Physics Properties and Flexibility of the QPS Configuration

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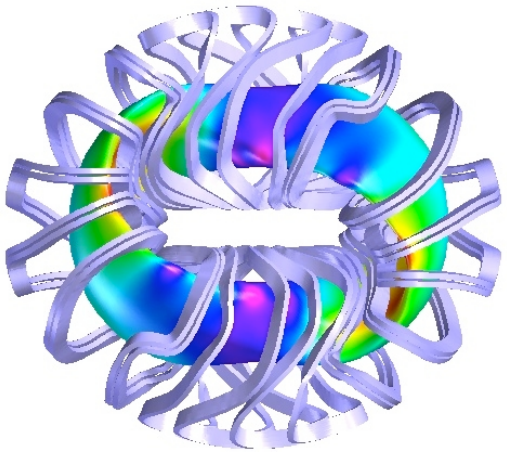
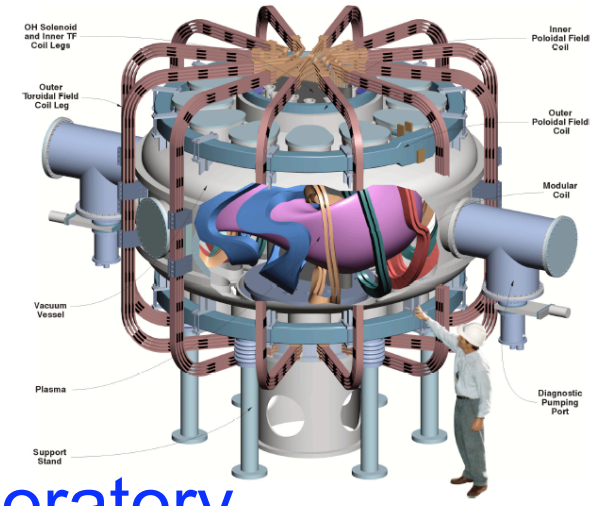




QPS PAC Review

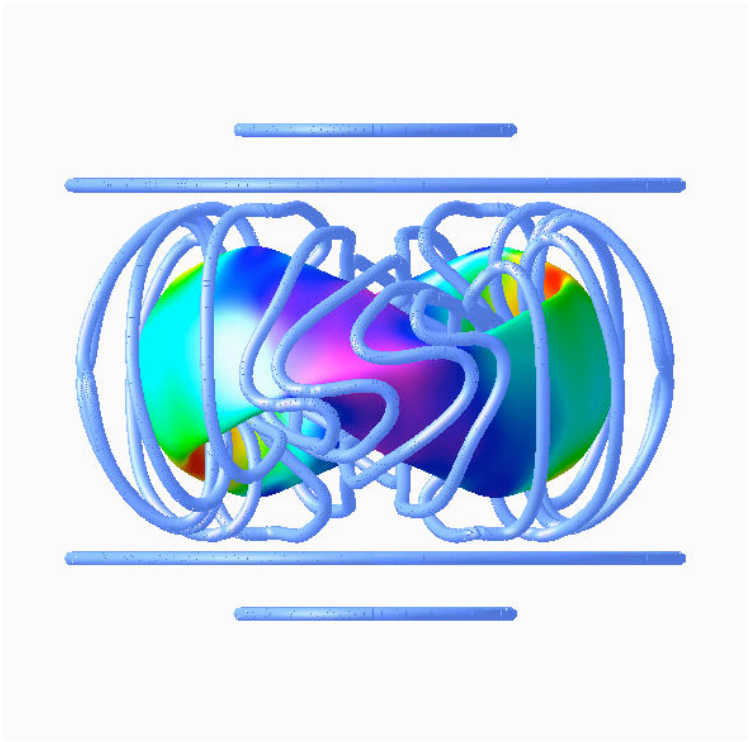
December 11-12, 2002

Princeton Plasma Physics Laboratory

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Goals of quasi-poloidally (QP) symmetric stellarators

- QPS is a very low aspect ratio (A = 2.7) Quasi-poloidal (QP) stellarator that will test:
  Equilibrium robustness at low A
  Neoclassical and anomalous transport
  Stability limits up to <□> = 2.2%
  Bootstrap current effects
  Reduced poloidal viscosity effects on shear flow transport reduction
  Configurational flexibility
- Design parameters: $\langle R_0 \rangle$ = 0.9 m, $\langle a \rangle$ = 0.33 m, <B> = 1 T ± 0.2T for 1sec, I_p □ 150 kA, P_{ECH} = 0.6-1.2 Mw, P_{ICH} = 1–3 Mw
- Motivations behind QP symmetry
  □**B** and **B** alignment - minimizes v_{drift}
  Near $P_{□}$ constancy ⇨ orbit width □$_{tor}$ rather than □$_{pol}$
  Minimum flow damping in $\mathbf{E_r x B}$ direction
  Trapped particles in low curvature regions + max. J drift reversal ⇨ stabilizing for DTEM/drift instabilities



Outline of this talk

- Optimization
  - QPS design requirements
    - Equilibrium resilience, good flux surfaces for $0 < \square < 2\%$
    - Transport significantly reduced from anomalous (ISS95)
    - Very low aspect ratio
    - Stable to at least 2%
    - Coils that are feasible to engineer and build
- Equilibrium
  - Flux surface robustness, $\square$ variation, flexibility
- Transport
  - Confinement quality, flexibility
- Stability
  - Ballooning, kink limits, flexibility

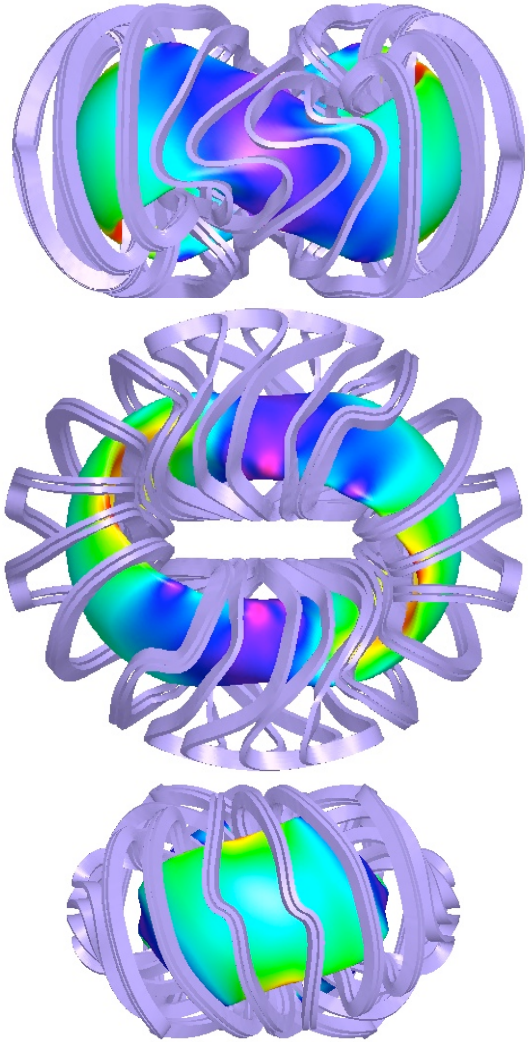
The QPS transport design requirements have been achieved through use of the following optimization targets:

TARGET	IMPROVES:	EXAMPLE
Bounce-averaged omnigeneity	Collisionless trapped/transitional particle confinement	$J = J(\Box)$ $B_{min} = B_{min}(\Box)$ $B_{max} = B_{max}(\Box)$
Nearby quasi-symmetries	Collisionless confinement of all orbit topologies	Minimize B_{mn} if $m \neq 0$ (QP)
Collisional transport coefficients	Collisional neoclassical transport	L_{11} coefficient from DKES at $\Box^* \sim 1$
Effective ripple $\Box_{eff}$	$1/\Box$ neoclassical transport regime	$\Box_{eff}^{3/2}$ from NEO[1] code

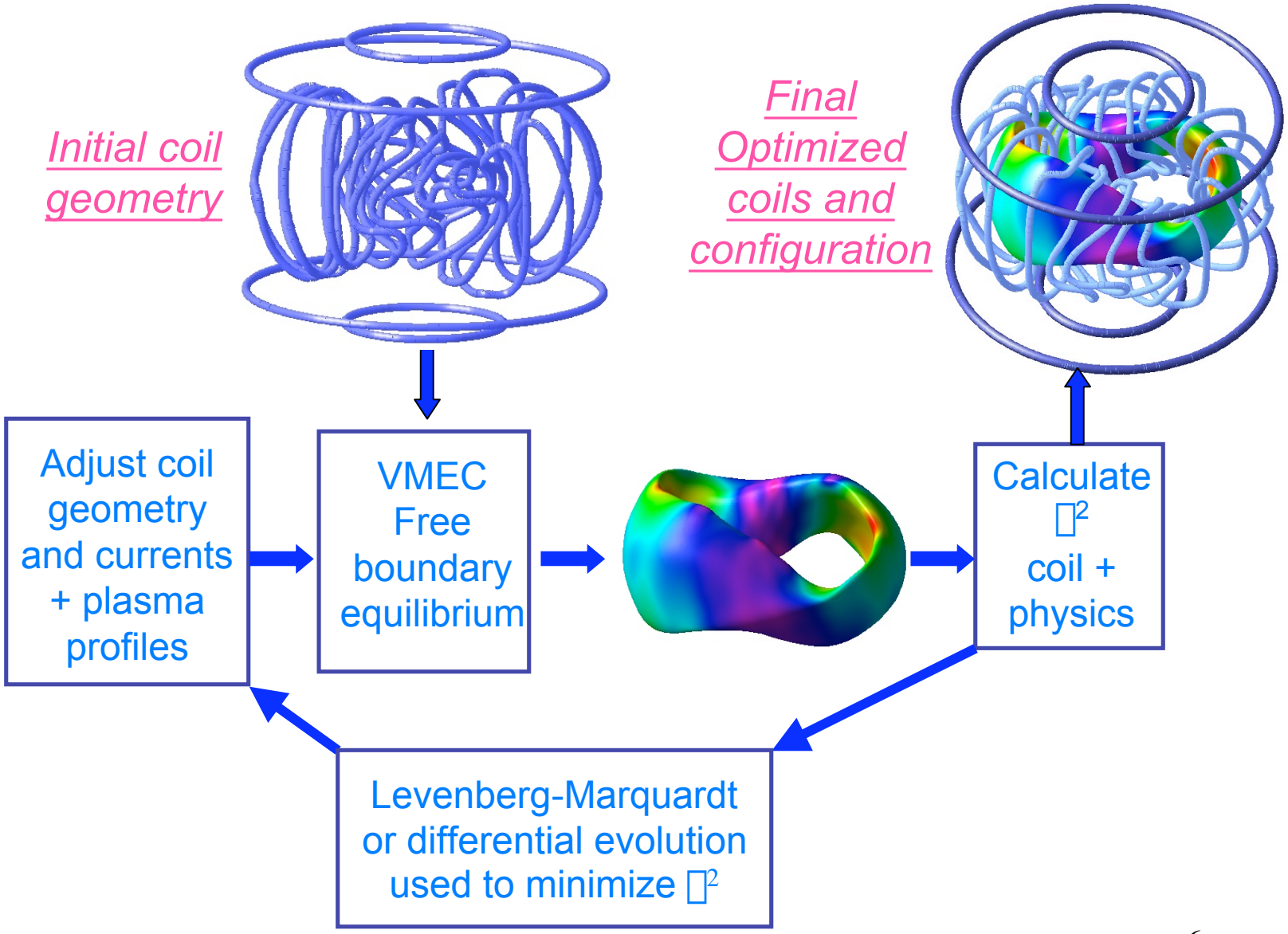
[1]Nemov, V. V., Kernbichler, W., et al., Phys. Plasmas **6**, 4622 (1999)

The transport targets are augmented by the following stability, configuration and engineering targets to accomplish the remaining QPS design requirements:

Targets **(Physics/Engineering)**	**Example**
Transport Measures	Effective ripple, D, QP-symmetry
Current profile	self-consistent I_{BS}, I(□) goes to 0 at edge
Limit maximum plasma current	e.g., I_{max} < 60 kAmps at <□> ~ 2%
Iota profile	*i*(□) = 0.2 (□=0) 0.3 (□=1)
Magnetic Well, Mercier	V" < 0, D_M > 0 over cross section
Ballooning stability	<□> ~ 2-3%
Aspect ratio	$R_0/a \approx 2.5$ to 3.5
Feasible coil design	Max. current density, non-intersecting coils/plasma
Adequate shielding of neutrals	Minimum "waist" thickness
Limit outer surface curvature	avoid strong elongation/cusps



Merged coil/plasma stellarator optimization

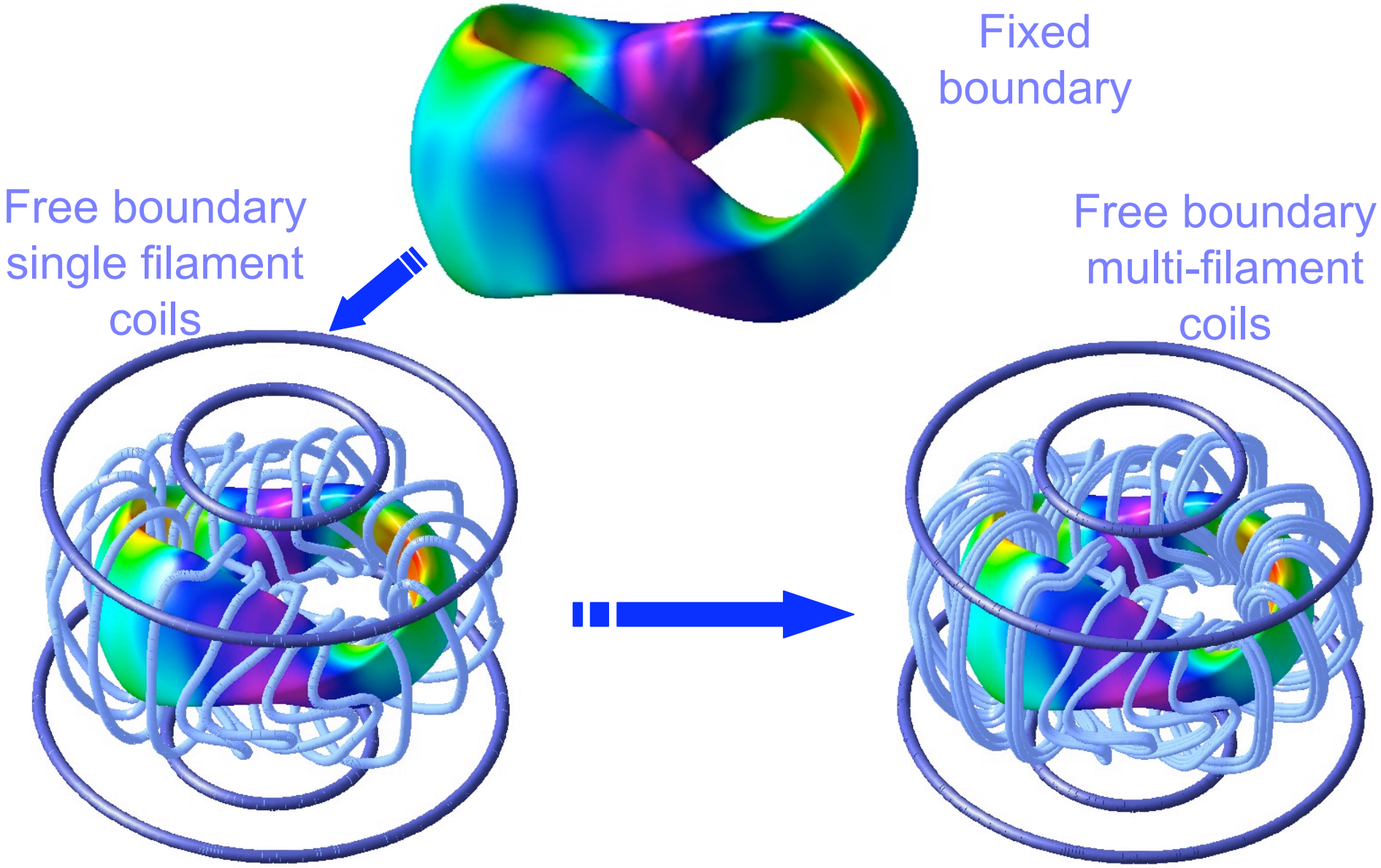


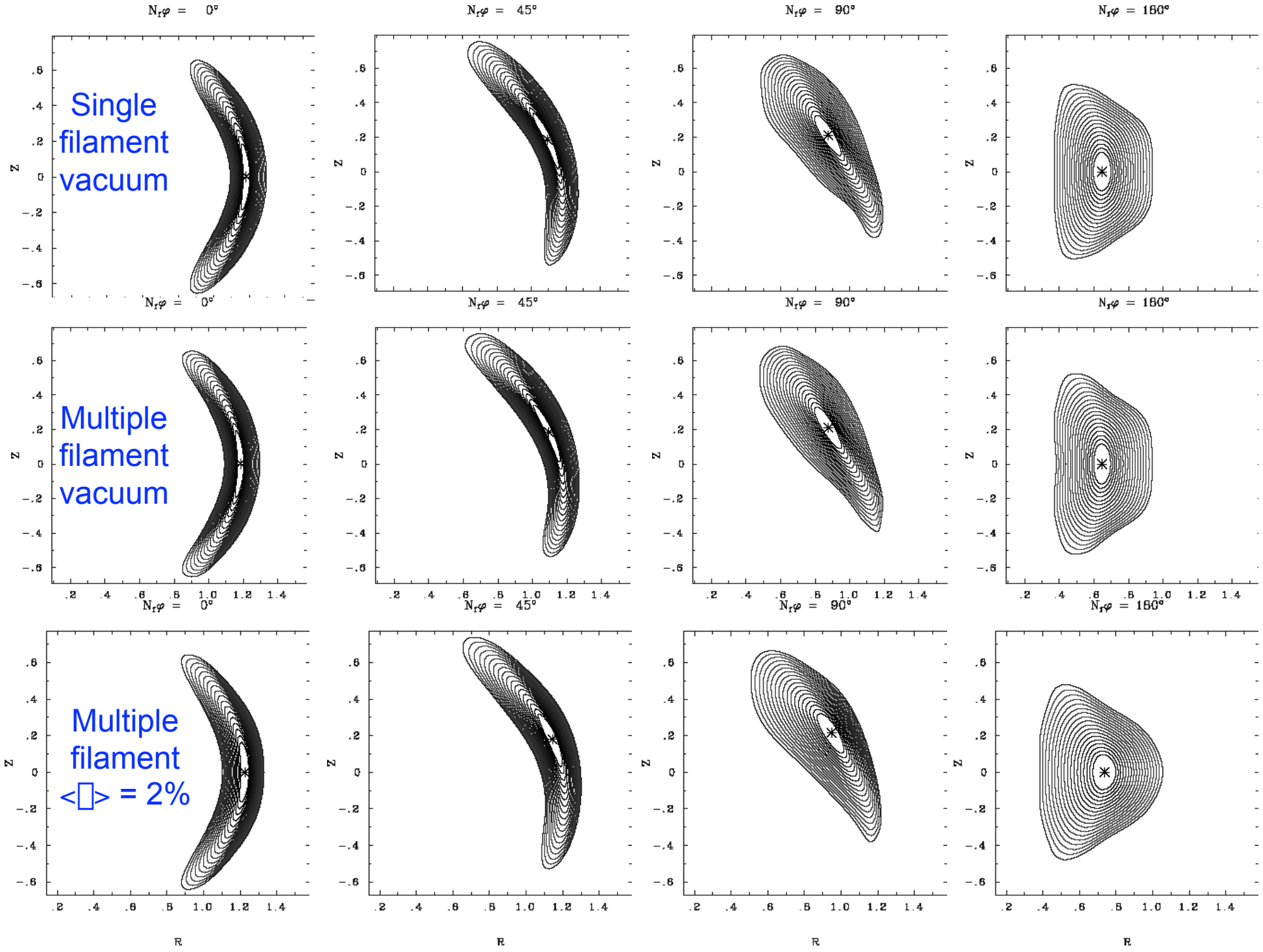
Coil geometry is typically characterized by several hundred parameters

Equilibrium quality is a primary QPS requirement underlying the other physics issues

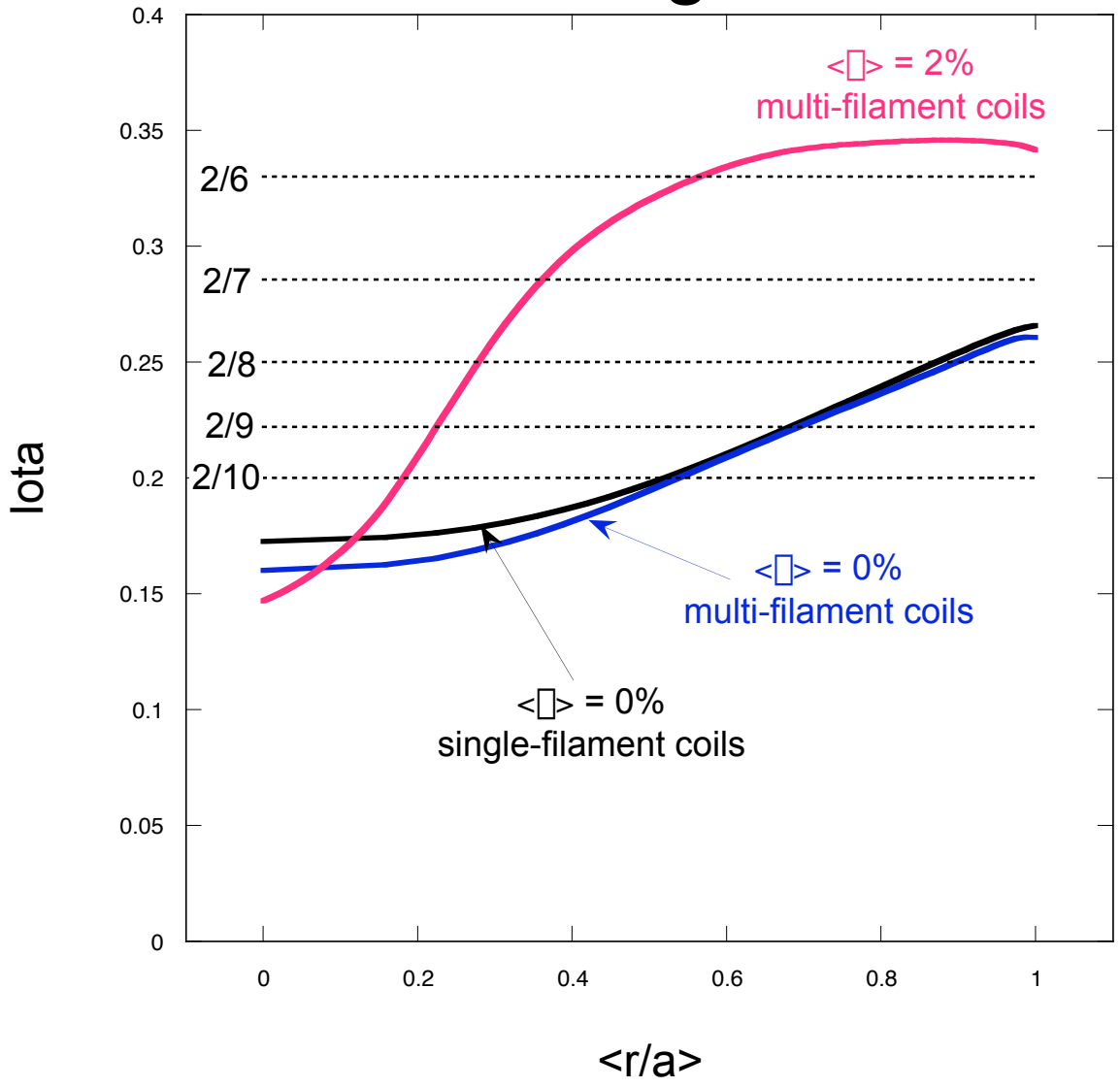
- QPS Issues:
  - Robustness of equilibria with varying plasma
    - Island size
    - Flexibility
  - Compatibility with bootstrap/Ohmic/RF driven currents
- AVAC
  - Vacuum field lines, islands, stochastic regions
- VMEC
  - Rapid calculation of finite 3D equilibria
  - Closed/nested flux surfaces assumed
- PIES
  - Finite 3D equilibria, islands, stochastic regions allowed

Evolution of QPS equilibrium models



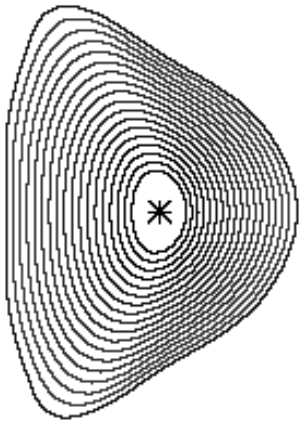

N_rφ = 0°
N_rφ = 45°
N_rφ = 90°
N_rφ = 180°
Single filament vacuum
Multiple filament vacuum
Multiple filament <□> = 2%
Z
R

Vacuum ι profiles for different coil models show good agreement; finite plasma pressure introduces strong central shear

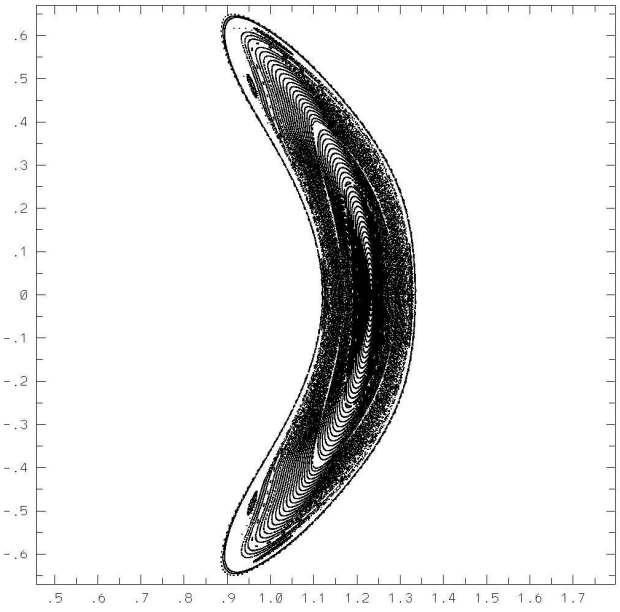


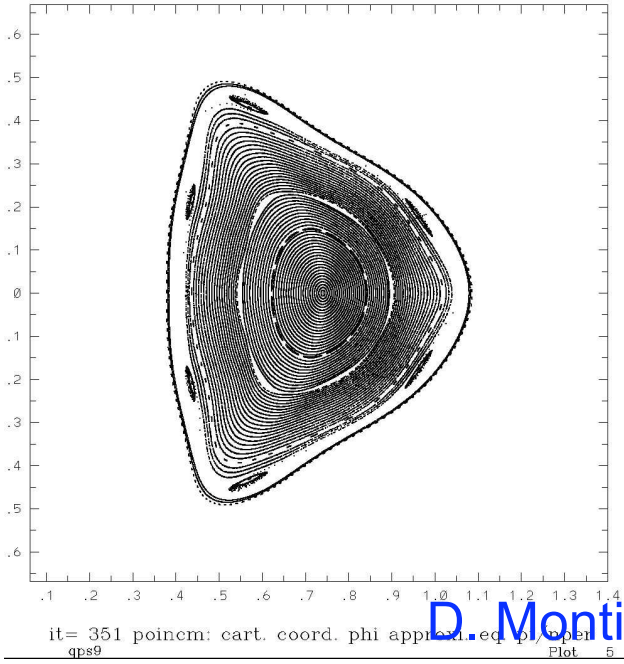
PIES calculations show that ι = 1/3 crossings at <□> = 2% introduce only small 2/6 island regions

VMEC surfaces



PIES surfaces





D. Monticello

Outline

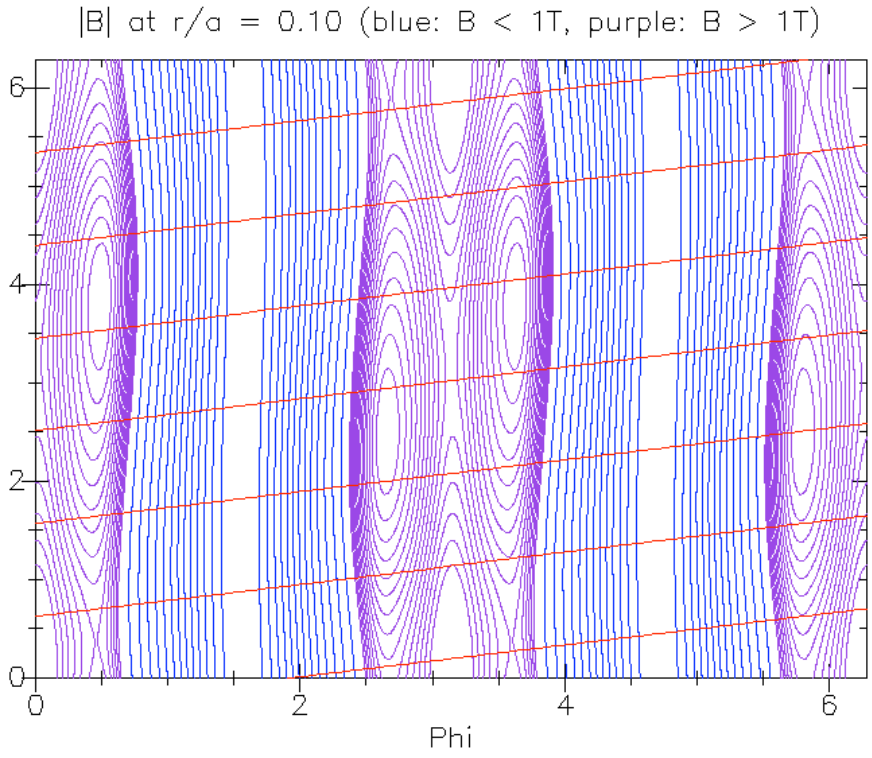
- Optimization
- Equilibrium
- Transport
  - QPS Design requirements
    - Dominant QP-symmetry in |B|
    - Neoclassical transport should be << anomalous
    - The design should have the flexibility to vary neoclassical transport over a significant range
    - Ability to operate with a range of bootstrap current levels
- Stability

Transport requirements of the QPS design have been checked with a variety of models:

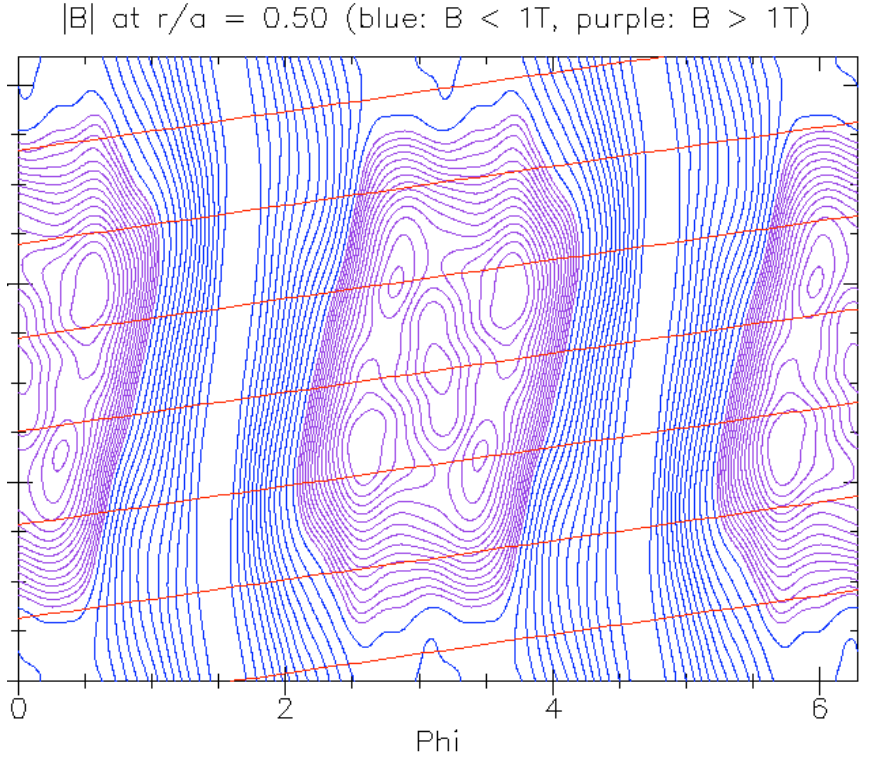
- 1-D model
  - Neoclassical transport coefficients determined by:
    - Low ι NEO effective ripple; Shaing-Houlberg electric field dependence
  - Anomalous transport is modeled using ISS95
- Local transport: low collisionality
  - Effective ripple: NEO; Bootstrap current: BOOTSJ
- Local transport: low to moderate collisionality - DKES
  - Transport matrix for particle, energy flows
  - Currents driven by gradients (bootstrap) and electric fields (neoclassical resistivity)
- Global transport: Monte Carlo - DELTA5D
  - Global particle and energy lifetimes
  - Bootstrap current, local transport (ιf)
  - Energetic particle confinement: alphas, ICRF, beams
- QPS participates in the IPP International Collaboration on neoclassical transport in stellarators

Magnetic field contours indicate the poloidal symmetry of the QPS reference design

Degree of symmetry varies with radial location

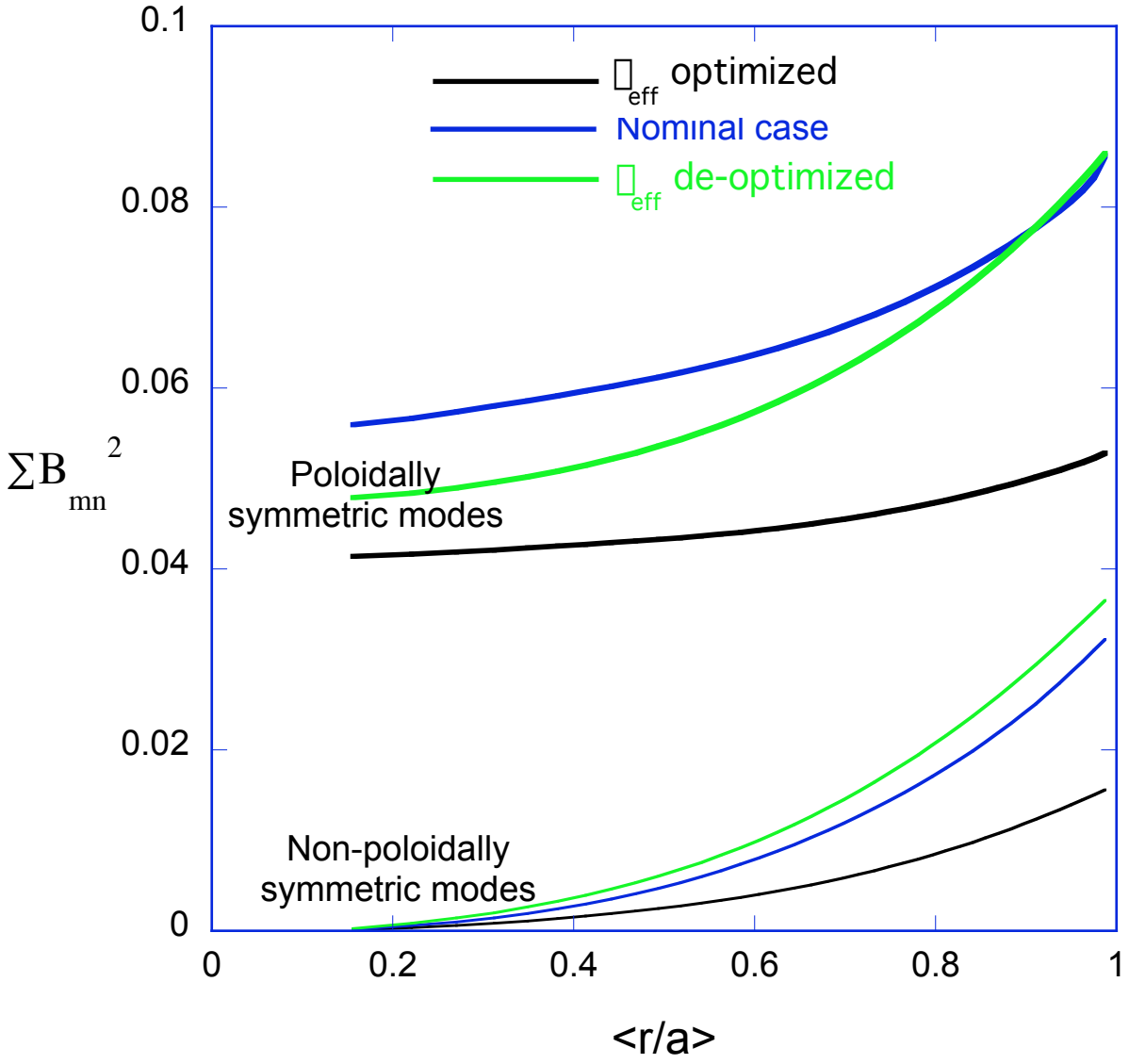


$(\Box/\Box_{edge})^{1/2}=0.1$

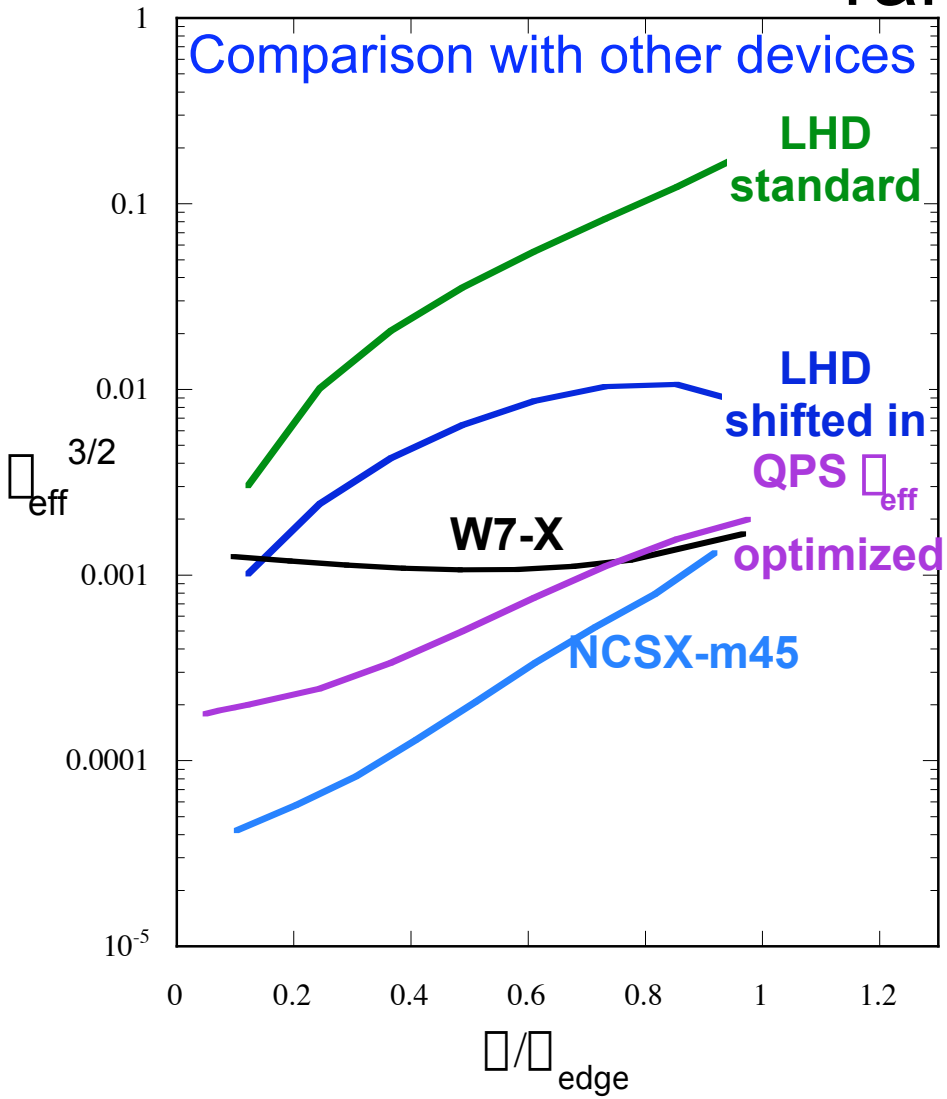


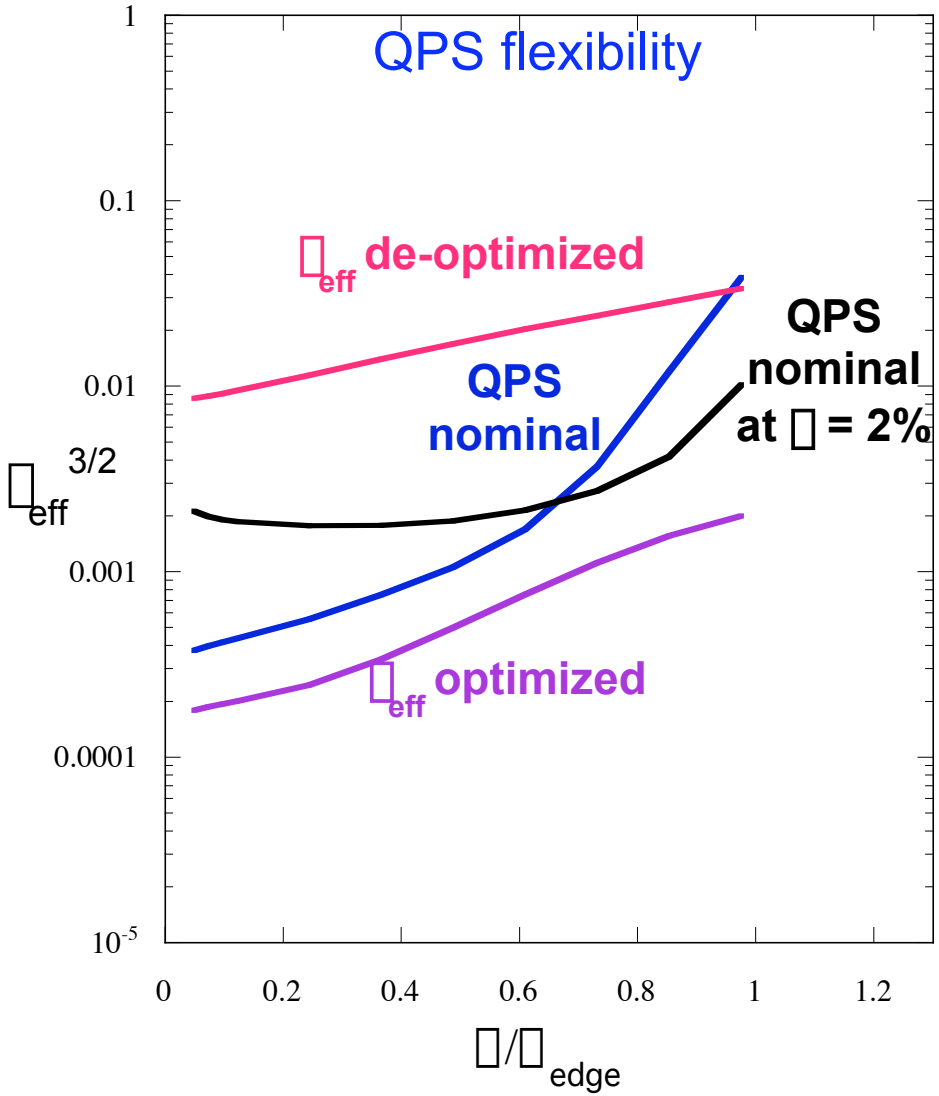
$(\Box/\Box_{edge})^{1/2}=0.5$

The magnetic field energy mode spectrum also demonstrates the poloidally symmetric nature of the QPS design and how it can be varied



The QPS effective ripple for low collisionality transport compares well with other larger aspect ratio devices and can be varied over a wide range





The DKES (Drift Kinetic Equation Solver) provides the neoclassical transport coefficient matrix (multi-helicity B)

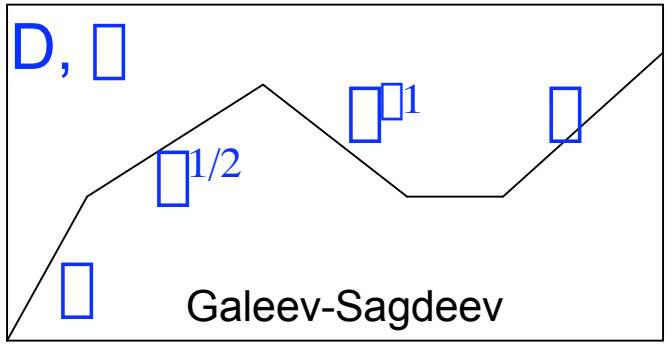
$$\begin{bmatrix} \\ Q \\ \left\langle n(\vec{u}-\vec{u}_s)\bullet\vec{B}\right\rangle \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} \begin{bmatrix} n & \frac{3}{2}\frac{T}{T}\left(\frac{eE_r}{T}\right) \\ n & \frac{T}{T} \\ \frac{e}{T}\frac{\left\langle \vec{E}\bullet\vec{B}\right\rangle}{\left\langle B^2\right\rangle} & \end{bmatrix}$$

$$D_{ij} = \frac{2n}{\sqrt{\pi}}\int_0 dK\sqrt{K}e^{-K}G_{ij}(K)L_{ij}$$

$$L_{ij} = L_{ij}\left(\frac{\nu}{v}, \frac{E_r}{v}\right) = \text{ monoenergetic transport coefficients}$$

In following, we will focus on **L_{11}** ⇨ D_{11}, D_{22}, D_{12}, D_{21} and **L_{13}** ⇨ D_{31}, D_{13}, D_{23}, D_{32}

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

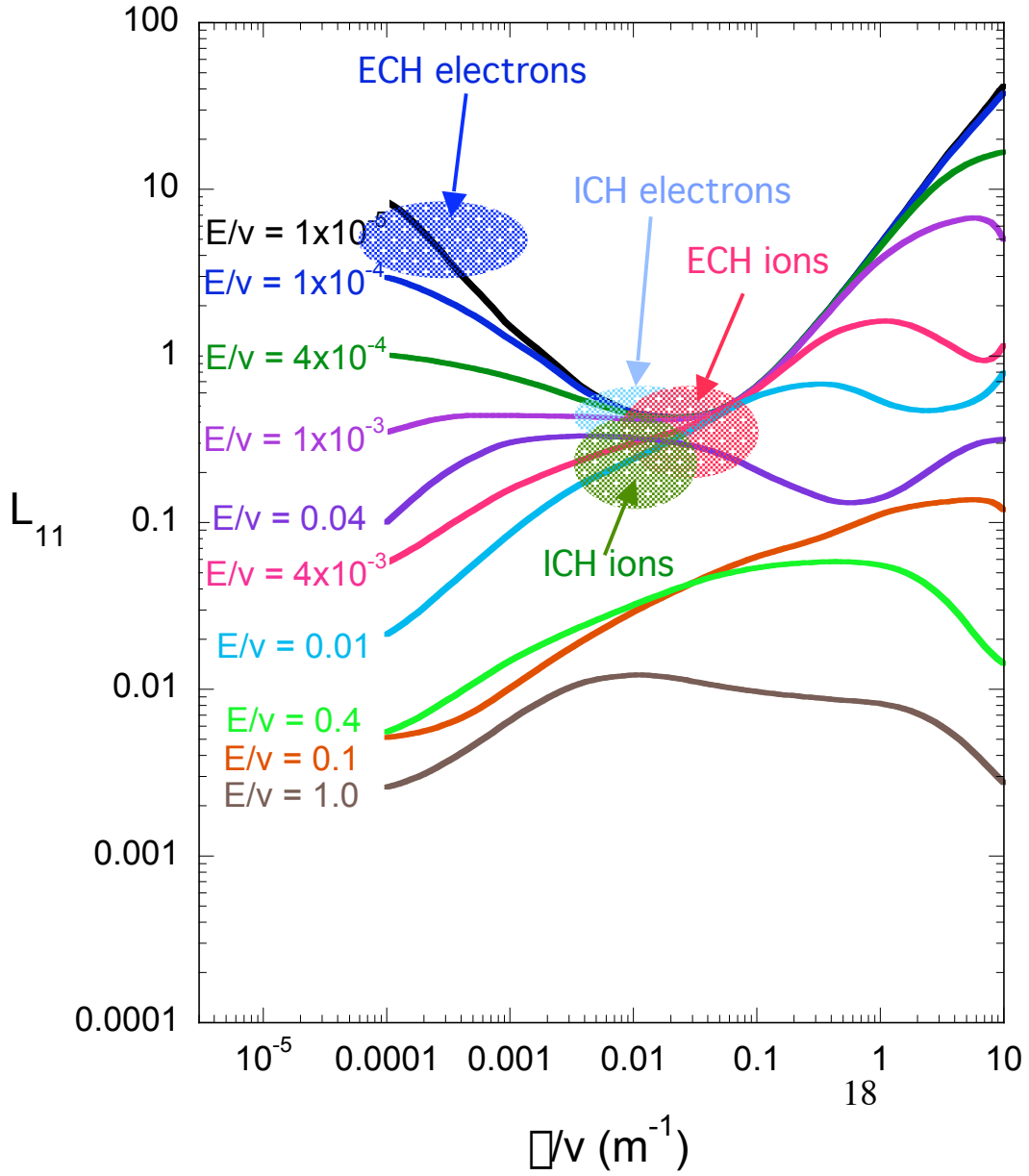


ECH regime: n = 1.8x10^{19}m^{-3}, T$_{e0}$=1.4 keV, T$_{i0}$=0.15 keV

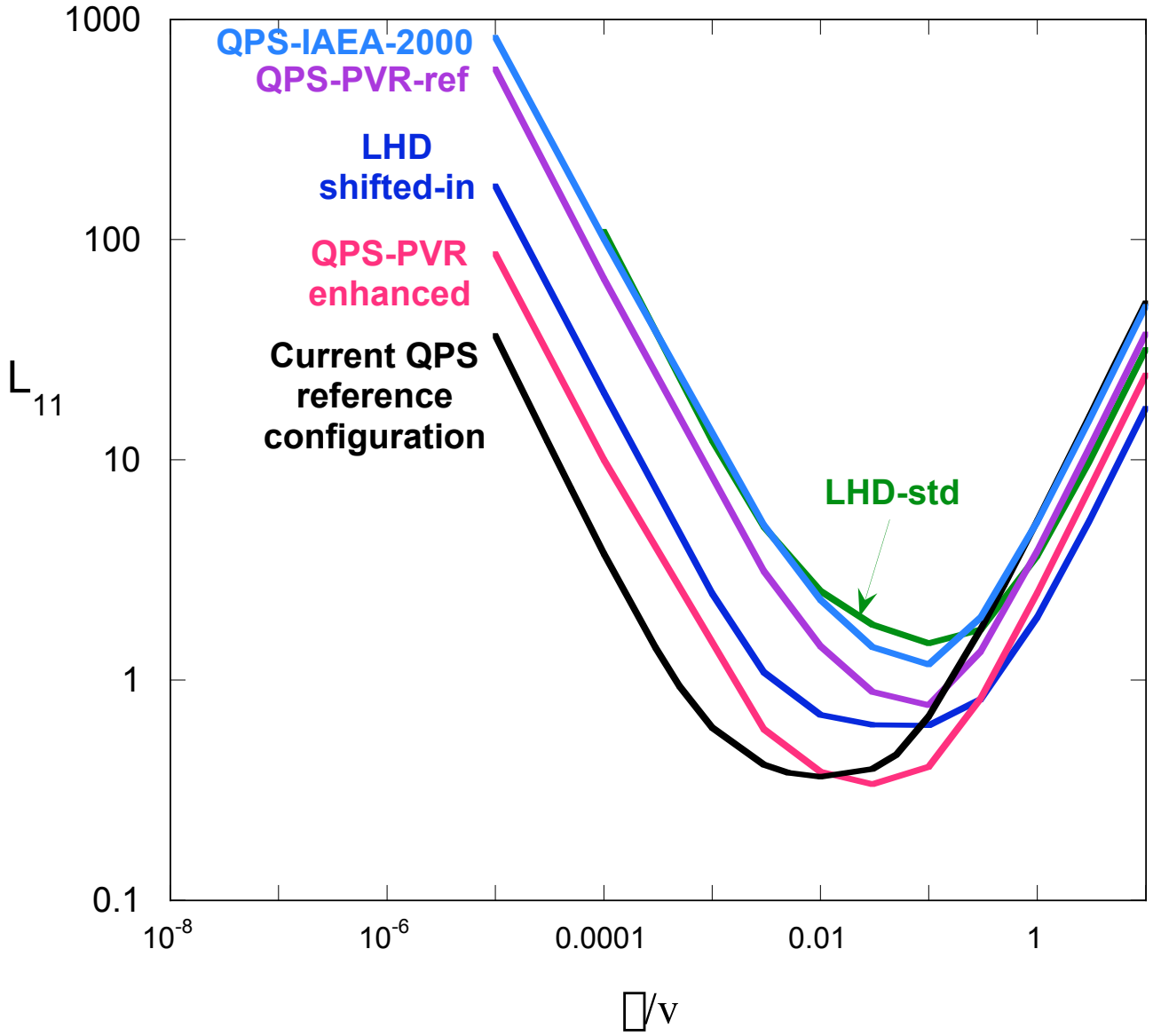
- **ECH electrons**:
  - 7x10^{-5} < □/v < 10^{-3}
  - 8x10^{-5} < E/v < 2x10^{-4}
- **ECH ions**:
  - 6x10^{-3} < □/v < 7x10^{-2}
  - 10^{-2} < E/v < 3x10^{-2}

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

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

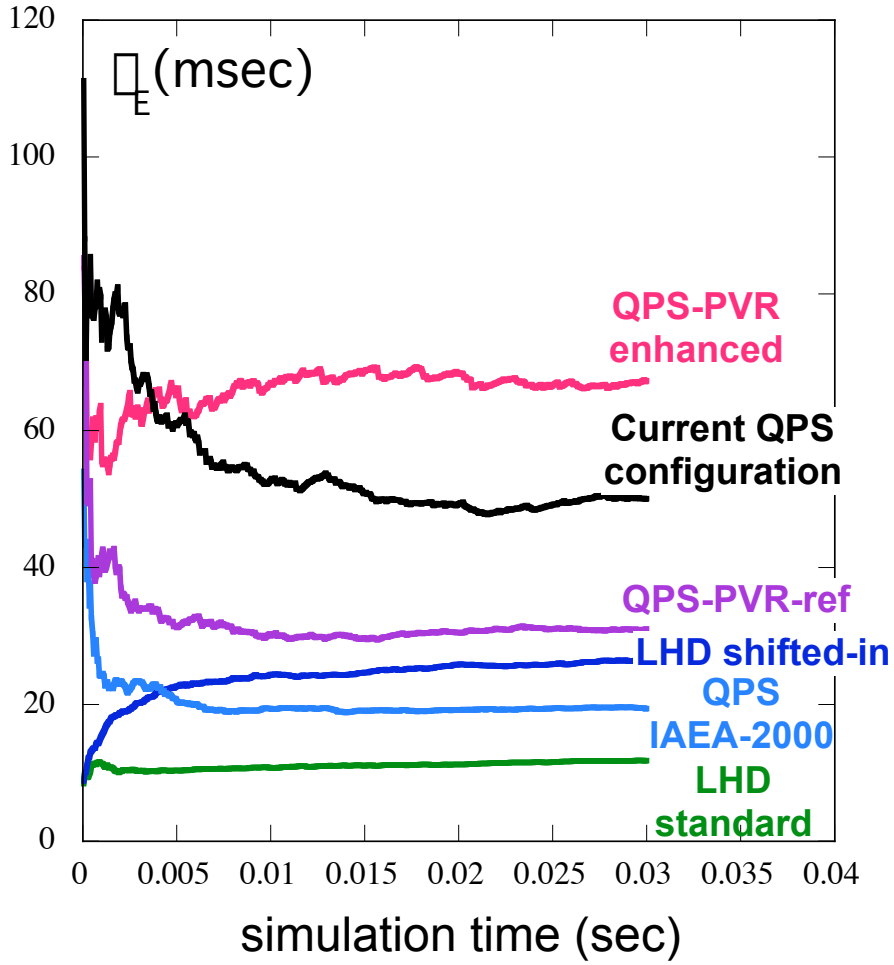


The low collisionality DKES transport coefficient of the current reference QPS configuration (shown here for $E_r = 0$ and at the half flux surface) is significantly reduced from earlier designs.

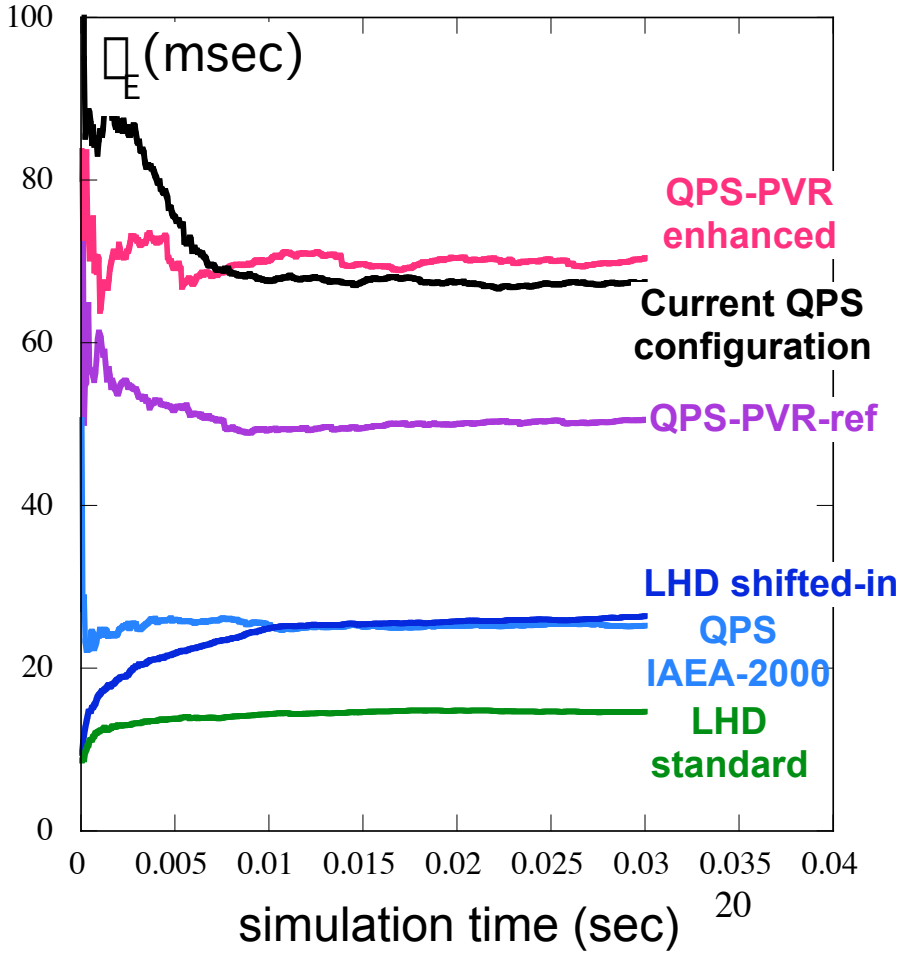


Monte Carlo ion energy confinement (at e□/kT = 0) also shows improvements over earlier designs

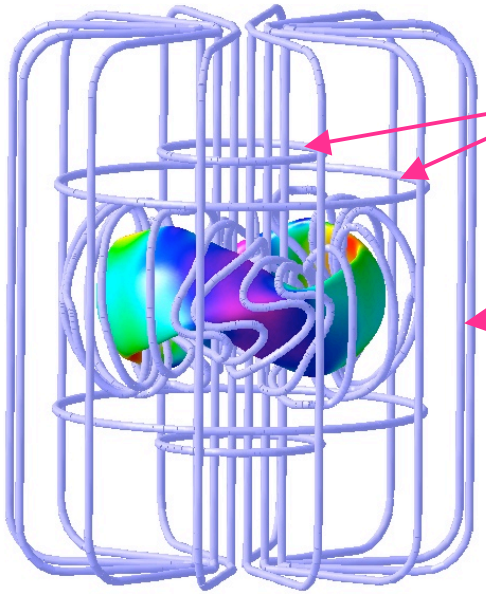
ECH: $n(0) = 1.8 \times 10^{19}$ cm^{-3}
$T_{ion}(0) = 0.15$ keV, $T_{ion}(0) = 1.4$ keV



ICH: $n(0) = 8.3 \times 10^{19}$ cm^{-3}
$T_{ion}(0) = 0.5$ keV, $T_{ion}(0) = 0.5$ keV



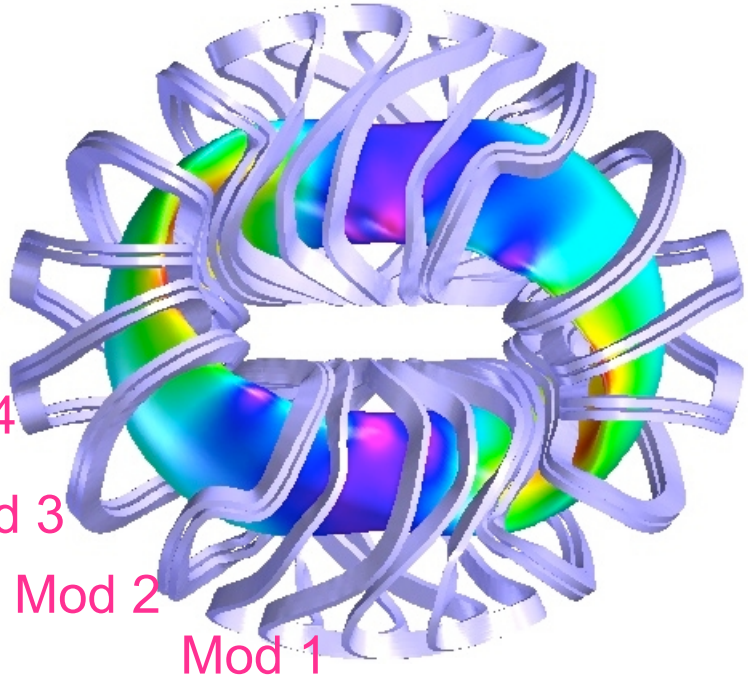
QPS Transport Flexibility Studies



2 vertical field coils

Toroidal 1/R field

4 independently powered modular coils

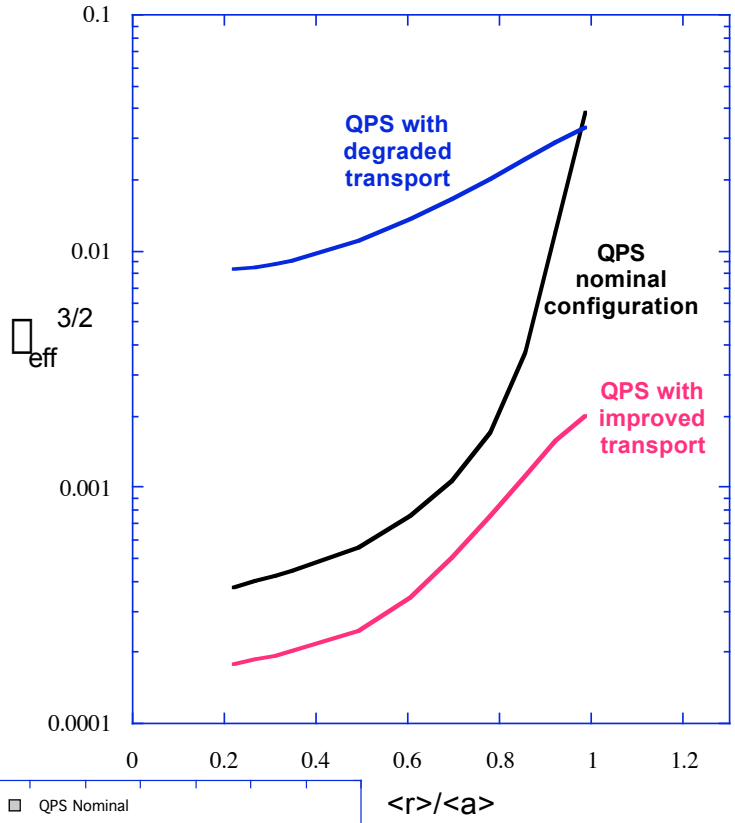


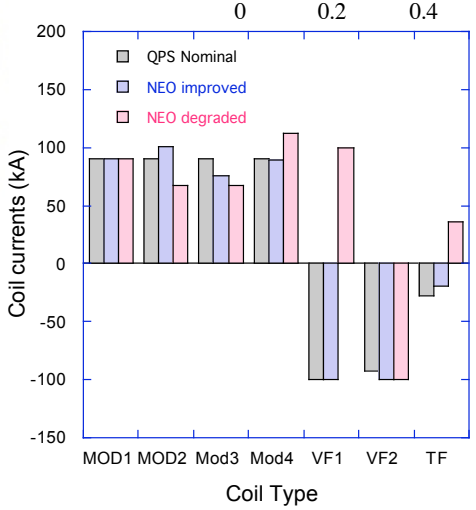
Mod 4

Mod 3

Mod 2

Mod 1 (split coil)

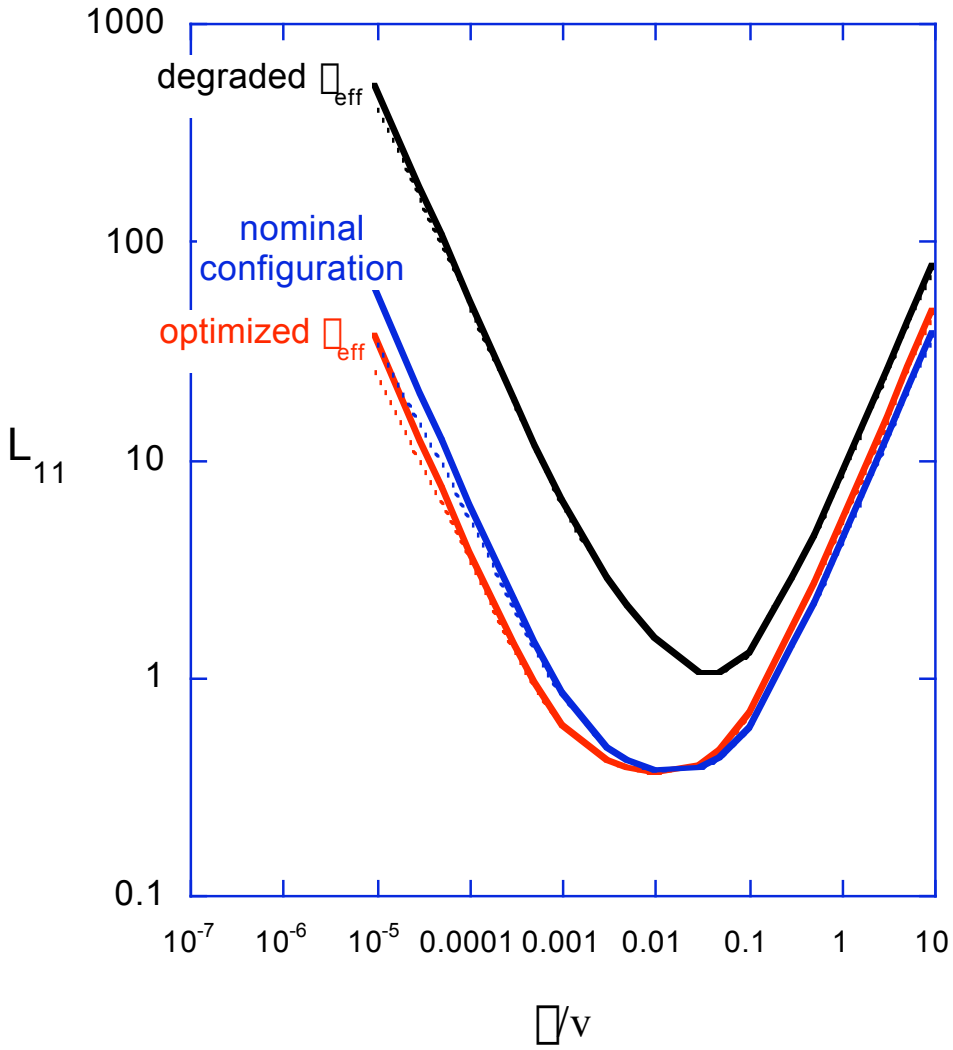


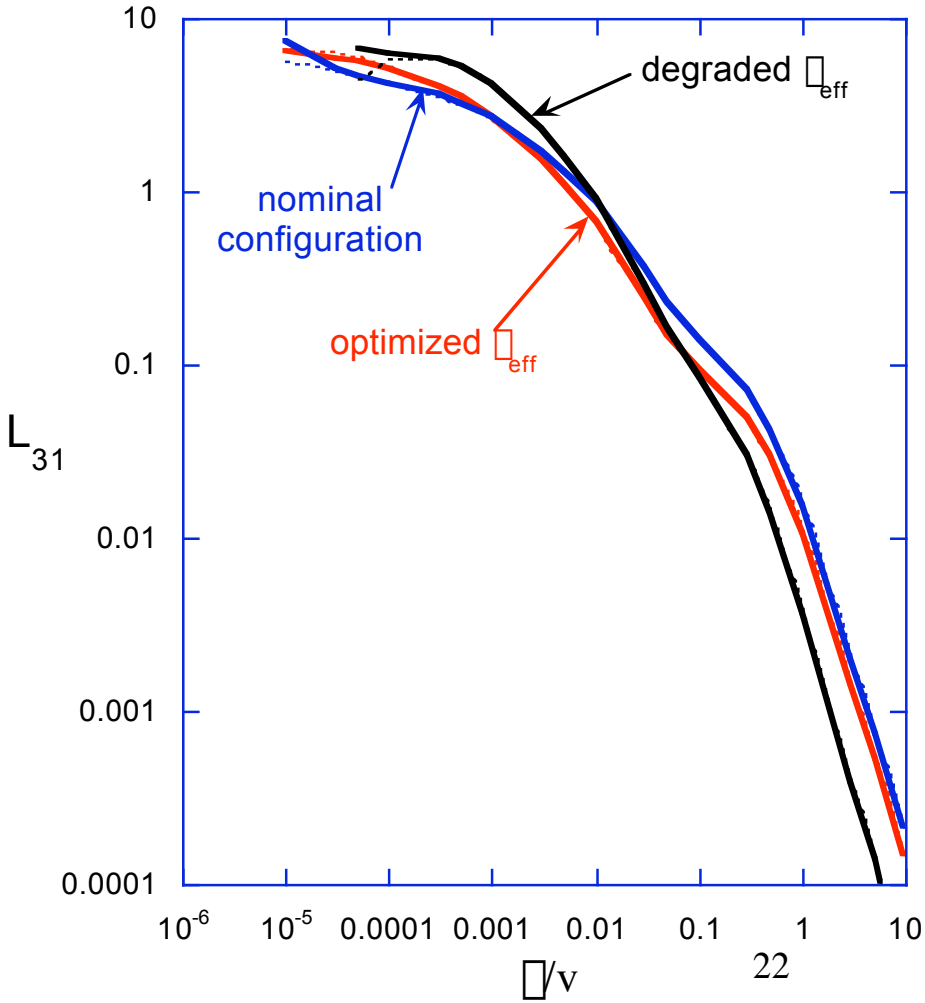


- Modular coil currents can vary ±25%
- Vertical field currents can vary ±100 kA
- Toroidal field currents can vary ±70 kA

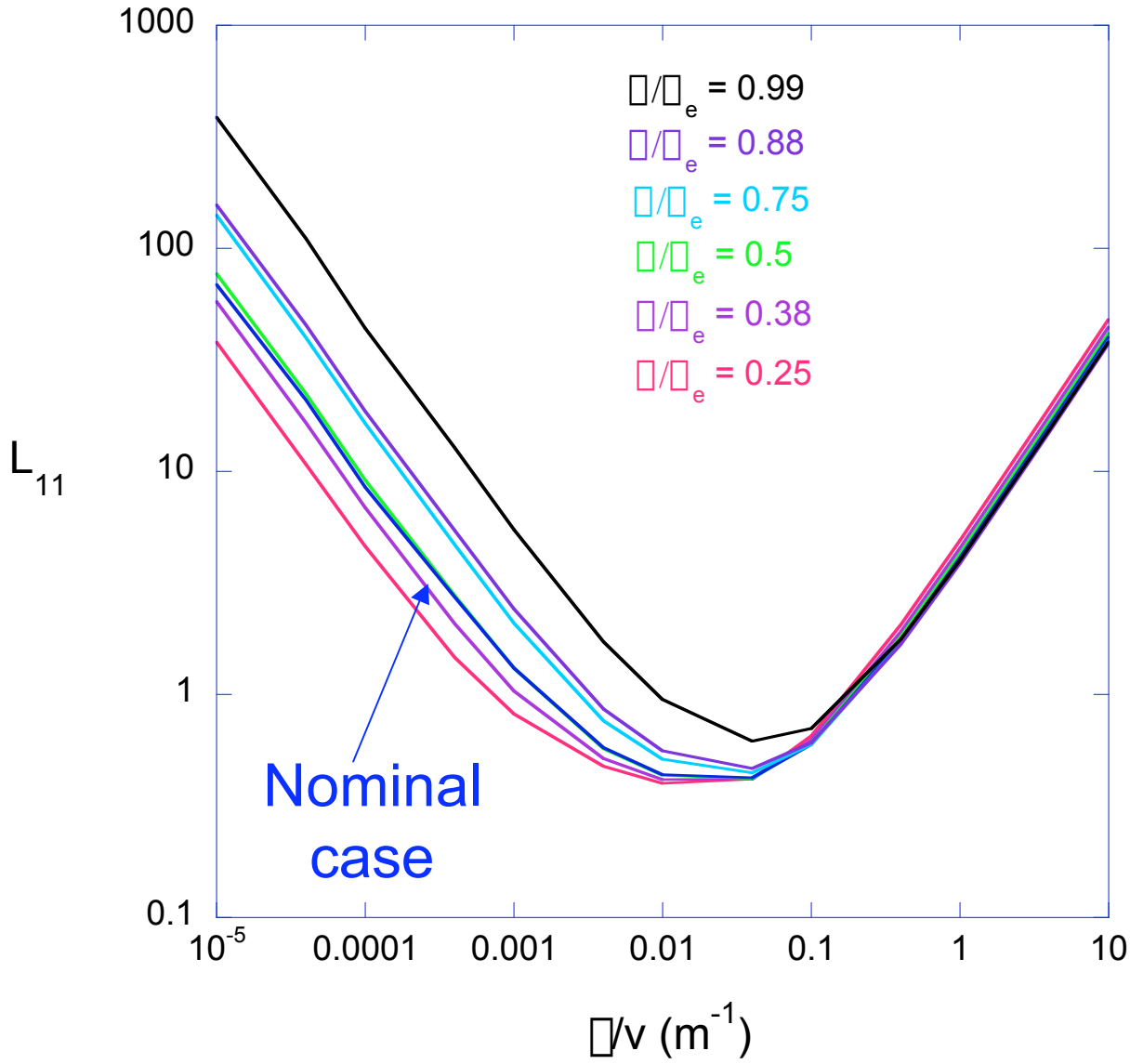
DKES L_{11} coefficient demonstrates the sensitivity of transport to coil current optimization

(shown here at ψ/ψ_{edge}=0.5)

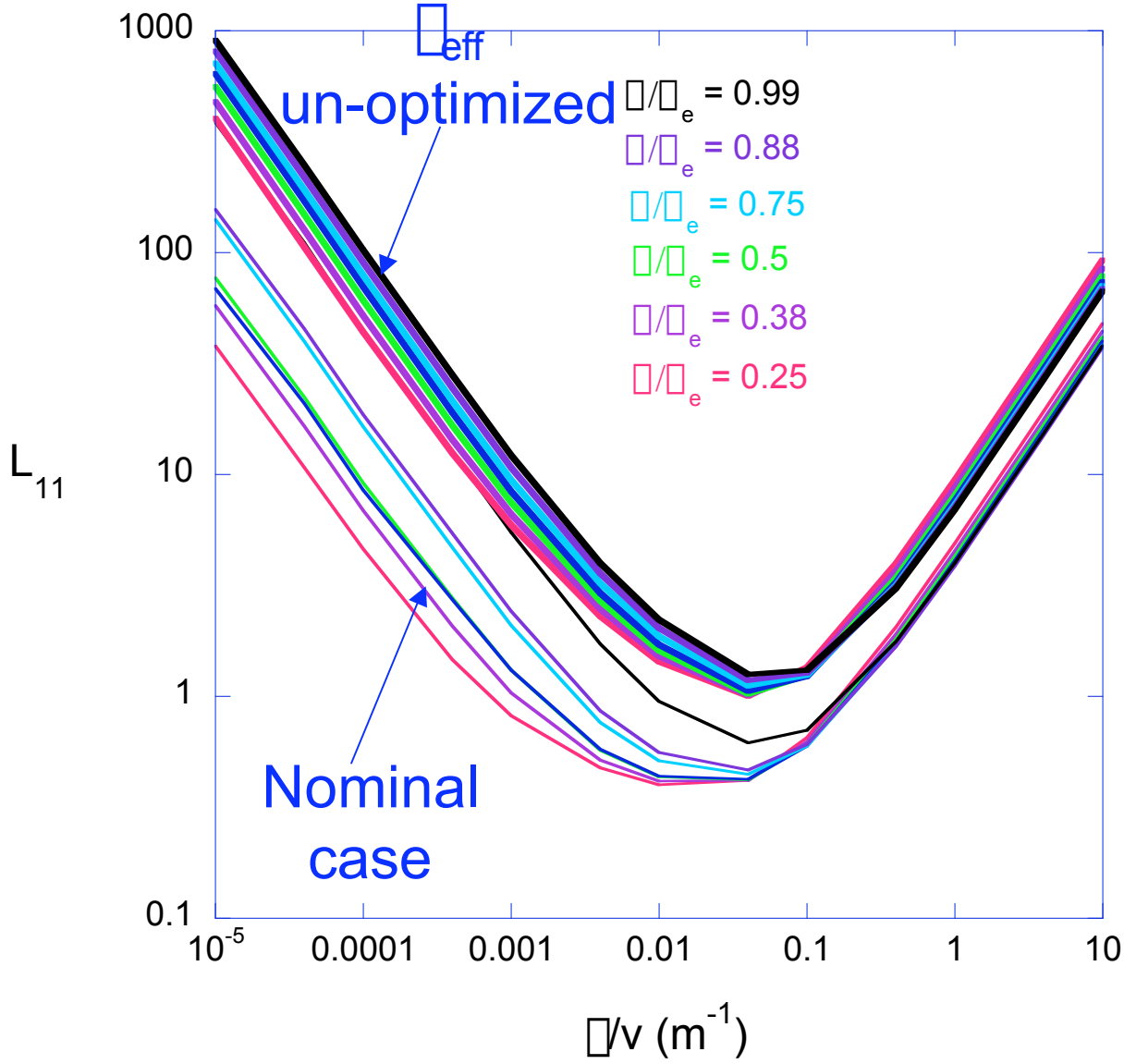




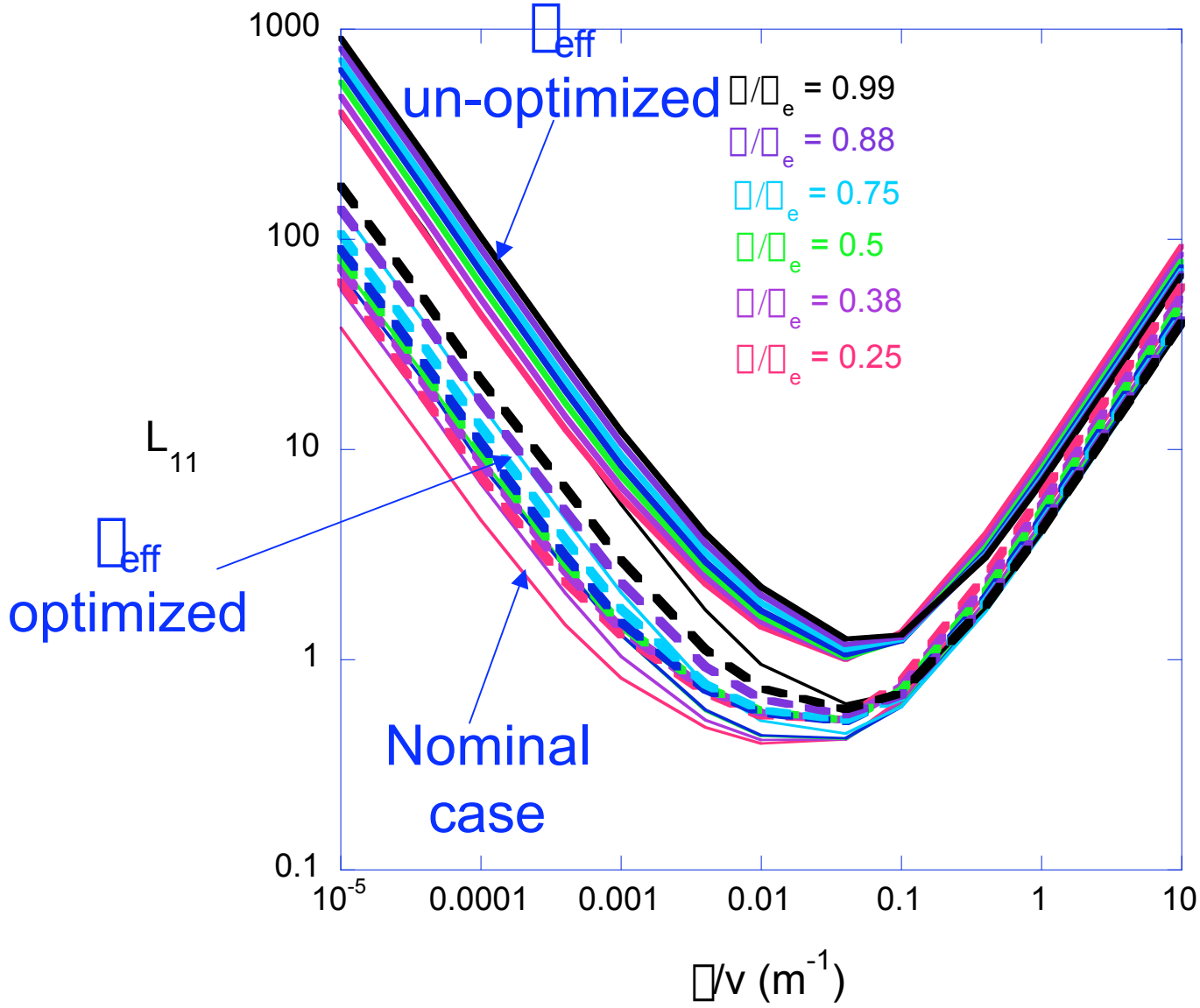
DKES monoenergetic L_{11} transport coefficient



DKES monoenergetic L_{11} transport coefficient

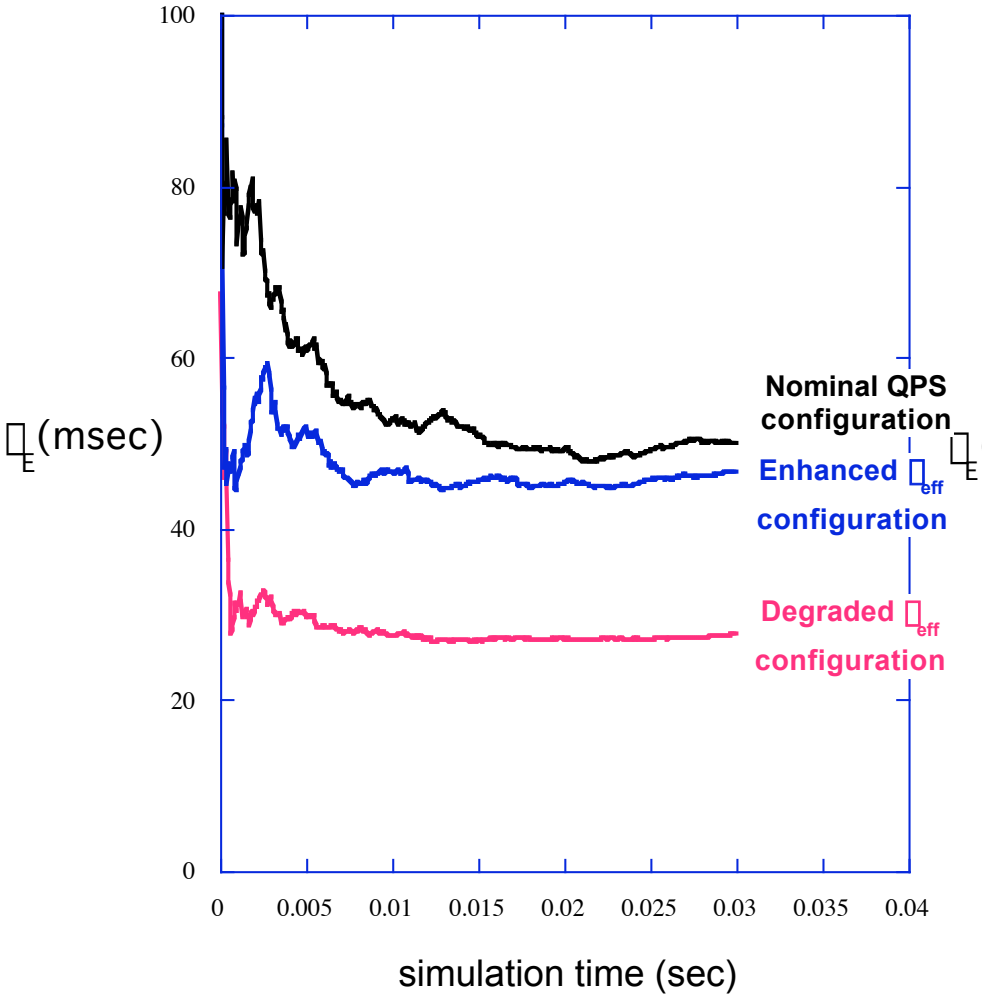


DKES monoenergetic L_{11} transport coefficient

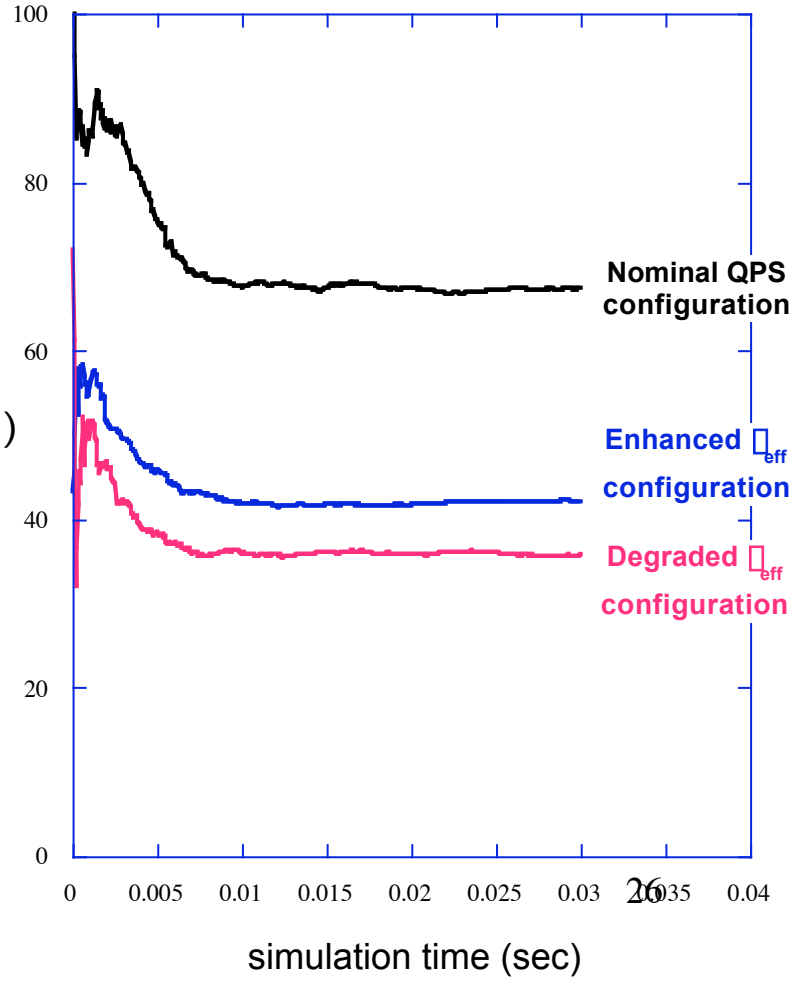


Cross-over of optimized transport coefficients at plateau regime is reflected in Monte Carlo ion τ_E's for different coil current options

ECH: $n(0) = 1.8 \times 10^{19}$ cm^{-3}
$T_{ion}(0) = 0.15$ keV, $T_{ion}(0) = 1.4$ keV



ICH: $n(0) = 8.3 \times 10^{19}$ cm^{-3}
$T_{ion}(0) = 0.5$ keV, $T_{ion}(0) = 0.5$ keV



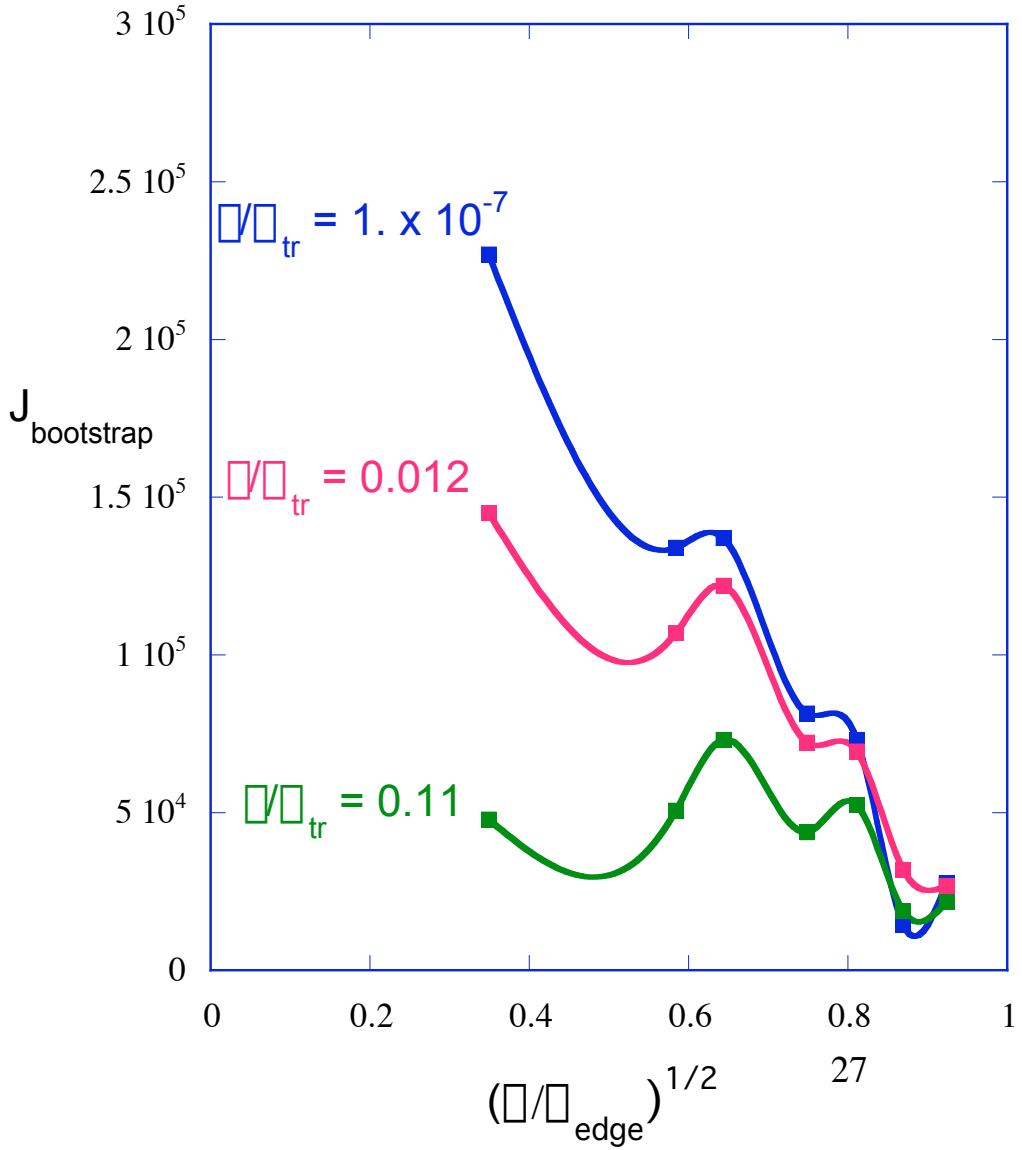
The energy integrated DKES L_{31} coefficient allows assessment of the dependence of the QPS bootstrap current on collisionality and ambipolar electric field

Bootstrap current in QPS will depend on:

- Collisionality
- Electric field (underway)
- Will be augmented by
  - Ohmic current
  - Lower hybrid current drive

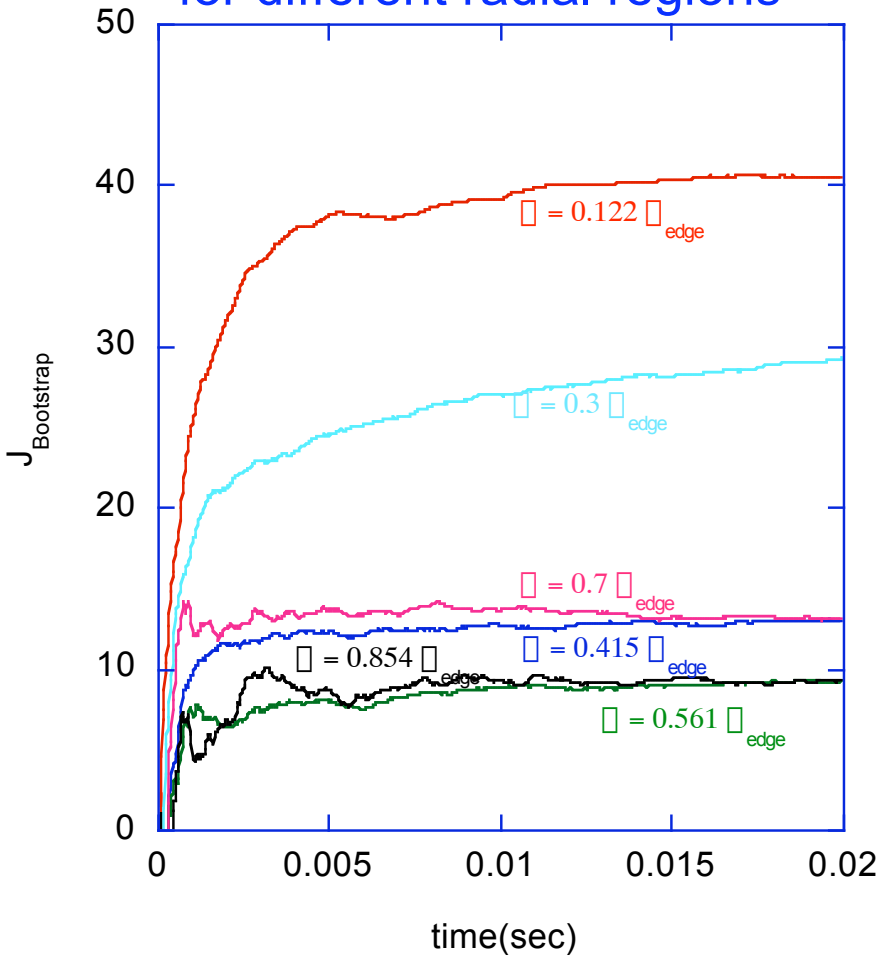
ν/ν_t

	ECH	ICH
electrons	0.005	0.18
ions	0.3	0.12

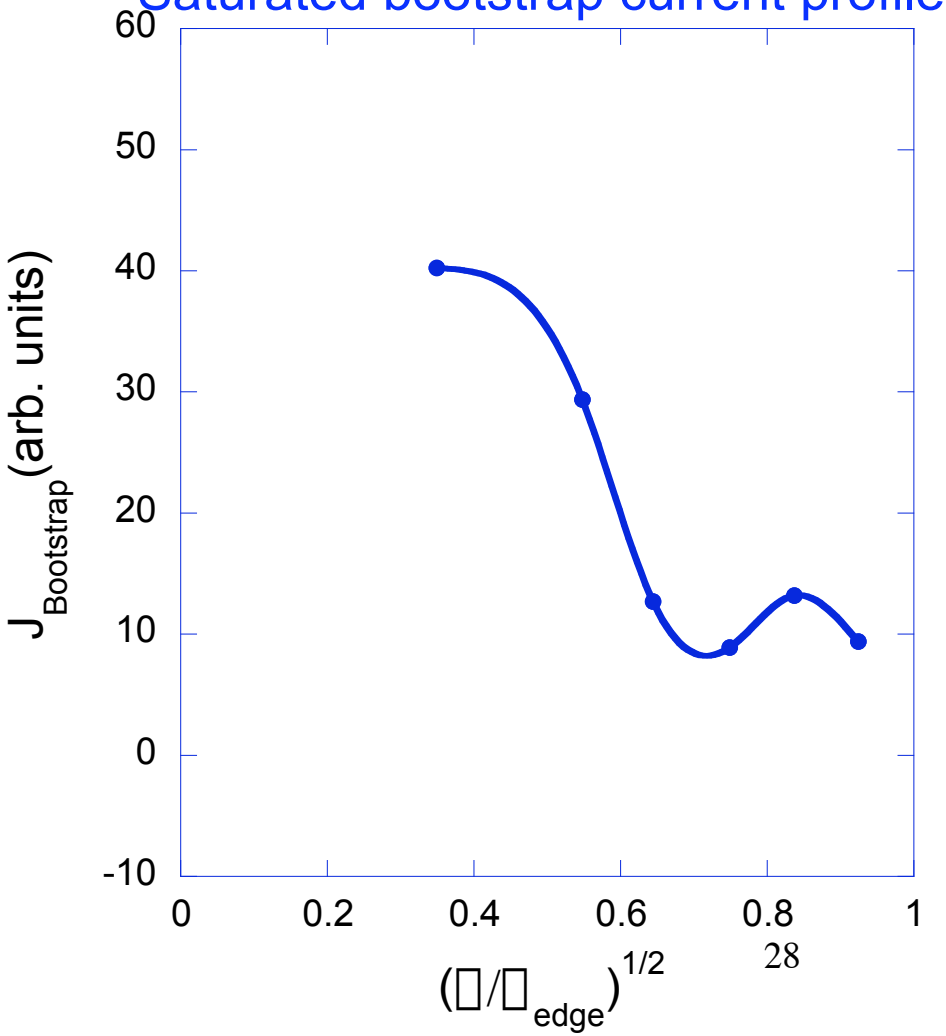


Monte Carlo □f techniques offer an alternate way to calculate bootstrap current profiles

Bootstrap current vs. time for different radial regions



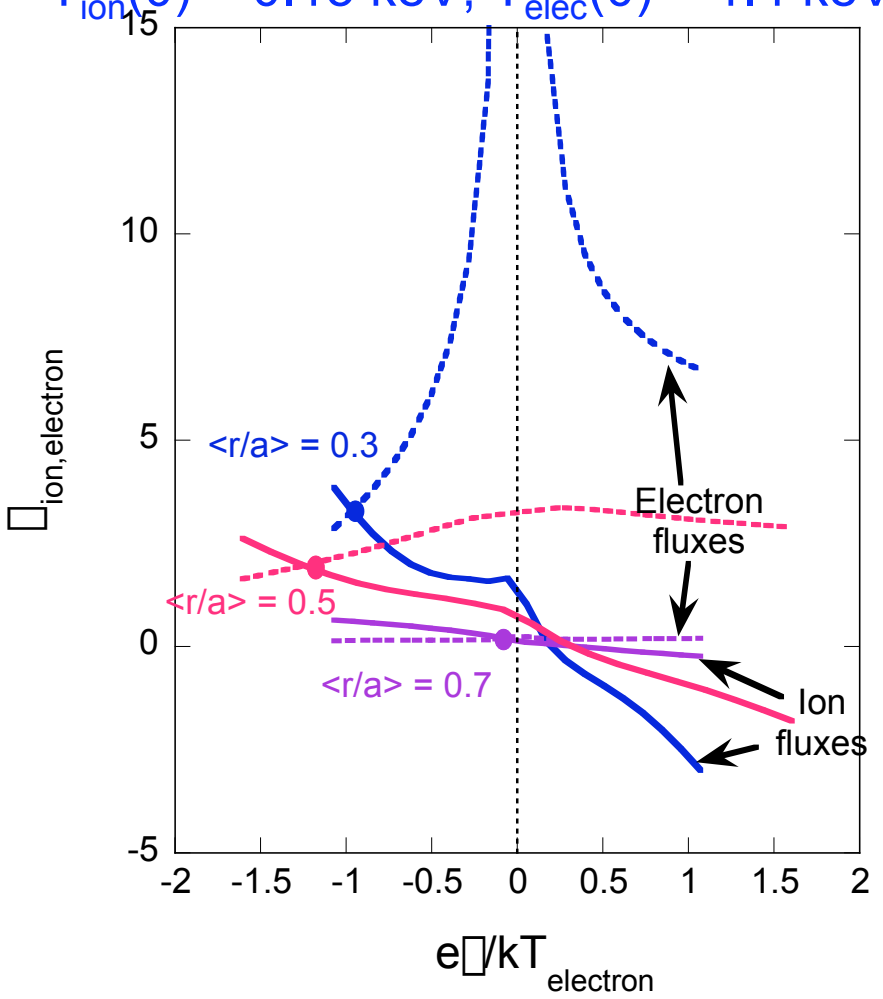
Saturated bootstrap current profile



QPS transport rates depend sensitively on the ambipolar electric field. DKES-based fluxes have been evaluated for ECH and ICH regimes:

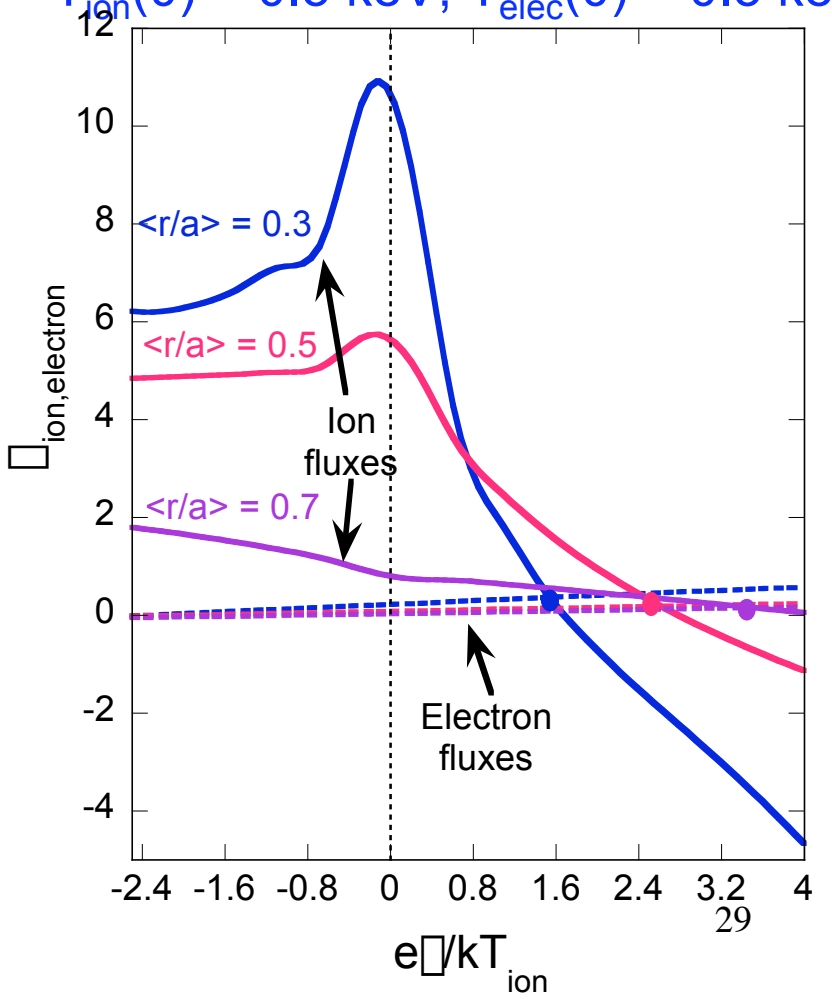
ECH: $n(0) = 1.8 \times 10^{19}$ cm^{-3}

$T_{ion}(0) = 0.15$ keV, $T_{elec}(0) = 1.4$ keV



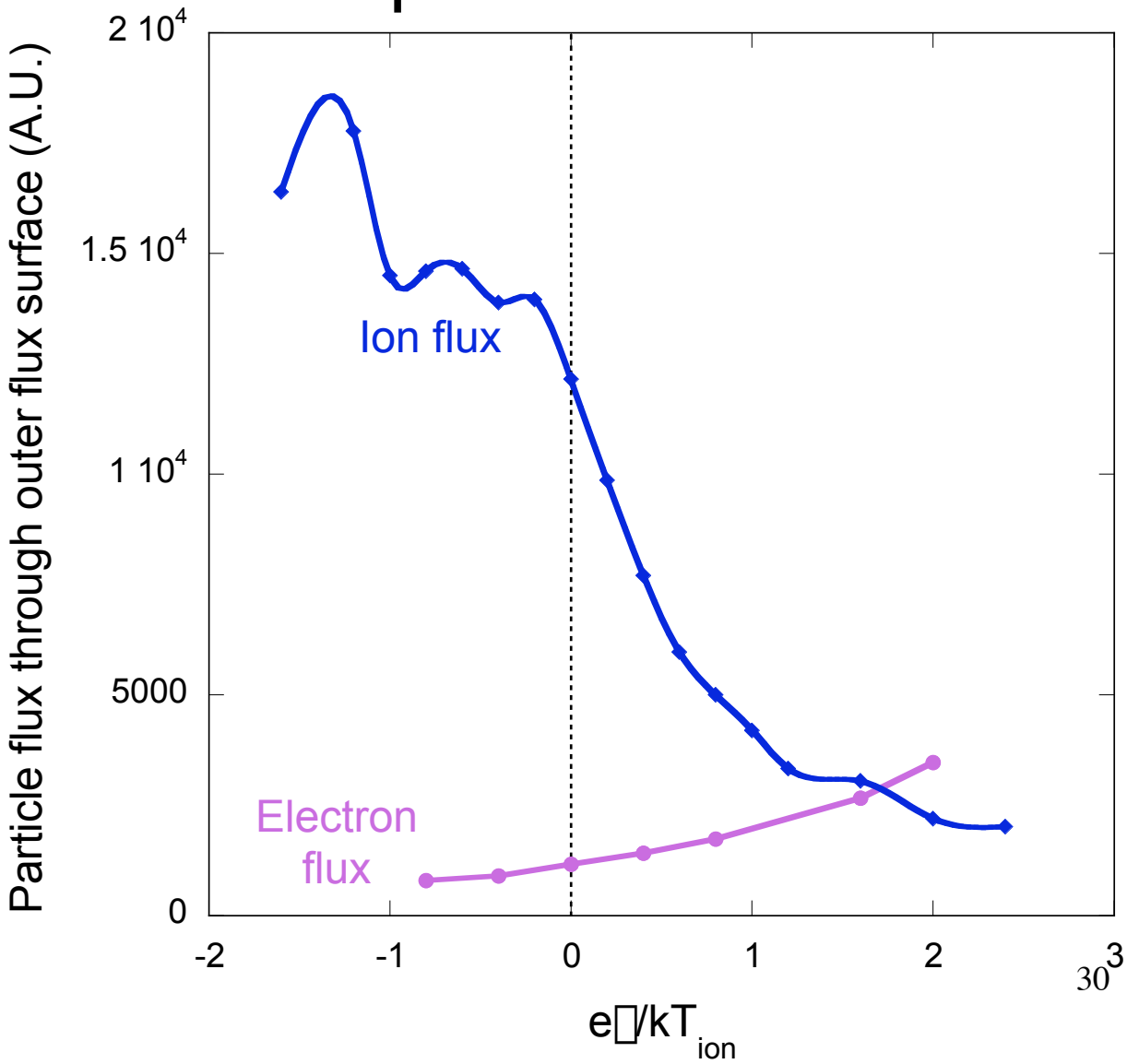
ICH: $n(0) = 8.3 \times 10^{19}$ cm^{-3}

$T_{ion}(0) = 0.5$ keV, $T_{elec}(0) = 0.5$ keV



In addition, global Monte Carlo simulations have been applied to the ICRH regime, indicating similar ambipolar roots:

ICH
$n(0) = 8.3 \times 10^{19}$ cm^{-3}
$T_{ion}(0) = 0.5$ keV
$T_{ion}(0) = 0.5$ keV



Outline

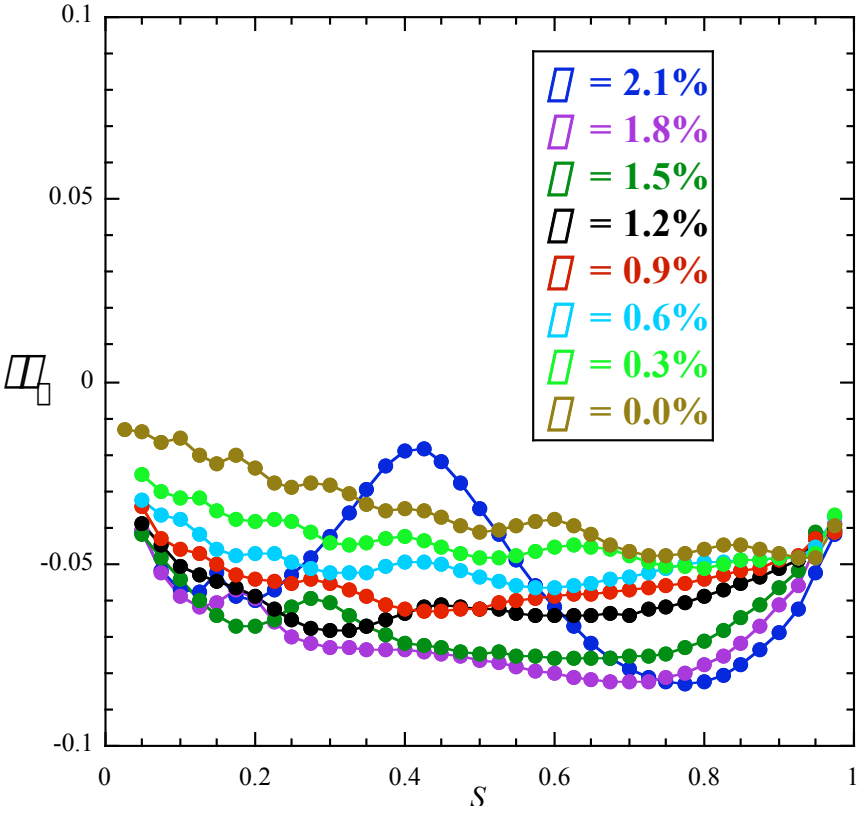
- Optimization
- Equilibrium
- Transport
- Stability
  - QPS Design requirements
    - Ballooning stability up to <□> = 2%
    - Sufficient design flexibility to test stability limits
    - Maintenance of kink and vertical stability with bootstrap current to <□> = 2%

Stability requirements of the QPS design have been checked with using the following models:

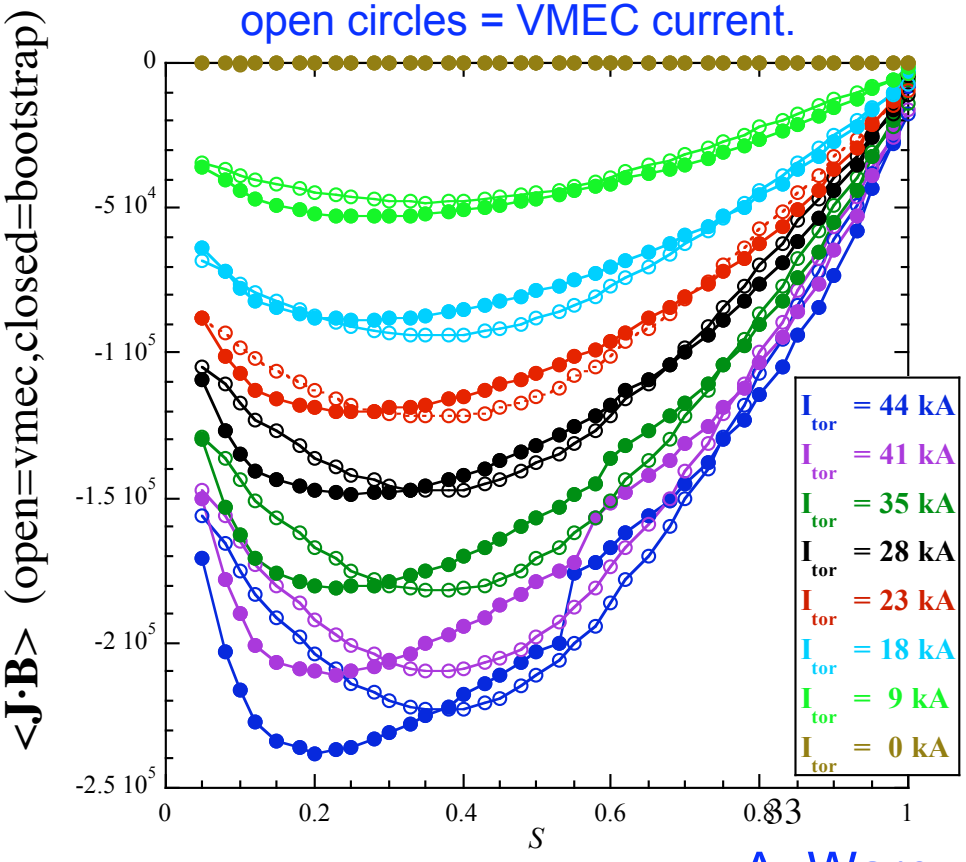
- Mercier
  - Evaluated within VMEC equilibrium code
  - Magnetic well stability, except at local resonances
- Ballooning
  - COBRA (high-n rapid ballooning analysis)
  - Sets the stability β-limits for QPS at $\beta \sim 2.1\%$
- Kink/vertical
  - TERPSICHORE (low-n variational principle)
  - Small amount of plasma current results in good kink and vertical stability (tested for older configuration, needs to be updated)
- Finite toroidal mode number and resistive stability
  - M3D (topic for the future)

Ballooning Stability: A free boundary □-scan shows that the QPS reference design is stable & bootstrap consistent up to <□> ≤ 2.1%

Ballooning growth rate calculated using the COBRA code with field-aligned equilibrium and predicted bootstrap currents



Closed circles = bootstrap current
open circles = VMEC current.



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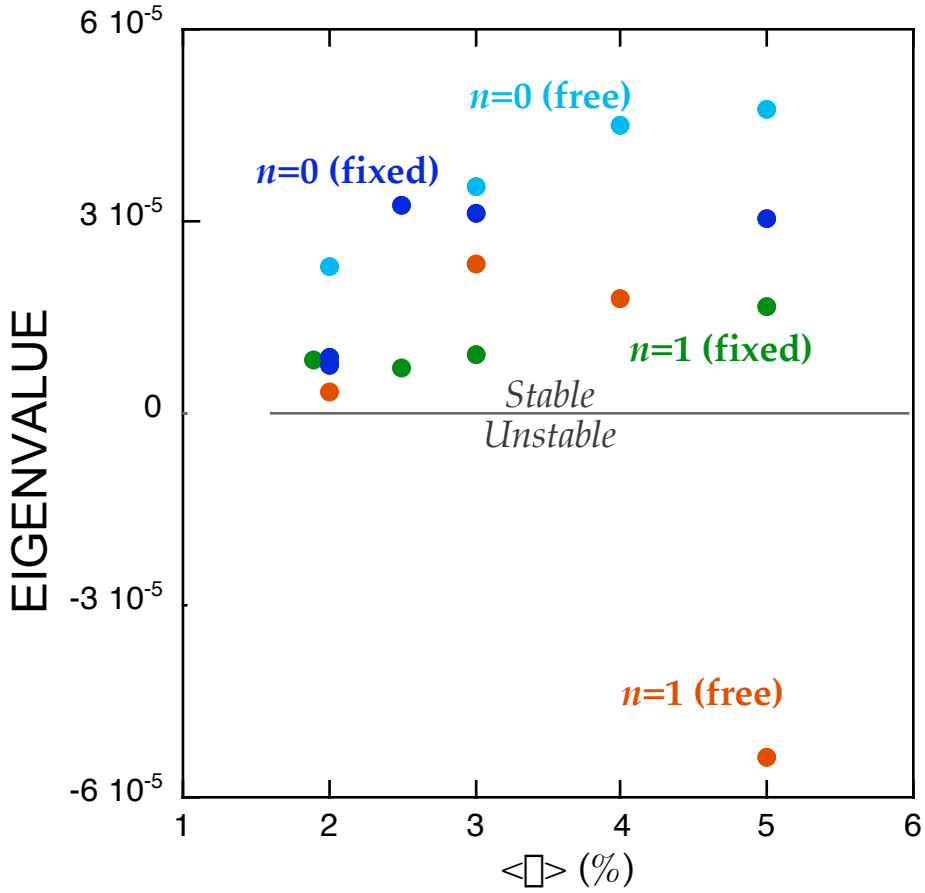
Kink & Vertical Stability: Older QPS configuration
kink/vertical stable for β < 5%

- TERPSICHORE Code used to evaluate *n*=0 (vertical) and *n*=1 (kink) stability
- *n*=0 and *n*=1 eigenvalues for a reference QPS plasma at various β



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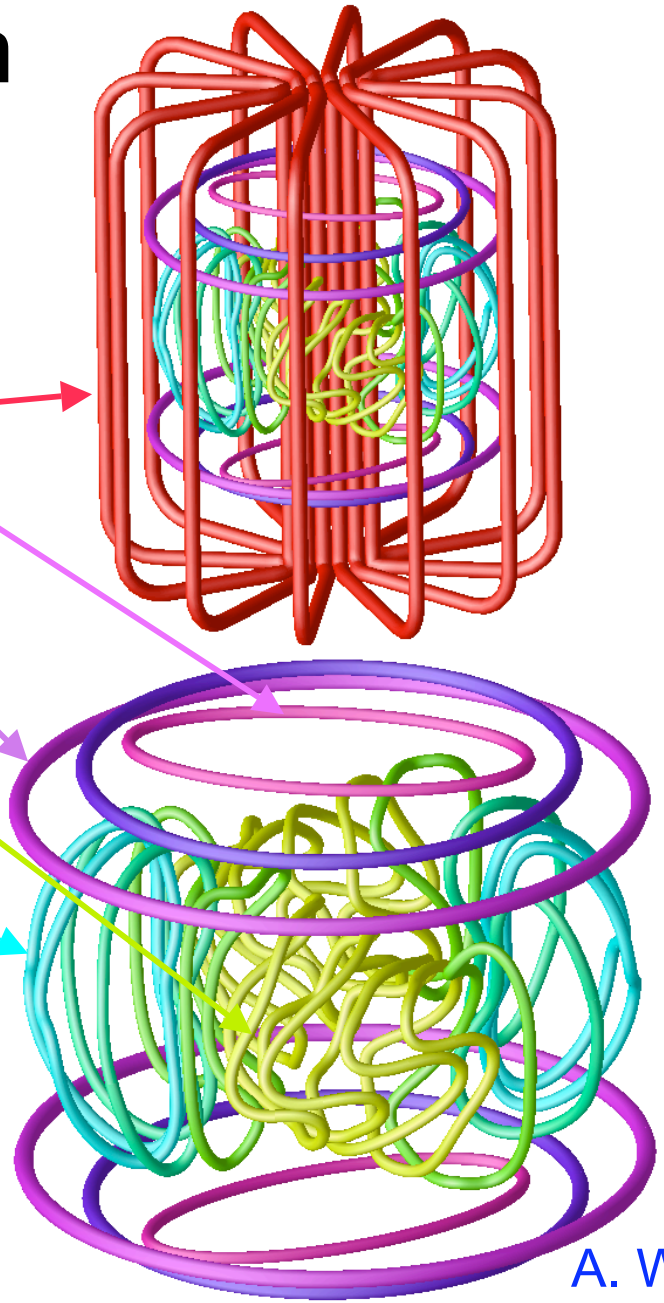
QPS MHD Stability can be controlled via External Current Variation

- QPS has a flexible coil system
  - Can vary the current separately in the
    - toroidal field coils (25 kA)
    - elliptical vertical field coils (114 kA)
    - outer vertical field coils (41 kA)
    - split modular coils (179 kA)
    - modular coils (360 kA)
- Ballooning Stability
  - Tested for a simple pressure profile:
    $p=p_0(1-S)^2$ at $\langle\beta\rangle$ = 1.83%



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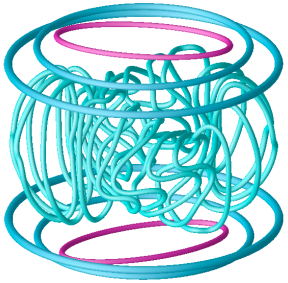
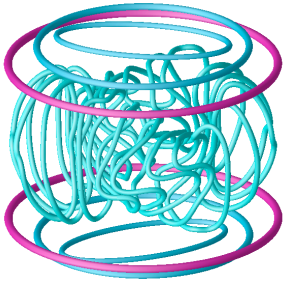
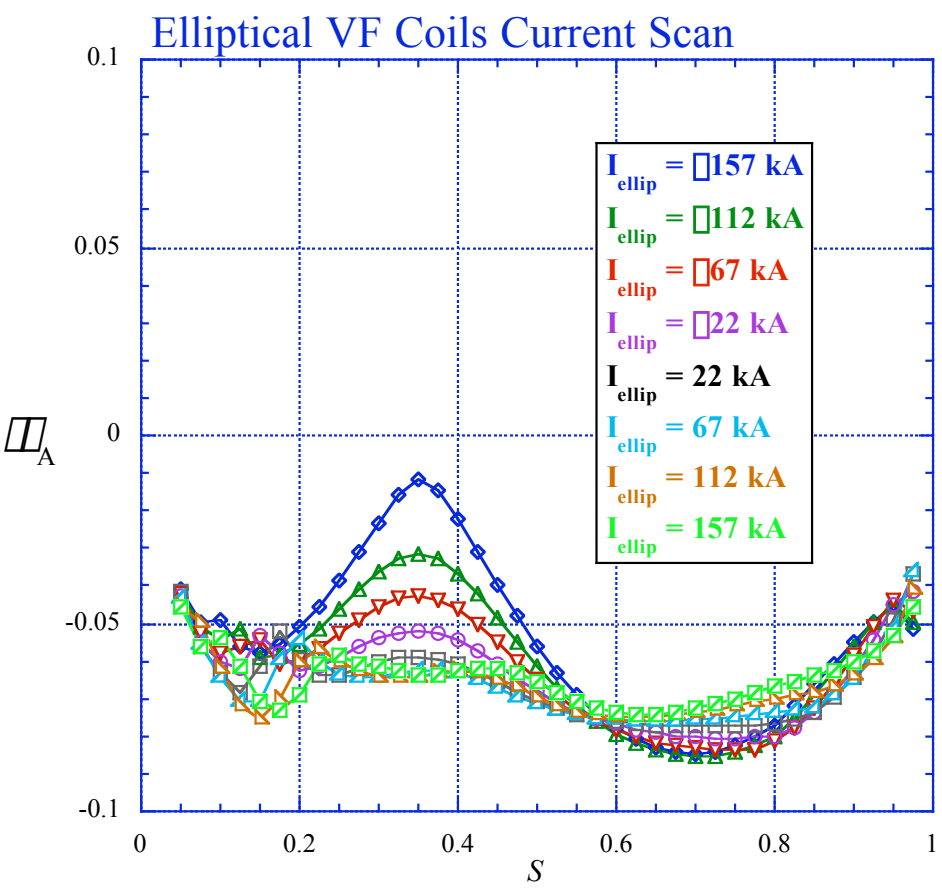
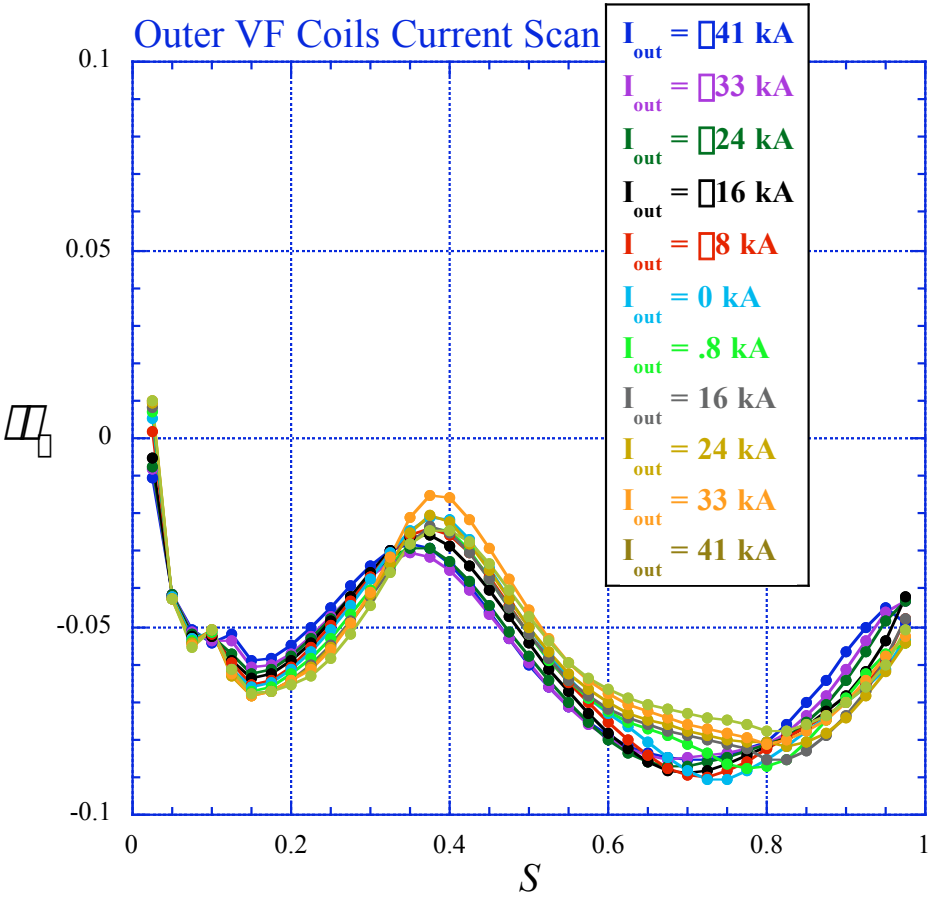


External Current Control:
Impact of elliptical and outer VF coils current on stability







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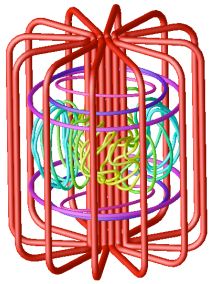
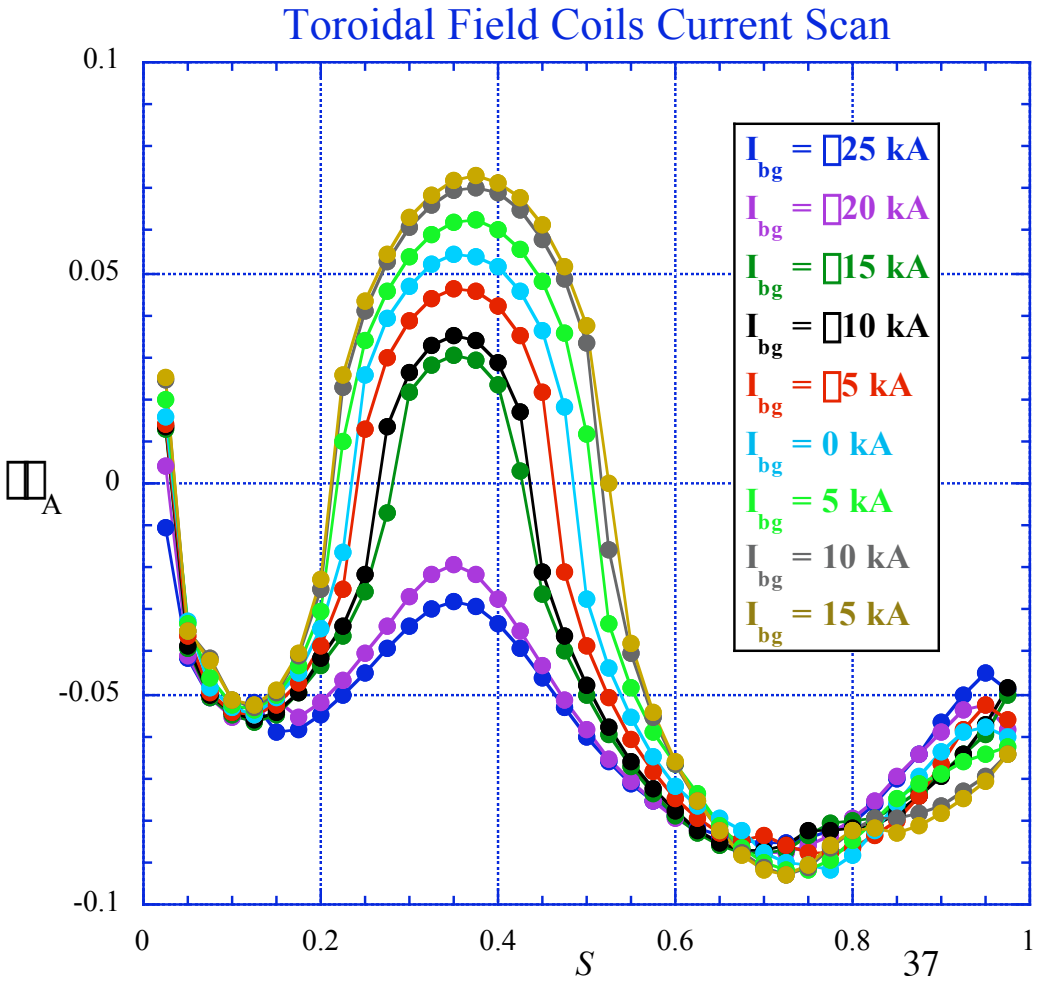
External Current Control: Toroidal field coil current variations can make ballooning modes weakly unstable



- Reference case: I_{TF} = -25 kA
- Plasma is stable at □ = 1.8% for I_{TF} = -25 kA and -20 kA
- Plasma is unstable at □ = 1.8% for I_{TF} = -15 kA to +15 kA



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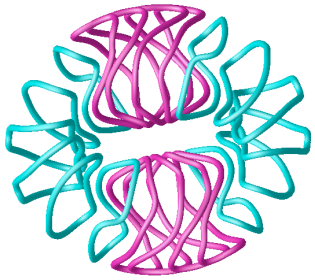
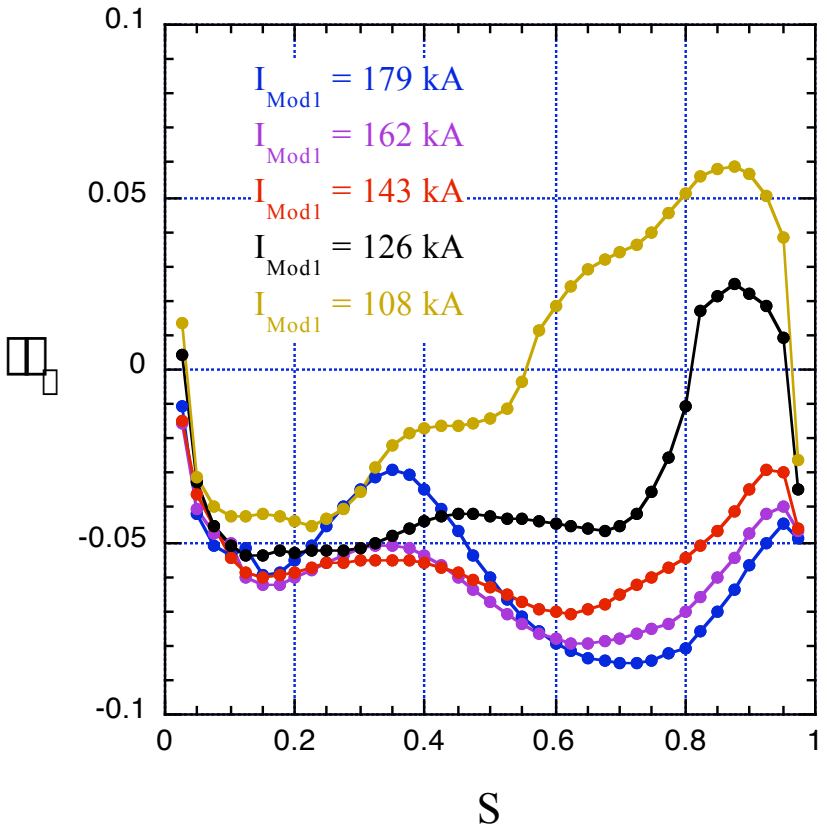
External Current Control: Impact of modular coil group 1 current on stability

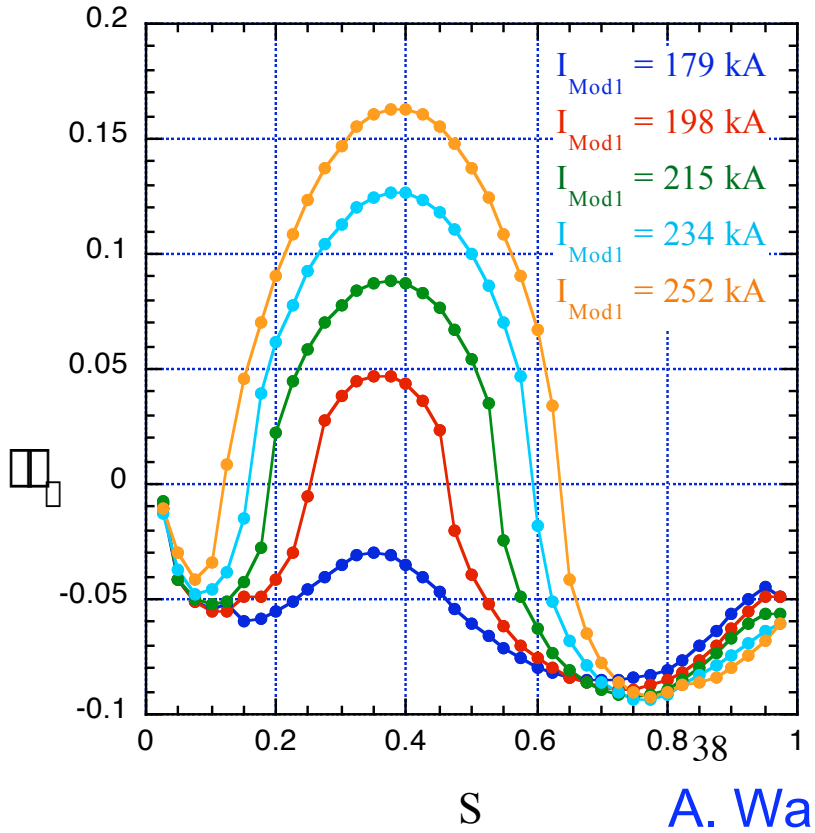


Reference case: I_{m1} = 179 kA

Decreasing M1 currents (Δ = 1.8%)



Increasing M1 currents (Δ = 1.8%)



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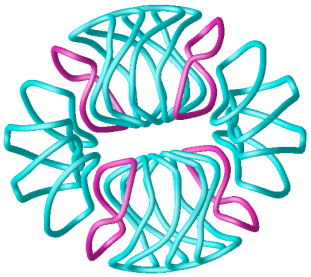
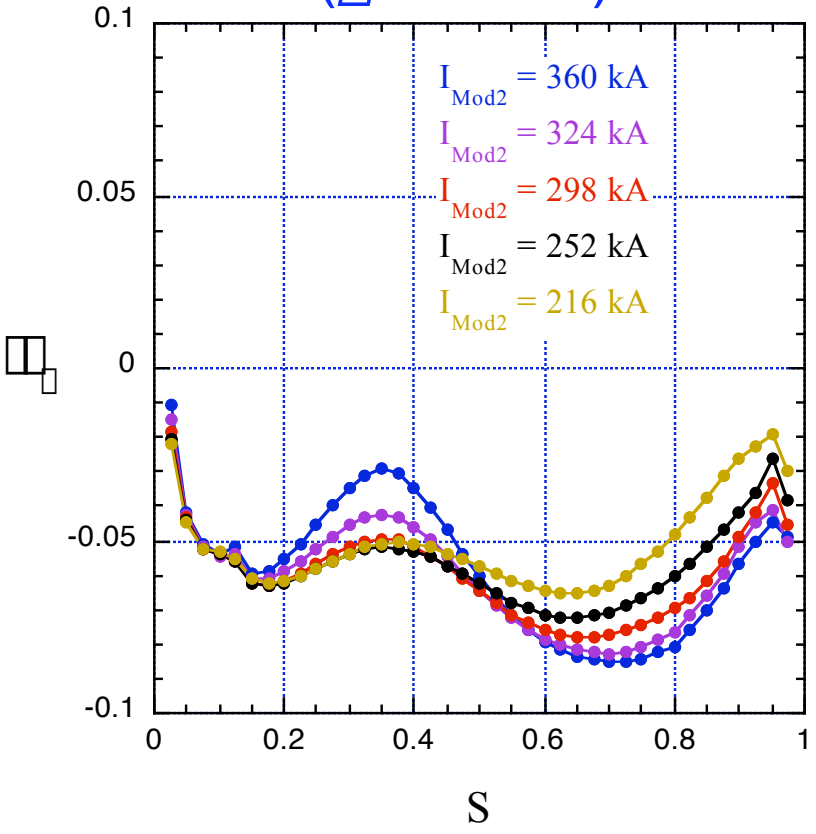
External Current Control: Impact of modular coil group 2 current on stability

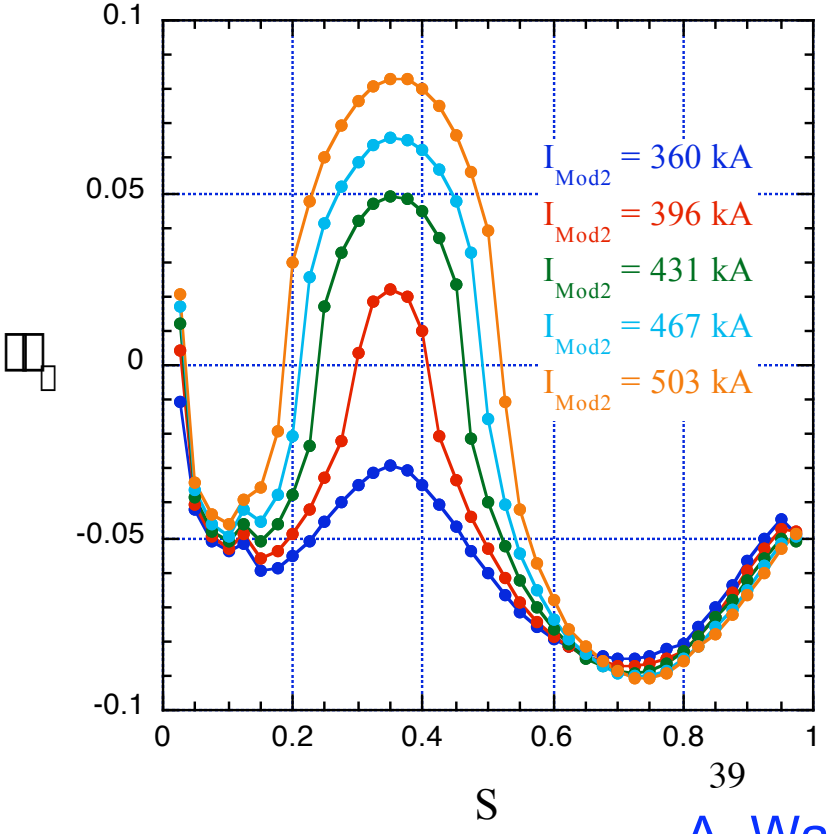


Reference case: I_{m2} = 360 kA

Decreasing M2 currents ($\Box$ = 1.8%)



Increasing M2 currents ($\Box$ = 1.8%)



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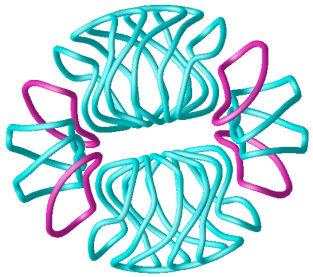
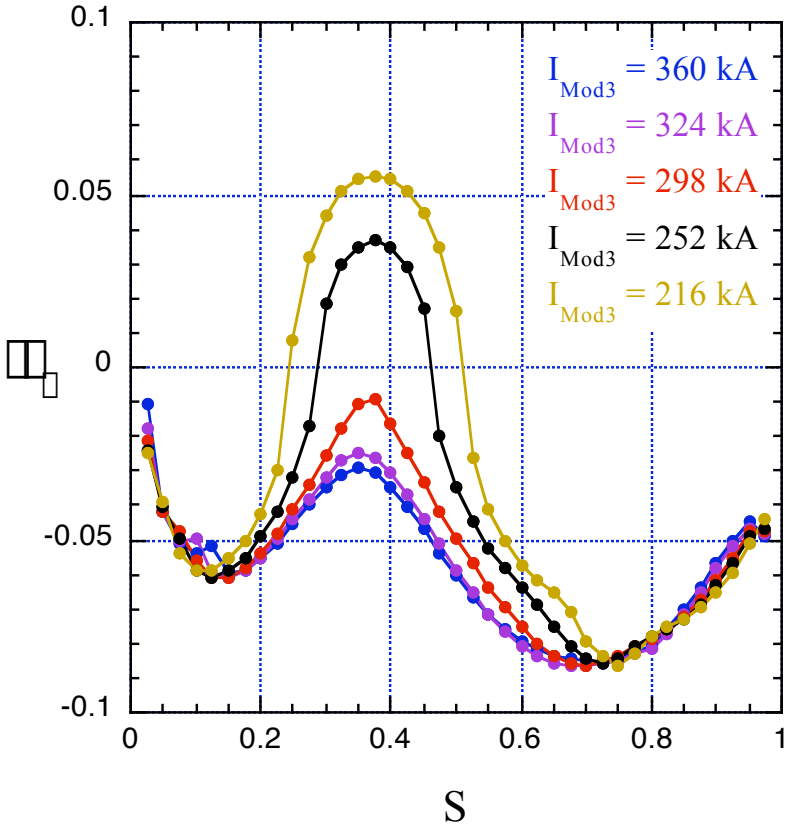
External Current Control: Impact of modular coil group 3 current on stability

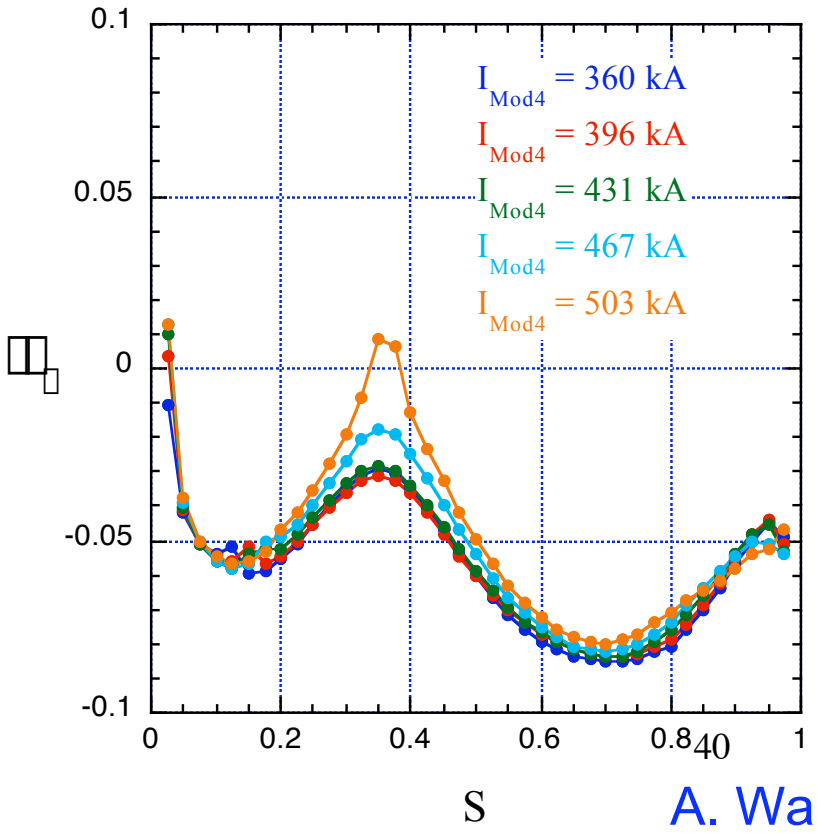


Reference case: I_{m3} = 360 kA

Decreasing M3 currents ($\Box$ = 1.8%)



Increasing M3 currents ($\Box$ = 1.8%)



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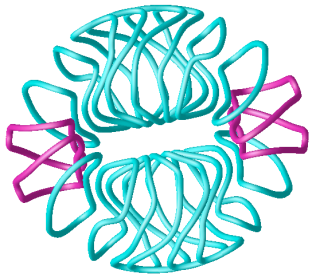
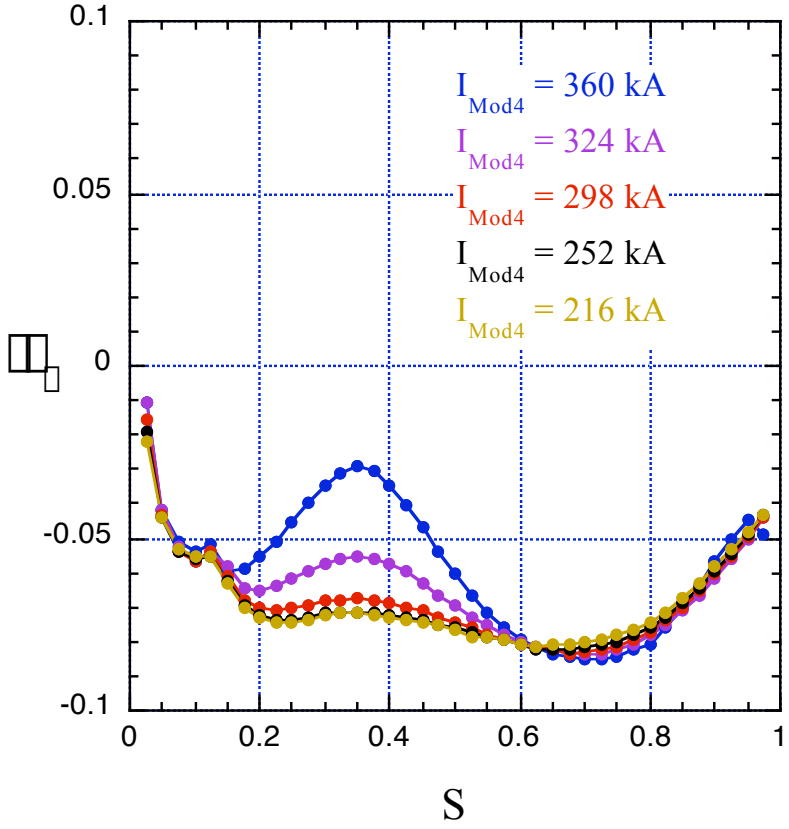
External Current Control: Impact of modular coil group 4 current on stability

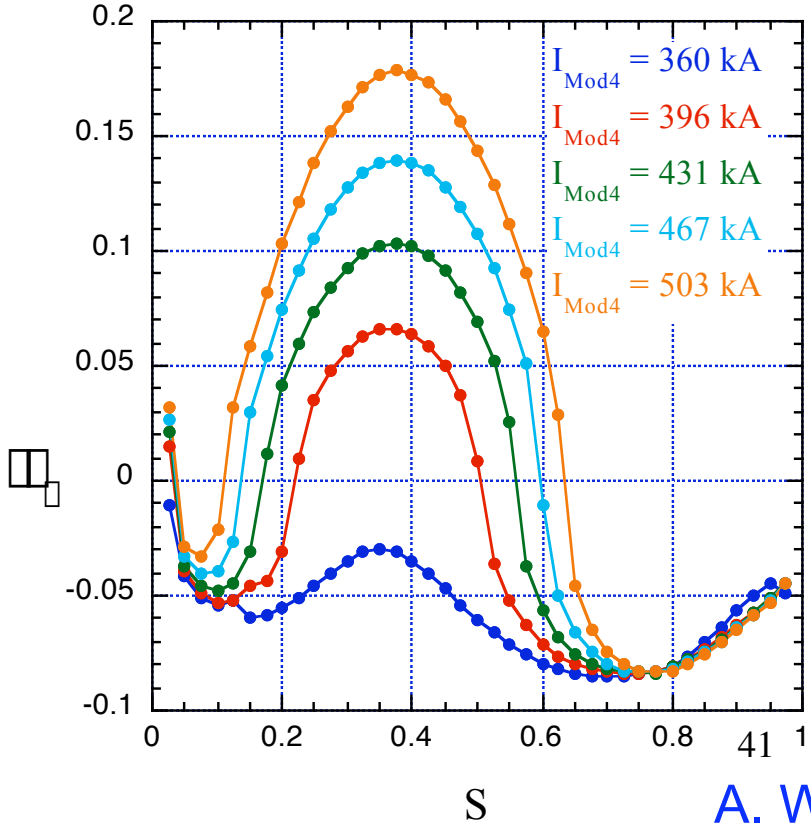


Reference case: I_{m4} = 360 kA

Decreasing M4 currents (ι = 1.8%)



Increasing M4 currents (ι = 1.8%)



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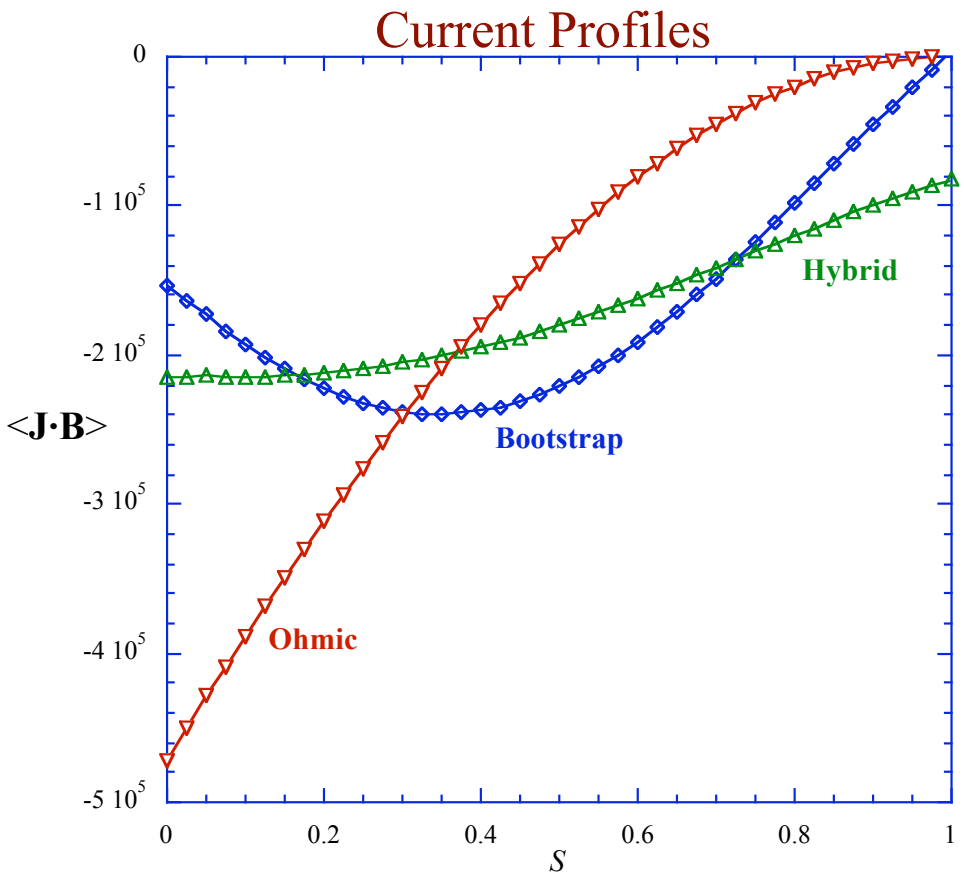
QPS MHD stability can also be influenced via plasma current control

- QPS will have the capability for Ohmic current drive
- Current profile variations have an impact on QPS stability
- Current profile control is thus a useful tool for testing stability predictions

Current Profile Control: Impact of different profiles on ballooning stability

Three test profiles used:

- a predicted bootstrap current profile
- an Ohmic current profile
- a hybrid current profile



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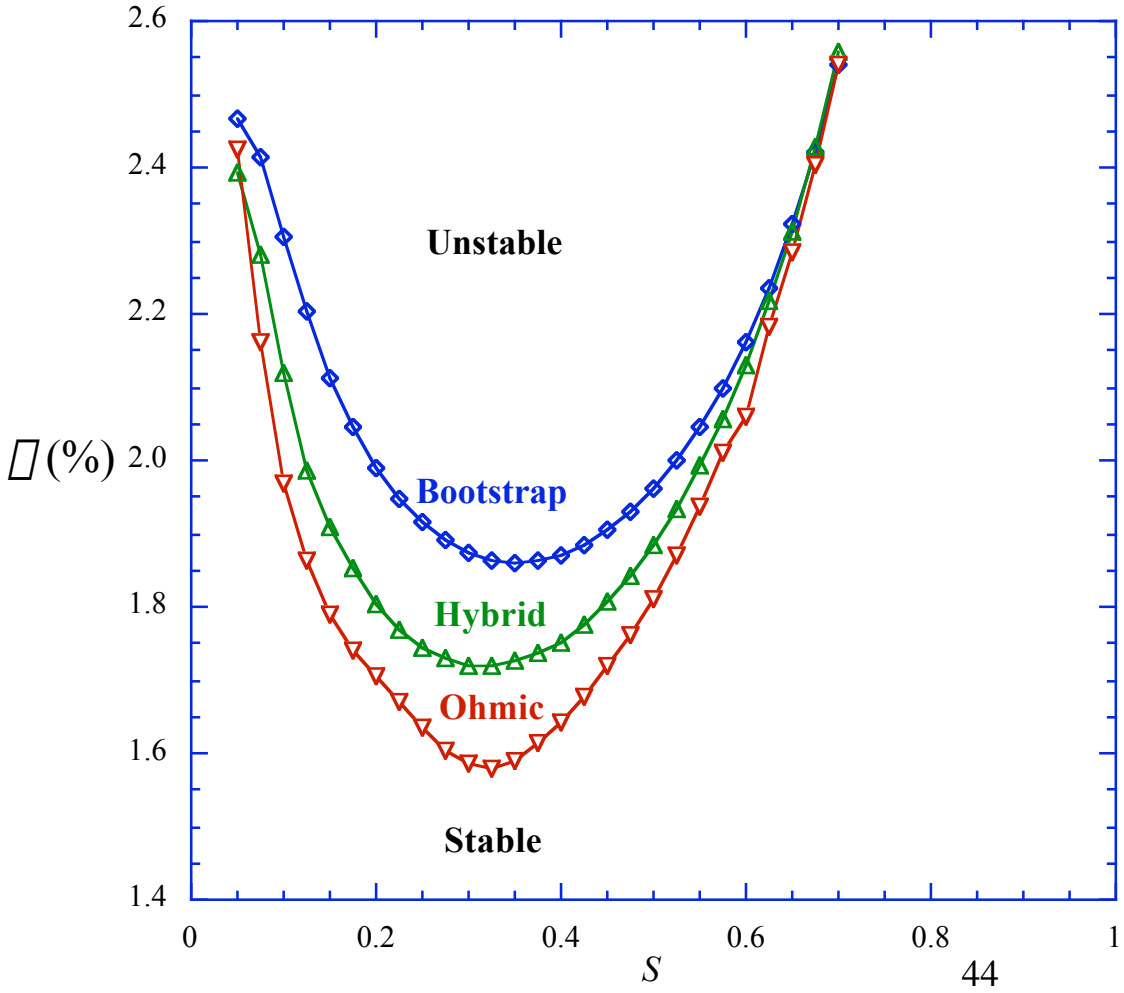
Current Profile Control: Impact of different profiles on ballooning stability

Volume averaged β's at which different flux surfaces go ballooning unstable: dependence on current profile:



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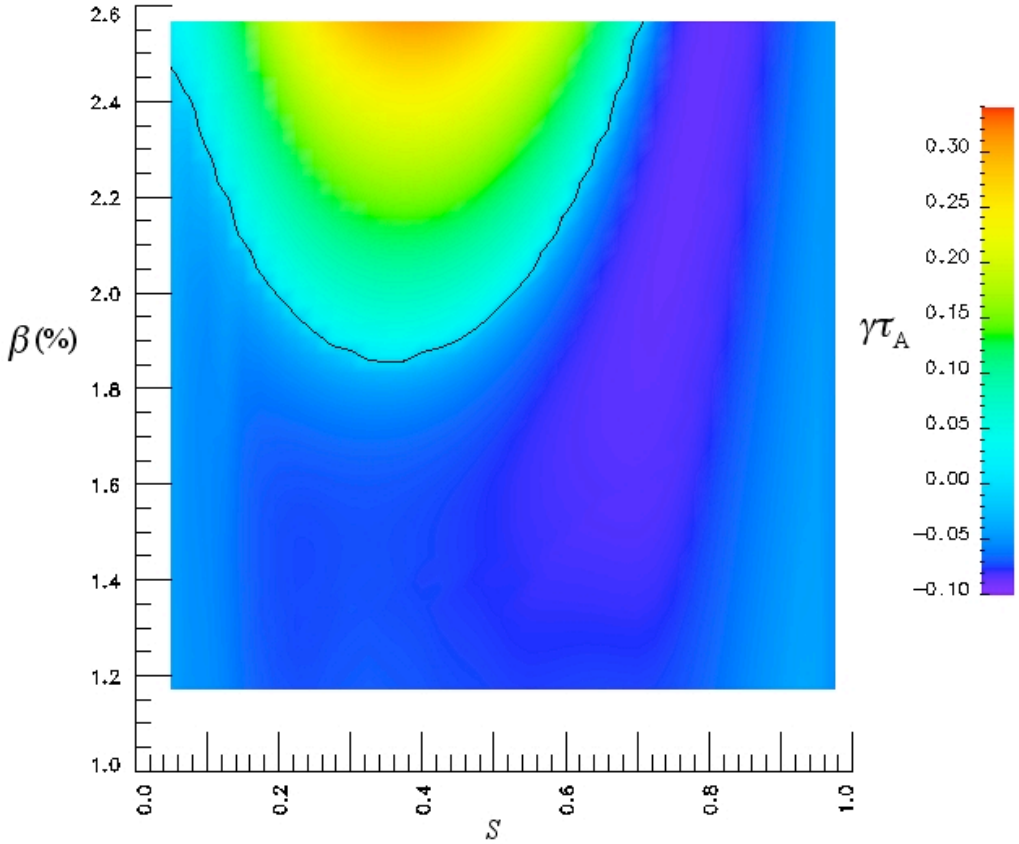
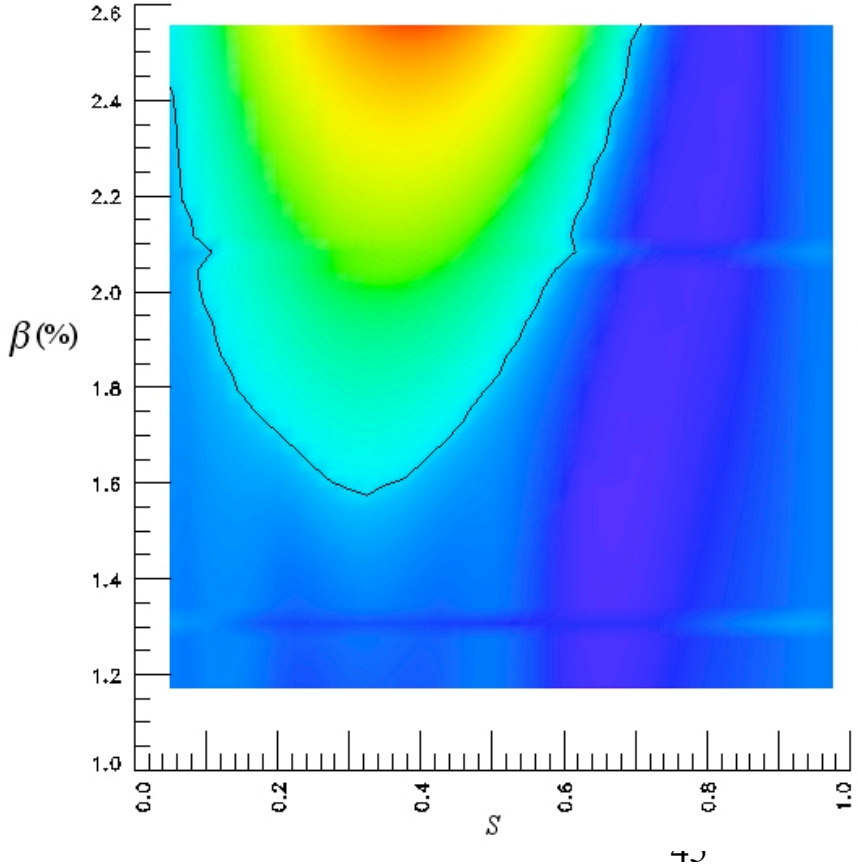
Current Profile Control: Impact of different profiles on ballooning stability

Color contours show ballooning growth rates vs. flux surface and volume averaged □

Bootstrap Profile

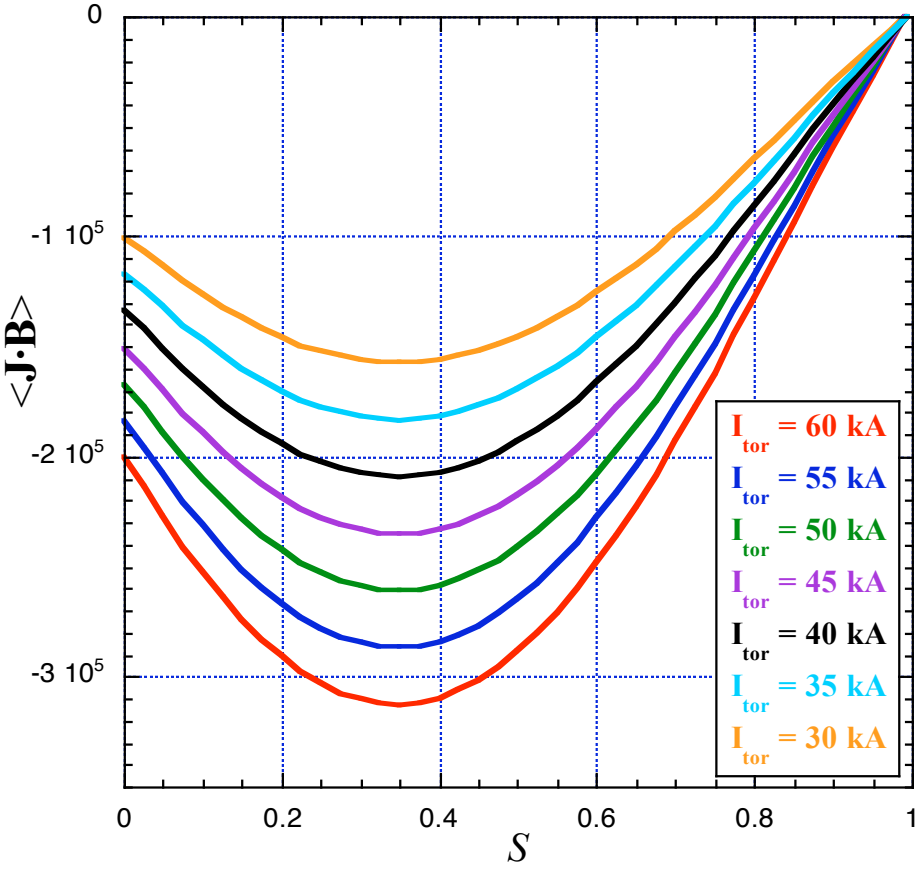


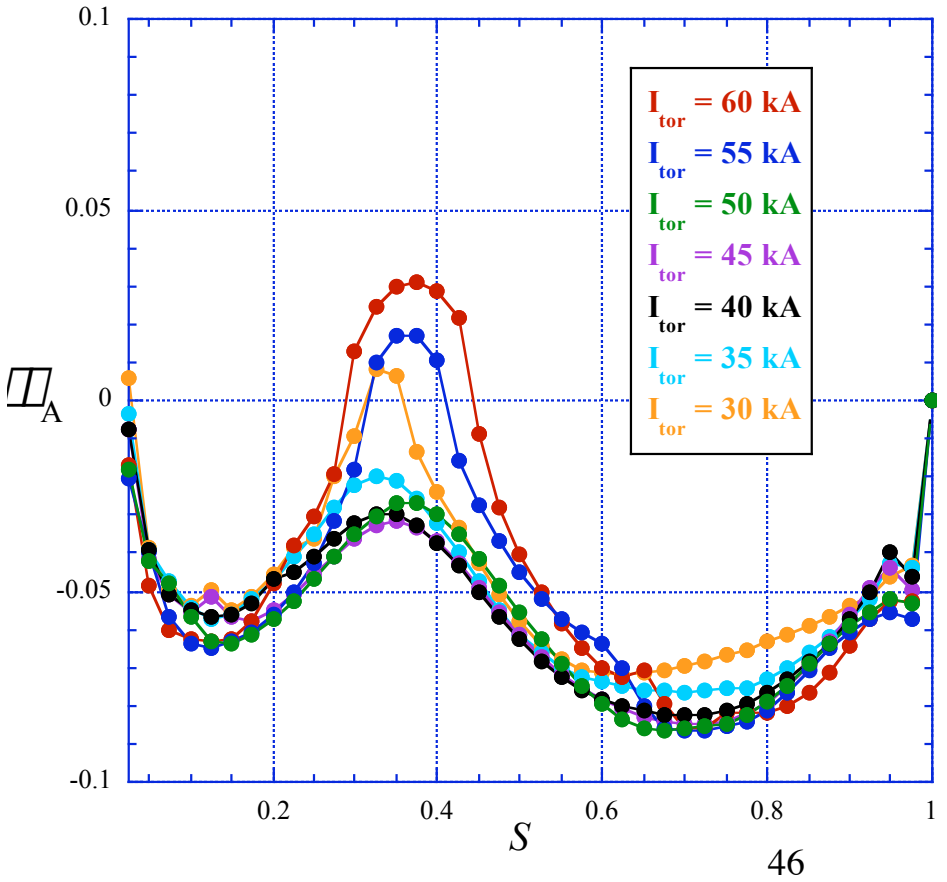
Ohmic Profile



Plasma Current Control: Impact of plasma current on ballooning stability

Field-aligned current & ballooning growth rates (self-consistent bootstrap current was 45 kA, <□> = 1.8%)





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Conclusions

- QPS reference configuration meets the physics goals
  - Equilibrium
    - Good flux surface reconstruction from coils
    - VMEC/PIES benchmarked for β running from 0->2%
    - Islands remain small
  - Neoclassical transport significantly reduced below anomalous scalings
  - ideal MHD stability at $\beta \geq 2\%$
- The QPS design allows significant flexibility for testing equilibrium/transport/stability physics
  - 4 independently powered modular coils + vertical and toroidal coils
  - Can modify transport
    - low collisionality (electron) transport by up to a factor of 50
    - Differential changes between ion and electron transport rates
  - Destabilization of ballooning modes for $\beta \geq 1.8\%$

Conclusions

- VMEC/PIES equilibria show good surfaces (only small islands) up to <□> = 2%
- QPS can impact ballooning stability through control of current in external coils
  - largest impact is from the TF and modular coils
- QPS can also impact ballooning stability through control of the current profile
  - with an Ohmic current profile QPS is more unstable to balloning modes than with a bootstrap current profile
  - increased plasma current can induce a weak ballooning instability

Future Work (CDR, post-CDR)

- Transport
  - Better understanding of flexibility issues
  - Further incorporation of DKES coefficients (energy integrated)
    - 1D and point models
    - Bootstrap current prediction
    - Ambipolar electric field profile prediction
  - Evaluation/extension of Sugama/Nishimura calculation (Phys. Plasmas, Nov., 2002) for QPS devices
    - Viscosity coefficients/flow dynamics
    - Multi-species momentum conservation corrections
  - Advanced Monte Carlo models
    - Current code limited by number of particles (noise), simulation time interval, disparate electron/ion timescale
    - New approaches (address self-consistent profiles, E_r, $E_{\square}$)
      - Hybrid models (DKES electrons, guiding center ions)
      - Bounce averaged Monte Carlo

Future Work (CDR, post-CDR)

- Stability
  - Better understanding of flexibility issues
  - More complete kink and vertical mode stability
  - Finite toroidal mode number calculations
  - Alfvénic modes
    - Explore possibilties for excitation at low B/density with probes (as done on CHS, APS meeting, 2002)
- Optimization
  - Continued analysis of opportunities for flexibility based on coil current variations