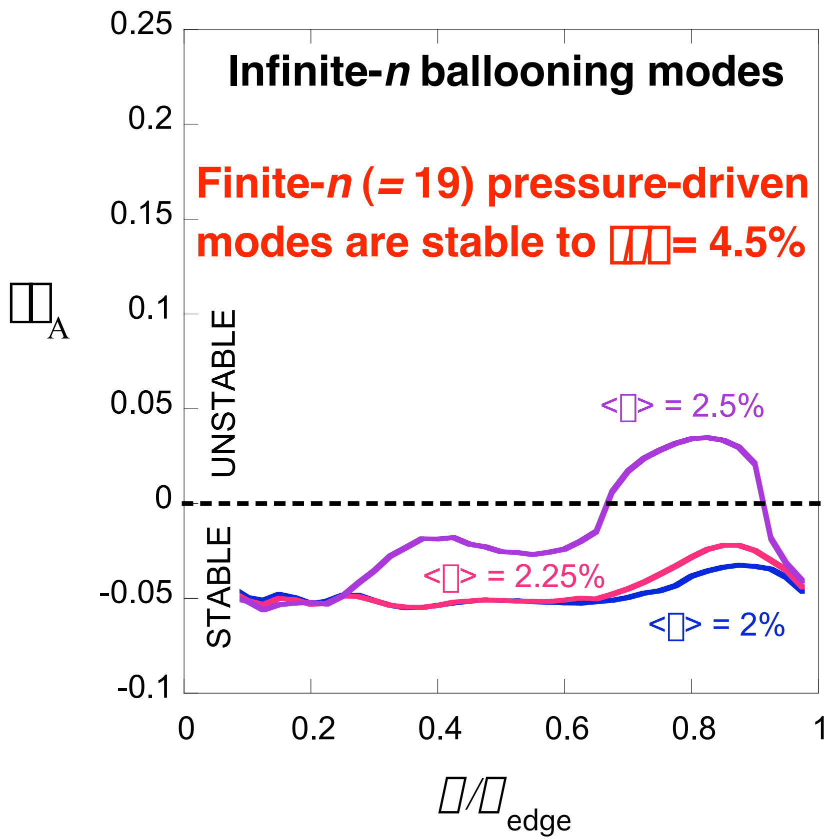
The bootstrap current and poloidal rotation can reduce magnetic islands and their effects

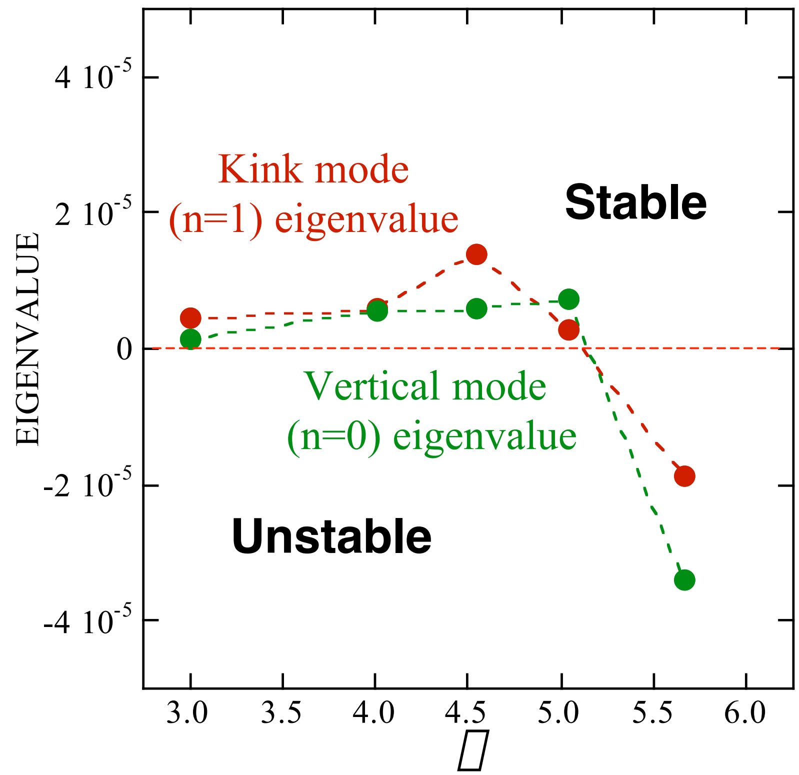
QPS Maintains a Magnetic Well and Is Stable to Mercier Modes up to ⟨β⟩~ 3%





QPS Is Stable to MHD Modes at $\langle\beta\rangle$ = 2.5-4.5%





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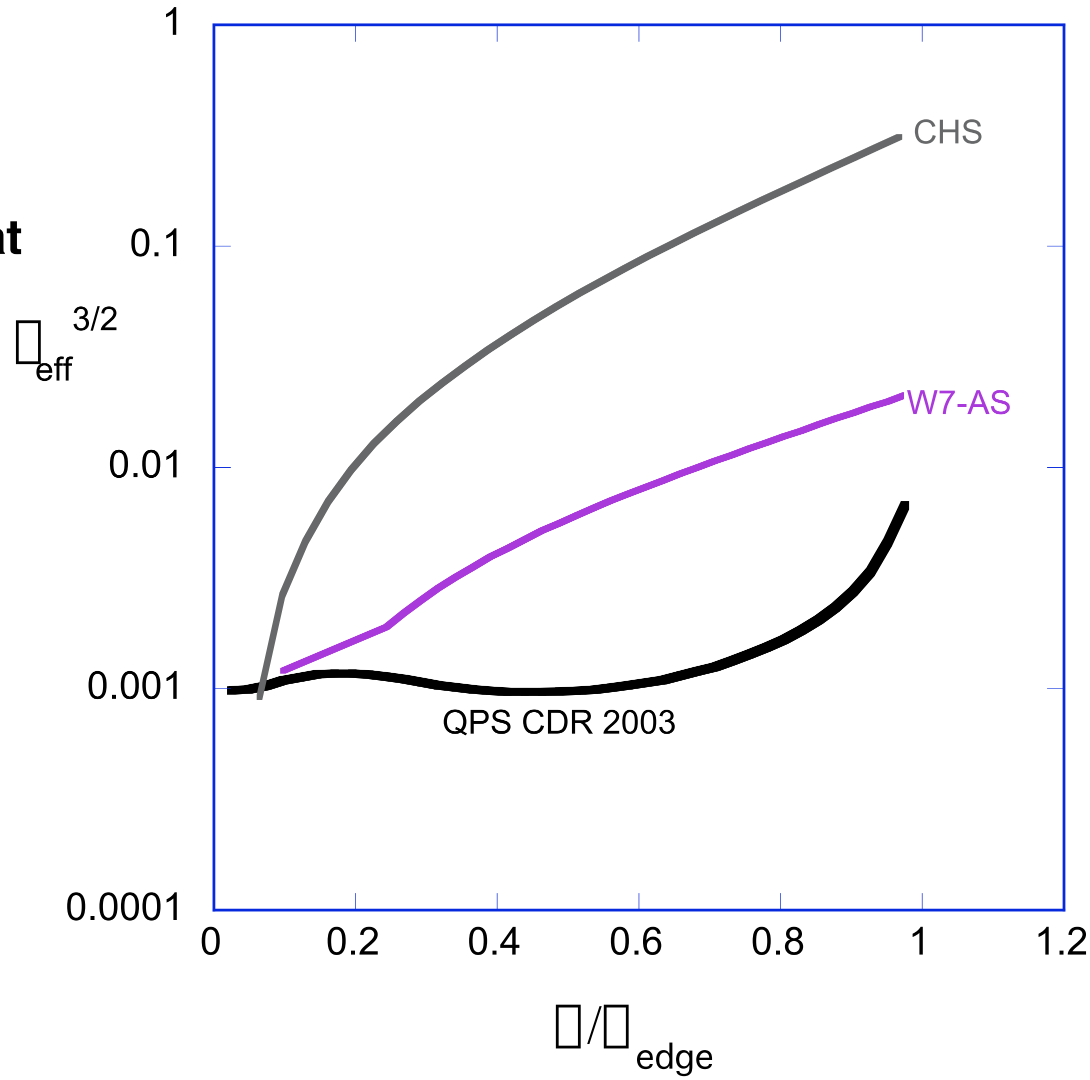
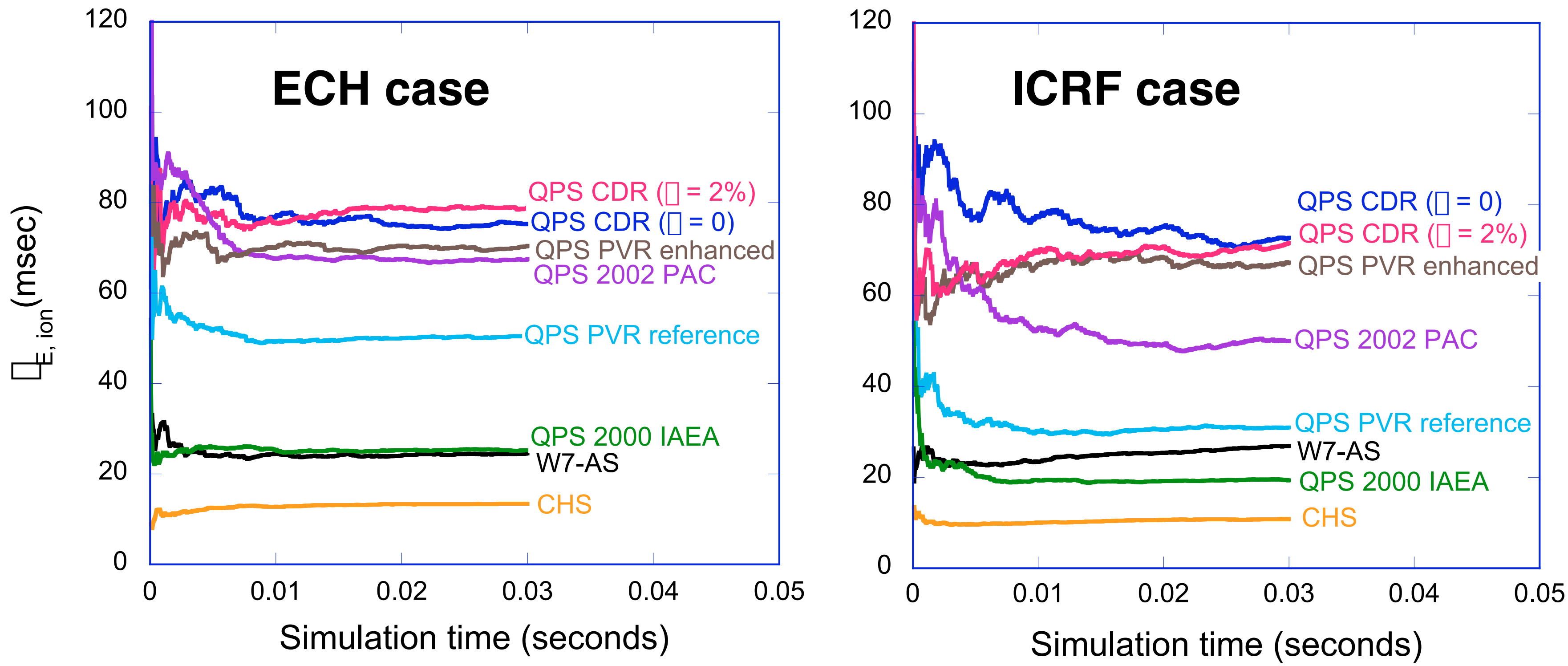
The Effective Ripple $\epsilon_{eff}^{3/2}$ in QPS Has Been Reduced to a Low Level

$\epsilon_{eff}^{3/2}$ 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

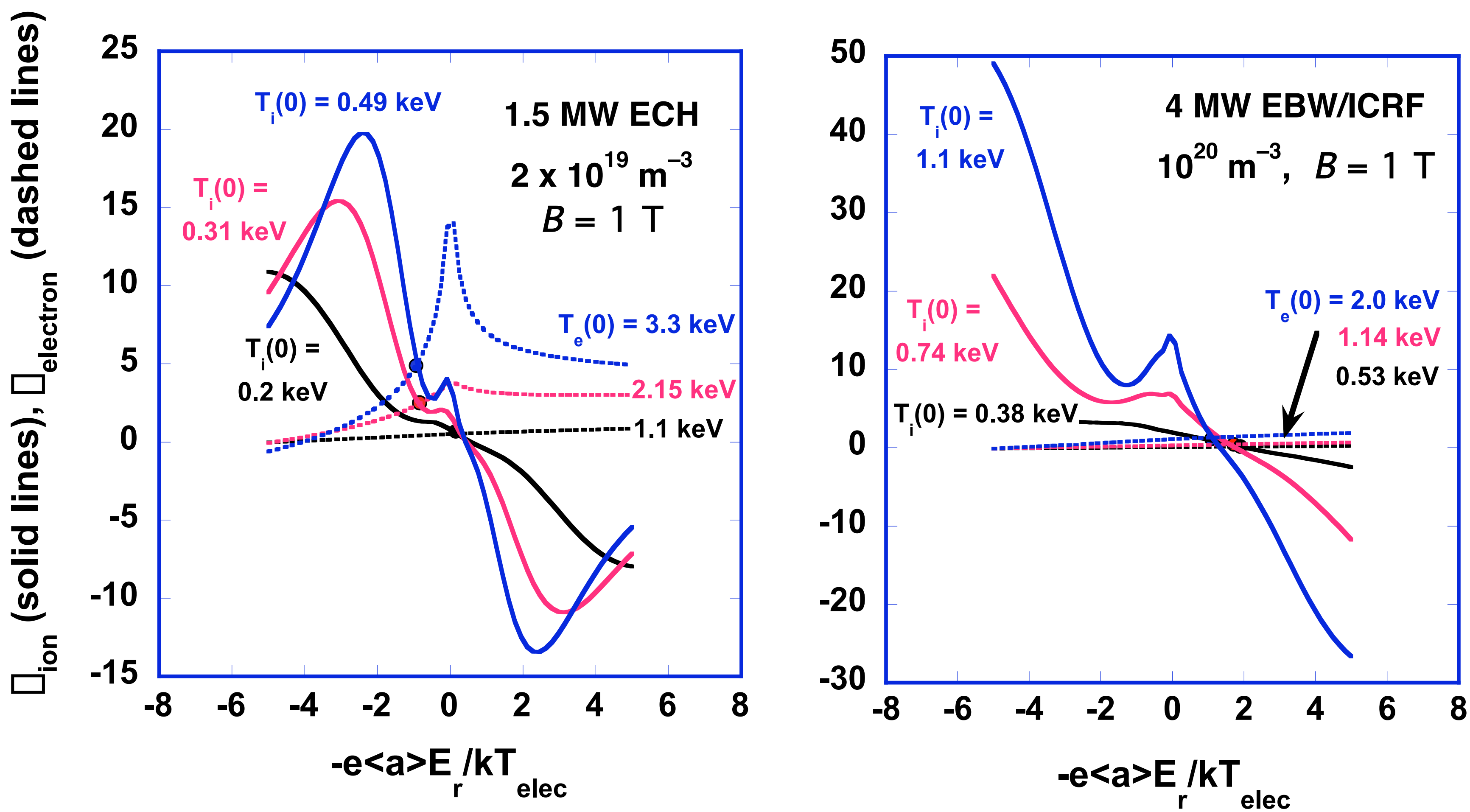


Ion Energy Lifetimes Are Improved Over Earlier QPS Designs and Similar Sized Devices

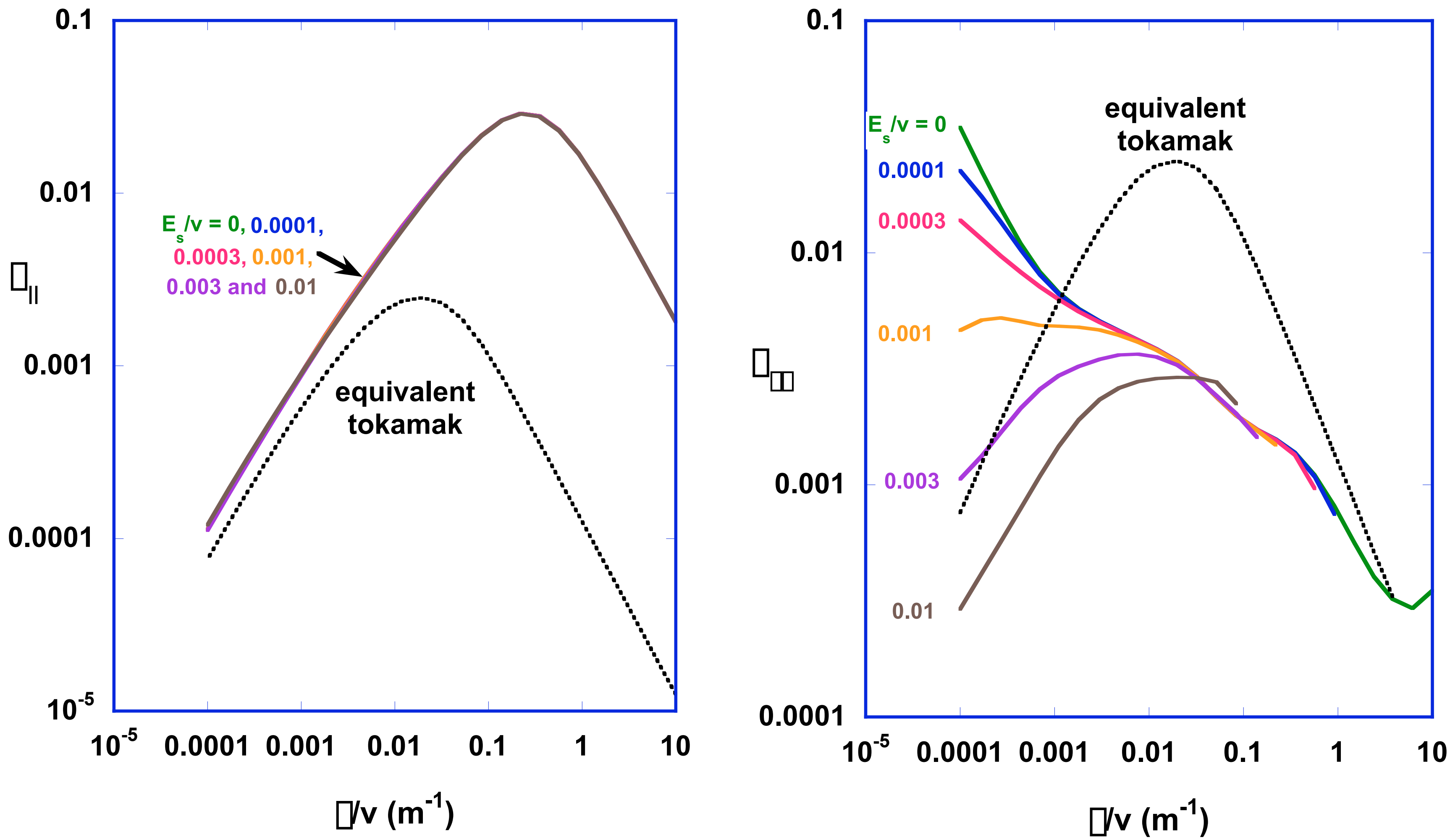


Monte Carlo calculations at higher collisionality

Ambipolar Electric Fields Provide a Source for Self-Generated *E* x *B* Poloidal Flows

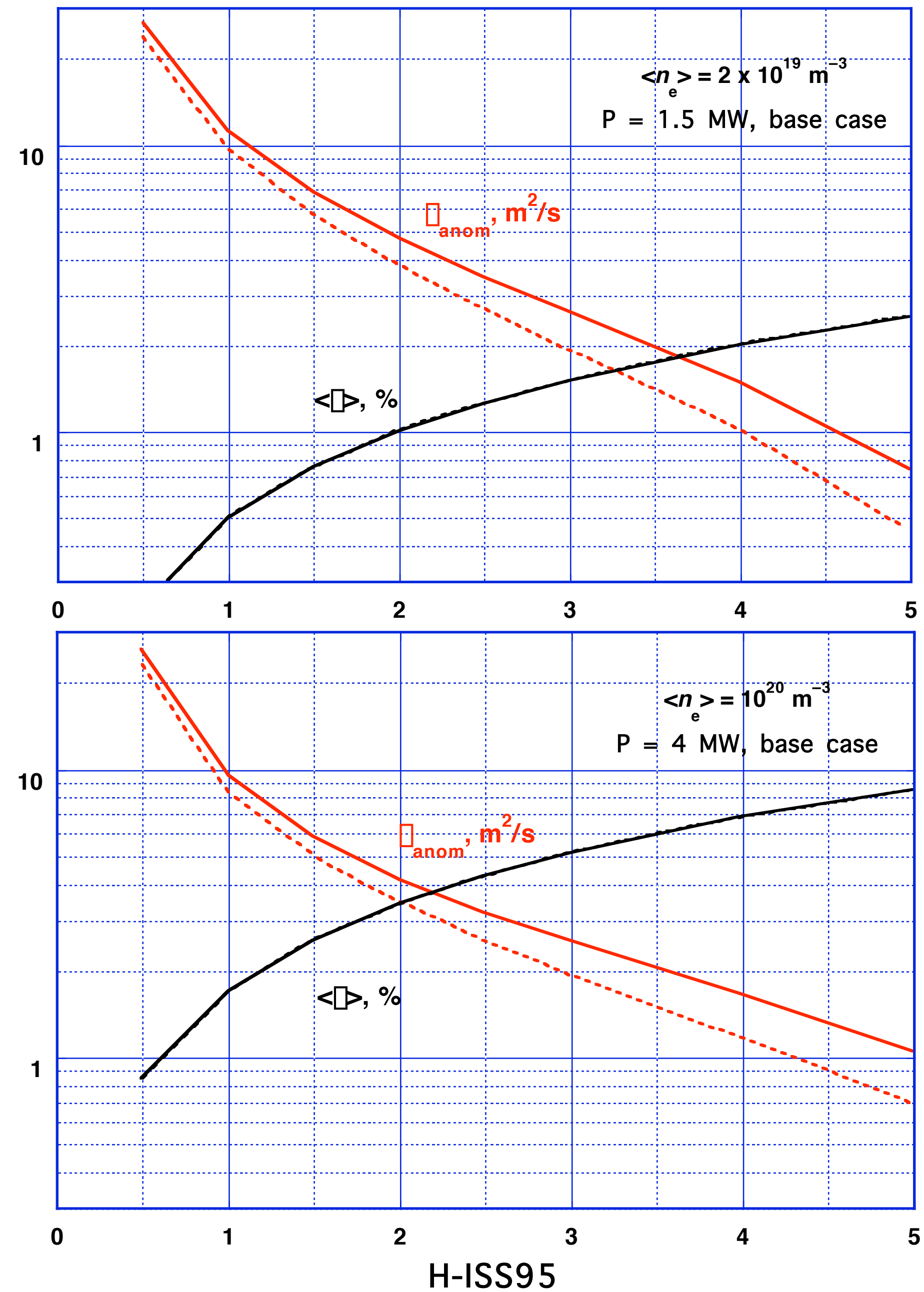


Viscosities (and Flow Damping) Depend on the Ambipolar Electric Field



Performance Allows Relevant □/□ Values

- **1-D transport calculations with self consistent radial electric field**
- **"H-ISS95" is the <u>net</u> confinement multiplier including both neoclassical and anomalous transport (□)**
- **Performance depends on degree of anomalous transport reduction, not sensitive to □ profile**
  - **dashed curves parabolic □ instead of constant □**



1-D Transport Calculations Indicate Possible Range of QPS Parameters

Case	Net H-ISS95	χ_{anom} (m^2/s)	$\langle\beta\rangle$ (%)	$T_e(0)$	$T_i(0)$
0.15 MW ECH 2×10^{19} m^{-3}	1	3.9	0.2	0.27	0.20
	2	1.5	0.4	0.61	0.40
	4	0.5	0.8	1.08	0.60
1.5 MW ECH 2×10^{19} m^{-3}	1	11.3	0.5	1.1	0.20
	2	4.8	1.0	2.15	0.31
	4	1.5	2.0	3.3	0.49
2 MW EBW/ICRF 10^{20} m^{-3}	1	7	1.3	0.36	0.30
	2	2.9	2.6	0.78	0.62
	4	1.2	5.2	1.5	1.0
4 MW EBW/ICRF 10^{20} m^{-3}	1	10	1.7	0.53	0.38
	2	4.2	3.4	1.14	0.74
	4	1.7	6.8	2.0	1.1
4 MW, 50-50 EBW/ICRF 10^{20} m^{-3}	1	10	1.7	0.45	0.47
	2	4.1	3.5	0.96	0.96
	4	1.7	6.8	1.56	1.71

Requires improved confinement

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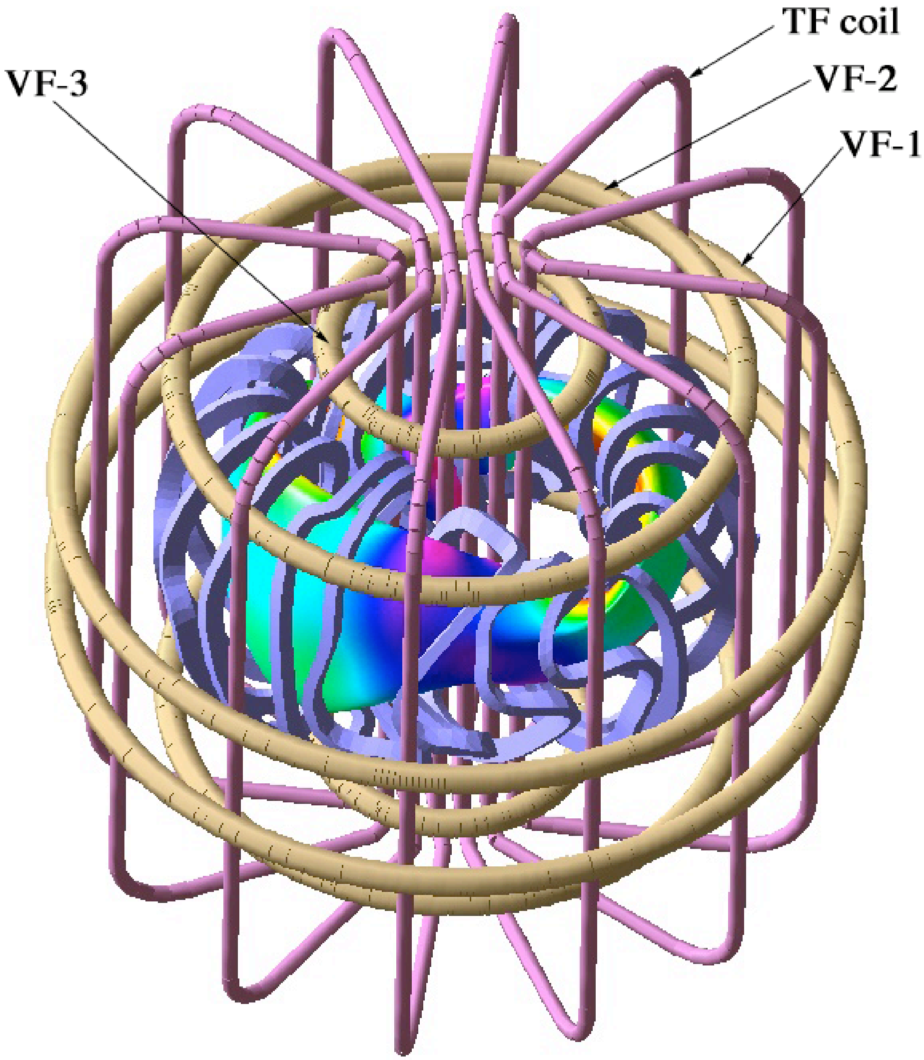
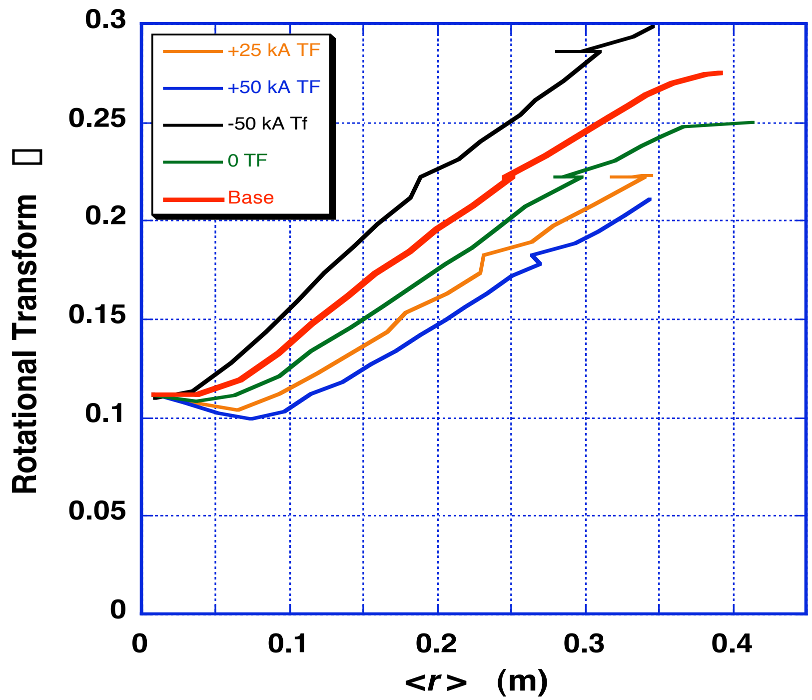
QPS Coil Sets Allow Configuration Flexibility



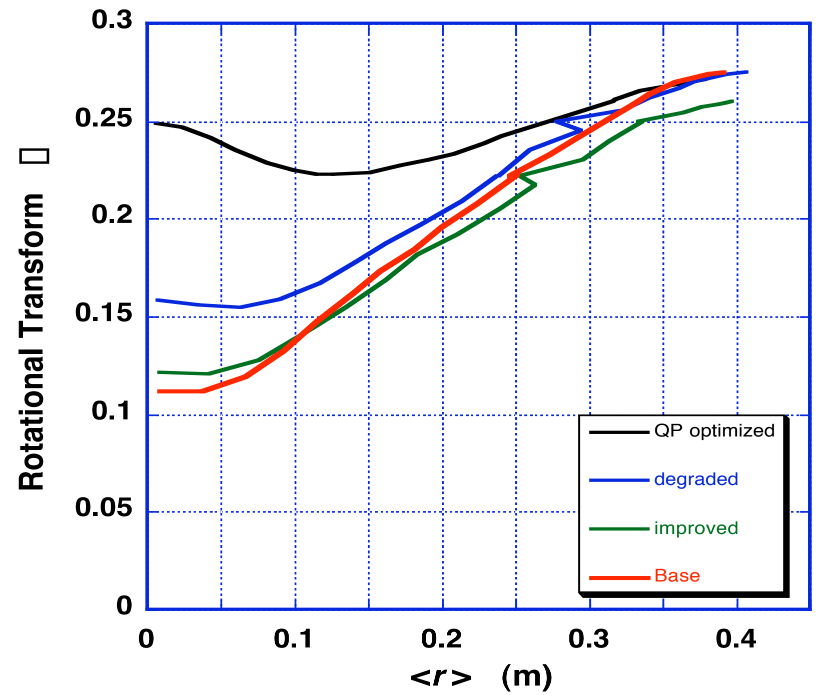
- 9 independent coil currents
  - 5 individually powered modular coil groups
  - 3 vertical field coil sets
  - Toroidal field coil set
  - Ohmic solenoid
    - Variable ratio of Ohmic to bootstrap current
- Allows a wide variation in
  - Neoclassical heat diffusivity
  - Degree of quasi-poloidal symmetry
  - Poloidal viscosity
  - Rotational transform and shear
  - β limits

Coils Allow Configuration Flexibility

- **Changing coil currents allows varying rotational transform profile**



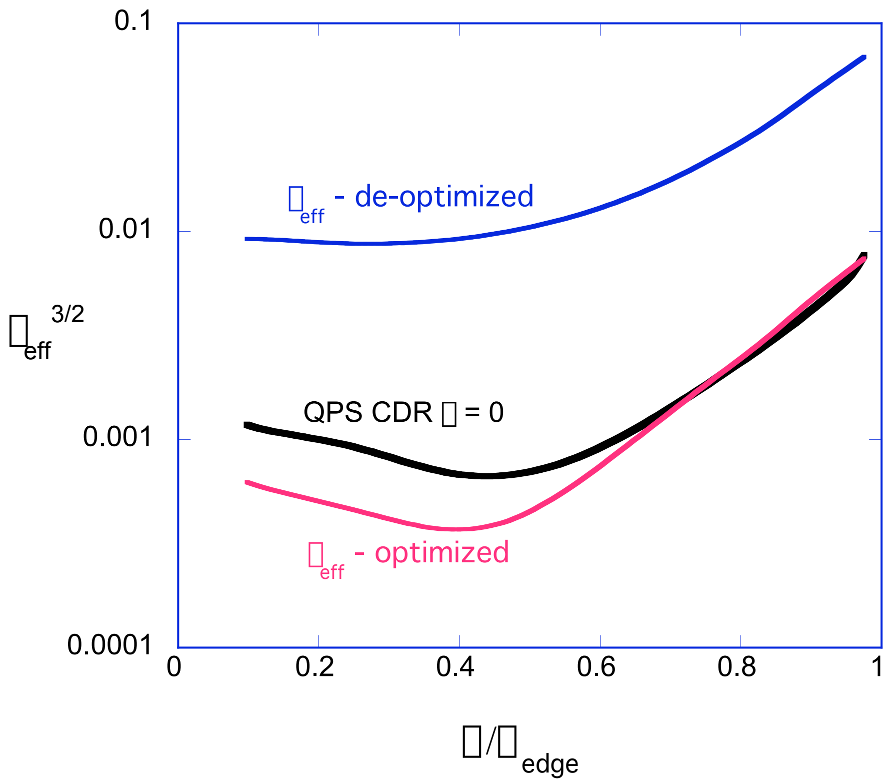
TF coil currents

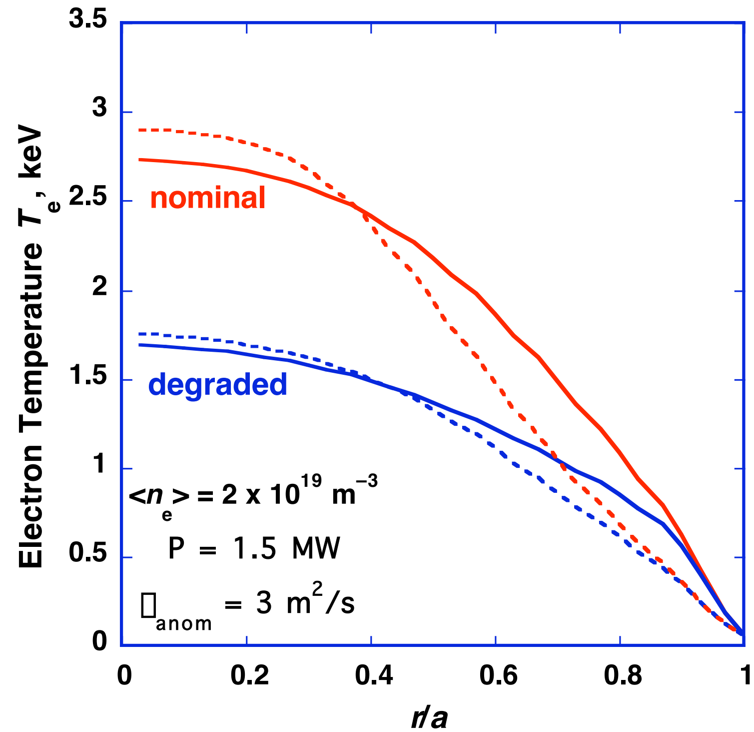


Different coil currents

Variation in Neoclassical Transport

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

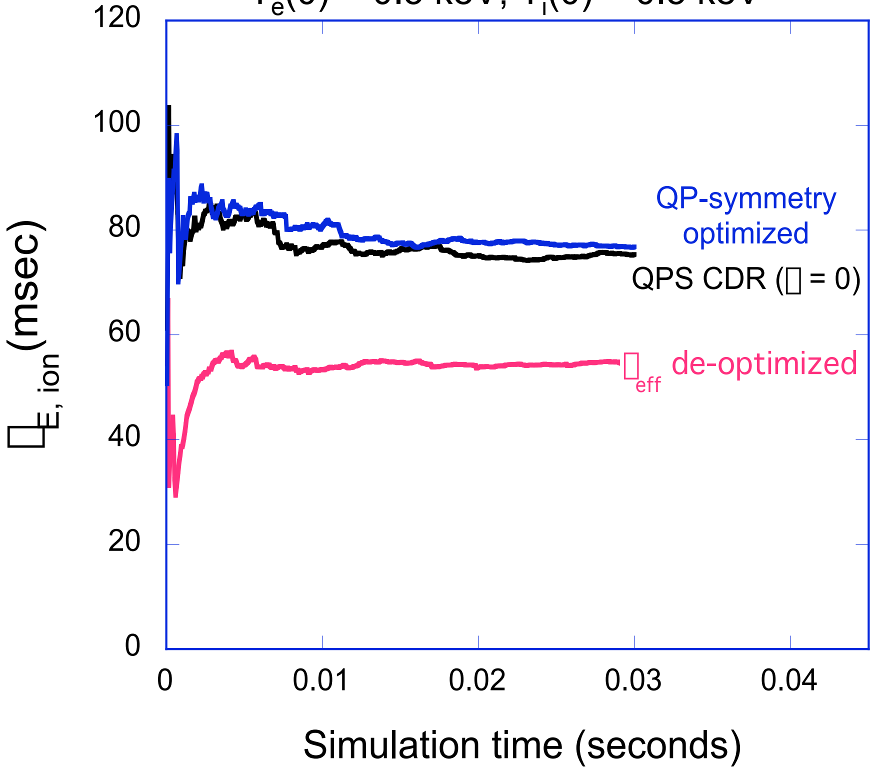




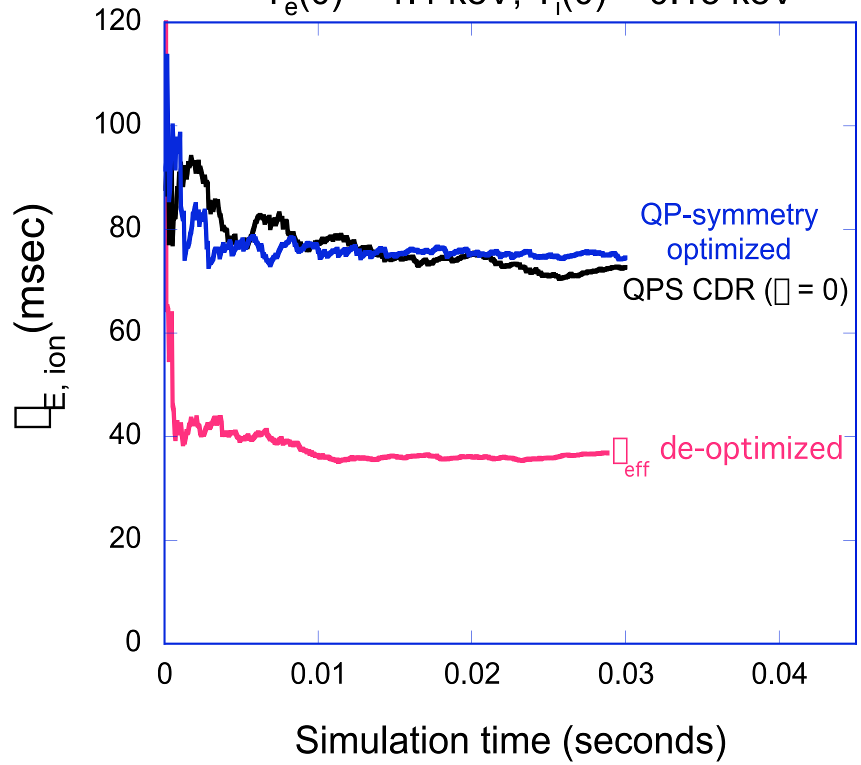
Coils Allow a 50 - 100% Variation in τ_E

- **Monte Carlo calculations of global ion energy confinement time with $E_r = 0$ at higher collisionality**

ICH regime: n(0) = 8 x 10^{19} m^{-3}, $T_e(0)$ = 0.5 keV, $T_i(0)$ = 0.5 keV



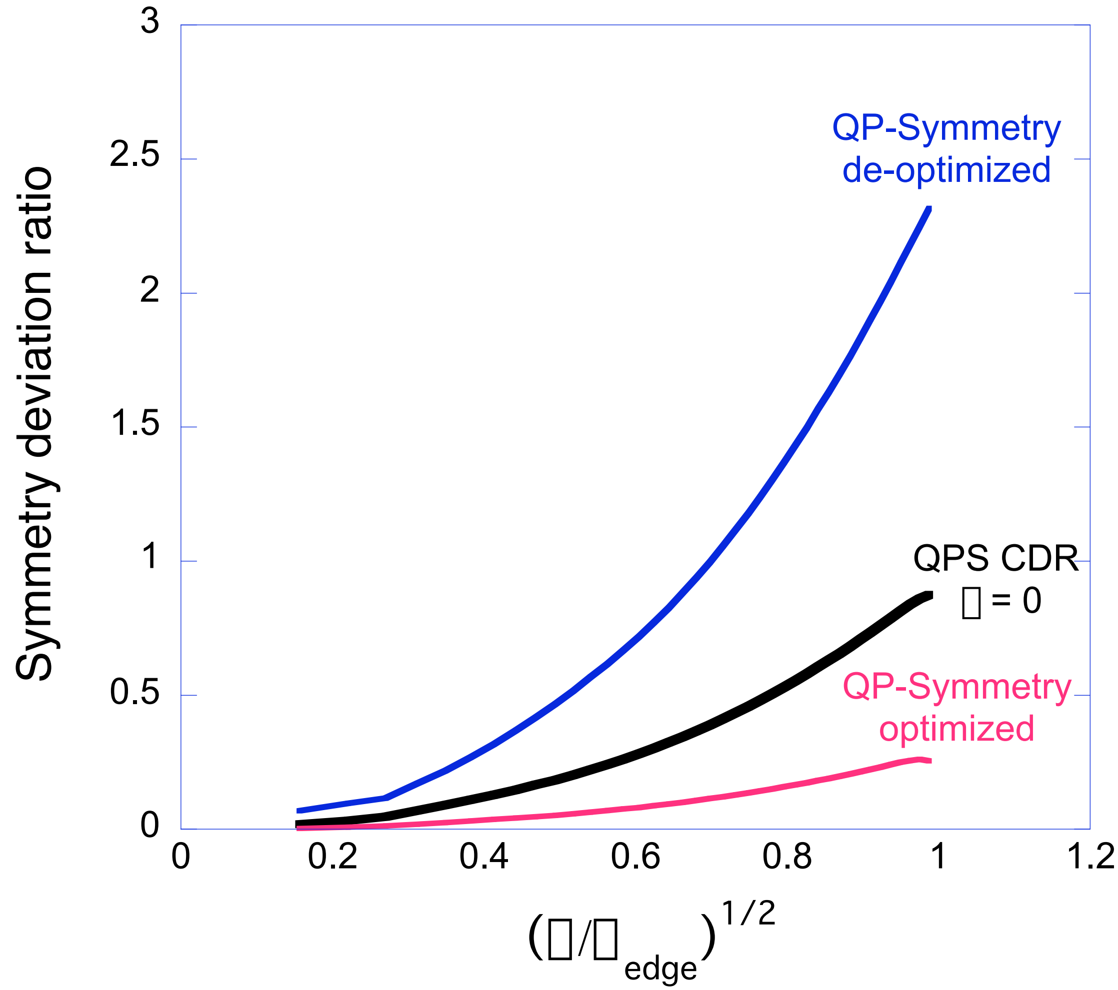
ECH regime: n(0) = 2 x 10^{19} m^{-3}, $T_e(0)$ = 1.4 keV, $T_i(0)$ = 0.15 keV



Variation in Quasi-Poloidal Symmetry

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

- **For fixed $v_{||}$, an ideal QPS device enhances E_r by $(B_t/B_p)^2$ over that in an axisymmetric device**



- **Changes in coil currents also allow a factor of 5-30 variation in the poloidal viscosity**

QPS Project Status

- Successful physics and concept design reviews
- The final QPS plasma and coil configuration has been selected and refined
- The next steps are
  - R&D studies for casting the stainless steel winding forms and the winding, vacuum canning, and potting of a prototype modular coil
  - Obtain DOE approval for completion of the design and fabrication

Summary

- **Equilibrium Robustness at *R/a* > 2.5**
  - Good flux surfaces obtained for a range of □s using coil current optimization and Ohmic/bootstrap current control to avoid low-order □ resonances
- **MHD Stability**
  - Mercier modes (□ = 3 %), infinite-*n* ballooning modes (□ = 2.5%), finite-*n* pressure driven modes (□ = 4.5 %), kink and vertical modes (□ = 5 %)
- **Transport**
  - Neoclassical << anomalous, can distinguish between them
  - Neoclassical improved over similar existing devices
  - Lowered poloidal viscous damping => improved control over electric field shear
  - 1-D transport calculations show □ and temperatures adequate for physics studies
- **Flexibility**
  - Wide range accessible in neoclassical □, quasi-poloidal symmetry, poloidal viscosity, □ and shear, MHD stability