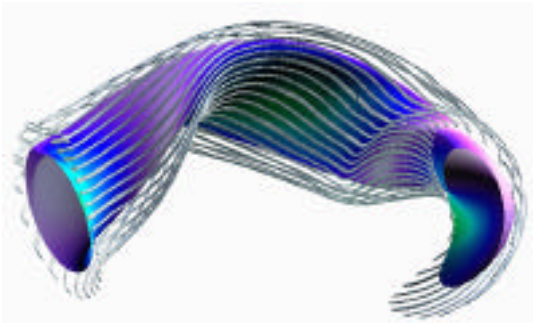
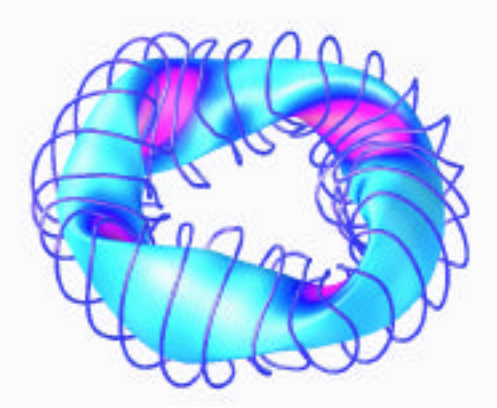
Confinement Studies of Low Aspect Ratio, Omnigenous Stellarators

D. A. Spong, S. P. Hirshman, D. B. Batchelor,
B. A. Carreras, V. E. Lynch, J. F. Lyon

Oak Ridge National Laboratory

1998 International Sherwood Theory Meeting
March 23-25, 1998
Atlanta, Georgia





Substantial progress has been made over recent months in the development of compact quasi-omnigenous (QO) stellarators:

- Optimized configurations extended to 2 - 4 field periods
  - good physics characteristics with lower ripple
  - stellarator-like iota profile ($d\iota/dr > 0$)
- Attractive modular coilsets developed
  - Adequate coil/plasma spacing for extrapolation to a compact reactor
  - Good flux surface reconstruction
  - Physics optimization properties preserved
- Transport physics
  - Favorable results for reactor extrapolation
- Improved ballooning stability through profile control

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A new set of stellarator optimization tools has identified attractive low aspect ratio hybrid configurations.

- Greater configurational flexibility
  - Uses second adiabatic invariant rather than symmetries in |B|
  - Targets desirable properties directly (well, iota profile, ...)
  - Varies both plasma current and shape of outer surface
  - Modular coils are generated from which flux surfaces can be reconstructed
- Attractive low aspect ratio ($R_0/a \approx 3$) devices
  - good confinement
  - confines energetic particles
    - can be scaled to confine 3.5 MeV alphas
  - good ballooning stability $\langle\beta\rangle = 6\%$
  - low plasma current

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Quasi-Omnigenous (QO) configurations have evolved to occupy a unique niche among advanced stellarators:

- Lower aspect ratio than possible with quasi-helical symmetry (HSX)
- Lower levels of bootstrap current (more transform provided by coils) than quasi-toroidal symmetry (QAS)
- More compact than W7-X style optimization

Attractive physics properties of QO configurations:

- Transport
  - Avoids $1/\nu$ regimes
  - Confines 3.5 Mev alpha particles
- Low bootstrap current/large fraction of built-in transform
  - small risk of disruptions
  - weakly coupled feedback

confinement → pressure profile → bootstrap current

- Good alignment between required and actual bootstrap profile
- High ballooning stable β (6 - 9%)
- Realizable coils - can be extrapolated to a compact reactor

Magnetic symmetry is sufficient, but not necessary for good confinement.

- Symmetries in $|B|$ ⟶ constant of the motion
- Quasi-symmetry ⟶ single dominant helicity
- J^* (omnigeneity) ⟶ longitudinal adiabatic invariant

Omnigeneity: $\langle \vec{v}_D \cdot \vec{\nabla}\psi \rangle \quad \partial J^* / \partial\theta \quad \oint \kappa \times \hat{n} \cdot \vec{\nabla}\psi$

quasi-omnigeneity ⟶ approximate $J^*(\psi)$

no single dominant helicity

Allowing multiple helicities provides flexibility for:

- reduction of finite β bootstrap current

Our optimization procedure accounts for physics issues specific to low aspect ratio stellarator hybrids:

- Flexible framework - can easily add new targets

$$\chi^2 = \frac{1}{\sigma \langle J^{*2} \rangle} \left\langle \left(\frac{\partial J^*}{\partial \theta} \right)^2 \right\rangle + \ldots$$

- Geometry of outer flux surface/current profile determines physics properties
  - more general description of boundary than other codes
- We vary the shape of the outer surface rather than coils directly
  - Coils “reverse-engineered” - separate optimization loop
  - Prevents loss of flux surfaces during the optimization
  - Coil reconstruction is non-unique
    - allows satisfaction of engineering constraints

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The optimization loop is driven by the components of χ^2 (flexible, easily extended):

Targets (Physics/Engineering)	**Example**
Bounce-average omnigeneity (drift surfaces and flux surfaces aligned)	$B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$ $J^* = J^*(\psi)$
Current profile	monotone increasing $I(\psi)$
Iota profile	$i(\psi) = 0.3$ $(\rho=0)$ to 0.45 $(\rho=a)$
Magnetic Well	$V'' < 0$ over cross section
Aspect ratio	$R_0/a \approx 3$ to 4
Minimize magnetic ripple	Min $(B_{max} - B_{min})$
Limit maximum plasma current	$I_{max} < 100$ kAmps
Limit outer surface curvature	avoid strong elongation/cusps

Control variables: ≈ 20 Fourier harmonics R_{mn}, Z_{mn} for outer surface + $I_0(\psi)$ - plasma current profile

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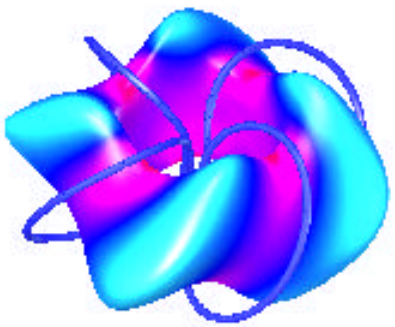
Stellarator optimization loop determines the outer flux surface shape. Coils which produce this shape are then derived:

Initial configuration: equilibrium from simple modular coils



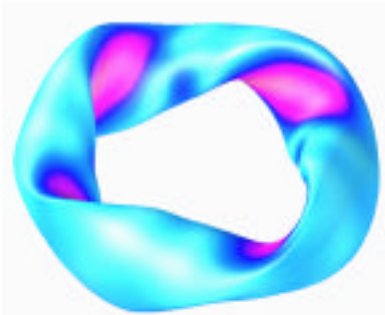
Adjust boundary shape and current density profile

Solve VMEC equilibrium

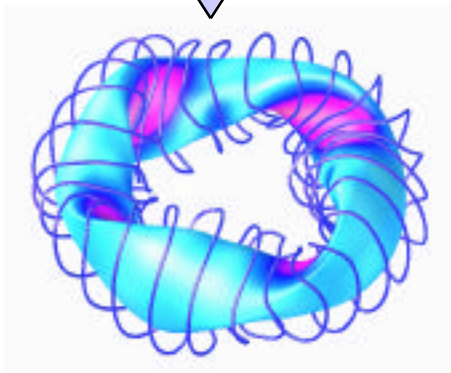
Convert to Boozer coords.

Calculate χ^2

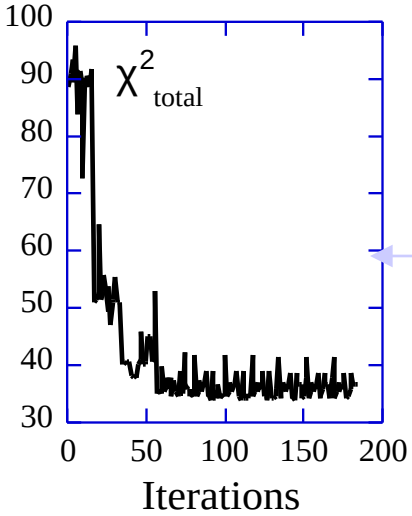
Final optimized configuration:



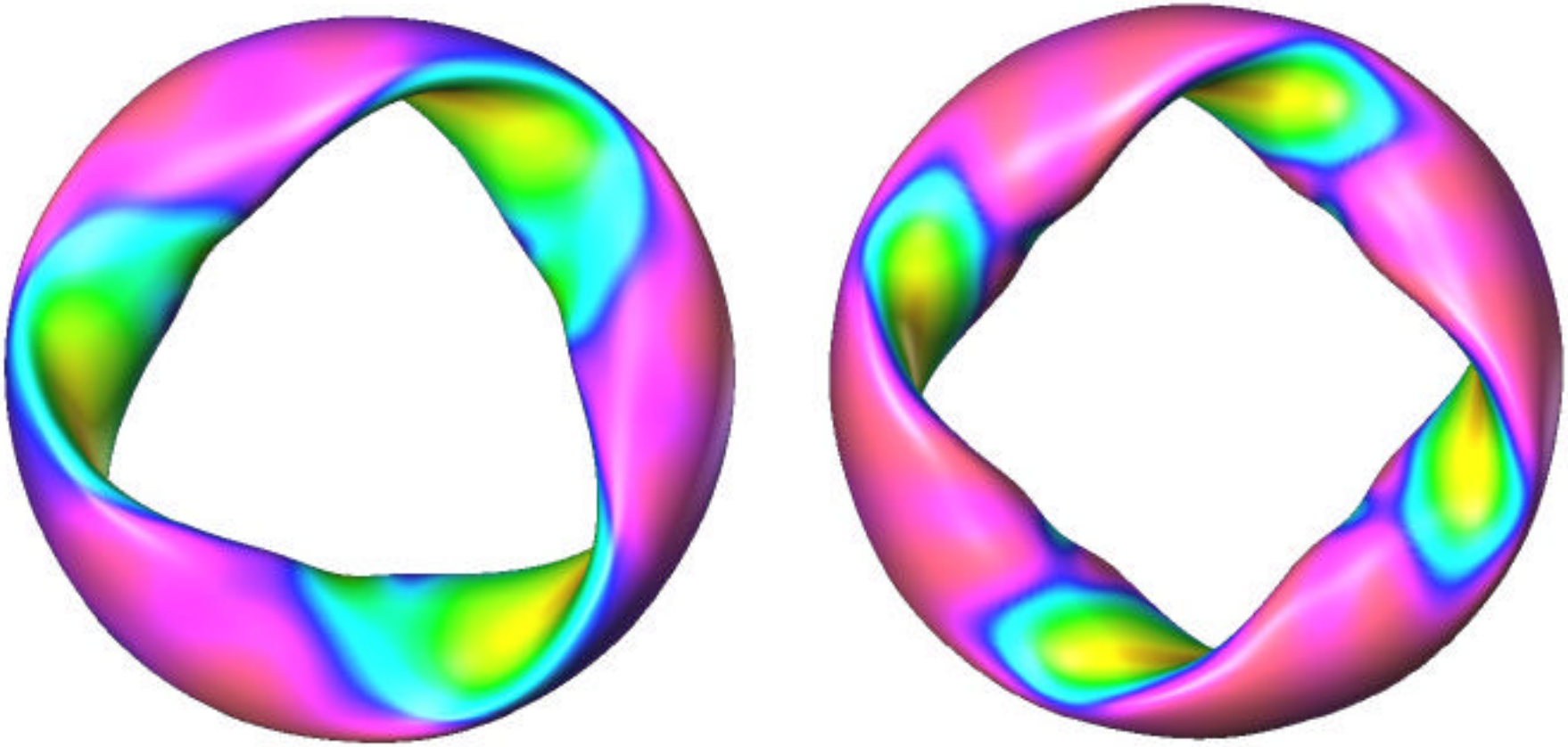
NESCOIL
COILOPT



Levenberg-Marquardt
Minimize χ^2



Top view of 3 and 4 field period physics optimized QO configurations



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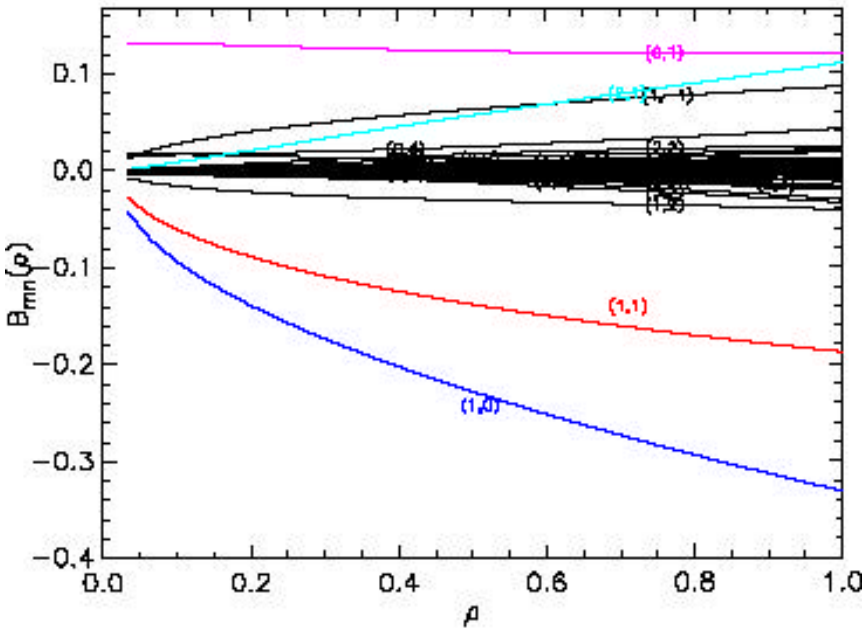
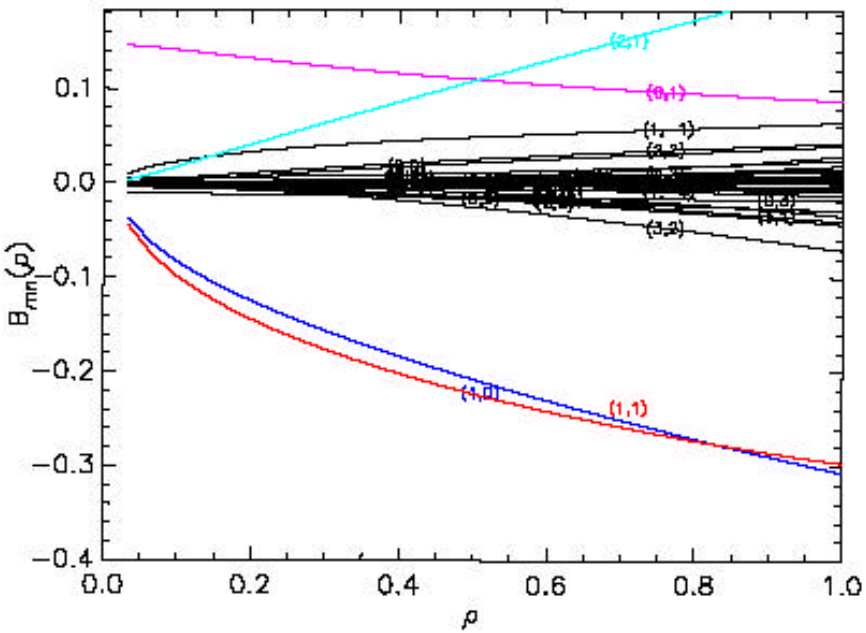
B_{mn} spectra for 3 and 4 field period quasi-omnigenous devices

3 field periods



4 field periods



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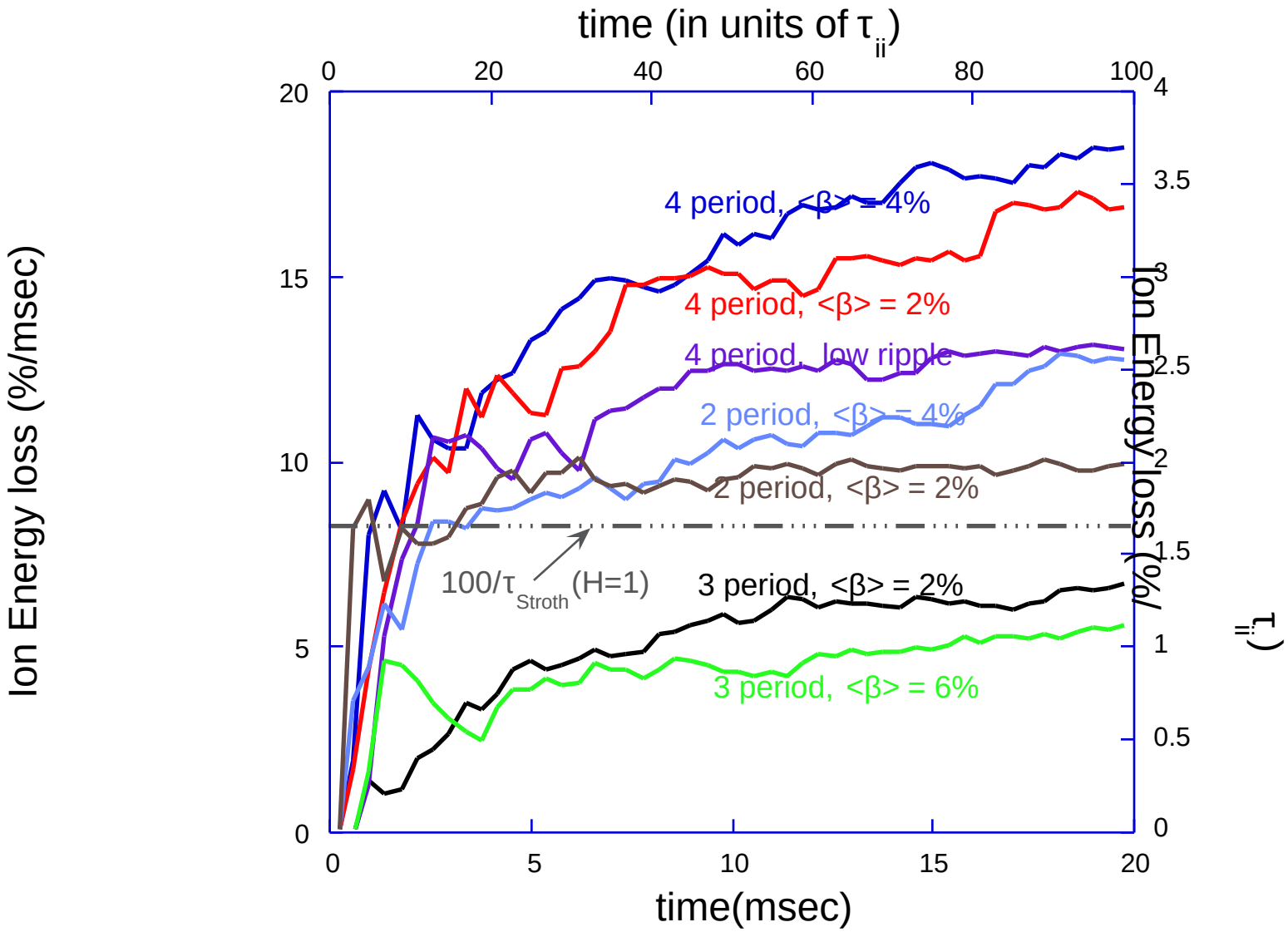
Monte Carlo calculations of ion energy confinement for a scan of modest sized 2-4 period devices

(for $e\varphi/kT = 0$, $T_{ion} = 1$keV, $n = 5\times10^{13}$cm^{-3}, a = 0.34m, $R_0 = 1.25$m, <B> = 2T):



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Neoclassical transport has been checked in a reactor-sized device (R_0 = 8m) with the size chosen to provide 2m of blanket thickness

- Scaled 3 period device: <a> = 2.2m, R_0 = 8m, <B> = 5T allows coil/plasma spacing of 2m
- Point model lifetimes (i.e., $\tau = a^2/D$) are in the range of 600 to 2500 τ_{ii} (Lawson criterion: needs $100\tau_{ii}$)
- All 3.5 MeV alpha orbits examined so far (starting at both r/a = 0 and 0.5) have been confined over the full range of pitch angles ($-1 < v_{||}/v < 1$)

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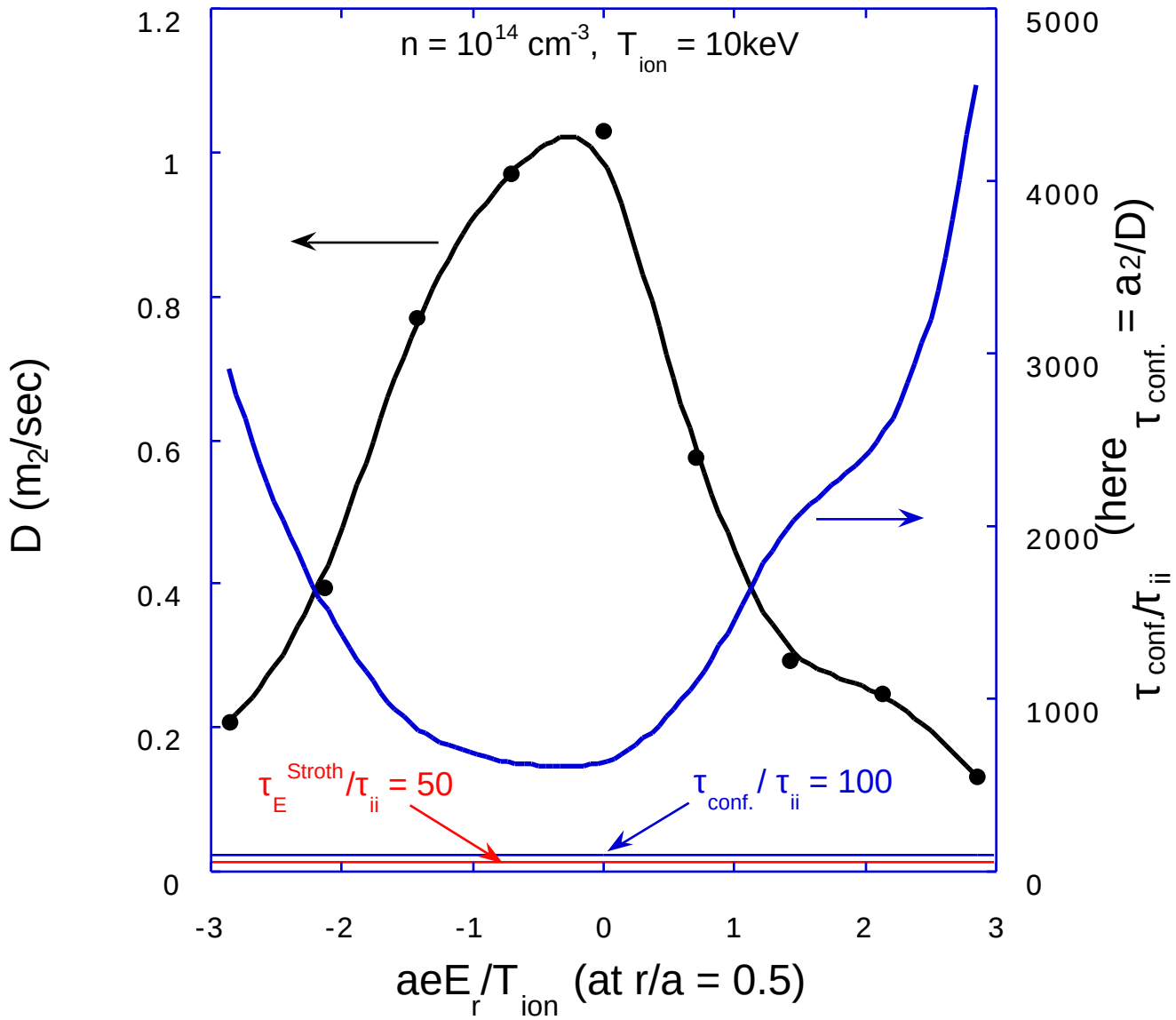
Scaling of 3 field period reactor Monte Carlo diffusion coefficient with electric field:



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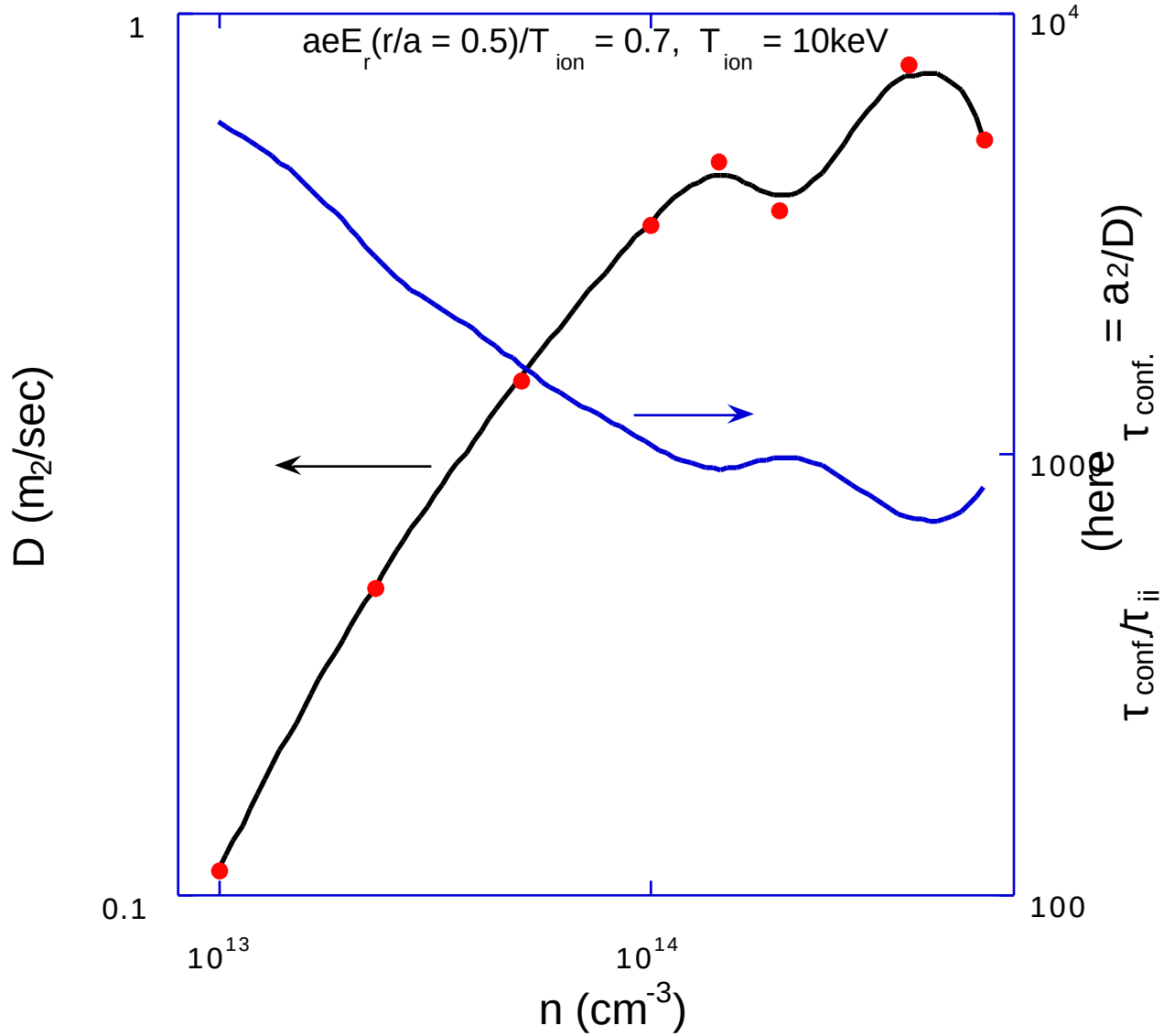
Scaling of 3 field period reactor Monte Carlo diffusion coefficient with density:



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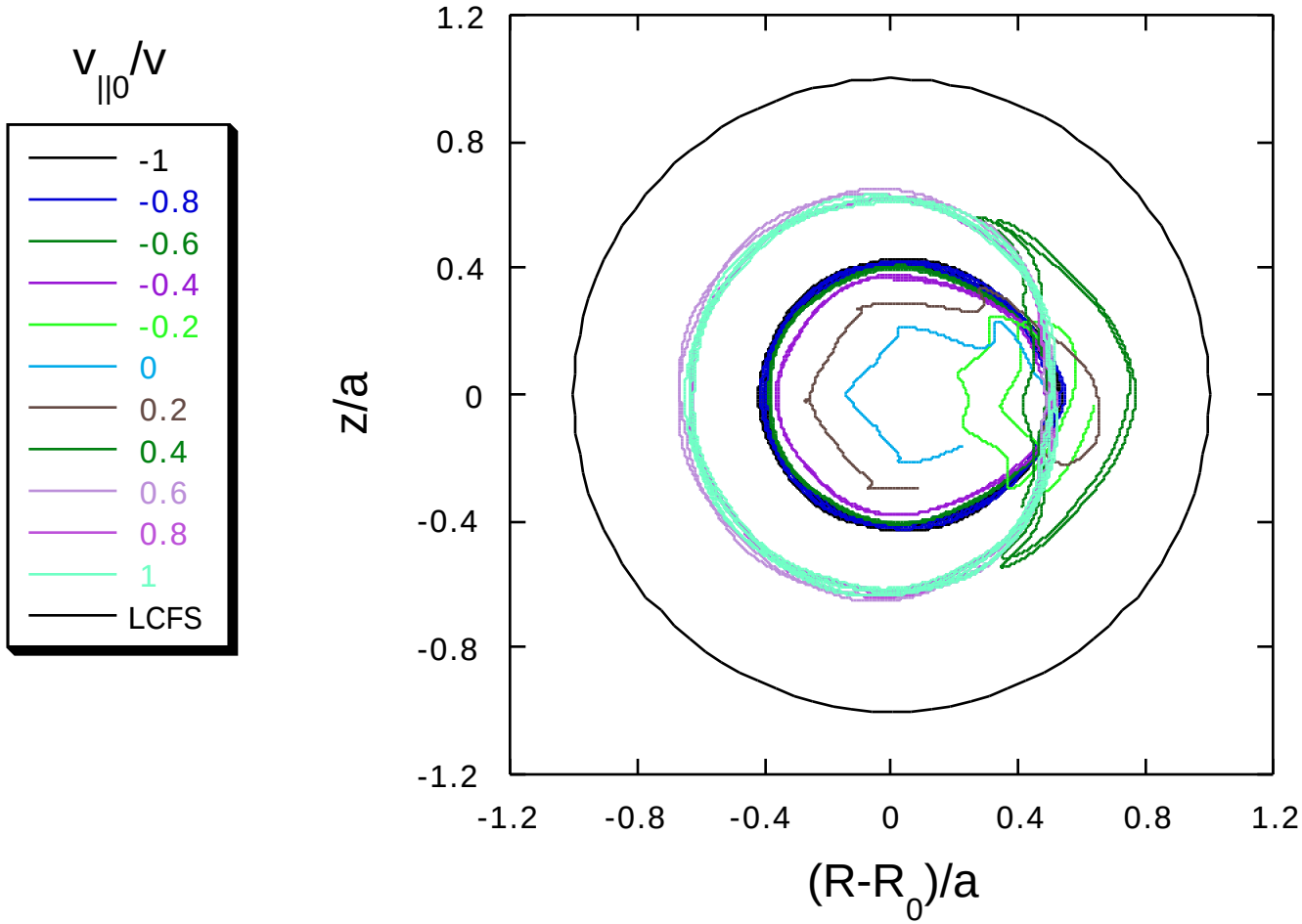
Orbits of 3.5 MeV alpha particles started at r/a = 0.5 are shown (in Boozer coord's.) for a 3 field period QO device which has been scaled to <a> = 2.2m, R_0 = 8m, <B> = 5T:



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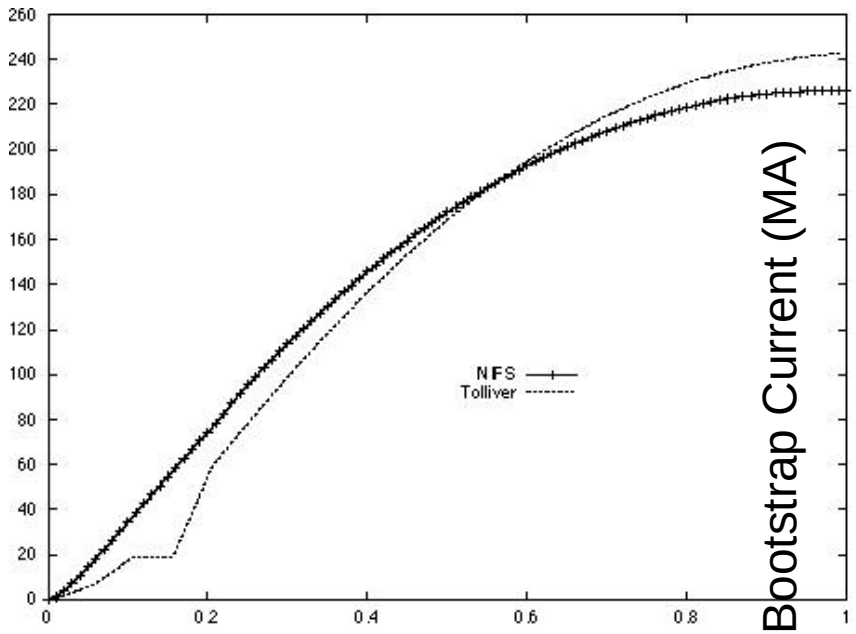
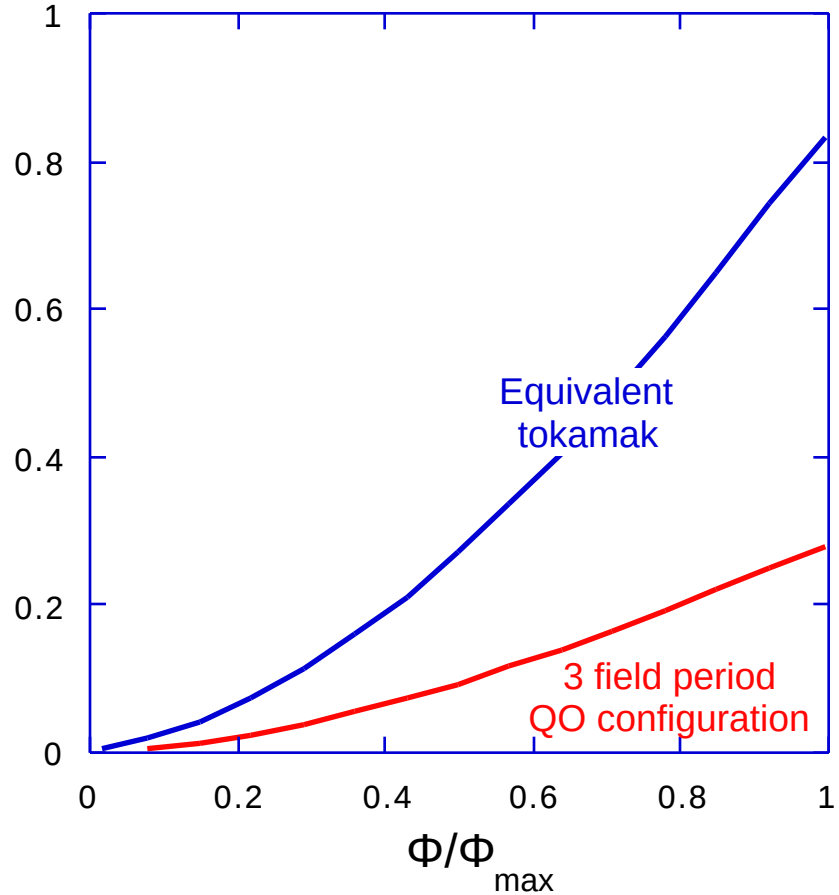
Bootstrap current models which can be coupled with the equilibrium are being adapted for QO configurations

Two different bootstrap current calculations have been benchmarked for QO configurations:



Bootstrap current levels are considerably reduced from those in the equivalent axisymmetric device:



Recent progress has been made in stabilizing ballooning instabilities in low field period QO configurations:

- Profile control is essential
  - toroidal current and iota profiles
- Toroidal current profile effects:
  - Configurations with substantial reversed current regions tend to be ballooning unstable
- Edge shear in iota
  - Effective at stabilizing edge ballooning unstable regions
- N = 3 configurations up to $\langle\beta\rangle$ = 9% now exist
  - only weakly ballooning ustable
  - complete stabilization likely from further profile optimization
- Longer term approach: include ballooning criteria in χ^2
  - vary shaping for stabilization

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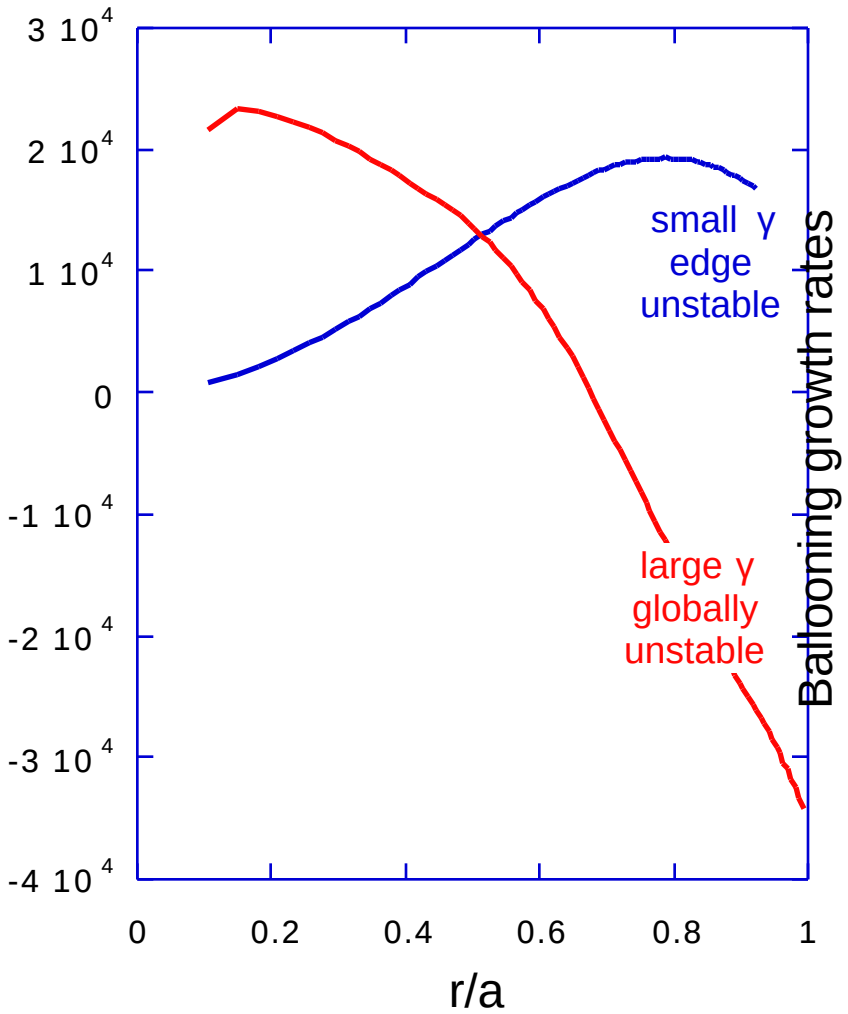
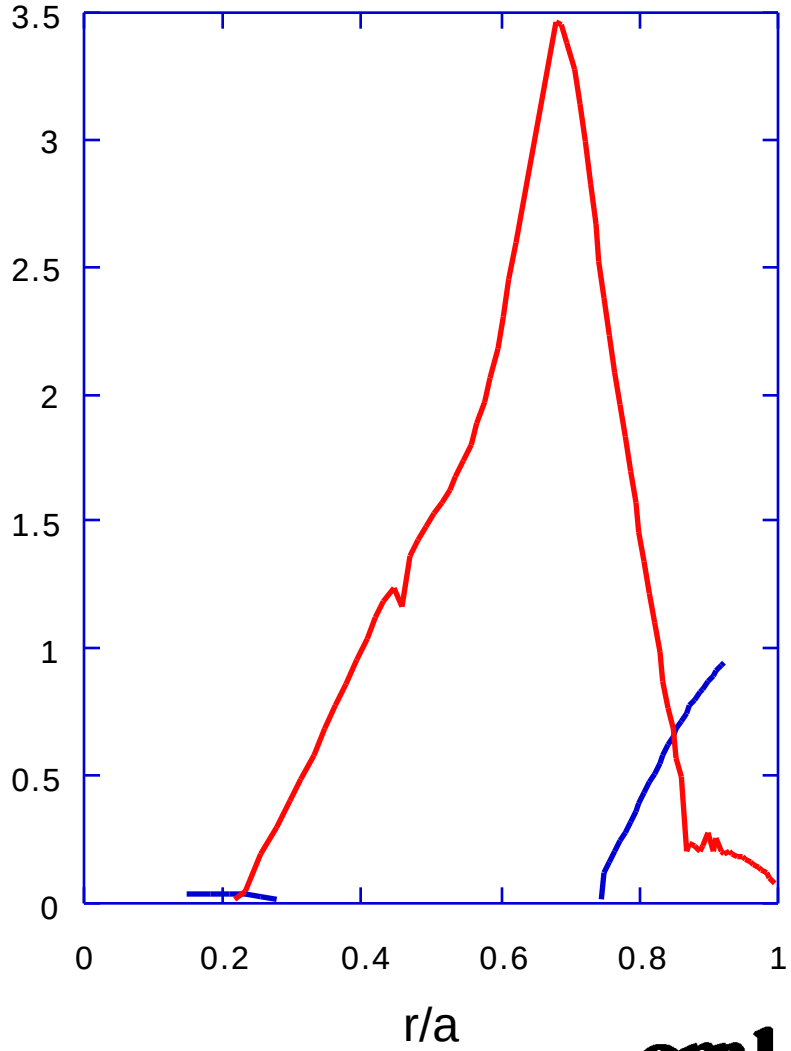
Ballooning stability is sensitive to the toroidal current profile:





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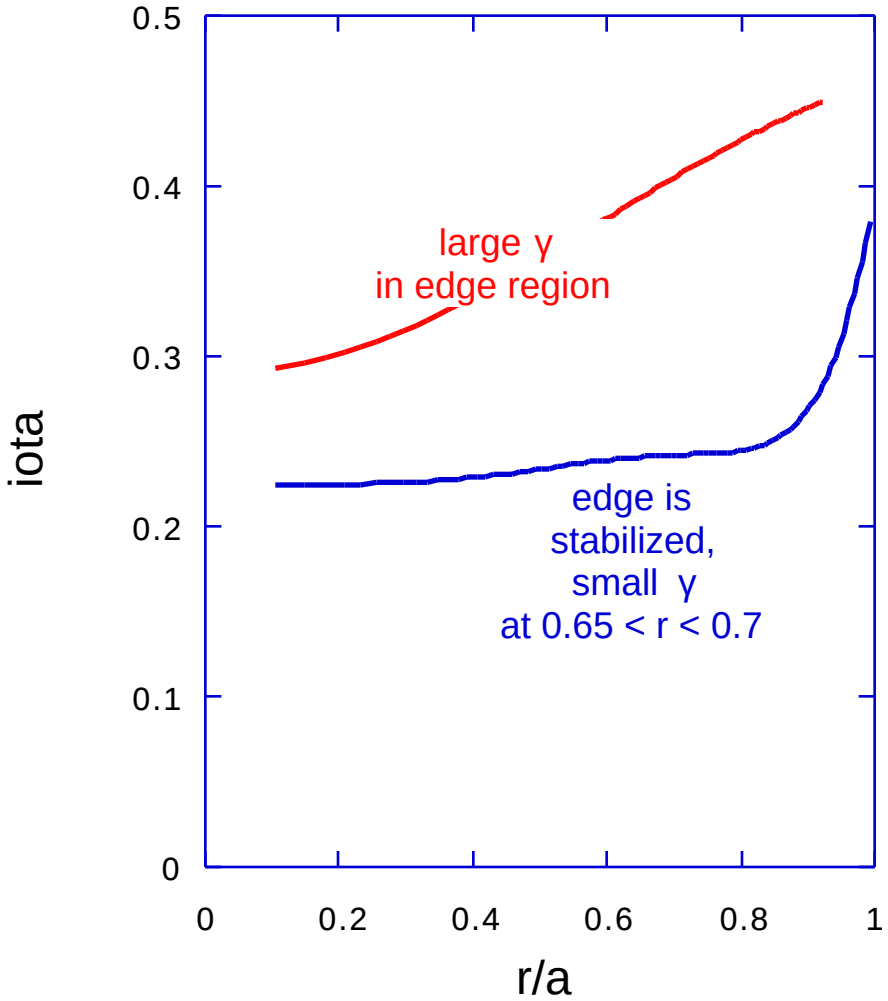
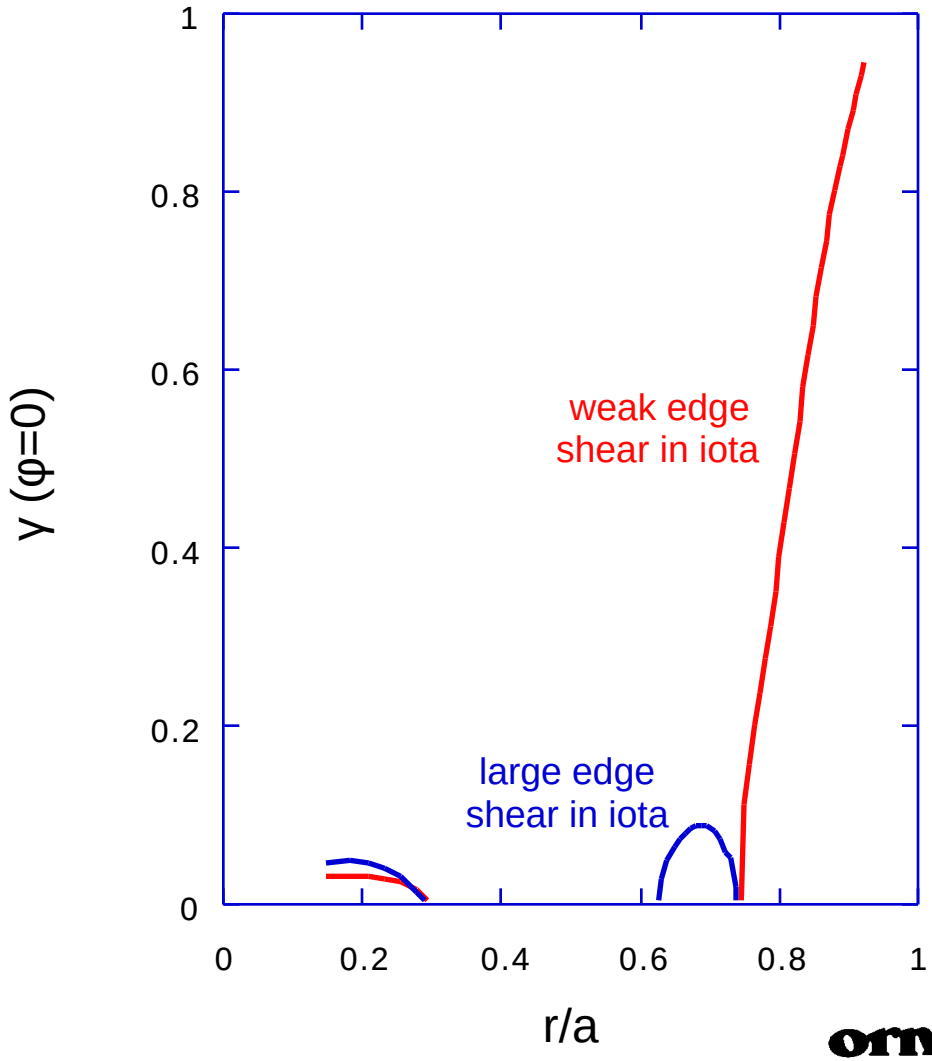
Localized edge shear in iota can remove the edge ballooning unstable region:





Recent Coil Design Results

- Two approaches:

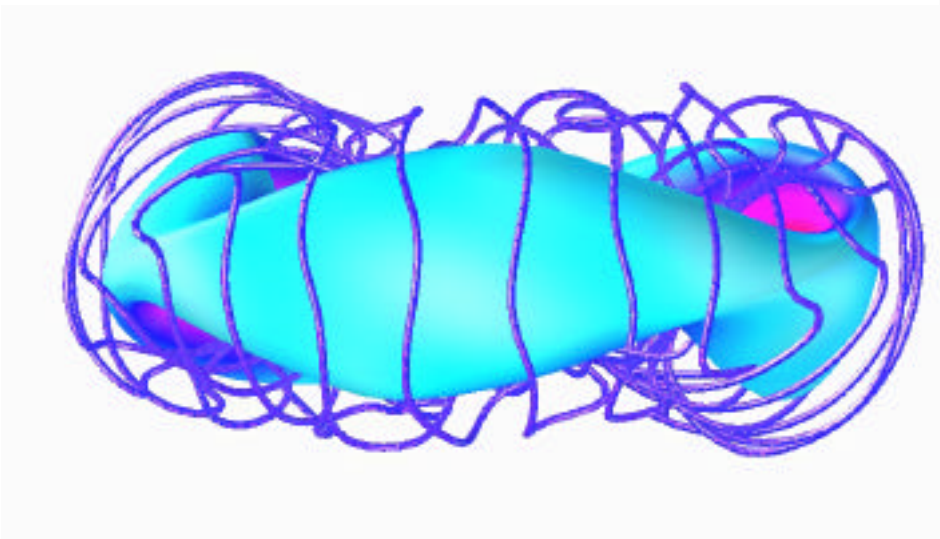
  NESCOIL - synthesizes coils from external currents on a winding surface

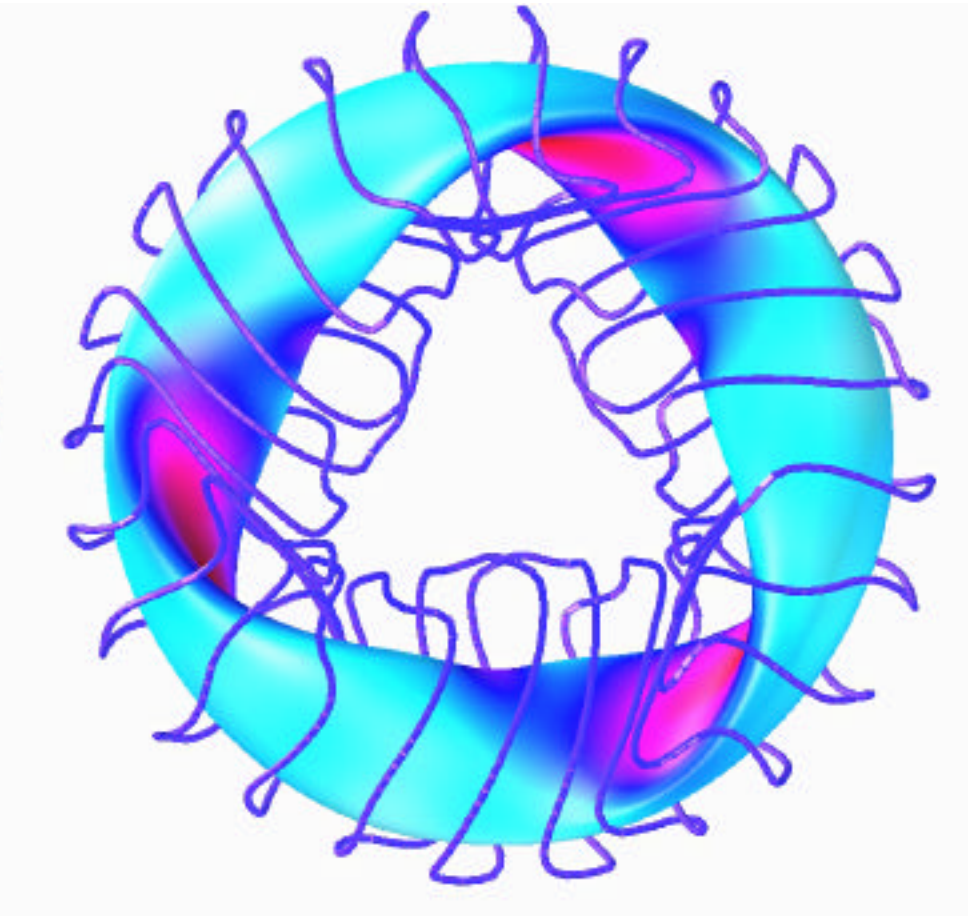
  COILOPT - places coils on a surface, varies surface shape and coil shape within the surface, minimizes coil length, nulls out B_{normal}

- Accomplishments:
  - NESCOIL/COILOPT have given preliminary designs for compact (A ~ 3.5), 3 and 4 field period devices
    - COILOPT: 5, 7 coils per period (odd numbers work best)
    - At A = 3.6, N_{fp} = 3, R = 1.5m find a_{coil} = 0.28m

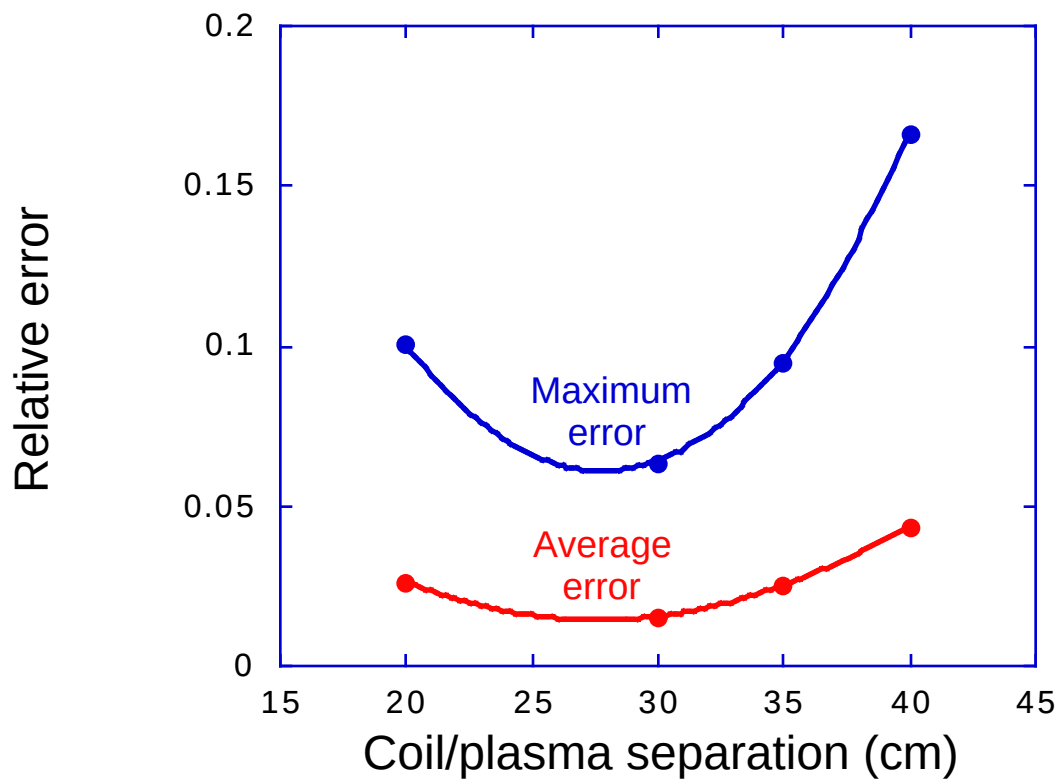
      ⇨ Reactor major radius ~ 9 m
    - 4 period configuration has been scaled to fit within PBX-M vessel

3 field period QO configuration with 8 coils/period (4 different coil types) - coils derived from NESCOIL





For a R_0 = 1.3m 4 field period device, the error from discrete coils has a minimum at a coil/plasma separation of 25 - 30 cm:



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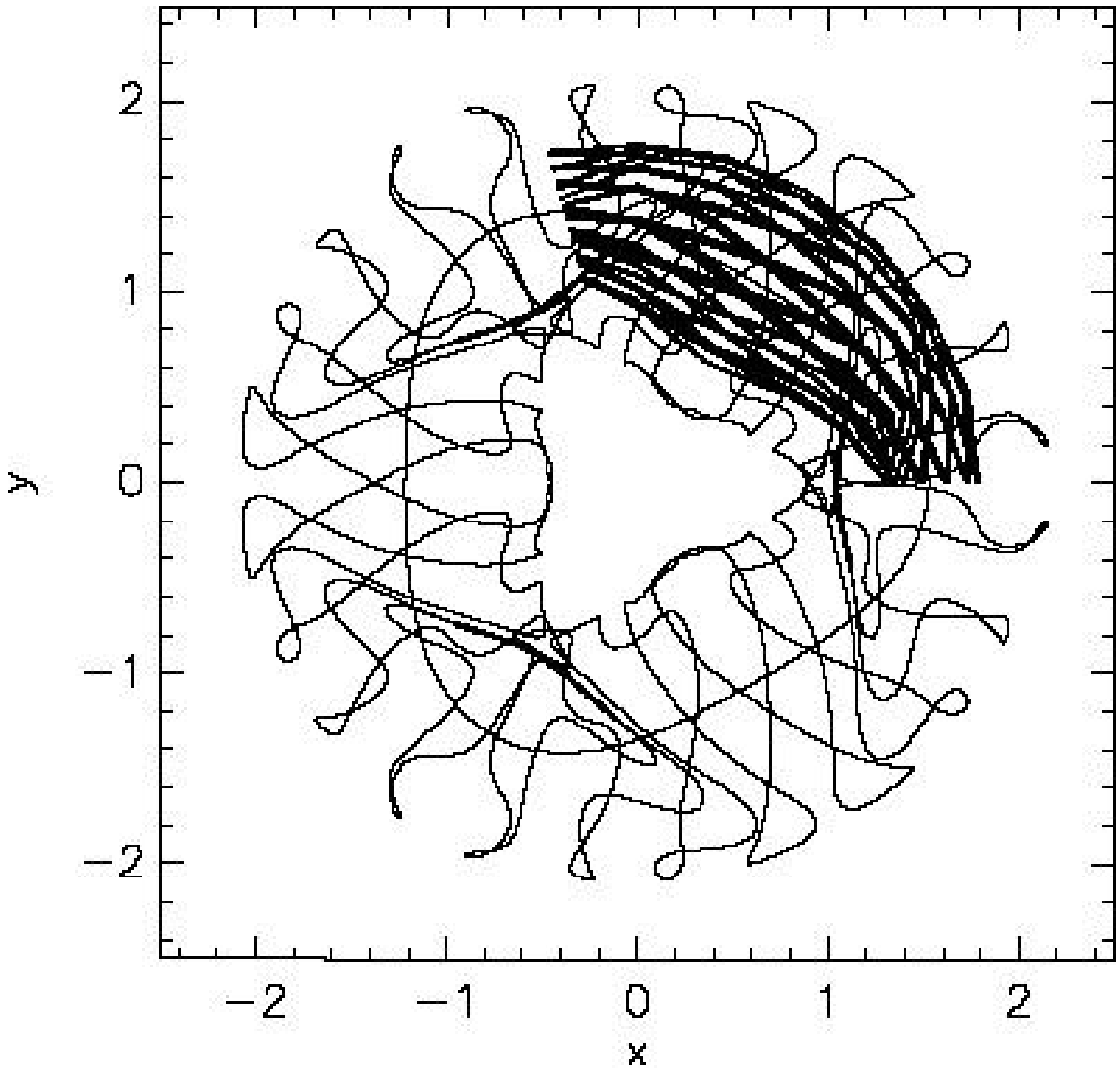
Top view of modular coils, field line trace and magnetic axis:



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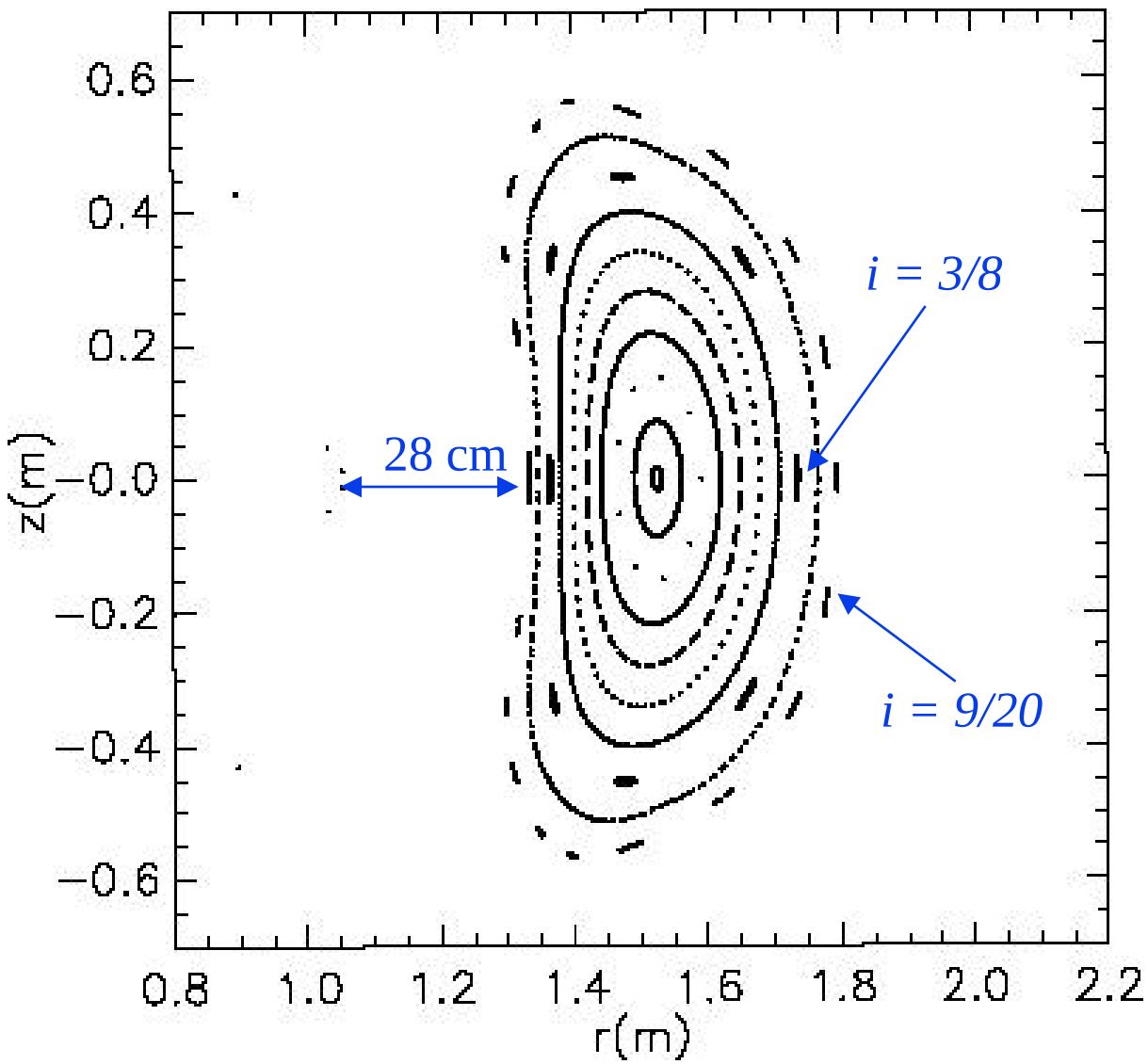
Flux surfaces reconstruction from coils at $\zeta = 0°$



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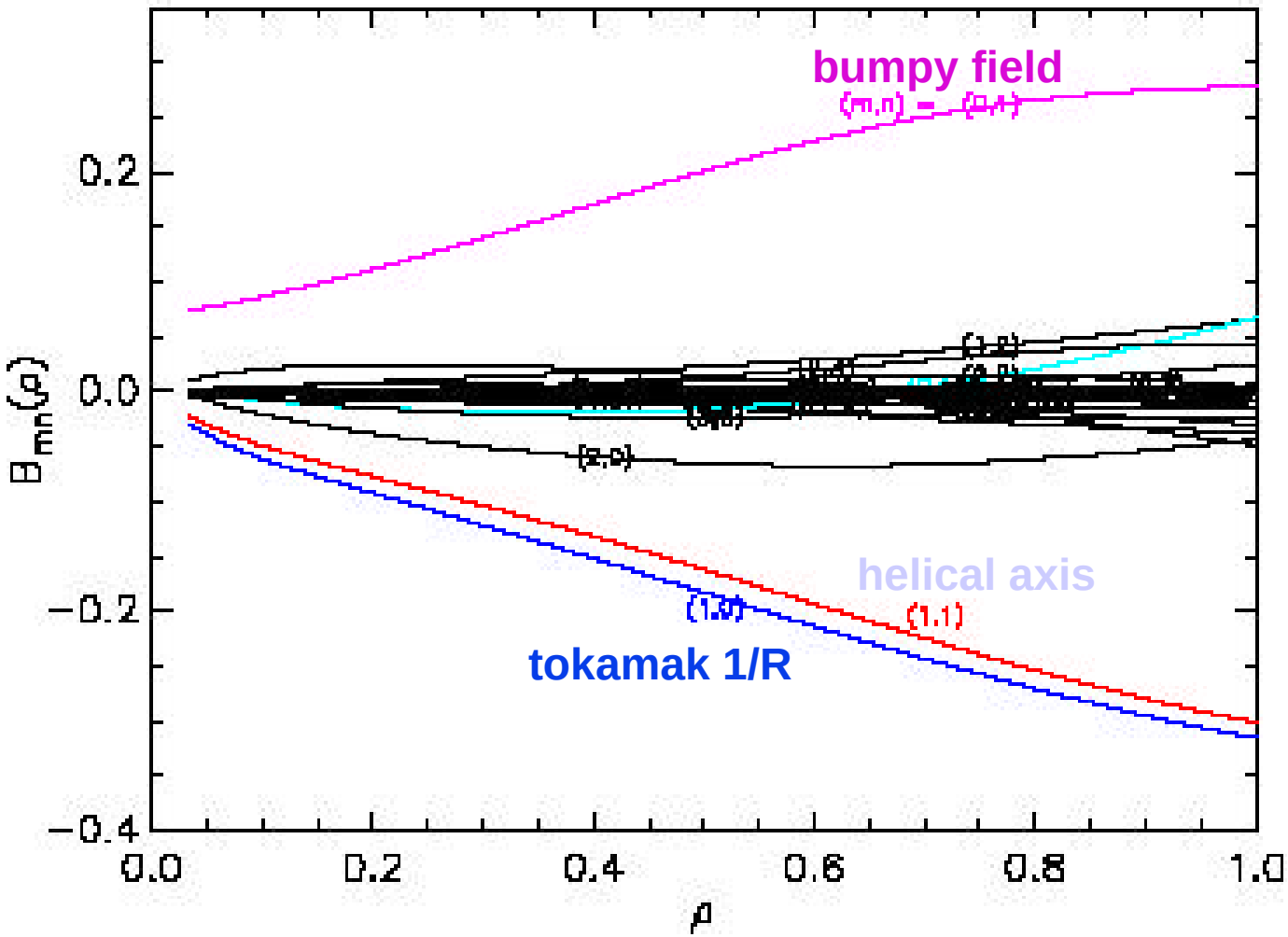
Our 3 field period optimized configuration departs from quasi-symmetry:

- different ratios of m/n present
- n > 0 components present



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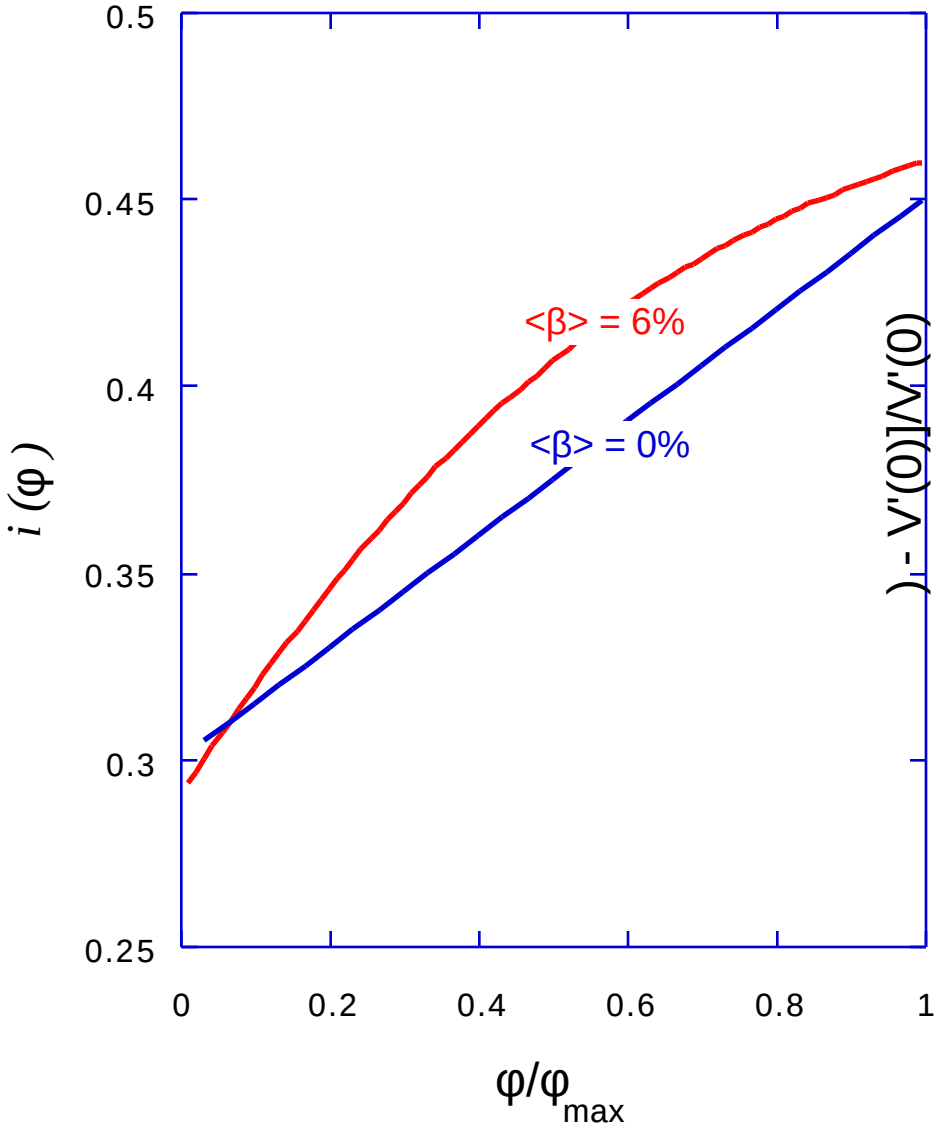
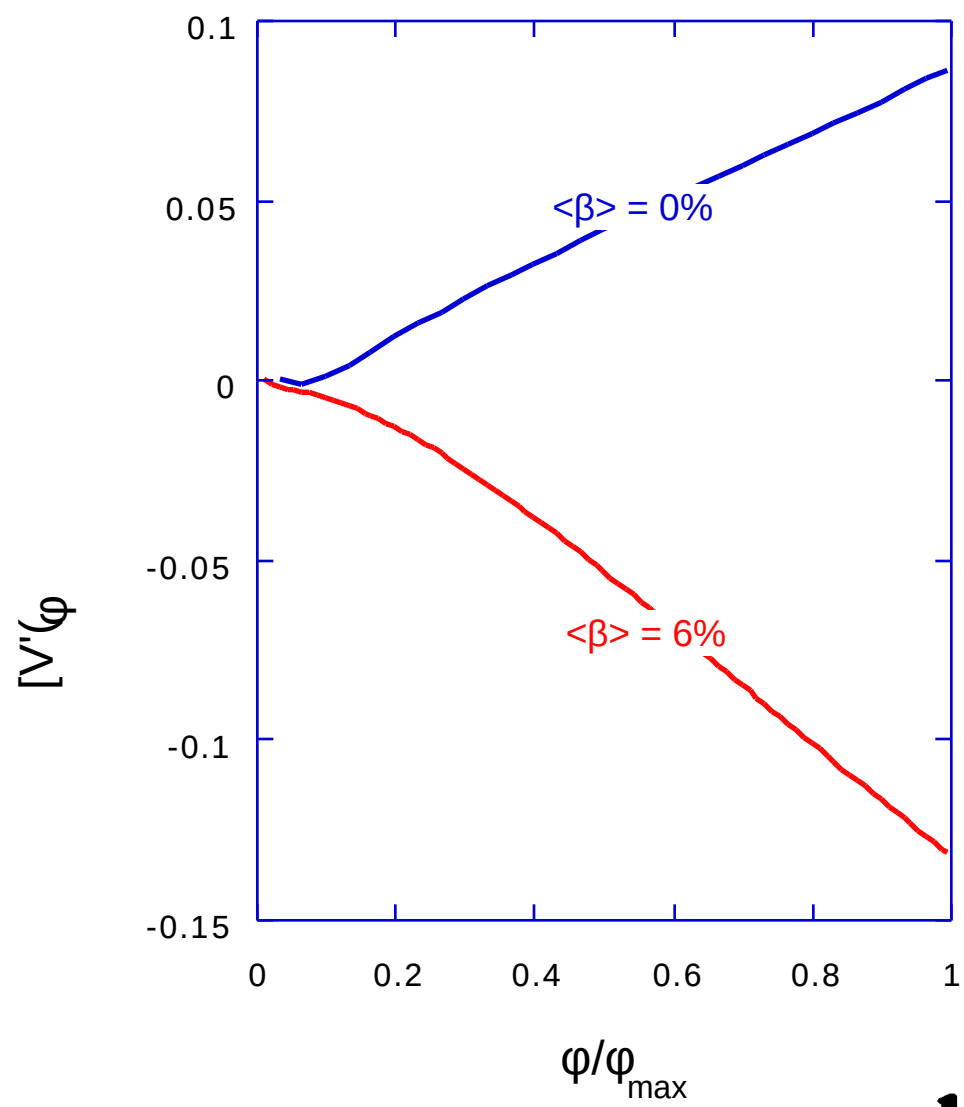
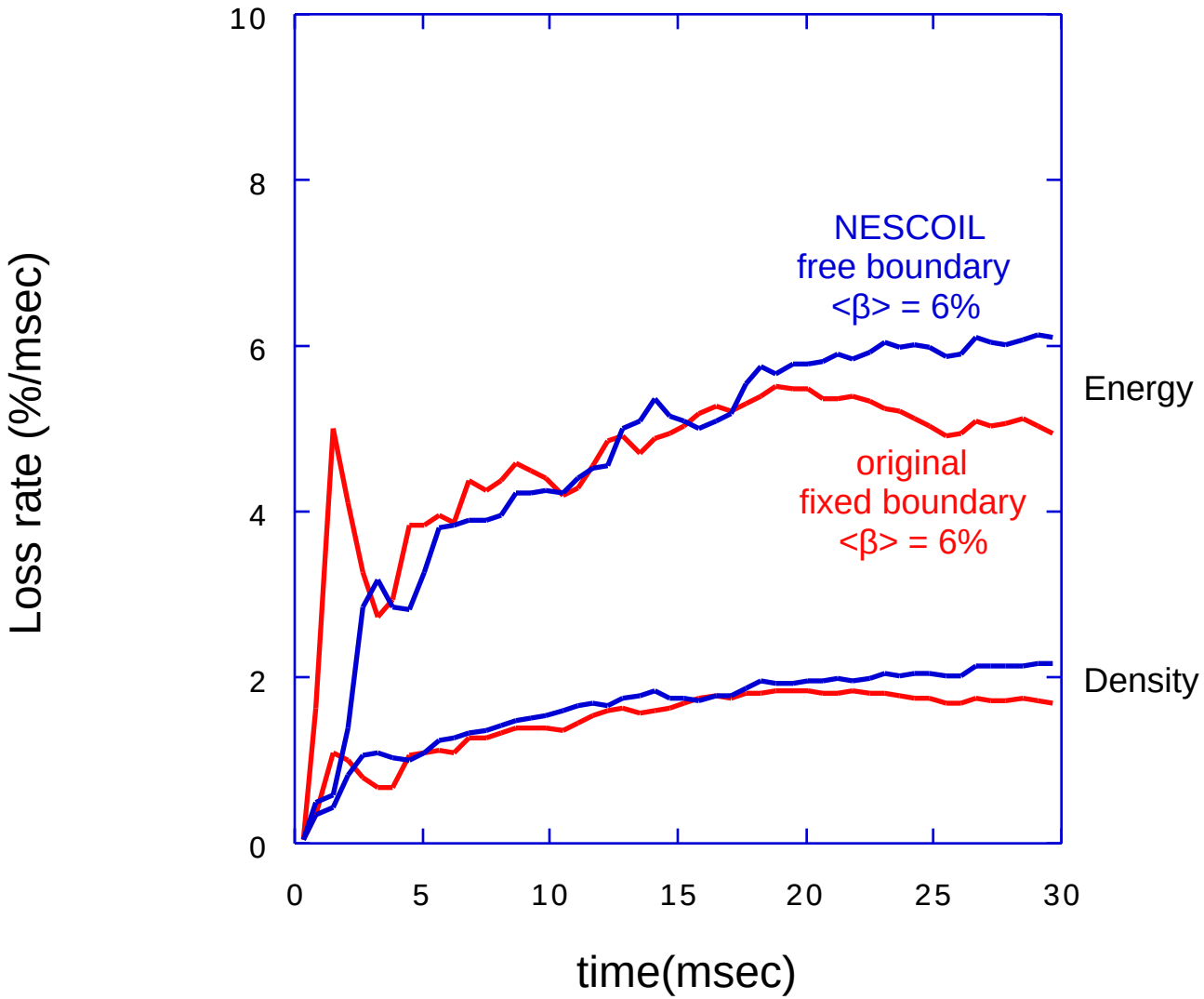
Transform and well for m = 3 QO configuration

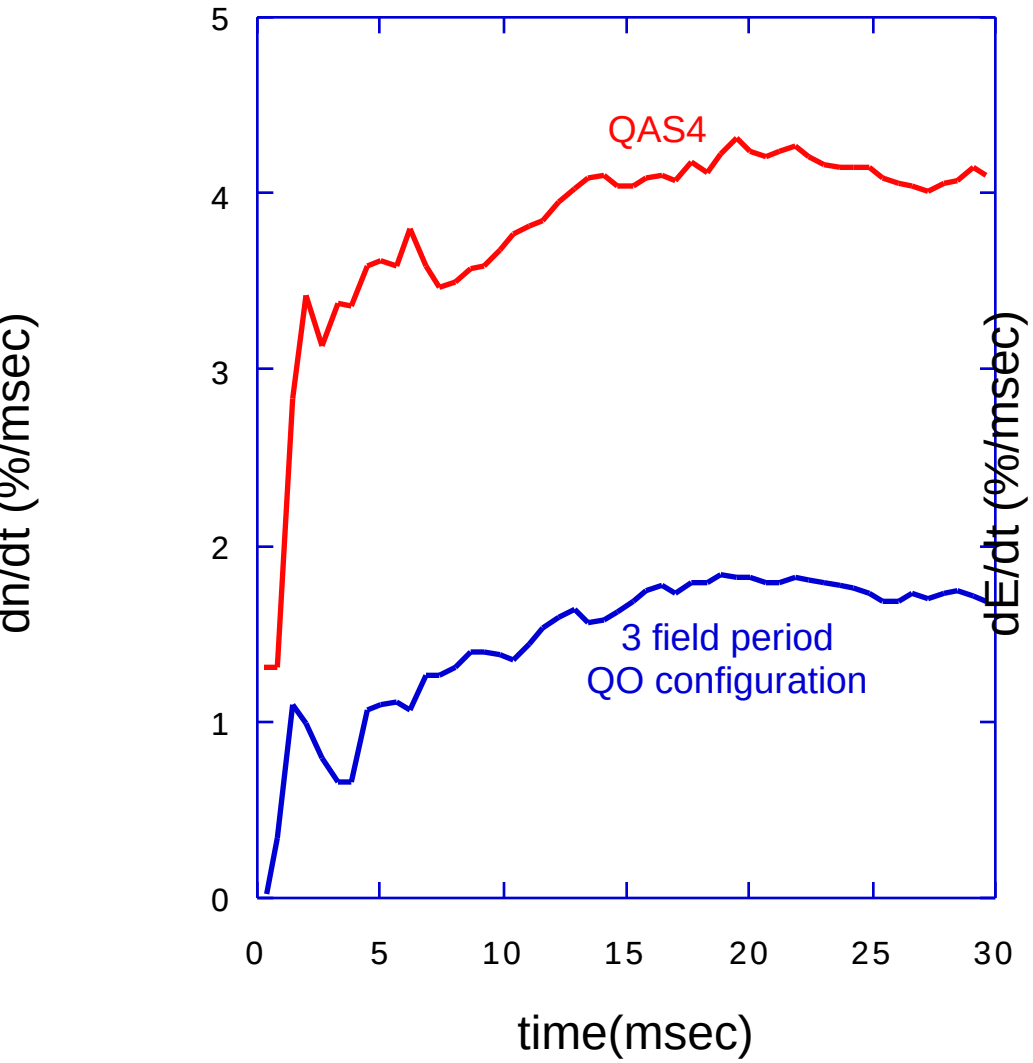


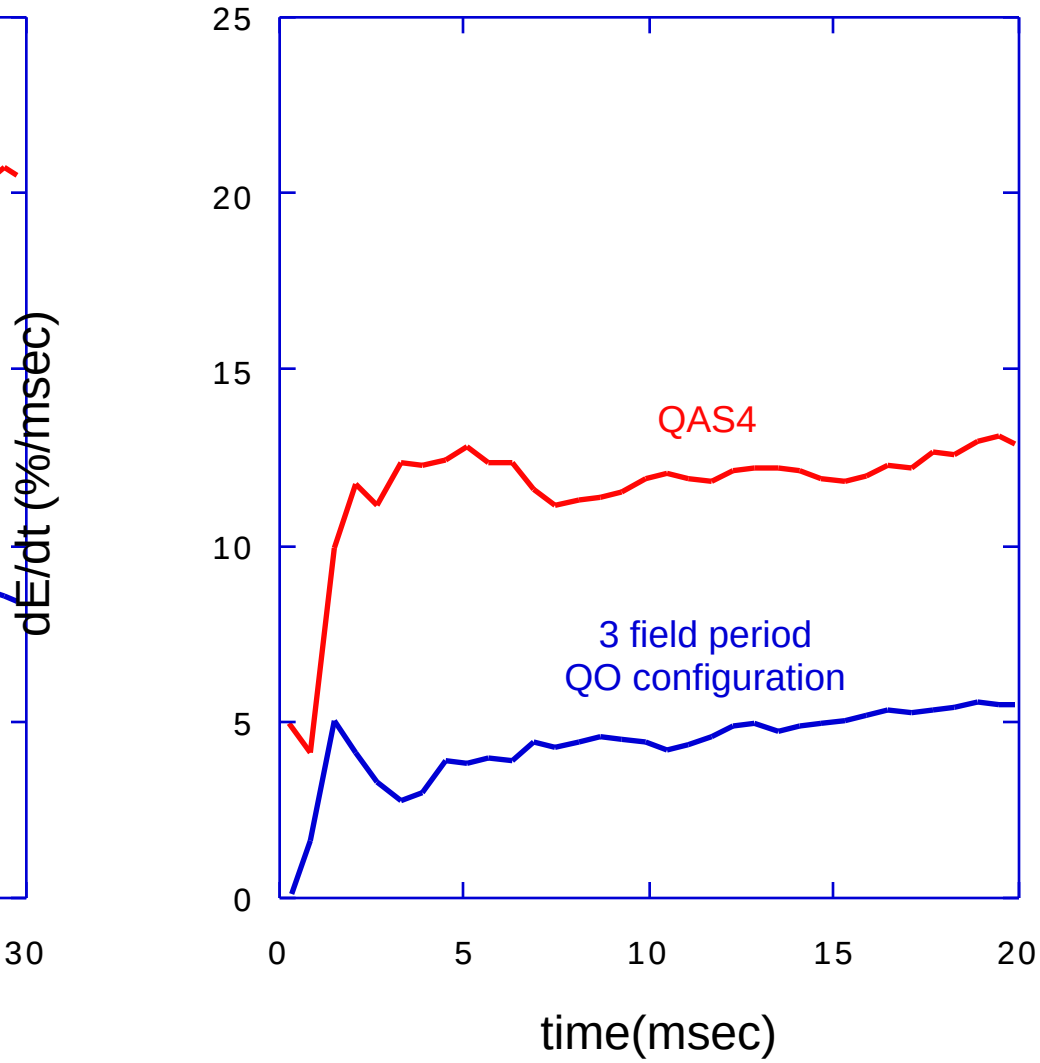


Comparing the original optimized 3 field period device with equilibria reconstructed from the NESCOIL coil set shows confinement optimization has been preserved.



Comparison of transport rates between a scaled QAS4 (A = 2.2, <a> = .36m, R_0 = 0.8m, <B> = 1.9T) and 3 field period QO device (A = 3.5, <a> = .36m, R_0 = 1.26 m, <B> = 1.9T)





- Conclusions -

- A new set of stellarator optimization tools has been developed
  - We target transport reduction (omnigeneity) rather than symmetries in |B|
  - Our optimization procedure is flexible and easily extended
- Leads to attractive low aspect ratio ($R_0/a \approx 3\text{-}4$) hybrid devices over a range of field periods ($N_{fp} = 2$ to 8)
  - Good thermal confinement (can approach that of tokamaks)
  - Alphas can be confined in reactor scaled device

    e.g., $R_0 = 8$m, $\langle a \rangle = 2.2$m, $\langle B \rangle = 5$T
  - Ballooning $\langle \beta \rangle$ limit at least 6%
  - Modular coils accurately reconstruct flux surfaces and allow sufficient coil/plasma spacing for 2m blanket in a compact reactor

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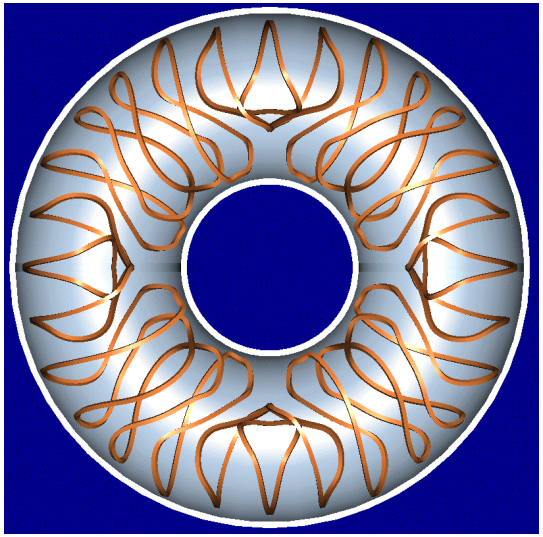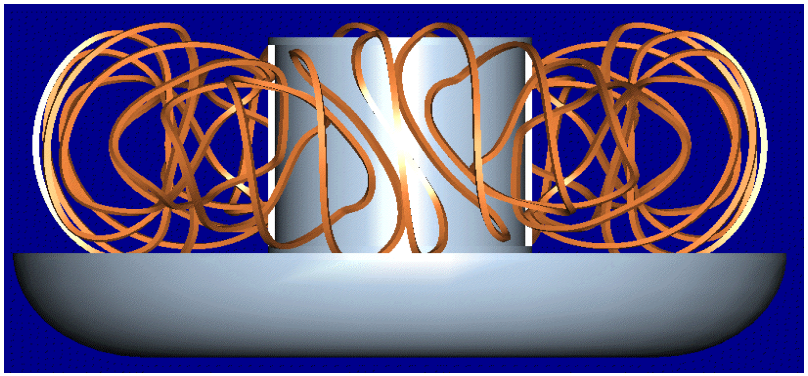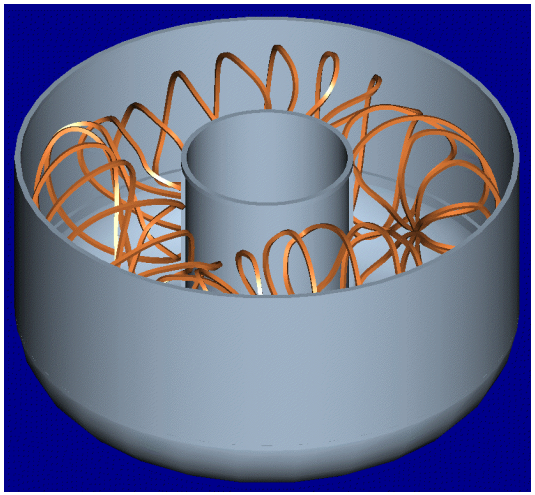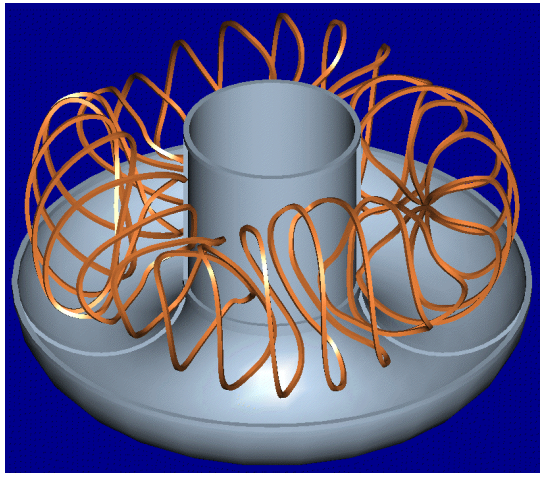
Coils for an optimized 4 field period configuration in the environment of the PBX vacuum vessel: