QPS TRANSPORT AND ENERGETIC PARTICLE PHYSICS

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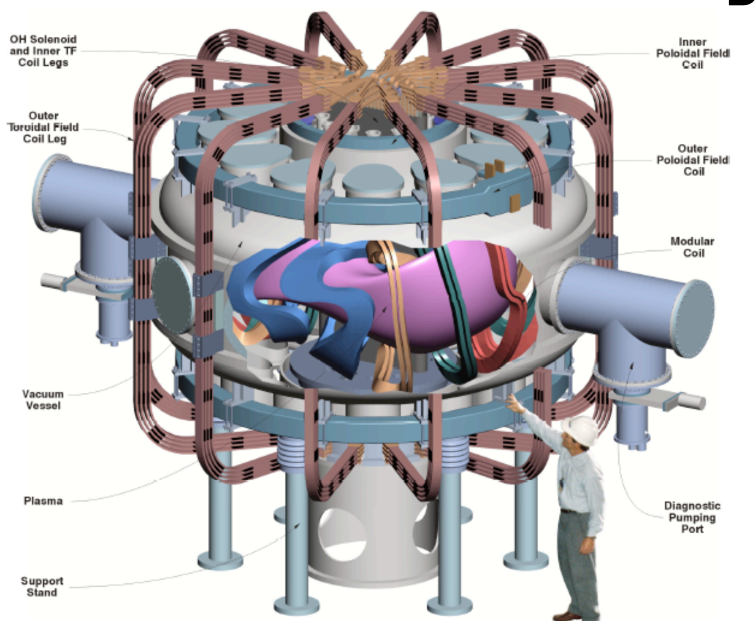


- QPS is a very low aspect ratio (A = 2.7) Quasi-poloidal stellarator that will test:
  - Equilibrium robustness at low A
  - Neoclassical and anomalous transport
  - Stability limits up to <□> = 2.5%
  - Bootstrap current effects
  - Reduced poloidal viscosity effects on shear flow transport reduction
  - and Configurational flexibility
- Design parameters: $\langle R_0 \rangle$ = 0.9 m, <a> = 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

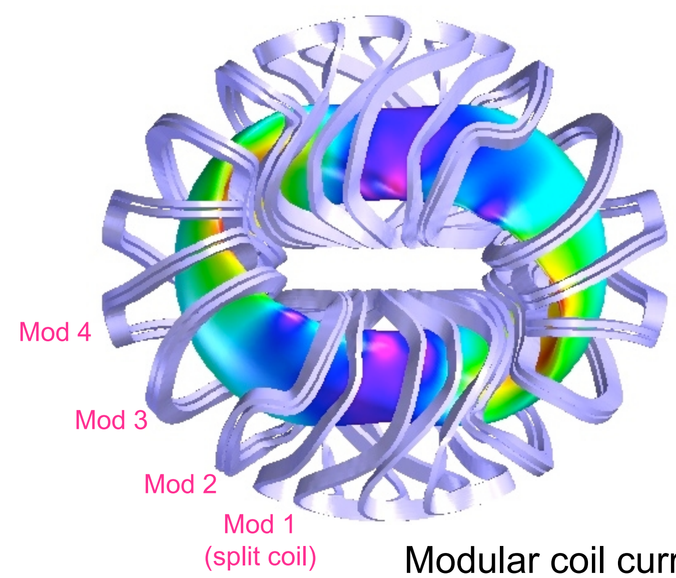
Optimization Strategy

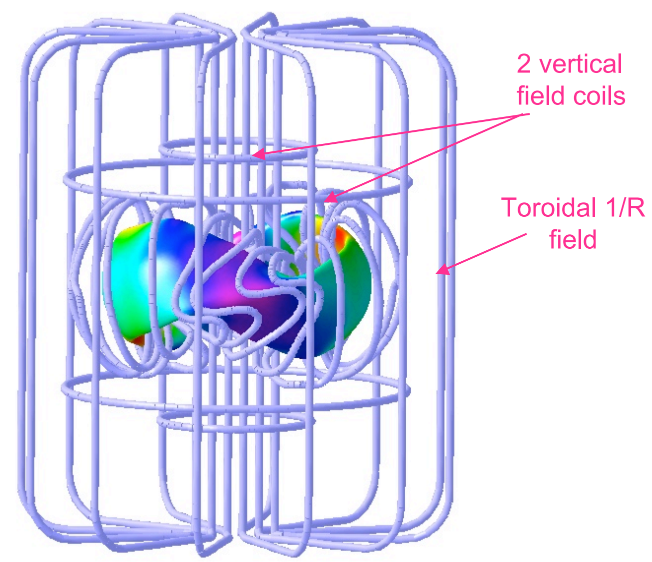
- QPS optimization targets:
  - $□_{eff}$
  - Poloidal symmetry
  - DKES
  - J, B_{min}, B_{max}
  - Ballooning stability (COBRA)
  - Bootstrap consistency
  - Iota profile
  - Mercier, well
  - Minimize B_{normal} on outer surface
  - Coil engineering
    - Coil-coi,l coil-plasma separation,
    - Minimumradius of curvature

Evaluation Tools

- TRANSPORT
- NEO $□_{eff}$, Poloidal symmetry
- DKES
  - Setup, mode selection
  - Parallel runs
  - Energy integration
- DELTA5D Monte Carlo
  - Global full-f model
  - ICRF heating
  - NBI heating efficiency
  - Alpha losses
  - □f bootstrap current
- 1-1/2 D fluid transport model

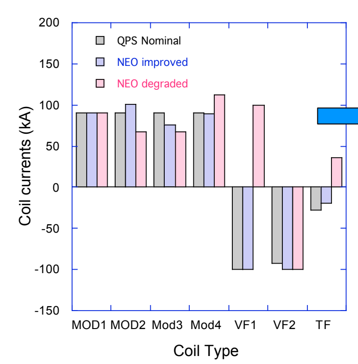
Transport flexibility studies (7 independently varialble coil currents)



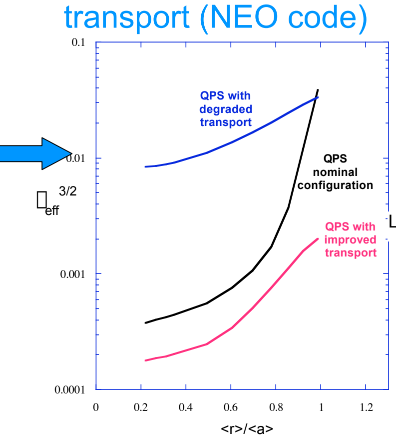


Modular coil currents can vary ±25%
Vertical field currents can vary ±100 kA
Toroidal field currents can vary ±70 kA

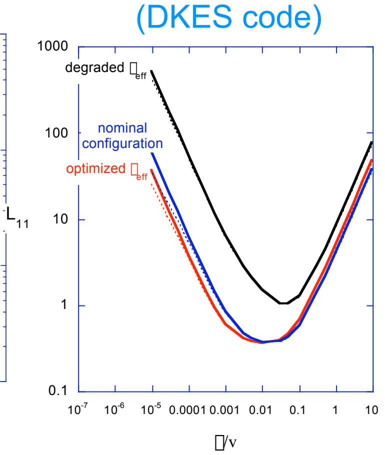
Coil Current distributions



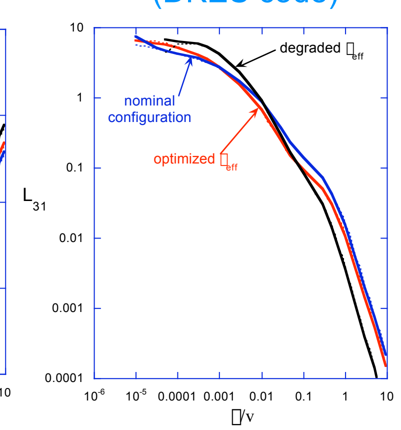
Low collisionality transport (NEO code)



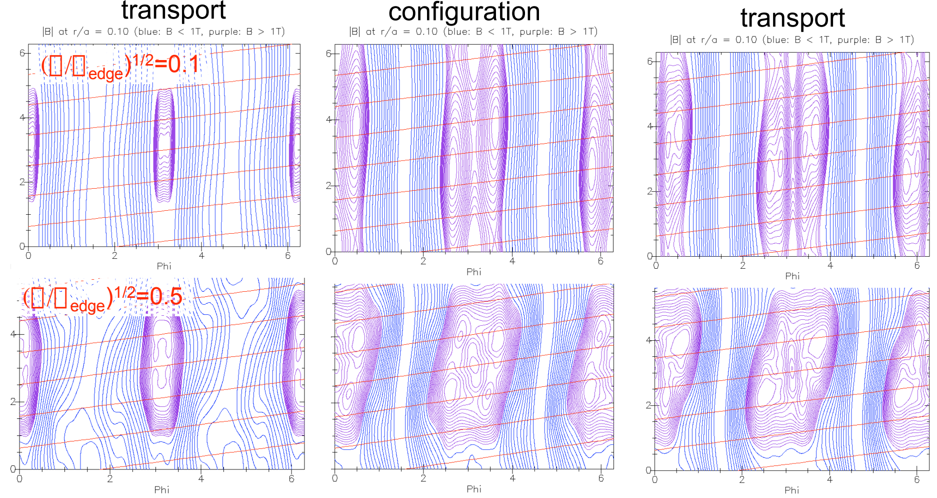
L_{11} diffusion coefficient (DKES code)



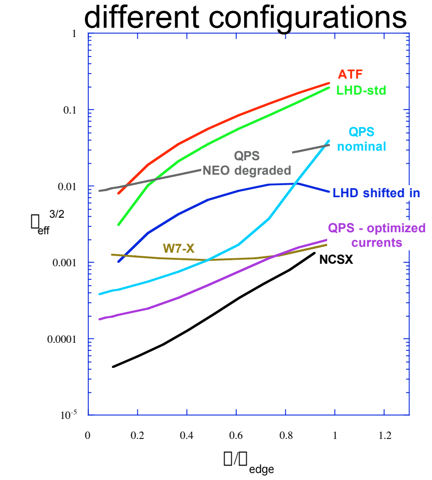
L_{31} bootstrap coefficient (DKES code)



|B| for degraded transport | |B| for nominal configuration | |B| for improved transport



Comparison of $□_{eff}^{3/2}$ among different configurations



Diffusive transport studies using the DKES model

$$I_i = \begin{bmatrix} □\cdot□s \\ \frac{1}{T}Q\cdot□s \\ n\langle(u□u_s)\cdot B\rangle \end{bmatrix} = □\sum_{j=1}^{3} L_{ij}A_j \qquad A_j = \begin{bmatrix} \frac{n'}{n} □ \frac{3}{2}\frac{T'}{T} □ \frac{eE_r}{T} \\ \frac{T'}{T} \\ □\frac{□\langle E\cdot B\rangle}{T\langle B^2\rangle} \end{bmatrix}$$

$$L_{ij} = n\frac{2}{\sqrt{□}}\int_0^{□} dK\sqrt{K}\, e^{□K} g_i g_j D_{ij}$$

where $g_1 = g_3 = 1,\ g_2 = K,\ K = \left(\frac{v}{v_{th}}\right)^2$

$$D_{11} = D_{12} = D_{21} = D_{22} = □\frac{v_{th}}{2}\left(\frac{□Bv_{th}}{□}\frac{d□}{dr}\right)^{□} K\sqrt{K}\,□_{11}$$

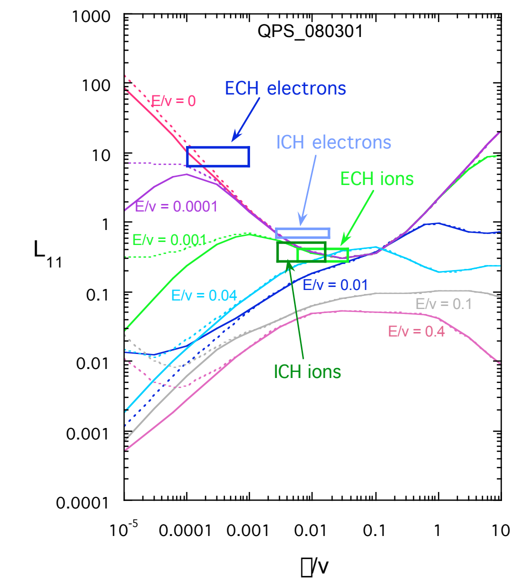
$$D_{31} = D_{32} = □D_{13} = □D_{23} = □\frac{v_{th}}{2}\left(\frac{□Bv_{th}}{□}\frac{d□}{dr}\right) K\,□_{31}$$

$$D_{33} = □\frac{v_{th}}{2}\sqrt{K}\,□_{33}$$

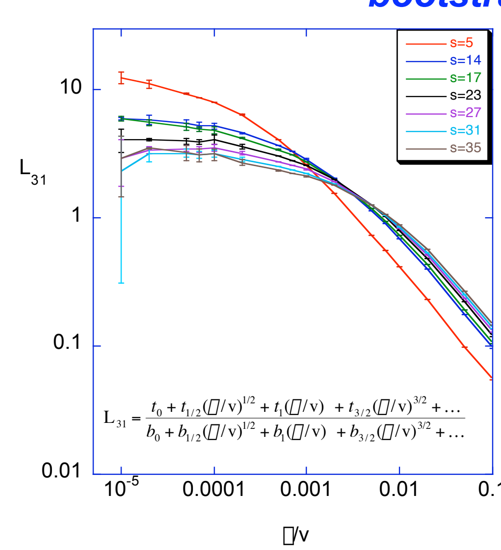
$$□_{ij} = □_{ij}\left(\frac{□}{v}, \frac{E_r}{v}\right)$$

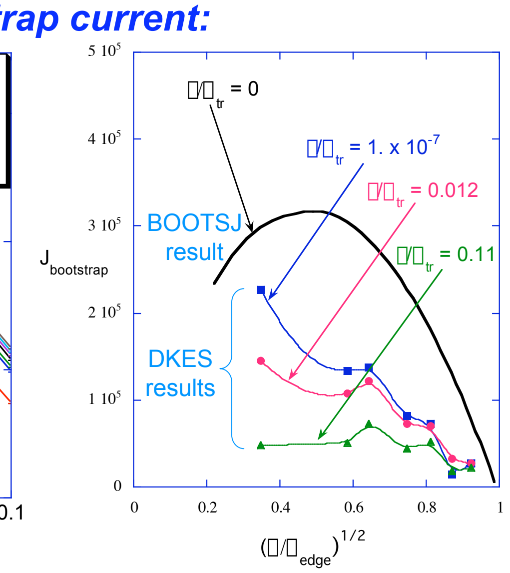
QPS Transport regimes:

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

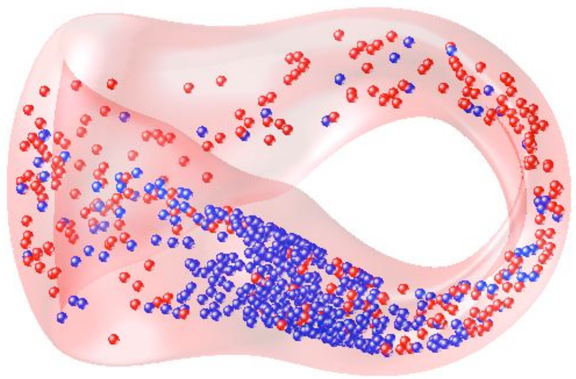


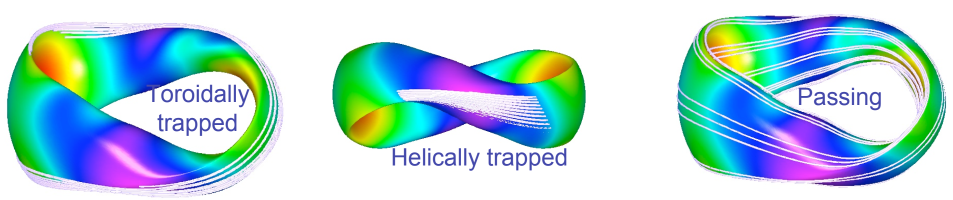
Comparison of collisional/collisionless bootstrap current:



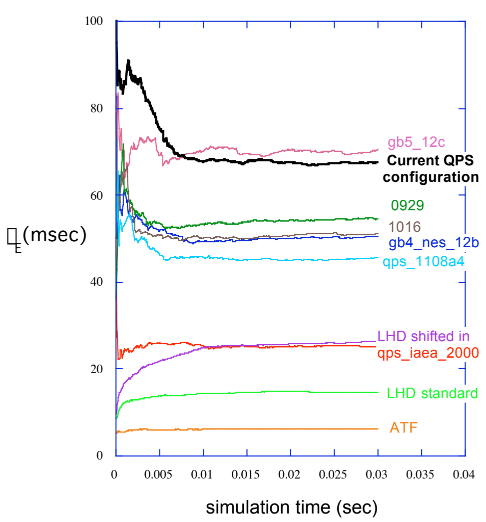


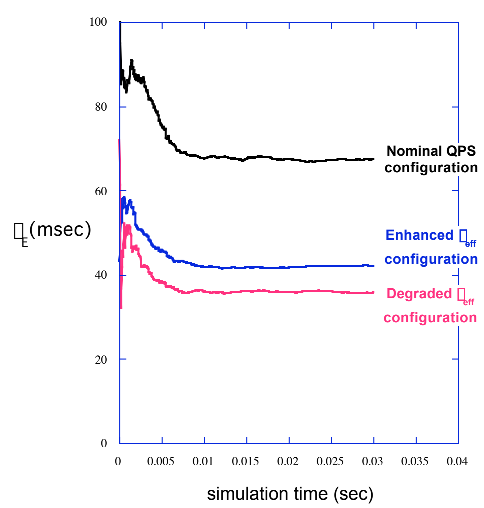
Monte Carlo transport studies using the DELTA5D model





Global ion confinement times for ICH parameters between devices (all at same R_0) and for QPS coil current variations





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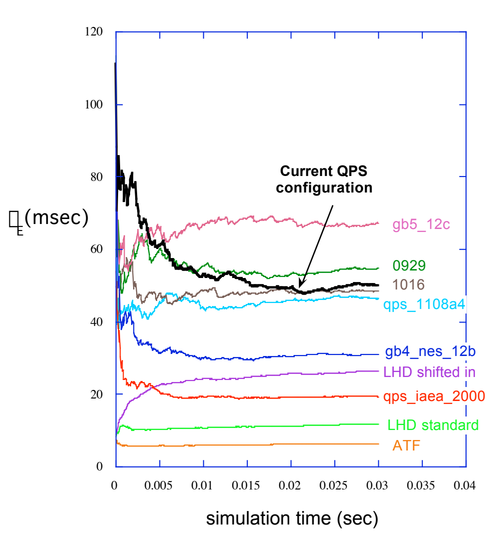
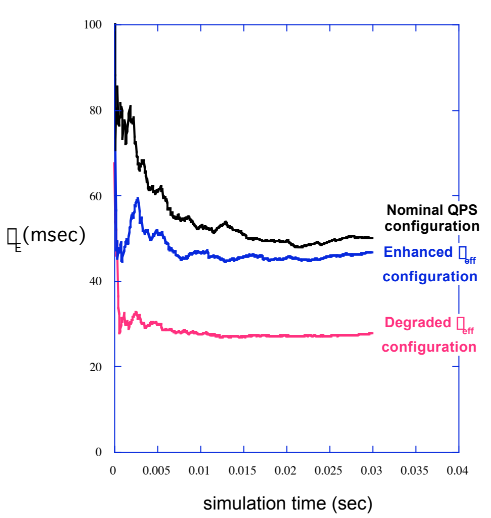




δf Bootstrap Current Calculation

[uses method of A. Boozer and M. Sasinowski, Phys. Plasmas **2** (1995) 610]

$$f = f_M + \delta f \qquad f_M = \frac{n}{(2\pi kT)^{3/2}} e^{-mv^2/kT}$$

$$\frac{d(\delta f)}{dt} - C(\delta f) = -\frac{\partial\psi}{\partial t}\frac{\partial f_M}{\partial \psi}$$

$$\delta f = -(\psi - \psi_0)\frac{\partial f_M}{\partial \psi} \quad (evaluated\ at\ particle\ locations)$$

$$J_{bootstrap} = q\int d^3x\ d^3v\ v_\parallel \delta f$$

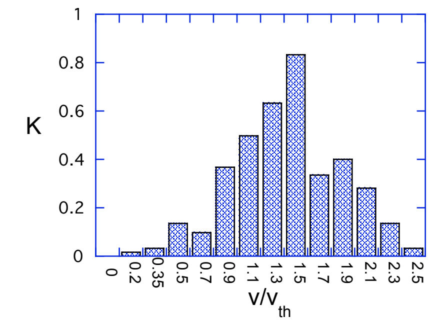
$$= \frac{2\pi q}{\int d^3x\ g^{1/2}}\int v^2 dv\ d\lambda\ d^3x\ v_\parallel\ g^{1/2}\ \delta f$$

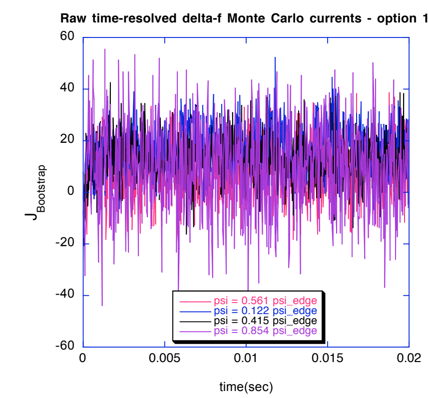
$$with\ \sqrt{g} = Jacobian = \psi_0(G + \iota I)/B^2$$

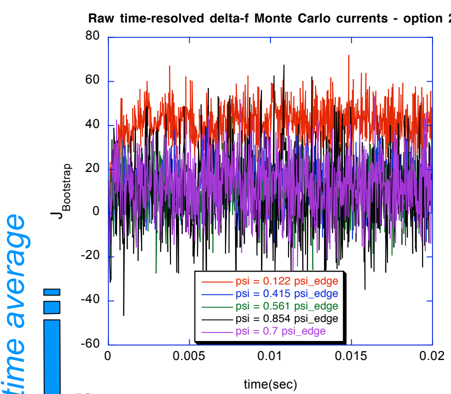
$$J_{bootstrap} = -4\pi q\int v^2 dv\ K(\psi, v, t)\frac{\partial f_M}{\partial \psi} \quad where \quad K(\psi, v, t) = \frac{\sum_{i=1}^{N} v_{\parallel,i}(\psi_i - \psi_0) g_i^{1/2}}{2\sum_{i=1}^{N} g_i^{1/2}}$$

Two options have been considered:

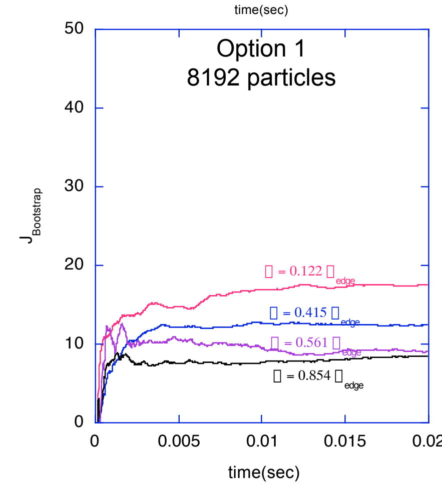
1. Radial drifts are included in d(δf)/dt, but orbits are kept bounded to within an annular flux shell
2. Radial drifts are not included in d(δf)/dt, and orbits remain confined to a single flux surface; radial drifts are confined to the same annular flux shell as for option 1

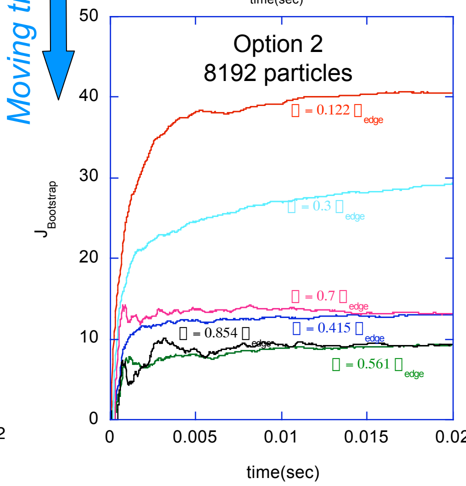


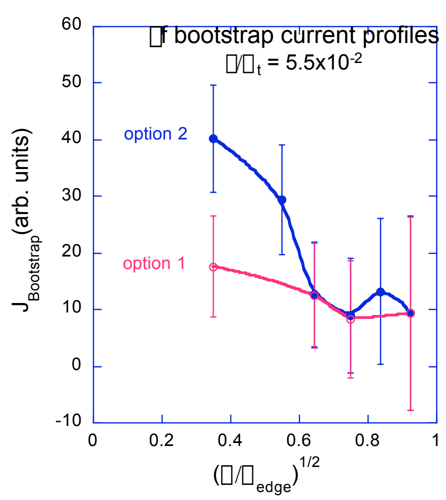




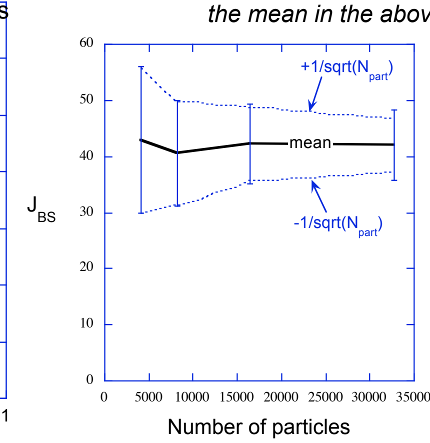
Moving time average

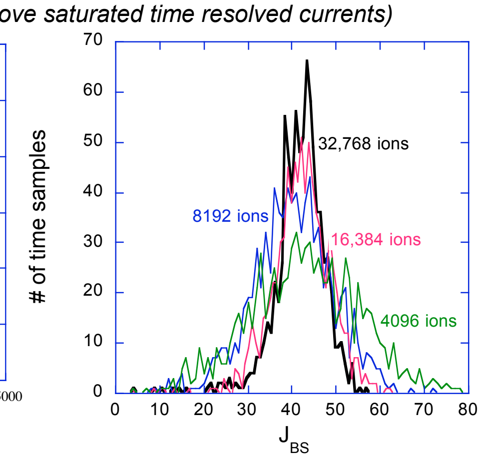






(Error bars are based on one standard deviation away from the mean in the above saturated time resolved currents)





Alfvén Gap structure using STELLGAP code

Stellarator Alfvén Couplings

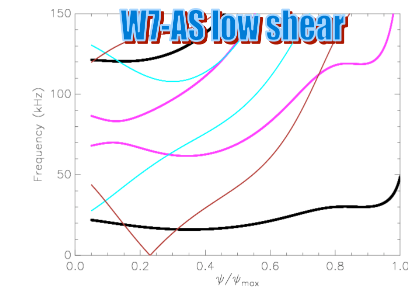
$$Alfvén\ \ coupling\ \ condition: \ k_{\parallel,m,n} = -k_{\parallel,(m+\mu),(n+\nu N_{fp})}$$

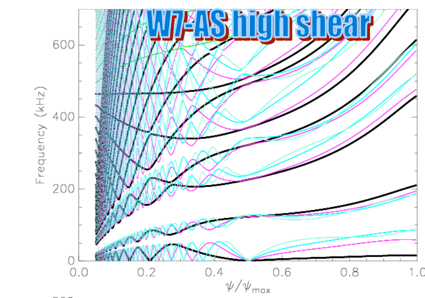
$$\mu,\ \nu = \text{integers}$$

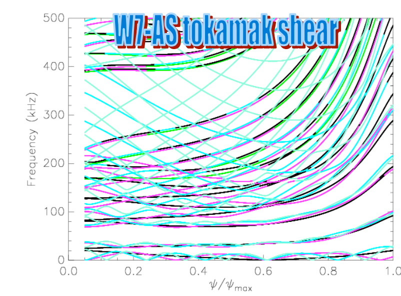
$$n - m\iota = -(n + \nu N_{fp} - m\iota - \mu\iota)$$

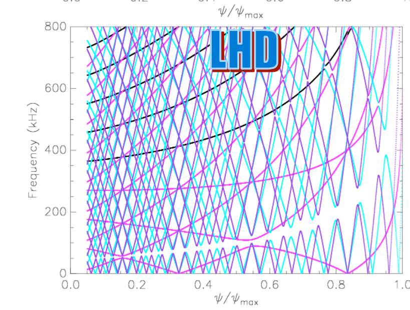
$$\iota = \frac{2n + \nu N_{fp}}{2m + \mu} \qquad \omega = \frac{v_A}{R}\frac{\mu n - \nu m N_{fp}}{2m + \mu}$$

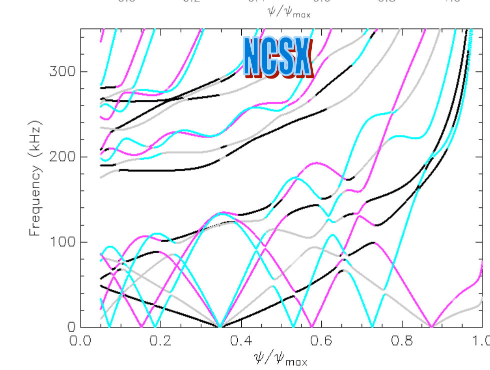
- GAE (global Alfvén mode): $\nu = 0,\ \mu = 0$
- TAE (toroidal Alfvén mode): $\nu = 0,\ \mu = \pm 1$
- EAE (elliptical Alfvén mode): $\nu = 0,\ \mu = \pm 2$
- NAE (noncircular Alfvén mode): $\nu = 0,\ |\mu| > 2$
- MAE (mirror Alfvén mode): $\nu = 1,\ \mu = 0$
- HAE (helical Alfvén mode): $\nu = 1,\ \mu \neq 0$

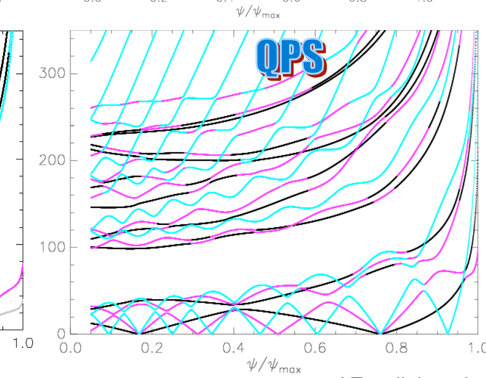




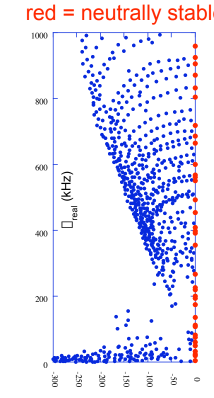




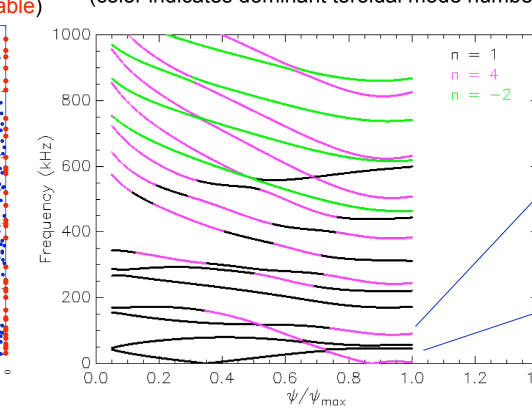




Discrete 3D Alfvén frequency spectrum (blue = damped red = neutrally stable)



Alfvén Continuum for QA-symmetric stellarator (color indicates dominant toroidal mode number)



AE radial mode Structure (multiple toroidal modes)