QPS Transport and Confinement

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QPS Physics Validation Review

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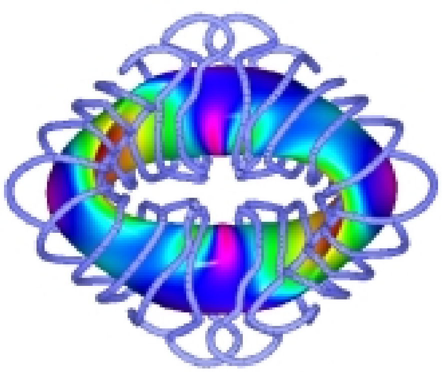
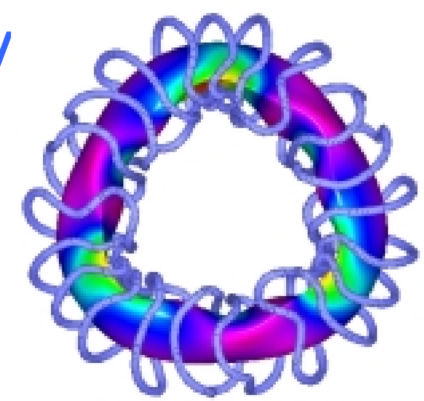
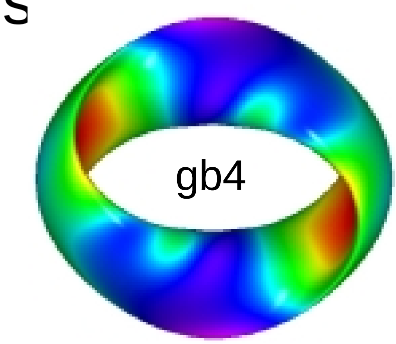
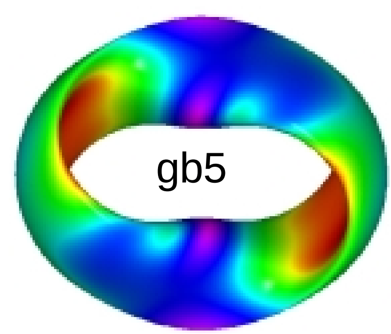




QPS Confinement and Transport Topics

- Is neoclassical stellarator transport sufficiently subdominant to anomalous transport ($\tau_{neo} >> \tau_{ISS95}$)?
  - to allow well defined enhanced confinement regimes
  - we consider both low (ECH) and higher collisionality (ICH)
- Can significant β's be attained?
  - to test bootstrap current/equilibrium robustness
  - to test ballooning stability
- Transport tools/QPS predictions
  - simple transport targets used in optimization
  - local diffusive transport models
    - DKES, NEO, 0-D, 1-D calculations
  - global Monte Carlo model





A range of transport models are used to evaluate QPS configurations:

Transport tool	Physical Model	Fixed Parameters	Predicted Parameters
0-D model	ISS95	P_{heat}, n	β, τ_E, T
1-D model[1]	ISS95 + Simplified neoclassical	$P_{heat}(r)$, n(r)	T(r), τ_E, $P_{loss}(r)$
NEO[2]	$1/\nu$, $E_r = 0$ neoclassical	n , T	$\varepsilon_{eff}^{3/2}$
DKES[3]	Local neoclassical	n , T , E_r, ν	Transport coefficient matrix
Monte Carlo[4]	Large orbit global neoclassical	N(r), T(r), ϕ(r)	τ_E, τ_p, ϕ_0

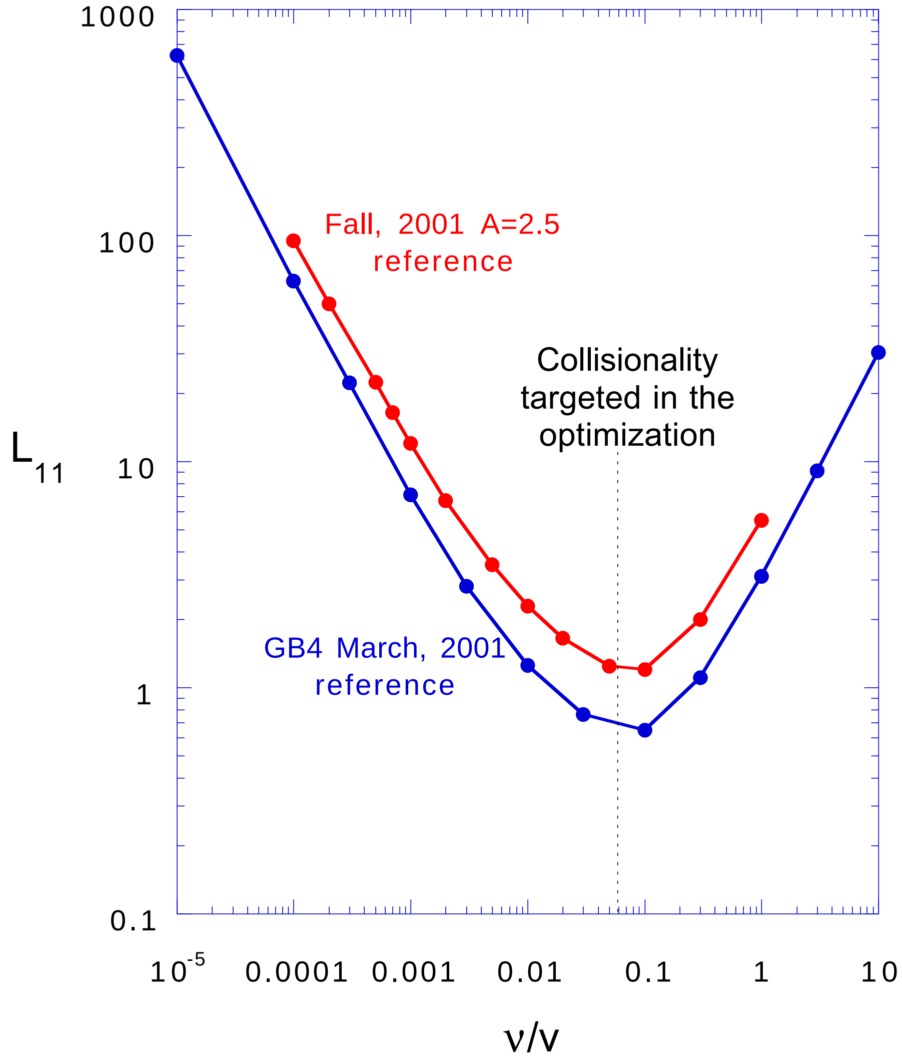
[1] D. Mikkelsen, NCSX PVR proposal Chapt. 8 (March, 2001).
[2] V. V. Nemov, S. V. Kasilov, W. Kernbichler, M. F. Heyn, Phys. Plasmas **6**, 4622 (1999).
[3] W. I. van Rij, S. P. Hirshman, Phys. Fluids B, **1** (March, 1989).
[4] D. A. Spong, et al., Nuclear Fusion **41**, No. 5 (2001).

Reduced (rapidly evaluated) measures of transport have been used to optimize QPS configurations:

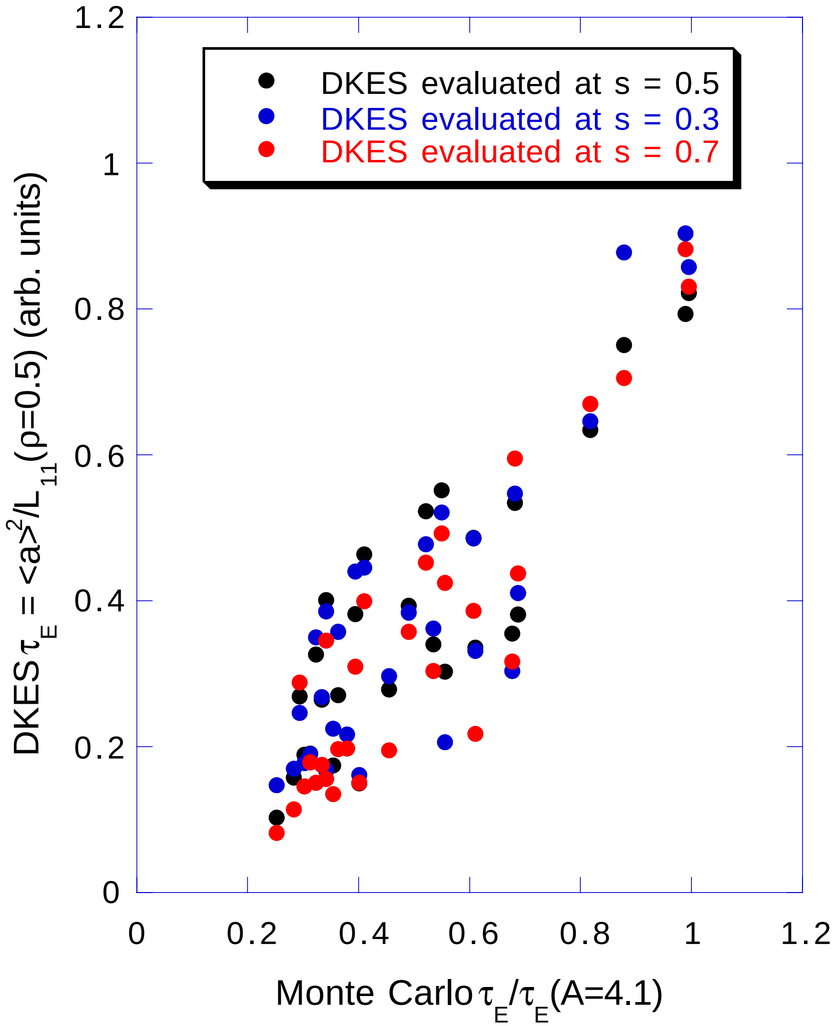
TARGET	IMPROVES:	EXAMPLE	
Bounce-averaged omnigeneity	Collisionless trapped/transitional particle confinement	$J = J(\psi)$ $B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$	Currently existing
Nearby quasi-symmetries	Collisionless confinement of all orbit topologies	Minimize B_{mn} if $m \neq 0$ (QP) Or if $m/n \neq 1$ (QH)	
Collisional transport coefficients	Neoclassical transport	L_{11} coefficient from DKES at $\nu^* \sim 1$	
Effective ripple ε_{eff}	$1/\nu$ neoclassical transport regime	$\varepsilon_{eff}^{3/2}$ from NEO code	Future
Large orbit effects	Energetic particle confinement	Reduced Monte Carlo model for alphas	

Transport optimizations using the DKES transport target have resulted in confinement improvement.

Stellarator optimization



Correlation of DKES and DELTA5D Confinement Times

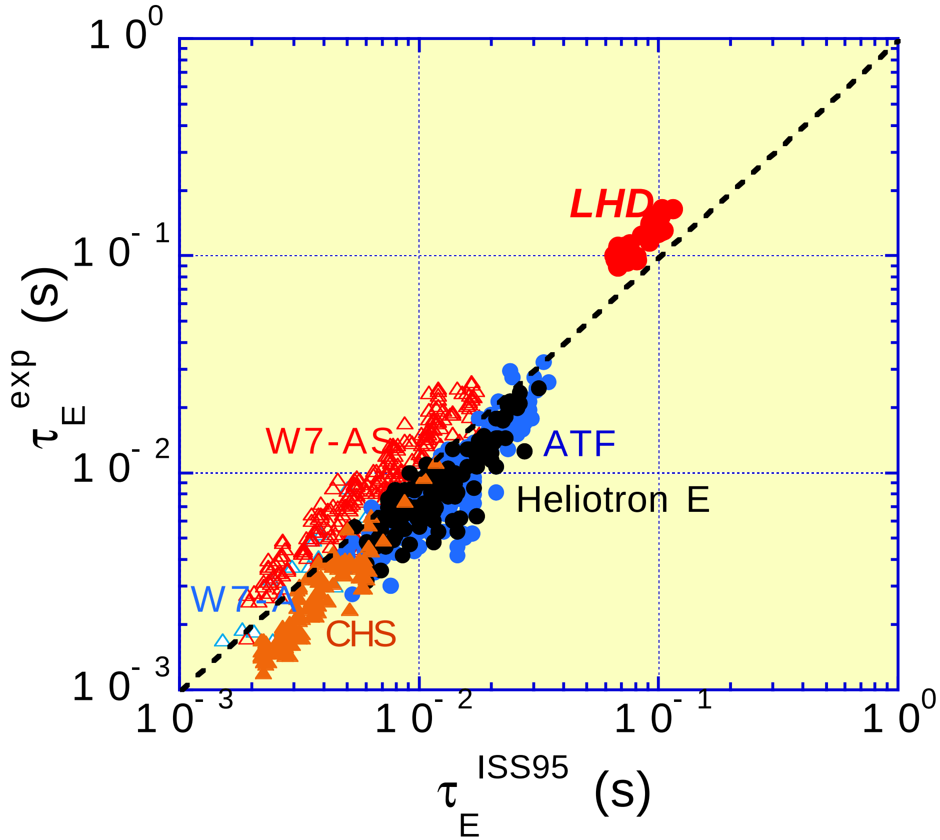


Global stellarator confinement scalings

$\tau_E^{ISS95} = 0.079 H_{ISS95}\, a_p^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{-0.4}$ 0-D model

$\tau_E^{ISS95} = W_{tot}/P \qquad W_{tot} = 1.5\langle\beta\rangle(B_0^2/2\mu_0)V_p$

$n_{Sudo} = 0.25[PB/Ra_p^2]^{1/2}$



- Data only for $R/a_p > 5$
- W7-AS and LHD find H_{ISS95} up to 2.5
  - low shear (W7-AS), large a_p (LHD)
  - QPS will have both
- For fixed a_p, R, n, B, i, can calculate:

  $\langle T\rangle/H_{ISS95}$

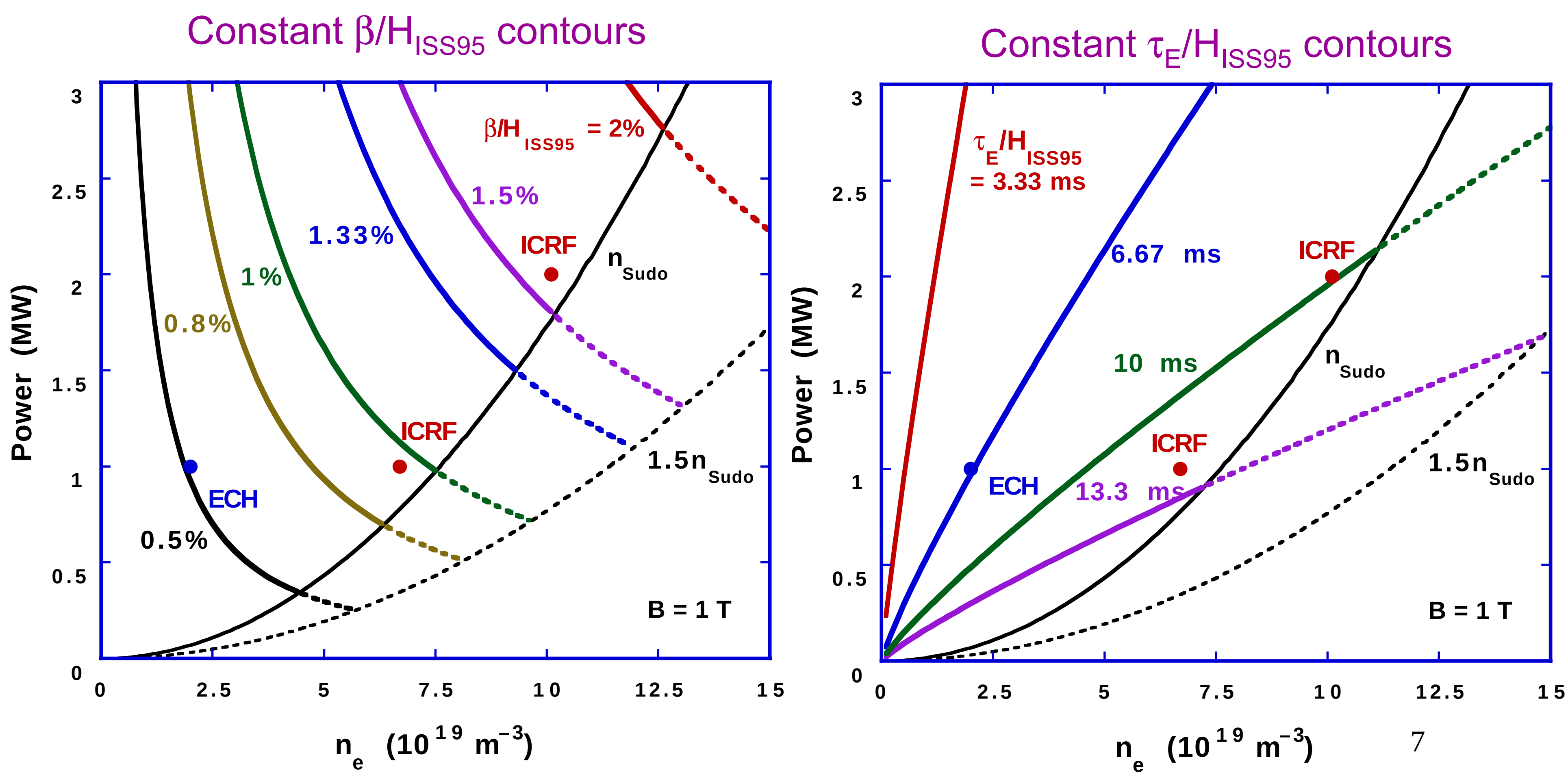
  $\langle\beta\rangle/H_{ISS95}$

  τ_E/H_{ISS95}

Global stellarator confinement scalings indicate the QPS CE device can achieve adequate plasma performance for its mission

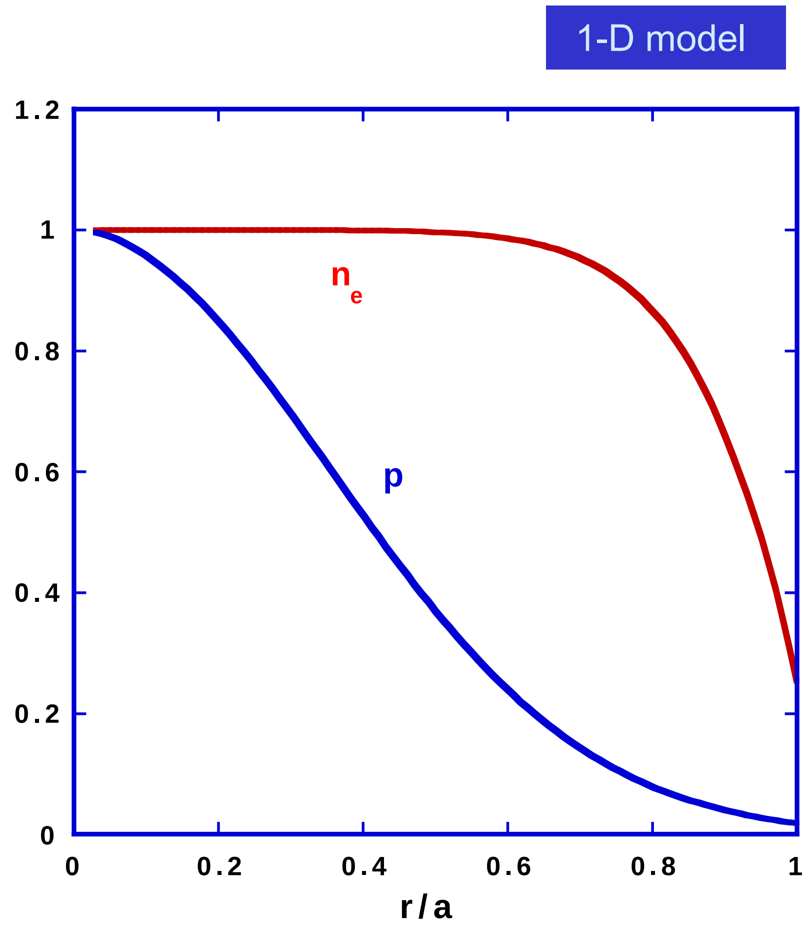
0-D model

(By suppressing neoclassical transport, QPS will achieve parameters close to these, e.g., for H = 1.5, β ~ 2.5%, τ_E ~ 20 msec)



1-D Model (Dave Mikkelsen) includes profile effects and self-consistent ambipolar electric field

- Coupled electron/ion power balance equations
- Ambipolar particle balance for neoclassical component
- Thermal diffusivities
  - ISS95 with H = 1.5
  - Neoclassical coefficient using $\varepsilon_{eff}^{3/2}$ from NEO code
  - E_r dependence from Shaing-Houlberg single helicity model
- Density and power deposition profiles assumed as shown

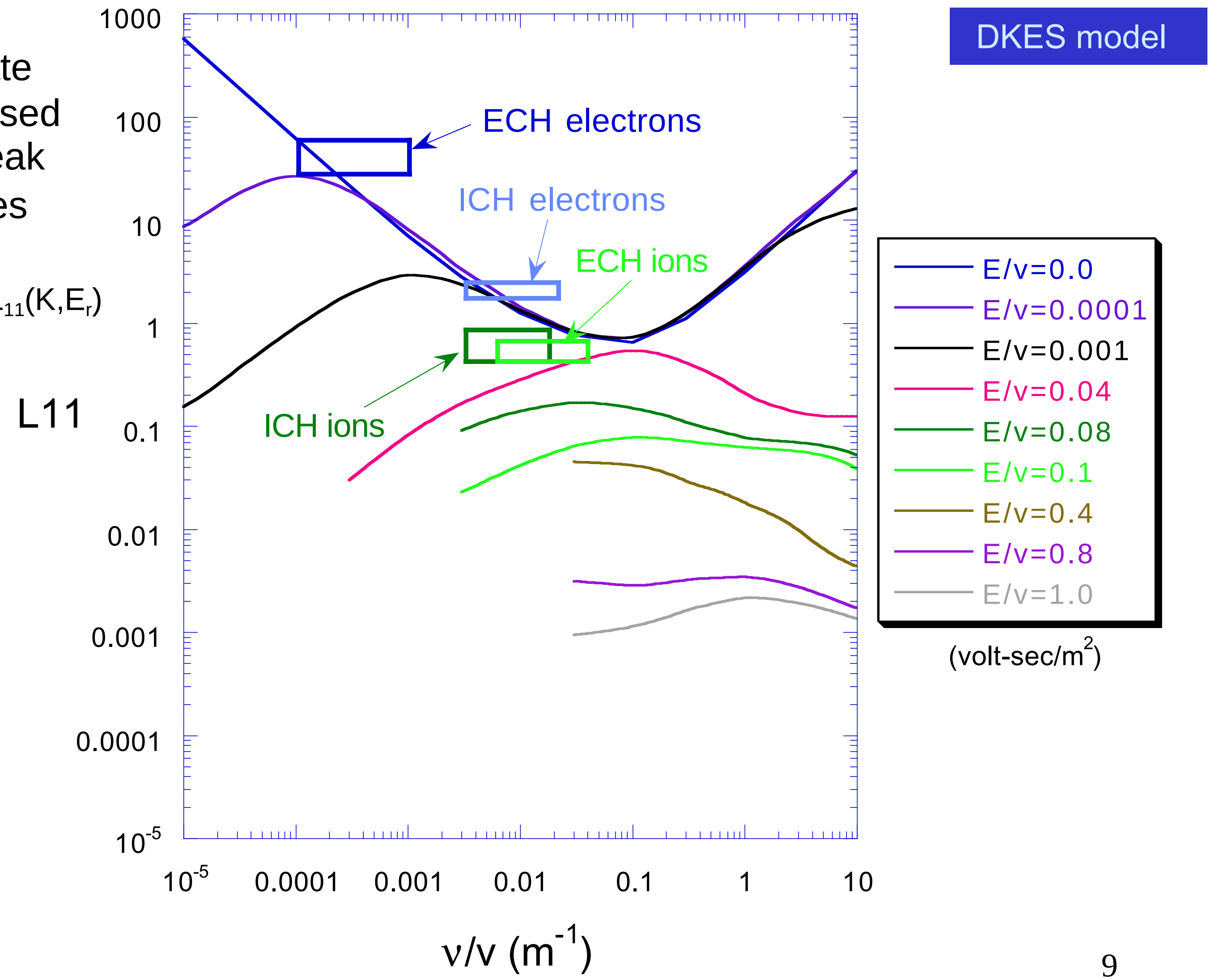


This model has been motivated by more comprehensive calculations (DKES, Monte Carlo)

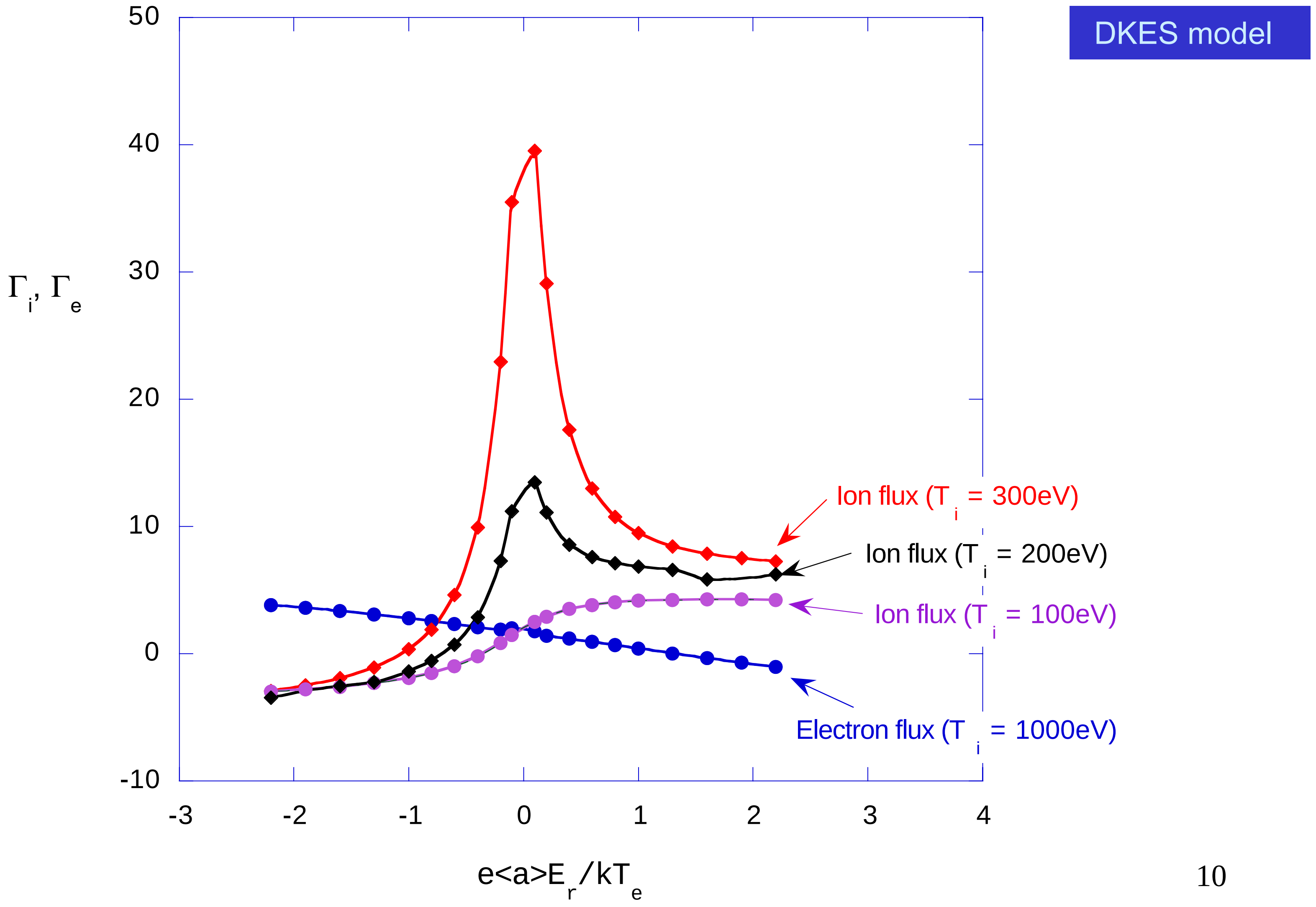
This model is motivated by the more complete DKES calculations that indicate electrons are generally in the 1/ν regime:

(Boxed regions indicate paramter ranges accessed by χ integral for the peak temperatures densities in profiles)

$\chi = (n v_{th}{}^3 B^2)/(\Omega^2 \pi^{1/2}) \int dK e^{-K} K^4 L_{11}(K,E_r)$



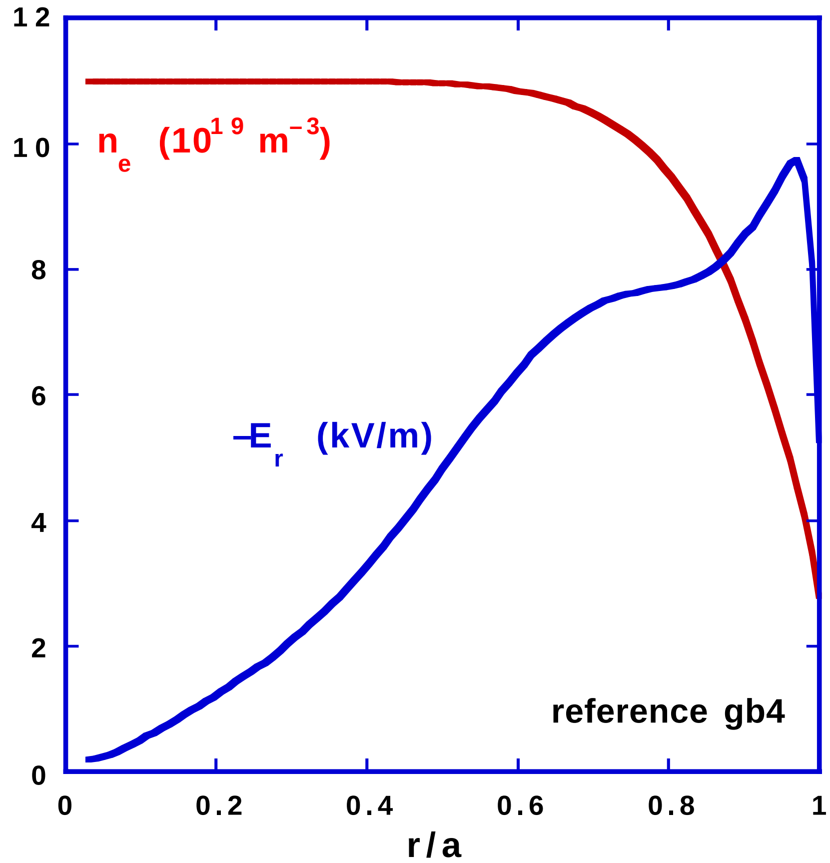
Typical DKES ambipolar calculations also show that overall transport level is generally set by lowering ion flux down to that of the electrons.

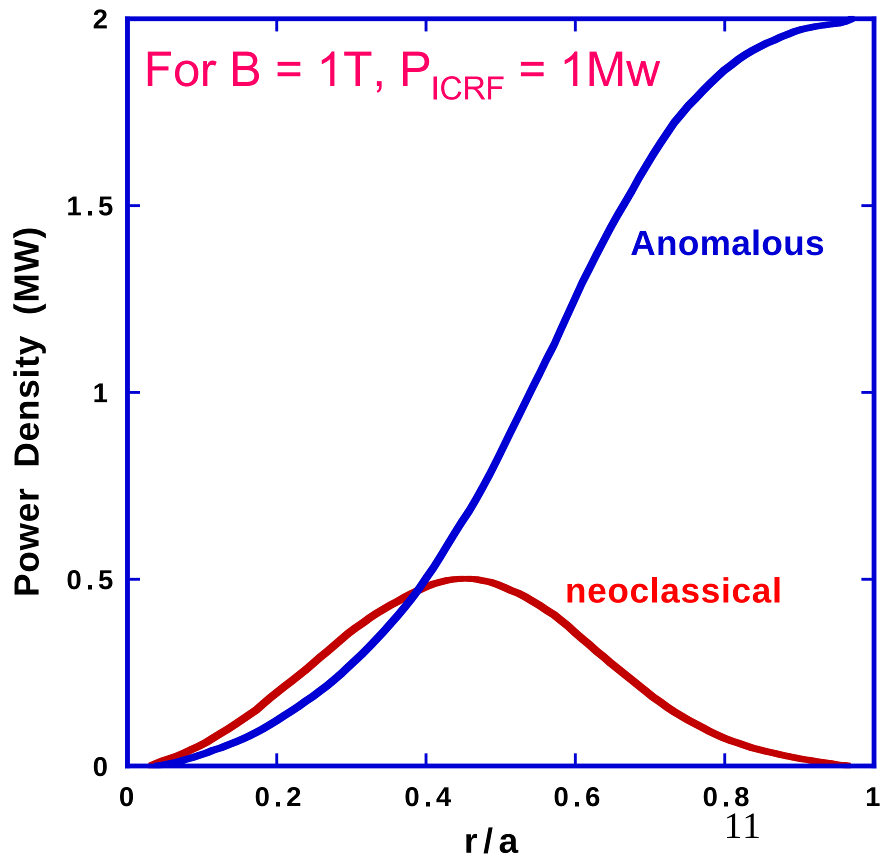


1-D transport model shows that anomalous transport is dominant for ICRF heated plasmas

1-D model

Device	τ_E (msec)	<β>
gb4	18.3	1.4
gb5_12c	18.8	1.44
gb5_12d	18.9	1.46

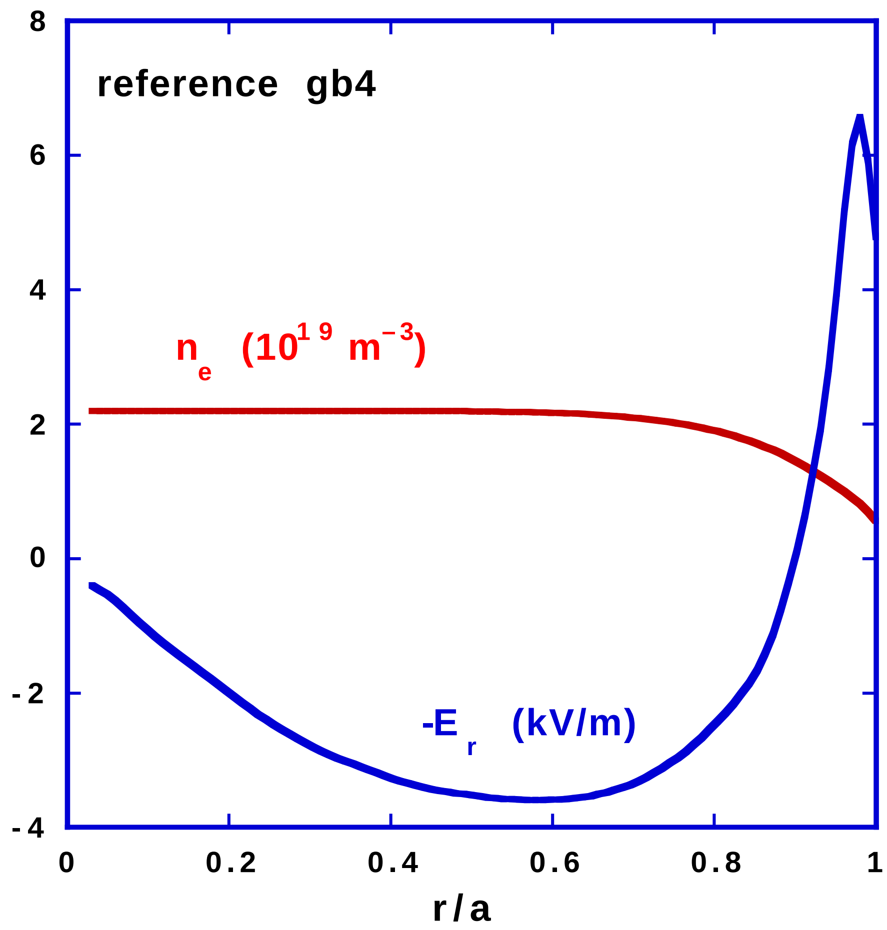


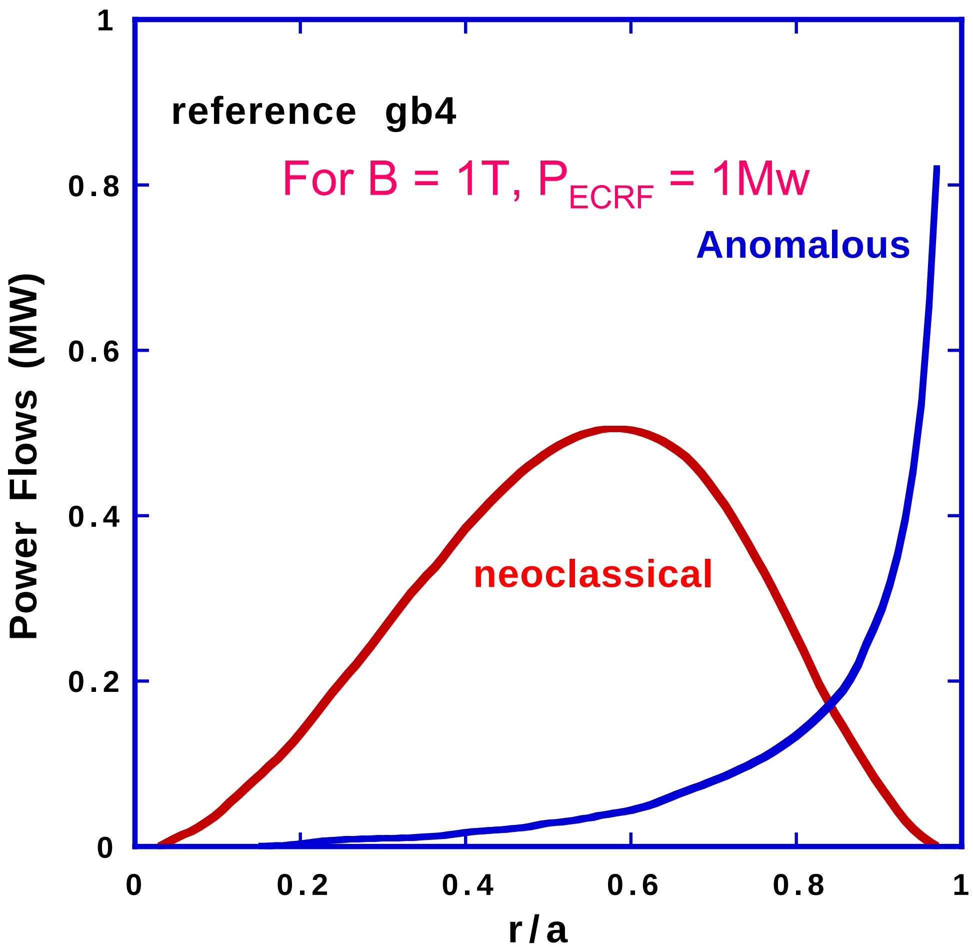


For ECRF heated plasmas in the gb4 configuration, anomalous and neoclassical losses are competitive.

1-D model

Device	τ_E(msec)	<β>
gb4	10.0	0.77

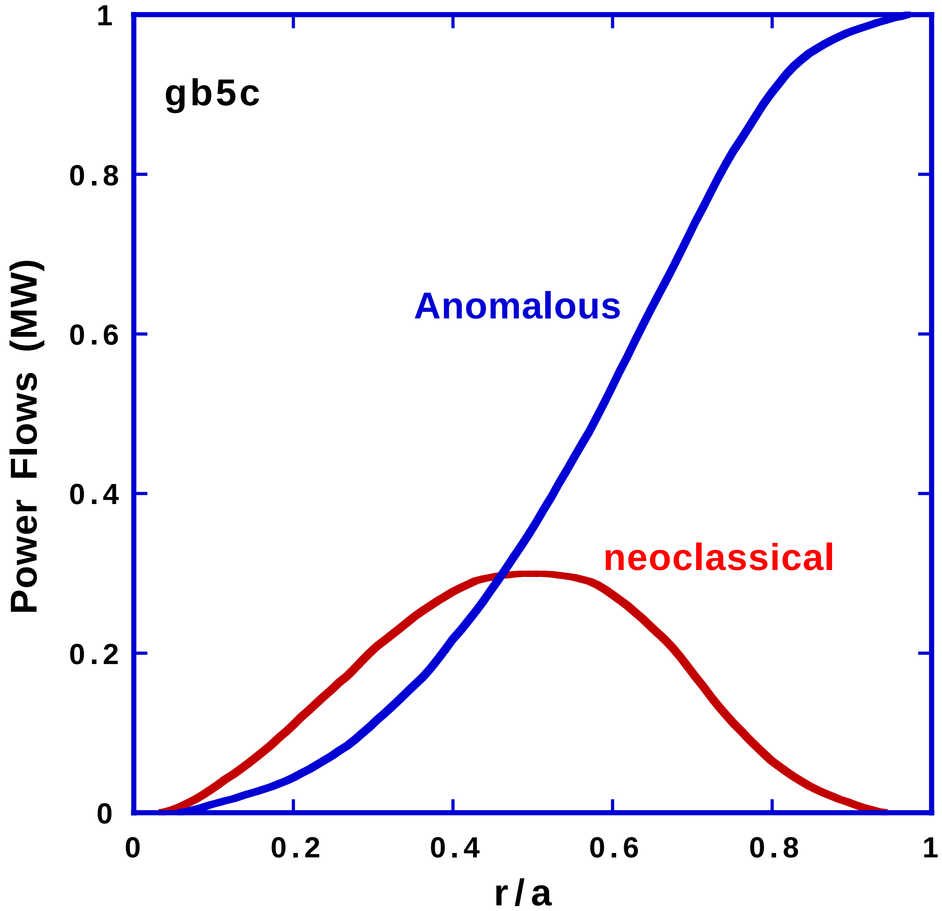


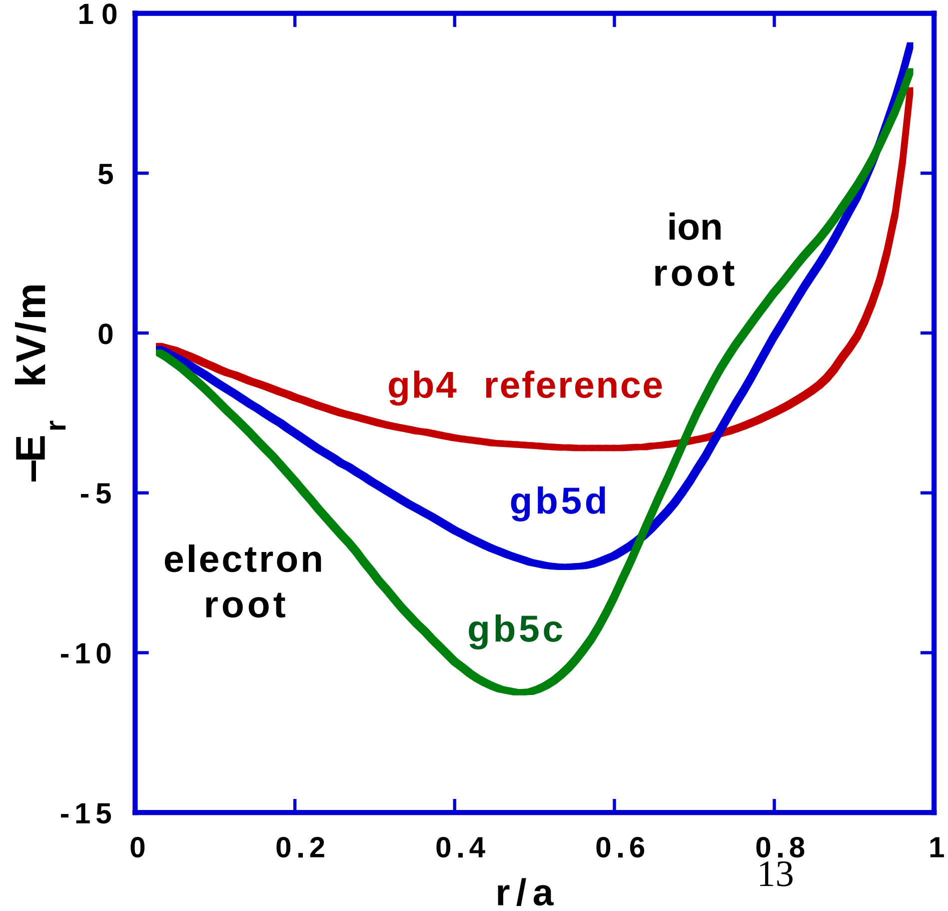


For ECRF heated plasmas in the gb5 configuration the neoclassical component is subdominant to anomalous

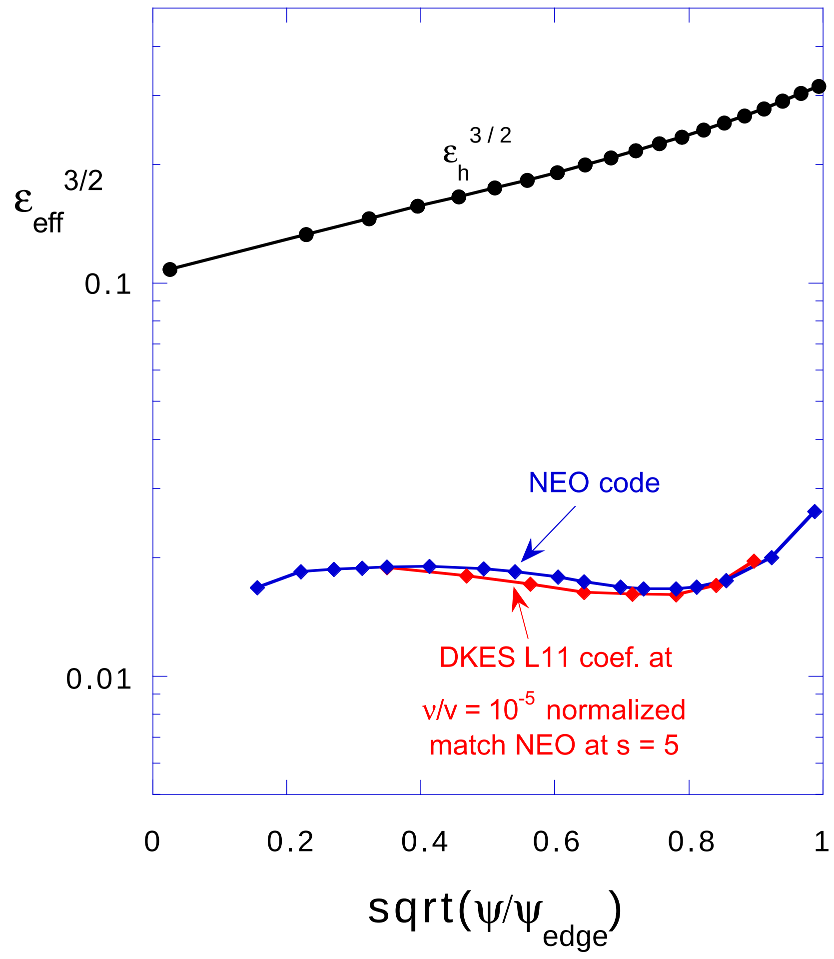
Device	τ_E(msec)	<β>
gb4	10.0	0.77
gb5c	10.1	0.78
gb5d	10.2	0.79

1-D model



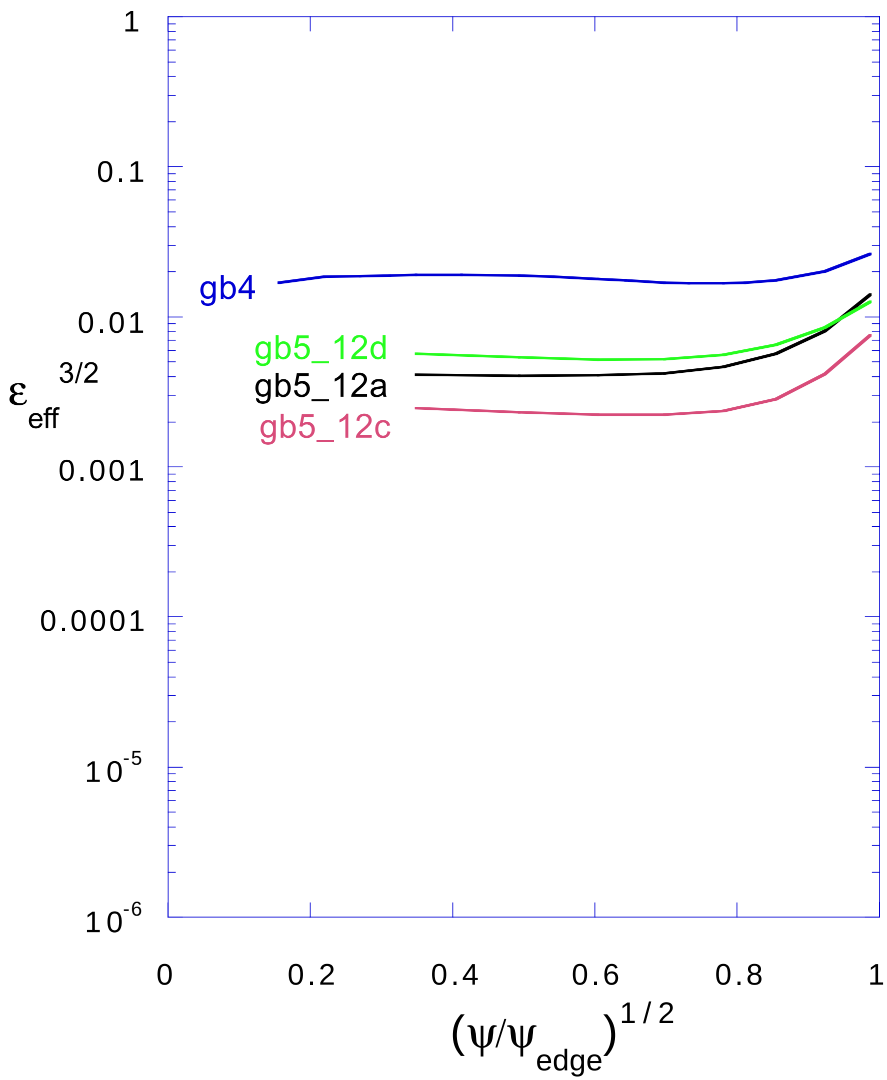


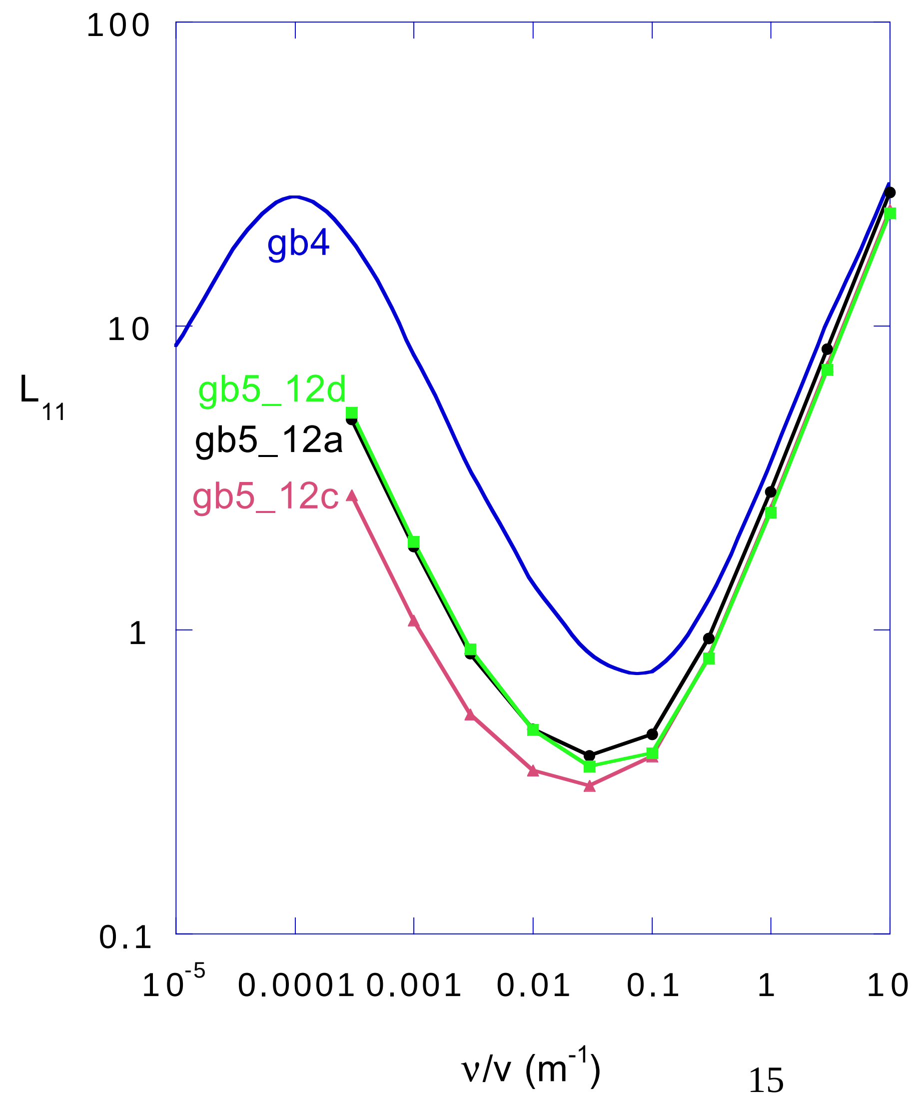
NEO code provides $\varepsilon_{eff}^{3/2} \sim D^{1/\nu}$, $\chi^{1/\nu}$. Demonstrates effectiveness of QPS transport optimization.



DKES L_{11} transport coefficient at E_r/v = 0.0001 show similar trends at low collisionality among gb4/gb5 devices as NEO $\varepsilon_{eff}^{3/2}$ coefficient

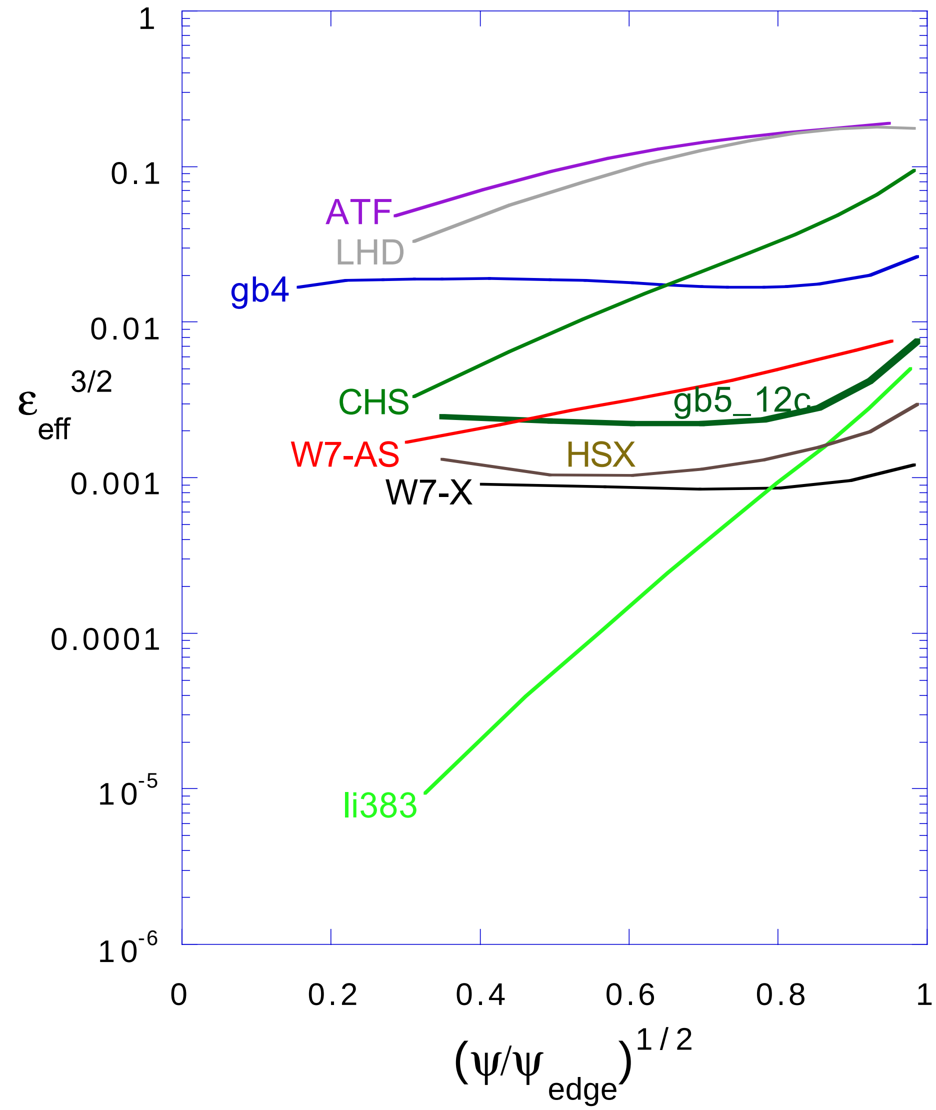
DKES and NEO ε_{eff} model



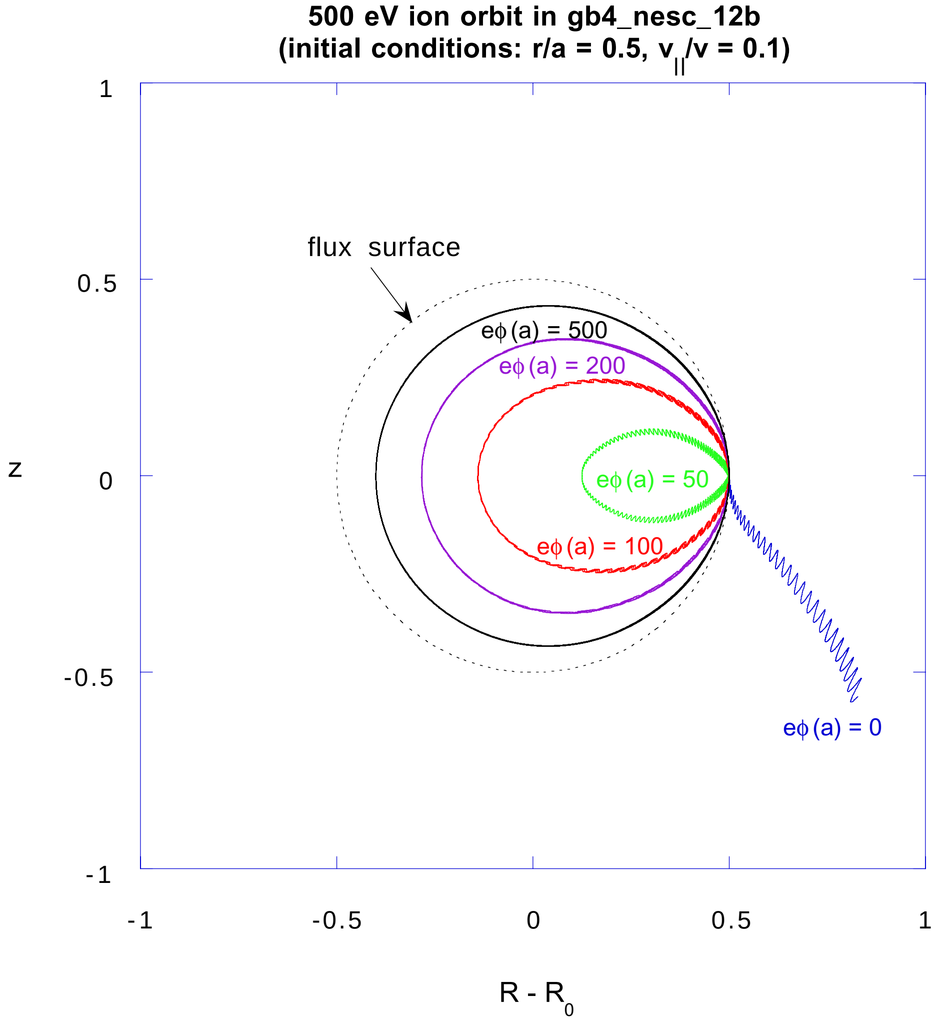


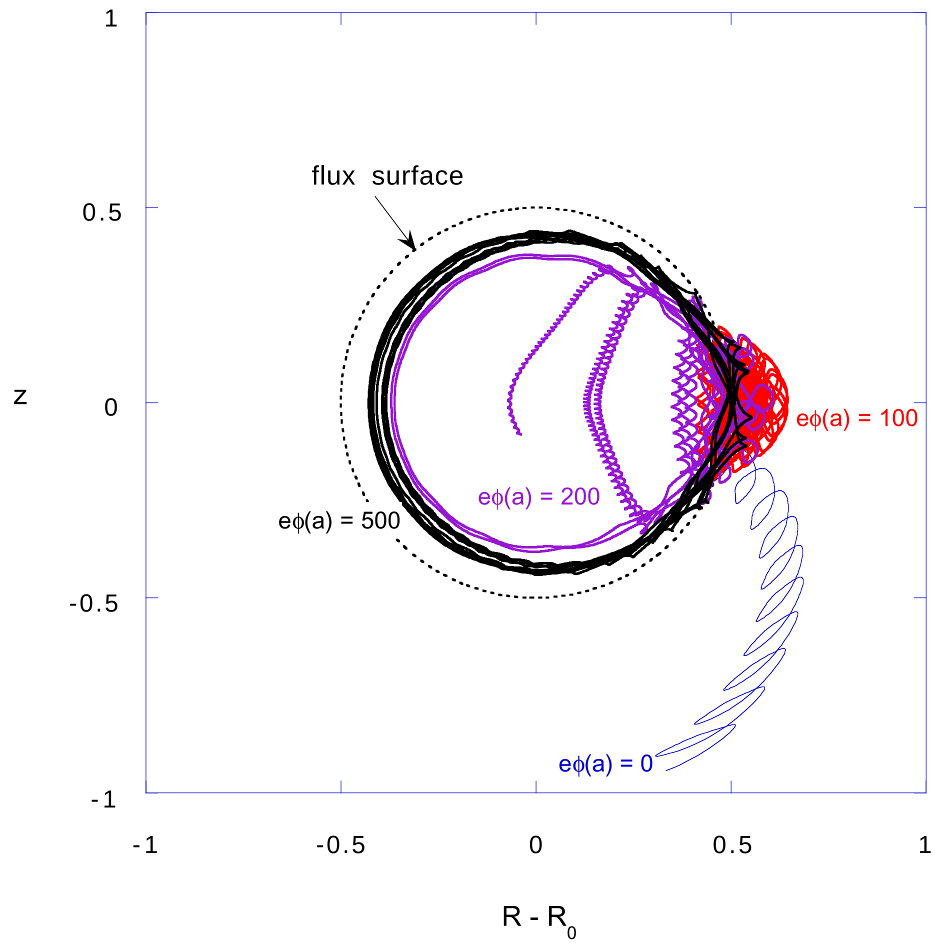
NEO ε_{eff} code

Comparison of QPS configurations (gb4/gb5) with existing and planned devices

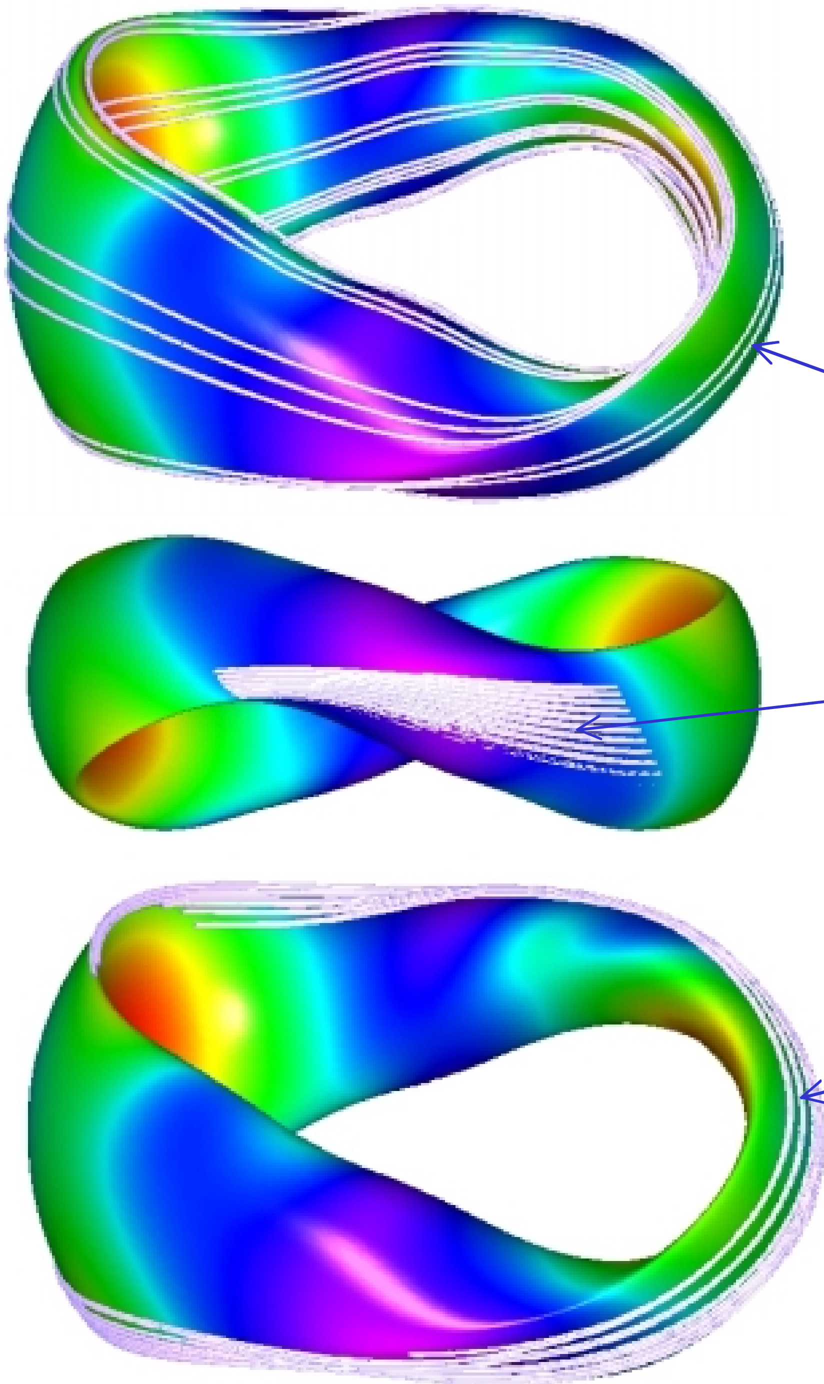


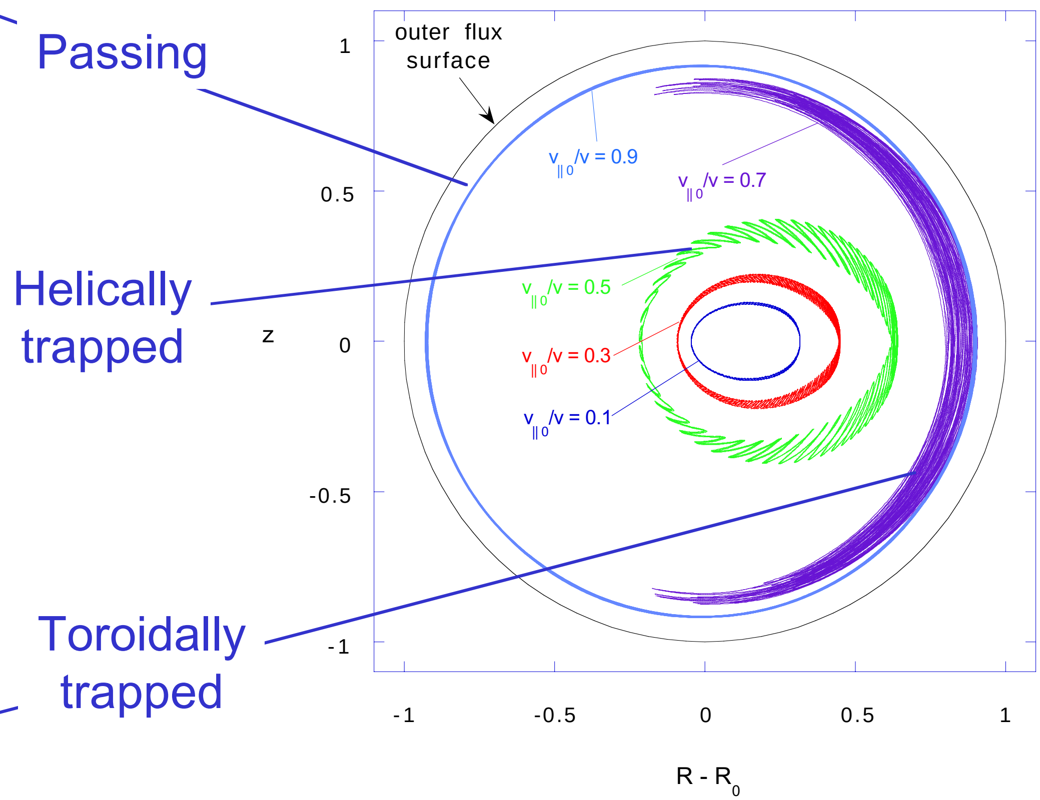
The confinement of trapped orbits is more rapidly improved with small electric fields for the QPS(gb4) configuration than for conventional stellarators (ATF)





QPS orbit topologies



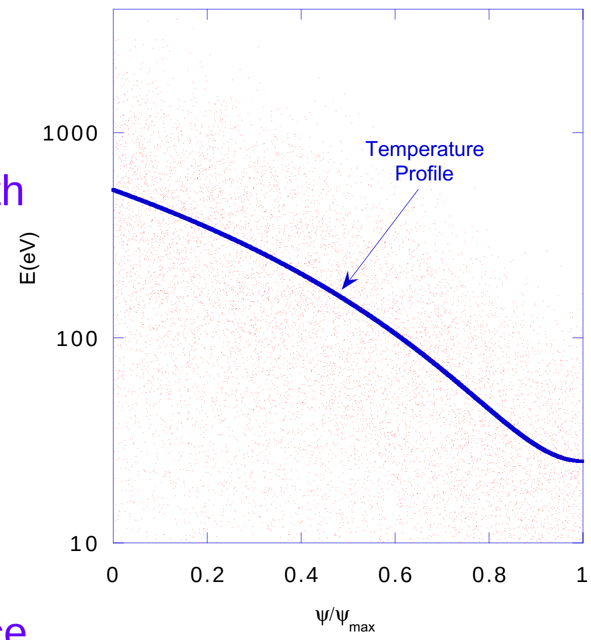


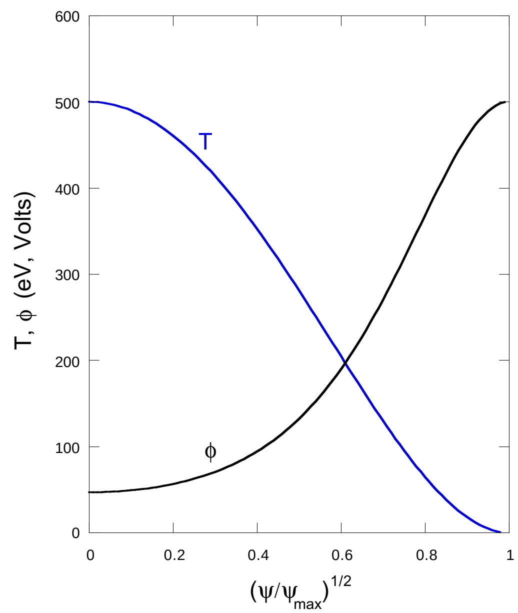
Monte Carlo procedure for estimating global energy lifetimes (DELTA5D code)

DELTA5D Monte Carlo

- Distribute particles over cross section consistent with assumed profiles and local Maxwellians
- Replacing particles (consistent with initial PDF's) as they leave outer surface
- Accumulate energies of escaping particles -> τ_E
- Follow until approximate steady–state is achieved
- Vary potential (with fixed profile shape) -> global ambipolar balance

Typical initial Maxwellian particle loading for T = 500eV $(1 - \psi/\psi_{max})^2$

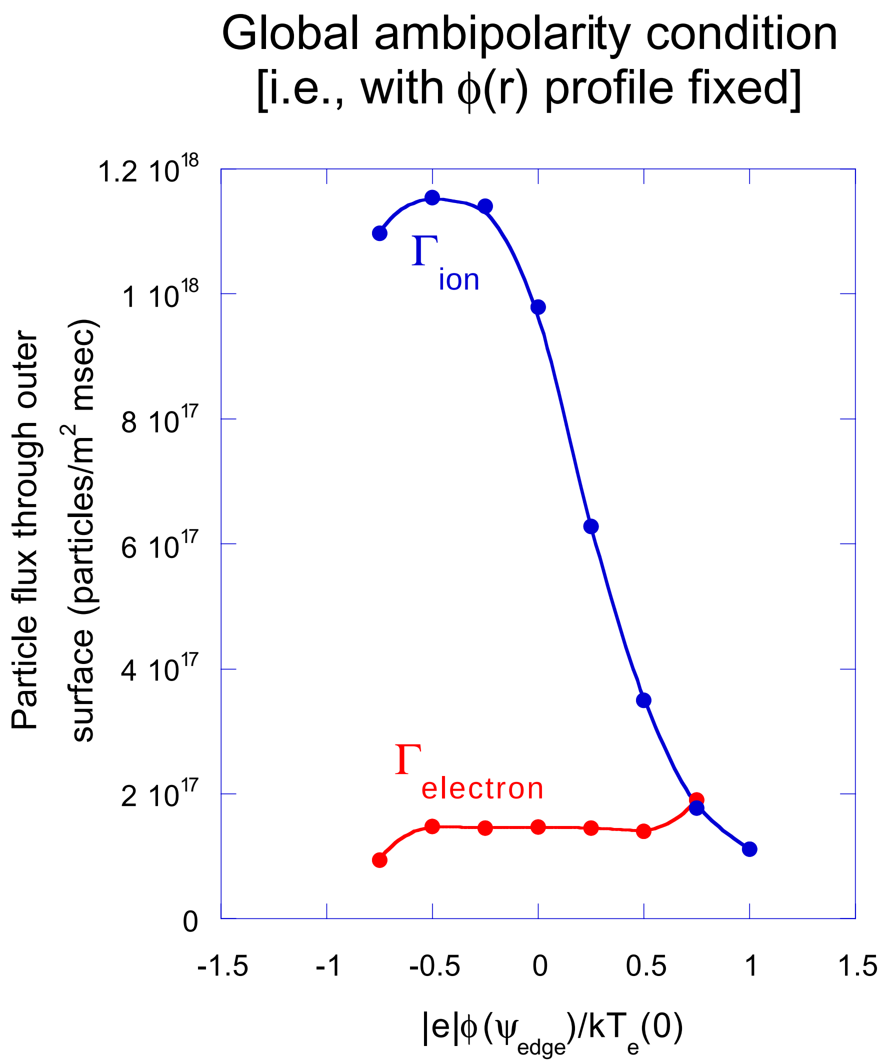


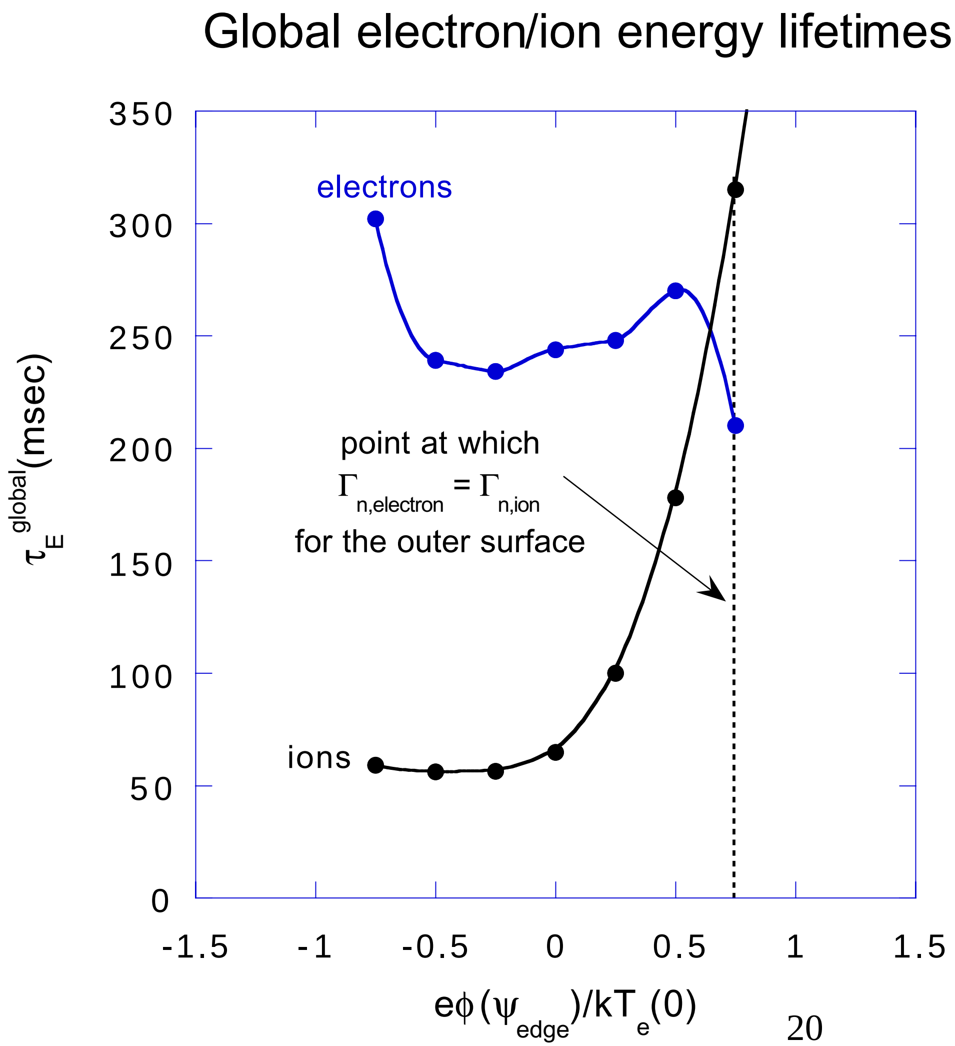


Monte Carlo (DELTA5D)

Monte Carlo lifetimes for ICH heated gb4 configuration

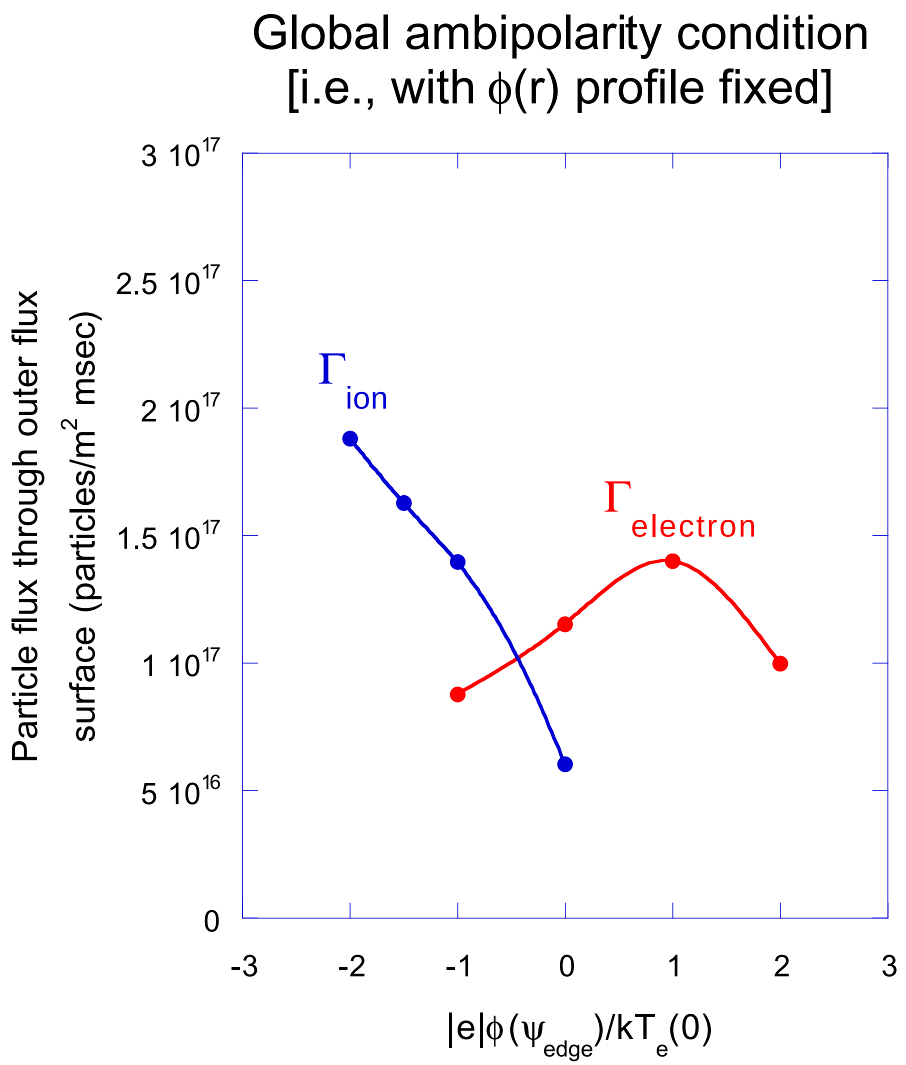
[$n(0) = 8.3 \times 10^{19}\ m^{-3}$, $T_e(0) = 500eV$, $T_i(0) = 500\ eV$, flat density profile, $(1 - \psi)^2$ temperature profile]

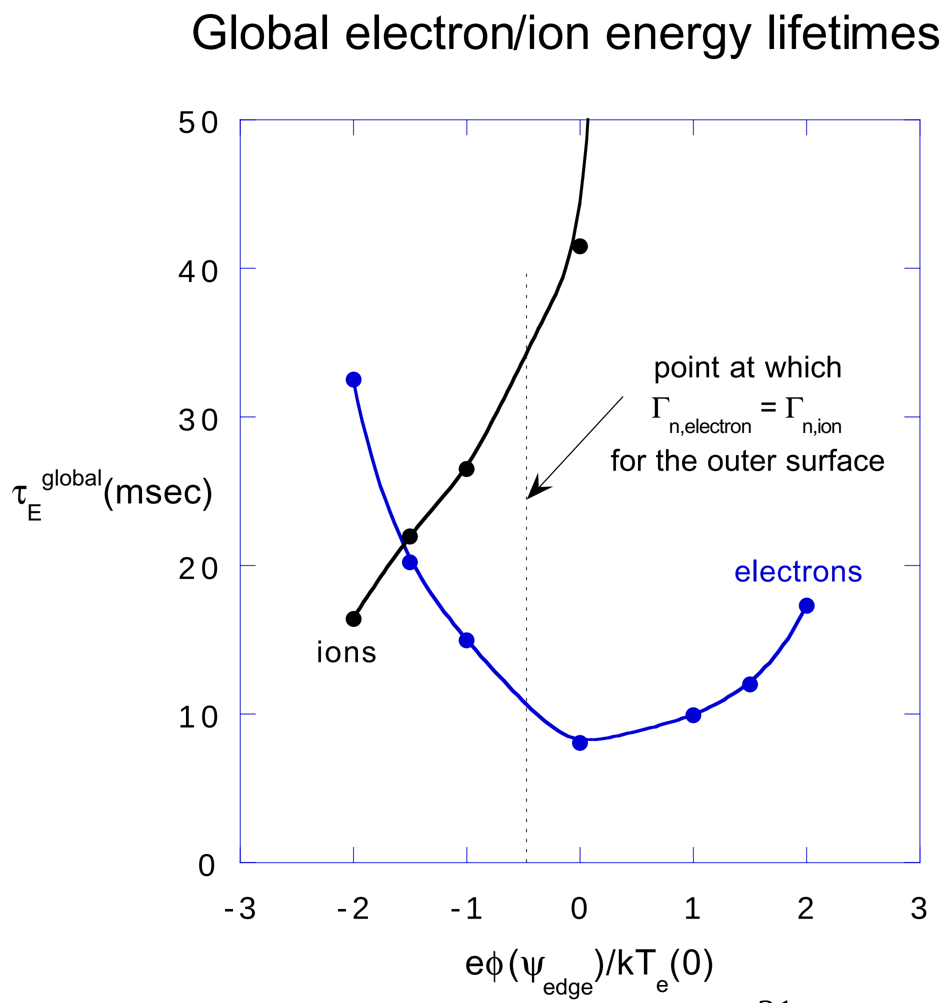




Monte Carlo lifetimes for ECH heated gb4 configuration

[n(0) = 1.8 x 10^{19} m^{-3}, $T_e(0)$ = 1400eV, $T_i(0)$ = 150 eV, flat density profile, parabolic**2 temperature profile]





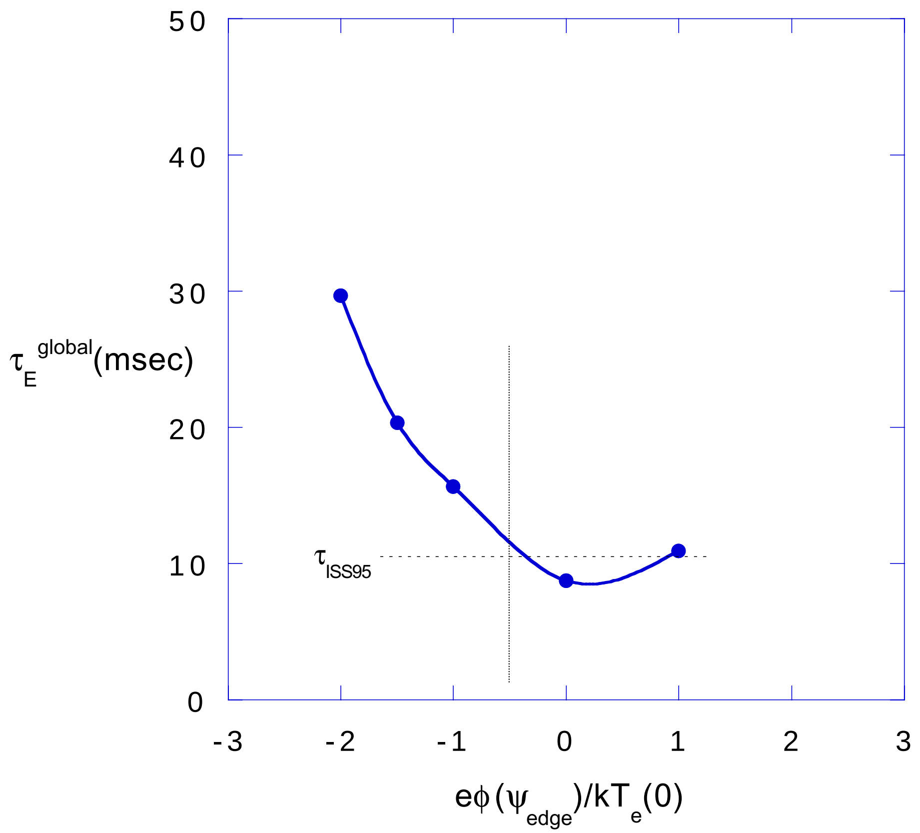
Monte Carlo (DELTA5D)

Comparison of ECH/ICH global lifetimes with ISS95 scaling law for GB4 configuration

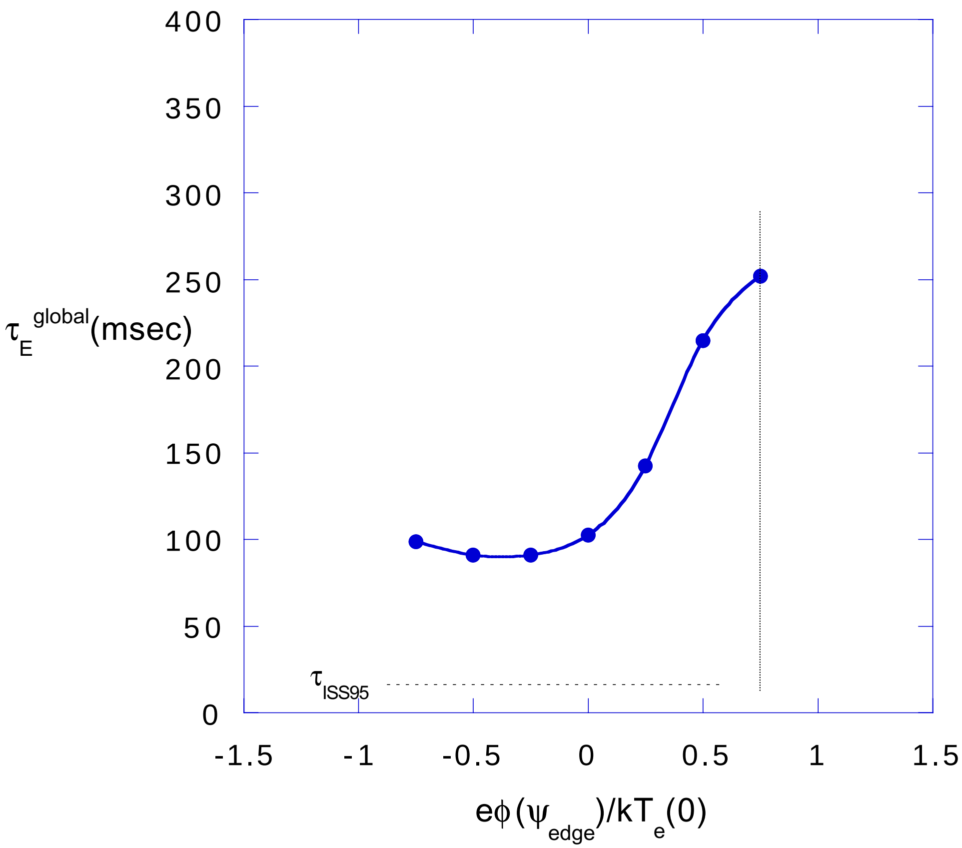
τ_{gl}^{MC} = global lifetime, taking into account electron and ion loss channels:

$$\tau_{gl}^{MC} = \frac{(T_e + T_i)\tau_e \tau_i}{T_e \tau_i + T_i \tau_e}$$

ECH heated gb4 case

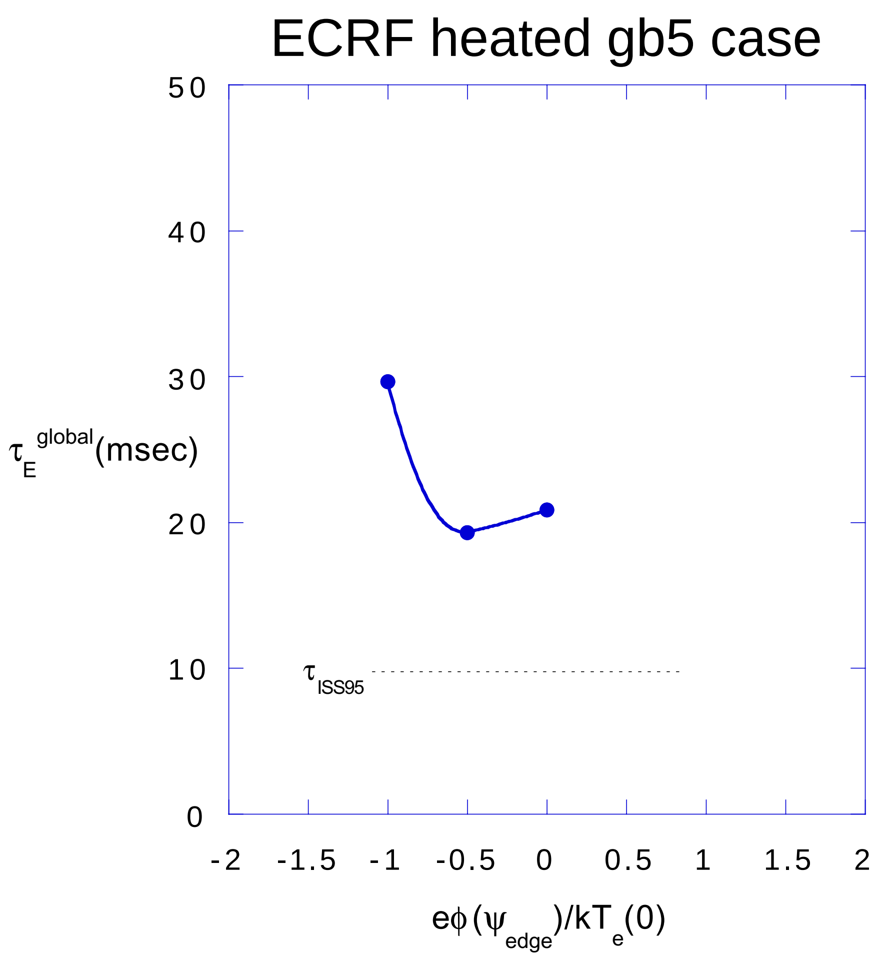


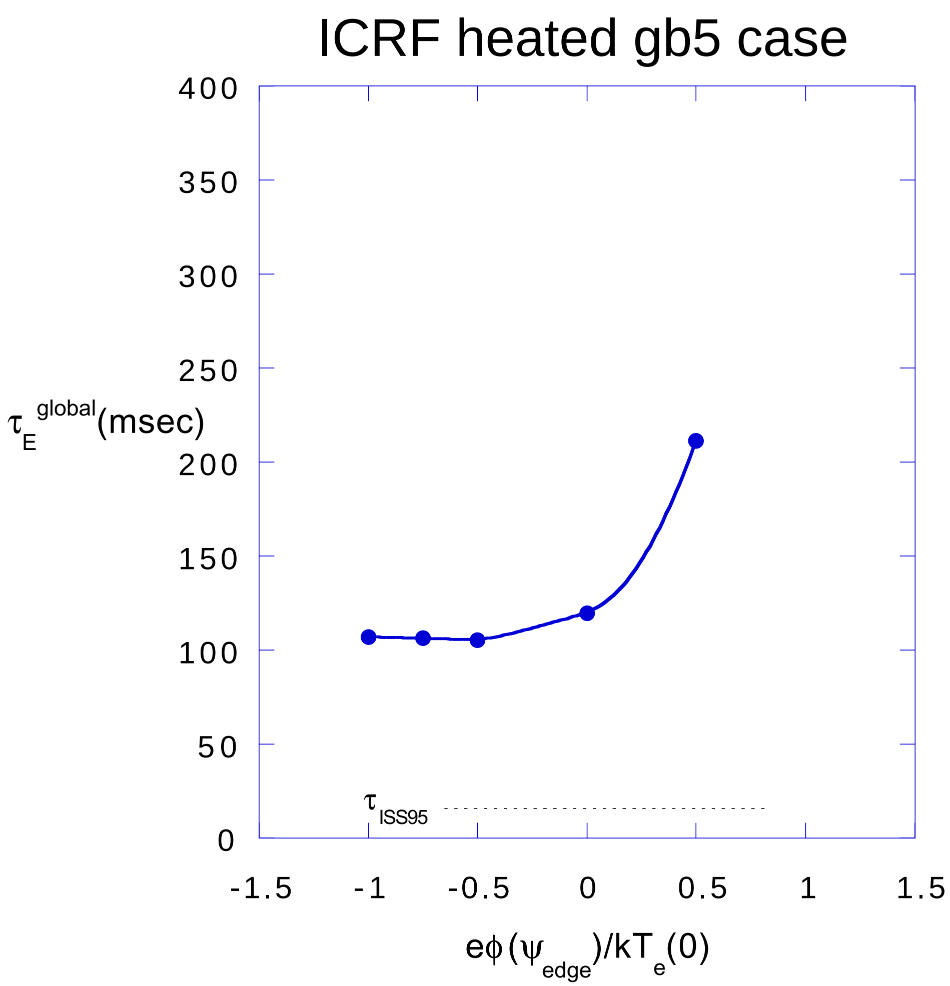
ICH heated gb4 case



Monte Carlo (DELTA5D)

Comparison of ECH/ICH global lifetimes with ISS95 scaling law for gb5a configuration





Conclusions

- QPS should be able to reach the plasma performance needed for its mission
    - Good separation between neoclassical and anomalous losses
    - Achievement of β s above ballooning threshold
- ISS95 scaling + ripple transport (0-D and 1-D) predict good performance
    - $\langle\beta\rangle$ = 1 - 3%, energy confinement times = 10 - 20 msec
- Monte Carlo model shows neoclassical component is not a limiting feature
    - 2 to 8 x improvement over ISS95
- An improved configuration (gb5) has good neoclassical confinement at low collisionality
    - 2 x improvement over ISS95
- A spectrum of transport analysis tools has been developed
    - good basis for supporting a future experiment