OPTIMIZATION AND TRANSPORT ANALYSIS OF QUASI-POLOIDAL STELLARATORS

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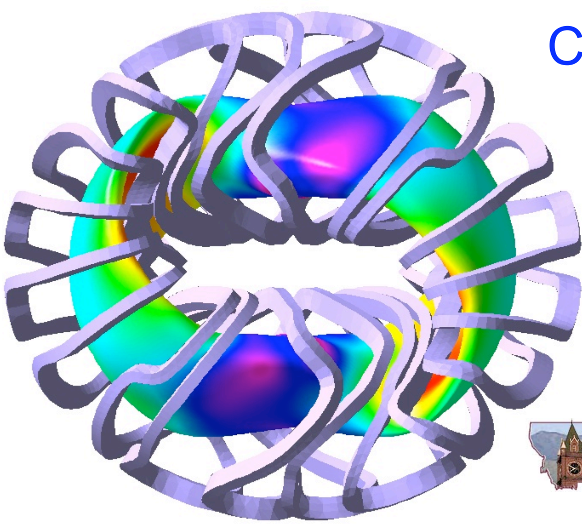
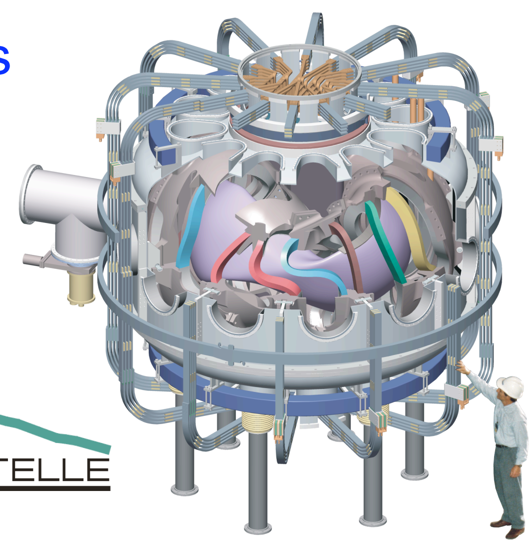
IAEA Technical Meeting on Innovative Concepts and Theory of Stellarators

September 29 - October 1, 2003

IPP - Greifswald, Germany

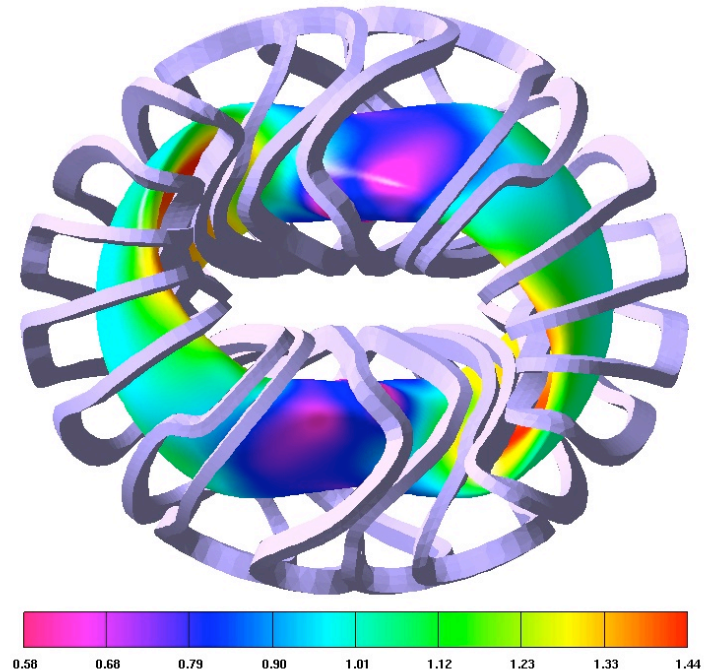


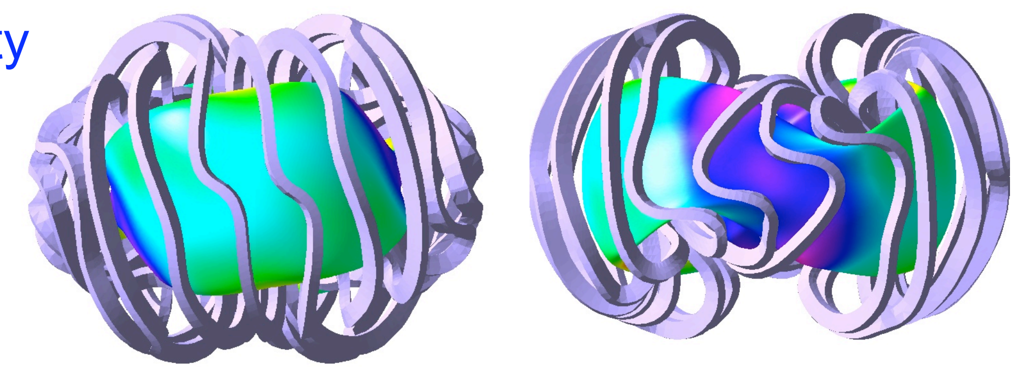


QPS (Quasi-Poloidal stellarator) incorporates compactness and unique physics goals

QPS

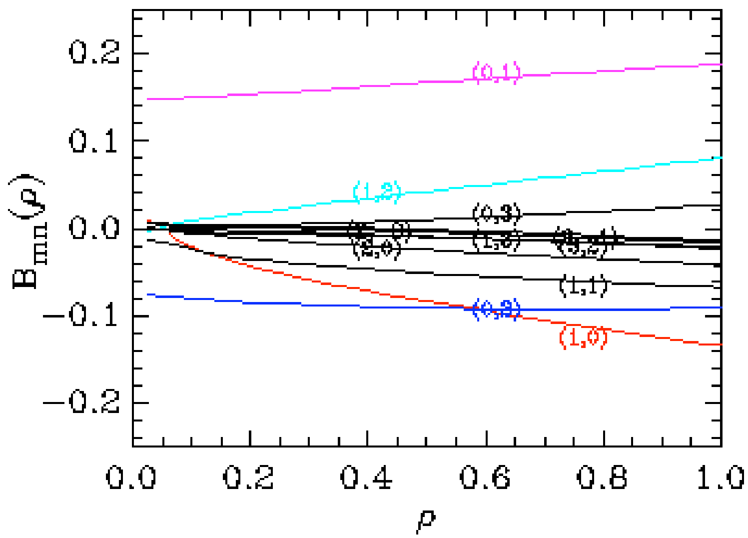
- QPS is a very low aspect ratio (A = 2.7) Quasi-poloidal (QP) stellarator that is unique in the world fusion program
- The QPS physics design meets the following requirements:
  - Equilibrium robustness at low A
  - Neoclassical << anomalous transport
  - Reduced poloidal viscosity effects on shear flow -> transport reduction
  - Stability limits up to $\langle\beta\rangle = 2.2\%$
  - Significant configurational flexibility

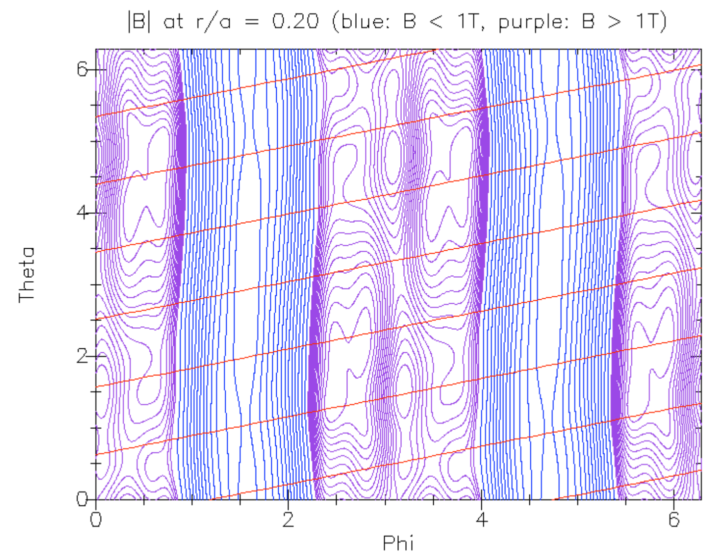


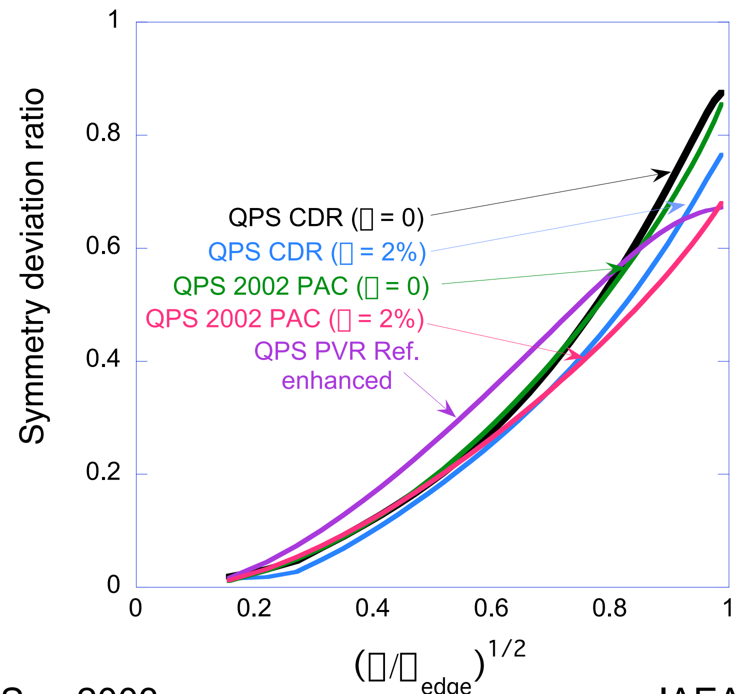


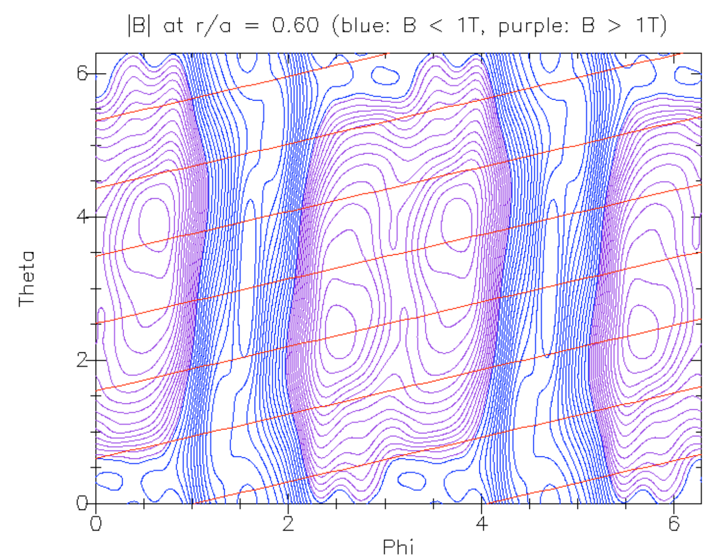
QPS-CDR maintains a high degree of QP-Symmetry in the central plasma region

QPS









The QPS physics studies have been enhanced by improvements in our design and analysis tools:

- Improved optimizations
  - Merged coil/plasma optimizations
    - allowed significant cost reductions in coil design (Dec., 2002)
  - Effective ripple transport target
    - improved transport properties (~50-100% increased τ_E)
  - New flux surface quality target
    - $B_{normal.vacuum}$ = 0 on β = 2% VMEC surface
    - Less configurational change with β
- Improved flexibility and physics analysis tools
  - Fixed coil geometry/variable coil current optimizations
    - Transport
    - Stability
  - VMEC/DKES
  - AORSA RF code applied to 3D equilibria
  - Finite-n MHD stability analysis with Terpsichore
  - Viscosity/flow damping
  - Runaway electron losses
  - Alfvén continuum calculation for 3D systems

Outline

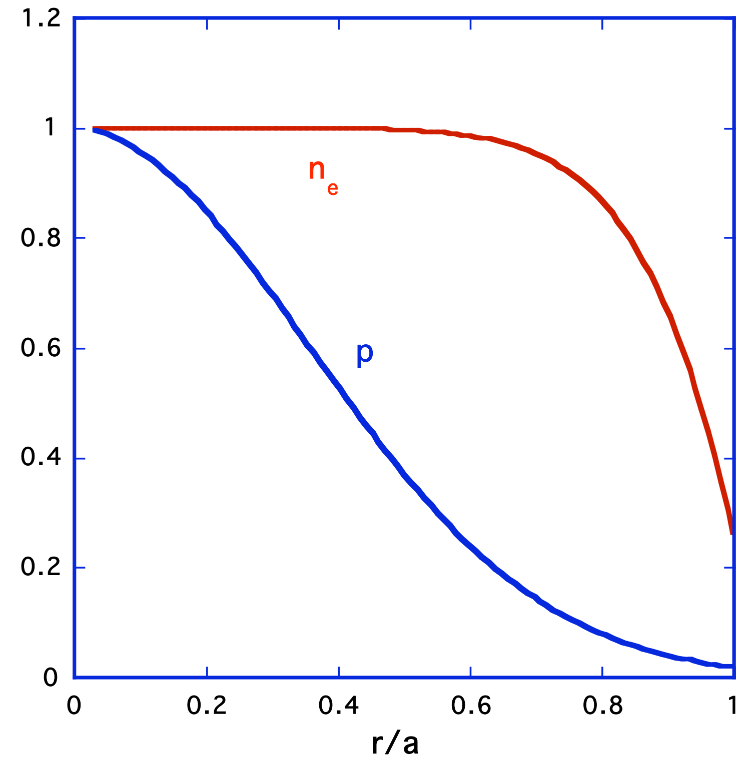
QPS

- Performance predictions
- Confinement properties
  - Low collisionality $\square_{eff}$ coefficient, QP symmetry
  - Diffusive DKES neoclassical transport coefficients
  - Monte Carlo global energy lifetimes
  - Viscosities/flow damping effects
  - Runaway electron losses
- Flexibility Properties
  - Transport optimization/de-optimization
  - Iota control: island avoidance
- Conclusions

QPS performance predictions show for normal regimes (H = 1) neoclassical power flows << anomalous.

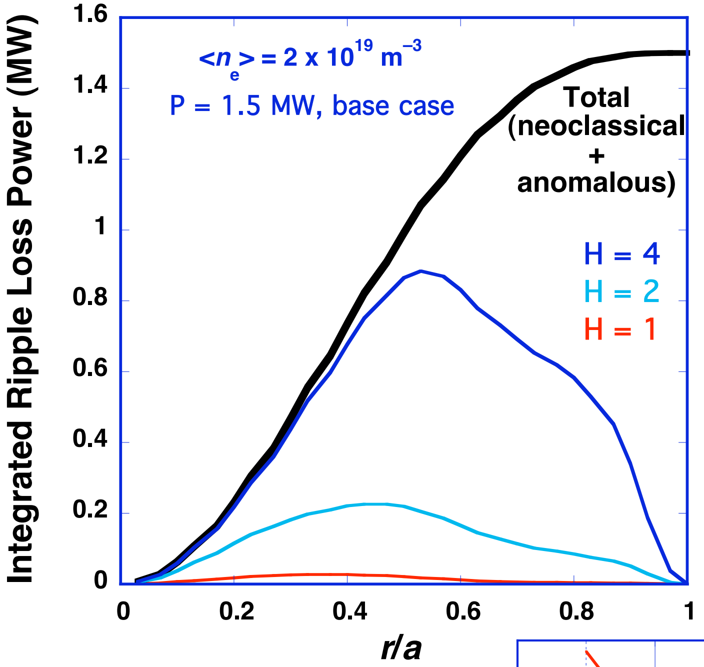
QPS

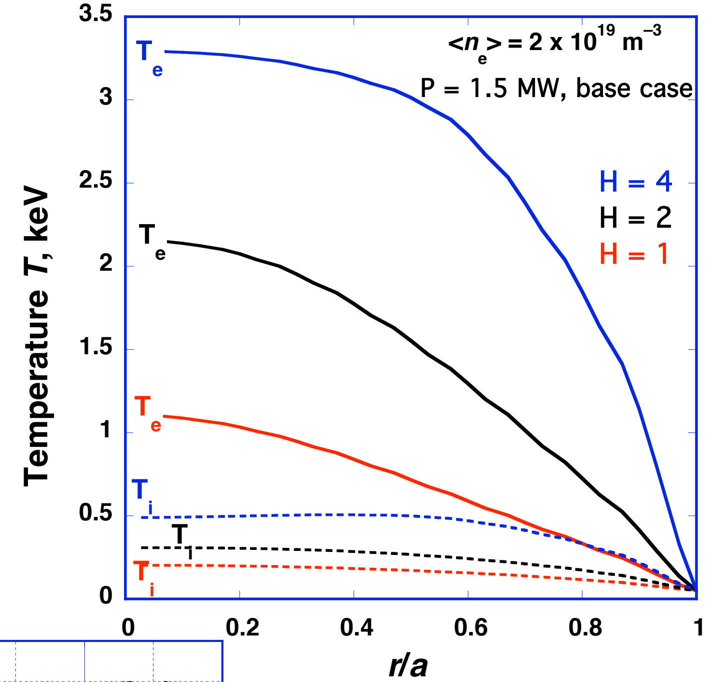
- Simple 1-D transport model used to asses performance
- Fixed density/power deposition profiles
- Neoclassical (Shaing-Houlberg E_r dependence with overall scaling by $\epsilon_{eff}^{3/2}$)
- Anomalous ISS95 transport
  - Anomalous transport scaled for various H-ISS95 factors

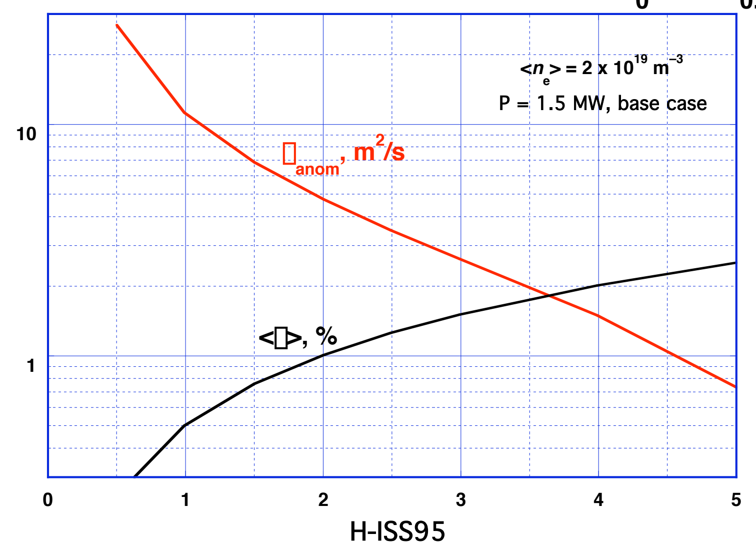


With moderate Power ECH (1.5 MW), H > 2, $T_e(0)$ = 2-3 keV, $T_i(0)$ = 0.2-0.5 keV

QPS







Four heating scenarios have been analyzed that allow exploration of significant parameter ranges

QPS

Case	H-ISS95	$□_{anom.}$ (m²/sec)	<□> (%)	$T_e(0)$	$T_i(0)$
0.15 MW ECH $2x10^{19}m^{-3}$	1	3.9	0.2	0.27	0.2
	2	1.5	0.4	0.61	0.4
	4	0.5	0.8	1.08	0.6
1.5 MW ECH $2x10^{19}m^{-3}$	1	11.3	0.5	1.1	0.2
	2	4.8	1.0	2.15	0.31
	4	1.5	2.0	3.3	0.49

= require successful transport reduction (H = 4)

The following cases will require development of high density heating techniques.

Case	H-ISS95	$□_{anom.}$ (m²/sec)	<□> (%)	$T_e(0)$	$T_i(0)$
2 MW EBW/ICRF $10^{20}m^{-3}$	1	7	1.3	0.36	0.3
	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

D. Mikkelsen
PPPL

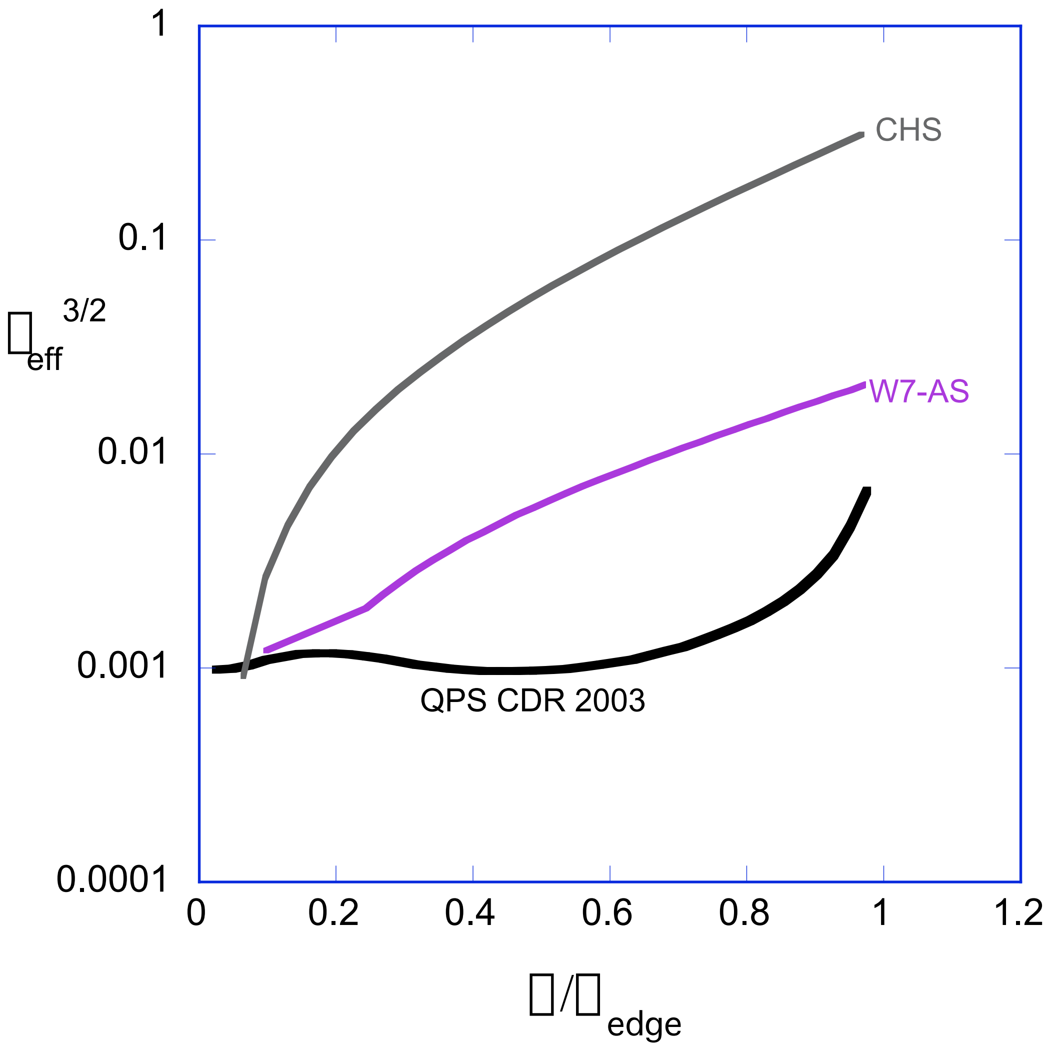
Quasi-poloidal symmetry: understand its effect on neoclassical transport, bootstrap current, and plasma flow damping.

- In order to develop a sound scientific basis for the QPS stellarator we use a spectrum of tools as measures of transport:
  - Effective ripple[1] $\epsilon_{eff}^{3/2}$: asymptotic low collisionality transport
  - QP symmetry: ratio of energy in non-symmetric modes ($m \neq 0$) to that in symmetric modes ($m = 0$)
  - Diffusive transport coefficient matrix (DKES code)
    - Will be integrated into 1-D models in the near future
    - Monte Carlo δf used to supplement low collsionality regime
    - Viscosities: related to DKES coefficients by recent work of Sugama[2]
  - Global Monte Carlo energy lifetimes

[1]V.V. Nemov, et. al, Phys. Plasmas **6**, 4622 (1999).
[2]H. Sugama, S. Nishimura, Phys. Plasmas **9**, 4637 (2002).

Our design has made continuing improvements in the effective ripple $\epsilon_{eff}^{3/2}$

QPS



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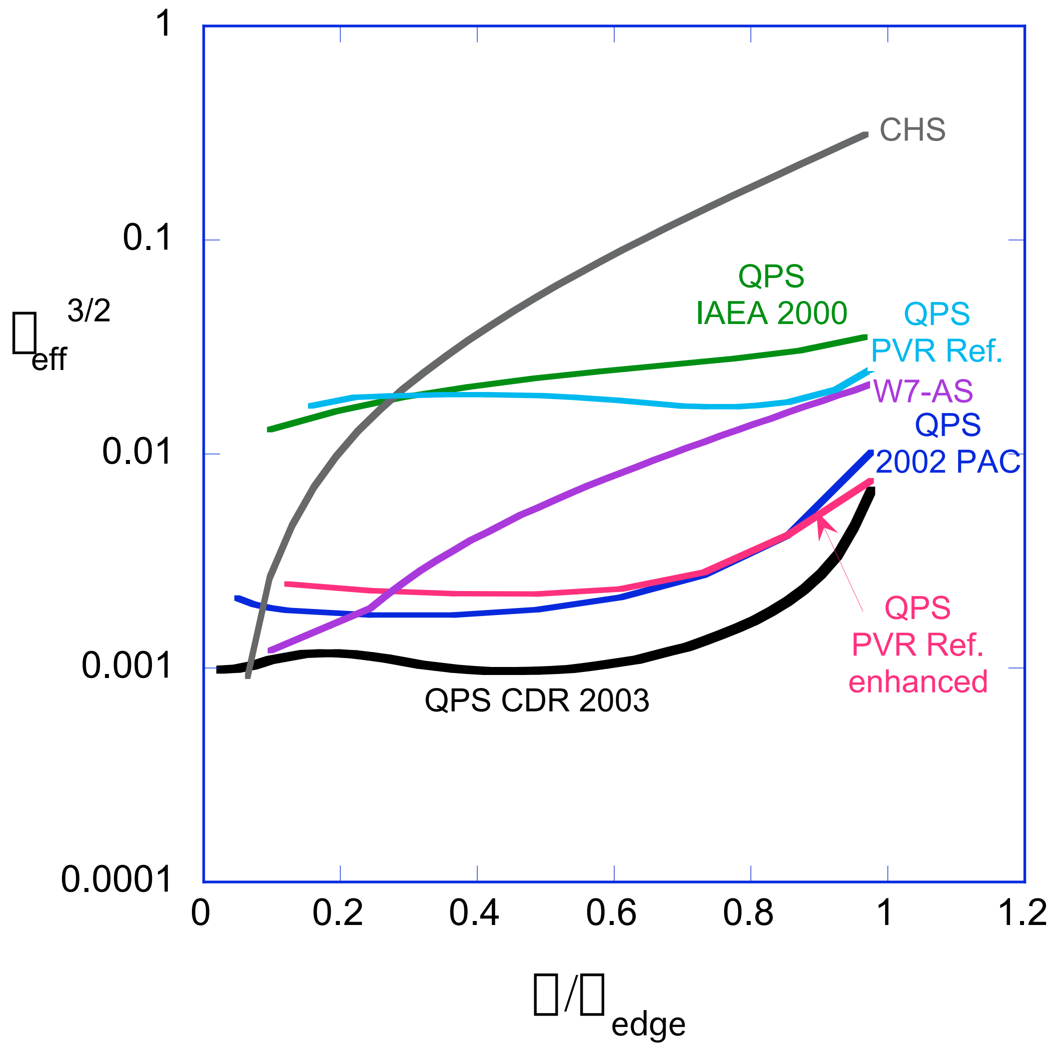
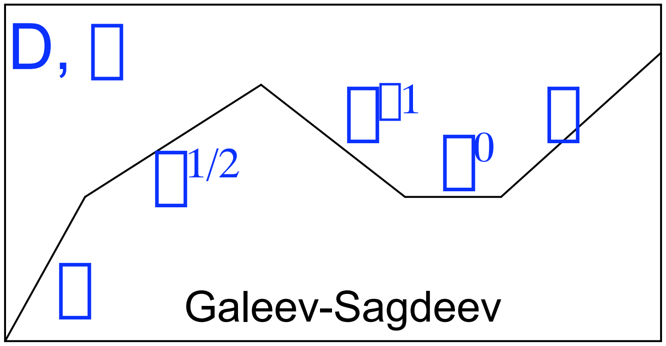


Local QPS DKES transport coefficients show that both plateau and $1/\nu$ regimes are accessed.

QPS

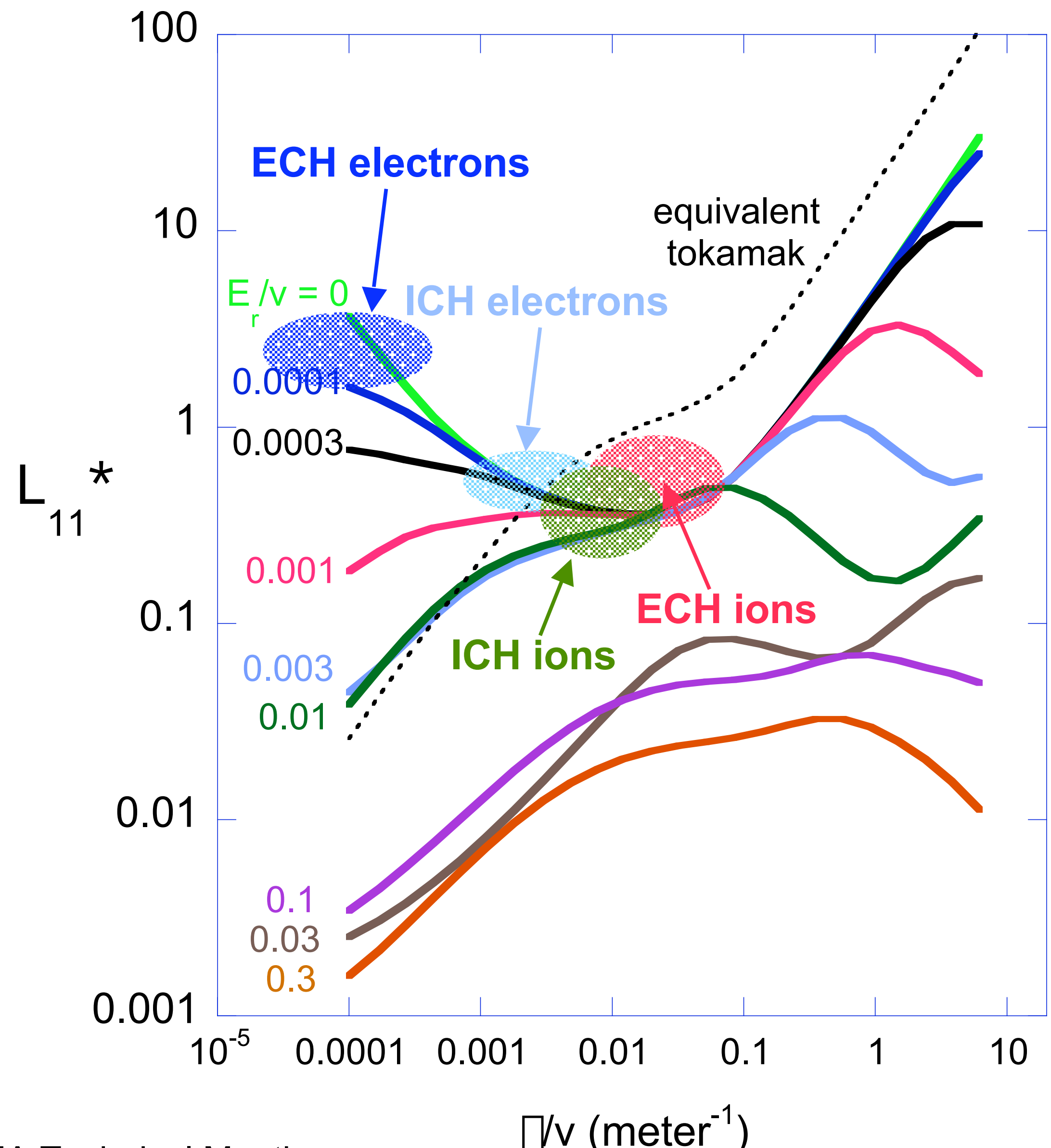


ECH regime: n = 1.8x10^{19}m^{-3}, T_{e0}=1.4 keV, T_{i0}=0.15 keV

- **ECH electrons**:
  - 7x10^{-5} < ν/v < 10^{-3}
  - 8x10^{-5} < E/v < 2x10^{-4}
- **ECH ions**:
  - 6x10^{-3} < ν/v < 7x10^{-2}
  - 10^{-2} < E/v < 3x10^{-2}

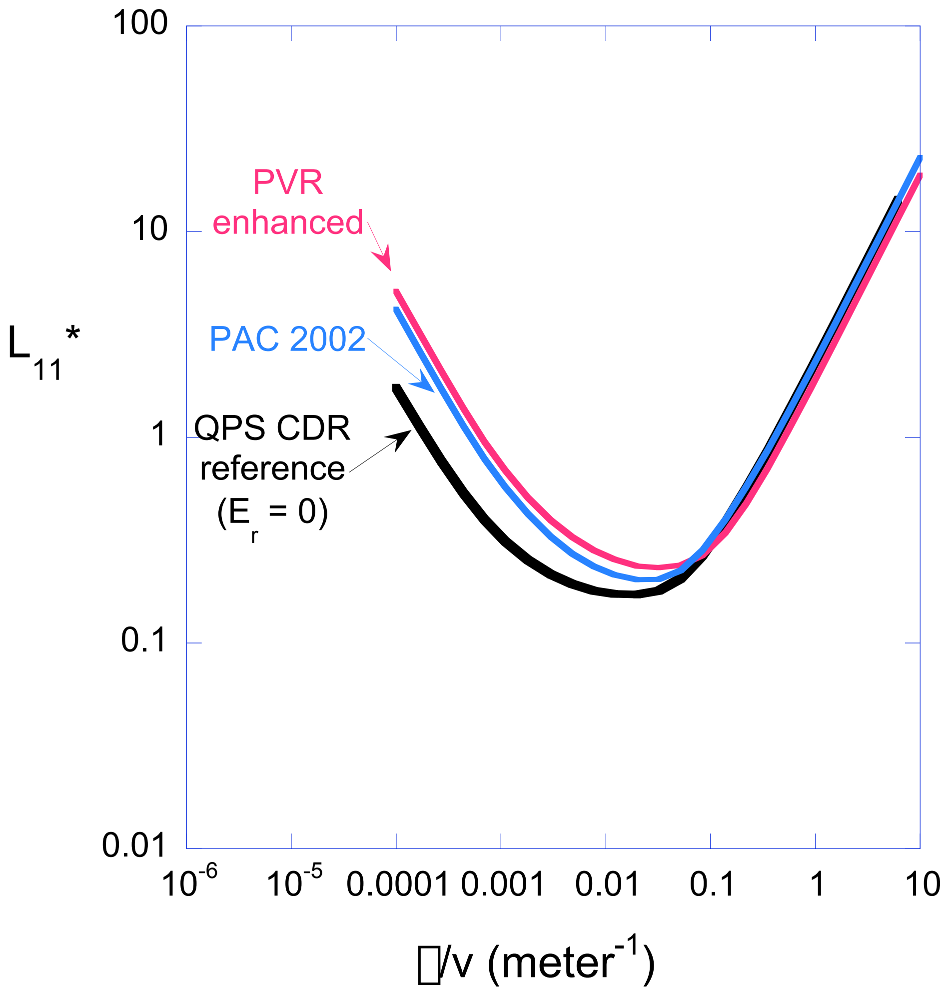
ICH regime: n = 8.3x10^{19}m^{-3}, T_{e0}=0.5 keV, T_{i0}=0.5 keV

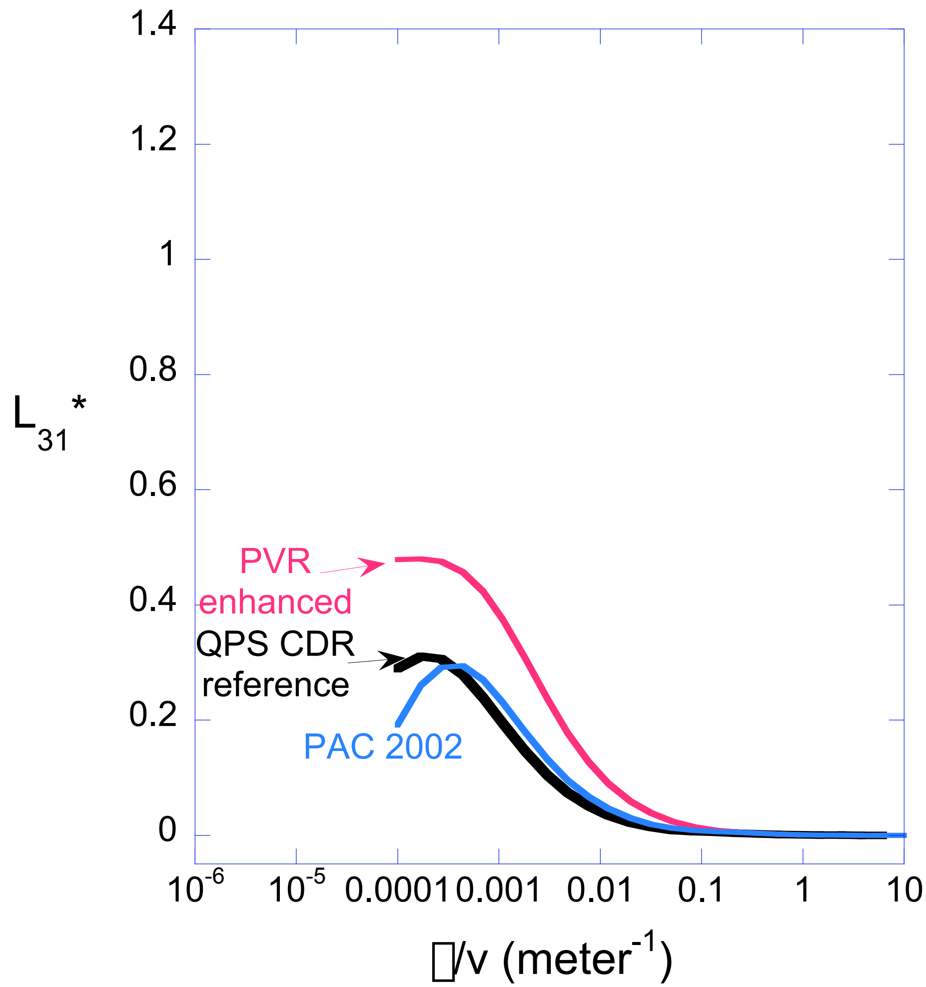
- **ICH electrons:**
  - 3x10^{-3} < ν/v < 4x10^{-2}
  - 5x10^{-5} < E/v < 2x10^{-4}
- **ICH ions:**
  - 2x10^{-3} < ν/v < 3x10^{-2}
  - 2x10^{-3} < E/v < 6x10^{-3}



DKES transport coefficients show similar improvements in our design as □$_{eff}^{3/2}$

QPS





DKES transport coefficients show similar improvements in our design as $\epsilon_{eff}^{3/2}$

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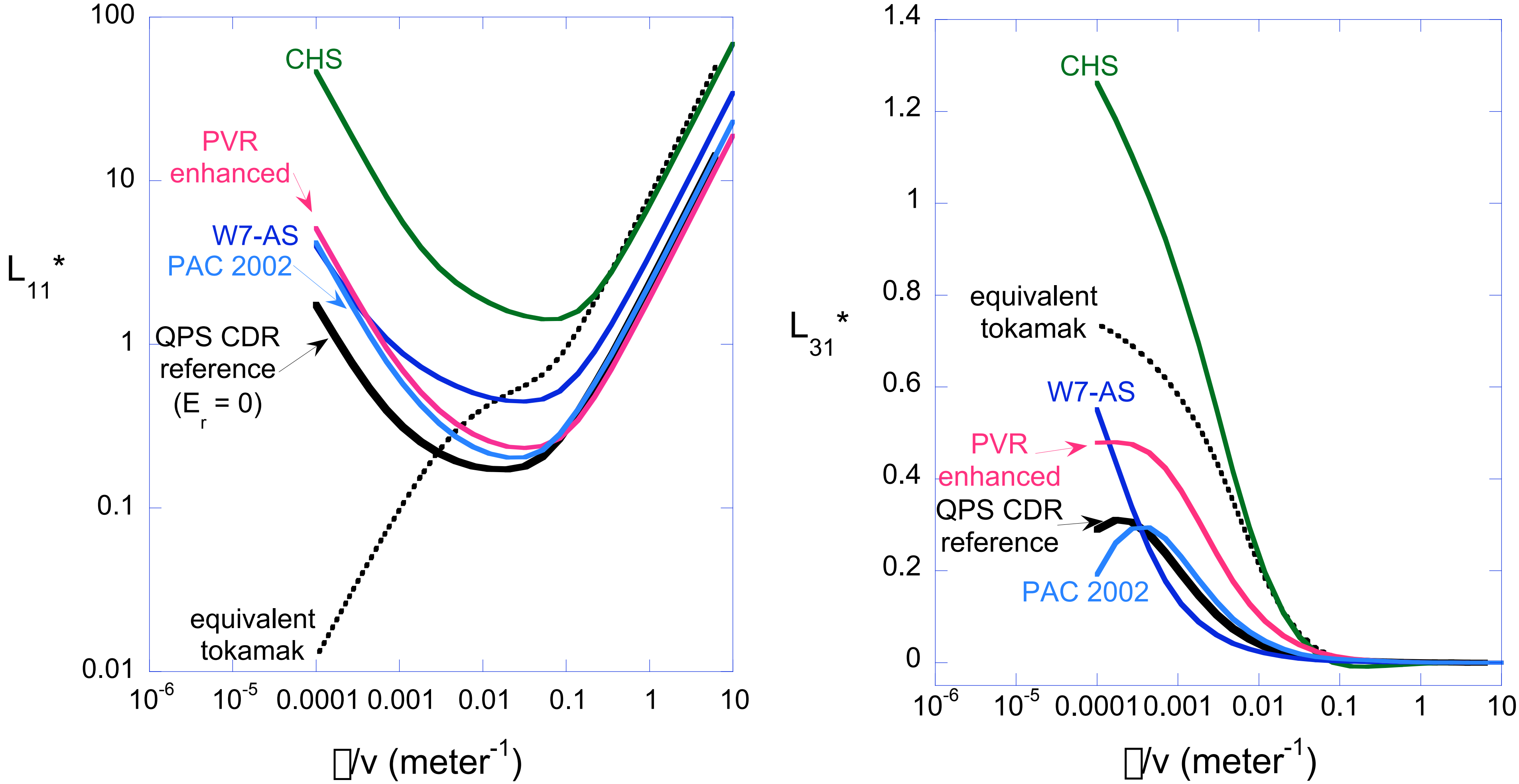
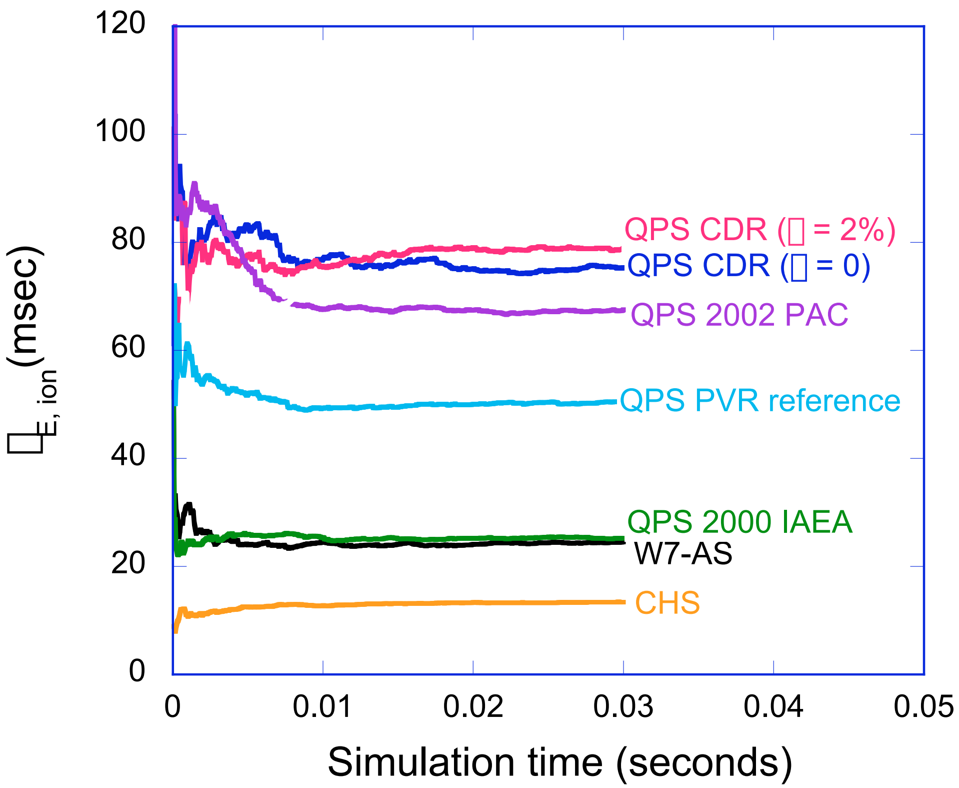
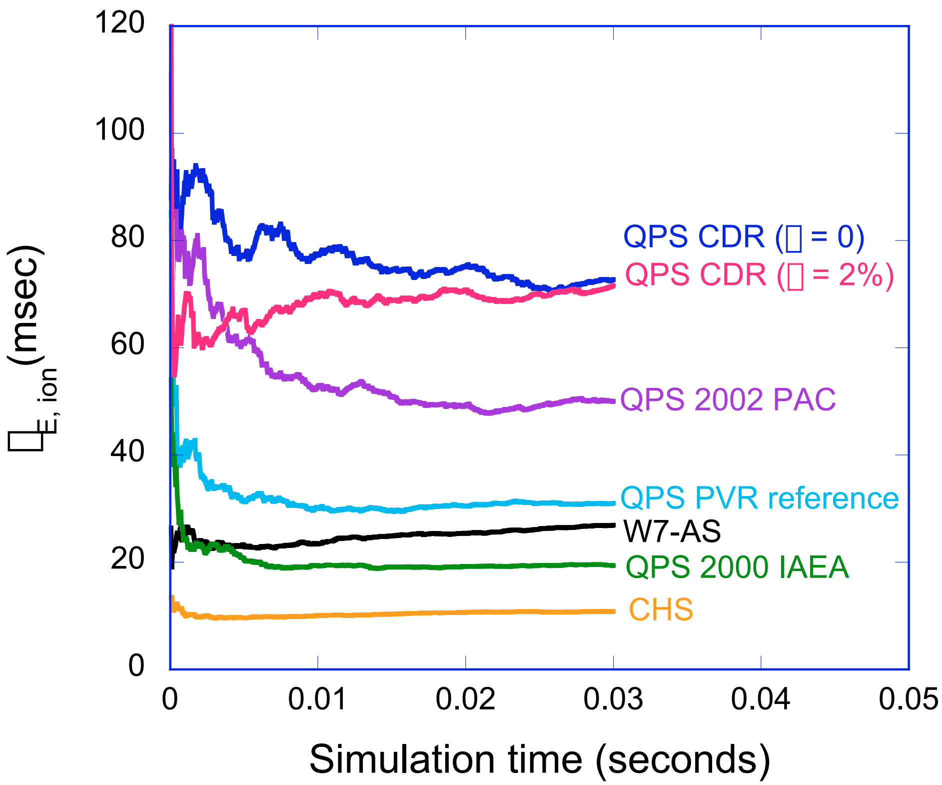


Monte Carlo ion energy lifetime estimates show improved neoclassical confinement over previous configurations:

QPS





Monte Carlo analysis of runaway electrons provides information about confinement and loss locations

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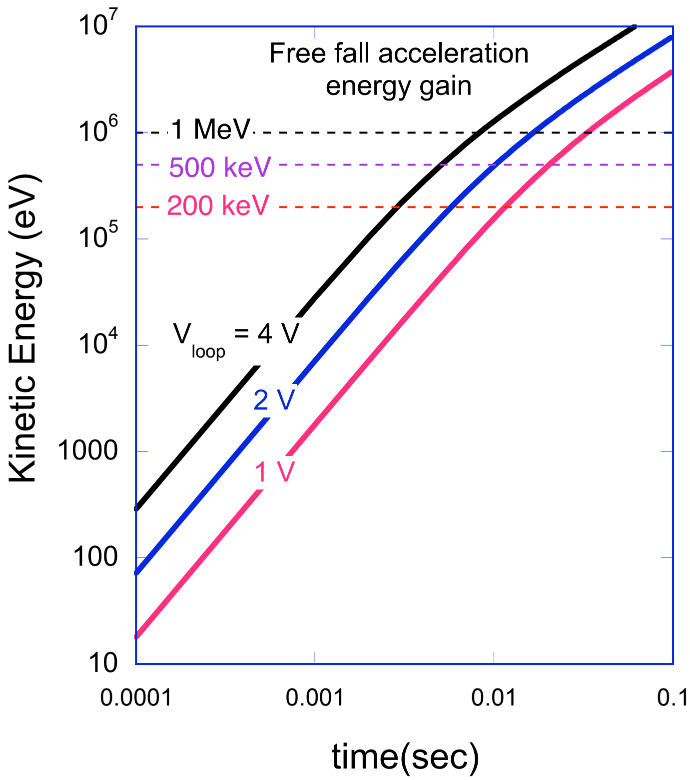
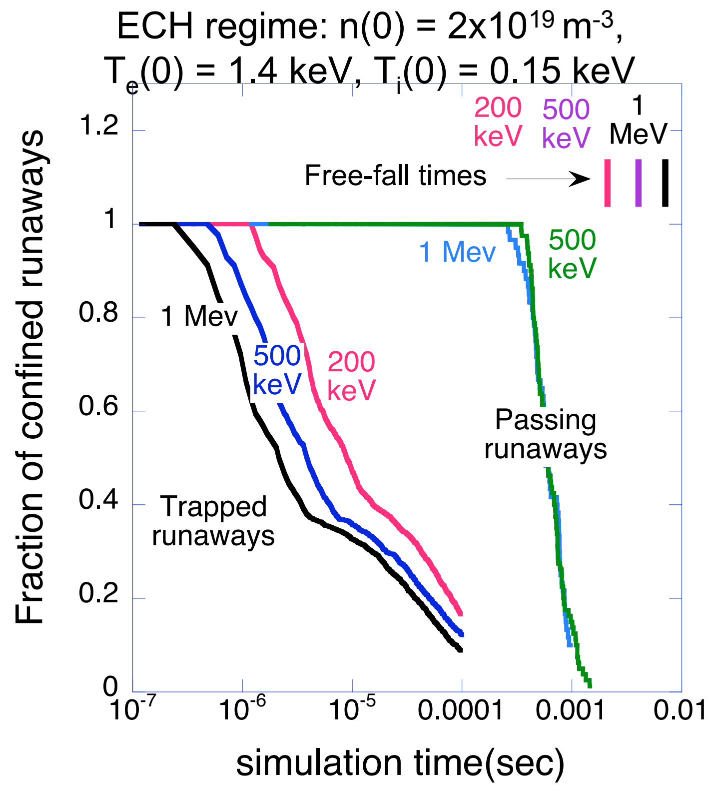
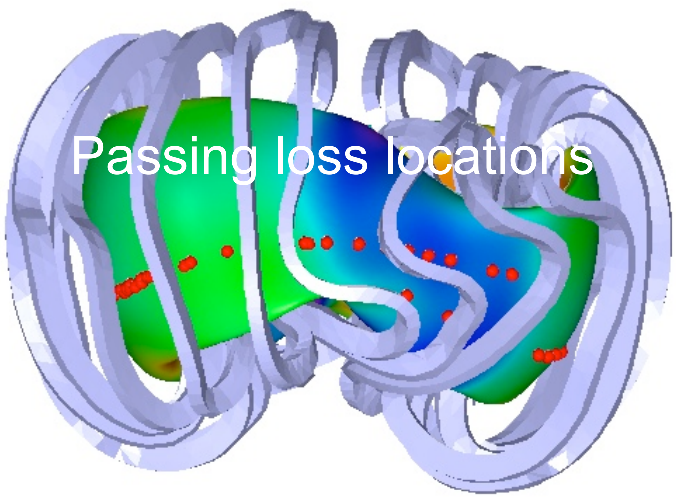
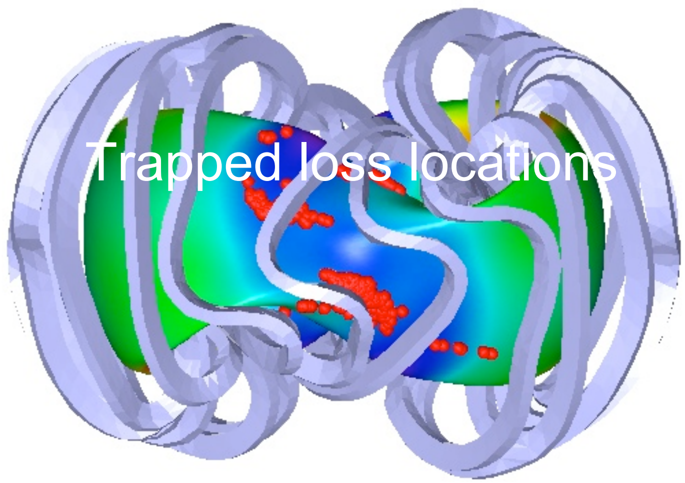








QPS Transport Enhancement: understand the unique effects of quasi-poloidal symmetry on anomalous transport suppression

- Enhanced confinement regimes in tokamaks have been attributed to electric field shear
  - Shredding of turbulent eddys
- This can be driven by a variety of sources
  - Self-amplified background plasma flows
  - Flows driven by external sources (beams, RF)
  - Turbulence
  - Pressure gradient drive
- The QPS design has achieved several goals that will allow a better understanding of enhanced confinement regimes in compact stellarators
  - Neoclassical transport << anomalous
  - Poloidal flow damping reduced from that of equivalent tokamak

Transport Enhancement Mission: Poloidally symmetric devices offer unique flow damping characteristics that can help access enhanced confinement regimes

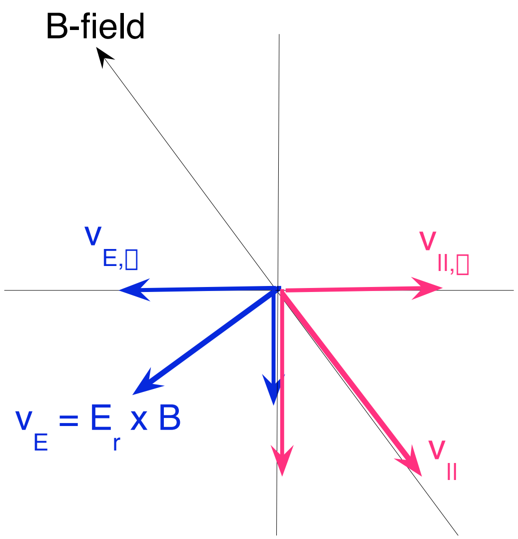
QPS

Tok. QPS

$u_p \square\ 0$ $u_t \square\ 0$

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

Tokamak: exact symmetry



$$\frac{E_r B_t}{B^2} = \mathrm{v}_\parallel \frac{B_p}{B} \ \square\ \ \mathrm{v}_\parallel \ \square\ \frac{E_r}{B_p} \ \text{ or } E_r = \frac{B_p}{B_t} B\mathrm{v}_\parallel$$

Transport Enhancement Mission: Poloidally symmetric devices offer unique flow damping characteristics that can help access enhanced confinement regimes

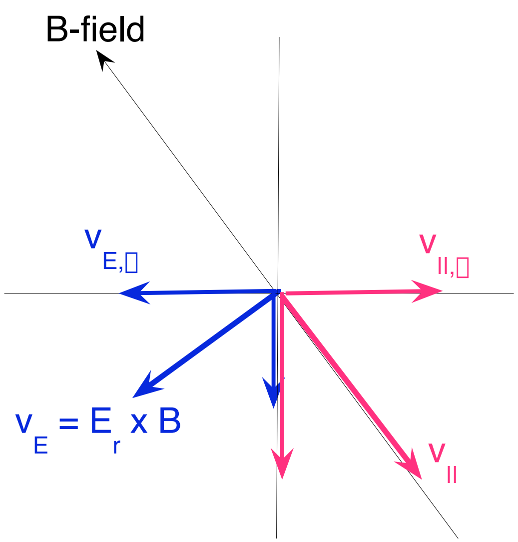
QPS

Tok. QPS

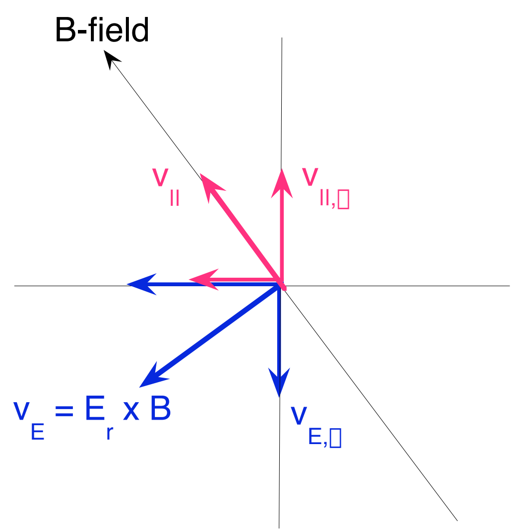
$u_p \approx 0$ $u_t \approx 0$

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

Tokamak: exact symmetry



QPS: exact symmetry



$$\frac{E_r B_t}{B^2} = v_{\|}\frac{B_p}{B} \Rightarrow v_{\|} \approx \frac{E_r}{B_p} \text{ or } E_r = \frac{B_p}{B_t}Bv_{\|}$$

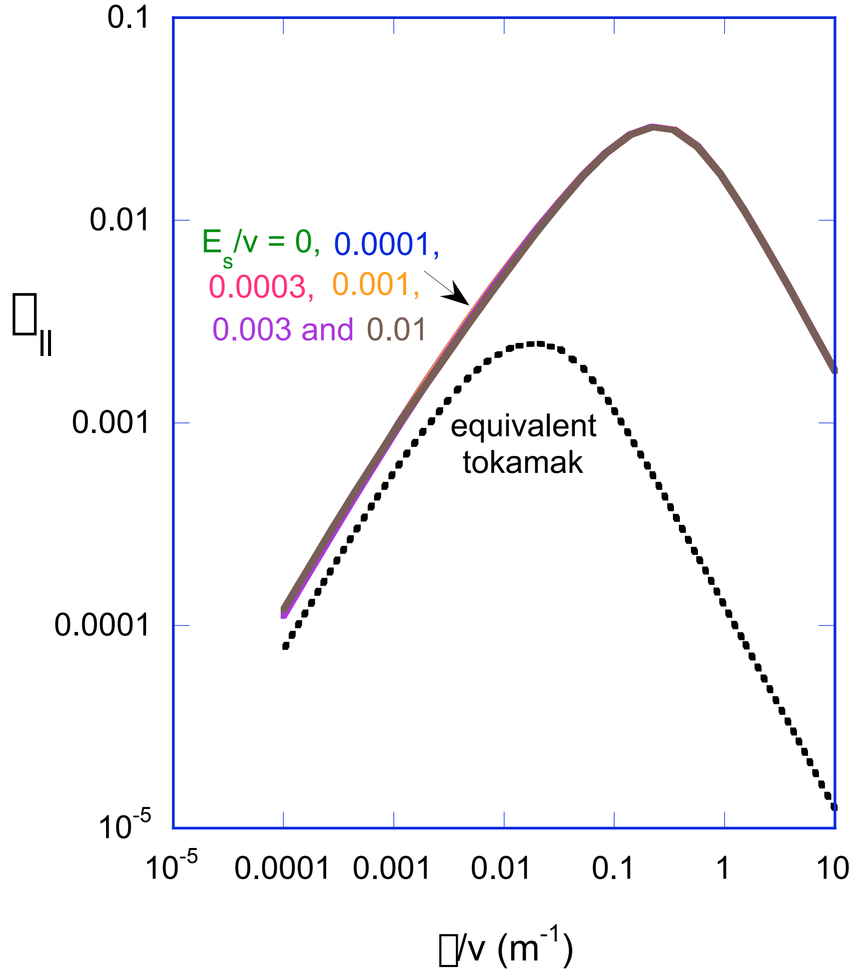
$$\frac{E_r B_p}{B^2} = v_{\|}\frac{B_t}{B} \Rightarrow v_{\|} = \frac{E_r}{B_t}\frac{B_p}{B} \text{ or } E_r = \frac{B_t}{B_p}Bv_{\|}$$

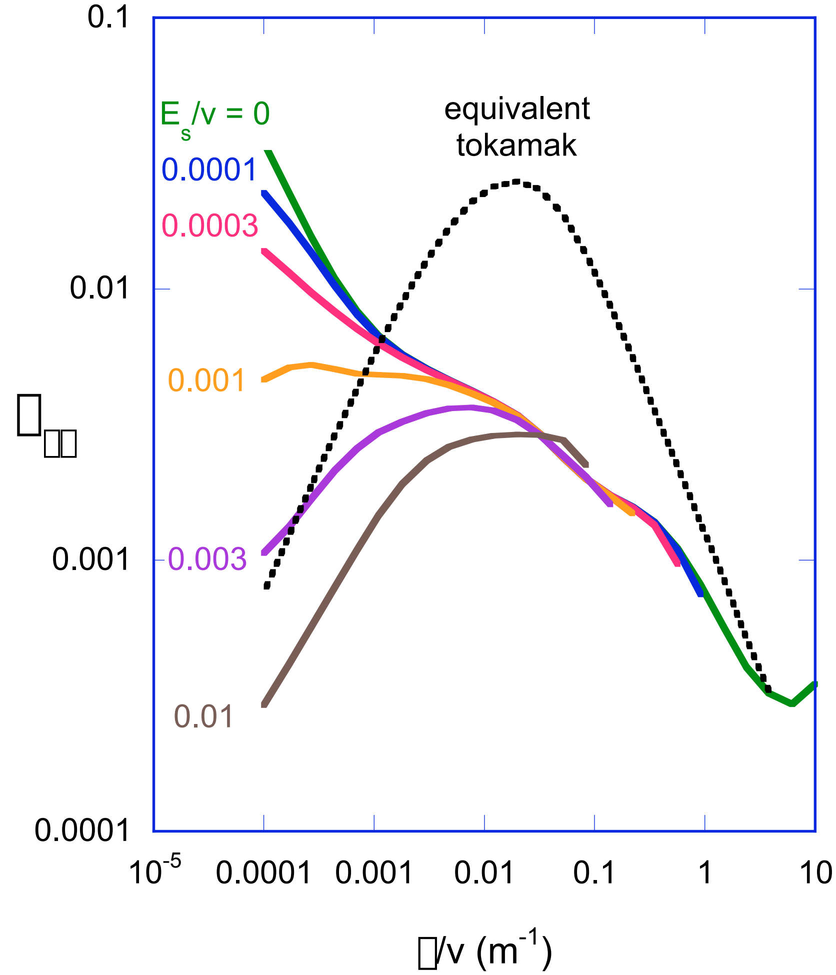
For fixed $v_{\|}$, QP device enhances E_r by $(B_t/B_p)^2$

Further reductions in poloidal viscosity occur when ambipolar electric fields are present.

QPS

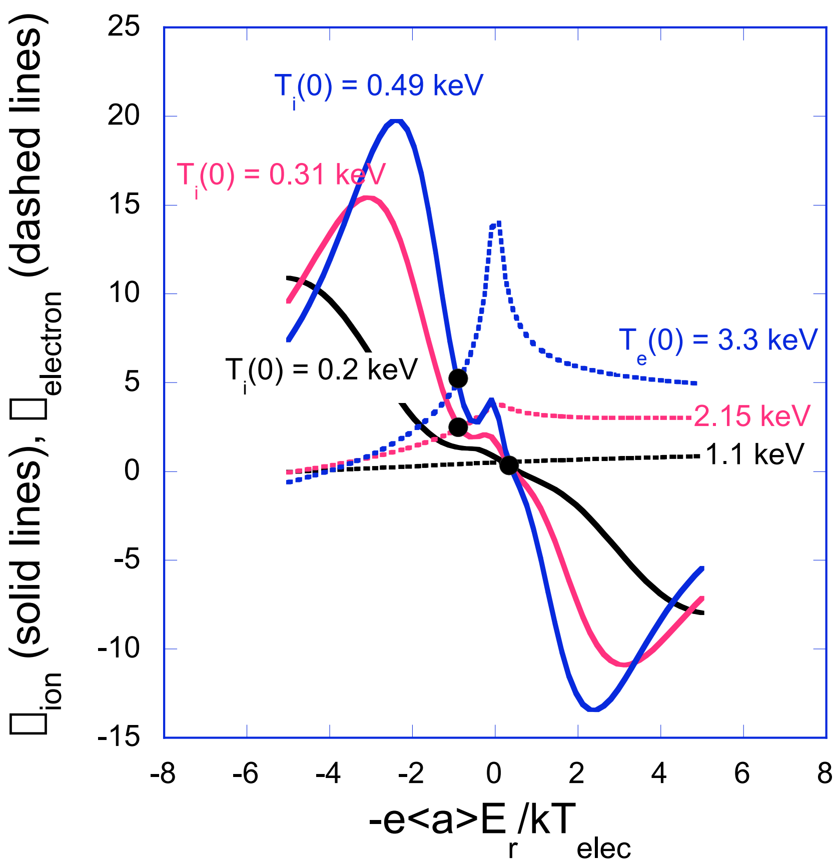
Viscosity analysis based on method of H. Sugama, S. Nishimura, Phys. Plasmas 9, 4637 (2002).



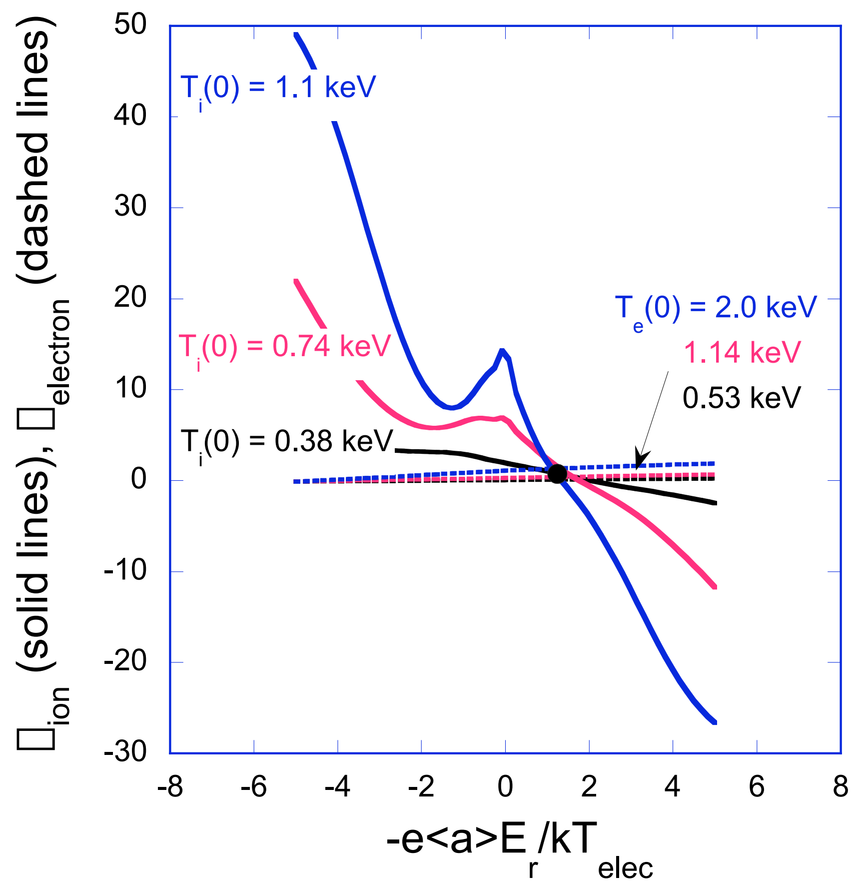


Ambipolar electric fields provide a source for self-generated poloidal flows (QPS can access both electron and ion roots)

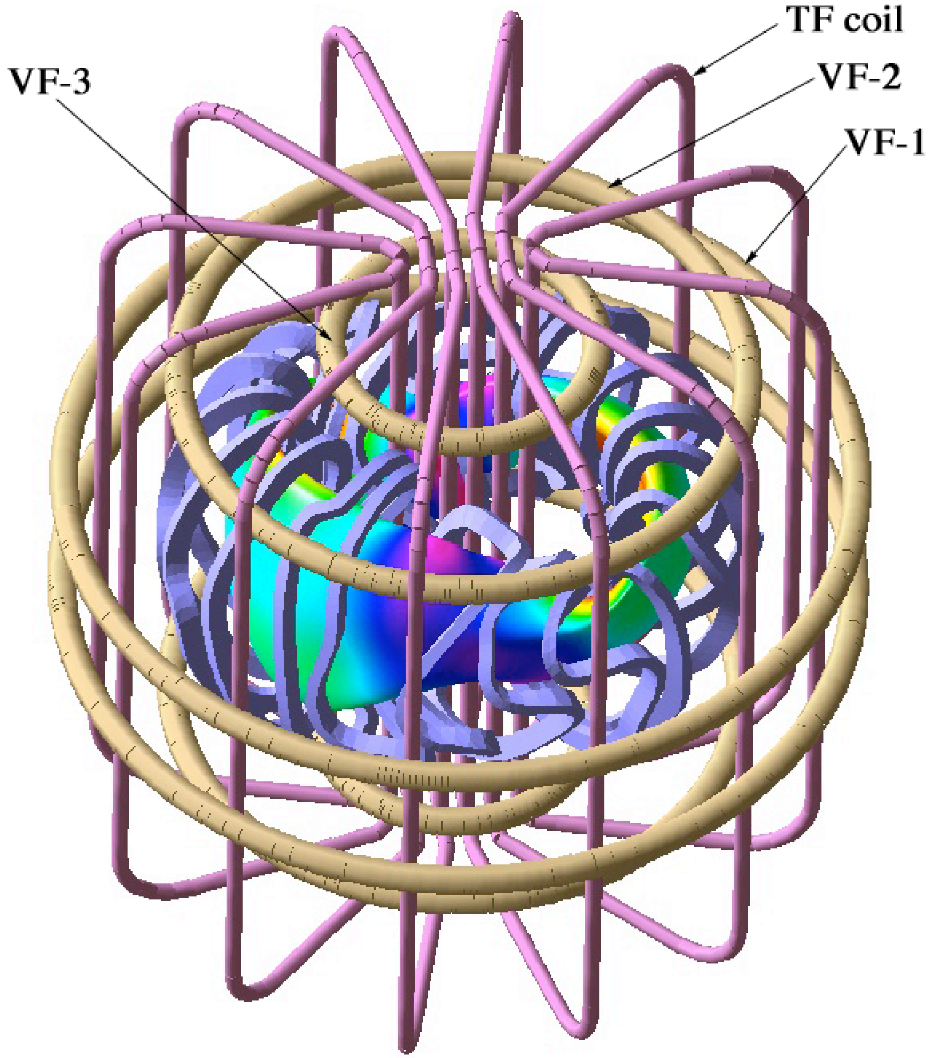
ECH [n(0) = 2 x 10^{19} m^{-3}]



ICH [n(0) = 8 x 10^{19} m^{-3}]



QPS offers substantial flexibility through 9 independently variable coil currents

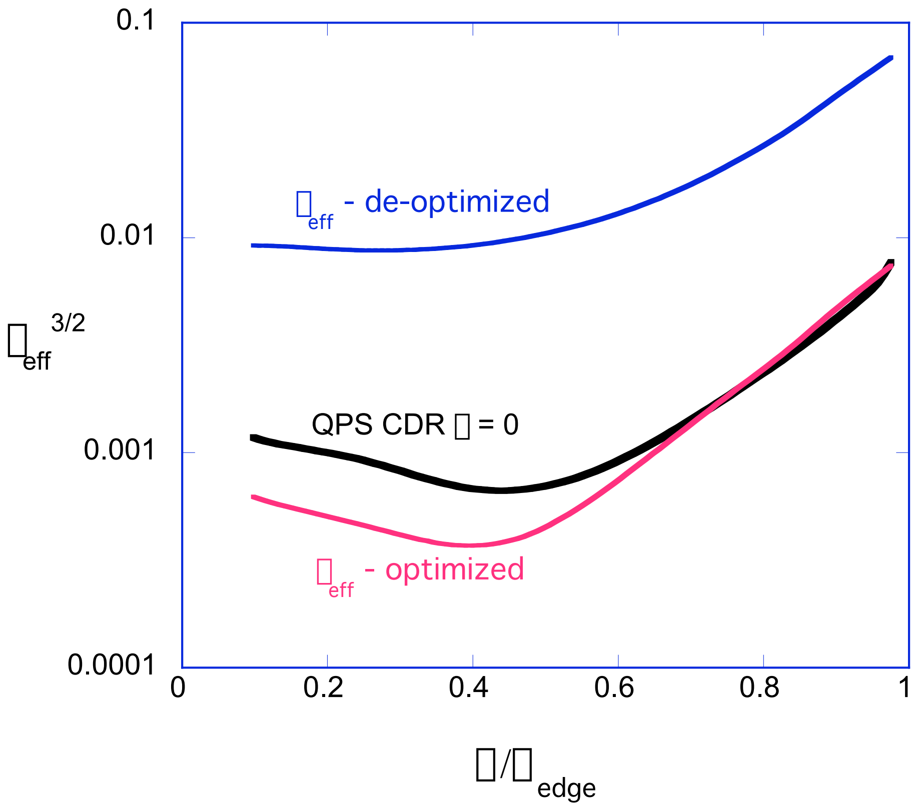


- Flexibility is a significant advantage offered by stellarator experiments
- Flexibility will aid scientific understanding in:
  - Flux surface fragility/island avoidance
  - Neoclassical vs. anomalous transport
  - Transport barrier formation
  - Plasma flow dynamics
  - MHD stability
- QPS offers flexibility through:
  - 5 individually powered modular coil groups
  - 3 vertical field coil
  - toroidal field coil set
  - Ohmic solenoid
    - Variable ratios of Ohmic/bootstrap current

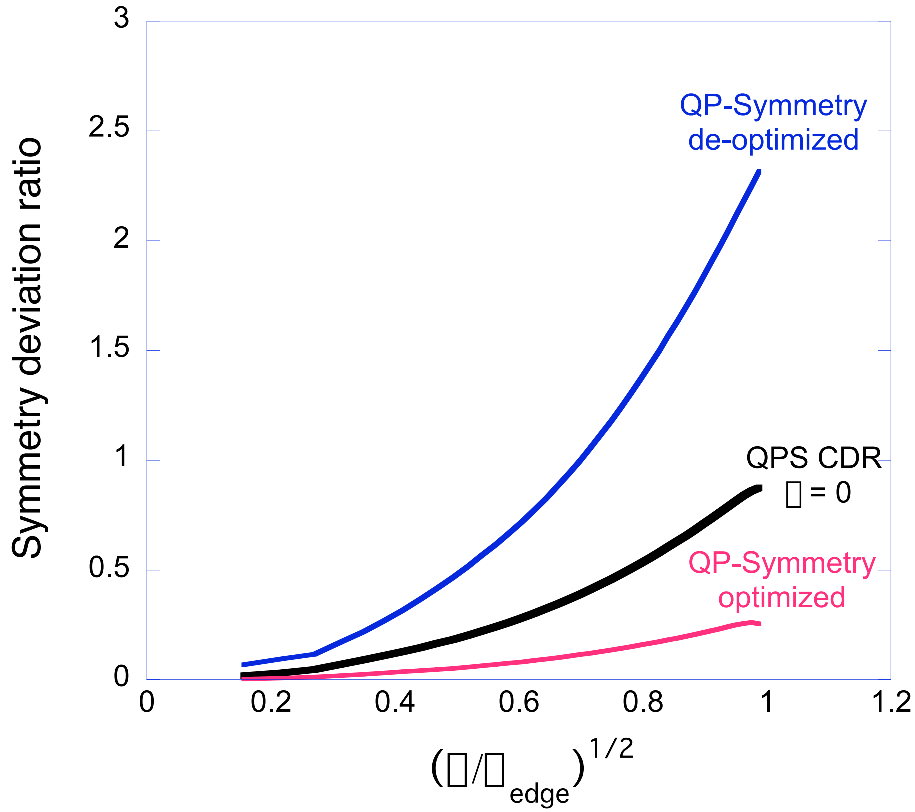
QPS can vary low collisionality levels by a factor of ~25 and QP symmetry by a factor of ~10

QPS

Low collsionality transport

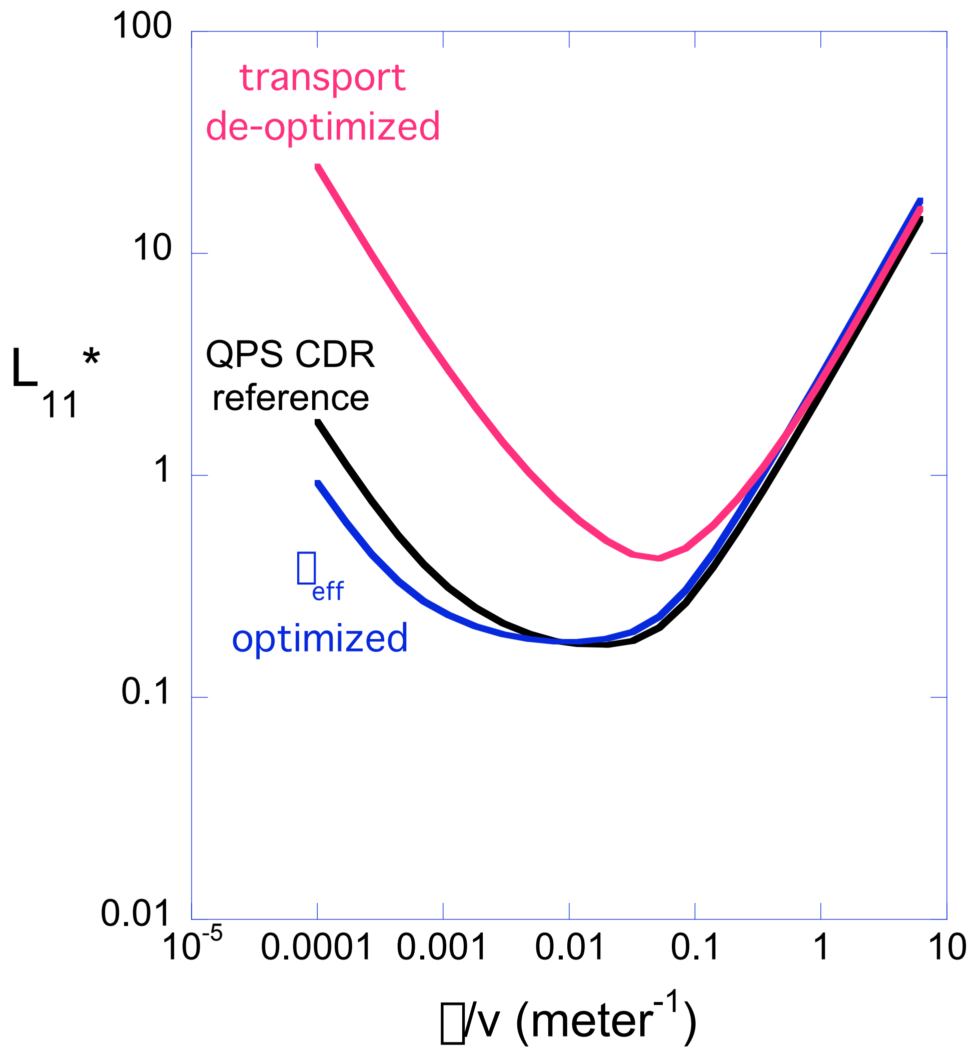


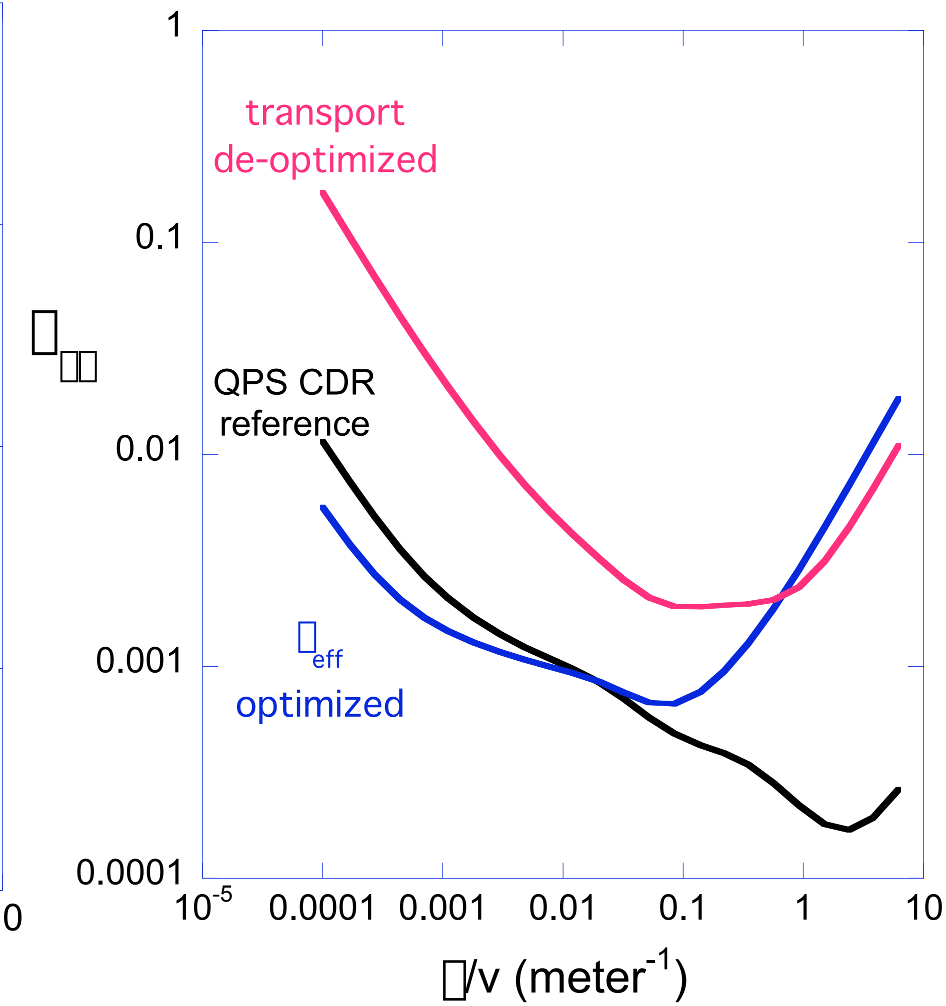
QP-symmetry



Collisional transport (□□≤□plateau regime) shows a factor of ~25 variation. Poloidal viscosities show factor of 5-30 variation.

QPS

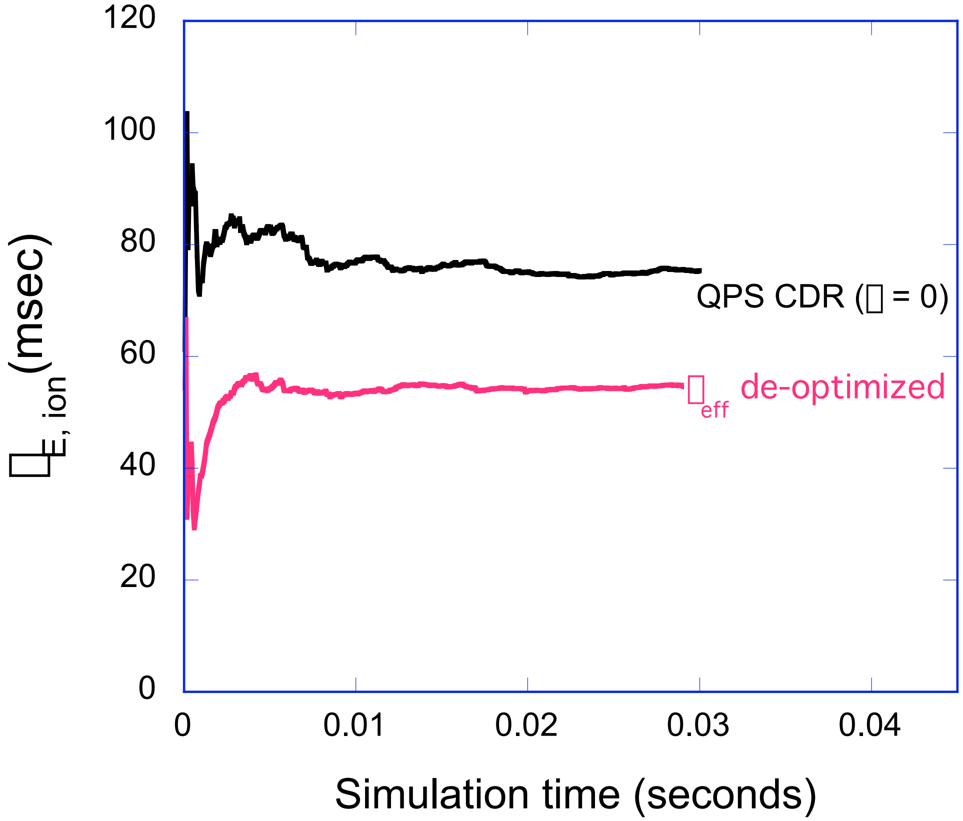




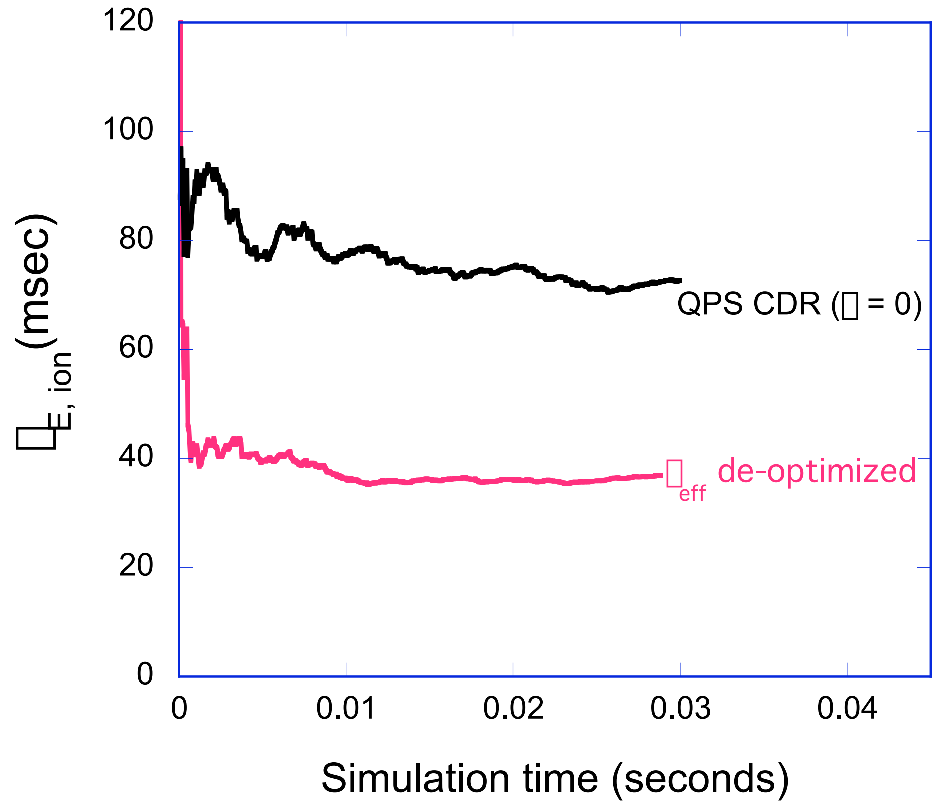
Monte Carlo global energy lifetimes (E_r = 0) indicate that a 50 - 100% variation is possible.

QPS

ICH regime: n(0) = 8x10^{19} m^{-3}, T_e(0) = 0.5 keV, T_i(0) = 0.5 keV



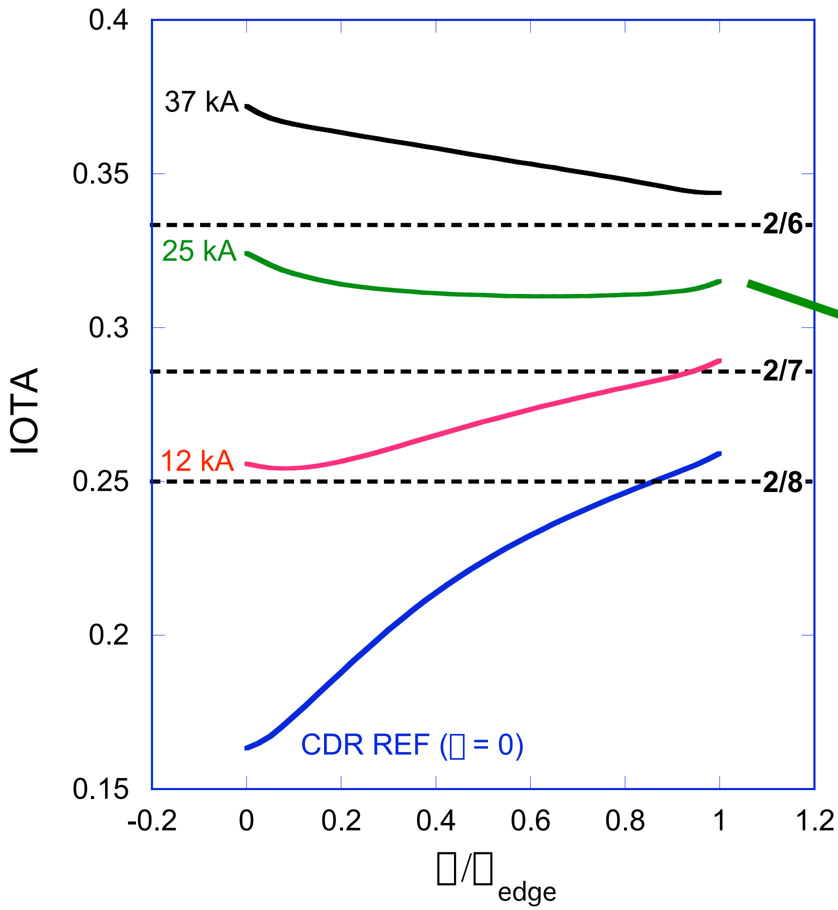
ECH regime: n(0) = 2x10^{19} m^{-3}, T_e(0) = 1.4 keV, T_i(0) = 0.15 keV

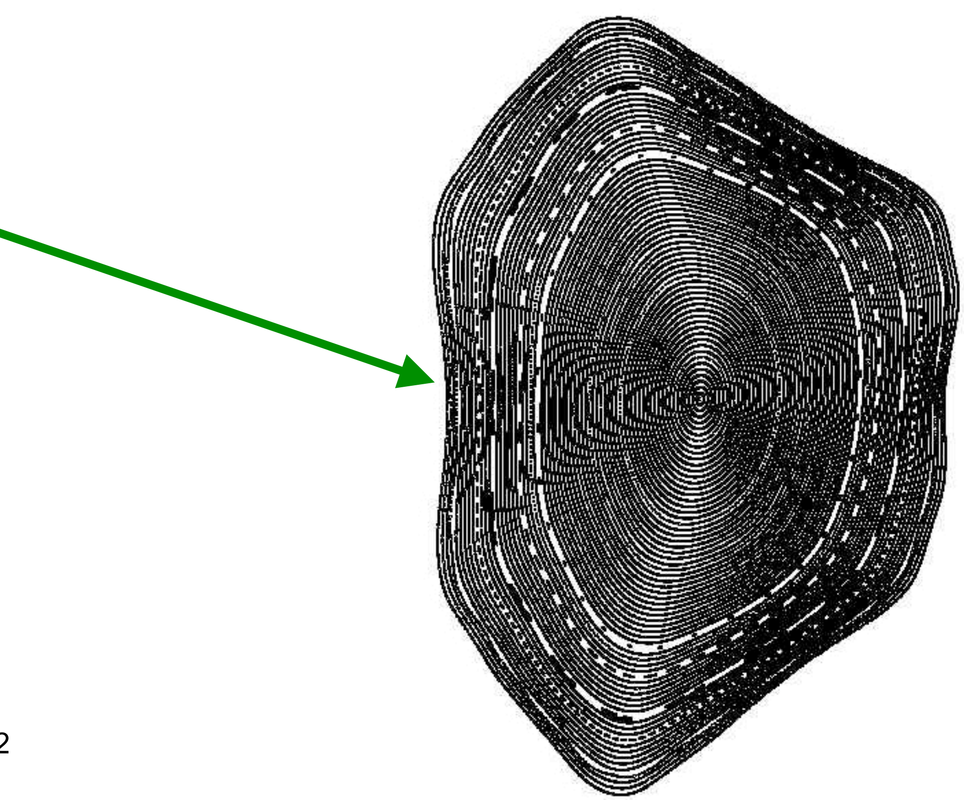


<u>Flux surface fragility</u>: Coil current optimizations coupled with Ohmic current allow low shear iota profiles in QPS at = 0.

QPS

As in the W7-AS approach, these transform profiles can be placed in windows that avoid low order rational surfaces

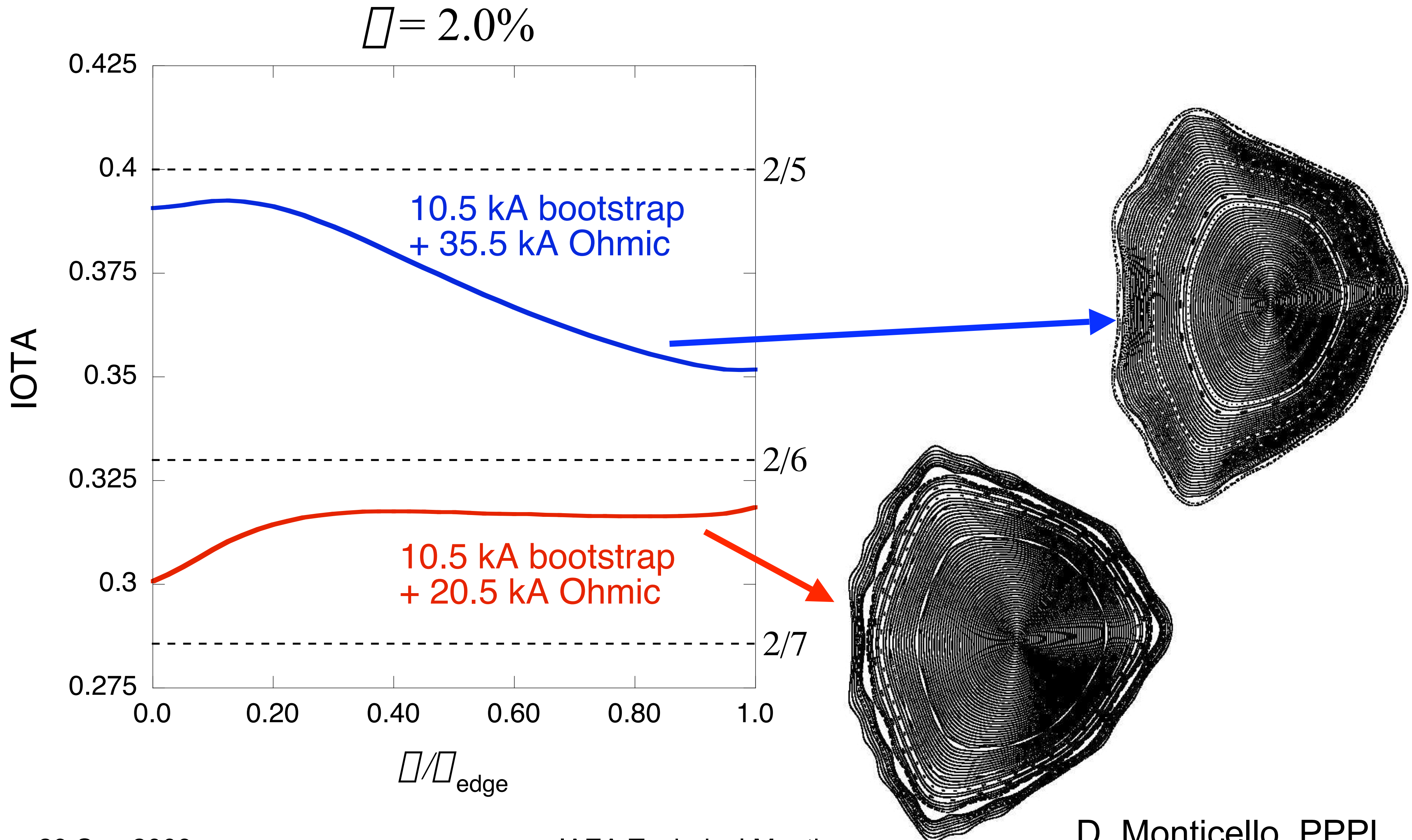




D. Monticello, PPPL

Flux surface fragility: Good surfaces and resonance avoidance is possible for β > 0 with Ohmic current.

QPS

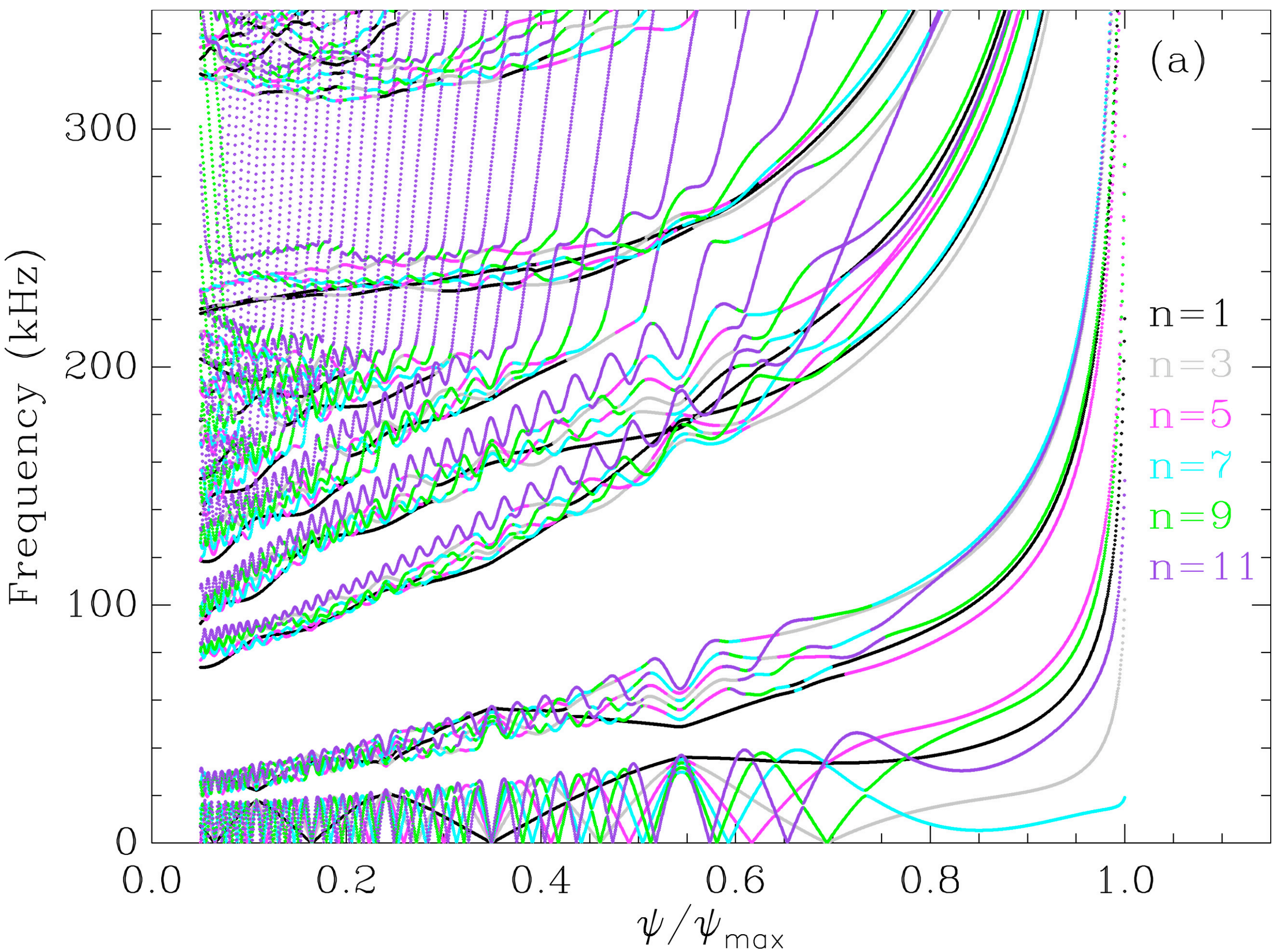


D. Monticello, PPPL

We have started the development of tools to analyze AE gap modes in compact stellarators

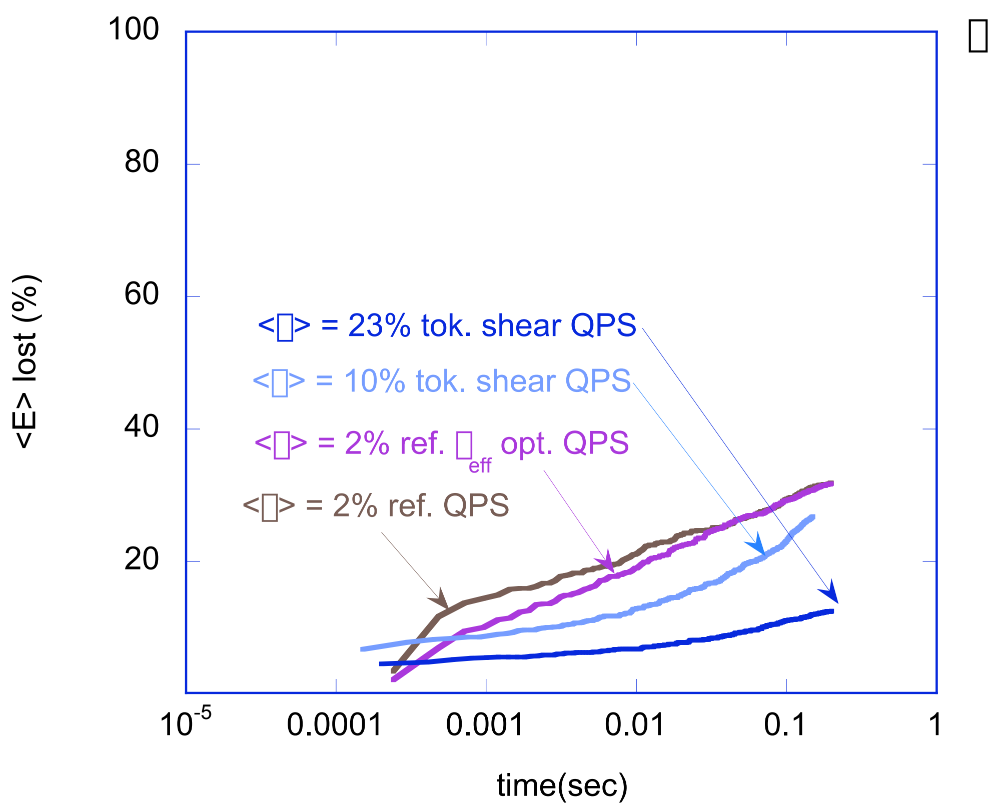
QPS

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

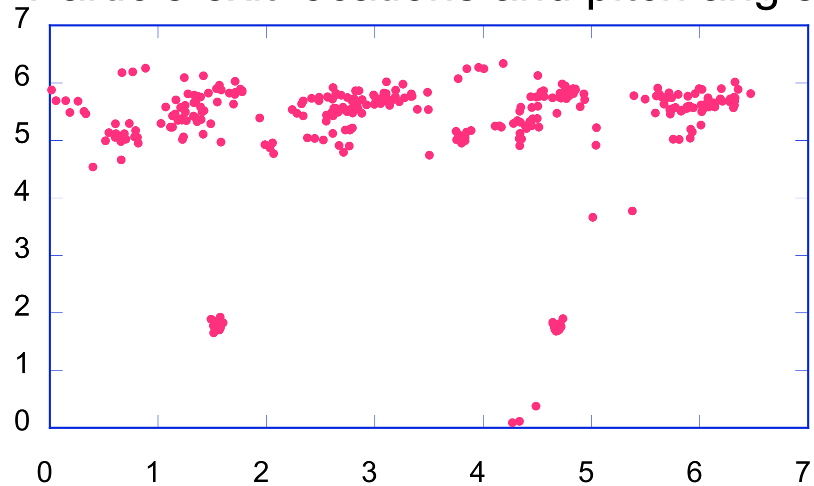


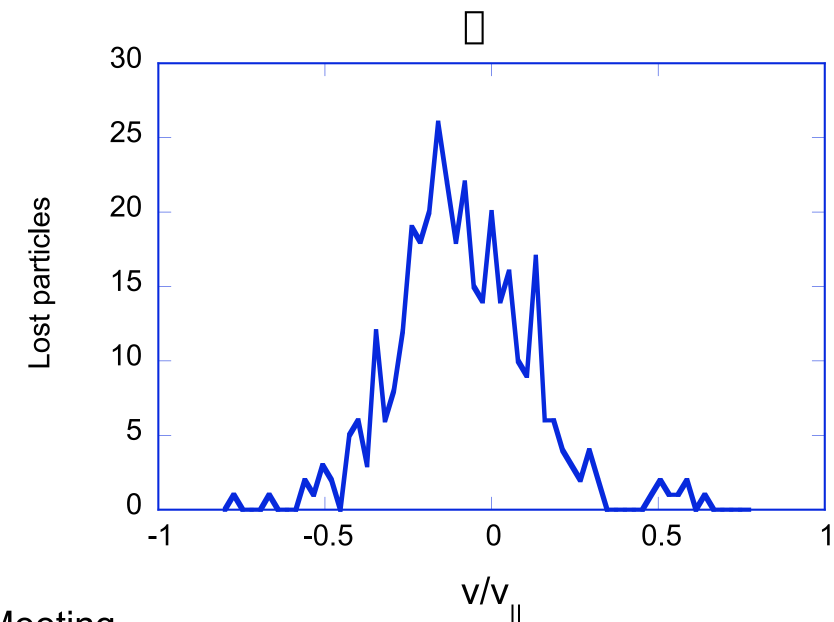
Alpha confinement is adequate for ignited power balance. Localized nature of losses may allow removal for direct conversion

Alpha losses for R_0 = 10m, B = 5T device
n□ (1 - □²)⁵ with collisional slowing down



Particle exit locations and pitch angle





Conclusion:

- Equilibrium robustness at low A
  - PIES and field line following (AVAC) analysis shows good surfaces for a range of □’s with:
    - Ohmic/bootstrap current control
    - Coil current optimization
- Transport
  - Can access interesting parameter regimes
  - Can control transport in measurable ways
  - Lowered poloidal viscous damping relative to tokamak
    - Improved control over electric field shear
- Stability
  - Can vary ballooning stability limits and test with access to enhanced confinement regimes
- Flexibility
  - Significant control demonstrated over: transport, iota, flux surface robustness, MHD stability