Transport Assessments for Selecting the QOS Reference Configuration

D. A. Spong, S. P. Hirshman, A. S. Ware, R. Sanchez, J. F. Lyon, L. A. Berry, D. B. Batchelor, J. H. Fowler, W. A. Houlberg, P. Strand, D. J. Strickler, J. C. Whitson, G. Y. Fu, W. H. Miner, JR., P. M. Valanju, J. A. Carlsson

- Transport analysis tools
- Transport optimization targets
- Configurations considered
- Electron and ion neoclassical losses
- Energetic orbit losses

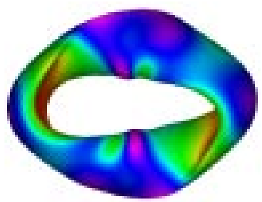
Transport analysis tools

- General purpose stellarator particle simulation code (DELTA5D)
  - thermal electron/ion transport, bootstrap current
  - alpha particles
  - neutral beams, ICRH tails
  - uses MPI to achieve near linear speedup with number of processors
- Drift Kinetic Equation Solver (DKES)
  - variation of bootstrap current with collisionality and electric field
  - local diffusion coefficients → ambipolarity condition
  - integrate over profiles to obtain global lifetimes
  - uses shared memory OpenMP parallelism to achieve ~ x 3 speedup (with Ed D'Azevedo, ORNL CCS Division)
- Other qualitative measures: J, B_{min}, B_{max}, |B| contours

Transport optimization targets for compact drift-optimized stellarators

- Longitudinal adiabatic invariant J = $\oint dl\, v_{\|}$ constant on flux surface
- B_{min}, B_{max} alignment with ψ
- Drift Kinetic Equation Solver (DKES) transport coefficients
- Nearby symmetries in |B|
  - quasi-poloidal
  - quasi-helical

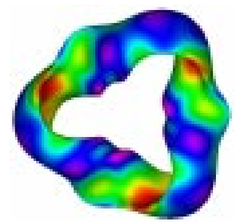
Transport analysis of 2.5 < A < 3.0 candidate configurations:



A2.5_M_B1.3

τ_{ISS95} = 2.08 msec

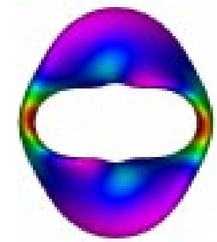
$\tau_{E,global}$ = 8.5 msec



A3.0_M3_B1.9

τ_{ISS95} = 2.98 msec

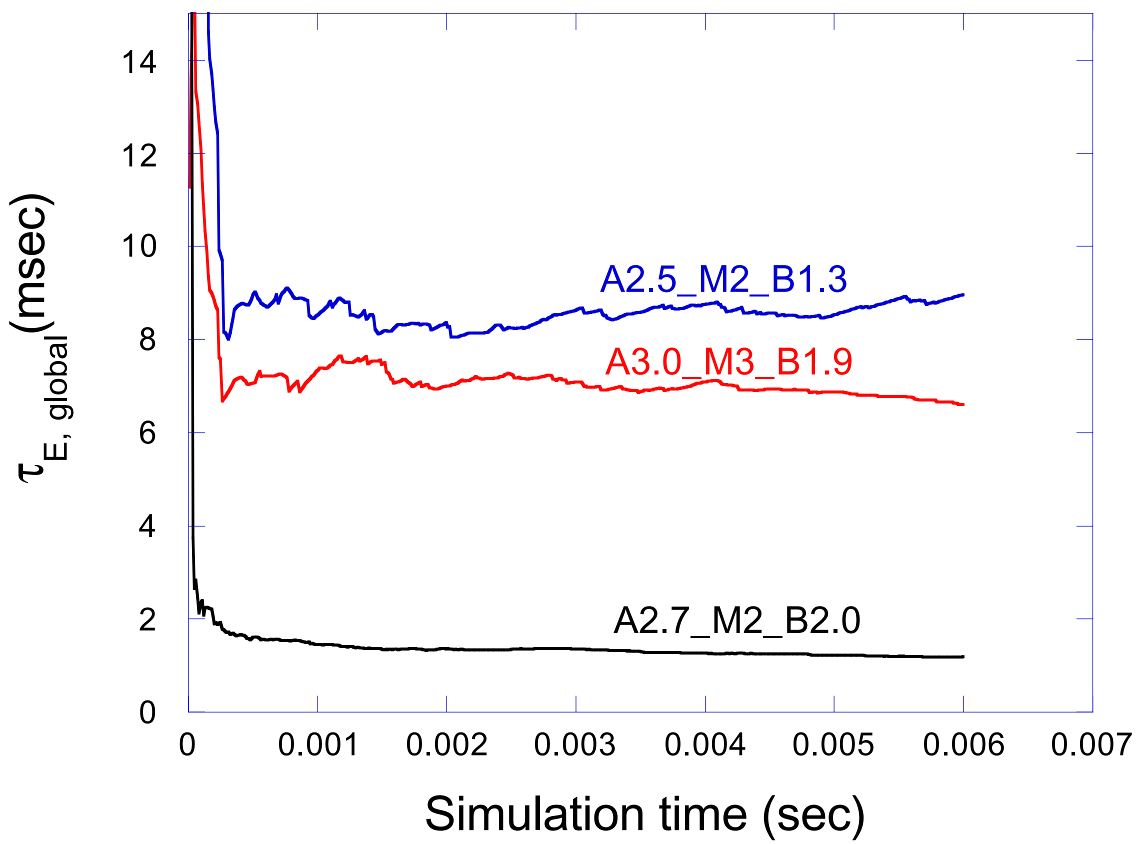
$\tau_{E,global}$ = 7.0 msec



A2.7_M2_B2.0

τ_{ISS95} = 0.79 msec

$\tau_{E,global}$ = 1.3 msec



Lifetimes are based on:

$T_e(0) = T_i(0) = 1.8$ keV

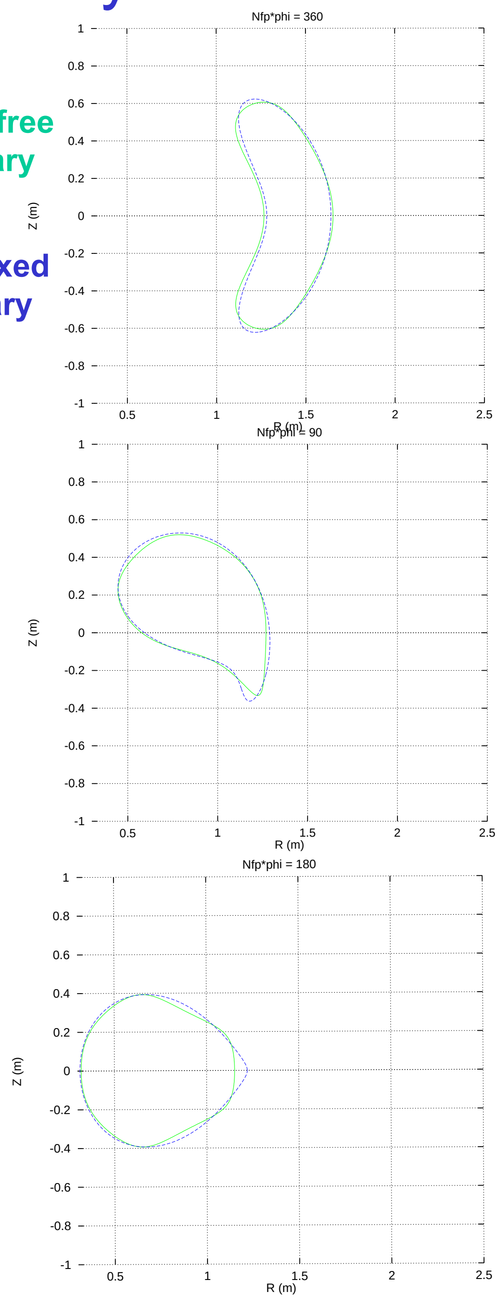
$n = 3 \times 10^{13}\ cm^{-3}$

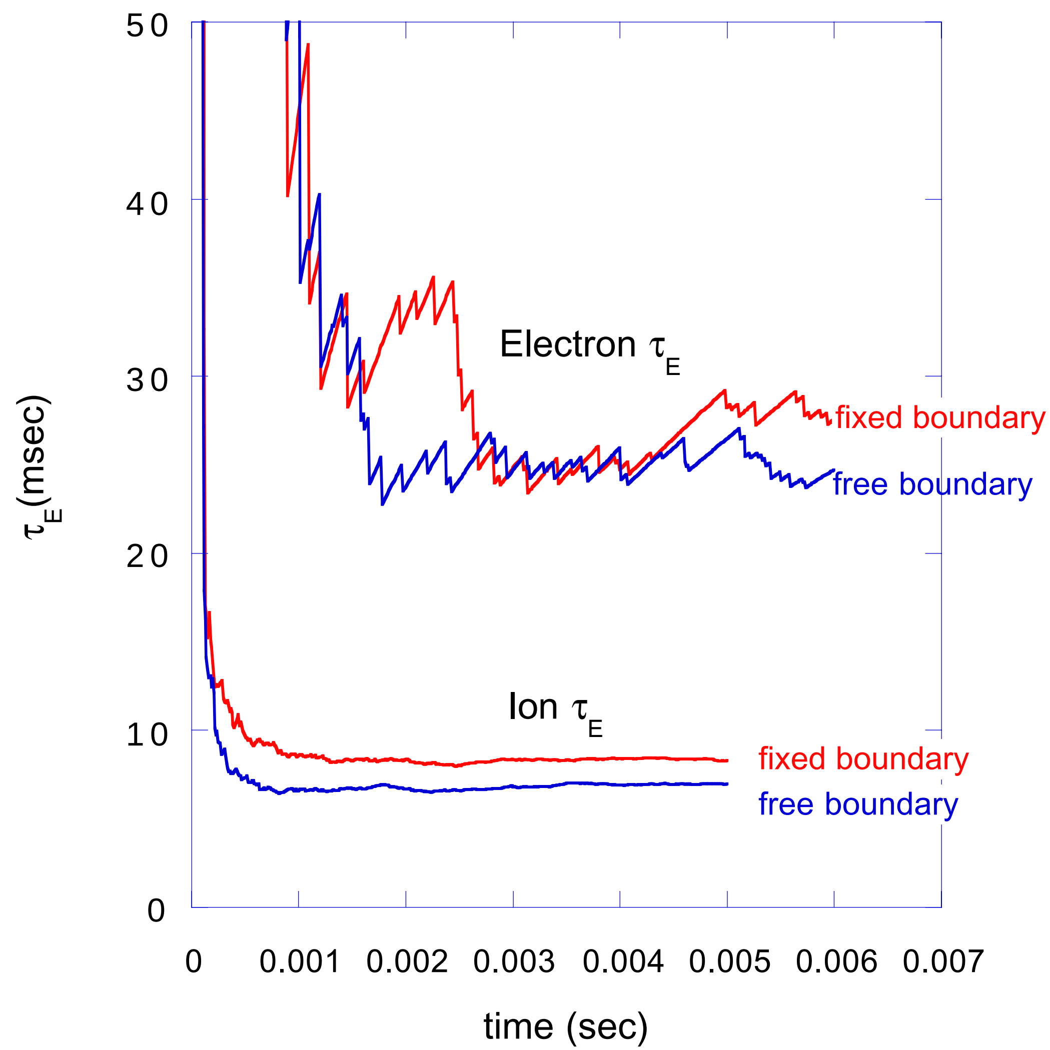
$\nu_{*e} = 0.02,\ \nu_{*i} = 0.018$

Free boundary A2.5_M2_B1.3 configuration (from coils) yields very similar transport as original fixed boundary case:

green = free boundary

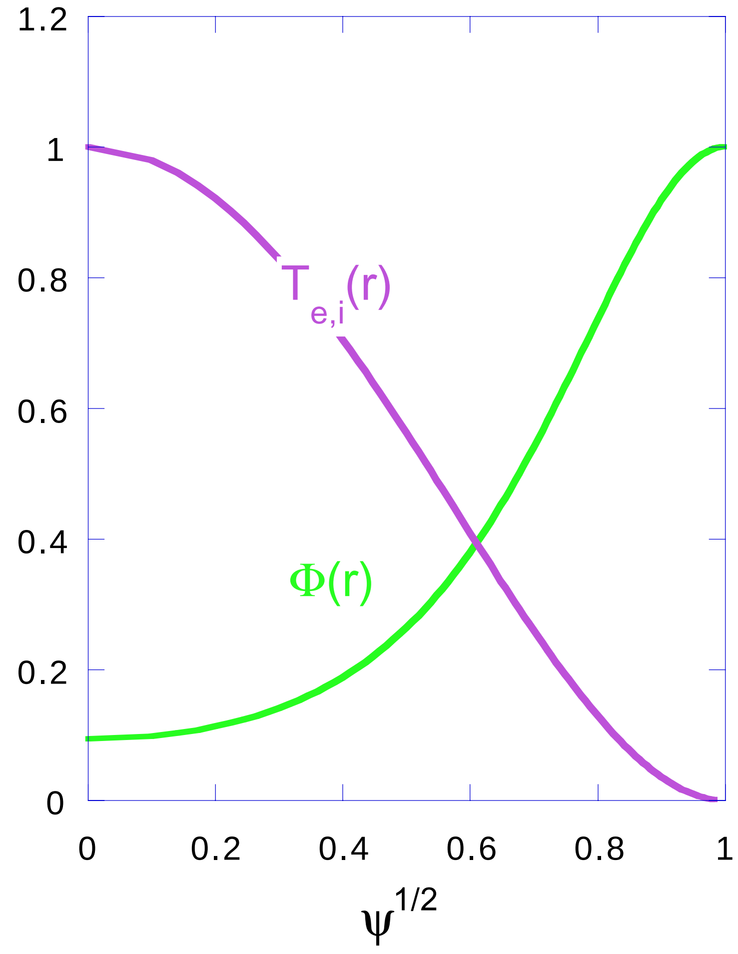
blue = fixed boundary





Profiles used in transport studies

- n = constant, $Z_{eff} = 1$
- $(1 - r^2)^2$ T_e, T_i profiles
- $e\phi(r)$ varies inversely with kT_e
- ion root
- electron root to be investigated



Projected QO/CE heating scenarios include both ECH and ICH regimes

#	$n/10^{20}\ m^{-3}$	T_e(keV)	T_i(keV)	τ_{ISS95}(msec)	ν_{*elec}	ν_{*ion}	$<\beta>$
1	0.18	1.4	0.15	8.1	0.019	1.6	0.7
2	0.045	2.1	0.2	1.5	0.0021	0.22	1
3	0.83	0.5	0.5	11.7	0.68	0.64	2
4	0.59	0.4	0.25	5.5	0.75	1.8	3.7

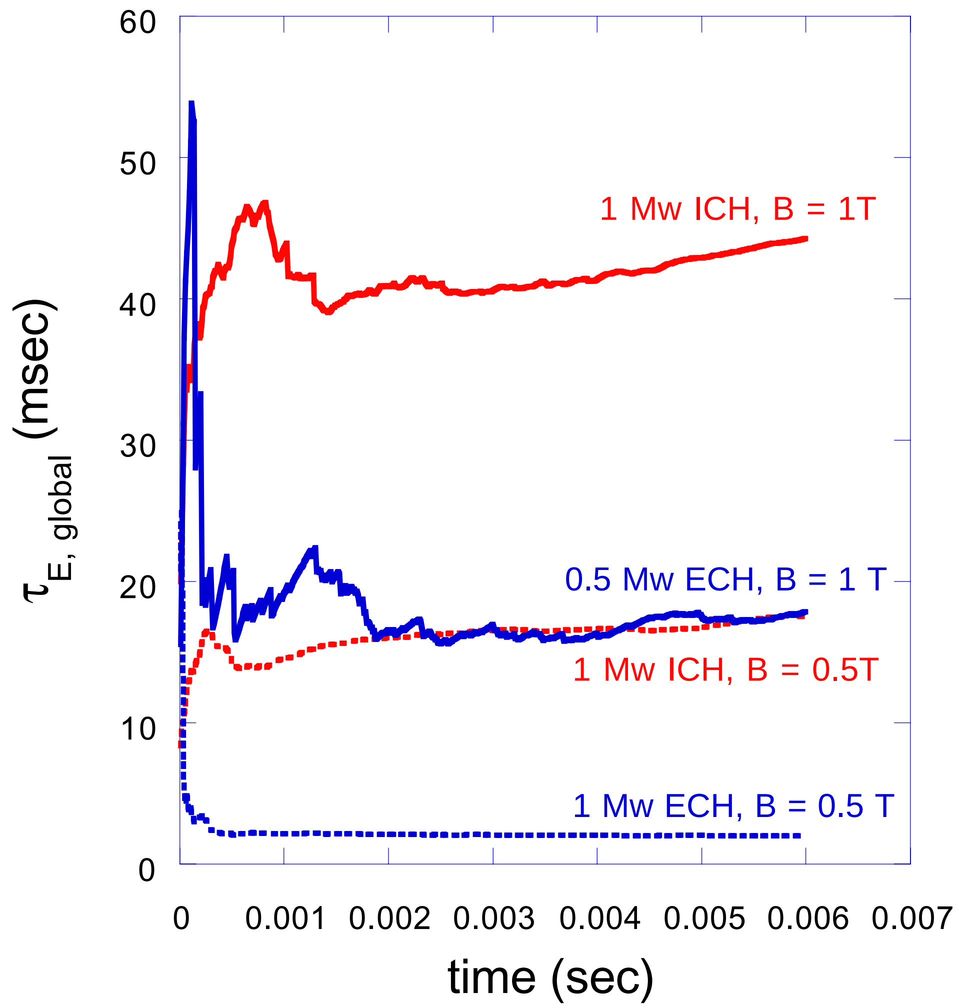
Heating and magnetic field levels

1	ECH	0.5 Mw	B = 1 T
2	ECH	1 Mw	B = 0.5 T
3	ICH	1 Mw	B = 1 T
4	ICH	1 Mw	B = 0.5 T

Confinement in the 2 field period, A = 2.5 configuration covers a range from $\tau_{E,global}$ = (1.4 to 3.6)$\tau_{E,ISS95}$ for different ECRF and ICRF heating scenarios

case	$\tau_{E,ion}$ (msec)	$\tau_{E,elec}$ (msec)	$\tau_{E,global}$ (msec)	$\tau_{E,ISS95}$ (msec)
ECH B = 1T	16.2	17.4	16.2	8.1
ECH B = 0.5T	4.27	1.95	2.1	1.5
ICH B = 1T	27	~100	41.7	11.7
ICH B = 0.5T	7.7	~55	16.4	5.5

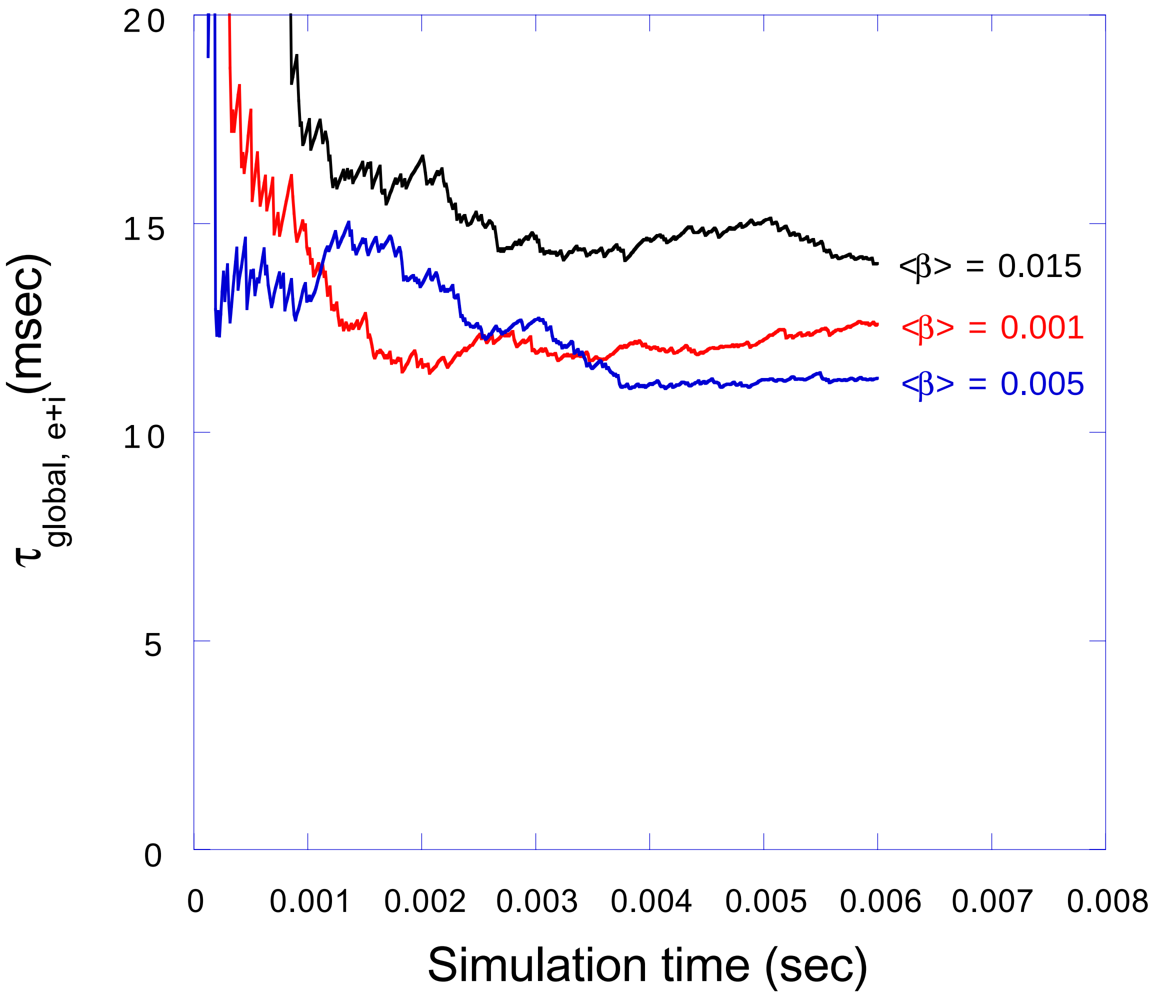
Monte Carlo energy lifetimes



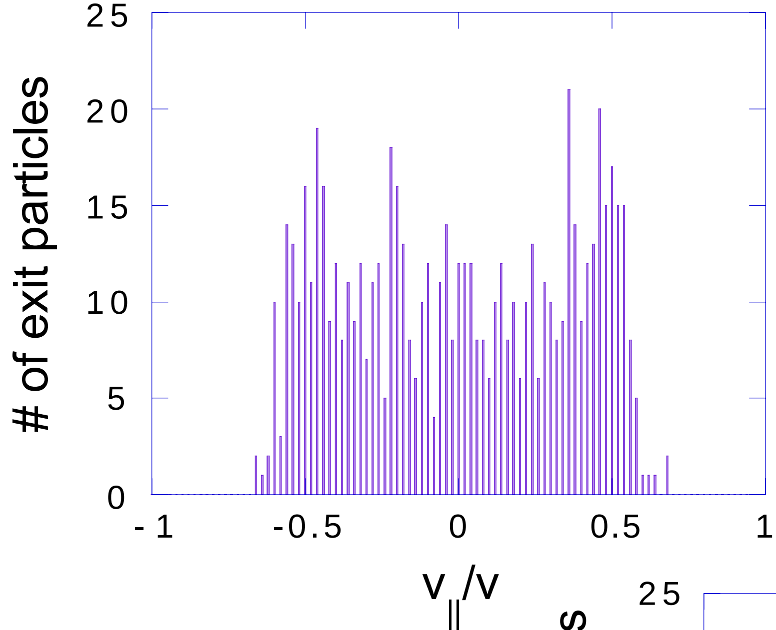
Transport analysis in regimes with (T_e > T_i) for the 2 field period A=2.5 device shows tendency to improve with increasing β:

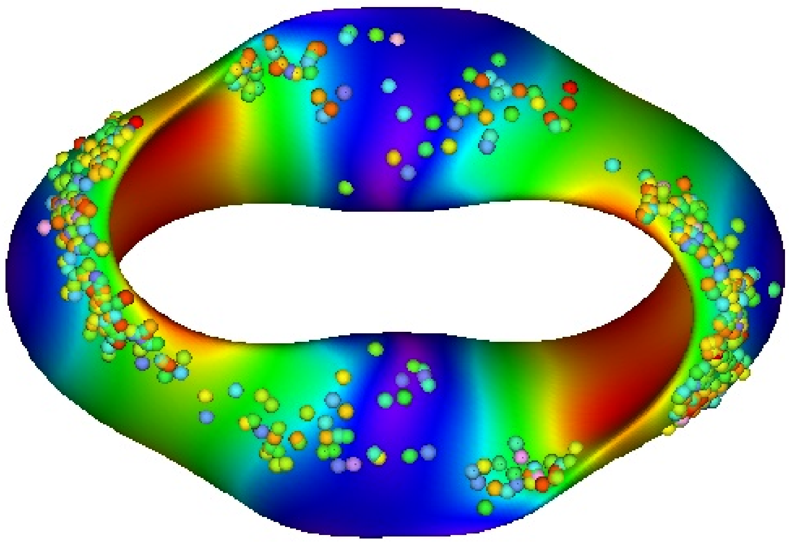
T_e = 1.8 keV, T_i = 0.5 keV, n = 3 x 10^{13} cm^{-3}

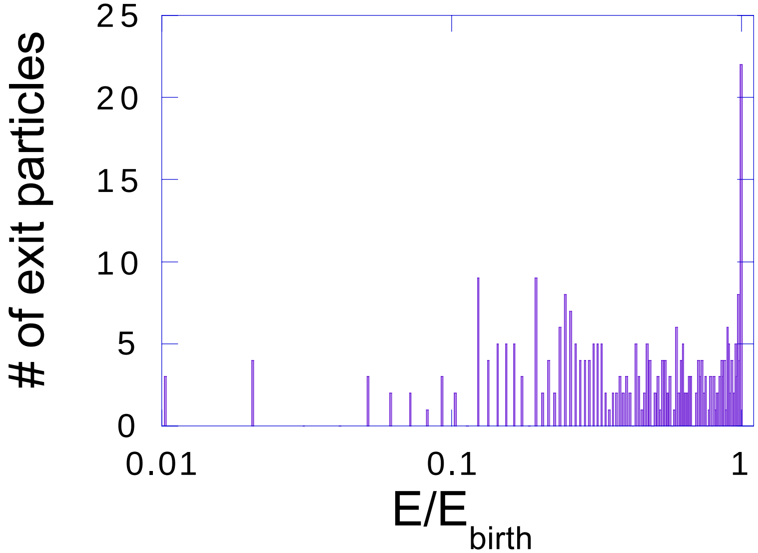
ν_{*e} = 0.019, ν_{*i} = 0.233



Energetic particle loss simulations show exit pitch angle, energy and exit position of ions on outer flux surface



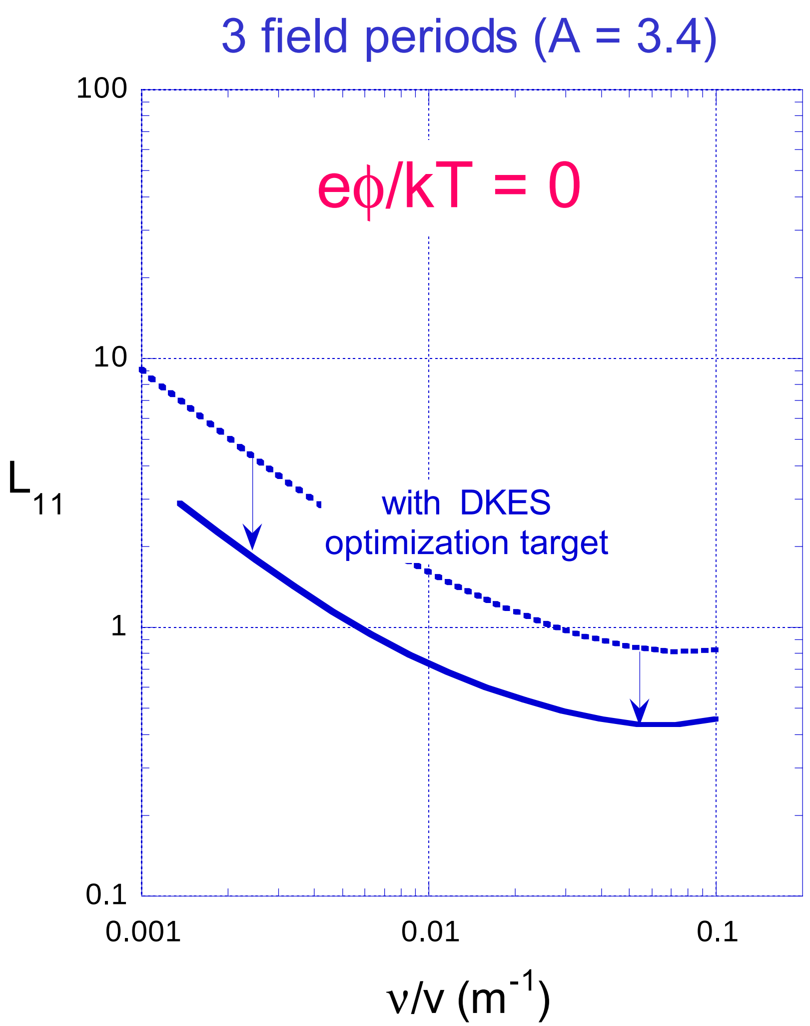


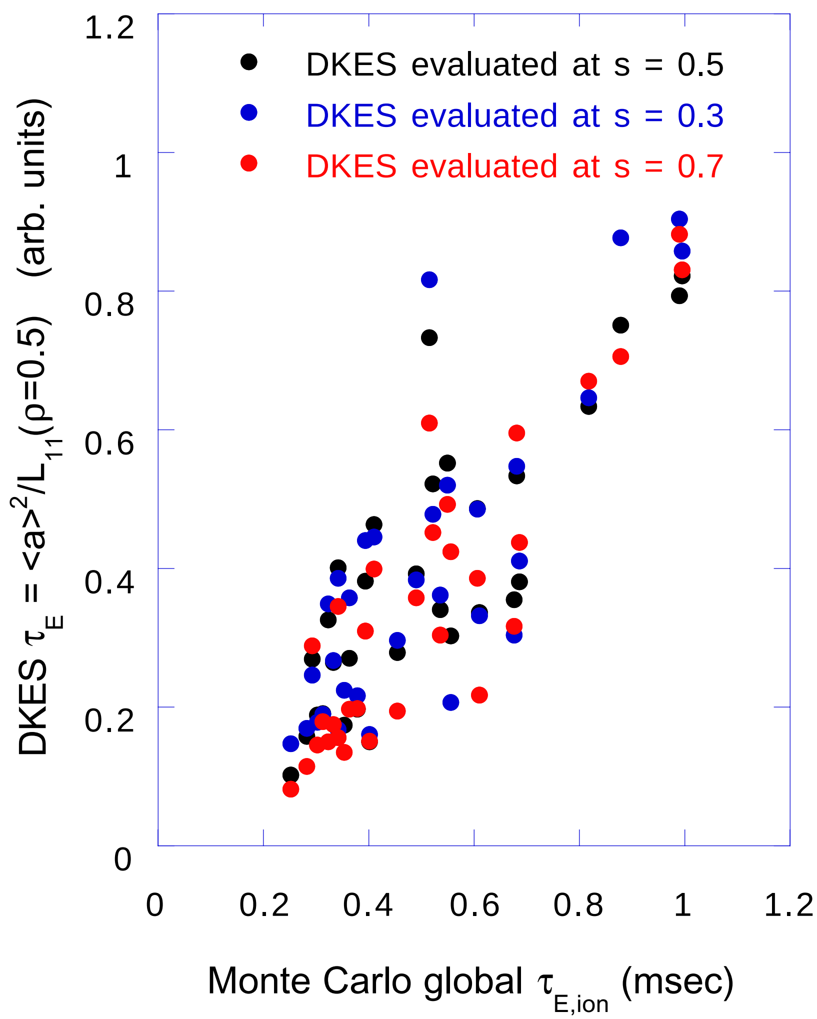


Applications of DKES to QO transport:

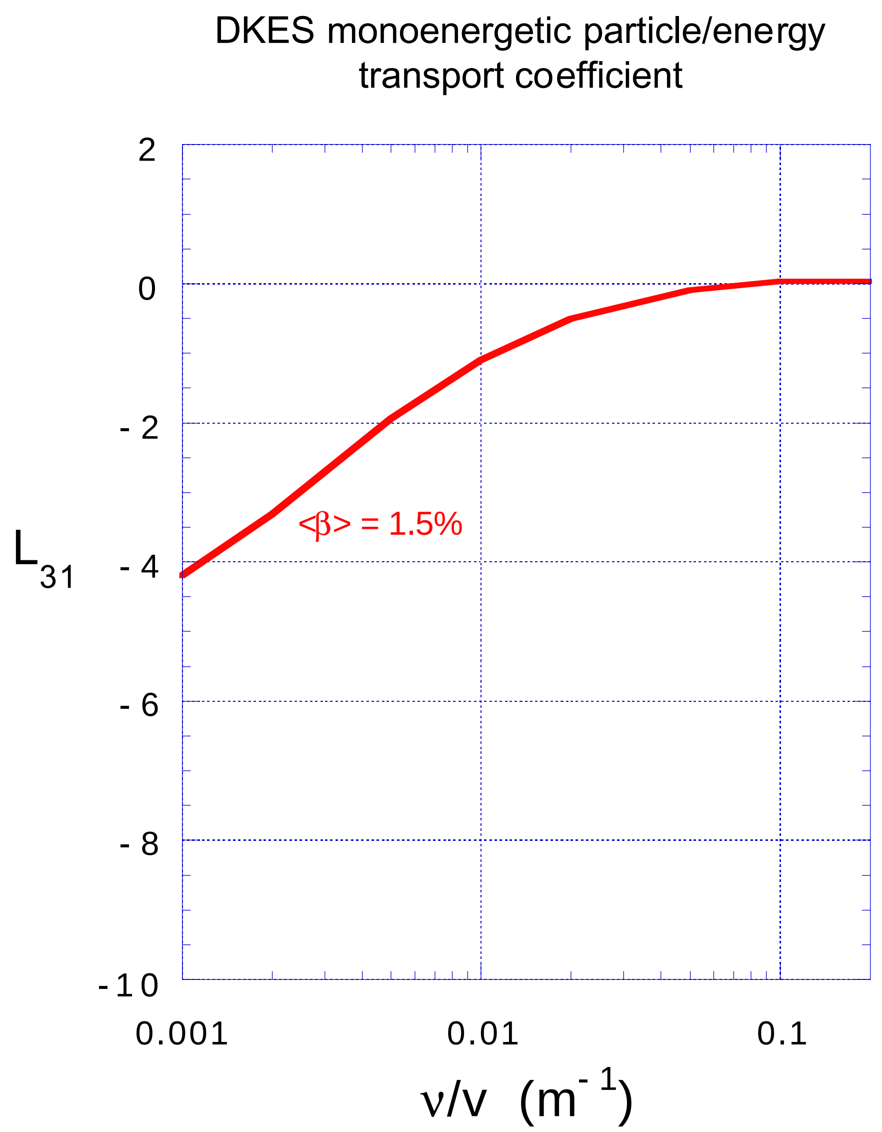
- Used in the optimizer
- Collisional bootstrap current
- Ambipolarity studies
  - Initially, use DKES for both electron and ion fluxes
  - Then hybrid model: DKES electron flux with ion particle flux from particle-based calculation

Transport optimizations using the DKES transport target has resulted in confinement improvements for earlier devices. We will also be applying these techniques to the more recent 2.5 < A < 3.0 devices.





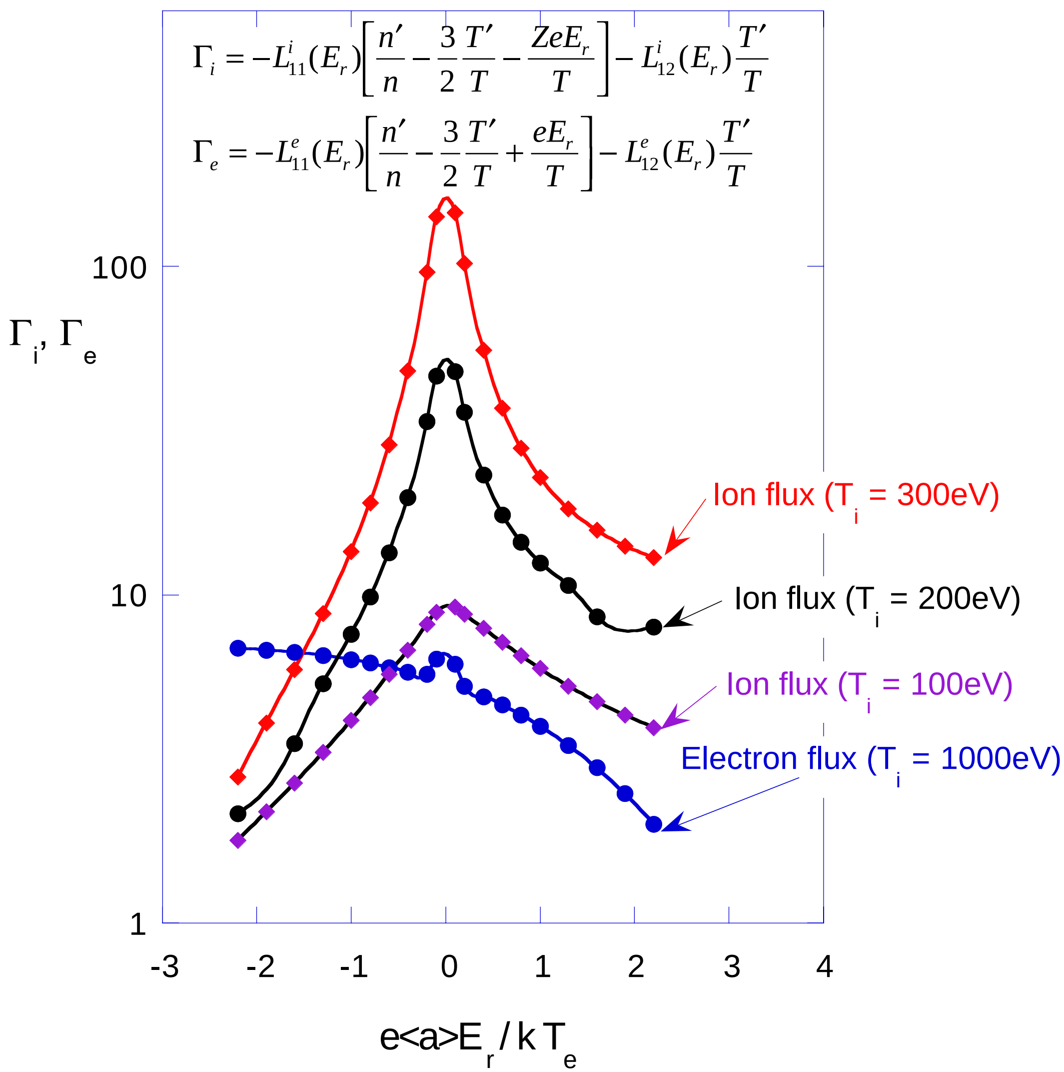
Collisionality dependence of bootstrap current coefficient (results shown are for A2.5_M2_B1.3 device)



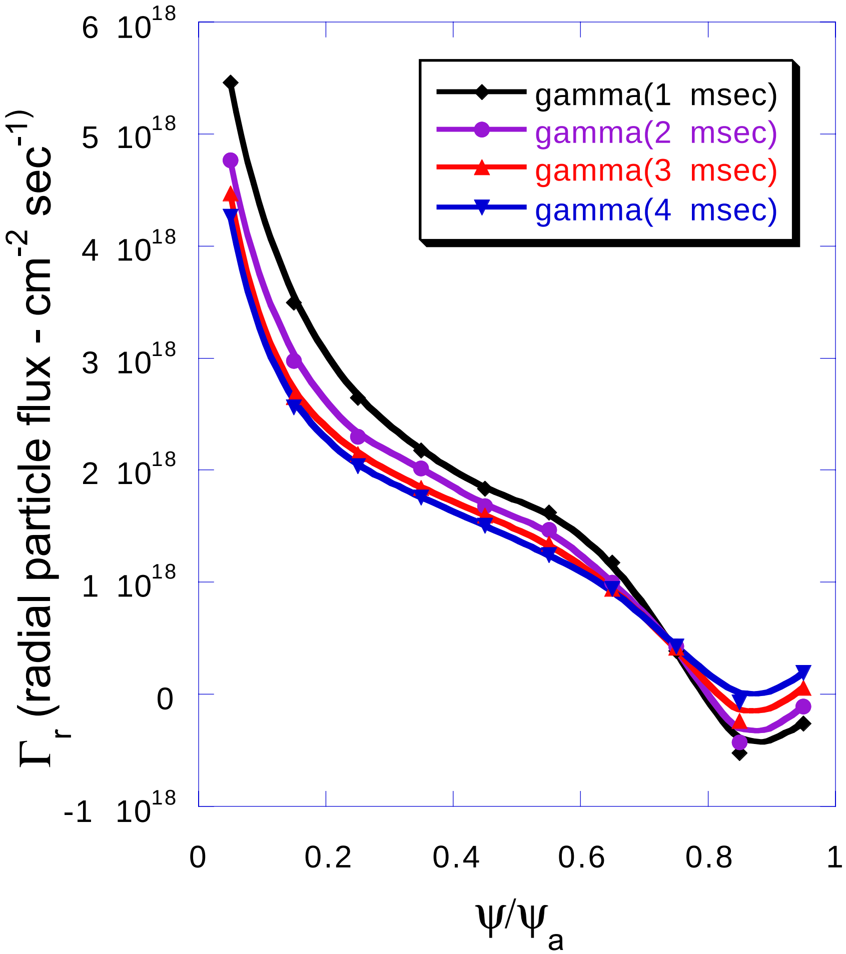
Self-Consistent ambipolar electric field calculations

- initially DKES will be used offline for electrons and ion to obtain $\phi(r)$ for DELTA5D
- next step is to use DKES for electron flux coupled with DELTA5D for ion flux

Ion, electron fluxes from DKES

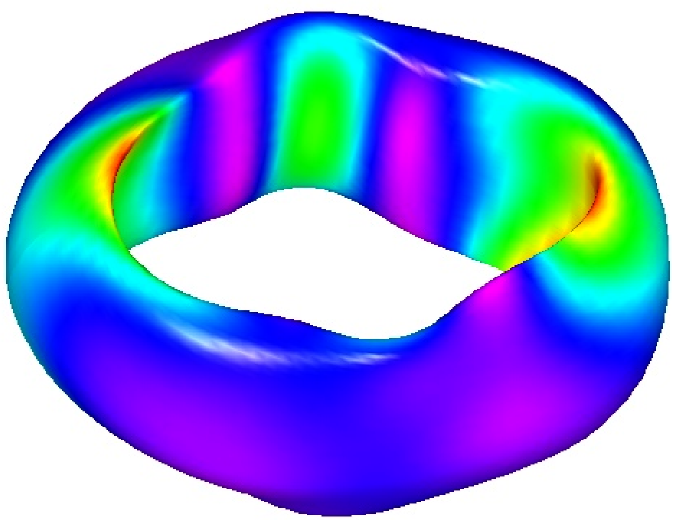


Ion flux from DELTA5D

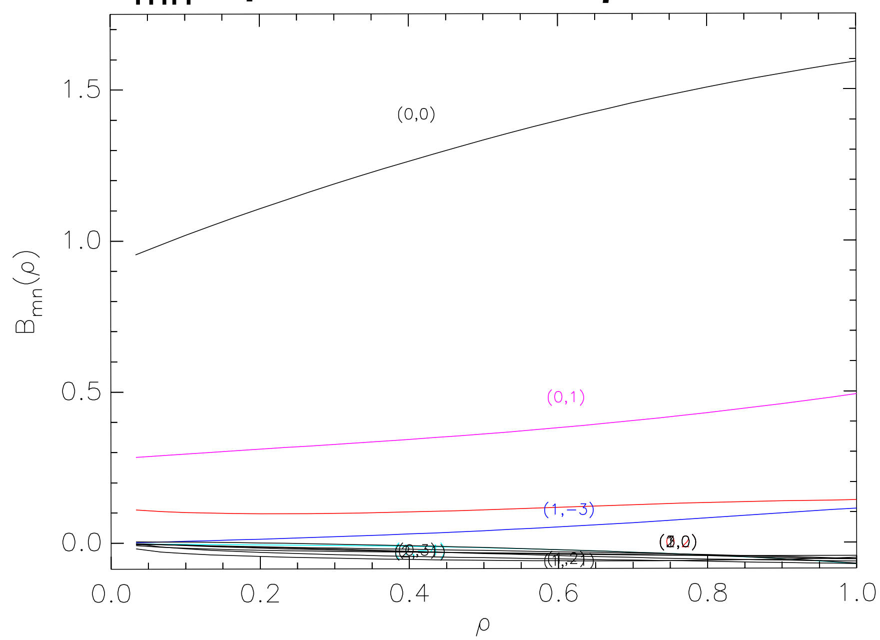


High β configurations achieve good confinement through the diamagnetic modifications of |B|:

- improved quasi-poloidal symmetry
- radial structure in the $B_{0,0}$ component leading to significant poloidal ∇BxB drifts

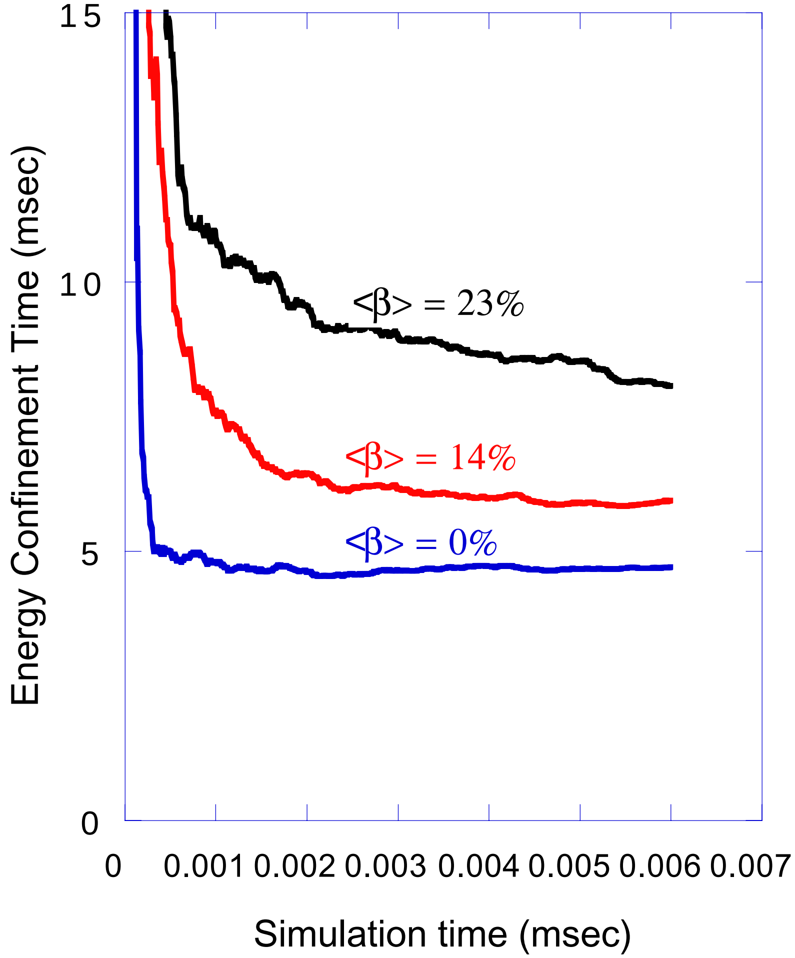


B_{mn} spectrum at <β> = 23%

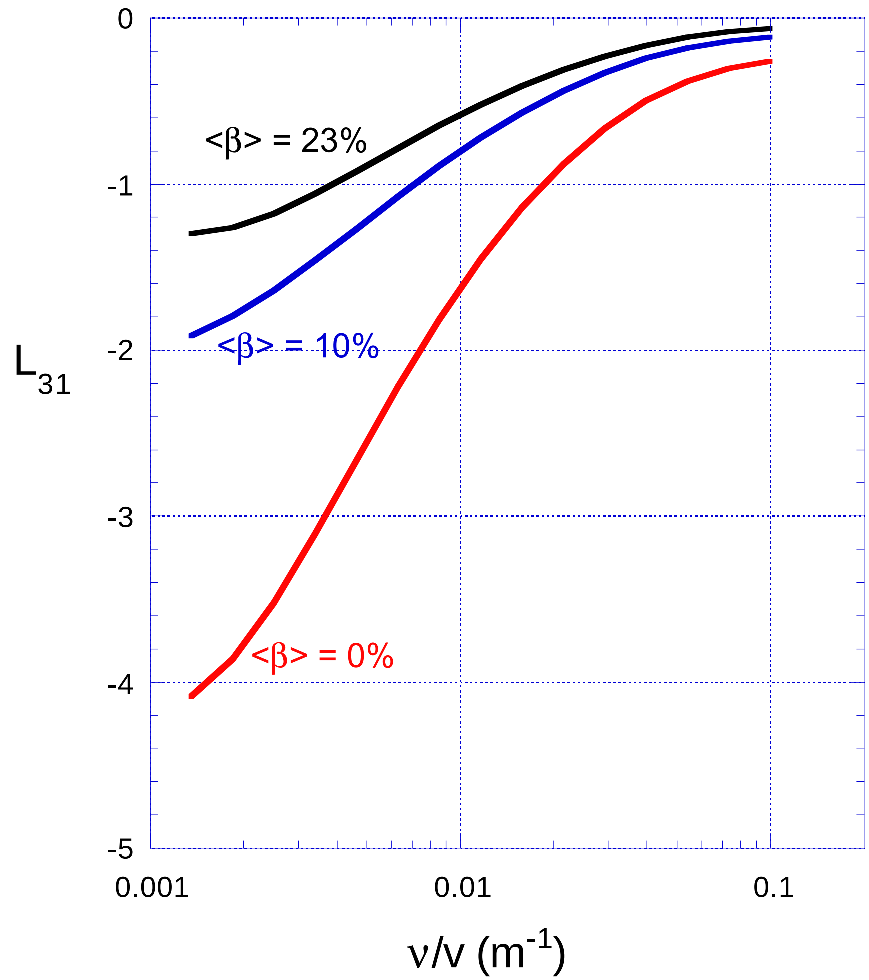


Through its modification of |B|, high β changes both the thermal neoclassical transport and bootstrap coefficient

Monte Carlo calculation of energy lifetimes

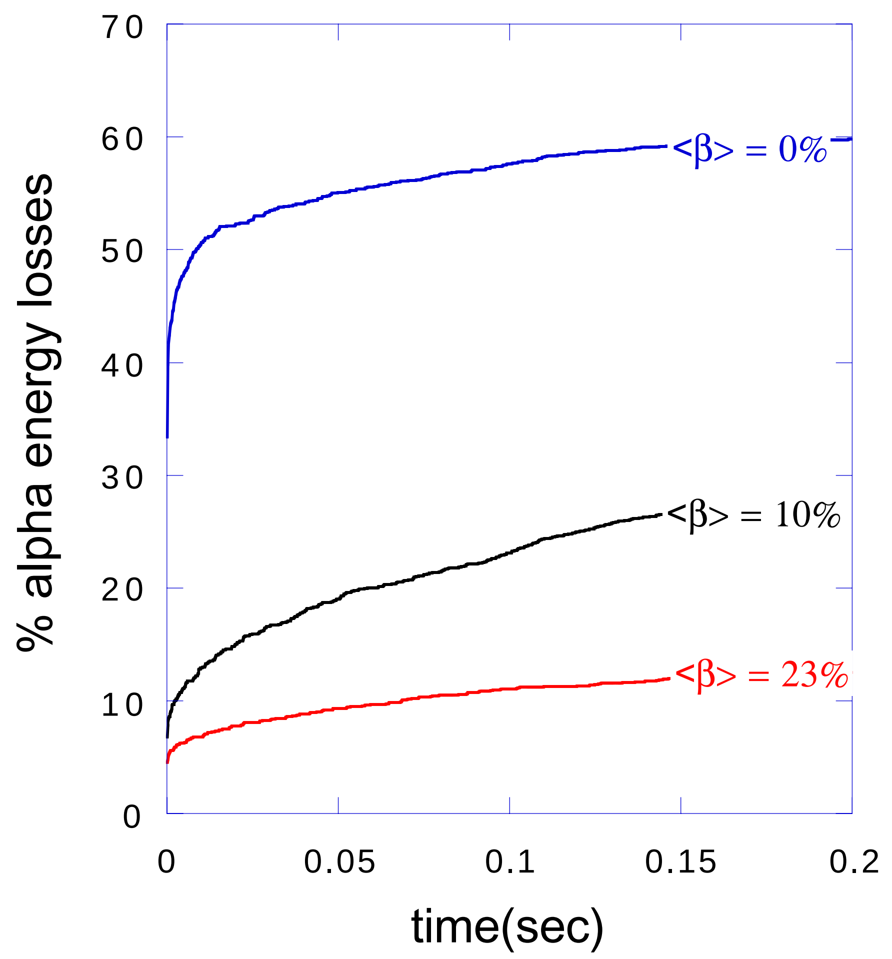


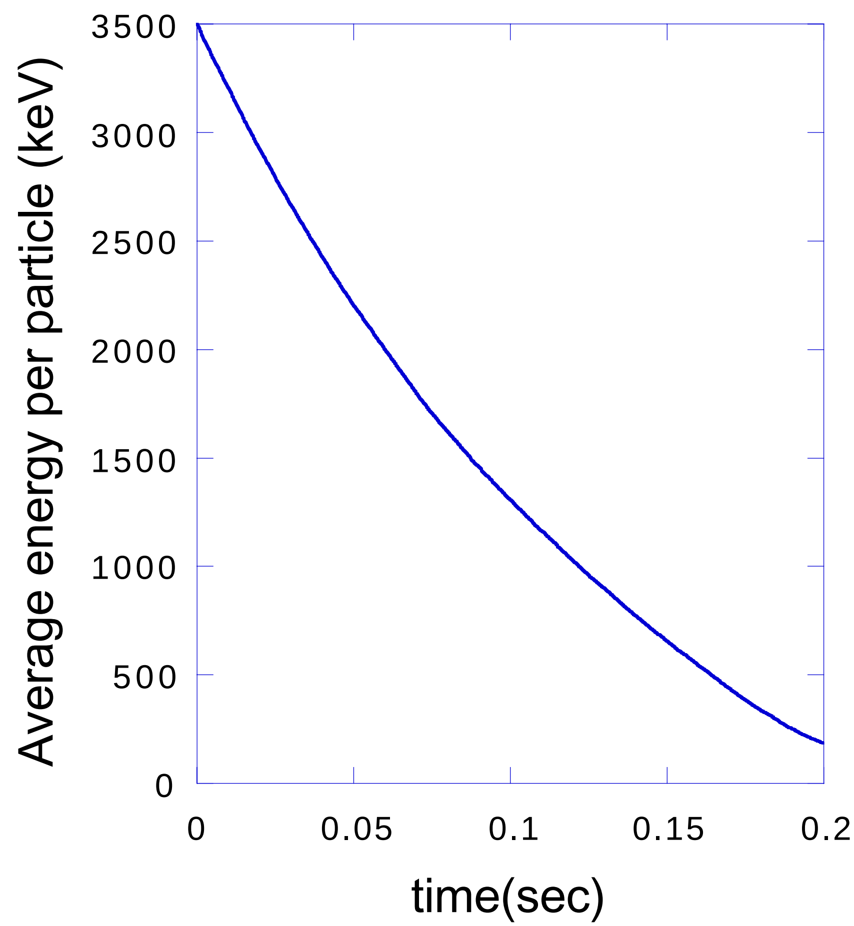
DKES calculation of L_{31} bootstrap coefficient



α-particle slowing-down simulations show these devices indicate very good confinement with increasing β.

The configuration was scaled to <B> = 5T and R_0 = 10m for alpha confinement studies





Summary

- Transport analysis indicates best confinement times in the 2 field period A = 2.5 configuration
- Different heating options and magnetic field variation (0.5 – 1T) allow exploration of different confinement regimes
  - ECH: τ_{neo}/τ_{ISS95} from 1.4 to 2
  - ICH: τ_{neo}/τ_{ISS95} from 3 to 3.6
- Reconstruction from coils preserves transport properties
- High β configurations offer improved confinement with increasing β
  - Have achieved lowest alpha losses (~12%) of any of our configurations