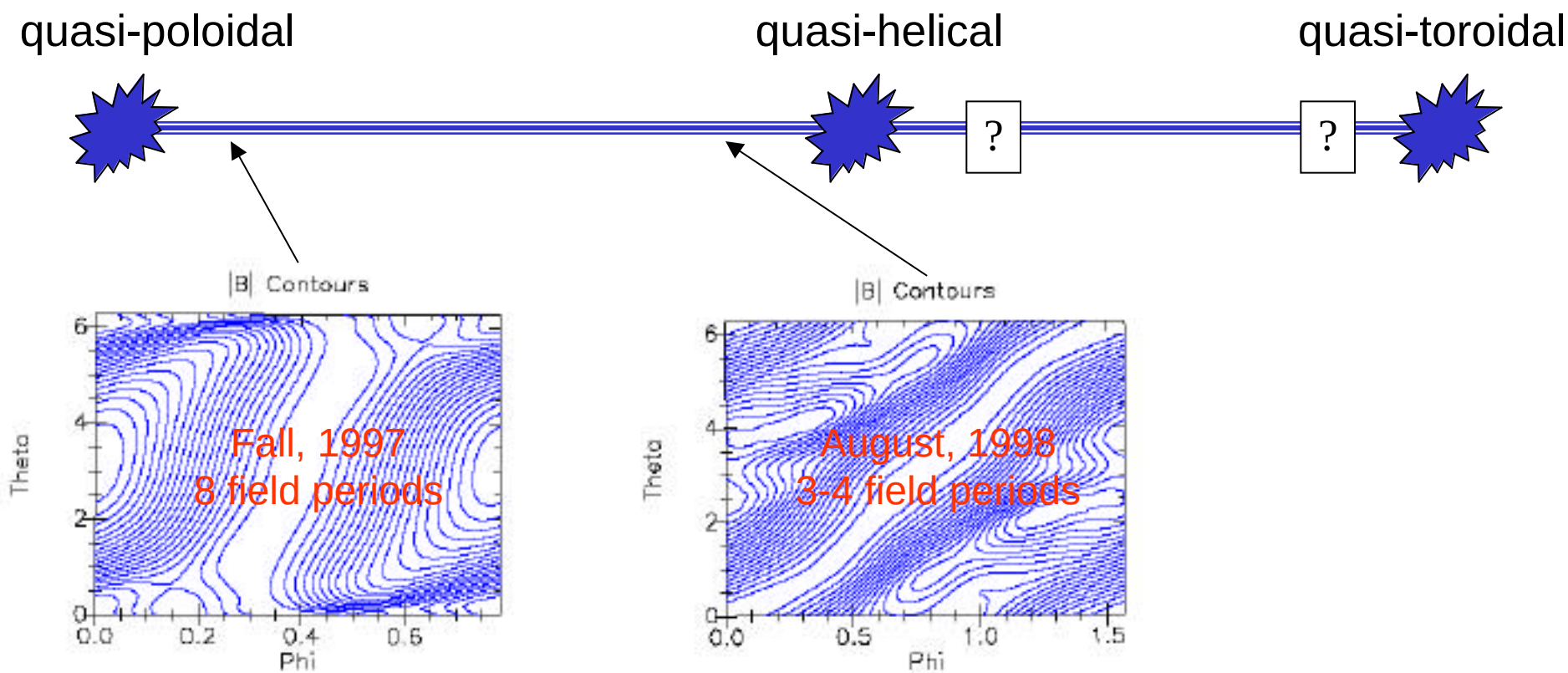
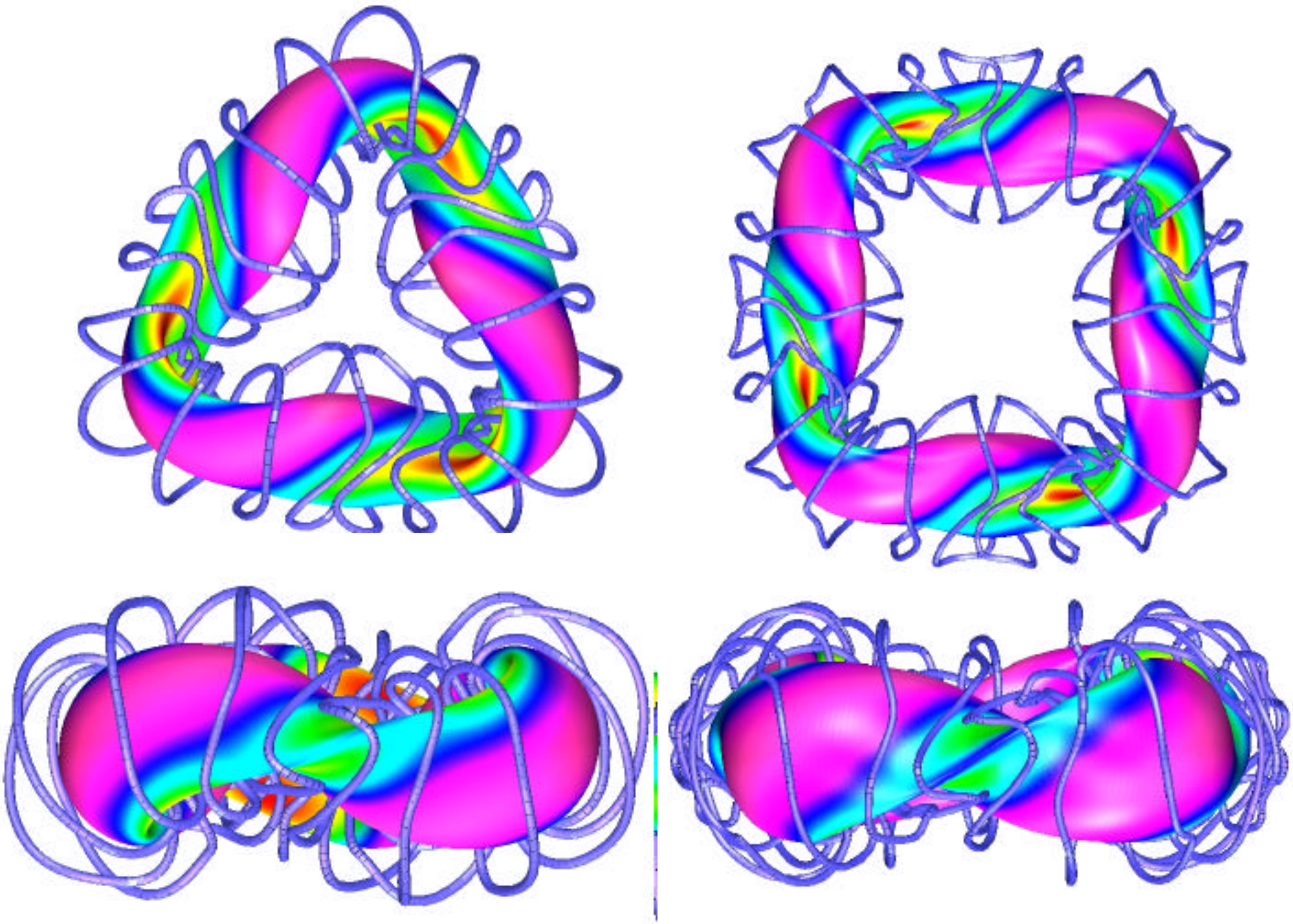
We have recently explored QO-optimized systems which are nearer to quasi-helical than our earlier configurations:

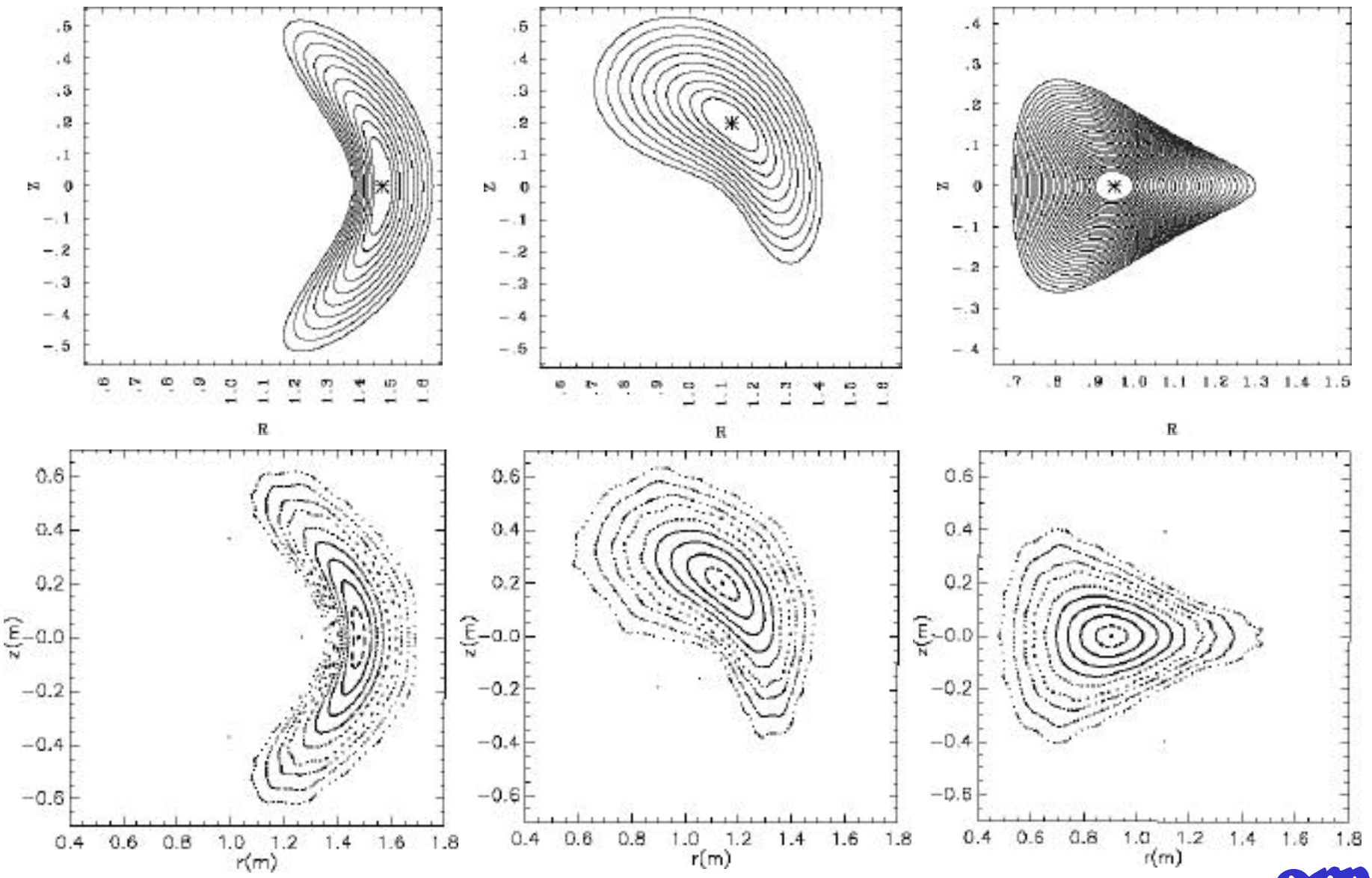
- These are all realizable systems
  - we have developed modular coils which reproduce closed flux surfaces
- Systems close to quasi-helical seem to allow improved QO-optimization at low field periods (2-4)
- These devices have iota in a higher range (0.6 to 0.9) than previous optimizations
- By QO-optimized we mean QO+other targets (stability, iota, compactness, etc.)
  - i.e., the goal is to achieve good (but not necessarily perfect) confinement consistent with other physics requirements

Note: These configurations have not yet been made self-consistent with bootstrap current profiles. As recently calculated by Mike Zarnstorff, configurations with B_{11} dominant have J_{Bs} of opposite sign and larger than assumed here (needs $di/dr < 0$ to supress neoclassical tearing modes).

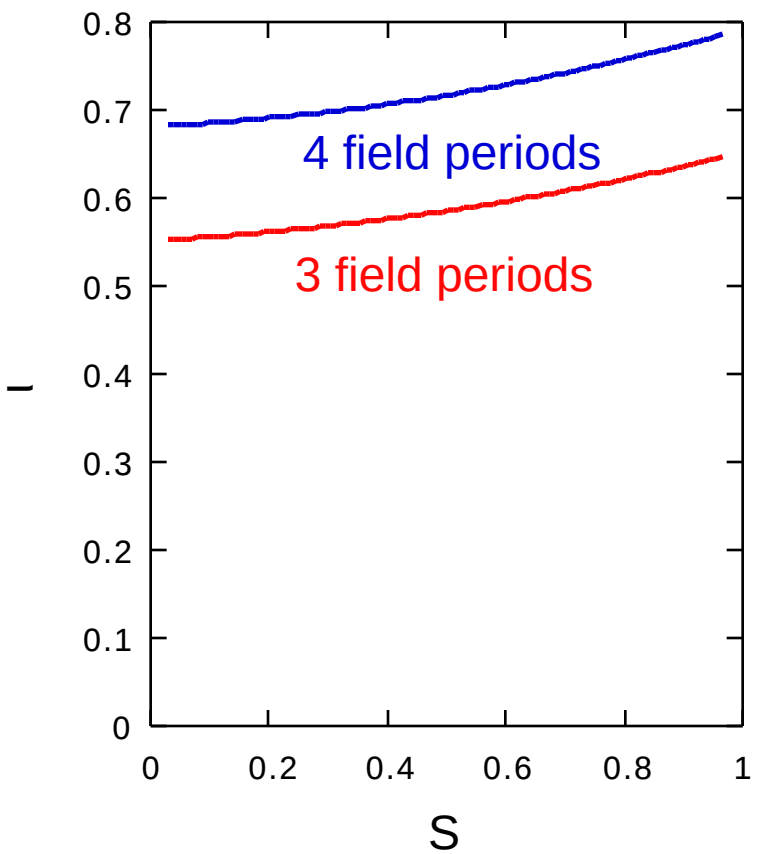


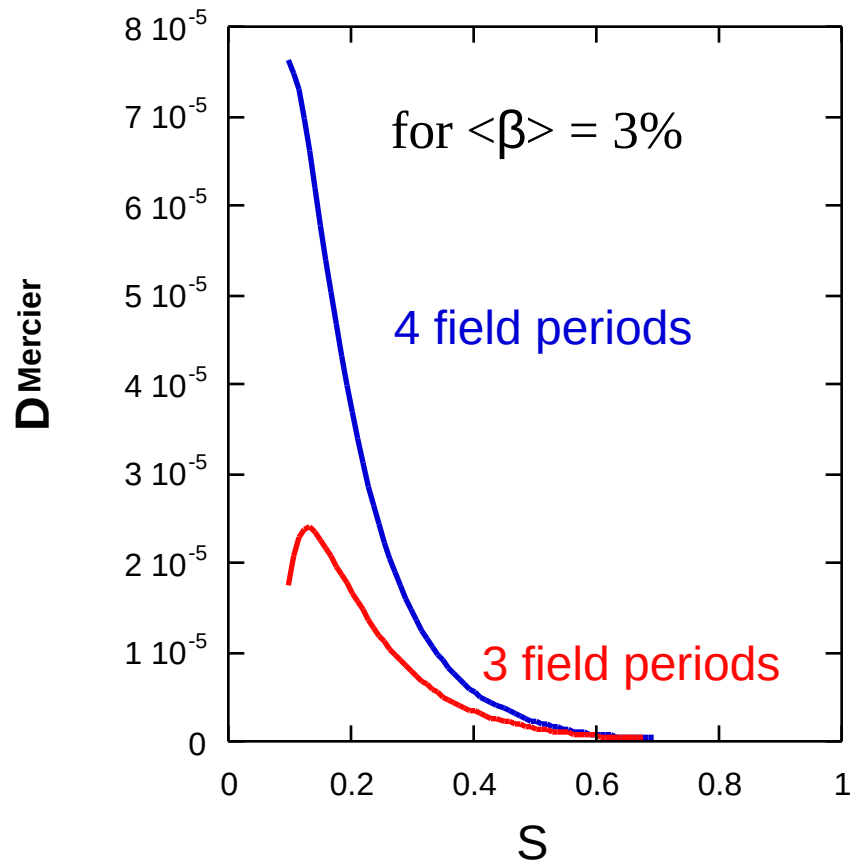


Excellent flux surface reconstruction is obtained using modular coils generated by the COILOPT code:



Rotational transform and Mercier coefficient profiles for N_{fp} = 3 and 4 configurations

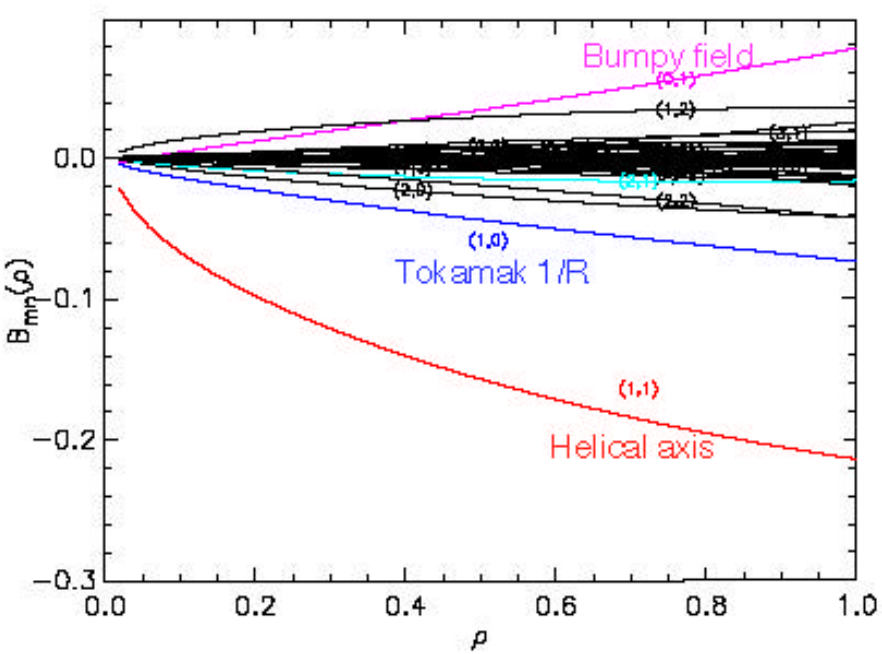




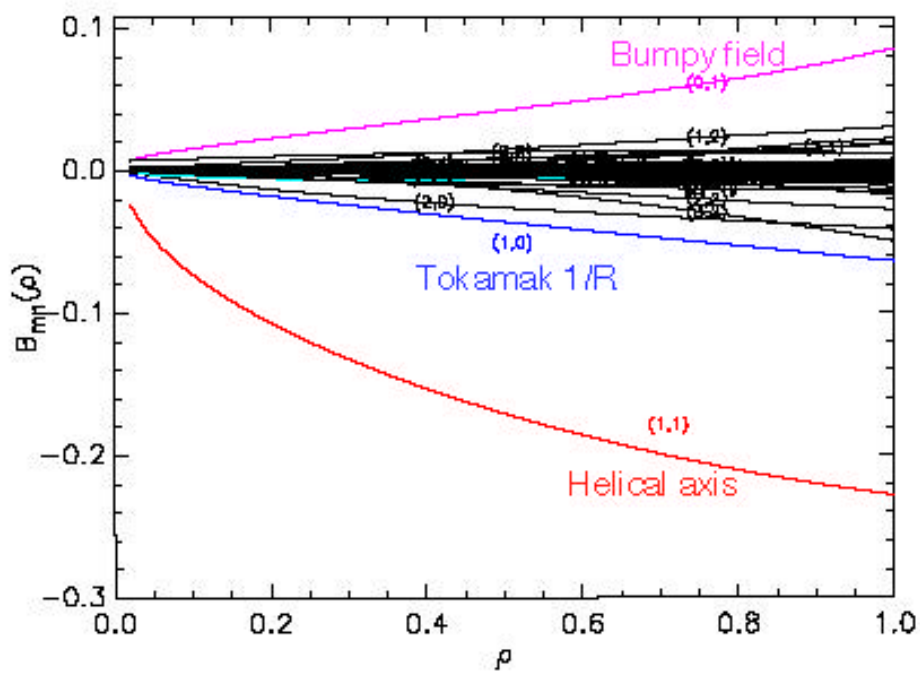
The B_{mn} spectra show that the helical component is dominant. The 1/R term is down from its axisymmetric tokamak level about a factor of 4.

Note: For these cases, $B_{0,0} \approx 1$

$N_{fp} = 3$, $R_0/\langle a \rangle = 3.6$



$N_{fp} = 4$, $R_0/\langle a \rangle = 4.2$



Effectively a hybrid of W7-X and HSX: strong helical component is like HSX, bumpy component is like W7-X

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Energetic Collisionless Orbit Confinement

- ICRF tail populations
  - –ensemble of particles started out at $B = B_{res}$ locations with $\varepsilon/\mu = B_{res}$ (i.e., $v_{||0} = 0$)
- Beams
  - – particles born as beam ionizes on intersection with 3D flux surfaces
- Alpha -particles
  - – uniform distribution in $v_{||0}/v$, θ, ζ
- Two issues:
  - – losses due to localized regions of unclosed J* contours (all stellarators, even W7-X, Helias, etc., we have studied have this to some extent)
  - – deviation of energetic particle guiding center orbits away from J* contours (becomes larger proportional to $\rho/\langle a\rangle$)

Scaling with <a>/ρ of deeply Trapped proton orbit trajectories in a B = 1T N_{fp} = 3 QOS Device (shown in Boozer coordinates):

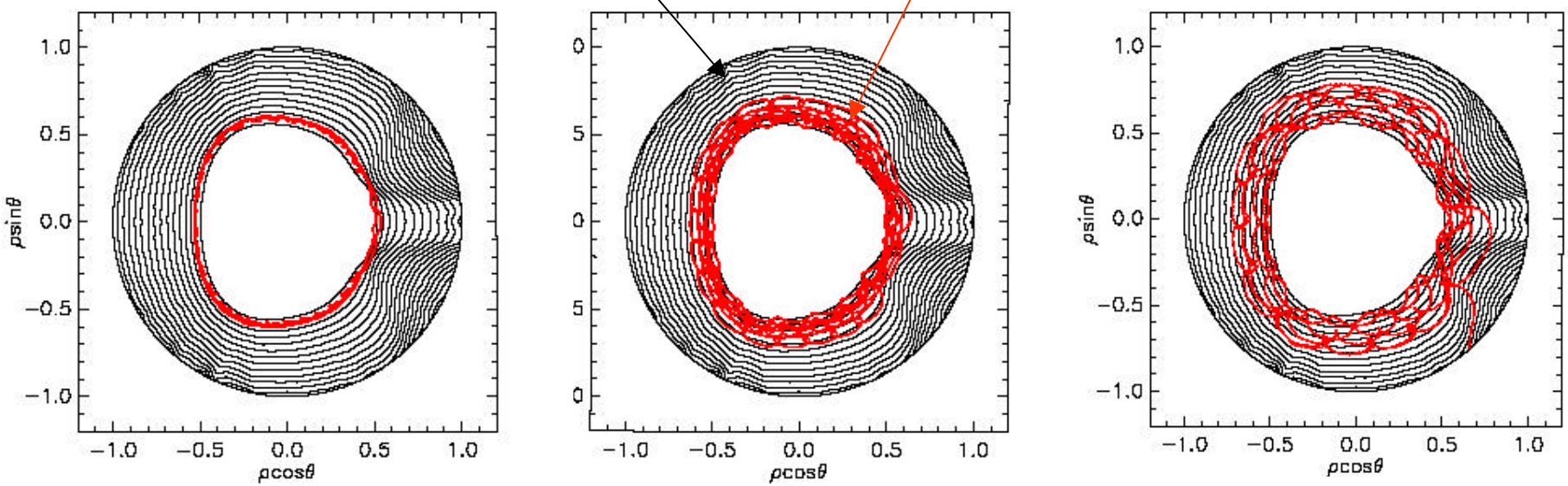
J* surfaces

GC Orbit

5 keV

20 keV

50 keV



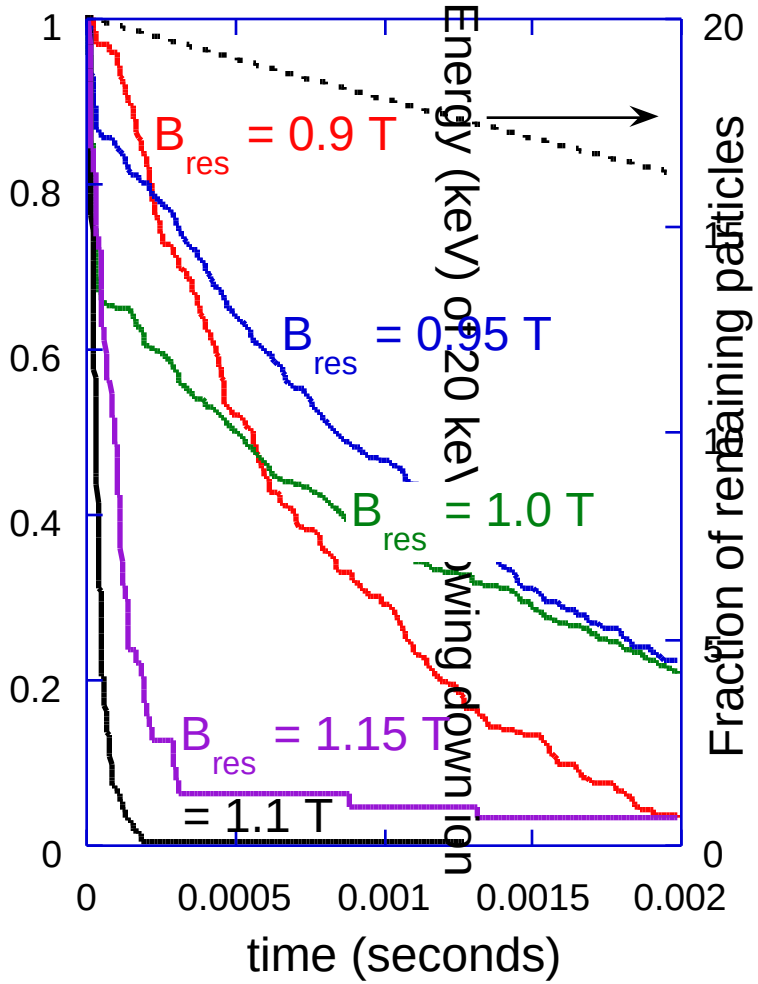
<a>/ρ = 27

<a>/ρ = 13.5

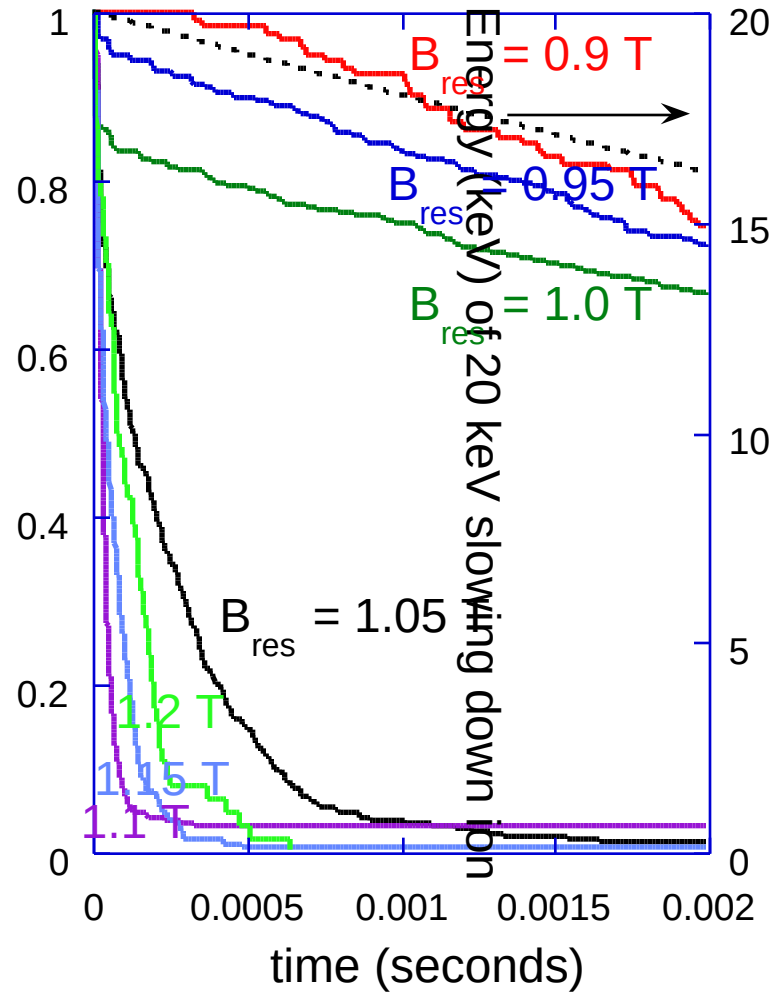
<a>/ρ = 8.5

Loss rates of 20 keV ICRF ion populations (500 particles) are a sensitive function of the resonant magnetic field $B_{res} = \varepsilon/\mu$

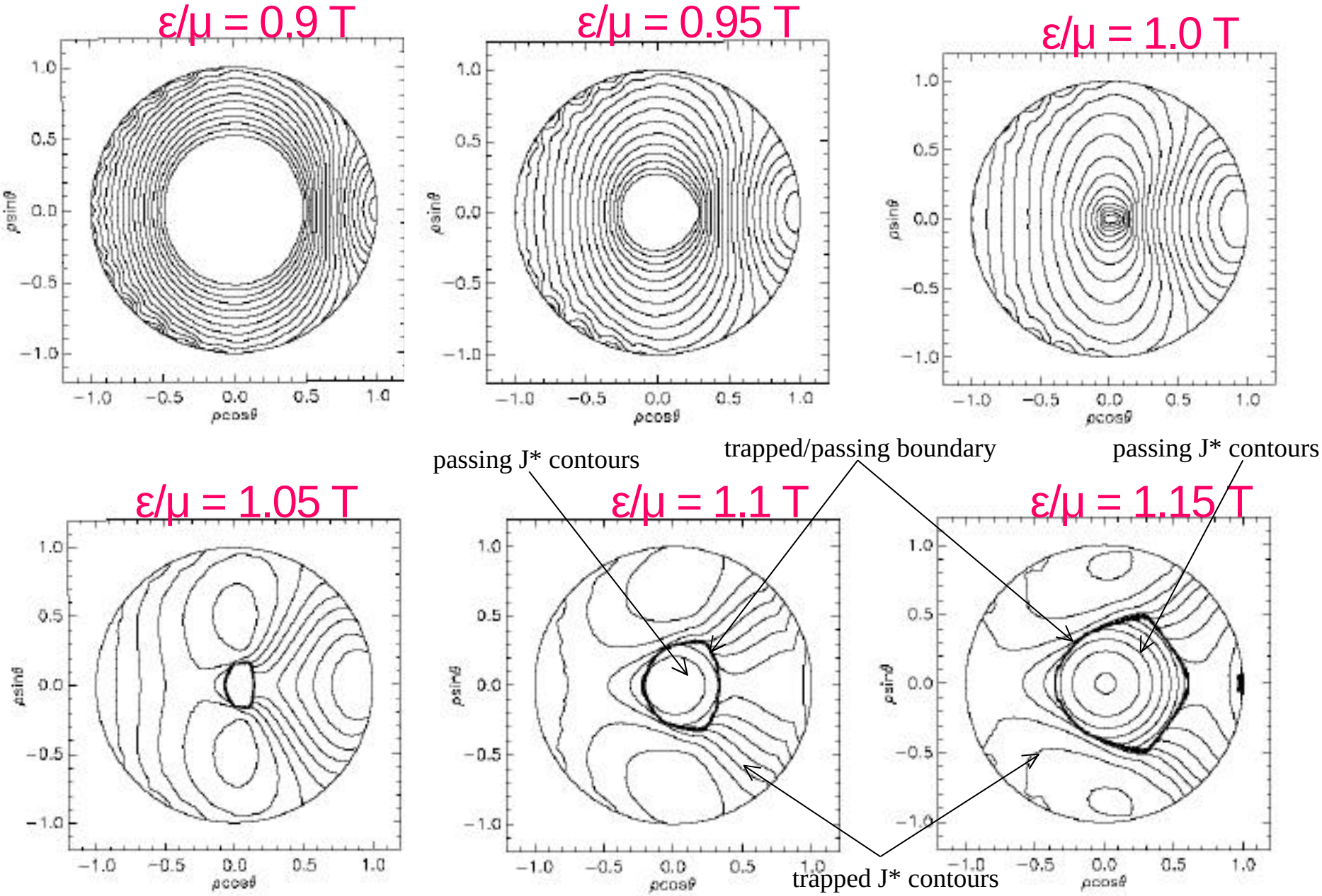
$N_{fp} = 3$



$N_{fp} = 4$

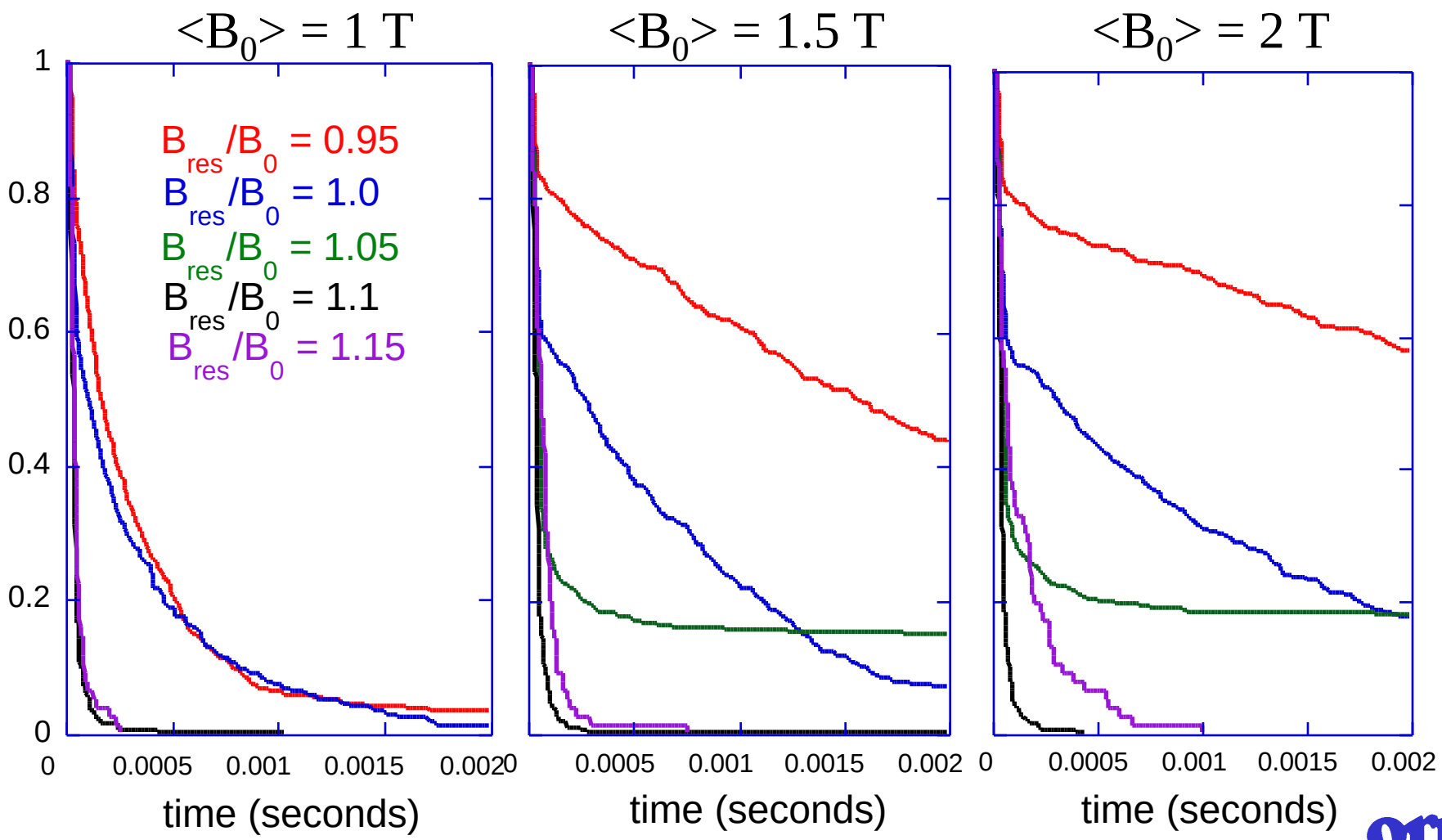


Trapped particle J* contours (N_{fp} = 4) correlate with guiding center ICRF loss regions. (i.e., open J* contours - lost orbits - are only present in localized regions of phase space)

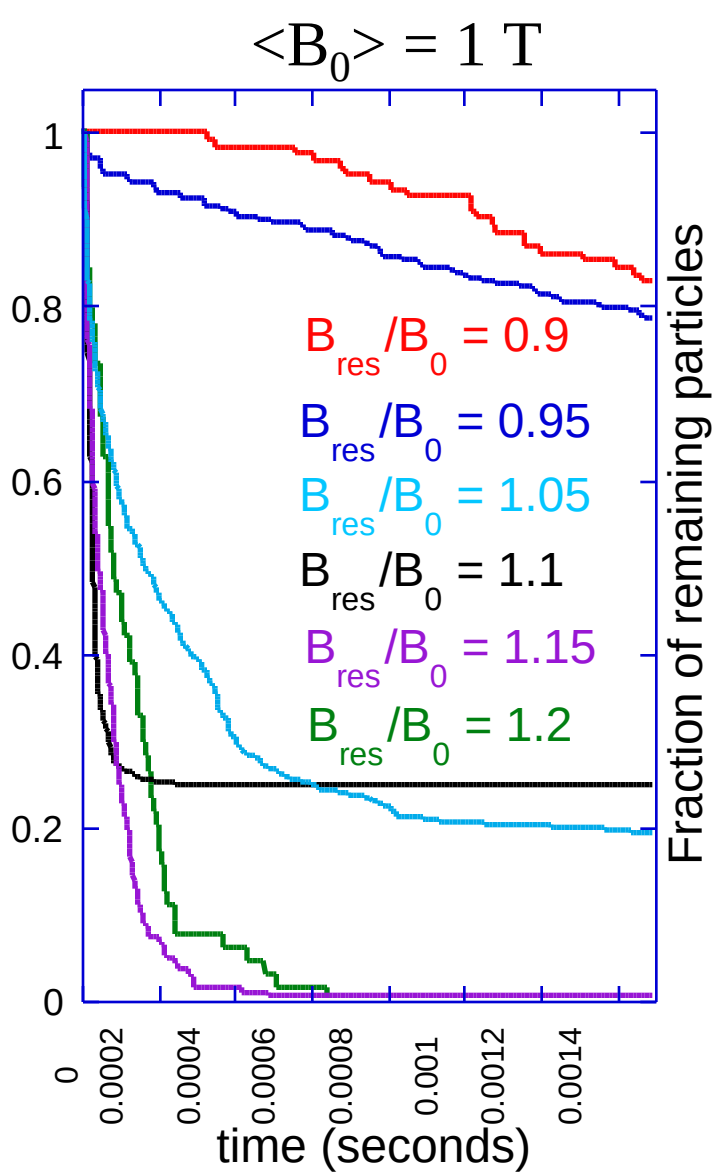


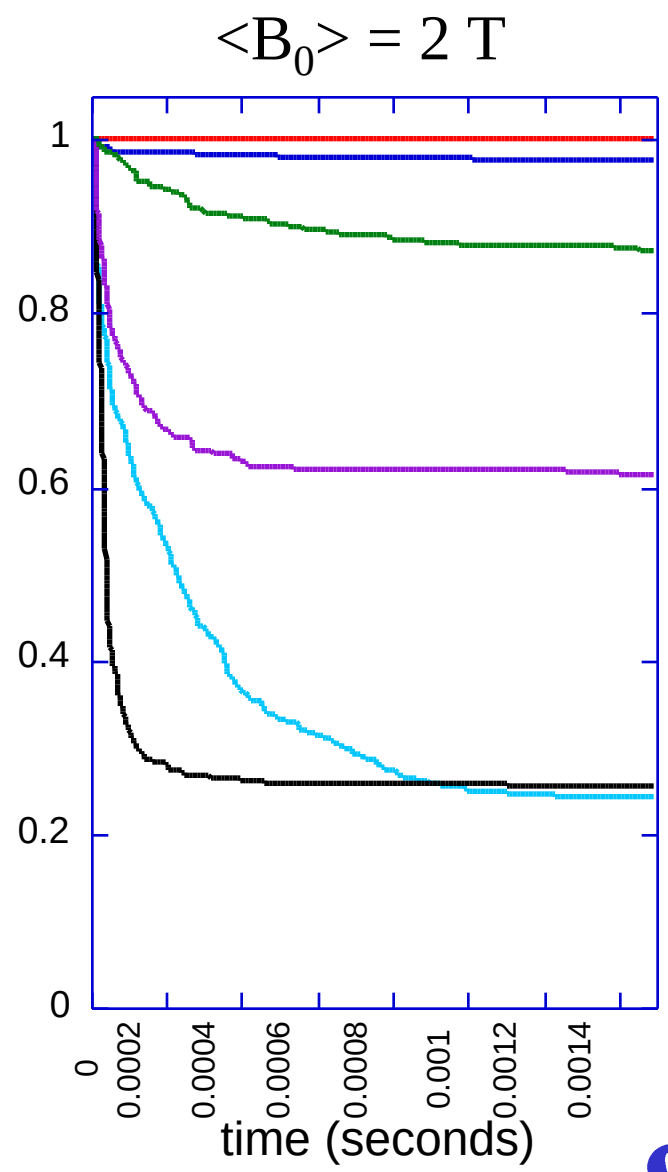
With increasing magnetic field, ρ/<a> gets smaller, reducing the orbit spread about the associated J surface, leading to improved confinement

(shown here for $N_{fp} = 3$). Jim Lyon has indicated that 1.5 to 2 T may be possible in a QOS at shorter pulse lengths.

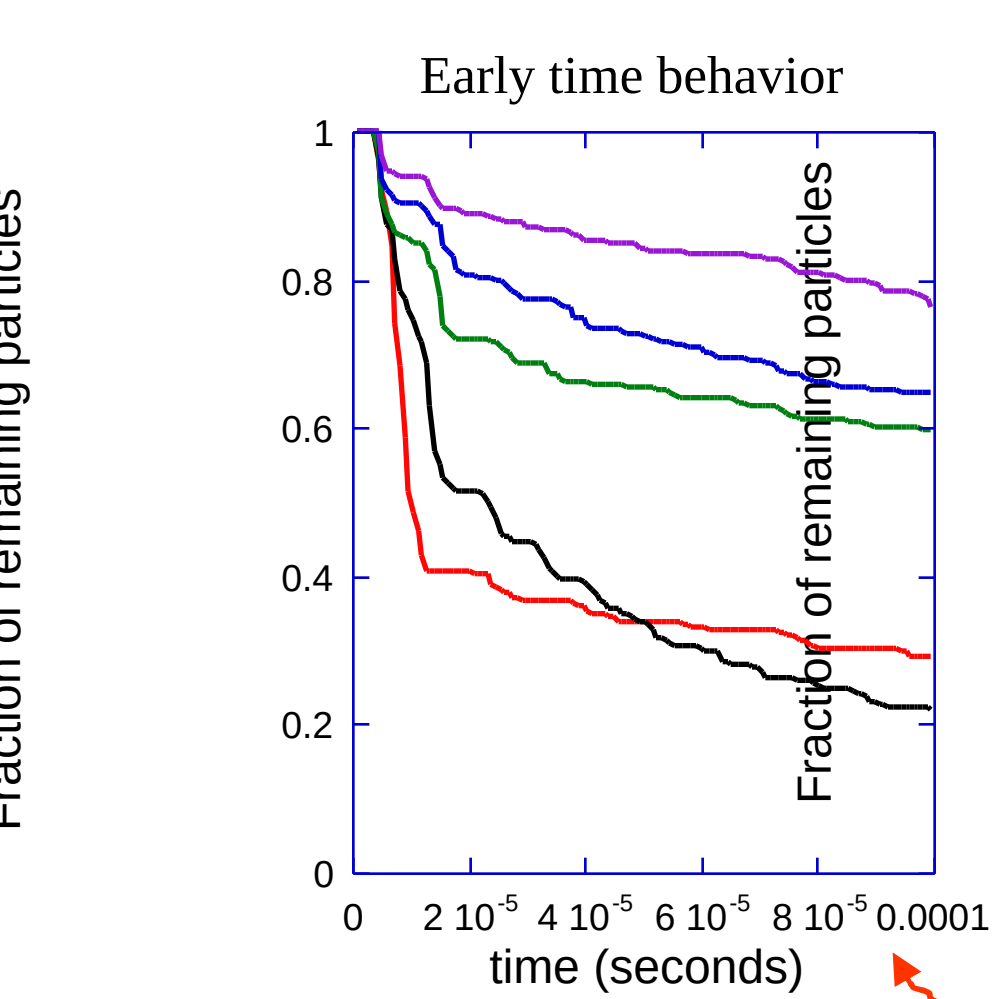


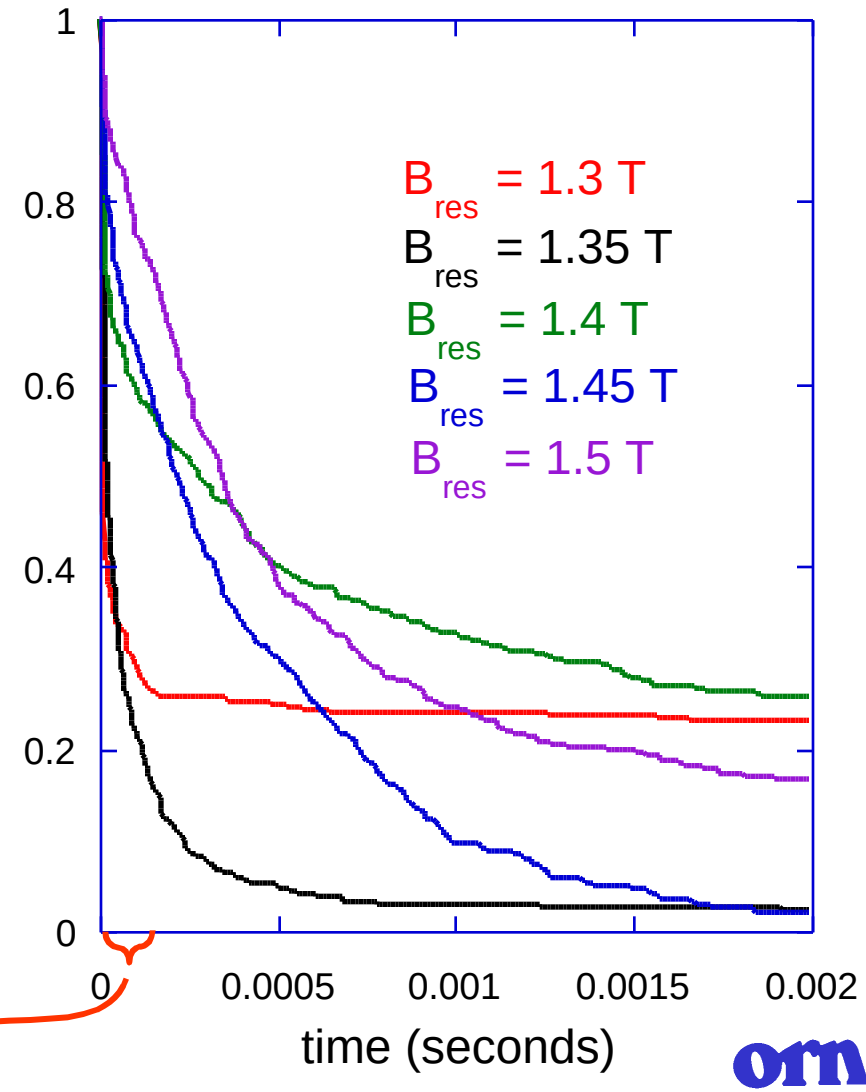
The N_{fp} = 4 configuration shows a similar confinement improvement with increasing B_0





Losses of ICRF populations have been calculated for CHS (magnetic axis = 92 cm) in regimes where heating was observed





Confinement of heating populations in near term devices can be more demanding than alpha confinement in reactor-sized systems:

- 20 keV proton B = 1T <a> = 24 cm
  $\rho = 2$cm <a>/ρ = 12

- 3.5 MeV alpha B = 5T <a> = 2 m
  $\rho = 5.4$cm <a>/ρ = 37

- Prompt orbit losses are determined by:
  - Closure of J* contours
  - degree of adiabaticity - related to size of <a>/ ρ

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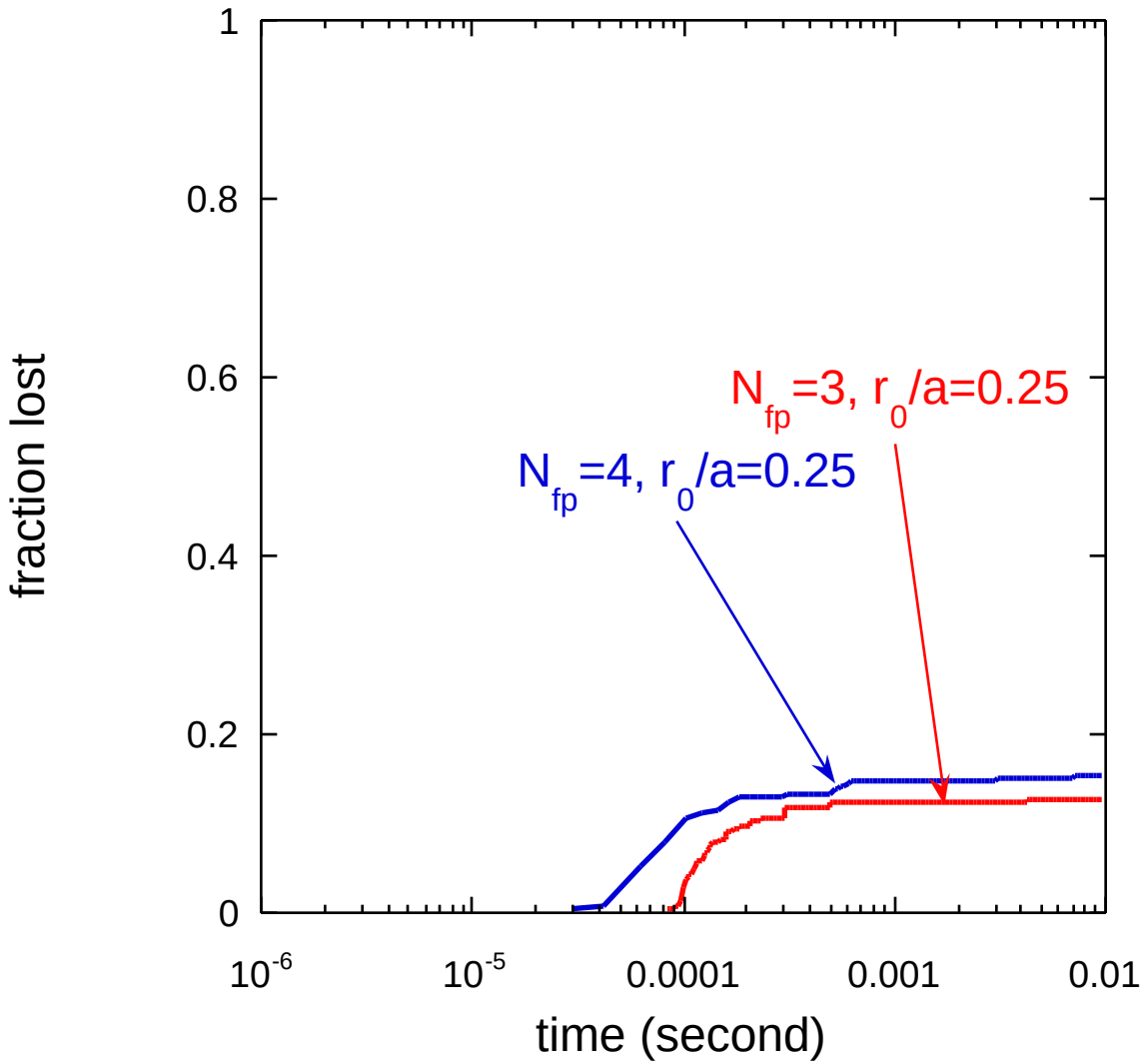
Collisionless α-particle losses are calculated for a reactor-scale version of the N_{fp} = 3 and 4 configurations (i.e., R_0 = 10 m, B_0 = 5 T, results are based on 500 α-particles per surface)



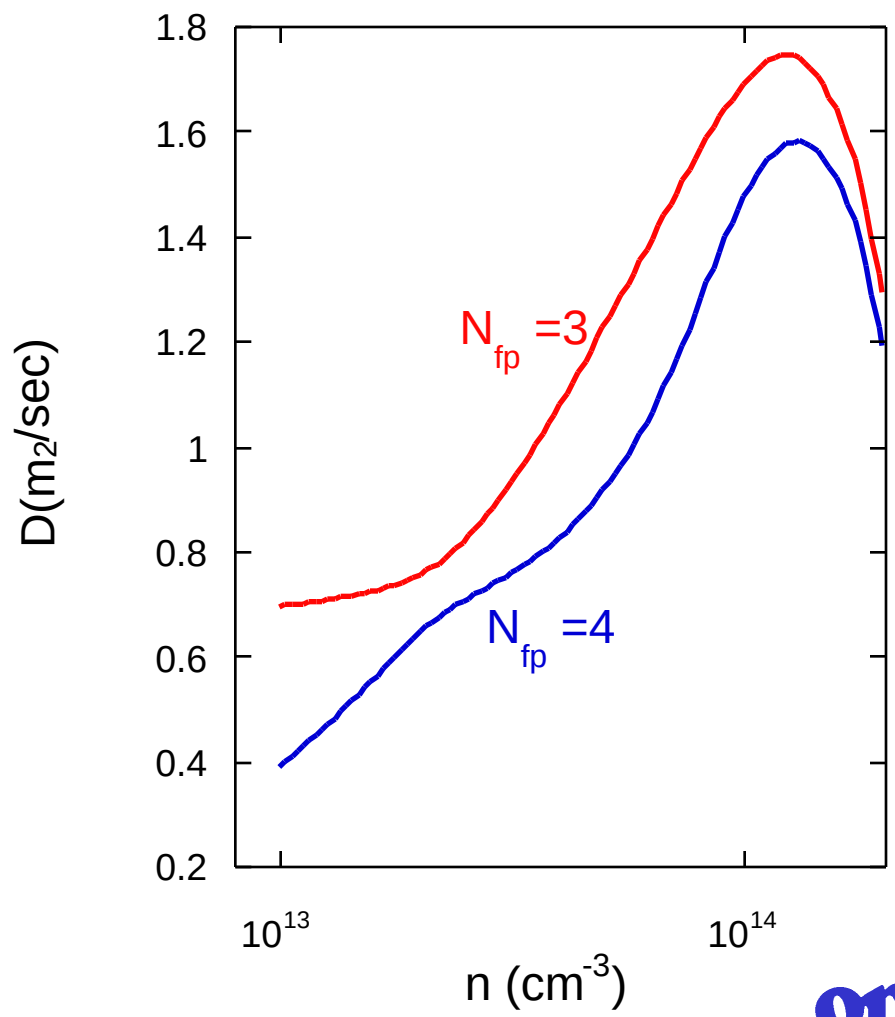
Note:

•These will be extended to $\tau_{SD} \approx 1$ sec with collisional effects

• This design has not yet been fully optimized for a reactor

Collisionality scaling of the diffusivity for $N_{fp} = 3$ and 4 devices shows a decrease with ν for $n < 10^{14}$ cm^{-3}

- $T_{field} = 1$ keV, $E_{test} = 2$ keV, $Z_{eff} = 1$, (monoenergetic, 2000 particles)
- No ambipolar electric field
- $N_{fp} = 3$
  - $0.006 < \nu_{eff}/\omega_b < 0.115$
  - $34 < L^* < 680$
- $N_{fp} = 4$
  - $0.004 < \nu_{eff}/\omega_b < 0.08$
  - $42 < L^* < 835$
- where $L^* = \lambda/L_c$, $L_c = \pi R_0/\iota$, λ = mean free path, $\nu_{eff} = \nu/\varepsilon_H$, ω_b = bounce frequency



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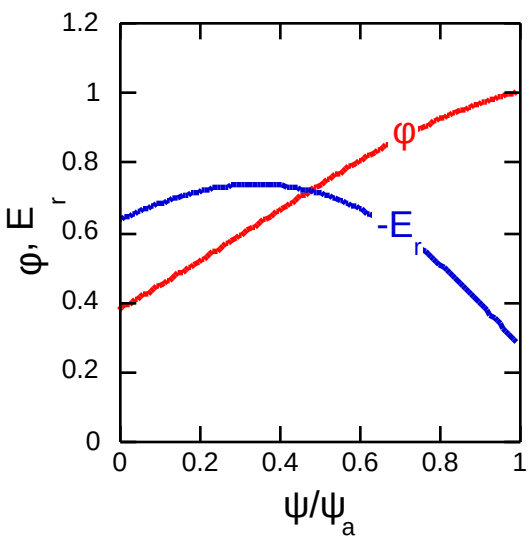
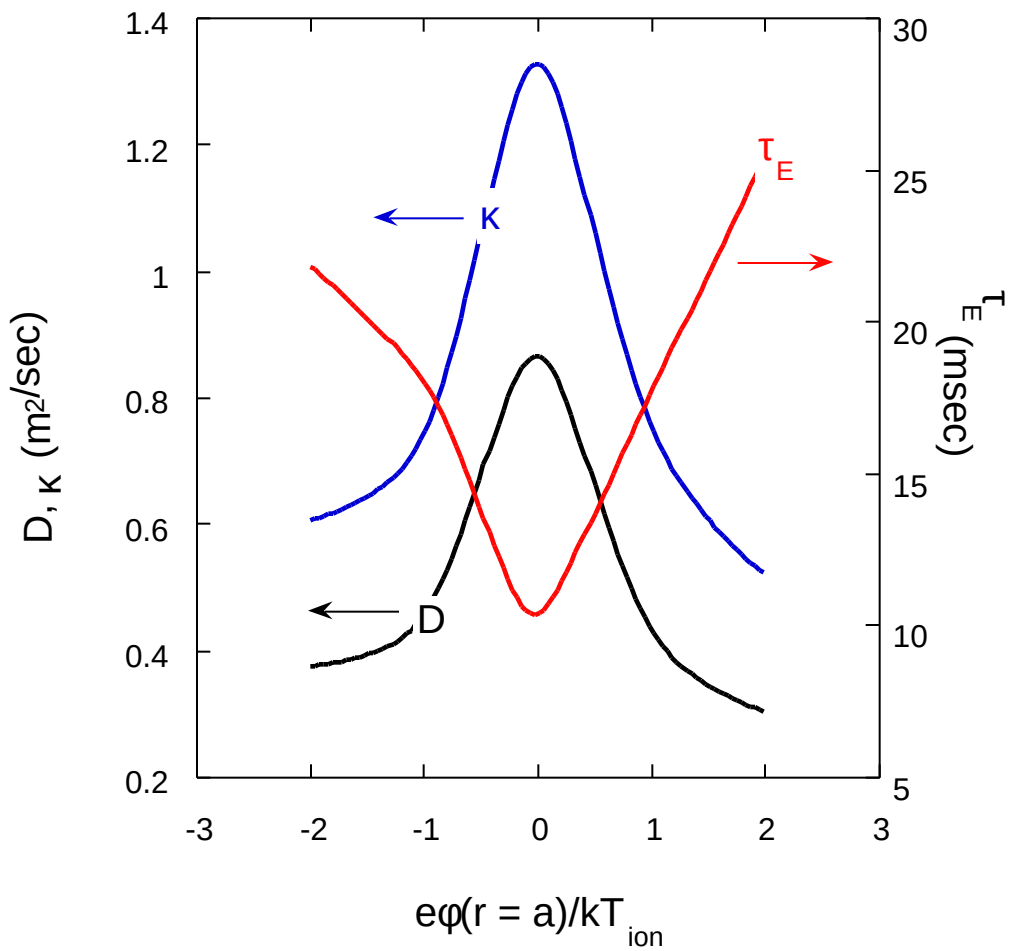
The diffusivities and 0-D energy confinement time show a strong dependence on electric field with $\tau_E \approx (2\text{-}3)\times\tau_{ISS95}$ for typical ambipolar potentials

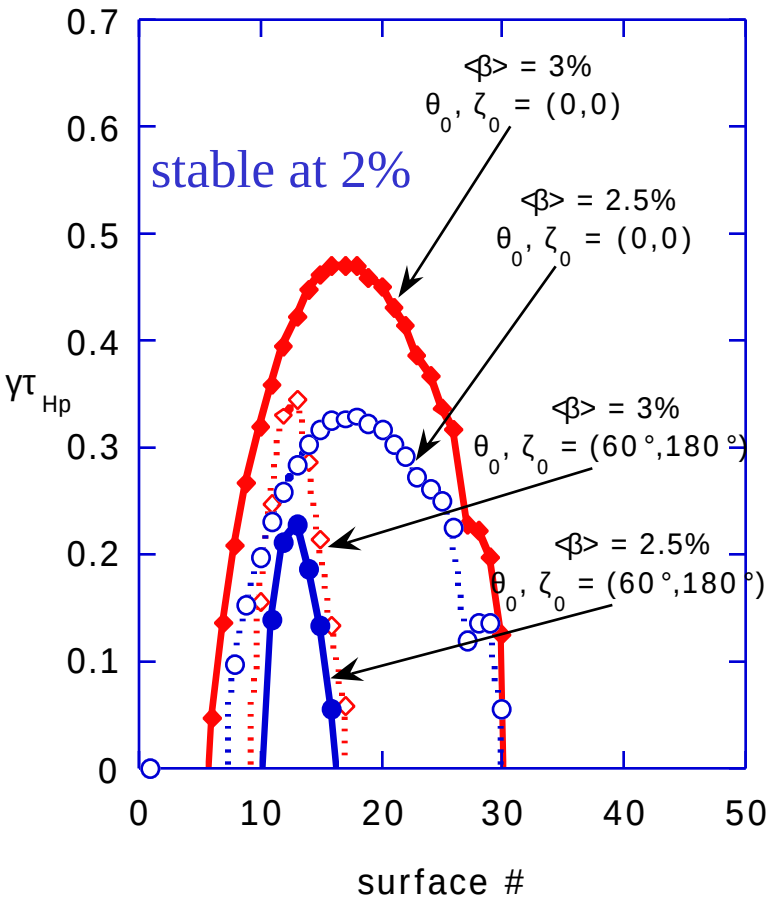
- $N_{fp} = 4$ configuration
- 4 monoenergetic ion Monte Carlo groups used (2000 particles each) to construct diffusiviites for a Maxwellian
- $T_{field} = 1$ keV, $E_{test} = 0.5, 1, 2, 3$ keV, $n = 5\times10^{13}$ cm^{-3}, $Z_{eff} = 1$
- Starting position: $\psi/\psi_a = 0.25$ ($r/a = 0.5$)



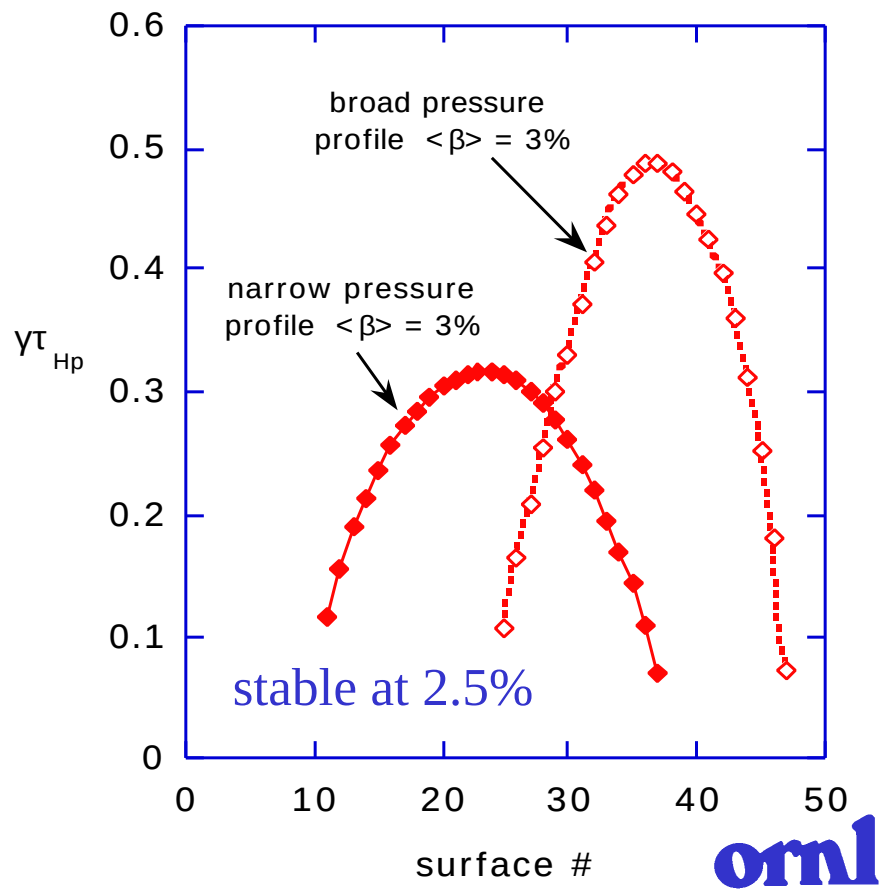


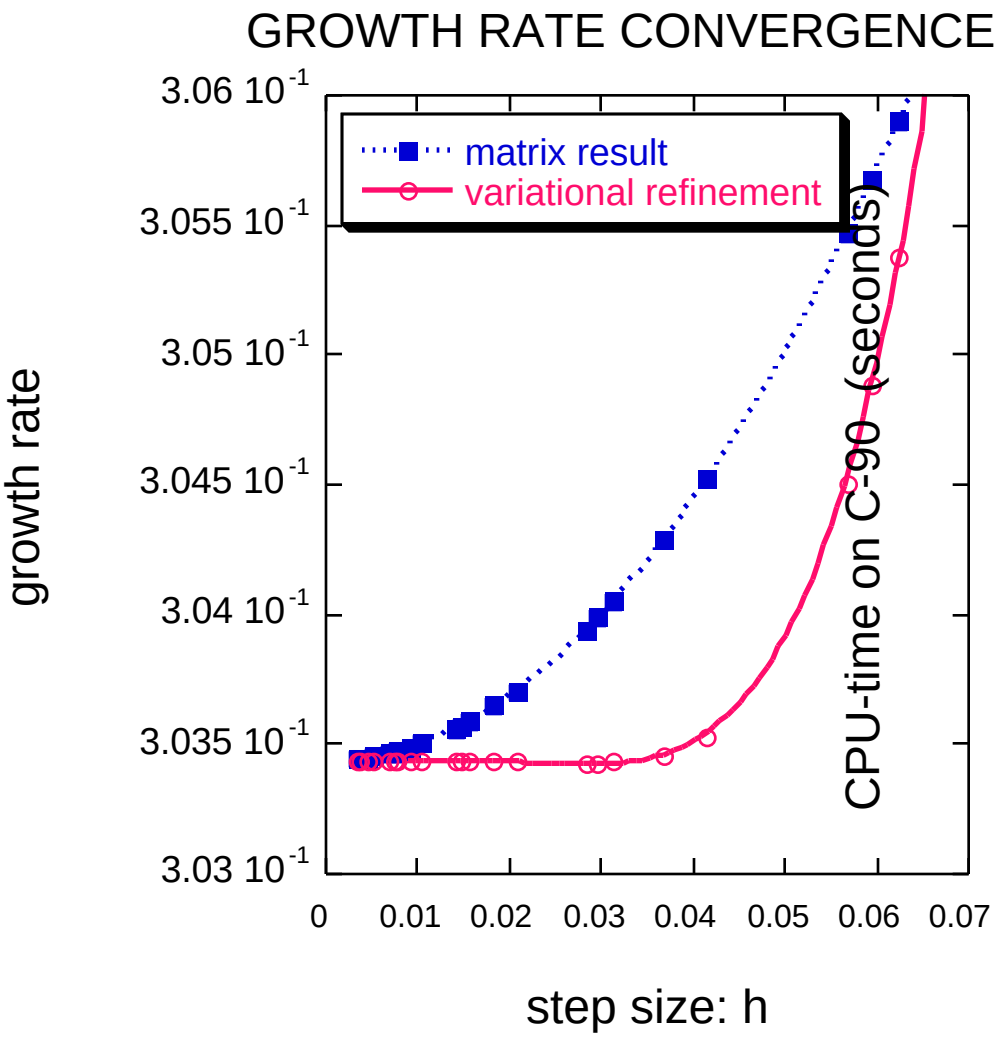
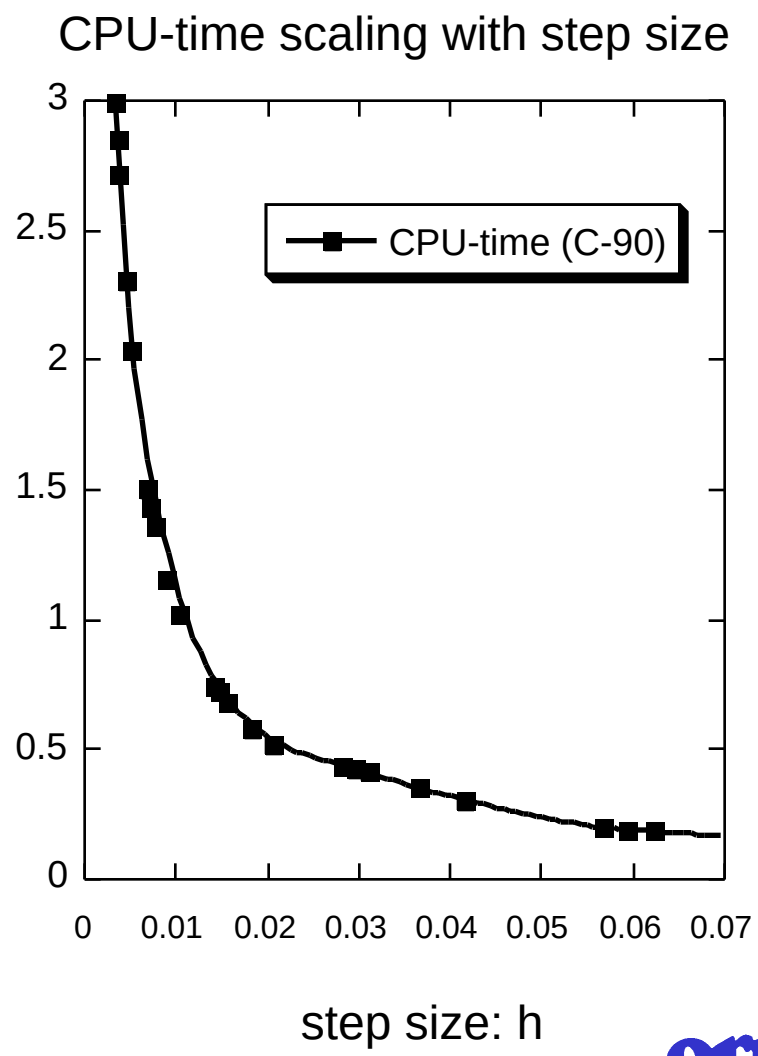
Ballooning growth rates can be a sensitive function of the pressure profile and matching point position along the field line. ***Note added***: In the past week Raul Sanchez has optimized the pressure profile for the 3 period device and gotten the β limit up to 3%

$N_{fp} = 3$



$N_{fp} = 4$



A new method for fast ballooning growth rate calculation has been developed for use in the optimization loop

Combining an initial matrix solution with a variational refinement allows very rapid convergence of the ballooning growth rate (h^4)