QOS Project Overview: Status and Plans

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TOPICS

- **Improved Optimization Tools**
- **Status of Low-Bootstrap-Current**
  $\langle\beta\rangle \approx$ **4% QOS with dι/dr > 0**
- **Higher-Bootstrap-Current** $\langle\beta\rangle$ **~ 15% QO Configurations with dι/dr < 0**
- **Plans**

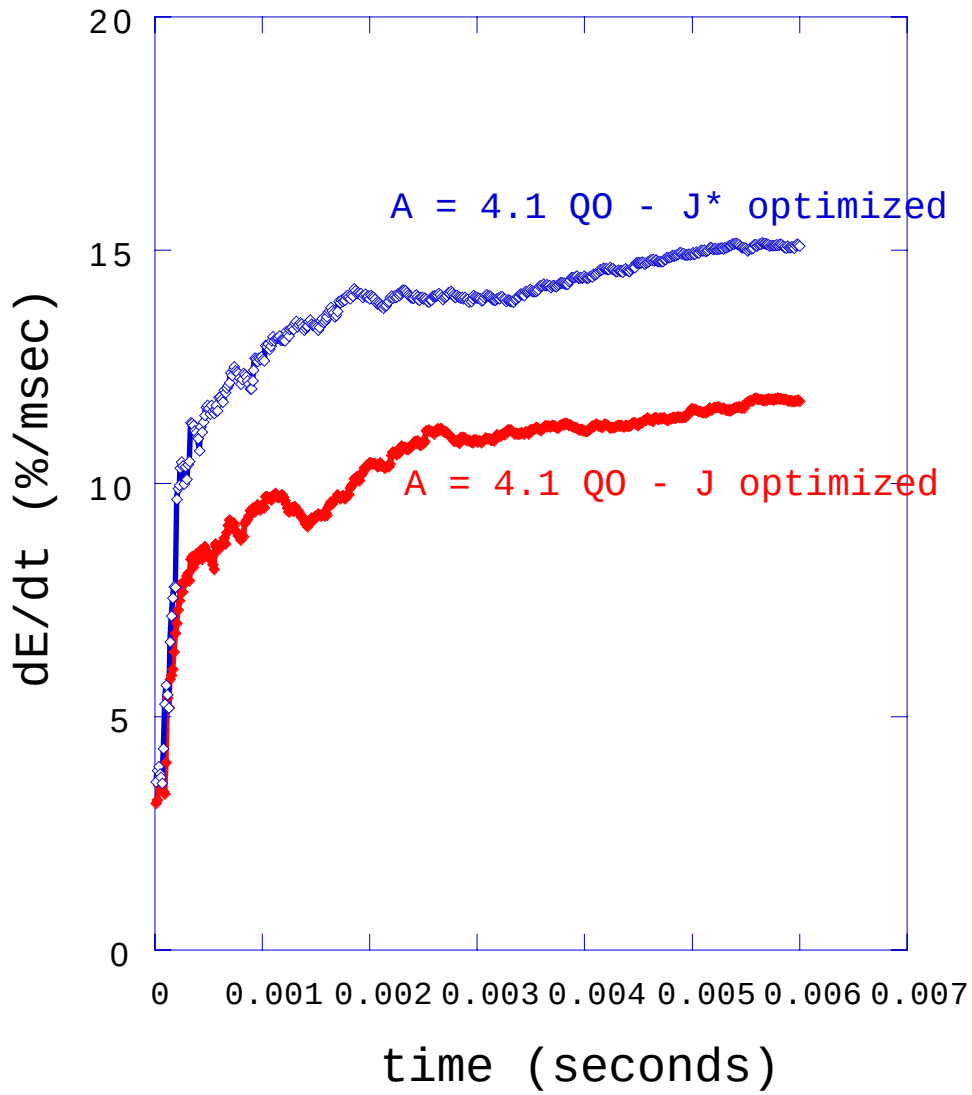
Tools Used in the Analysis of QO Configurations

- **3-D equilibrium:** VMEC (red = targets currently in the optimizer)
- **Stability**
  - COBRA (fast matrix/variational 3-D ballooning, R. Sanchez)
  - Terpsichore - Kink instabilities (R. Sanchez)
  - Resistive MHD for 3-D configurations (L. Garcia)
- **Bootstrap Current**
  - Tolliver/Berry code (collisionless limit), NIFS multi-regime code
  - Particle based δf calculation using DELTA5D
  - DKES (Drift Kinetic Equation Solver)
- **Transport, confinement**
  - DELTA5D (Stellarator Particle Simulation Code)
  - DKES (Drift Kinetic Equation Solver)
  - SYMPORBIT (symplectic orbit integrator)
  - J^*, J, B_{min}, B_{max} contour plotting
- **Coil generation:** COILOPT

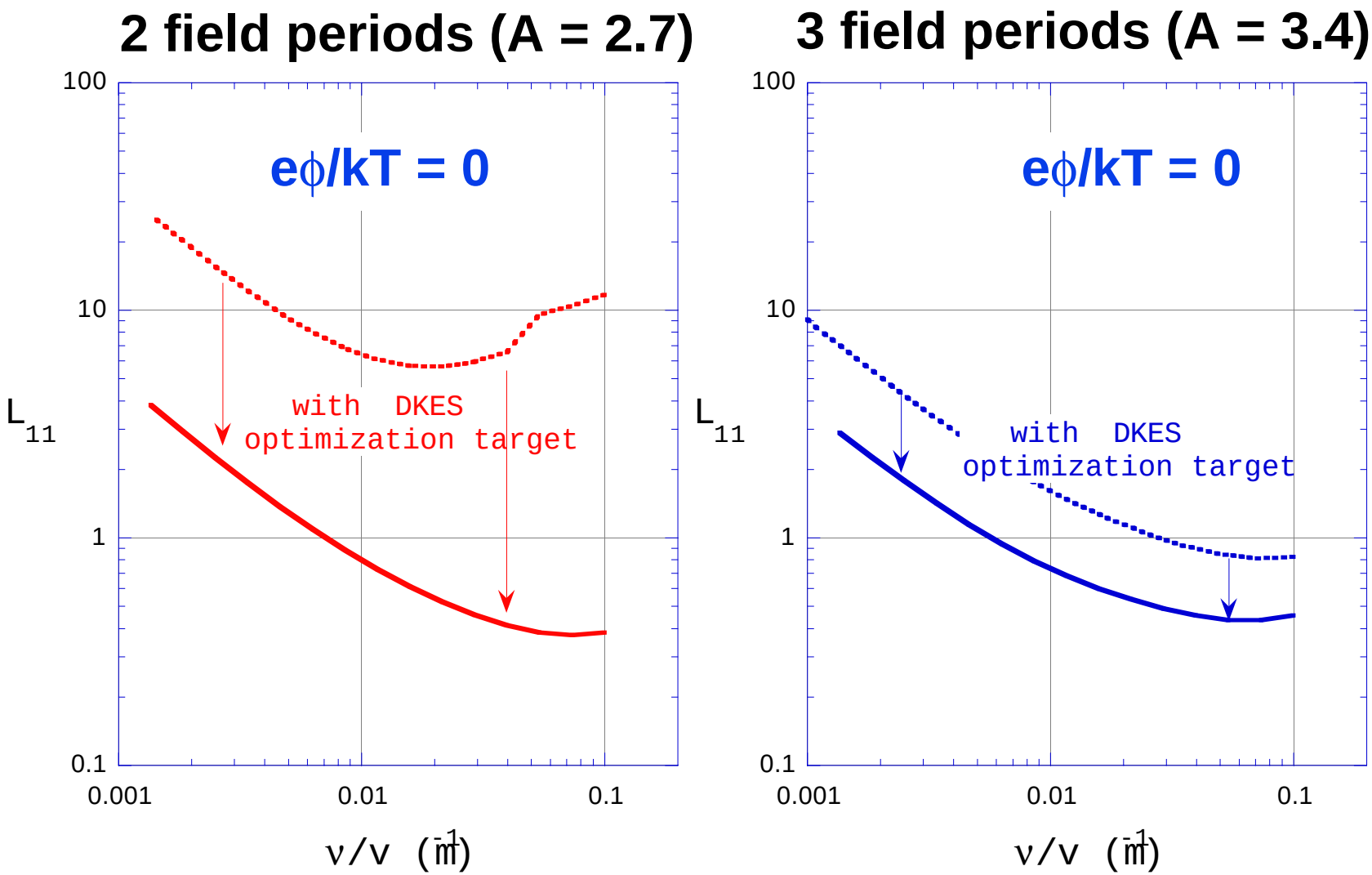
Recent Target Enhancements to the VMEC Physics Optimization Code

- **COBRA ballooning code modified to run in VMEC coordinates rather than Boozer coordinates: speed improvement**
- **Low collisionality self-consistent bootstrap current target**
- **J* confinement target upgraded to the more exact J invariant** $\left(J^* = \oint d\zeta \; v_{\parallel}, \quad J = \oint dl \; v_{\parallel} \right)$
- **DKES transport coefficient targeted at medium collisionality ($\nu/v = 0.05$) for a few surfaces**

Initial J-invariant Optimization Leads to ~25% Decrease in Global Thermal Energy Loss Rates



Using a DKES High Collisionality (ν/v = 0.05) Target Leads to Improvements at Lower Collisionality As Well



Recent Configuration Studies Have Focused on Two Distinct Types of QO Devices

- **Low-I_{BS} Configurations**
  - B_{mn} spectrum dominated by helically symmetric components
  - High rotational transform (~ 0.6 to 0.8), stellarator-like shear
  - Moderate ballooning $<\beta>$ limit (3 - 4%)
  - Low bootstrap current (1/10 of equivalent tokamak value); opposite direction from tokamak
  - Significant helical axis
- **Higher-I_{BS} Configurations**
  - B_{mn} spectrum dominated by poloidally symmetric components
  - Lower rotational transform (~ 0.45 to 0.1), tokamak-like shear
  - High ballooning $<\beta>$ limits (up to 23%)
  - Moderate bootstrap current (1/4 of equivalent tokamak value); same direction as tokamak
  - Moderate helical axis

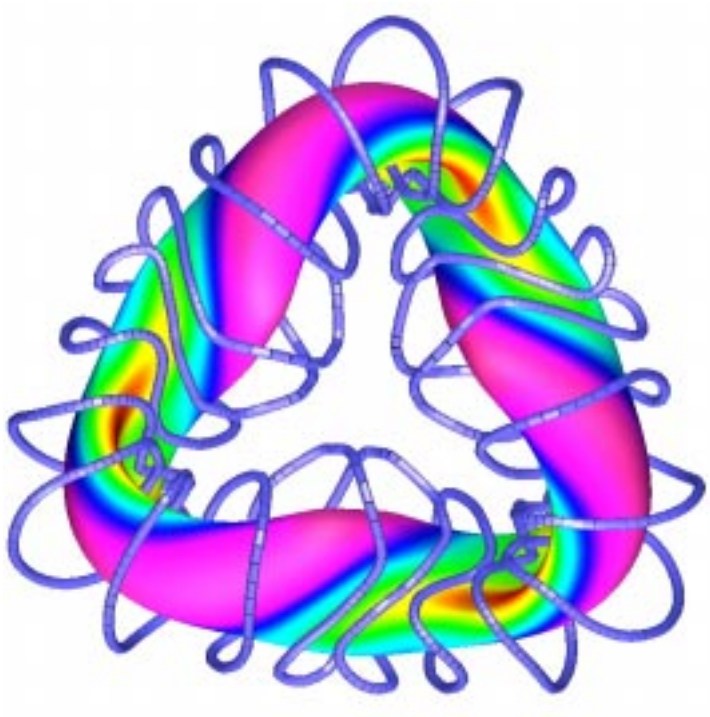
Low Bootstrap Current Configurations with <u>Stellarator</u> Shear ($d\iota/dr > 0$)

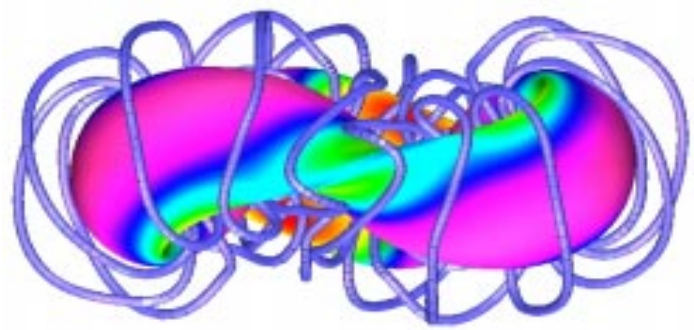
Progress Is Being Made in Different Areas

- **QOS physics studies are exploring different aspects of low R/<a> QO configurations**
  - ***Ballooning stability, thermal transport, energetic ion confinement, bootstrap current***
- **Configuration optimization studies are examining the best mix of features for a modest-size device**
- **Coil optimization studies are determining the best modular coil set for the optimized configuration**
- **Engineering studies are exploring different issues and approaches for a QOS device**
  - ***coil and vacuum vessel construction, costing***
- **Physics optimization and systems studies are exploring the extrapolation to an attractive reactor**

Features of Low-I_{BS} QO Stellarators

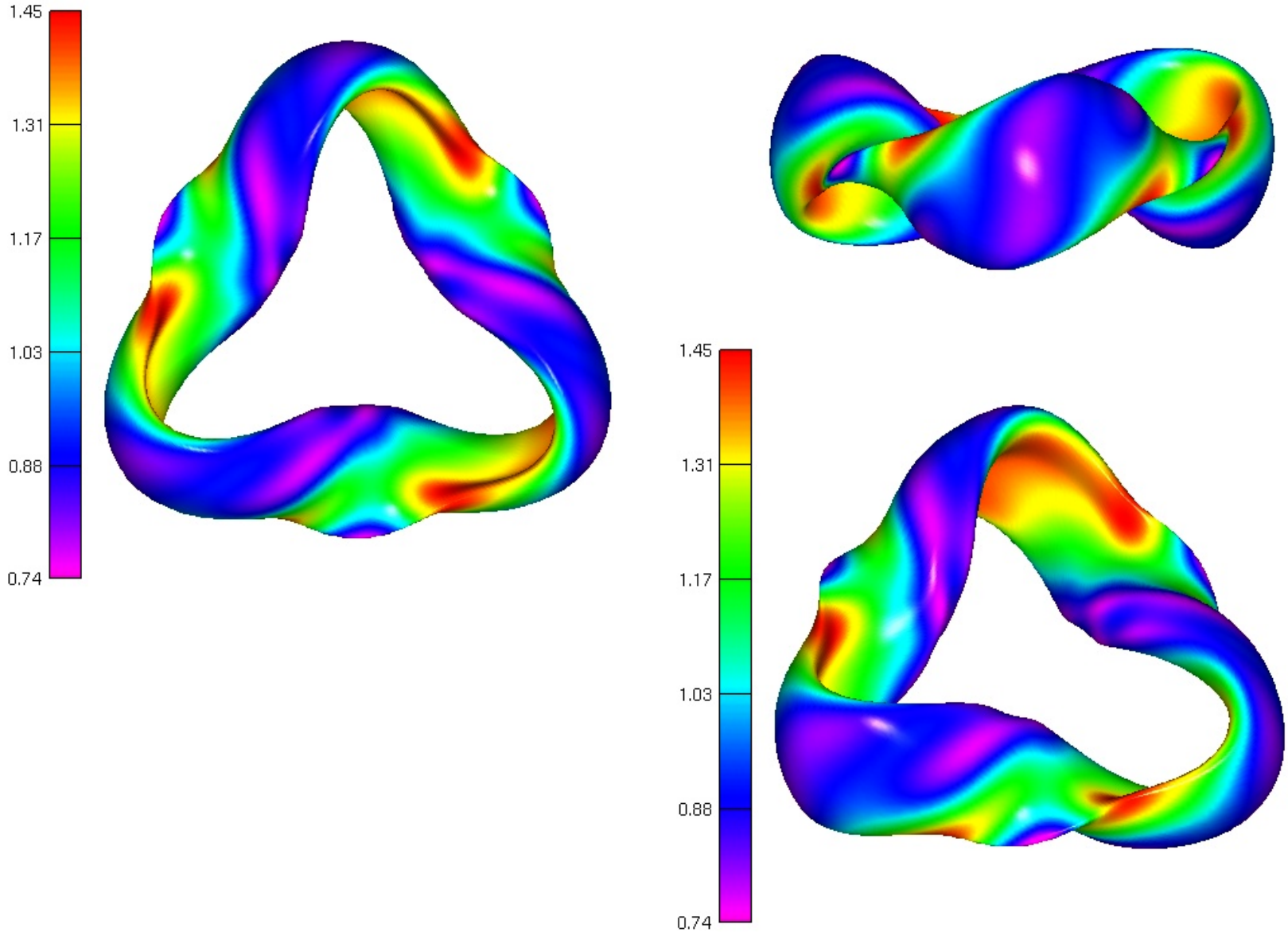
- **Stellarator-like shear , large helical component**
  - **typically $\iota(0)$ = 0.55-0.68, $\iota(a)$ = 0.74-0.87**
- **Bootstrap current ~1/10 current in a tokamak**
  - **configuration insensitive to increasing beta**
- **Ballooning stability limit 3-4%**
  - **magnetic well, Mercier stable out to plasma edge**



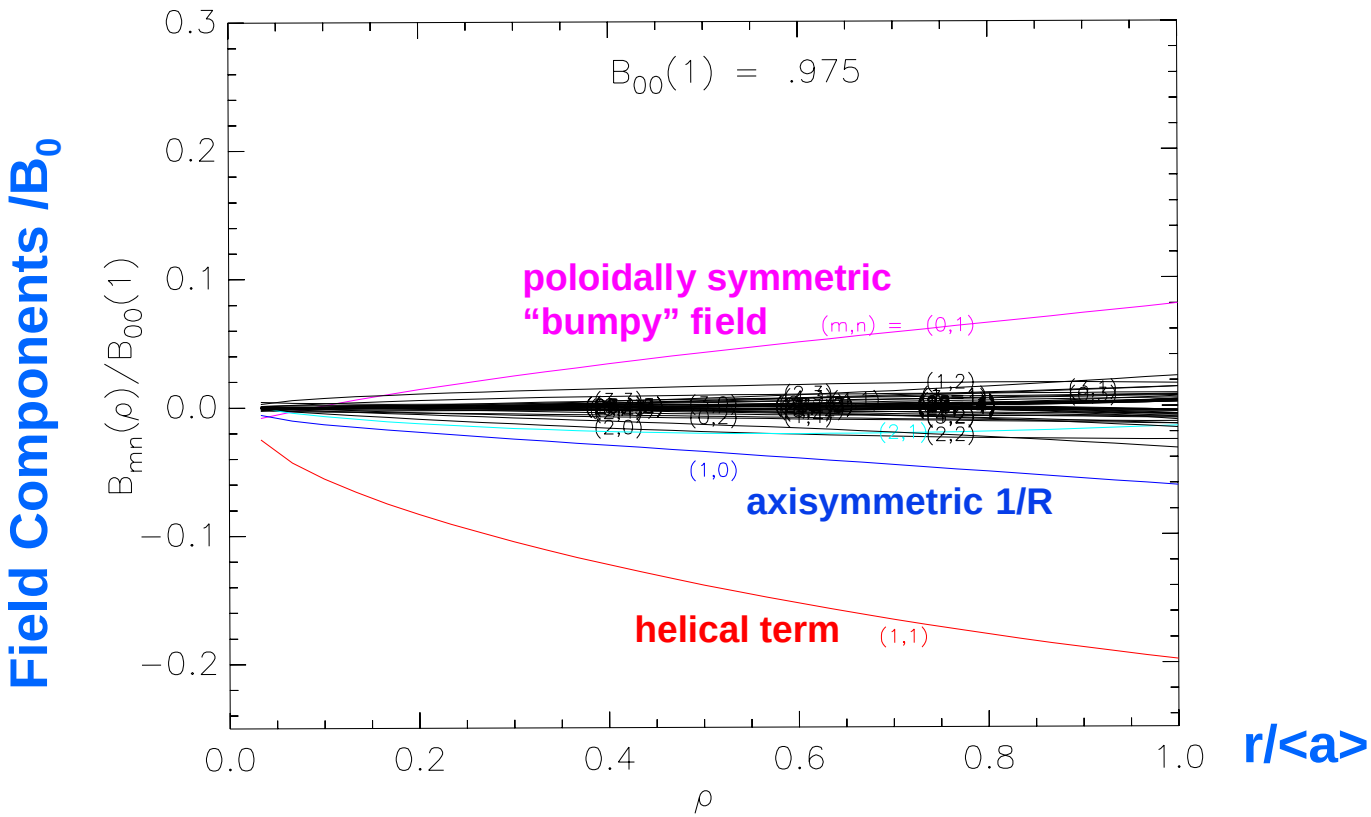


colors indicate contours of constant |B|

Low-I_{BS} QO Configurations

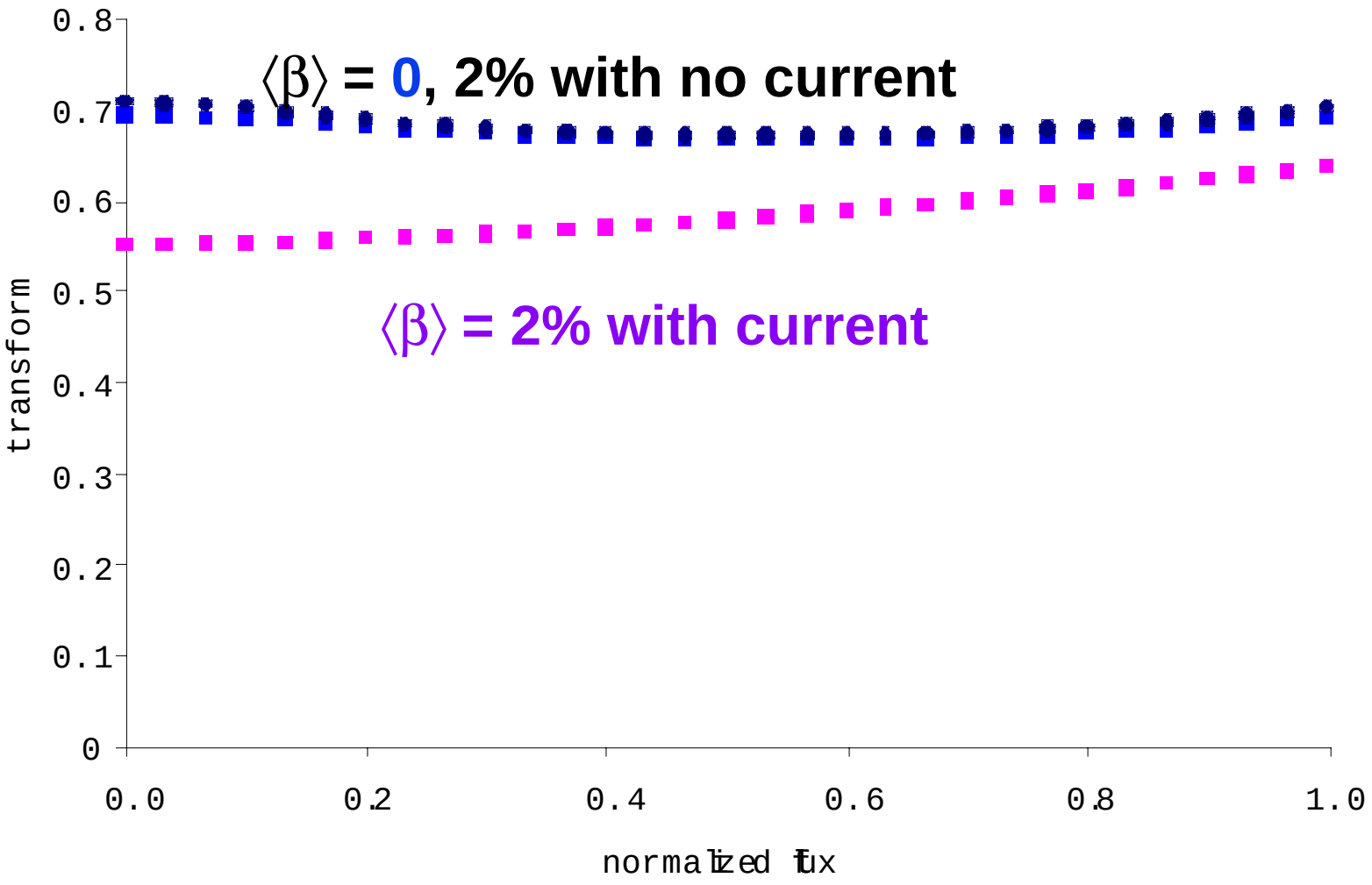


The Low-I_{BS} QO-Optimized Magnetic Field Has Several Spatial Components

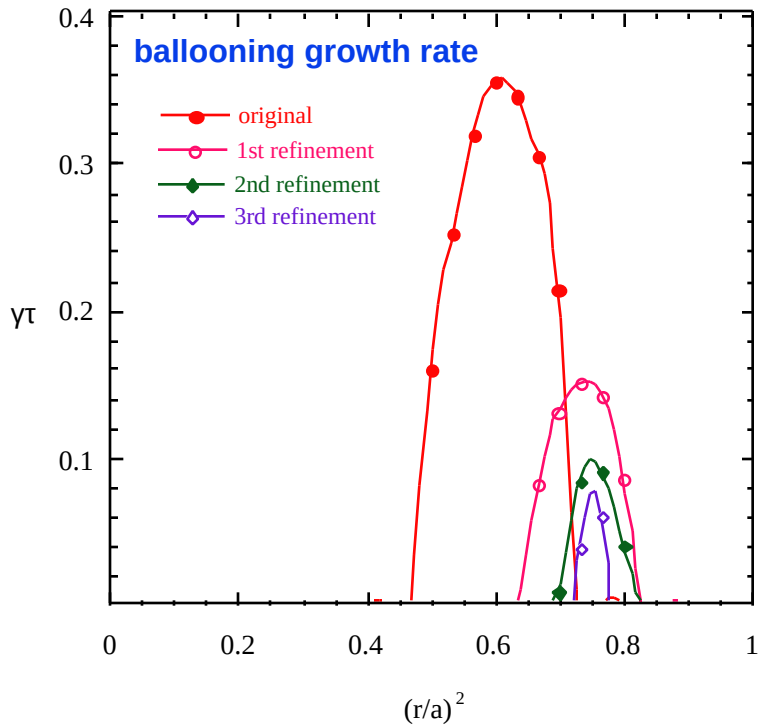


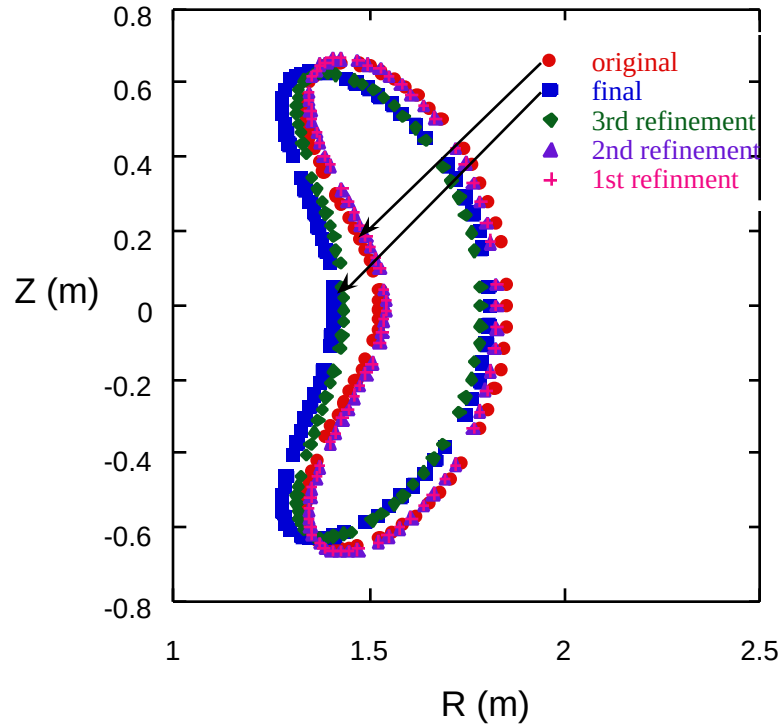
- Dominant helical shaping term produces higher rotational transform
- Small axisymmetric 1/R term reduces toroidal curvature drift
- Radially varying mirror "bumpy" term produces poloidal grad-B drift

Bootstrap Current Contributes ≈10% of the Net Transform Based on Equilibrium Calculations



Ballooning Stable at $\beta = 4\%$

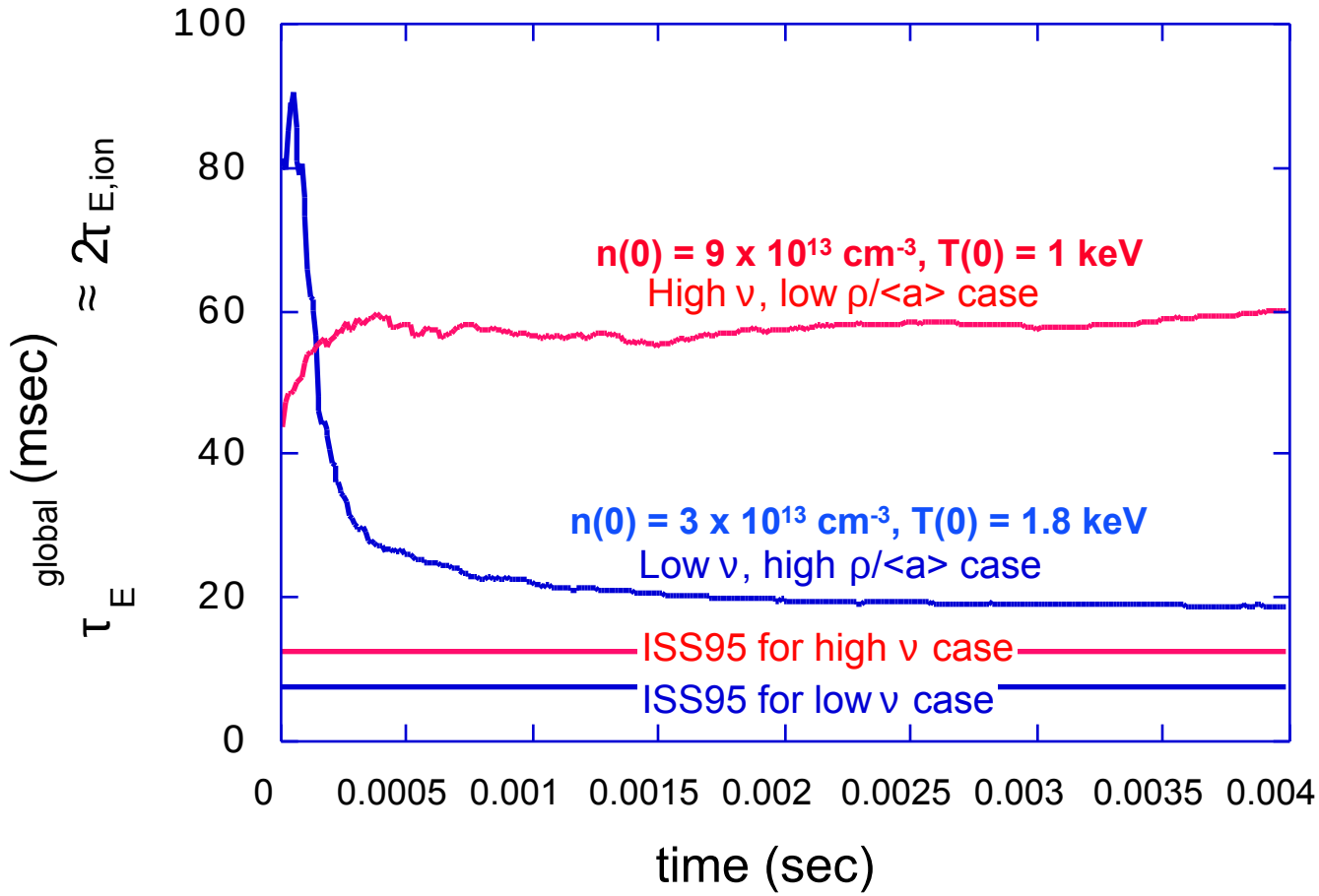




- **Original low-I_{BS} configuration, ballooning unstable at $\beta = 3\%$, was stabilized by small plasma boundary shape changes**
- **Pressure profile modification raises stable β to 4%**

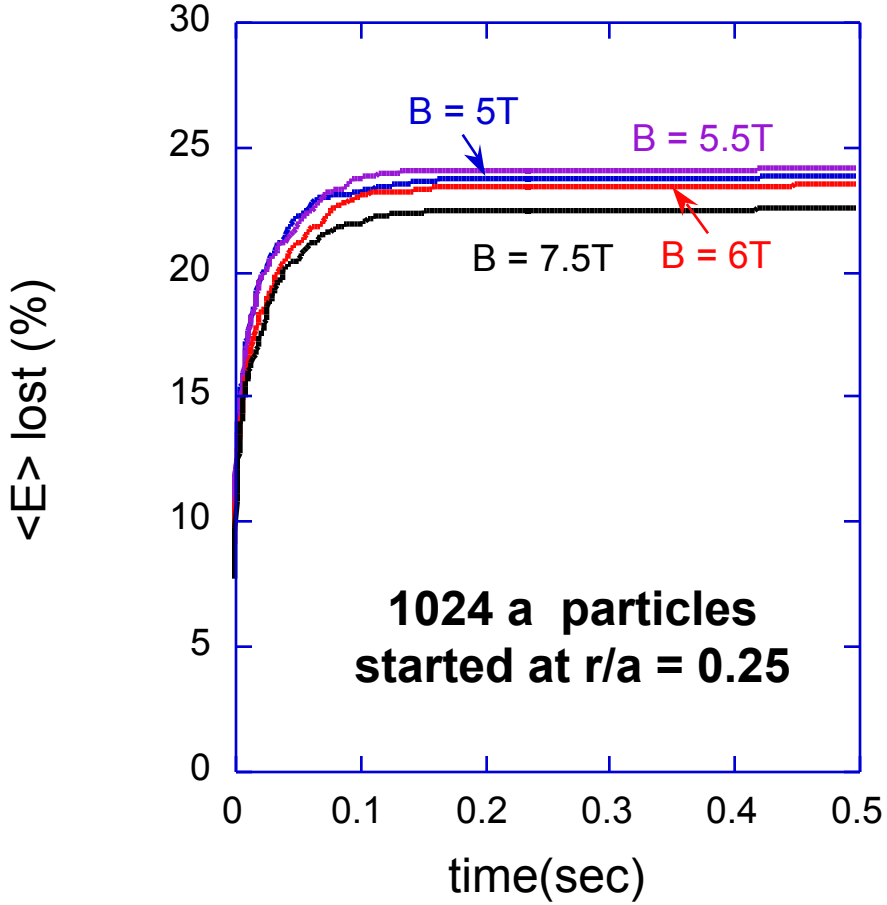
Global Transport Energy Lifetimes Are Not Dominated by Neoclassical Losses

- **Potential profile: ion root sign, follows temperature profile**
- **τ obtained from rate of ions escaping outer flux surface**

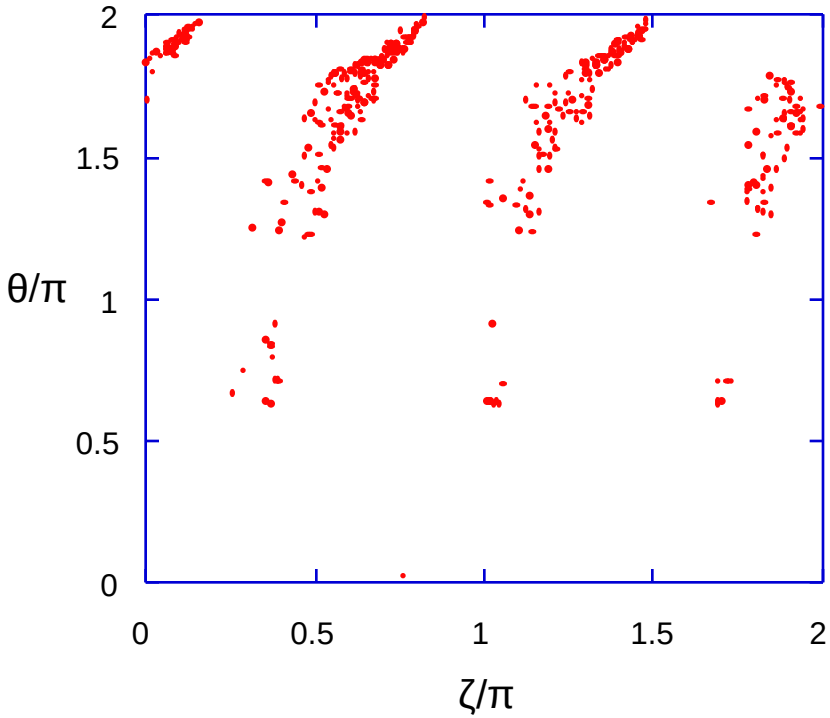


Configuration Not Yet Optimized for a Reactor

- **Alpha-particle losses are adequate for fusion power balance**
- **Impact points on wall compatible with divertor channel?**

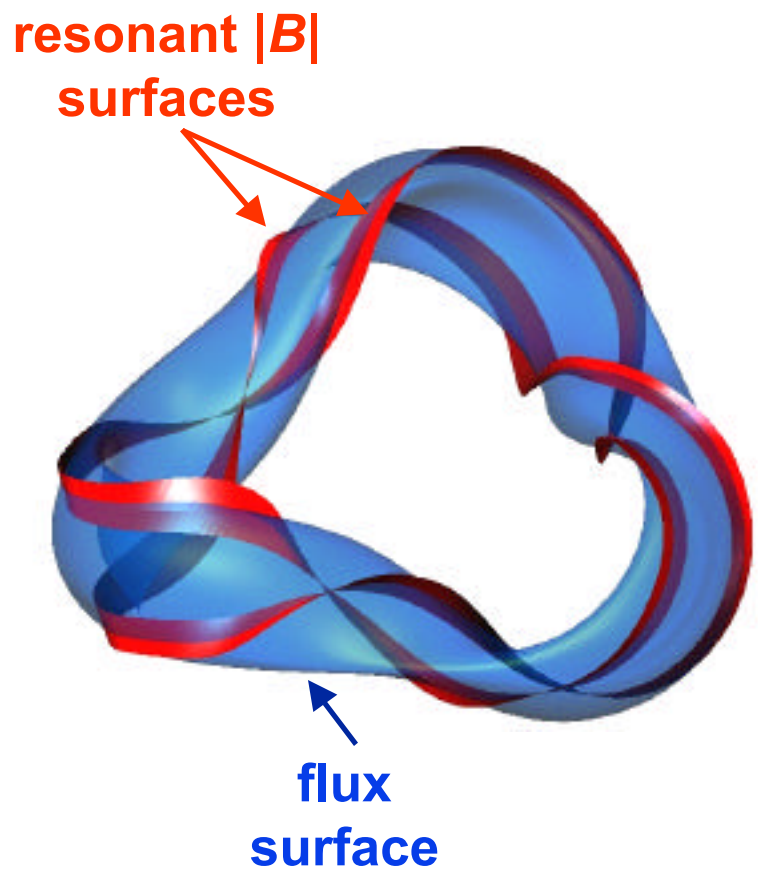


Alpha loss locations on outermost closed flux surface



Monte Carlo Calculations Used to Assess Energetic Ion Losses and ICRF Heating

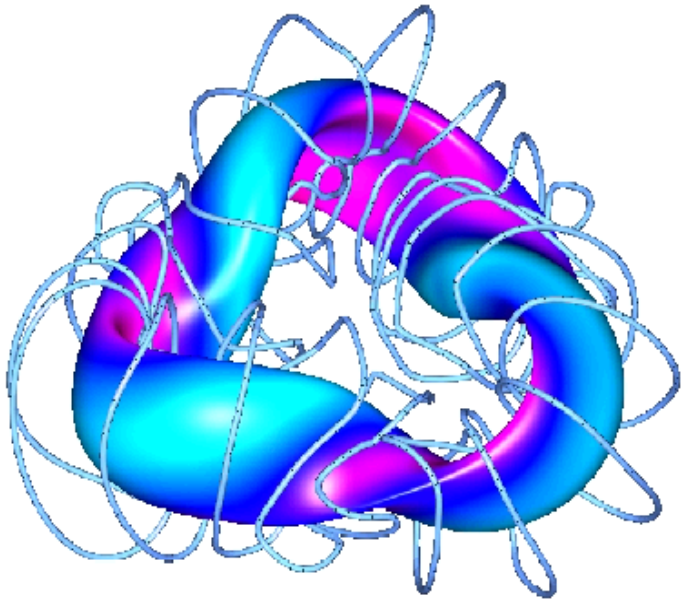
- Ions are started with $v_{||0}/v = 0$ at intersections of $|B| = B_{res}$ contours with flux surfaces
- Confinement of ICRF tail ions was examined
  - Loss rate was less than for CHS in which ICRF heating was successful
  - QOS would use ICRF bulk heating rather than energetic ion tail heating
- Quasi-linear ICRF diffusion heating/diffusion calculations are being done to follow ions as they increase in energy

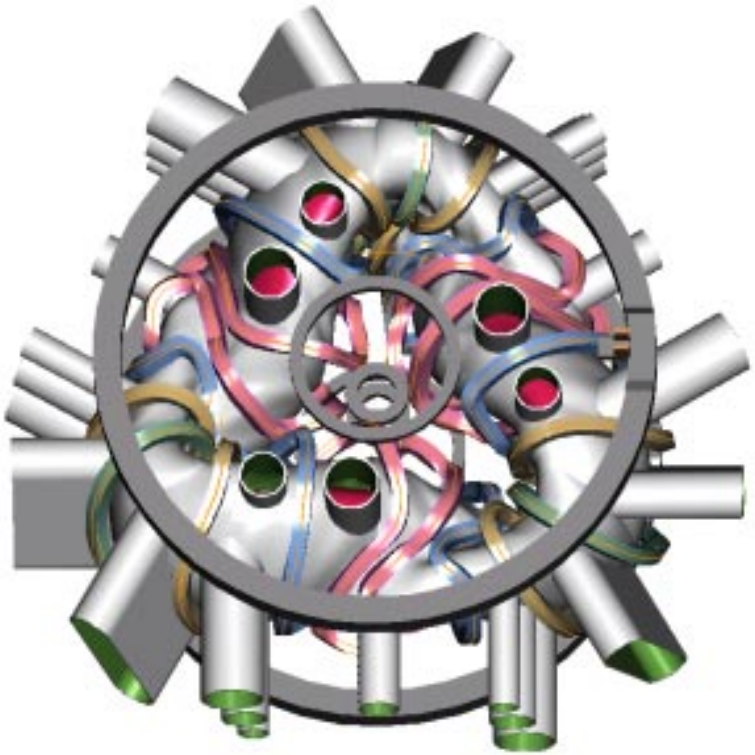


Reference QOS Properties

- 3 field periods, R/<a> = 3.6; global magnetic well
- $\iota(0) = 0.56$, $\iota(a) = 0.65$ (monotonic)
- Good vacuum flux surfaces; little change with β
- Bootstrap current < 1/10 current in similar tokamak
- Shaped plasma surface gives ballooning $\langle\beta\rangle$ limit 3-4%
- Good neoclassical transport ($\tau_{E,neo} \approx 3\text{-}5 \times \tau_E^{ISS95}$) from 3-D Monte Carlo loss rate calculation
- Confinement of ICRF-generated tails better than CHS
- 7 modular coils per period -- changing current in corner coils $\pm$50% changes R/<a> from 2.9 to 4.6

Transformation from Physics to Engineering





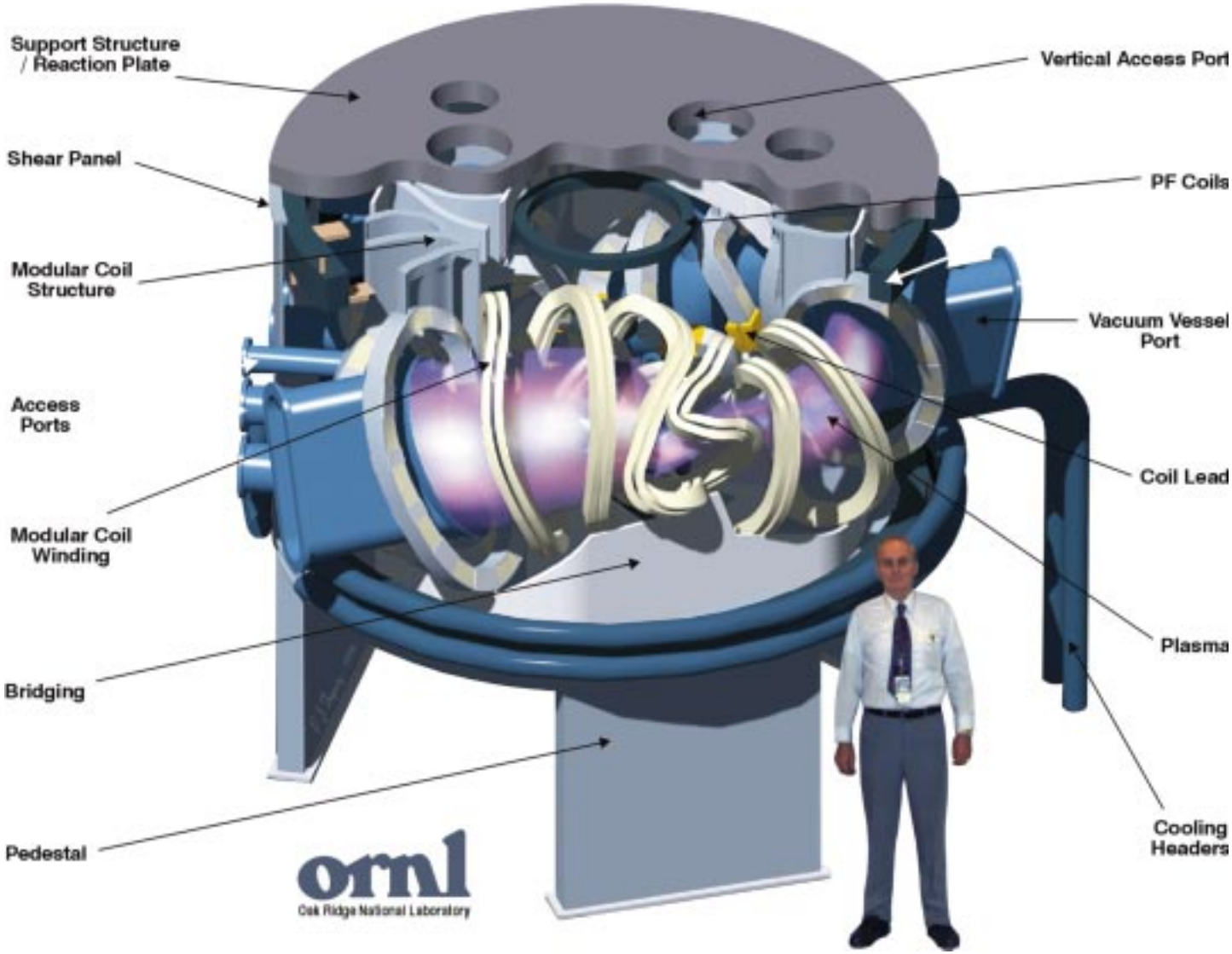
Scoping Study Parameters

- R_0 = 1 m, $\langle a \rangle$ = 28 cm
- B_0 = 1 T, t_{pulse} = 1 s

Q O S

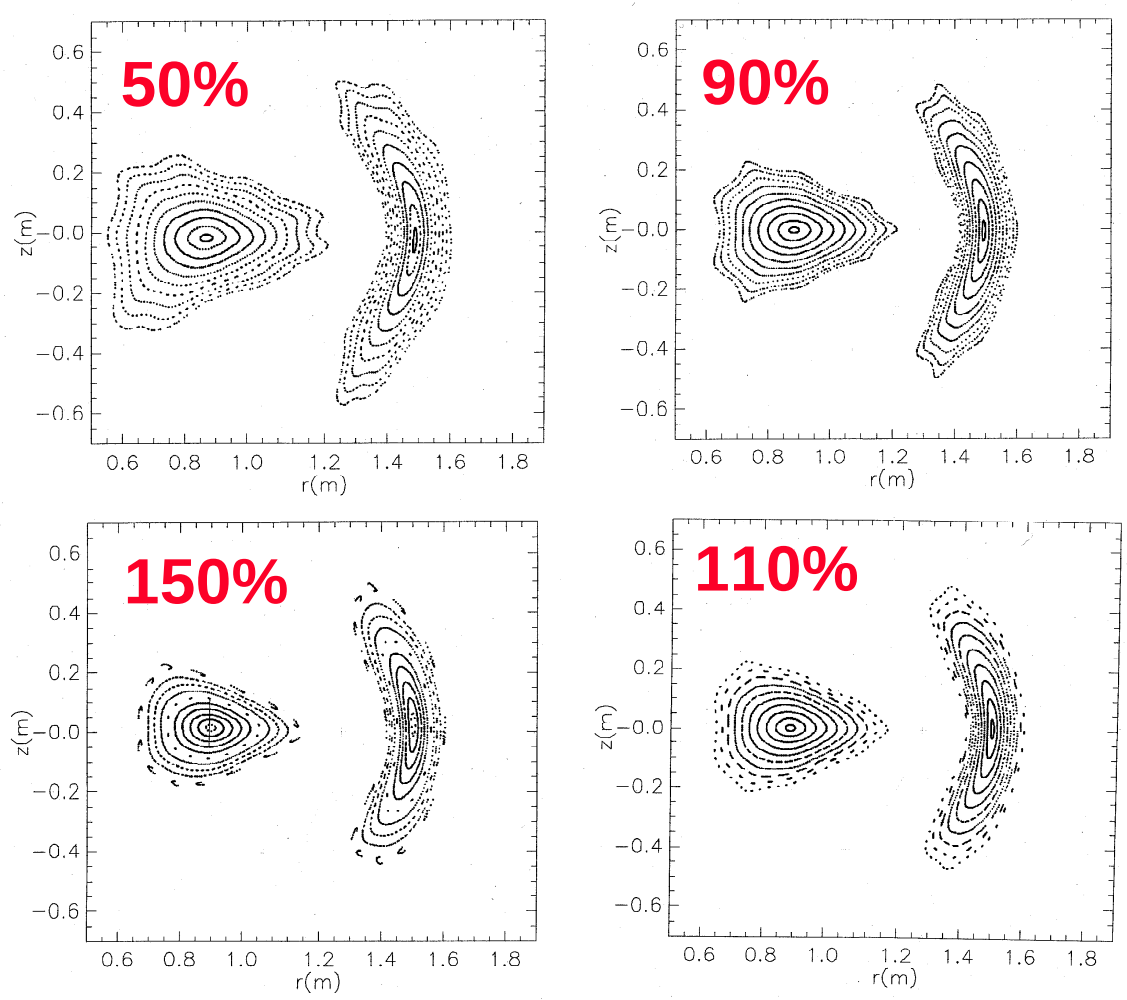
Quasi-Omnigeneous Stellarator

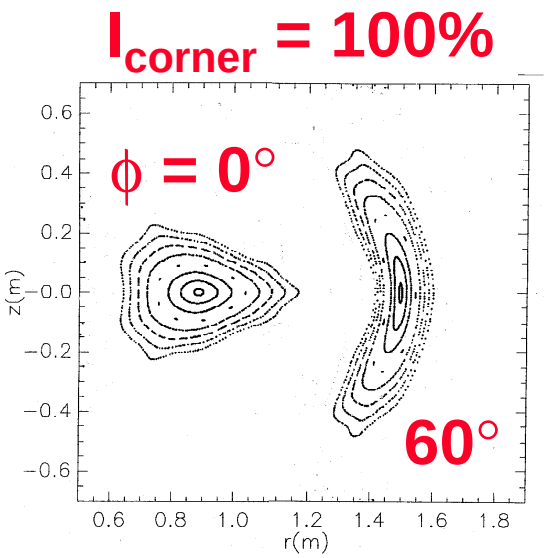
A Compact, Low Current Fusion Experiment



QOS Modular Coils Allow Configuration Flexibility, Show Robustness

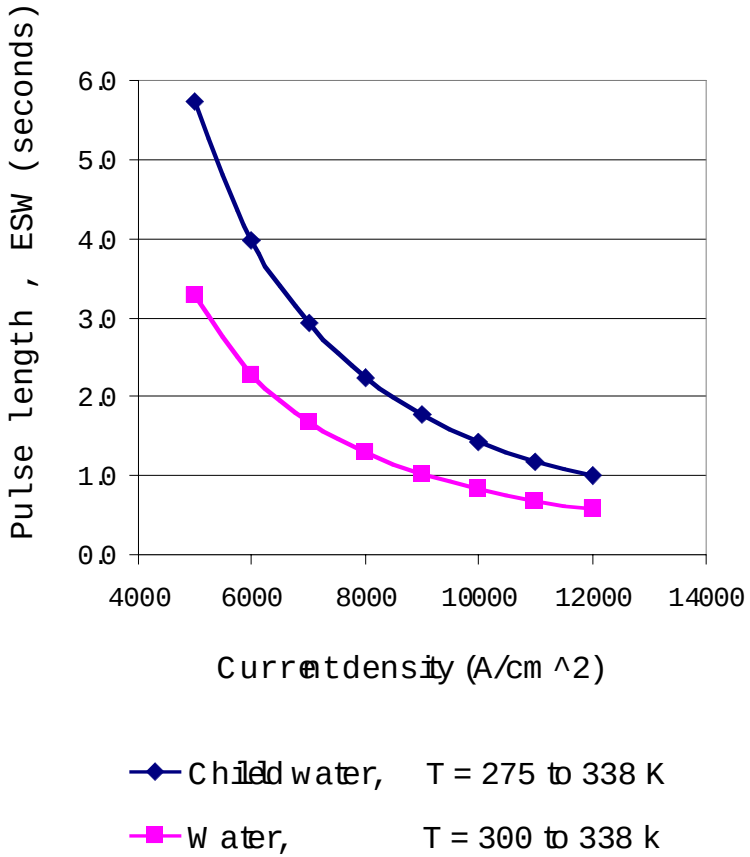
- ±50% change in corner coil current allows changing the plasma aspect ratio from 2.9 to 4.6



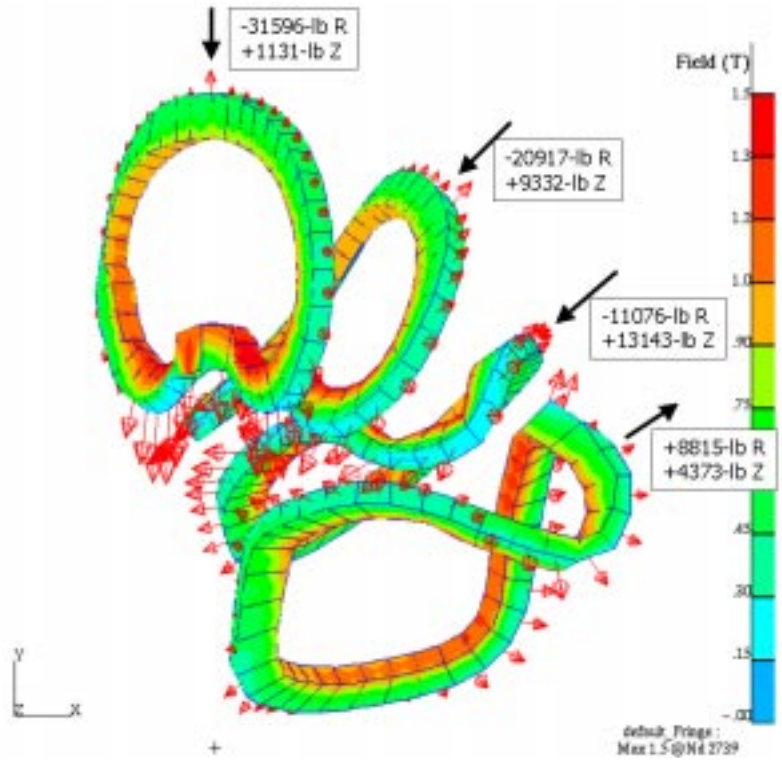


Initial Examination of QOS Modular Coils

Pulse Length



Forces

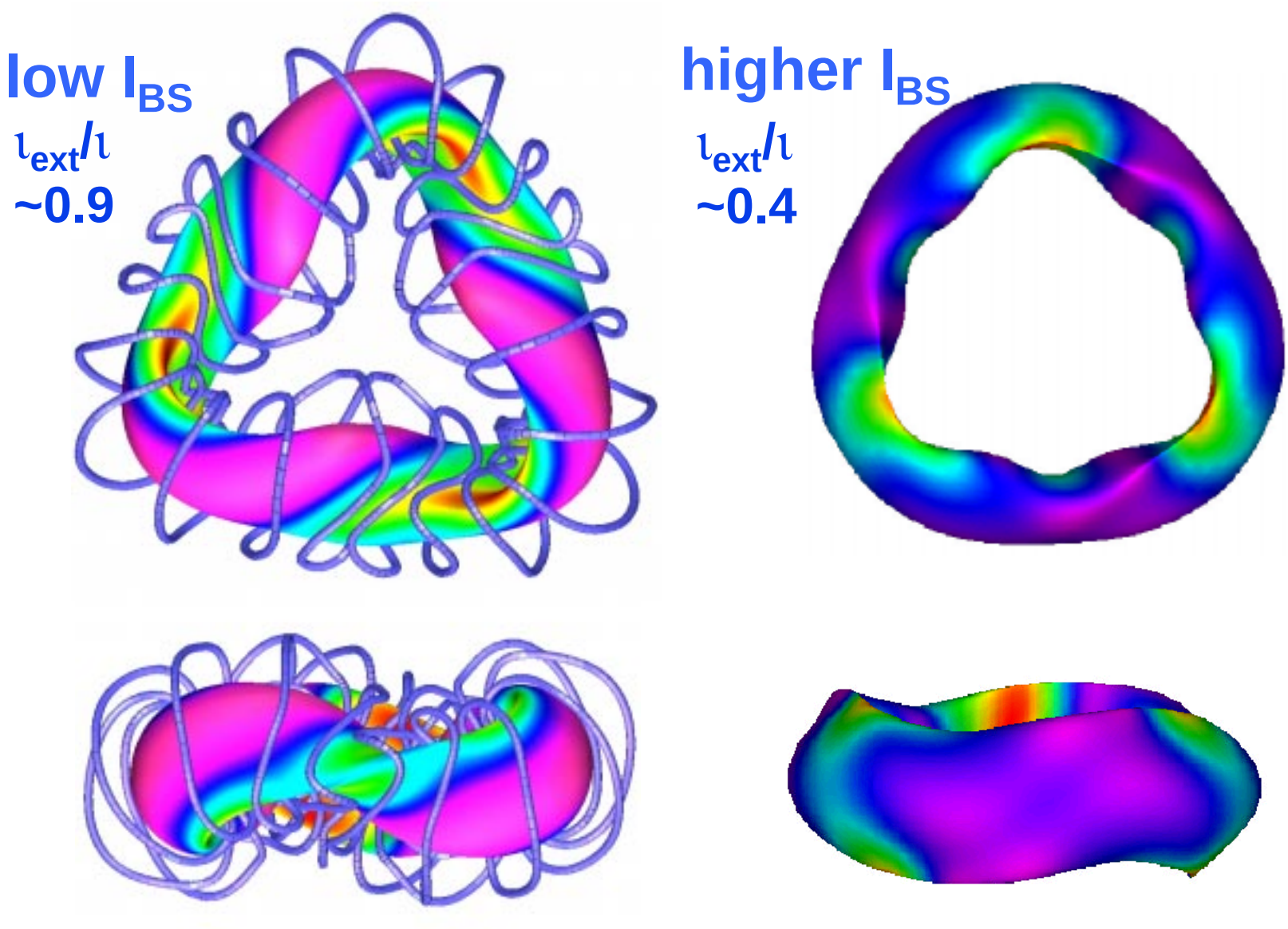


Higher Bootstrap Current Configurations with <u>Tokamak</u> Shear ($d\iota/dr < 0$)

Higher-I_{BS} QO Stellarator Features

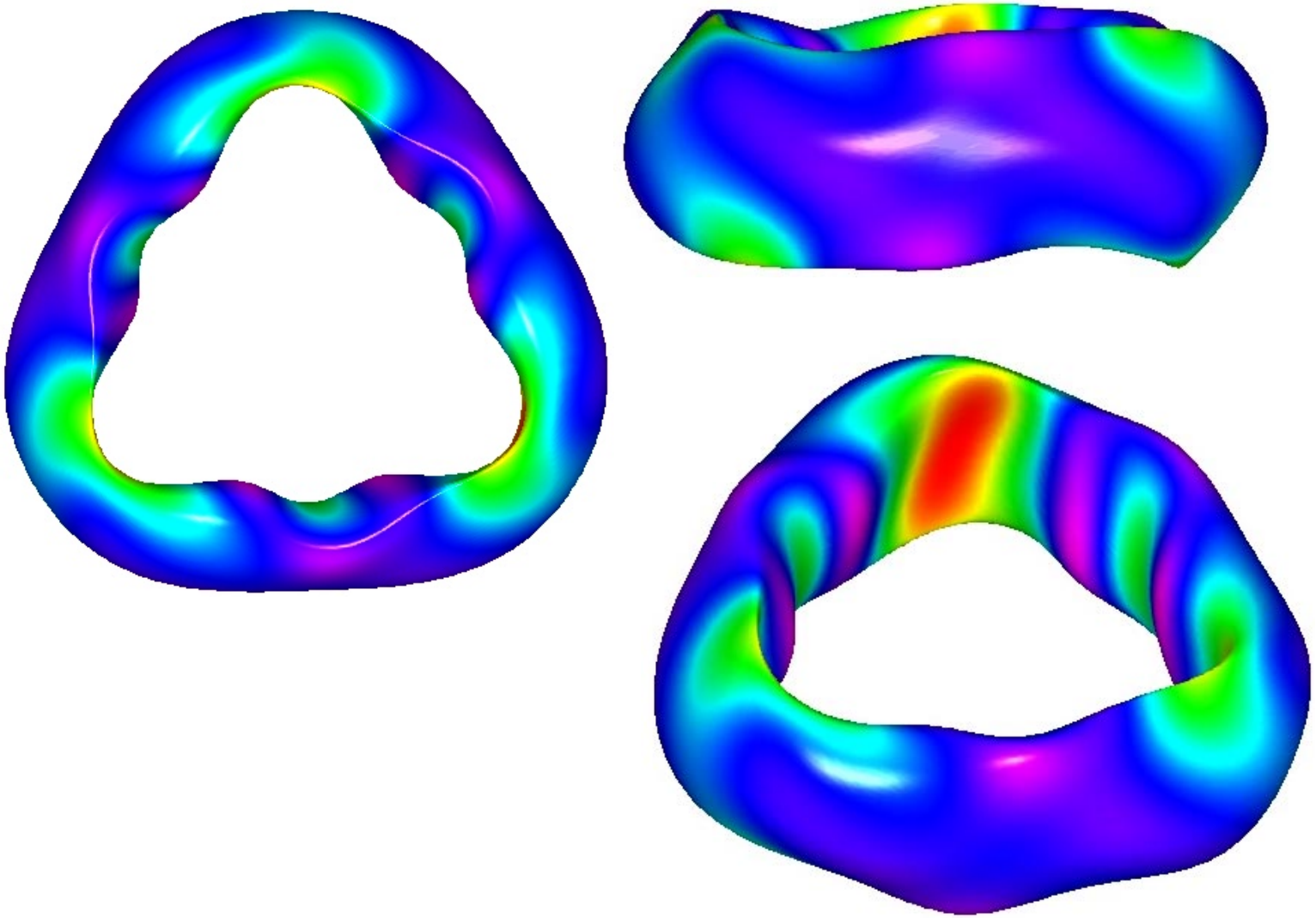
- **Tokamak-like shear ($d\iota/dr < 0$)**
  - $\iota(0) \approx 0.47$ ($q > 2$) and $\iota(a) = 0.12$ ($q \approx 8$)
- **Bootstrap current $\approx$1/4 that of equivalent tokamak**
  - $\approx$40% of the edge transform comes from the coils
- **Ballooning stable at $\langle\beta\rangle$ = 23%**
  - smoother corners lead to high ballooning beta limits
  - stable to Mercier modes and internal kinks
  - smaller j and ∇j near edge $\Rightarrow$ external kink limit >10%?
- **Less helical axis excursion**
  - simpler modular coils $\Rightarrow$ easier fabrication, lower cost?
- **More mirror-like |B| variation on a flux surface**
  - larger plasma-coil separation possible? $\Rightarrow$ smaller reactor
- **Transport ~2x higher than best lower-I_{BS} QO case, but still ~1.6 better than ISS95 stellarator scaling**

Comparison of QO Stellarators



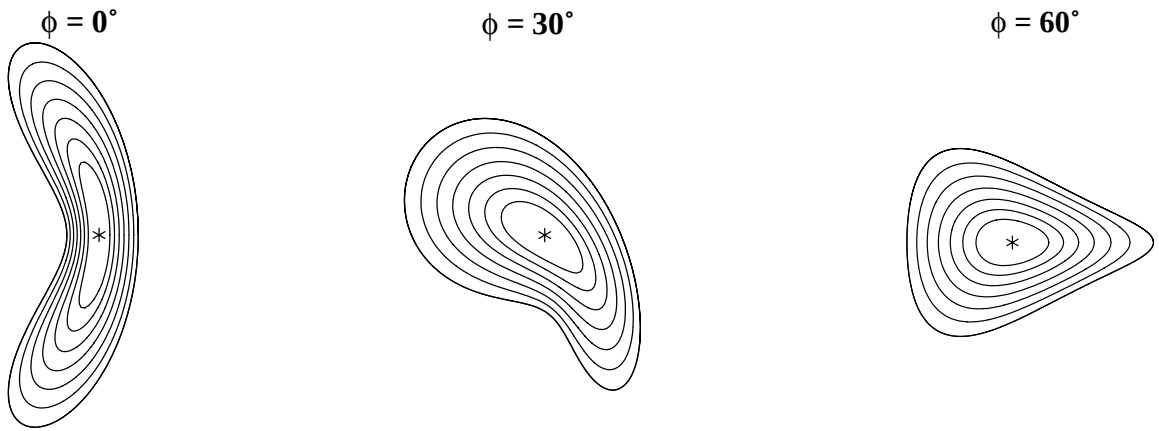
colors indicate contours of constant |B|

Higher-I_{BS} QO Configurations

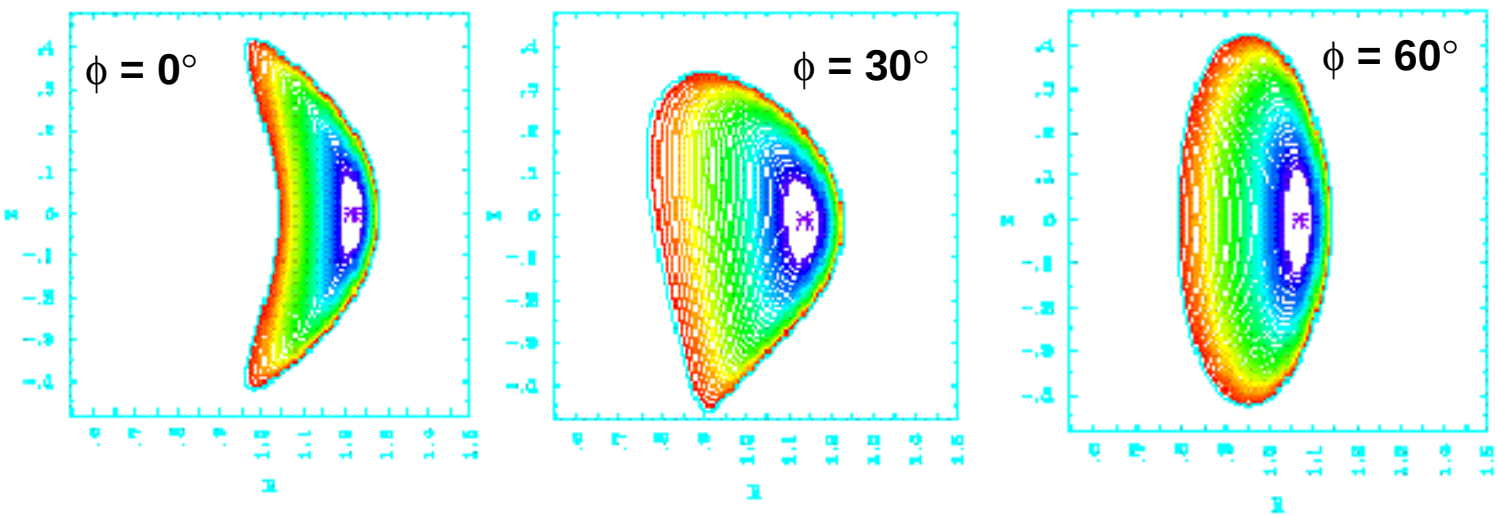


Plasma Geometry Is Very Different for the Two Types of QO Configurations

Low-I_{BS} , $d\iota/dr > 0$; <u>large helical axis excursion</u>, $\beta \sim 4\%$

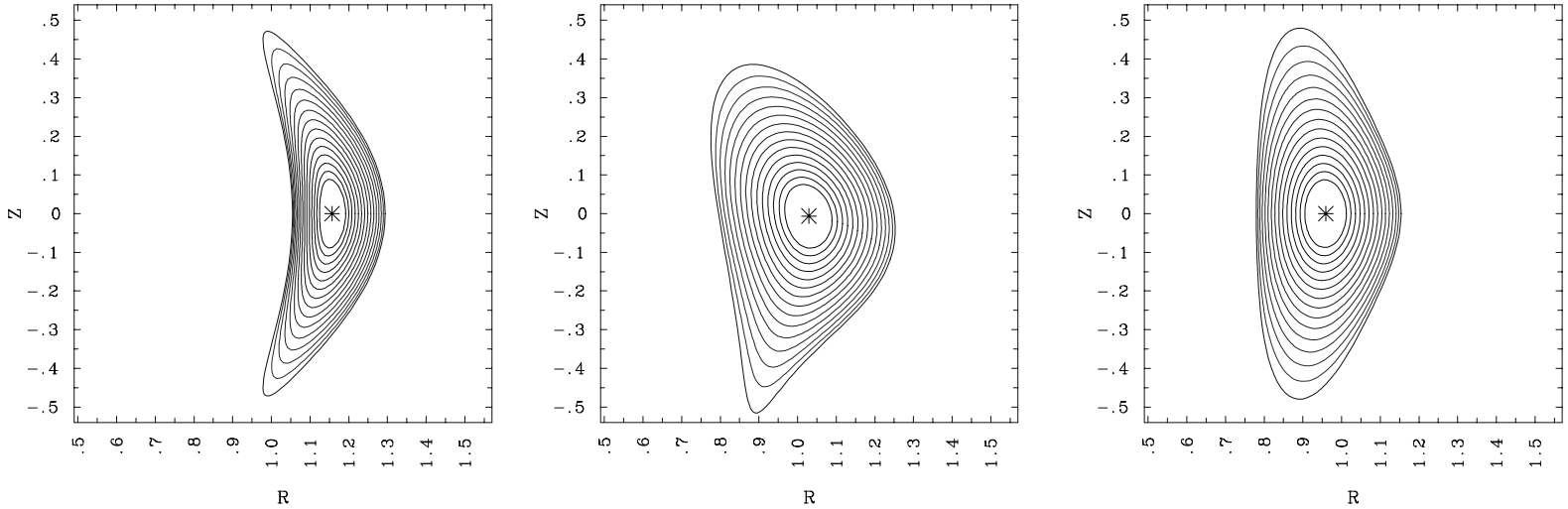


Higher-I_{BS} , $d\iota/dr < 0$; <u>nearly planar axis</u>, $\beta \sim 15\%$

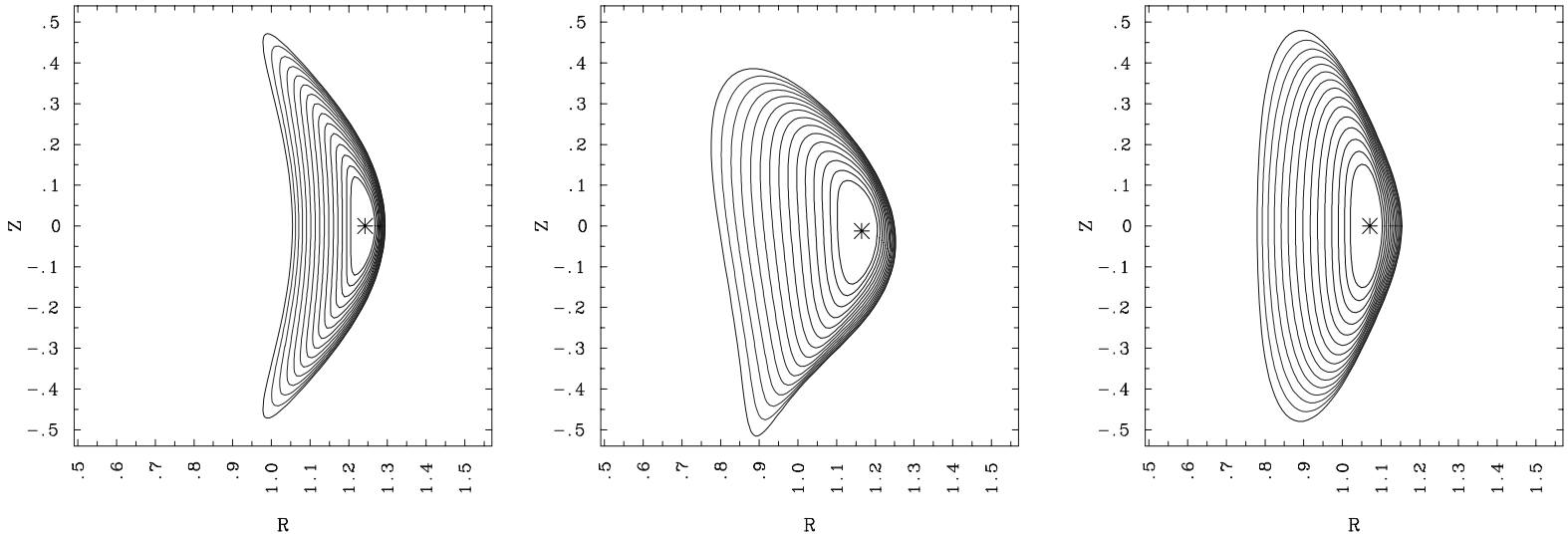


Magnetic Well Increases with β

⟨β⟩ = 0

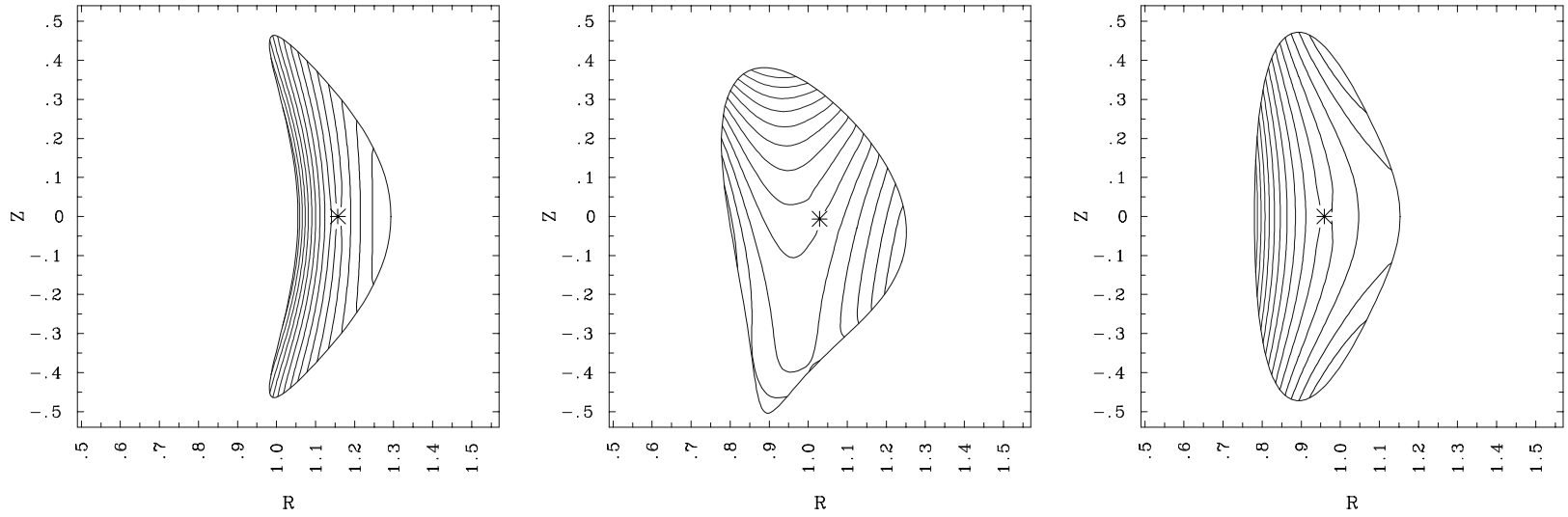


⟨β⟩ = 23%

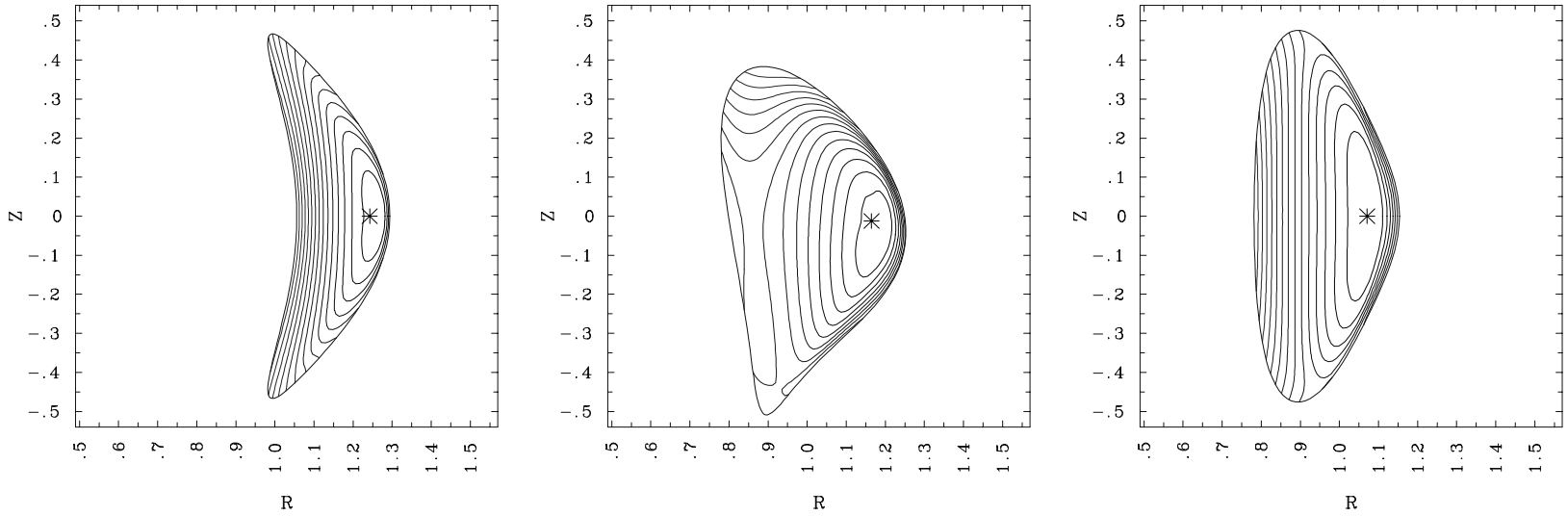


|B| Contours Close with Increasing β

⟨β⟩ = 0

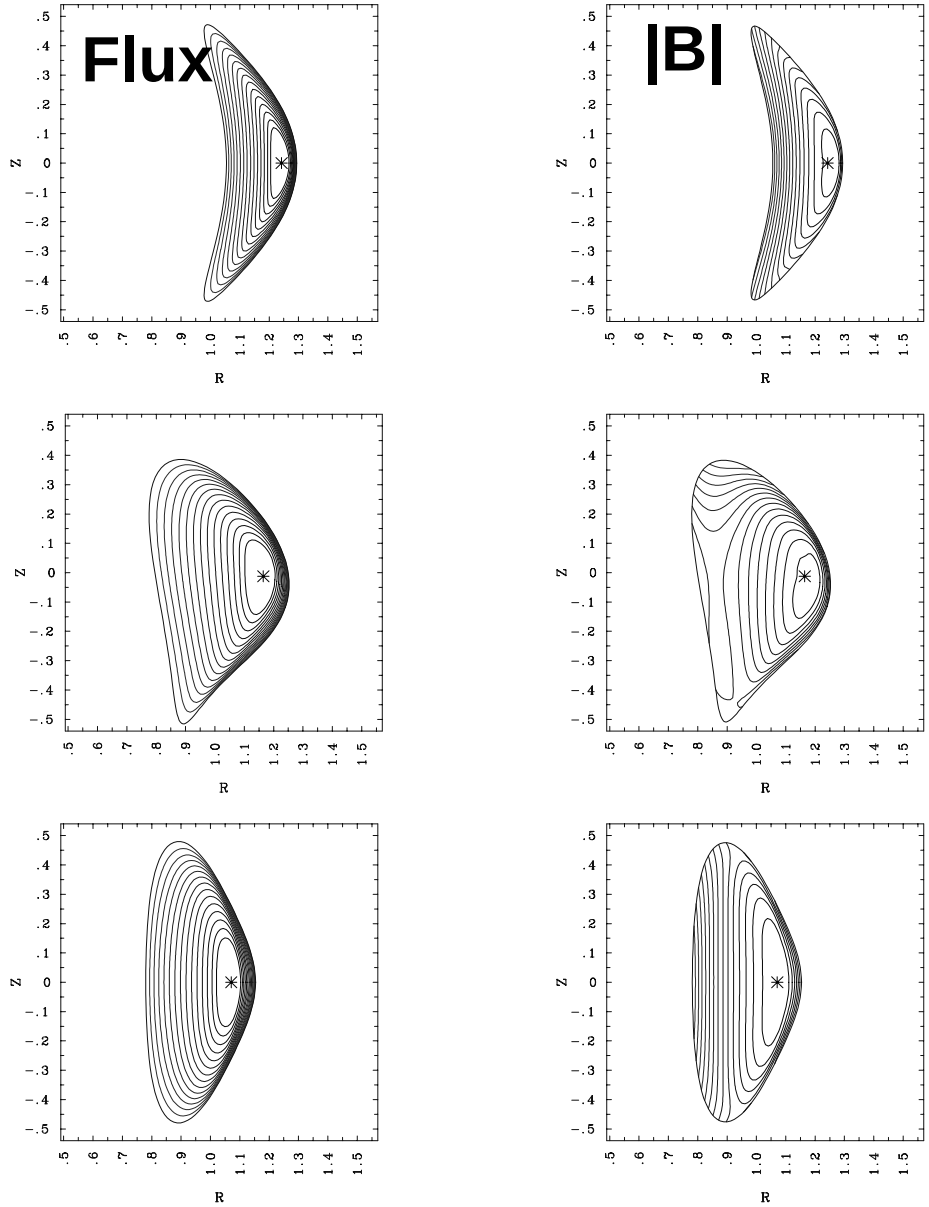


⟨β⟩ = 23%



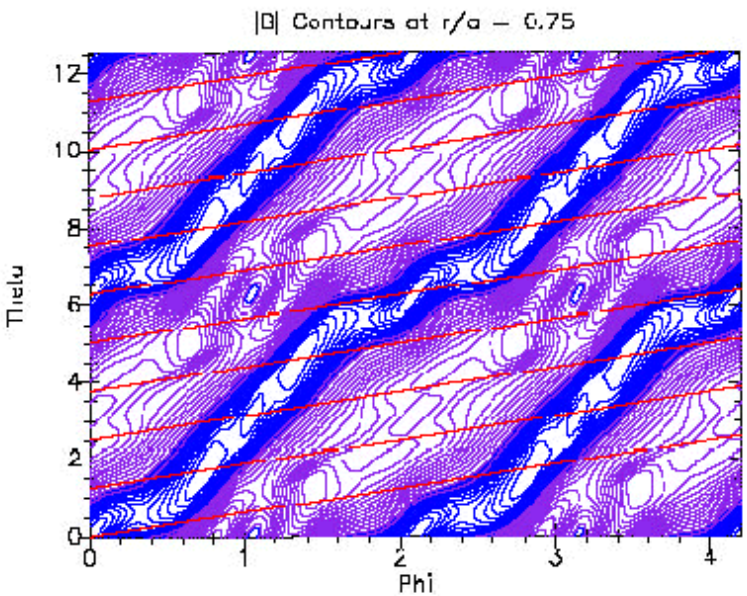
At High β |B| Surfaces Close and Have Similar Shapes As Flux Surfaces

<β> = 23%

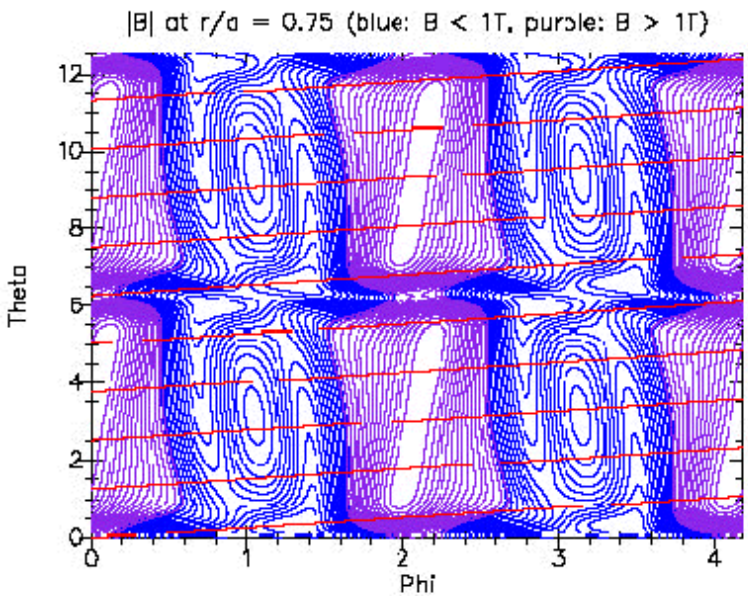


|B| Structure Is Very Different for the Two QO Stellarator Types

earlier near quasi-helical
$\langle\beta\rangle$ = 2% QO case

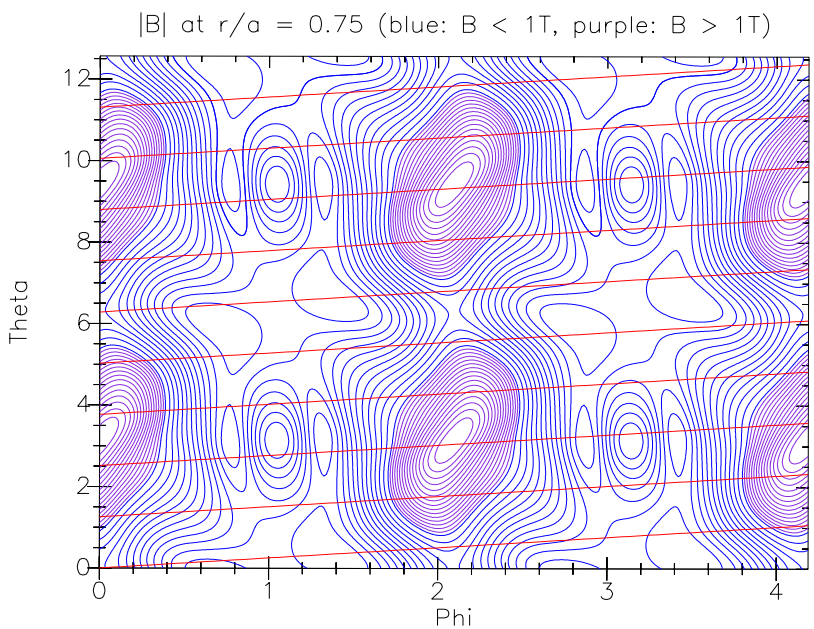


newer near quasi-poloidal
$\langle\beta\rangle$ = 14% QO case

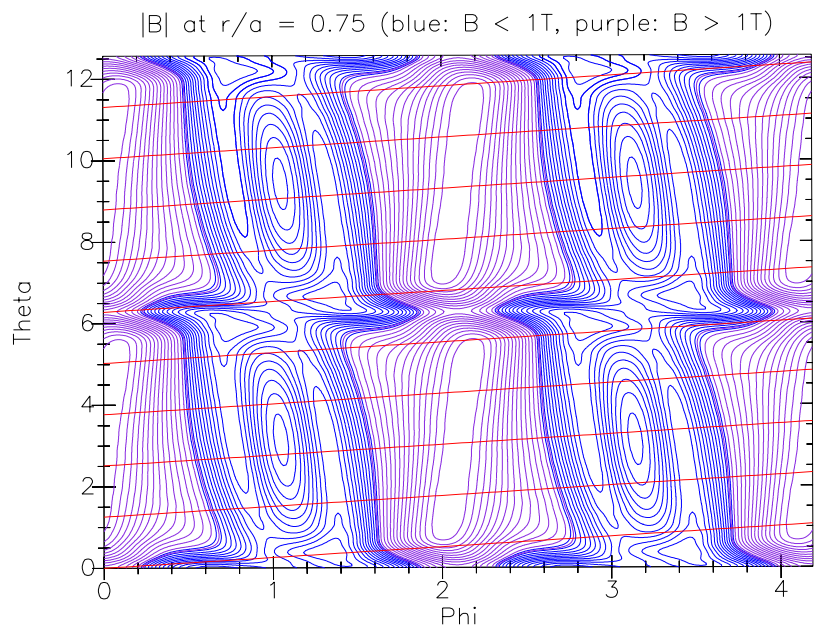


|B| Contours for Higher-I_{BS} Configurations Show a Significant Improvement in Poloidal Symmetry with Increasing <β>

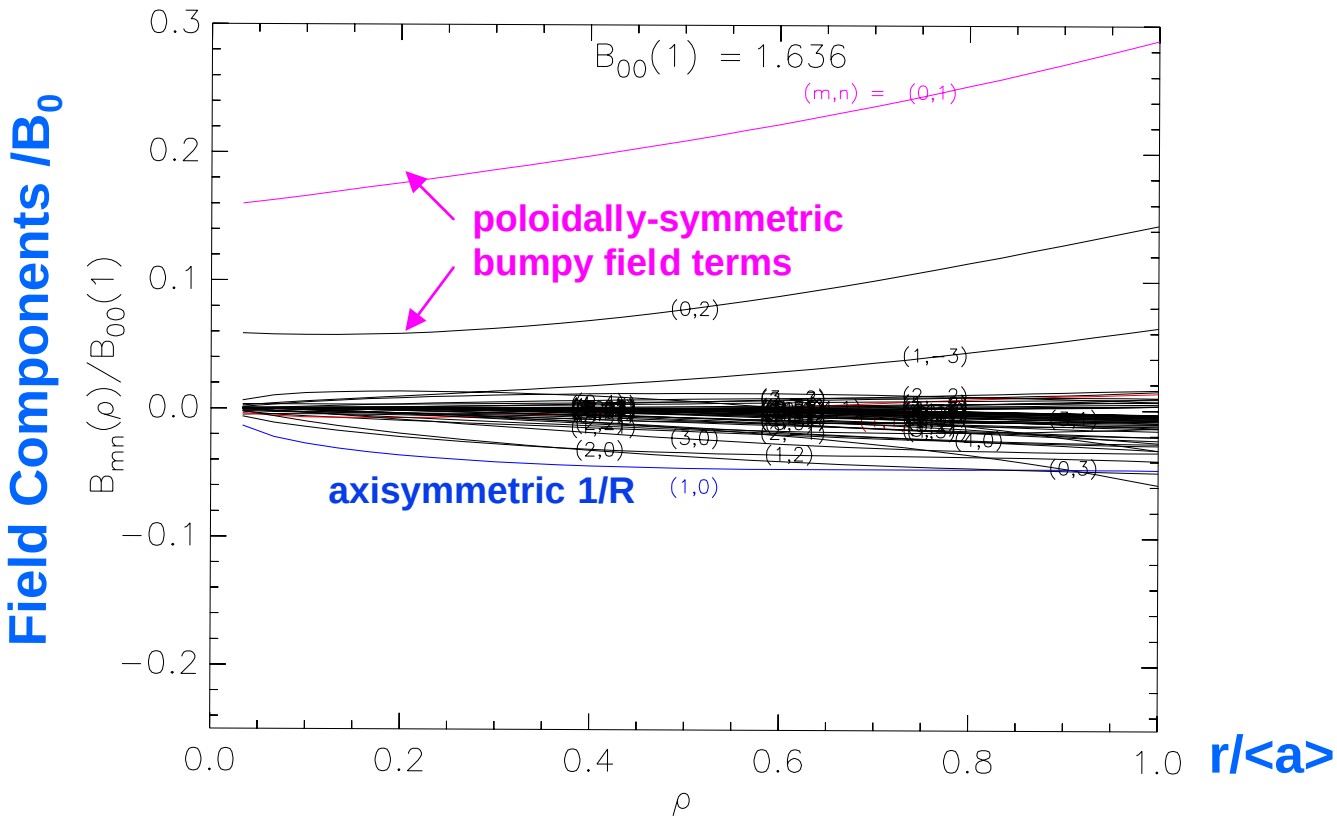
<β> = 0%



<β> = 23%



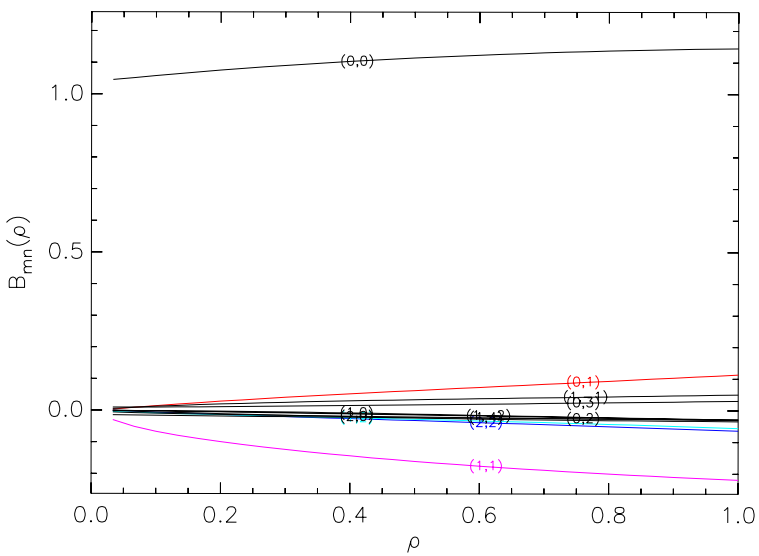
The Higher-I_{BS} QO-Optimized Magnetic Field Has Different Spatial Components



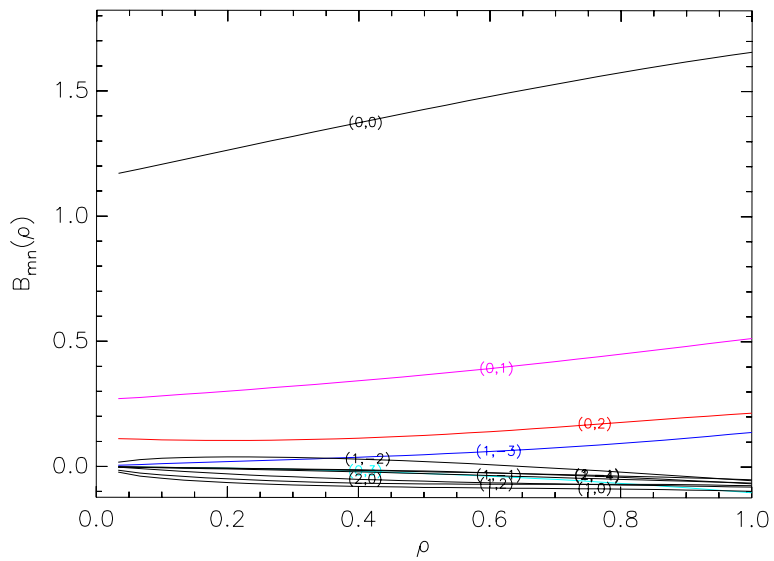
- Dominant poloidally-symmetric terms >5 times larger
- Small axisymmetric 1/R term reduces toroidal curvature drift
- Helically-symmetric terms >20 times smaller

Variation of B_{mn} Spectra with $<\beta>$ Differs for Low- and Higher-I_{BS} Configurations

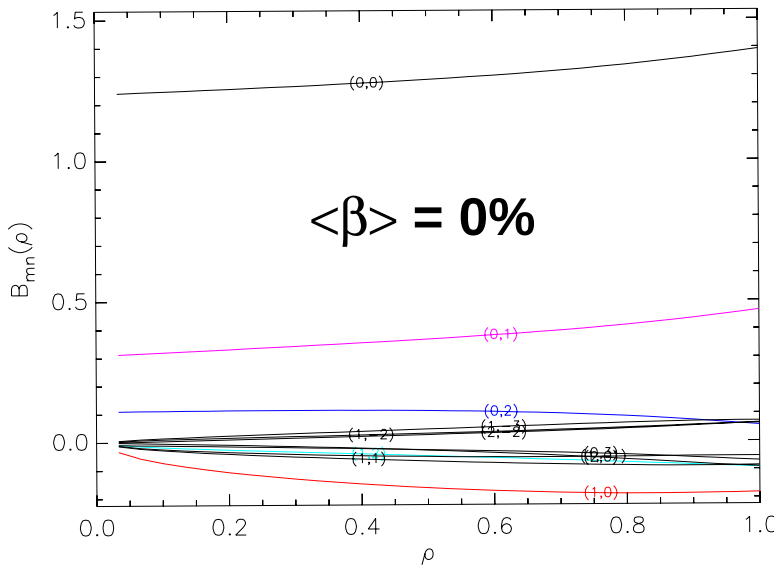
Low-I_{BS} QO Configuration (at $<\beta>$ = 2%)

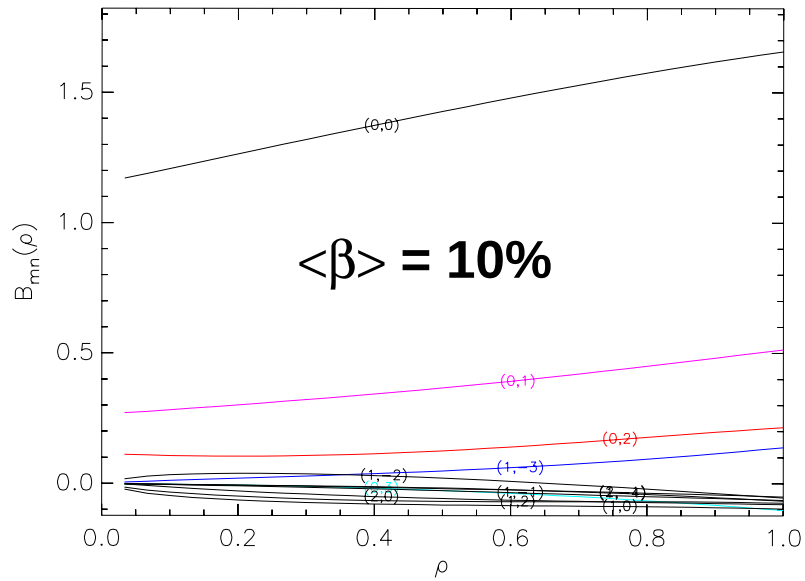


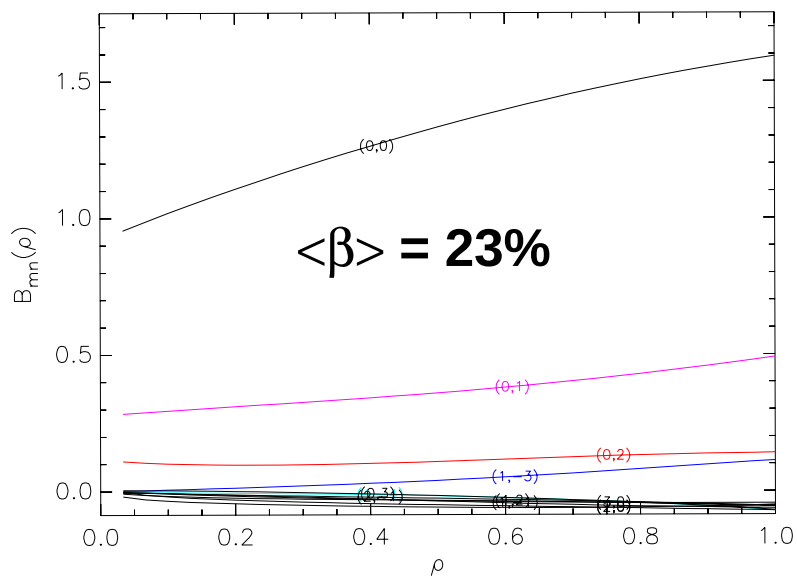
High-I_{BS} QO Configuration (at $<\beta>$ = 10%)



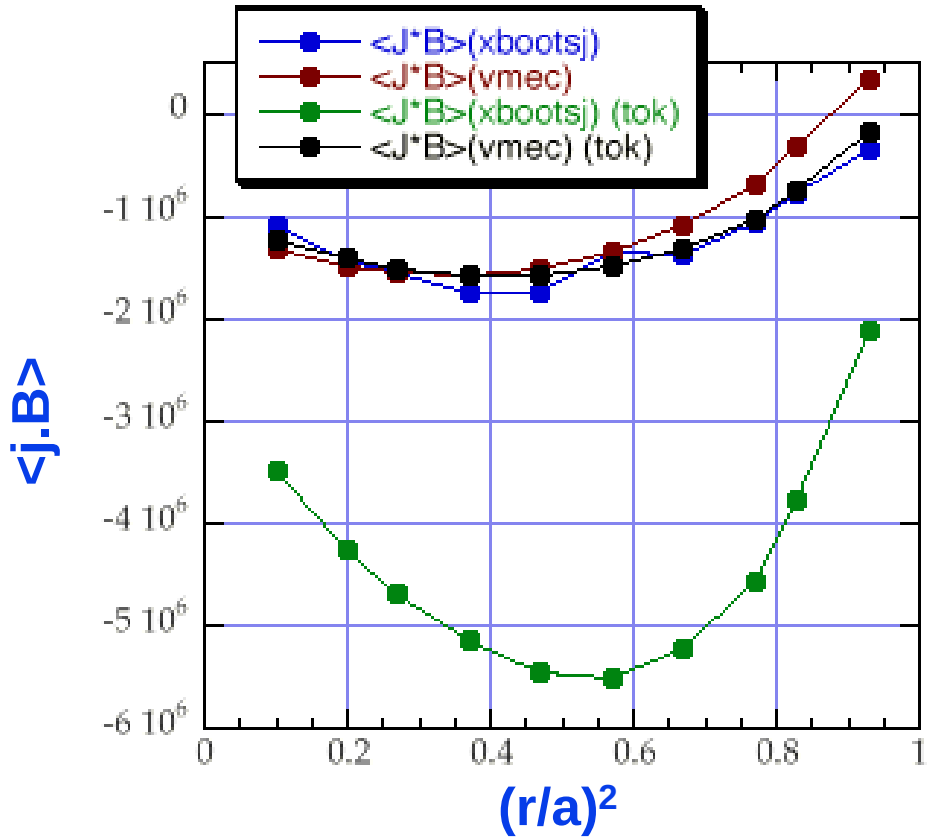
Variation of B_{mn} Spectra with <β> for Higher-I_{BS} Configurations







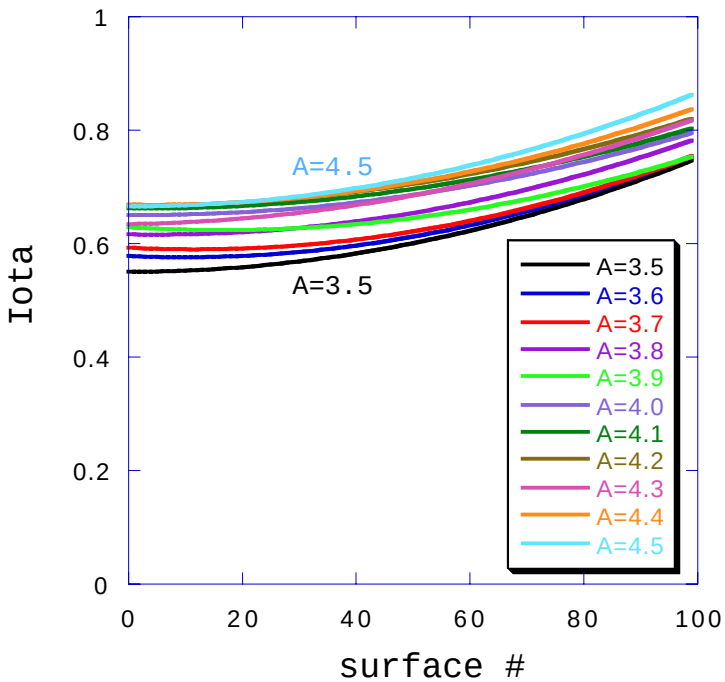
⟨β⟩ = 15% QO Configuration Has 1/4 the Bootstrap Current of Equivalent Tokamak



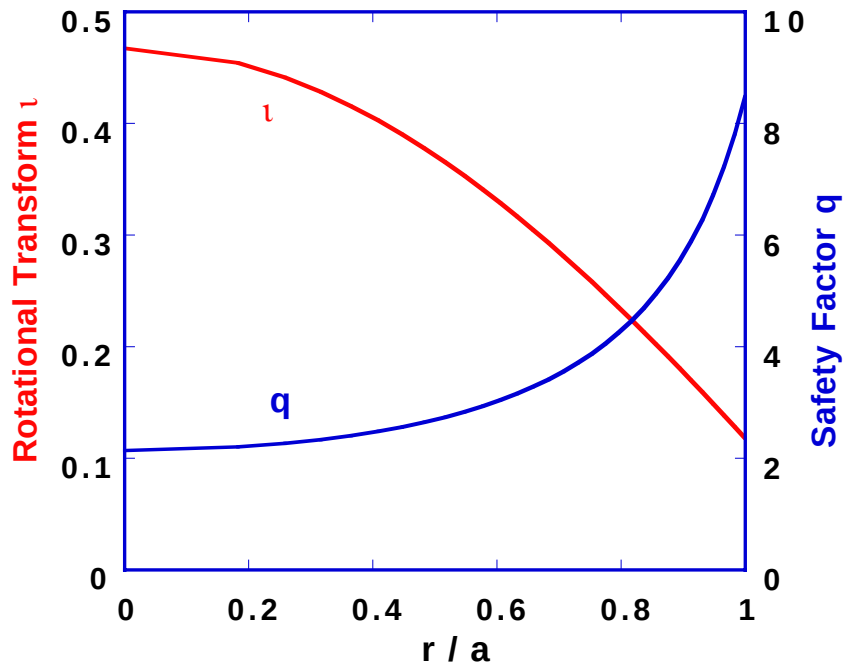
- QO case has self-consistent bootstrap current
- I_{BS} 4x larger in an equivalent tokamak; large opposing driven current needed for self-consistent equilibrium

Rotational Transform Profiles Are Very Different for the Two QO Types

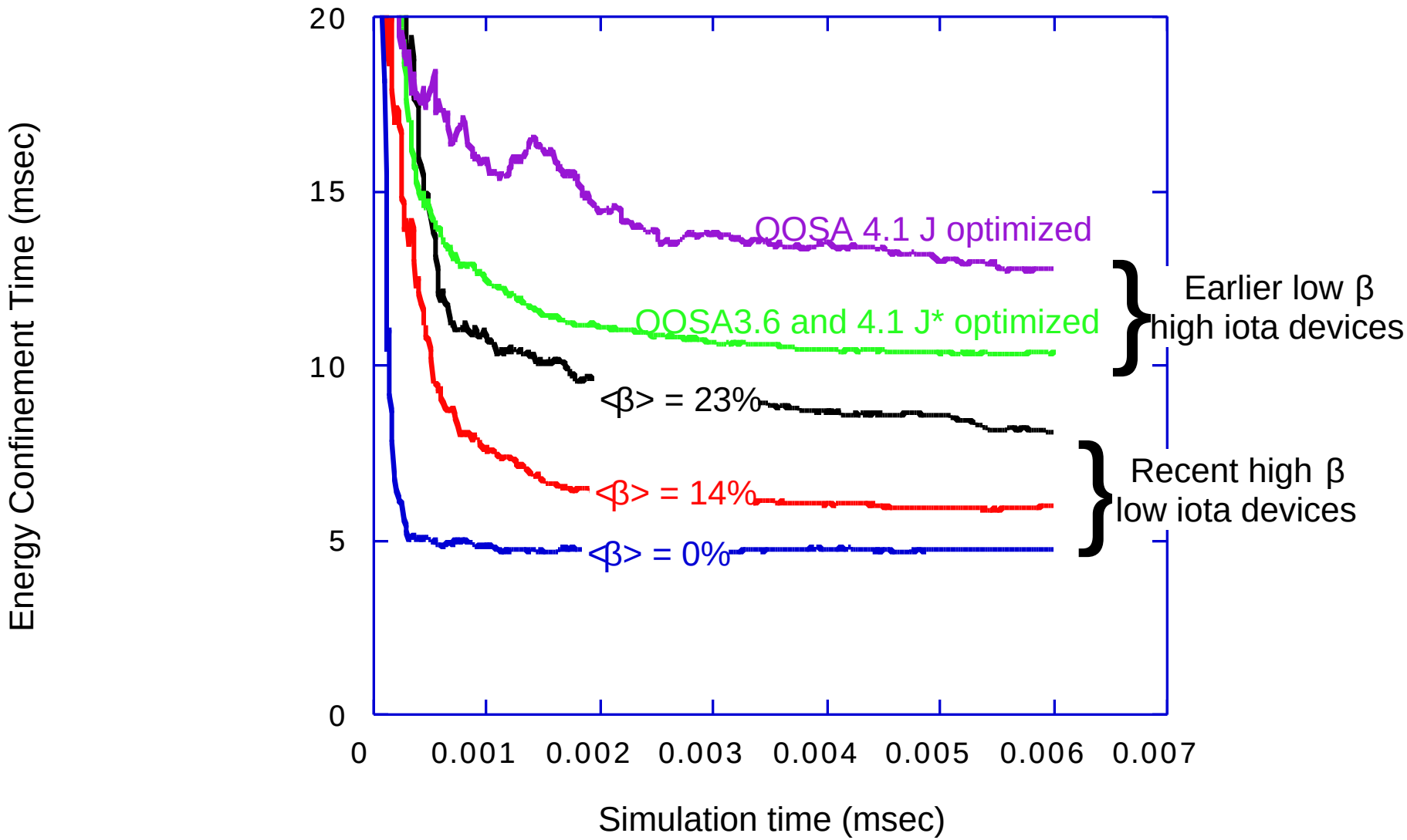
Low-I_{BS} QO cases



Higher-I_{BS} QO cases



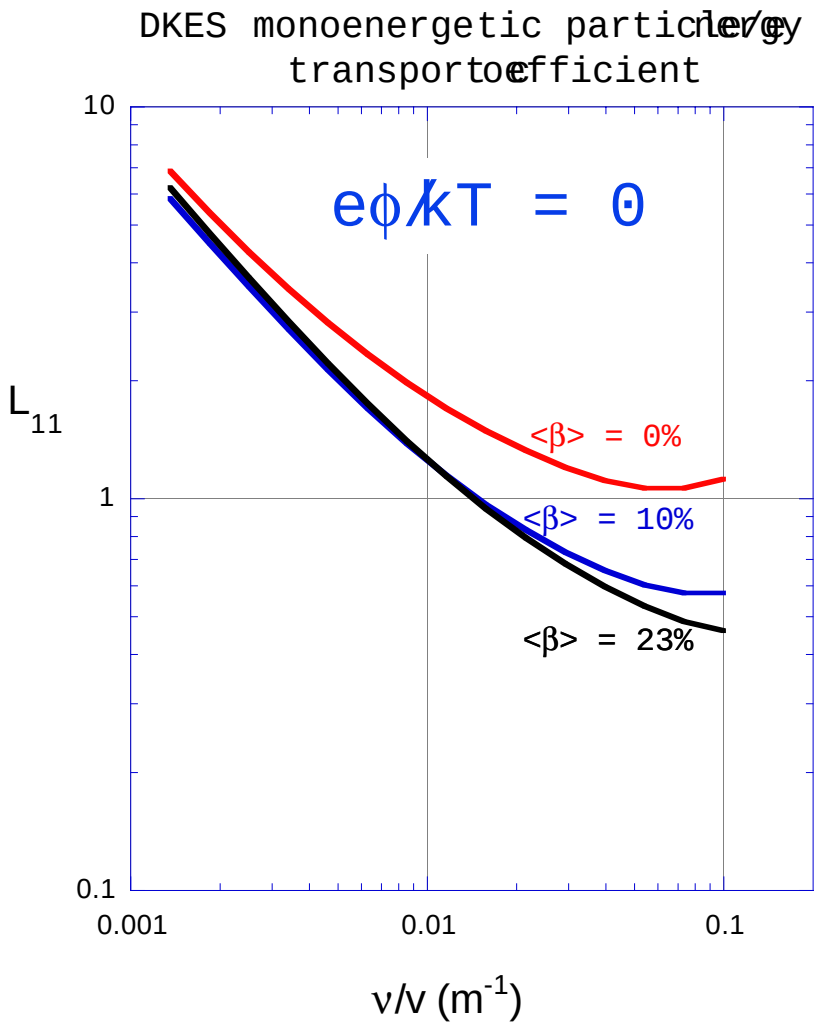
Confinement Improves with Increasing β

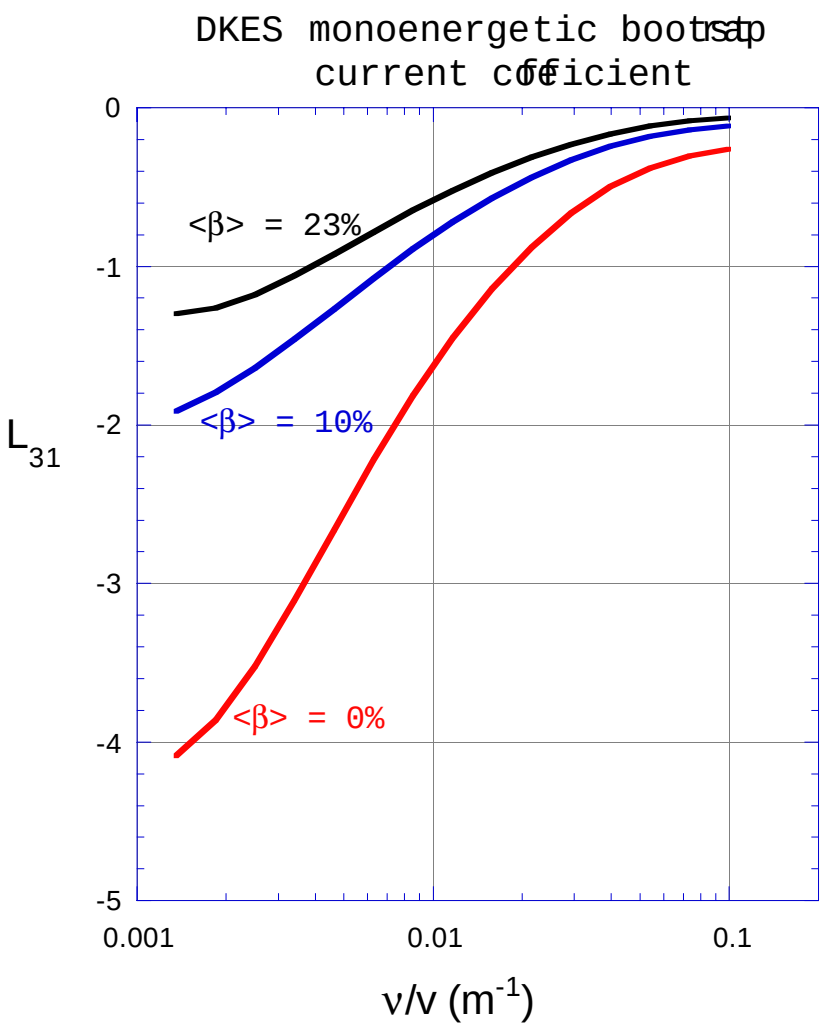


- **Low-I_{BS} configurations factor ~2 better confinement**

Increasing β Leads to Improved Neoclassical Transport and Decreased Bootstrap Current Coefficient

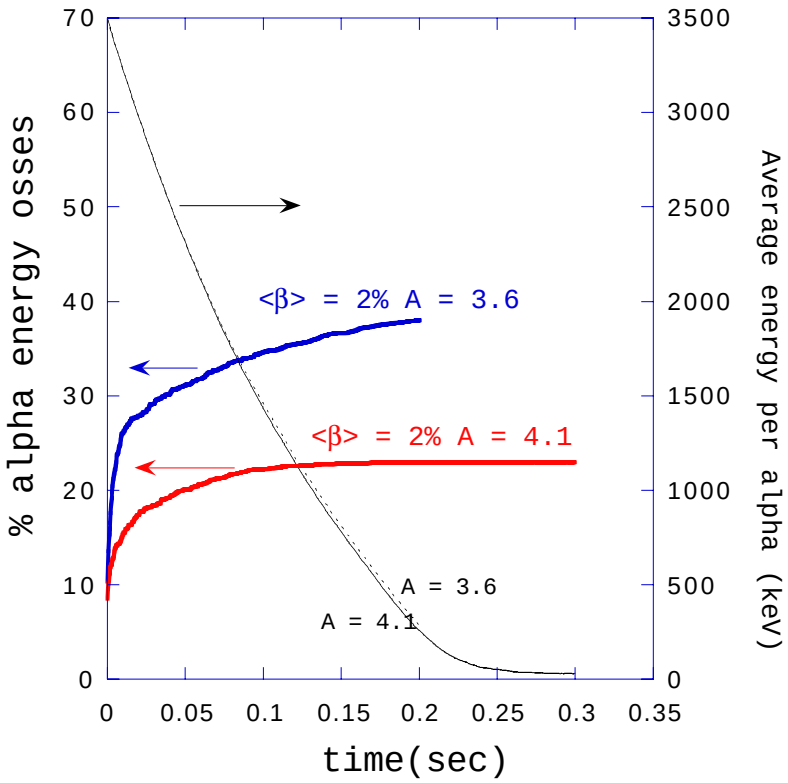
(results for 3 field period, A = 3.4 device)



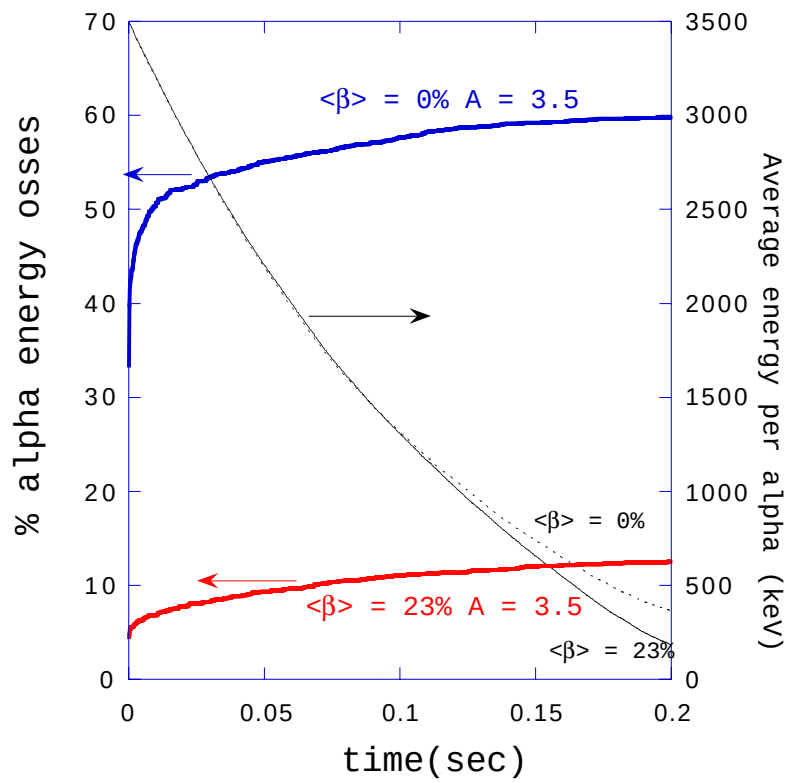


Monte Carlo Simulations Show that Higher-I_{BS} QO Devices Have Very Good α-Particle Confinement with Increasing β

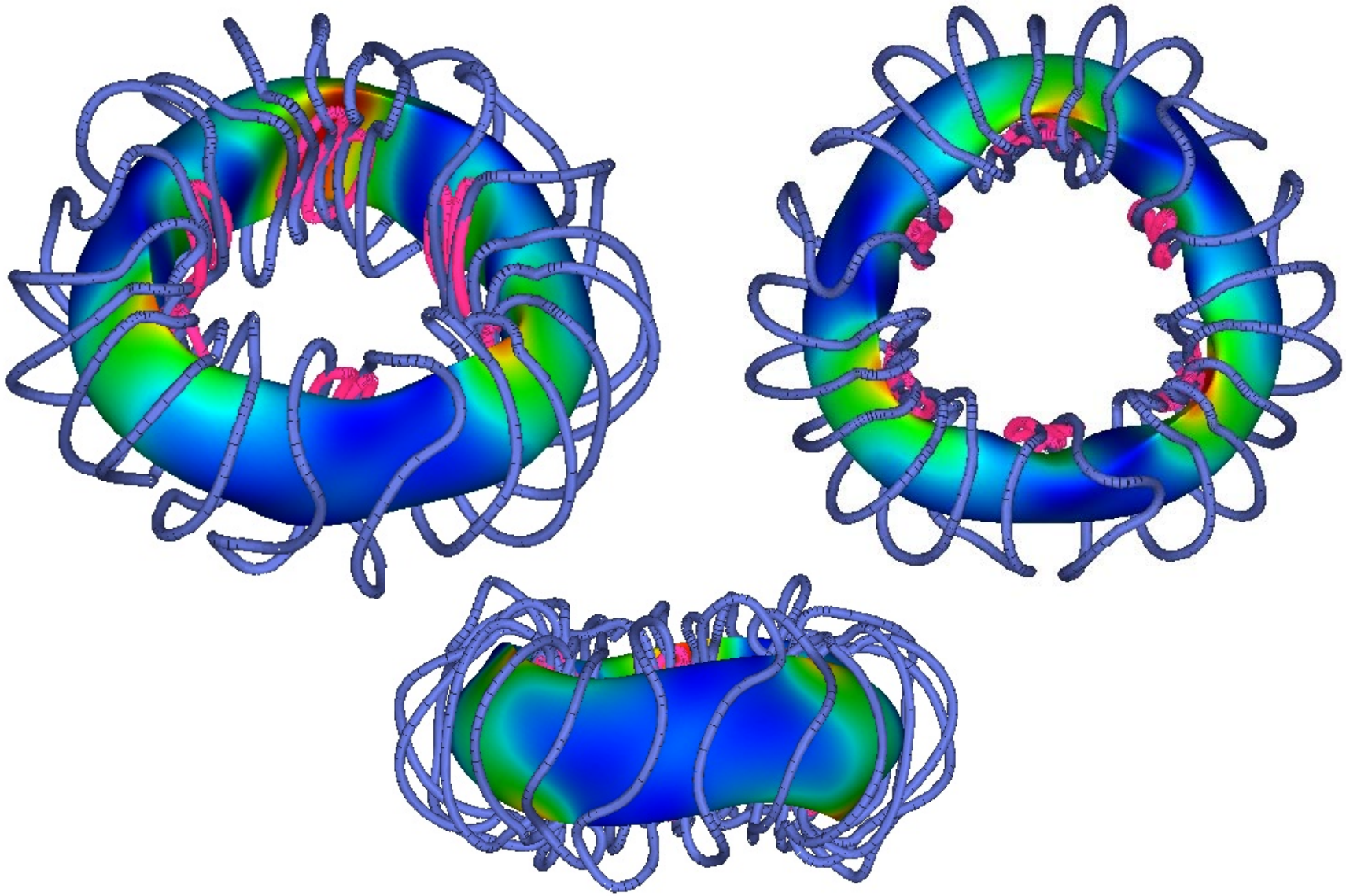
Low-I_{BS} Configurations



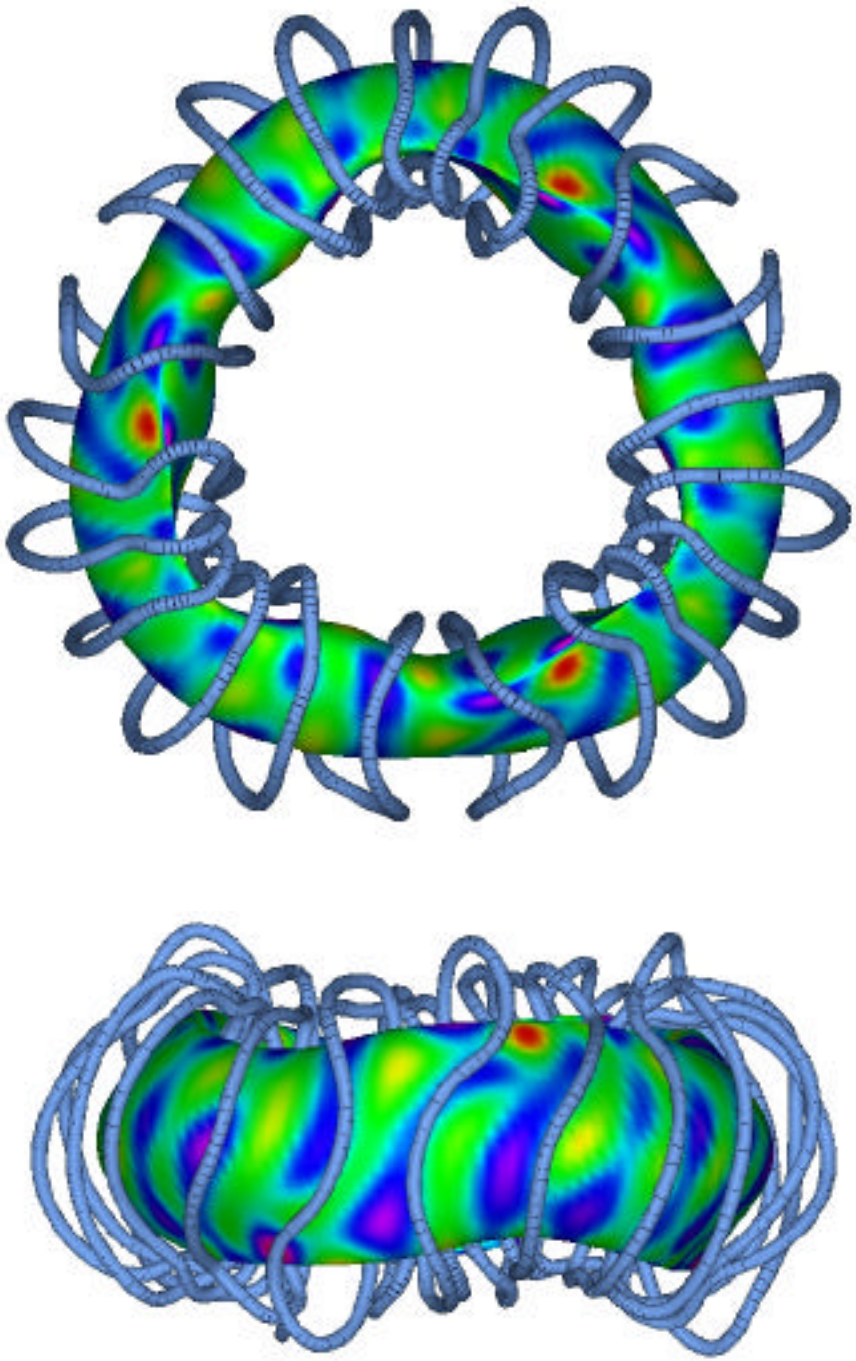
Higher-I_{BS} Configurations

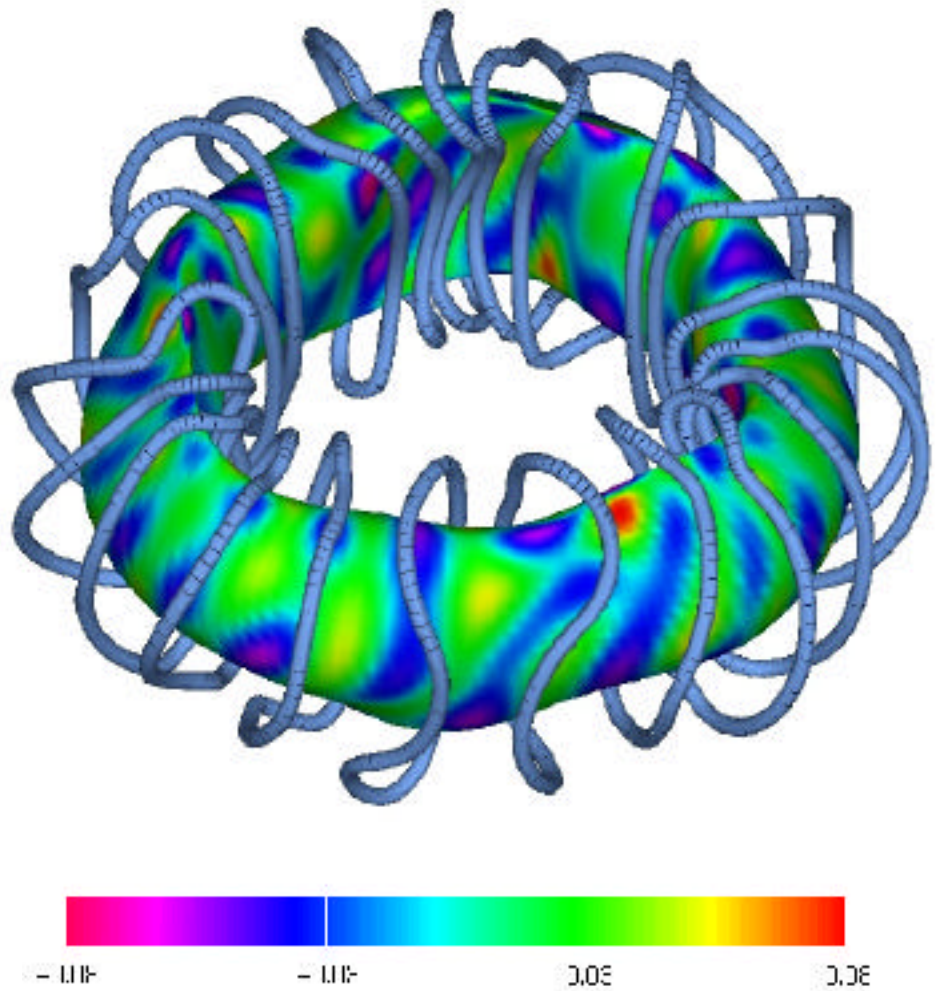


Coil Concepts for Higher-I_{BS} Configurations Combine Modular and Saddle Coils



Color contours show levels of B_{normal} error on last magnetic surface





Plans

- **Complete assessment of higher-I_{BS} configuration**
  - **kink stability and flux surface fragility at $\beta > 10\%$**
  - **confinement and stability from low β to high β**
- **Improve energetic and thermal ion confinement**
- **Improve coil configuration**
  - **small saddle coils in corners for higher-I_{BS} case**
  - **look at finite cross section modular coils for higher-I_{BS} case**
  - **improve plasma-coil and coil-coil spacings for low-I_{BS} case**
- **Assess low and higher I_{BS} configurations as reactors**
- **Milestones**
  - **9/00 -- select candidate QOS plasma and coil configuration**
  - **9/00 -- complete initial preconceptual design concept**
  - **5/01 -- develop final plasma and coil configuration, pre-conceptual design, and cost estimate for QOS proposal**

SUMMARY

- **Progress has been made in application of tools**
  - **3-D equilibrium, stability, bootstrap current, transport, coils**
- **Progress has been made in optimization of the low-I_{BS} QO approach (*R*/<*a*> = 3.6)**
  - **bootstrap current << current in tokamak for same size and ι**
  - **good neoclassical transport ($\tau_{E,neo} \approx$ 3-5 × $\tau_{E,ISS95}$), ι ≈ 0.7**
  - **ballooning stable at β ≈ 3-4%**
- **An engineering assessment has started**
  - **Work focused on coil calculations**
- **Work has started on a higher-β QO configuration**
  - **ballooning stable up to β ≈ 23%; kink stable at β ≈ 10%**
  - **may allow simpler modular coils and smaller reactor**
  - **neoclassical confinement still needs to be improved**