Quasi-Omnigenous Stellarator (QOS) Design Status

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Overview and Motivations

- We are developing a modest-sized experimental stellarator design based on the Quasi-Omnigenous (QO) optimization technique

- These studies are the first step towards understanding the physics of compact, low aspect ratio stellarators

- Significant progress has been made toward this goal
  - Experimental tests of these design concepts will be essential
  - Ongoing optimization effort is required to develop the concept's physics and engineering features to their full potential

- This talk will report progress in the areas of
  - coil design (preserves flux surfaces and physics properties)
  - core transport, confinement of ICRF heated populations
  - bootstrap current
  - stability

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The QOS Program uses innovative methods to develop compact stellarator devices:

- Quasi-Omnigeneity (QO) is a promising approach to improving transport in stellarators
  - approximately aligns bounce-average particle drift surfaces with flux surfaces
- Can do this at relatively small aspect ratio (A = 3-4)
  - and maintain: good neoclassical confinement, high ballooning and kink stability limits, good energetic orbit confinement
- QOS concept exploration experiment is proposed to test the QO approach
  - will determine the optimum QO coil set for possible larger experiment
- Parameters for our scoping study are: $\boldsymbol{R}_0$ = 1 m, <$\boldsymbol{a}$> = 0.28 m, $\boldsymbol{B}_0$ = 1-2 T, $\boldsymbol{P}_{ECH}$ = 0.6 MW, $\boldsymbol{P}_{ICRF}$ = 3 MW, $\boldsymbol{P}_{LH}$ = 1 MW, and $\boldsymbol{t}_{pulse}$ = 4 s (at 1 T) and 1 s (at 2 T).
- Program focus: improvement of neoclassical and anomalous confinement, use of external coils rather than bootstrap current to create most of the poloidal field.

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Quasi-omnigeneity is a stellarator optimization technique complementary to quasi-symmetrization methods.

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

Quasi-omnigeneity: $\left\langle \vec{v}_D \ \vec{\ } \psi \right\rangle \quad \partial J^* / \partial \theta \quad \oint \kappa \times \hat{n} \ \vec{\ } \psi$

→ approximate J*(ψ)

no single dominant helicity

Allowing multiple helicities provides flexibility for:

- reduction of finite β bootstrap current

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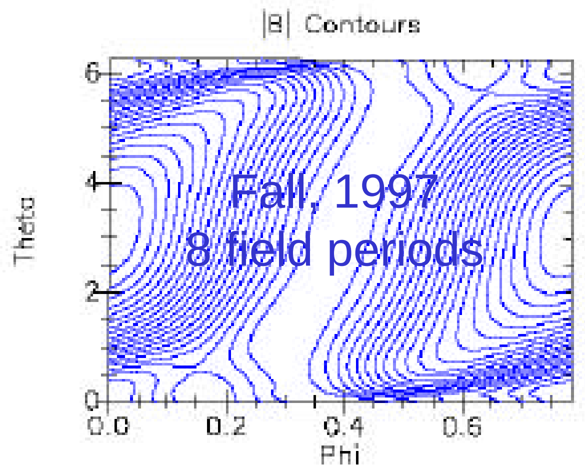
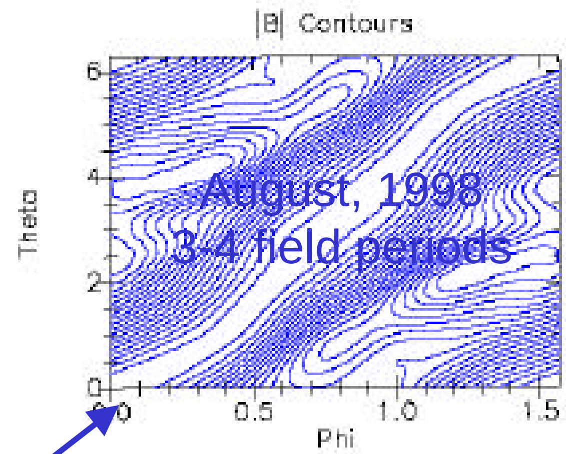
Evolution of Quasi-Omnigenous Devices

- QO configurations exist “in the neighborhood” of quasi-symmetric configurations
- Recently the QO has been used to extend nearly quasi-helical devices to low A

quasi-poloidal

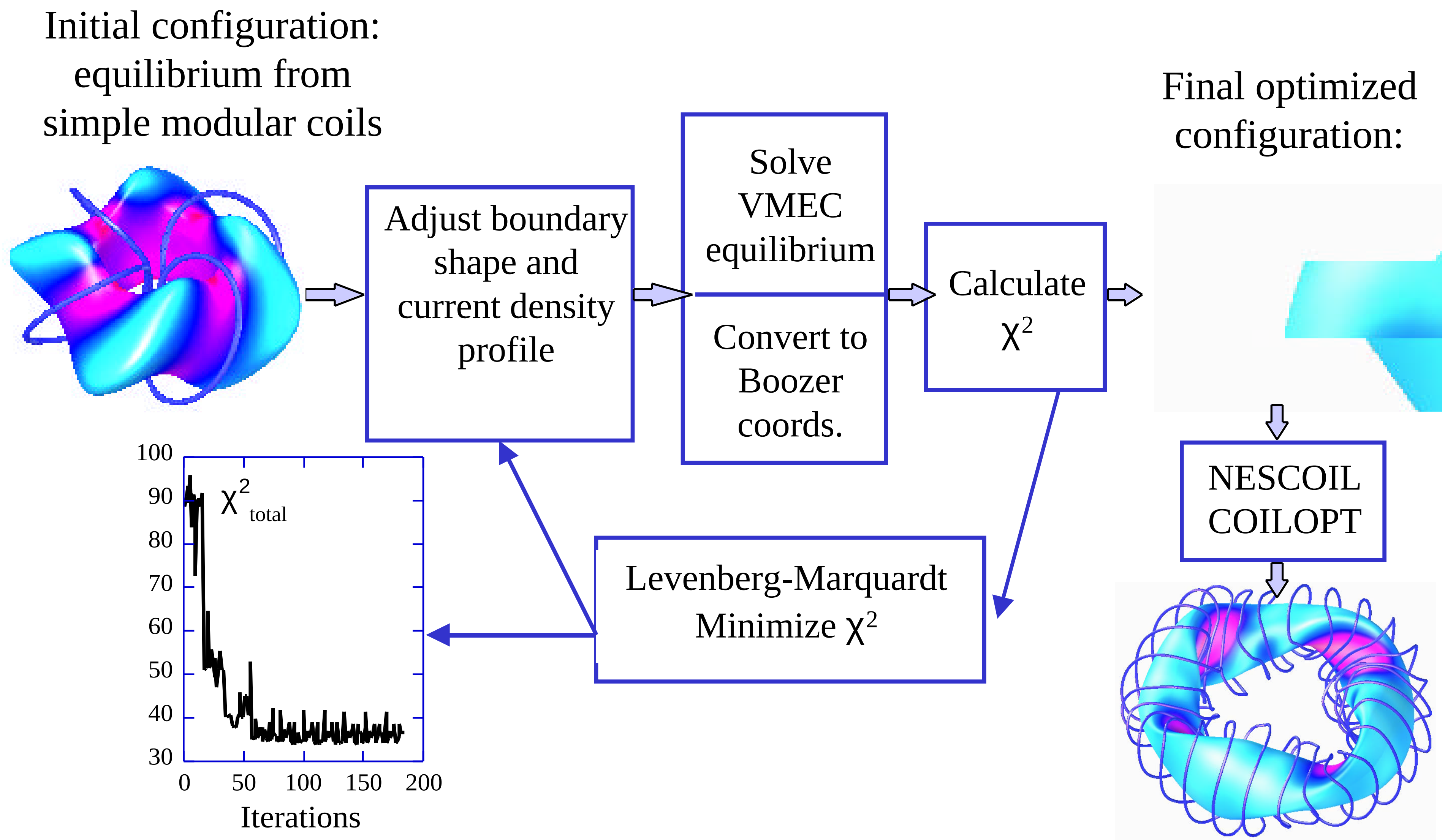


quasi-helical



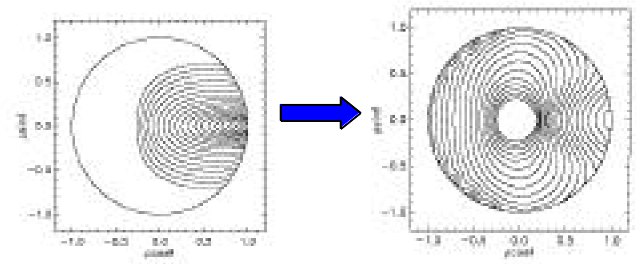
quasi-toroidal

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



QO configurations are based on a well–developed set of physics/engineering optimization targets

- Confinement is improved by aligning J $\int v_{\|} dl$ surfaces (trapped orbit trajectories) with magnetic surfaces:



- Stability: maintain magnetic well, Mercier, ballooning stability
- Transform profile: $0.5 < \iota < 0.8$, $d\iota/dr > 0$ with low bootstrap current
  - avoid resonances, positive transport scaling with i, avoid neoclassical island growth
- Coil optimization (separate from outer surface optimization)
  - maintain adequate coil/plasma separation, good surface reconstruction

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A New Concept Exploration Experiment, QOS, is needed to test Quasi-Omnigeneity

- Broaden the scientific base on the quasi-symmetry being tested in HSX and NCSX into low-aspect-ratio non-symmetric stellarators
- Test reduction of neoclassical transport via nonsymmetric quasi-omnigeneity, and the effect of radial electric fields on confinement
- Test reduction of energetic orbit losses in non-symmetric low-aspect-ratio stellarators
- Test reduction of the bootstrap current and the configuration independence on β
- Test methods to affect anomalous transport, such as producing sheared E x B flow, and understand flow damping in non-symmetric configurations

Requirements for Medium-Scale Experiment to Test the QO Optimization Principle

- **Adequate neoclassical confinement**
  - **transport reduced by factor of ≥ 2 relative to ISS95 to allow clear tests of enhanced confinement regimes**
  - **allow tests of improvement with ambipolar electric field**
  - **good reactor extrapolation**
- **Good confinement of energetic trapped ions**
  - **Viable ICRF heating efficiency**
  - **Adequate alpha-particle confinement for reactor extrapolation**
- **Bootstrap current provides < 30% of total transform**
  - **test configuration independence of β**
  - **demonstrate low risk of disruptions**
- **Adequate size, field, and pulse length so ISS95 scaling permits tests at relevant parameters (n, T, ν^*, $\langle\beta\rangle$)**
- **Coil sets with sufficient access for heating, diagnostics**
  - **3 or 4 field periods with 5-7 modular coils per period**
  - **$\langle a \rangle \sim 0.28$ m, $B_0 = 1 - 2$ T, pulse ≥ 1 second**

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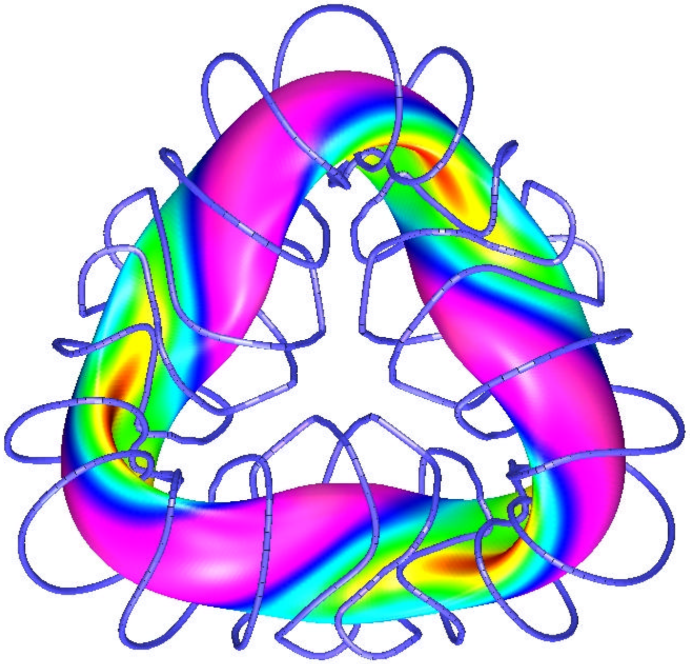
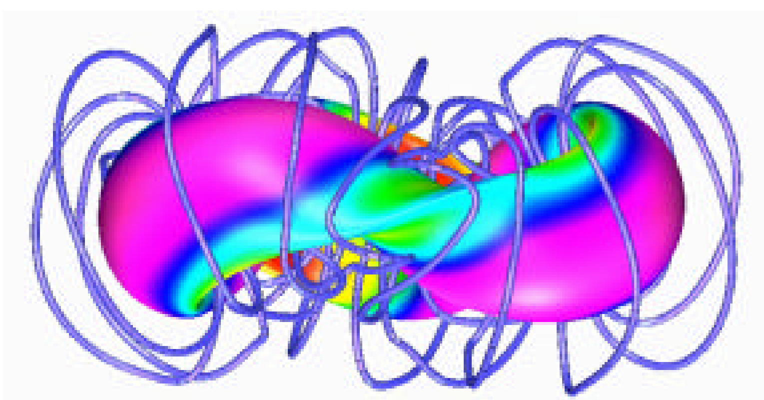
Quasi-Omnigenous Stellarator

(Scoping Study Parameters)





- **R_0 ≤ 1.0 m**
- **<*a*> ≤ 28 cm**
- **R_0/<*a*> ≈ 3.6**
- **Volume ≤ 1.6 m^3**
- **B_0 1 T (≤ 4 s)**
- **2 T (≤ 1 s)?**
- **Plasma Heating (10 s)**
  - **0.6 MW; 53.2 GHz**
  - **2 MW; 6-20+ MHz**
  - **1 MW; <40-80 MHz**
  - **1 MW; 2.45 GHz**

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QOS Plasma Performance

- **Consistent Sets of Plasma Parameters***

Plasma Parameter	0.4-MW ECH			1-MW ICRF		2.5-MW ICRF	
B_0 (T)	1	1	2	1 2	1	2	
n_e ($10^{19} m^{-3}$)	1.6[(a)]	3.2[(b)]	3.2[(c)]	11	15	17	24
τ_E (ms)	17	24	43	26	56	19	41
β (%)	0.7	1.0	0.5	2.8	1.5	5.2	2.8
T_{e0} (keV)	3.4	2.4	4.3	1.0	1.5	1.1	1.7
T_{i0} (keV)	--	--	--	1.0	1.5	1.1	1.7

- [(a)] 2nd harmonic X-mode
- [(b)] O-X electron Bernstein wave mode conversion
- [(c)] O mode fundamental

* based on ISS95 stellarator scaling with a confinement

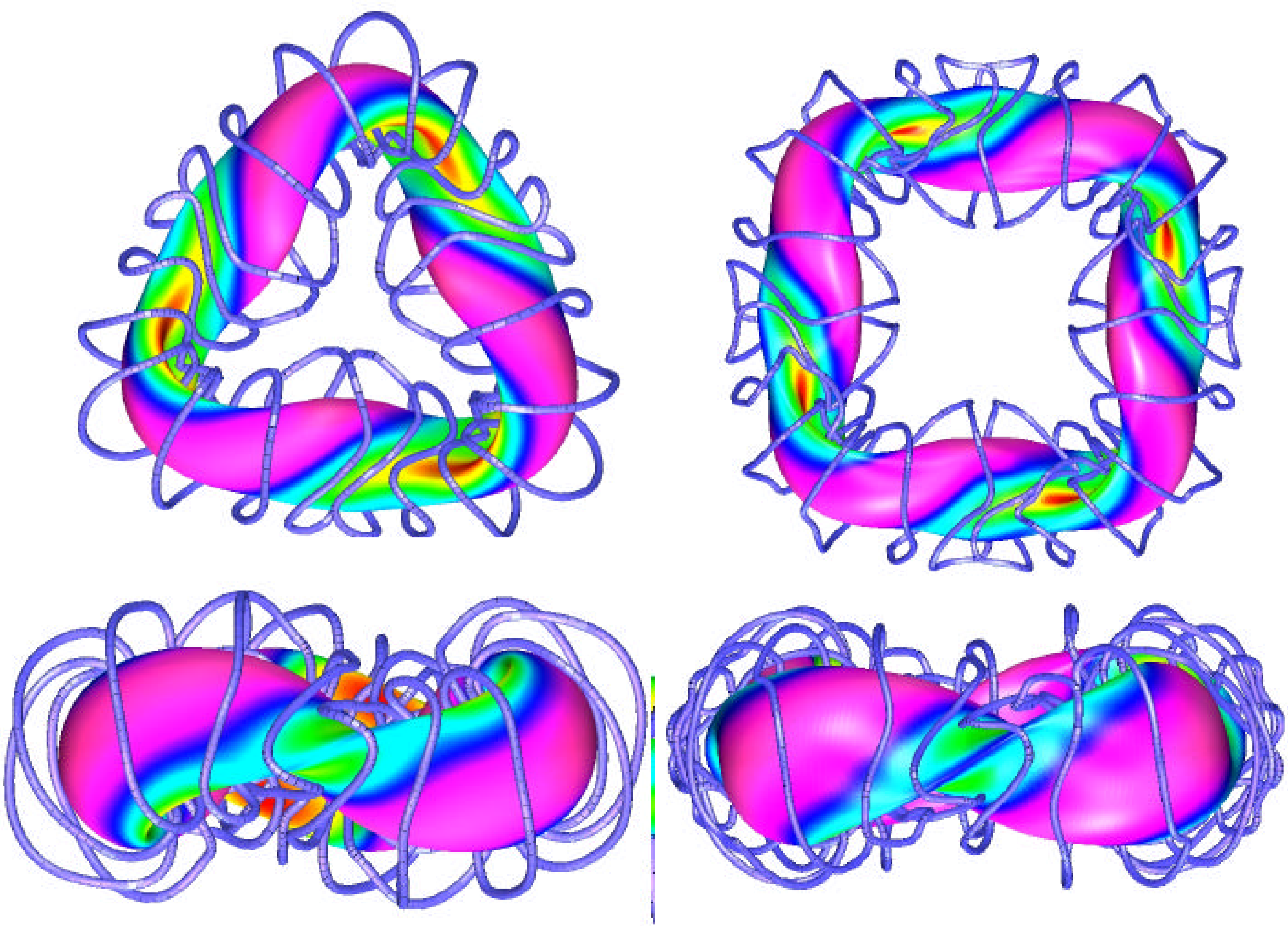
* improvement factor H = 2 (H = 1.4 - 3 obtained in W7-AS)

- τ_E (ISS95) = H x $0.079 \langle a \rangle^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{0.4}$
- assumes τ_E (neoclassical) > several times τ_E (ISS95)

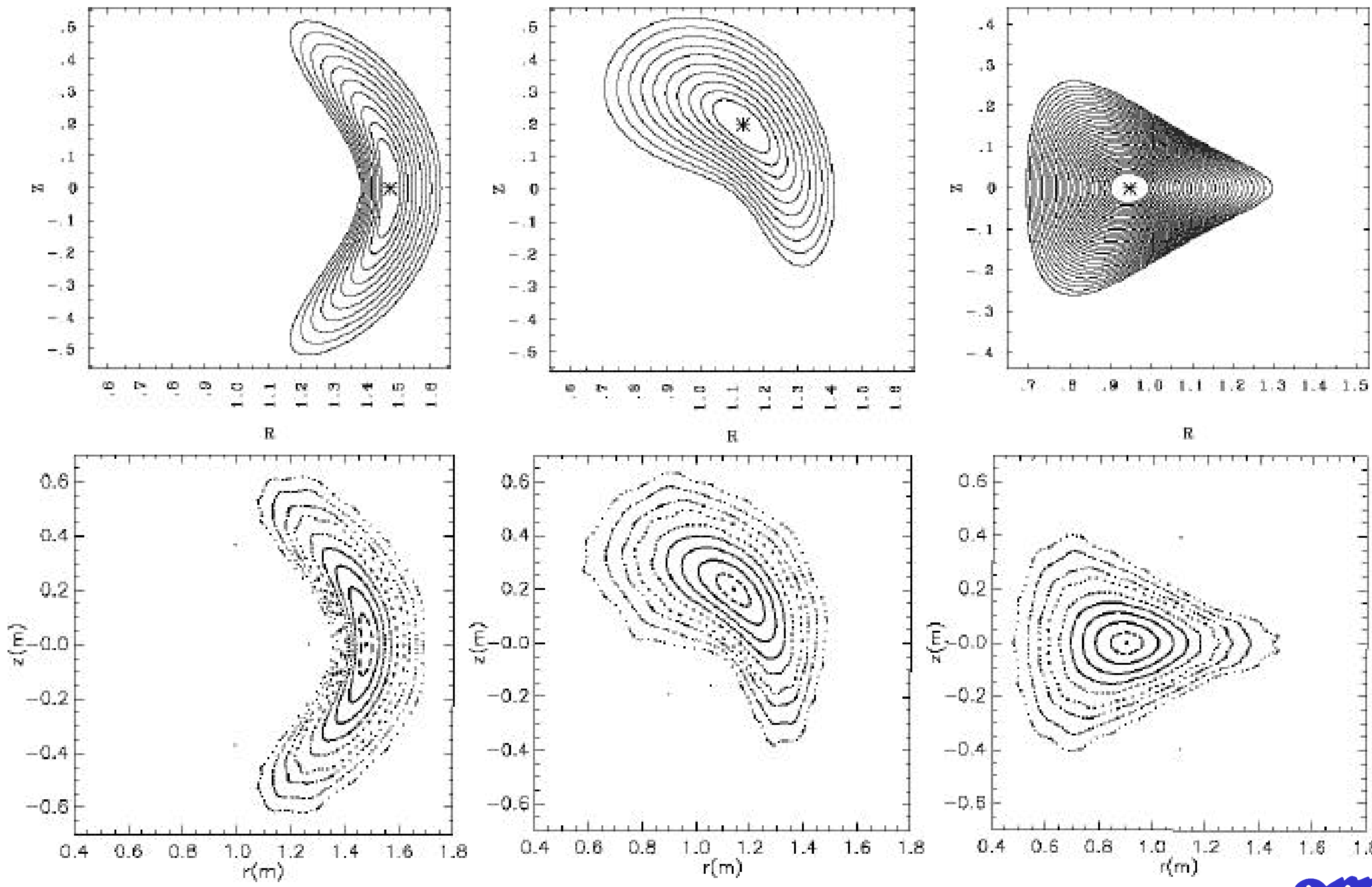
QOS Research Program Goals

- **Reduction of anomalous transport ⇨ H > 2**
  - **profile control, sheared E x B flow using ICRF**
- **Reduction of energetic orbit losses and neoclassical transport in low-A, non-symmetric configurations**
  - **modification of |B| Fourier components with auxiliary coils to spoil the optimization**
  - **modify radial electric field with ICRF, biased probes**
- **Study control of the bootstrap current**
  - **cancellation by different |B| harmonics, dependence on ι**
  - **test configuration independence on β**
- **Study stability at low β (< ~1.5%)**
  - **turbulence spectra, kink stability with OH driven current**

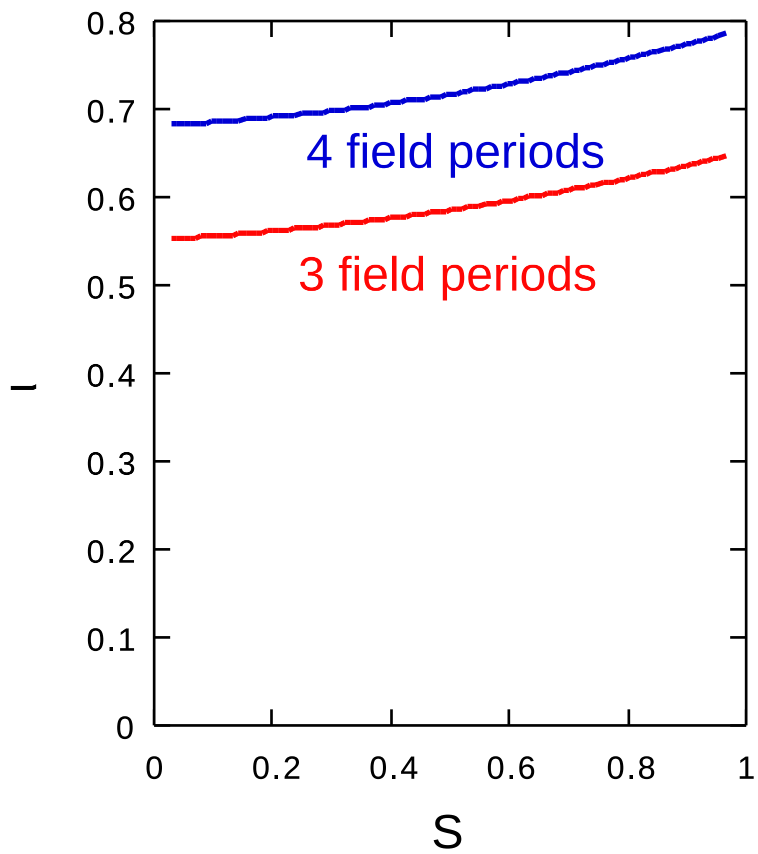
Recent 3 and 4 field period QO configurations

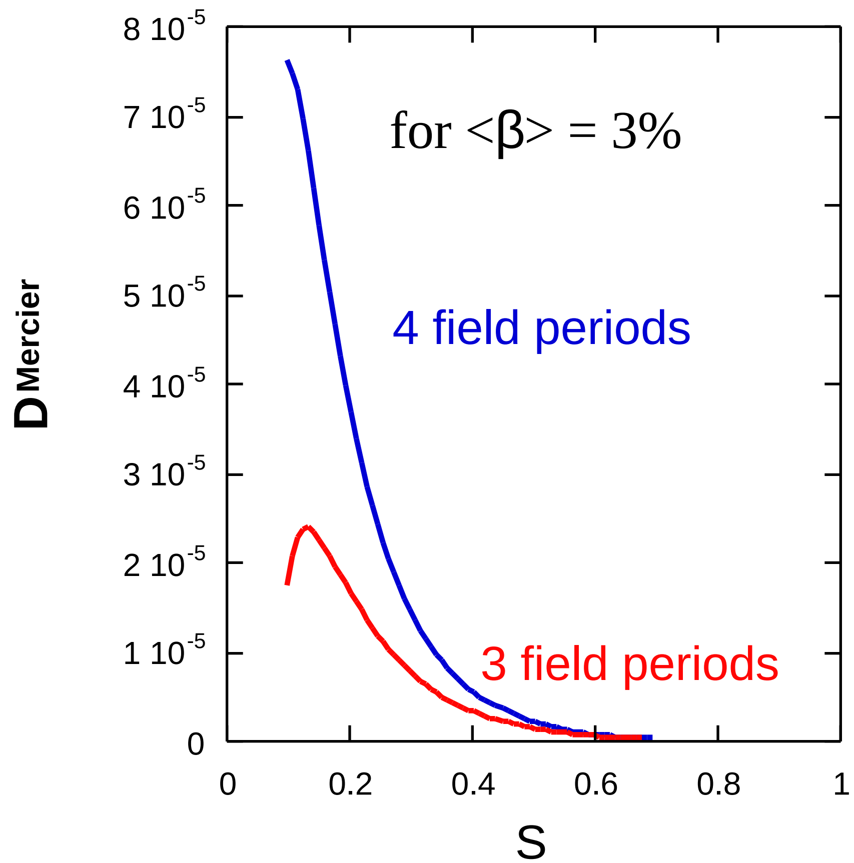


Excellent flux surface reconstruction is obtained using modular coils generated by the COILOPT code:



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





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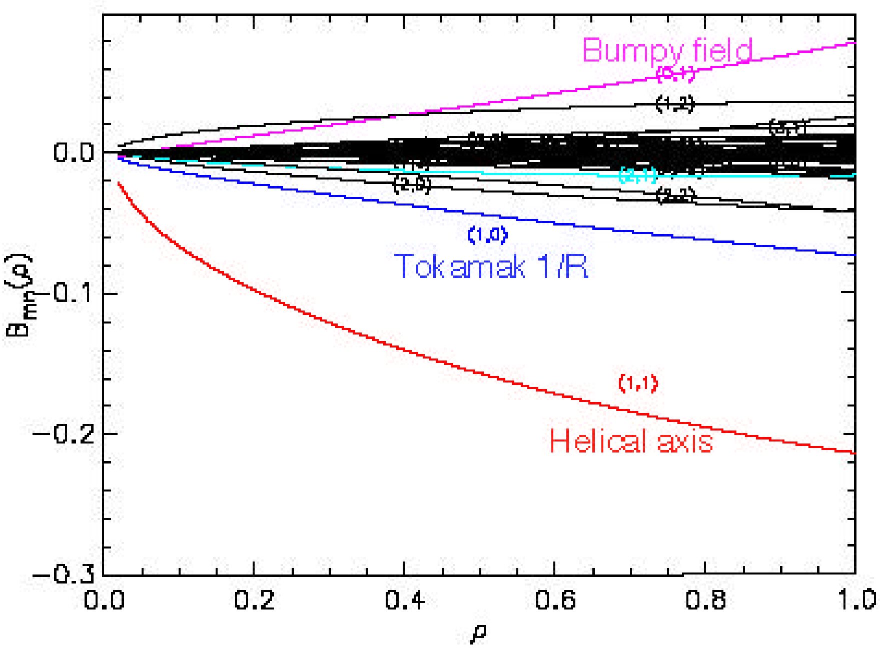
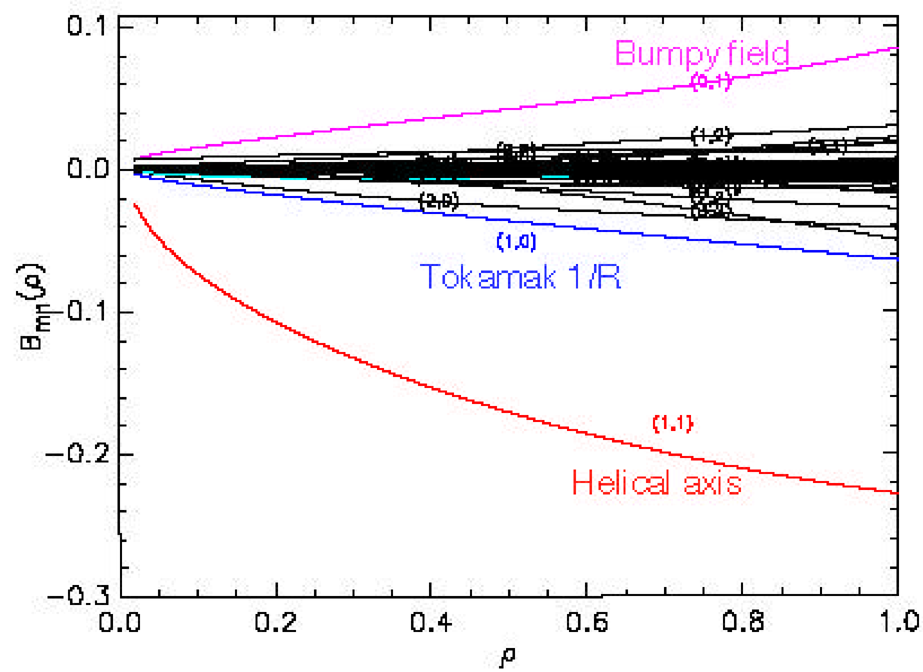
The B_{mn} spectra show that the helical component is dominant. The 1/R term is down from its axisymmetric tokamak level about a factor of 4.

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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Tools used/available in the analysis of QO configurations:

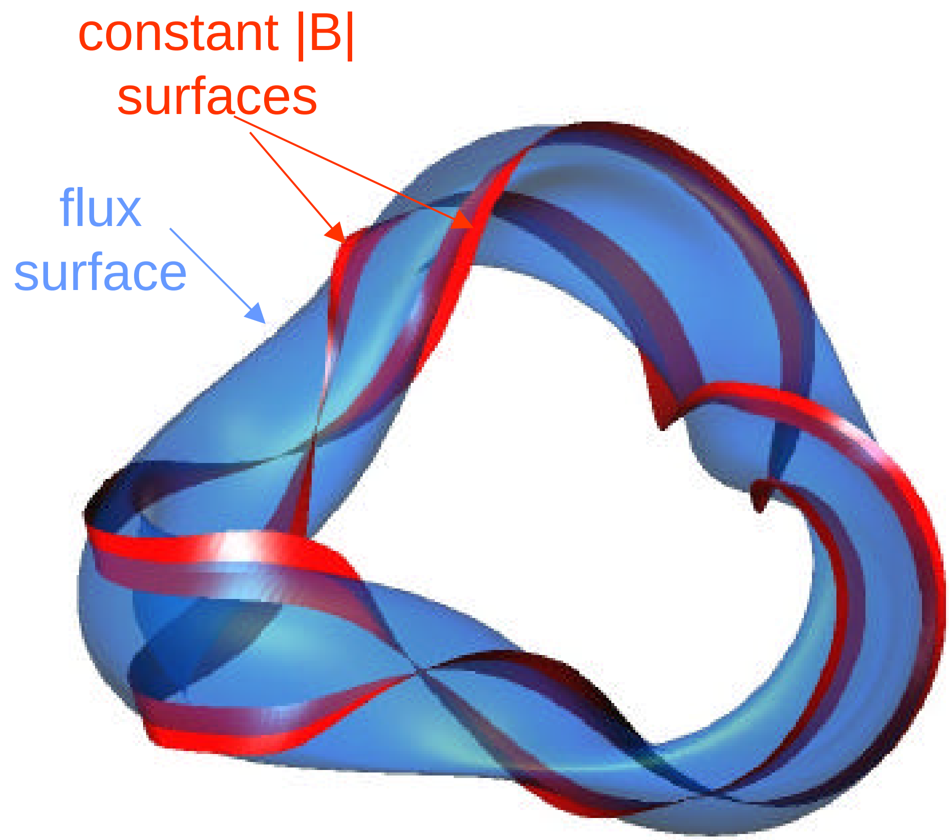
- Optimization, 3D equilibrium: VMEC
- Transport, confinement
  - DELTA5D (ORNL Monte Carlo Code)
  - FAFNER-2 (IPP/CIEMAT parallel Monte Carlo code for the T3E)
  - SYMPORBIT (symplectic orbit integrator)
  - J^*, B_{min}, B_{max} contour plotting
- Stability
  - COBRA (fast matrix/variational 3D ballooning, R. Sanchez)
  - CHAFAR (Averaging method)
  - Resistive MHD for 3D configurations (L. Garcia)
- Bootstrap Current
  - Collisionless limit
  - NIFS multi-regime code
- Coil Design
  - COILOPT
  - NESCOIL

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 $\rho/\langle a\rangle$)

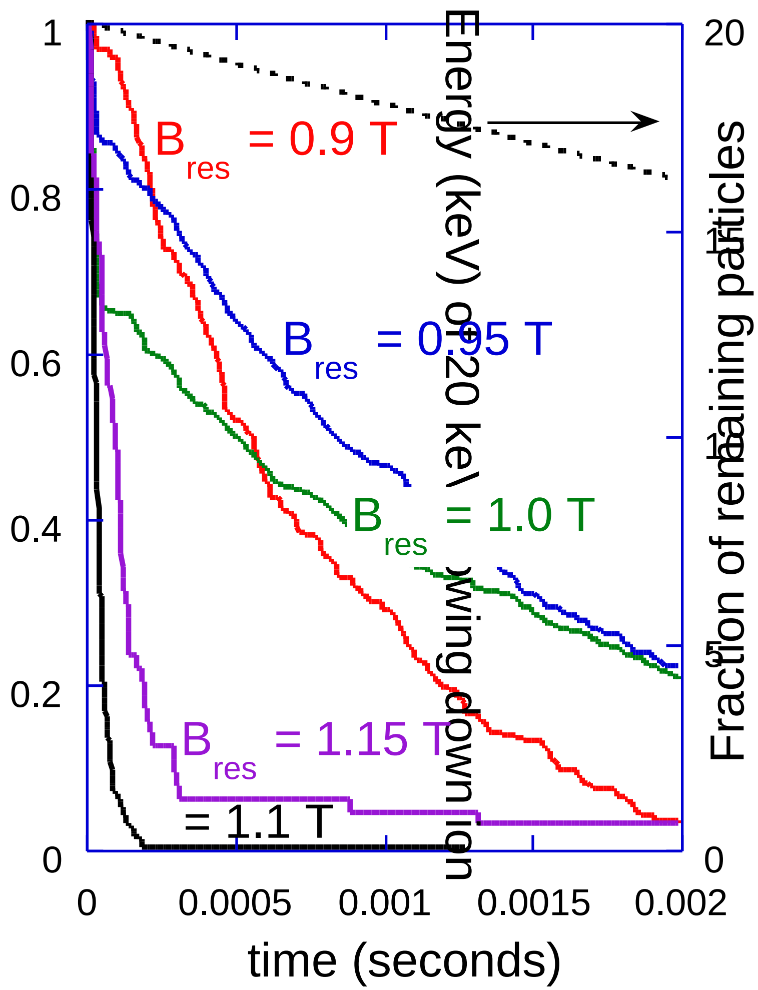
ICRF heating in stellarators depends on wave propagation, geometry of the resonant regions and the orbit confinement of the resonant ions

- Confinement of ICRF heated ions is examined by following ~500 orbits
- Intersections of |B| contours with flux surfaces are determined for inner half of the plasma volume
- Ions are started out at $B = B_{res}$ with $v_{||0}/v = 0$ (equivalent to $\varepsilon/\mu = B_{res}$)
- Ions leaving the outer surface are removed from the population

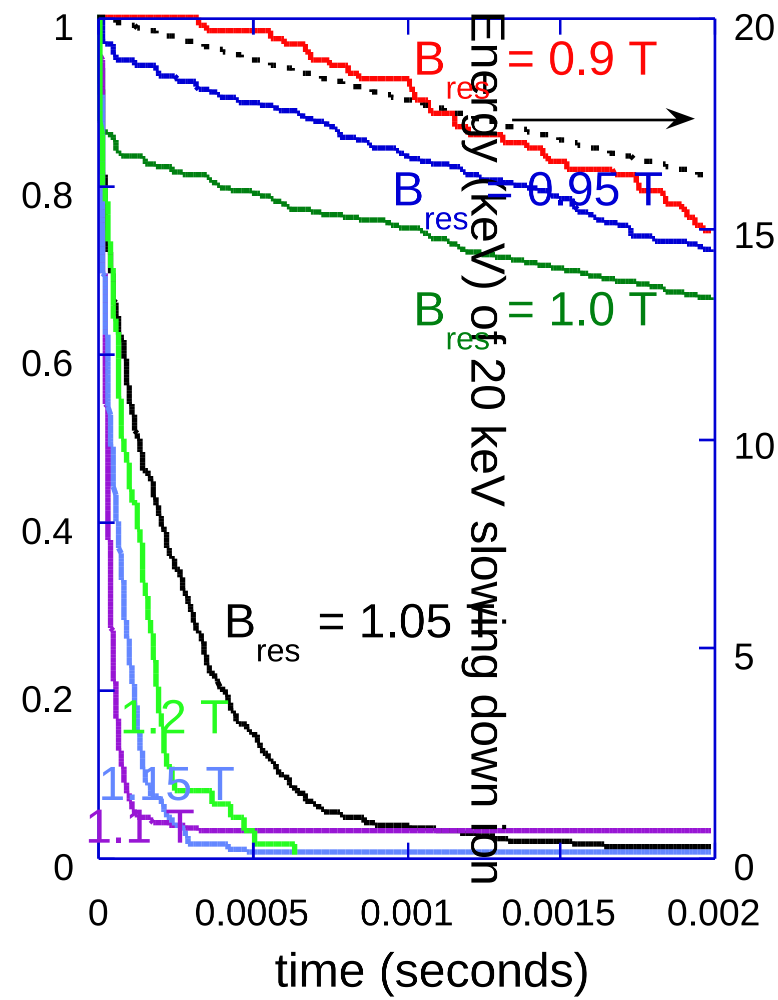


Loss rates of 20 keV ICRF ion populations (500 particles) are a sensitive function of the resonant magnetic field $B_{res} = \varepsilon/\mu$

$N_{fp} = 3$



$N_{fp} = 4$



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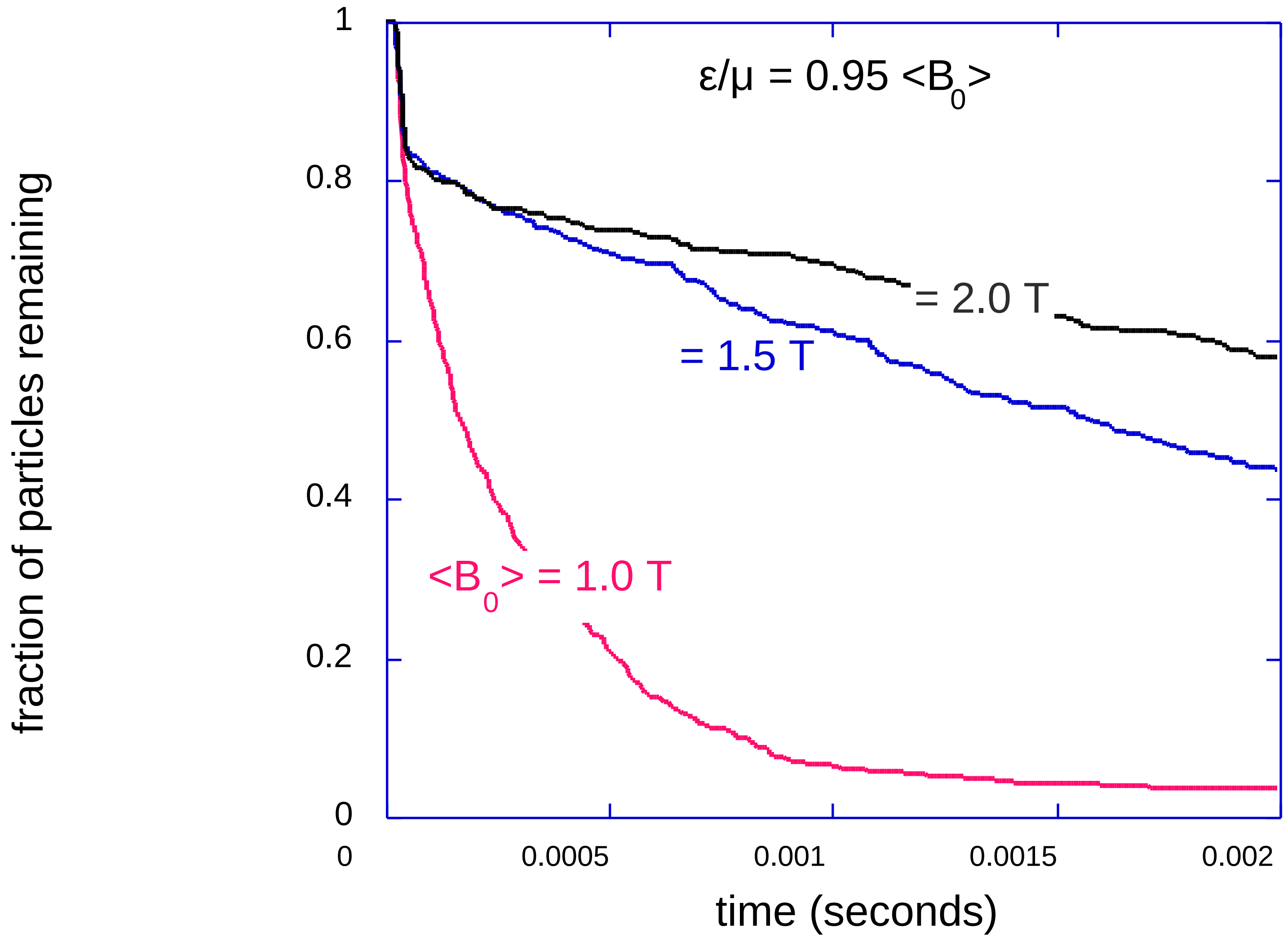
Increasing the magnetic field can significantly improve the confinement of trapped ICRF tail populations:



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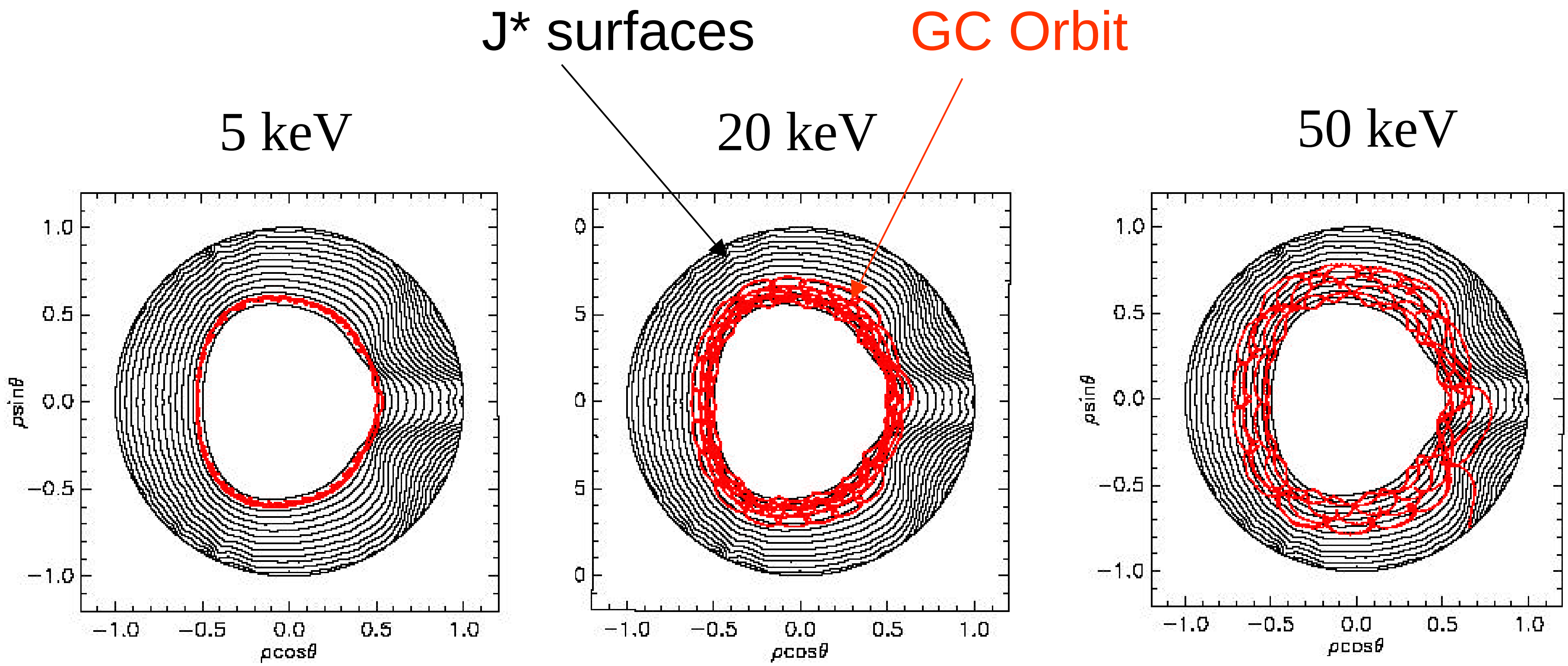
Scaling with <a>/ρ of deeply Trapped proton orbit trajectories in a B = 1T N_{fp} = 3 QOS Device (shown in Boozer coordinates):



<a>/ρ = 27

<a>/ρ = 13.5

<a>/ρ = 8.5

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

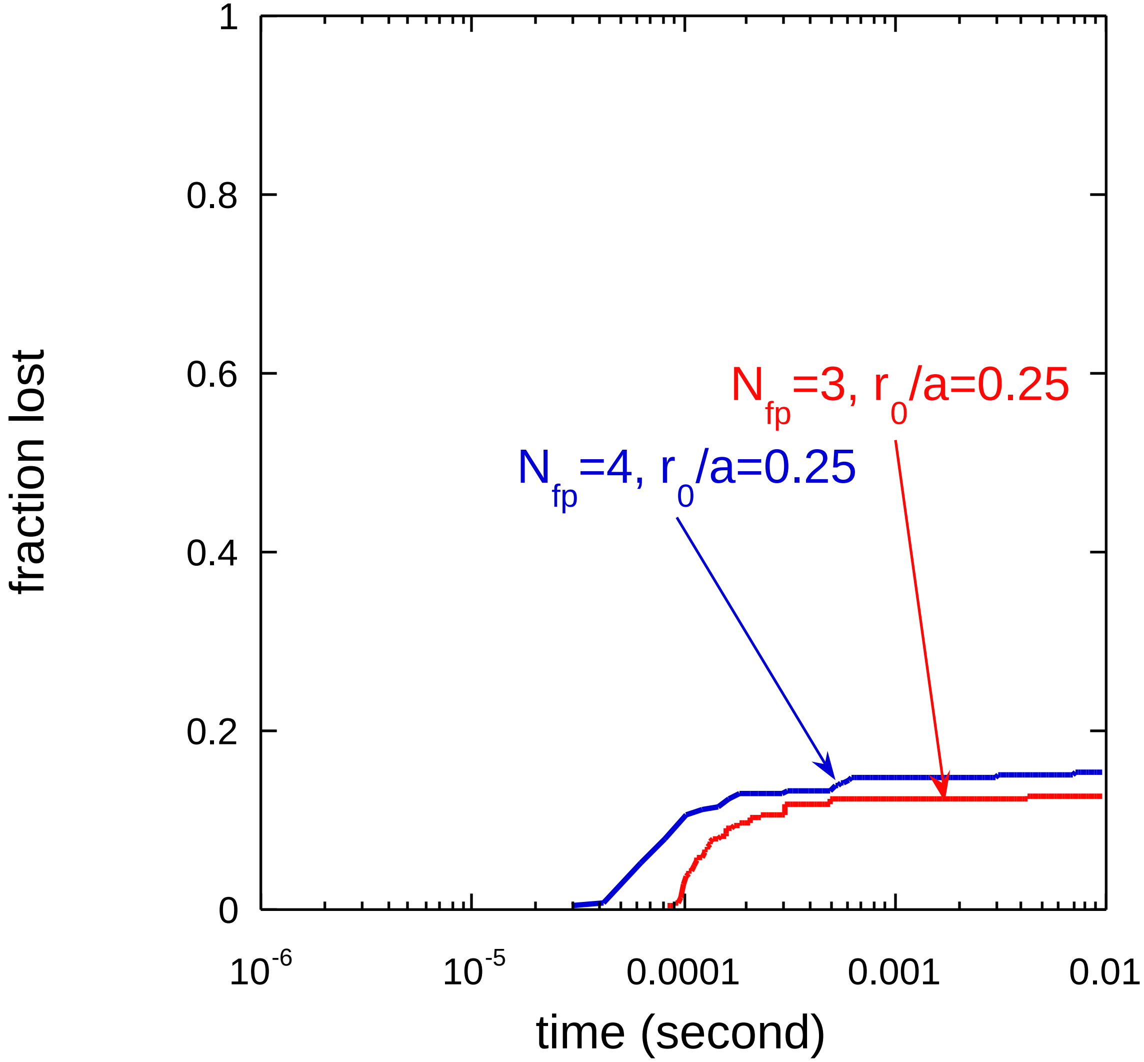
- 20 keV proton B = 1T <a> = 24 cm
  ρ = 2 cm <a>/ρ = 12

- 3.5 MeV alpha B = 5T <a> = 2 m
  ρ = 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

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)



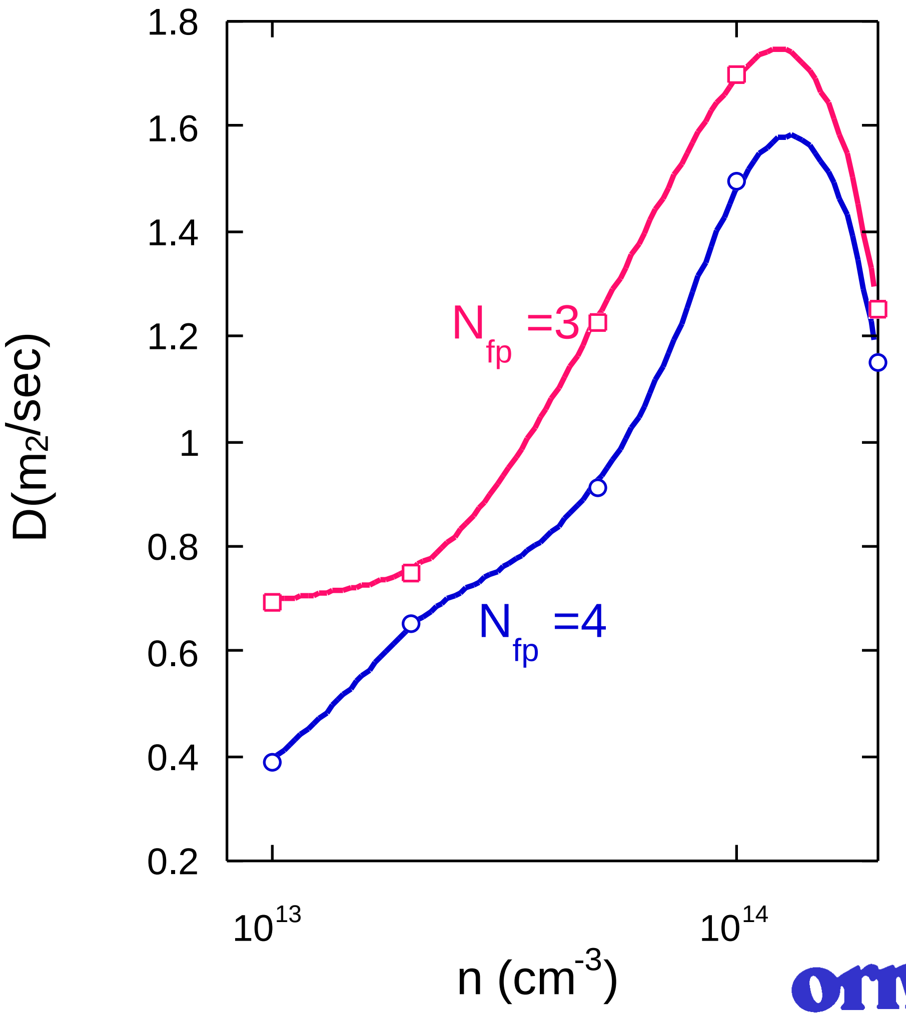
Note:

- These will be extended to $\tau_{SD} \approx 1$ sec with collisional effects
- This design has not yet been optimized for a reactor

Neoclassical Transport

Collisionality scaling of the diffusivity for N_{fp} = 3 and 4 devices shows a decrease with n 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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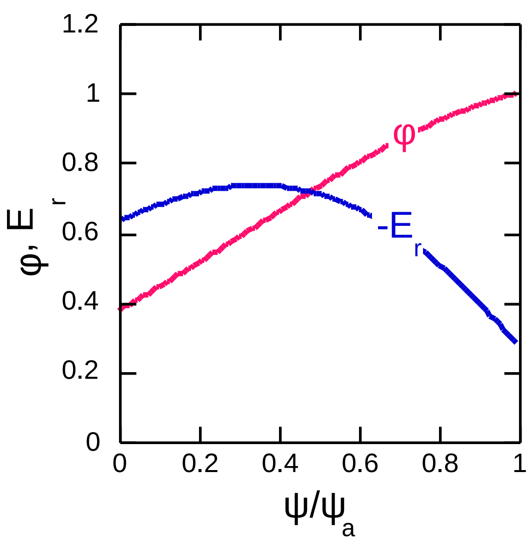
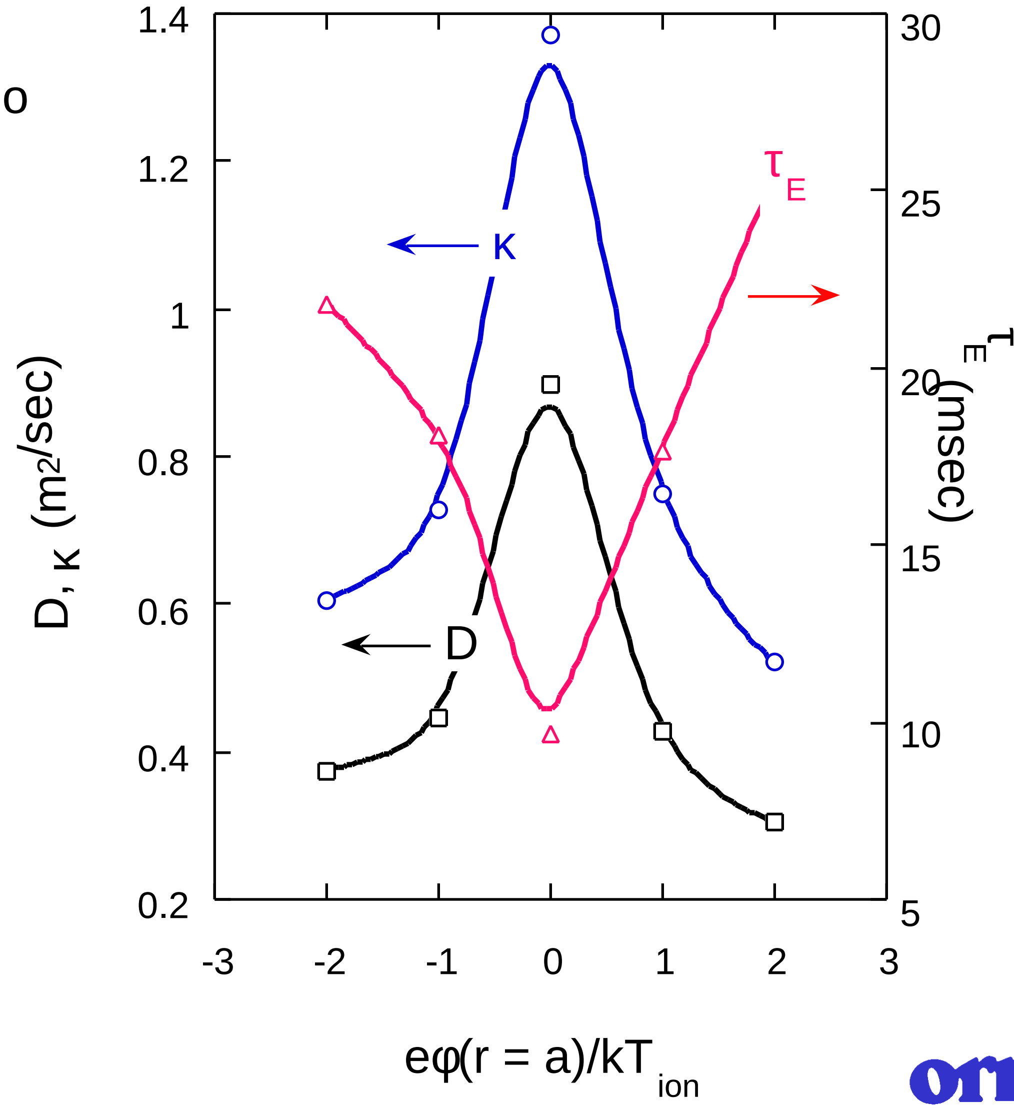
The diffusivities and 0-D energy confinement time show a strong dependence on electric field with $\tau_E \approx (2\text{-}3)\times\tau_{ISS95}$ for typical ambipolar potentials

- N_{fp} = 4 configuration
- 4 monoenergetic ion Monte Carlo groups used (2000 particles each) to construct diffusivities for a Maxwellian
- T_{field} = 1 keV, E_{test} = 0.5, 1, 2, 3 keV, n = 5×10^{13} cm^{-3}, Z_{eff} = 1
- Starting position: ψ/ψ_a = 0.25 (r/a = 0.5)





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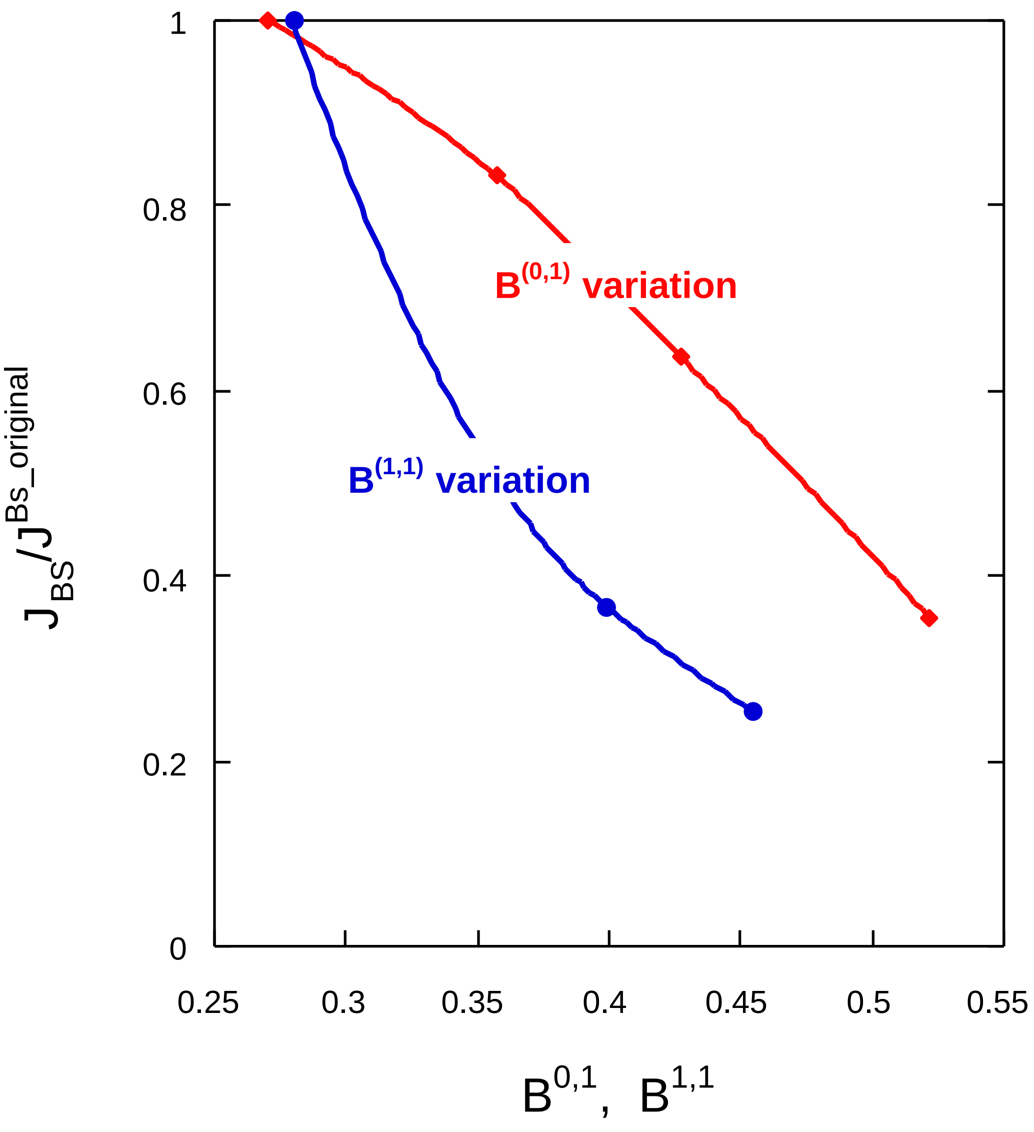
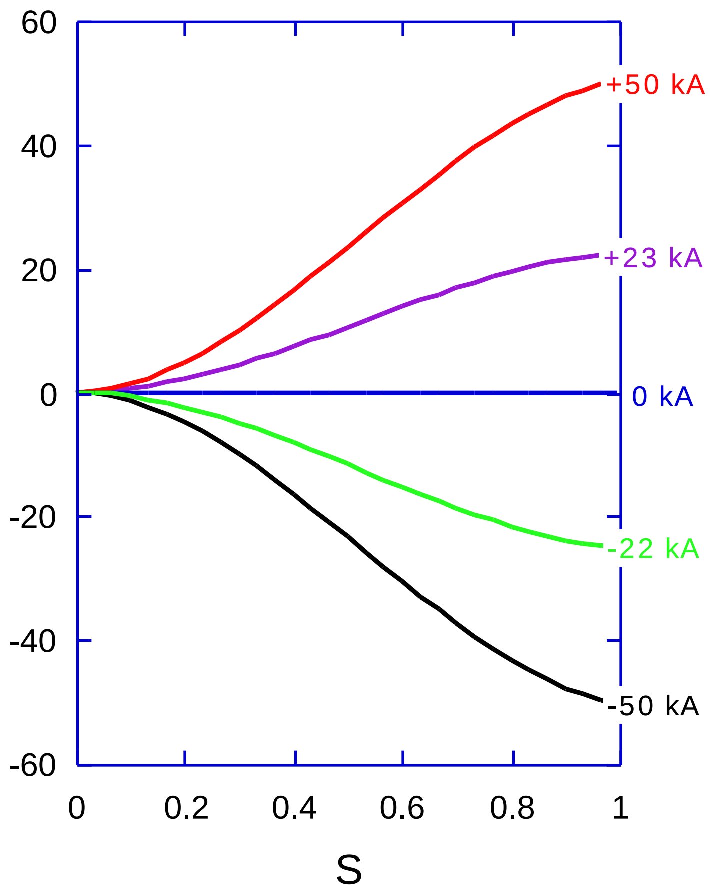
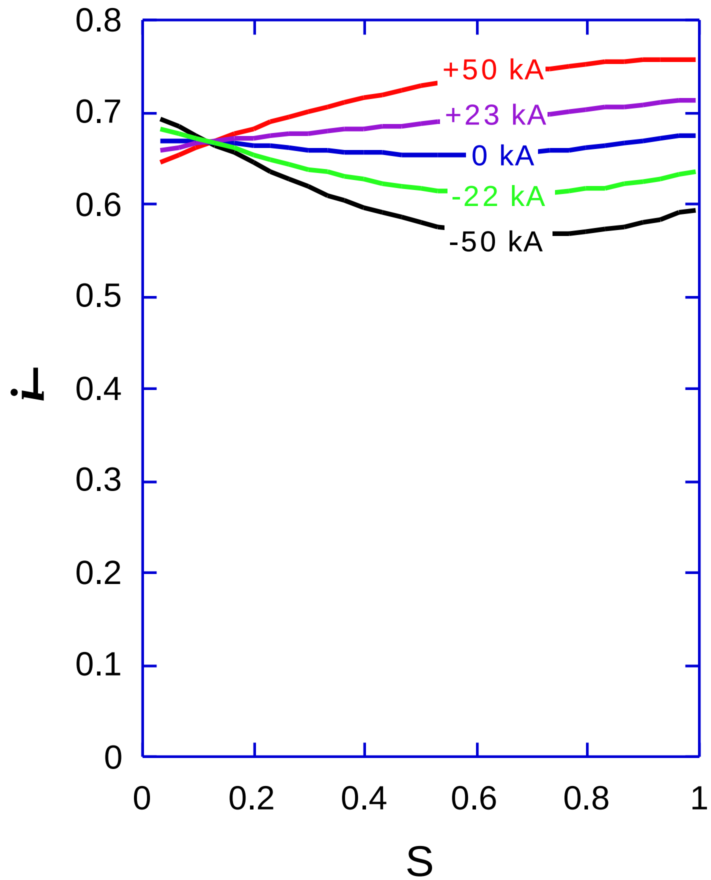
Bootstrap Current

QO configurations allow flexibility with respect to the level of bootstrap current

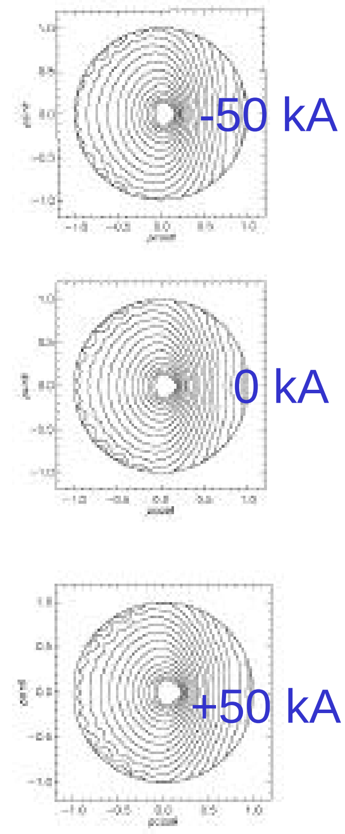


The transform and J* surfaces of the 3 field period QO configuration are not strongly modified by various levels/signs of bootstrap current





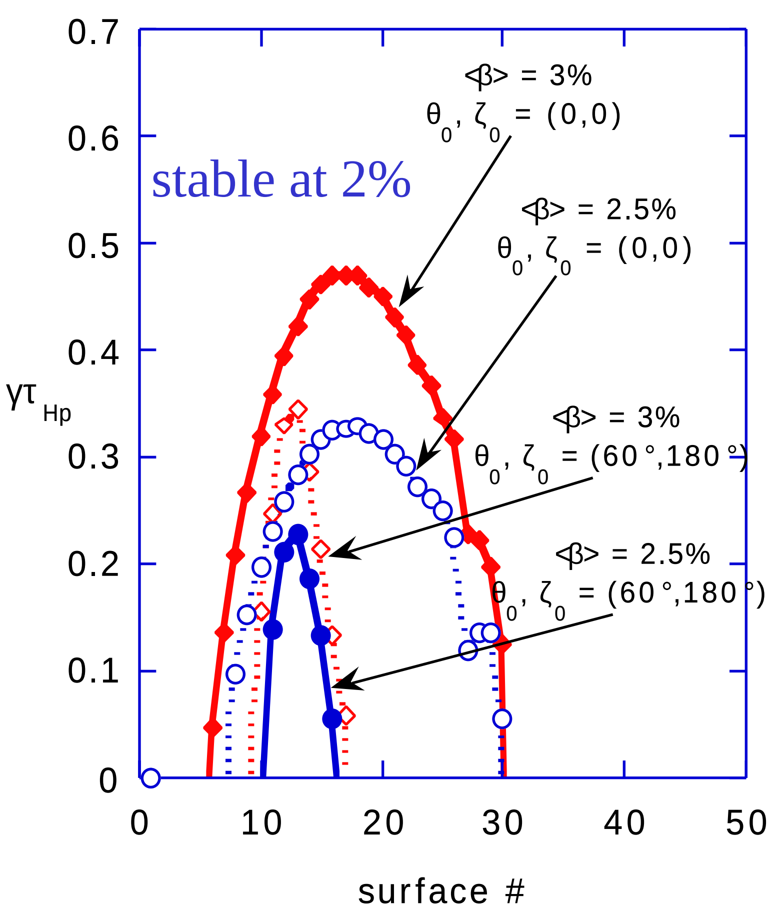
J* contours
at ε/μ = 1



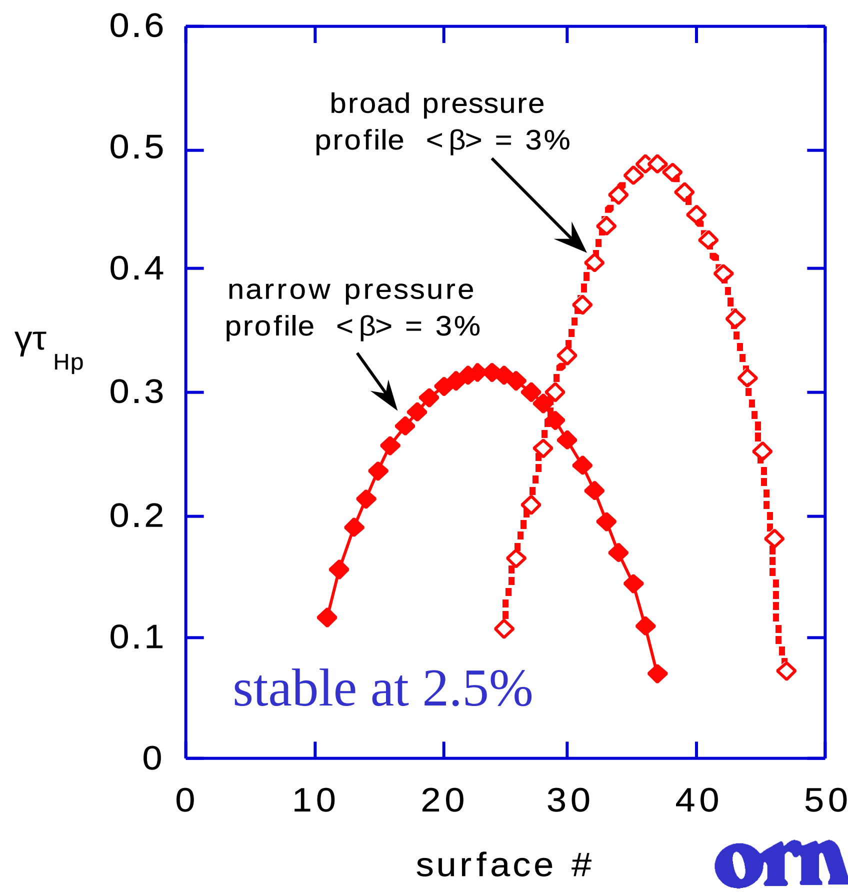
Stability

Ballooning growth rates can be a sensitive function of the pressure profile and matching point position along the field line. Recent pressure profile optimizations for the 3 period device have gotten the β limit up to 3%

$N_{fp} = 3$



$N_{fp} = 4$



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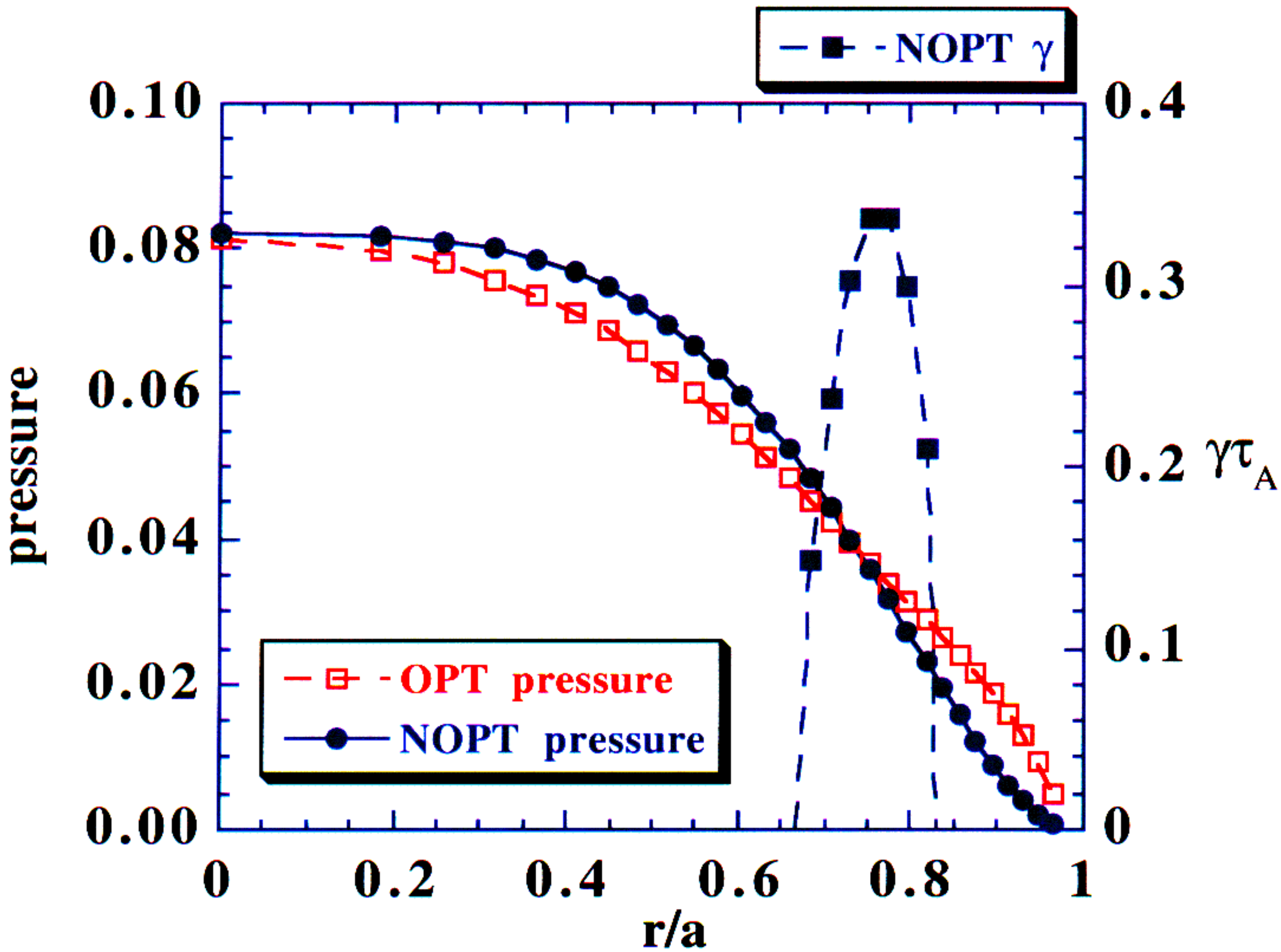
The first step of ballooning β optimization (profile modification) has recently been completed, leading to ~20% increase in the stable β:

QOS CONFIGURATION: M=3 ,<β>=3%, A=3.2



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Areas for Further QOS Development

- **Optimization:** self-consistent bootstrap current and ballooning stabilty improvement; evaluate tradeoffs of performance vs. cost
- **Neoclassical transport:** further improvement to allow better exploration of improved confinement regimes?
- **Fast ion confinement:** sufficient for bulk ICRF heating
  - better confinement of energetic perpendicular ions needed to explore minority species heating?
- **Beta limit:** increase <β> limit above 3% for better experimental test of reduction of bootstrap current and of beta limit dependence on magnetic configuration properties?
- **Modular coils:**
  - 5 instead of 7 coils per period for better experimental access?
  - reduce minimum bend radius for easier fabrication?

CONCLUSIONS

- Progress has been made with the preliminary design phase for a small scale QO concept exploration experiment
  - 5-7 modular coils per period - good flux surface reconstruction
  - good neoclassical transport ($\tau_{E,neo} \approx 2\text{-}3 \times \tau_{E,ISS95}$)
  - confined ICRF tail - efficient heating
  - can suppress/control bootstrap currents
  - ballooning $\langle\beta\rangle \approx 2 - 3\%$ - appropriate range for experimental tests
- Unique features of QO devices
  - good test-bed for RF heating
    - optimized for confinement of high v trapped particles
    - high field access
  - can be designed to access $0.5 < \iota < 1$
  - rotational transform comes predominantly from coils