# QOS Project Overview: Status and Plans

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NCSX Project Meeting

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# TOPICS

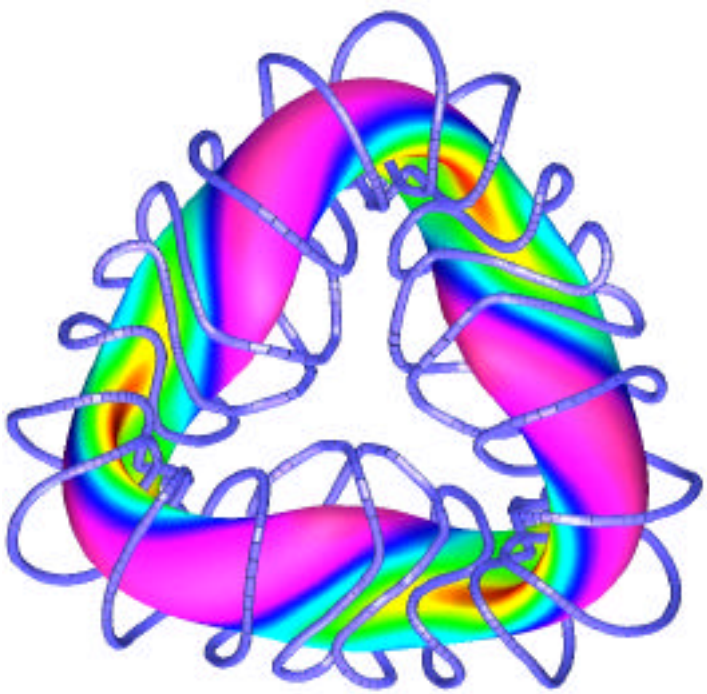
- **Status of Low-Bootstrap-Current**
  **$\beta \approx$ 4% QOS with $d\iota/dr > 0$**

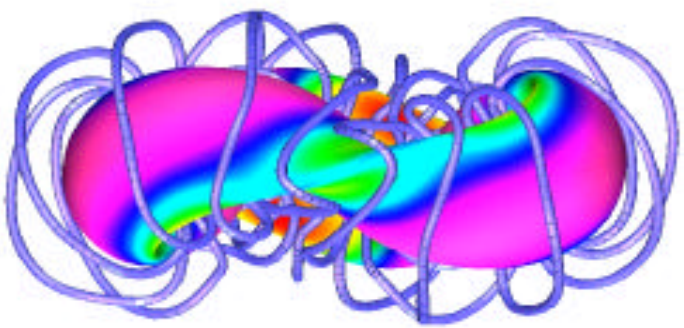
- **Higher-Bootstrap-Current $\beta \sim$ 15%**
  **QO Configurations with $d\iota/dr < 0$**

- **Plans**

# 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**



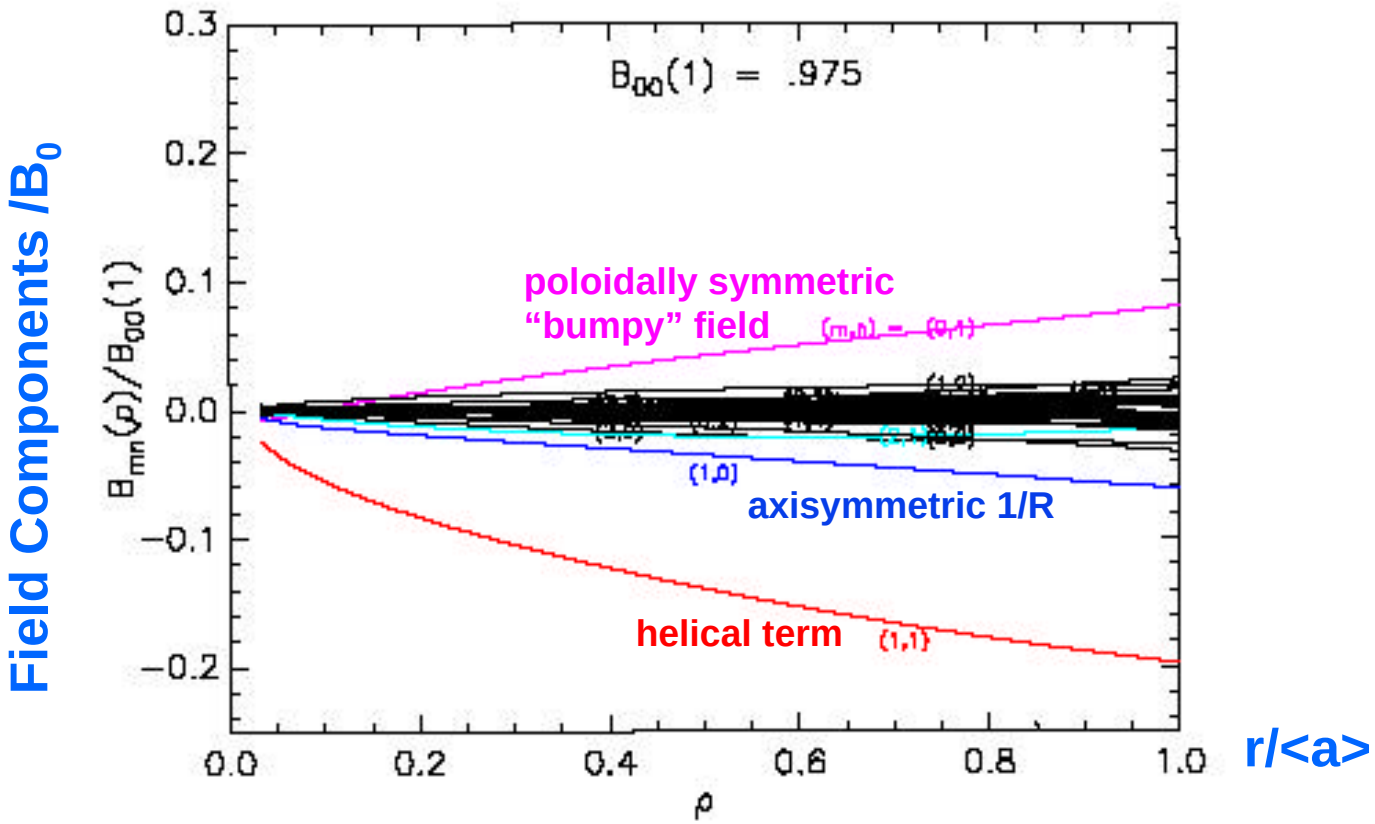


**colors indicate contours of constant |B|**

# Progress Is Being Made in Different Areas

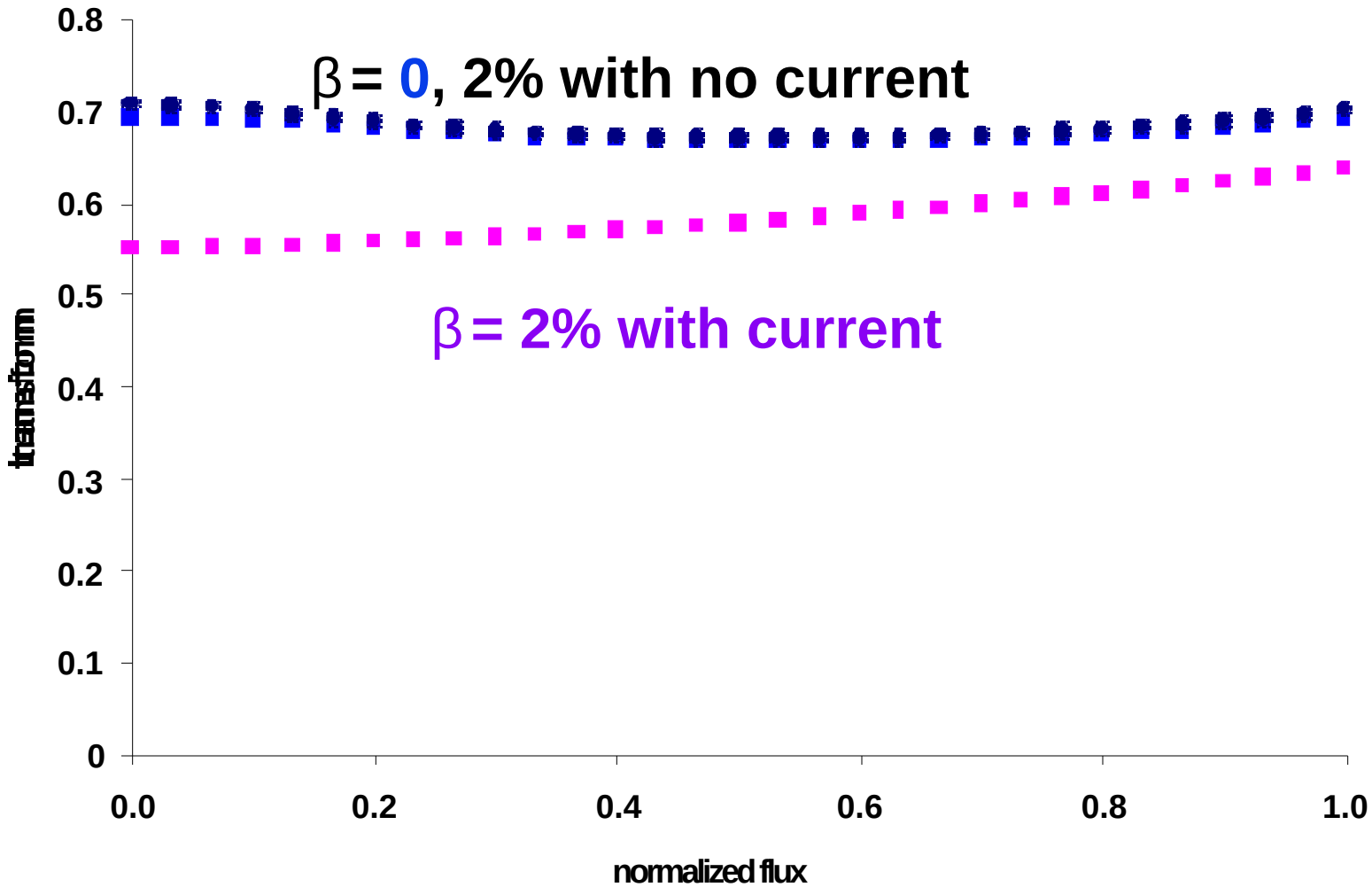
- **QOS physics studies are exploring different aspects of low R/<a> QO configurations**
  - ***Ballooning stability, thermal transport, energetic ion confinement, bootstrap current***
- **Configuration optimization studies are examining the best mix of features for a modest-size device**
- **Coil optimization 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**

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

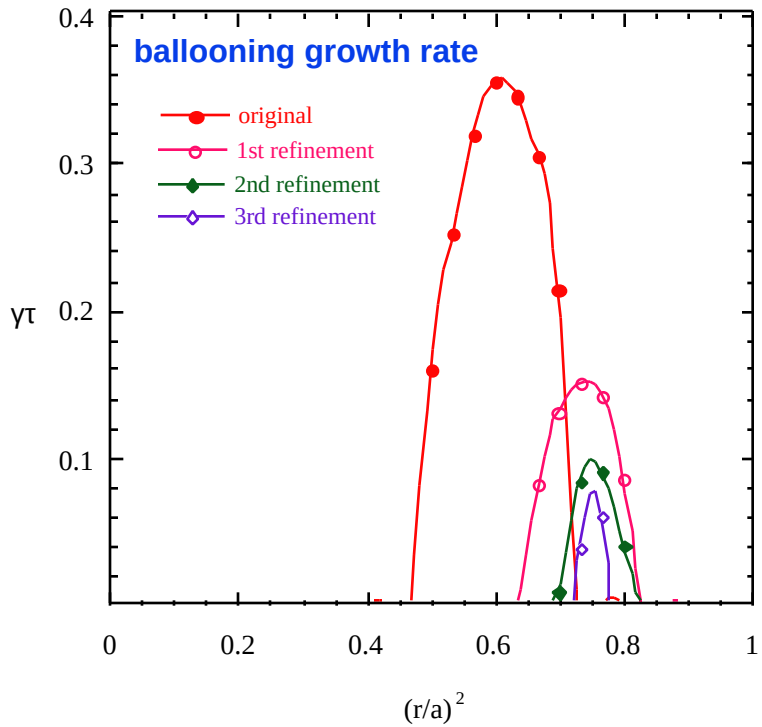


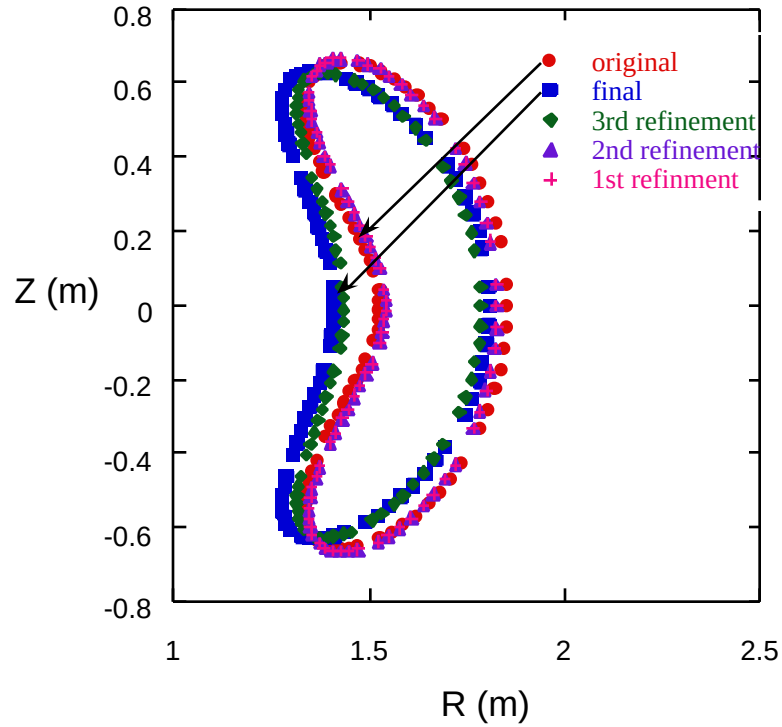

- Dominant helical shaping term produces higher rotational transform
- Small axisymmetric 1/R term reduces toroidal curvature drift
- Radially varying mirror "bumpy" term produces poloidal grad-B drift

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



# Ballooning Stable at $\beta = 4\%$

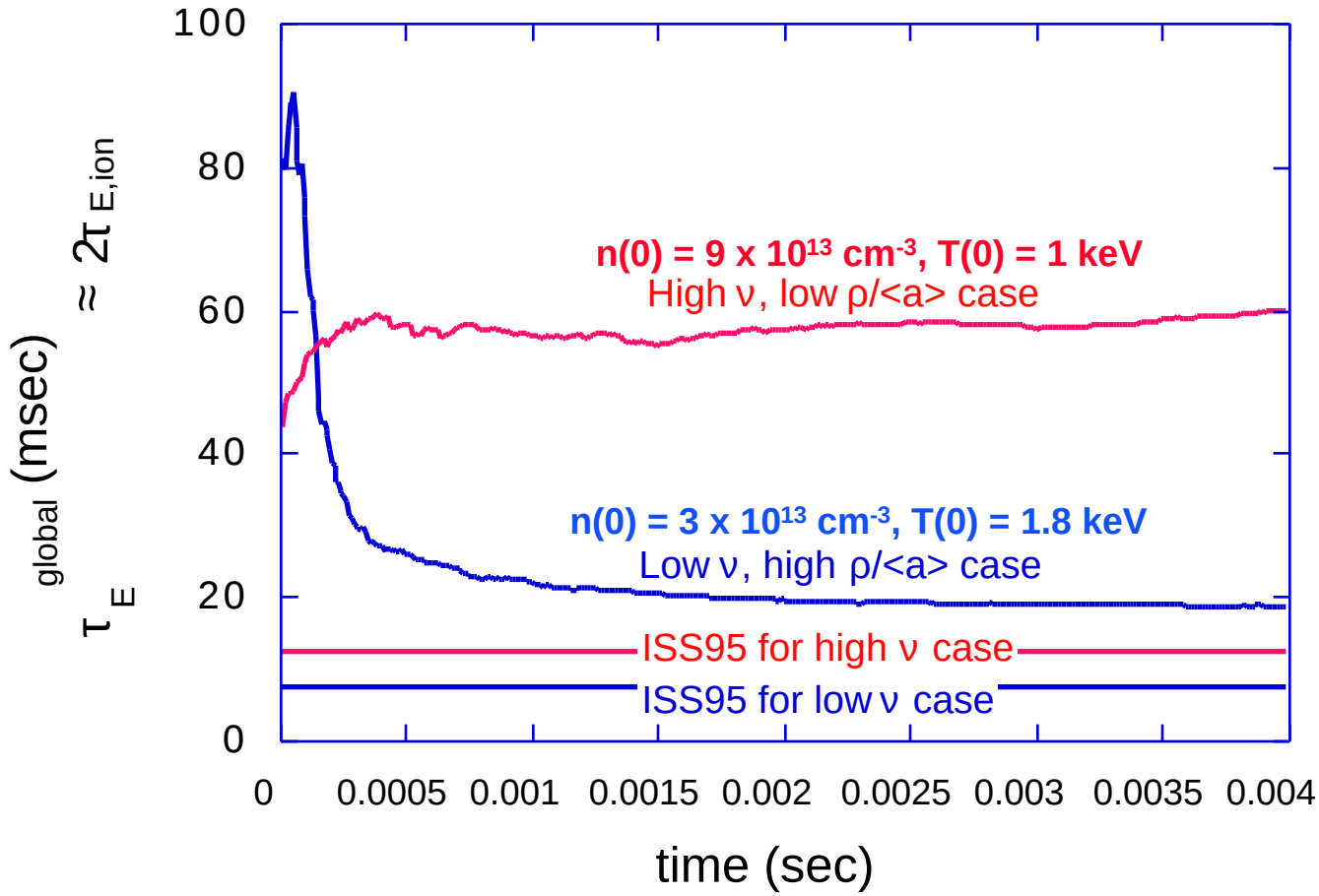



- **Original low-$I_{BS}$ configuration, ballooning unstable at $\beta = 3\%$, was stabilized by small plasma boundary shape changes**
- **Pressure profile modification raises stable $\beta$ to 4%**

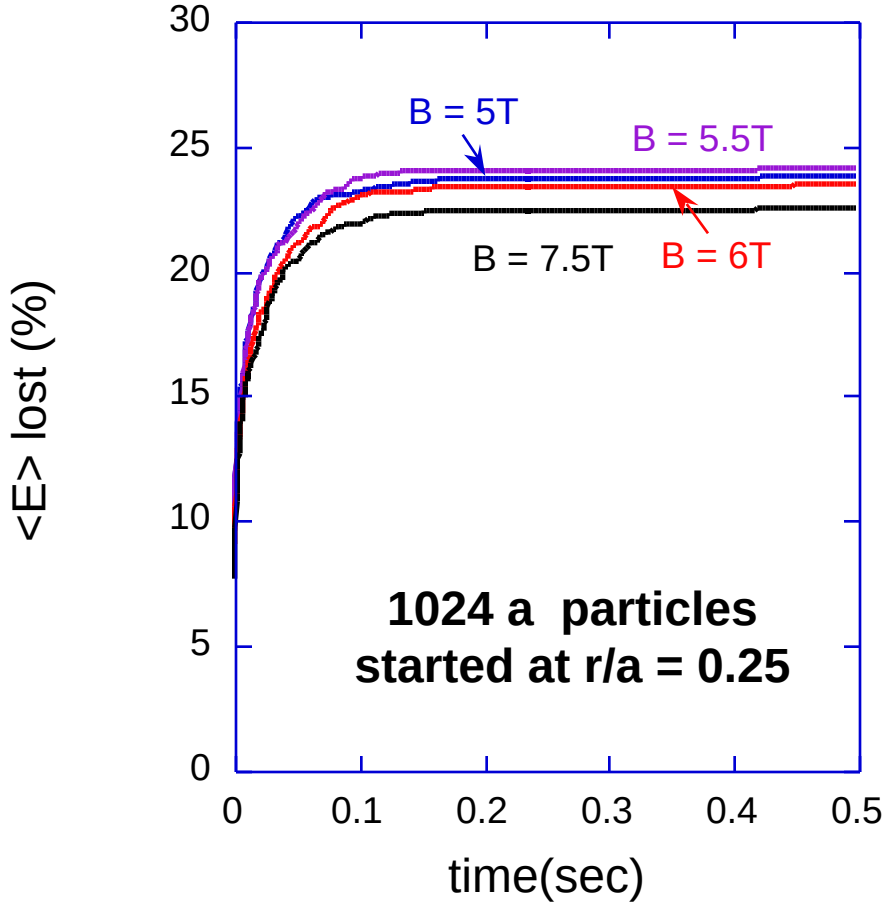
# Global Transport Energy Lifetimes Are Not Dominated by Neoclassical Losses

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

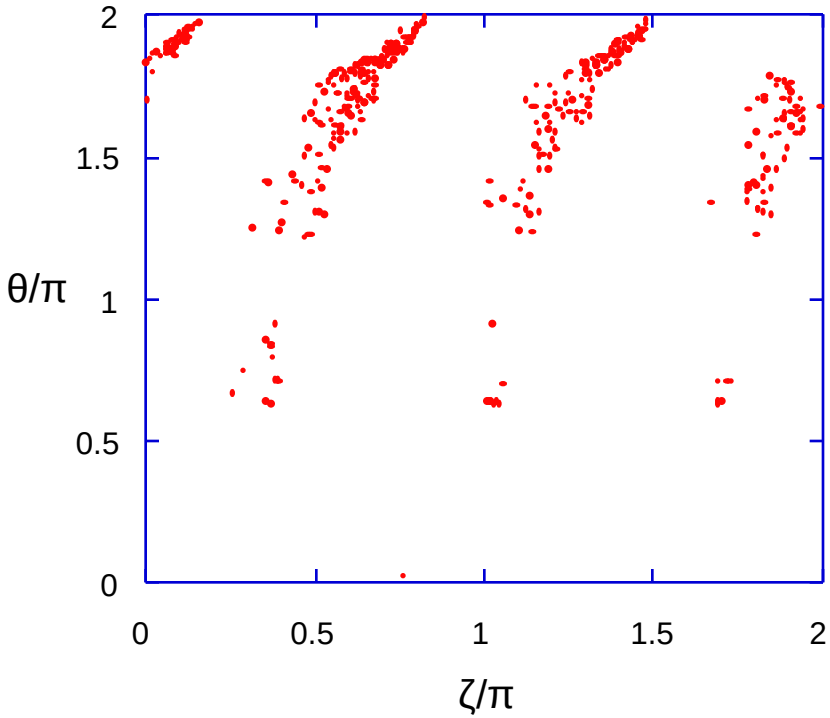


# Configuration Not Yet Optimized for a Reactor

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

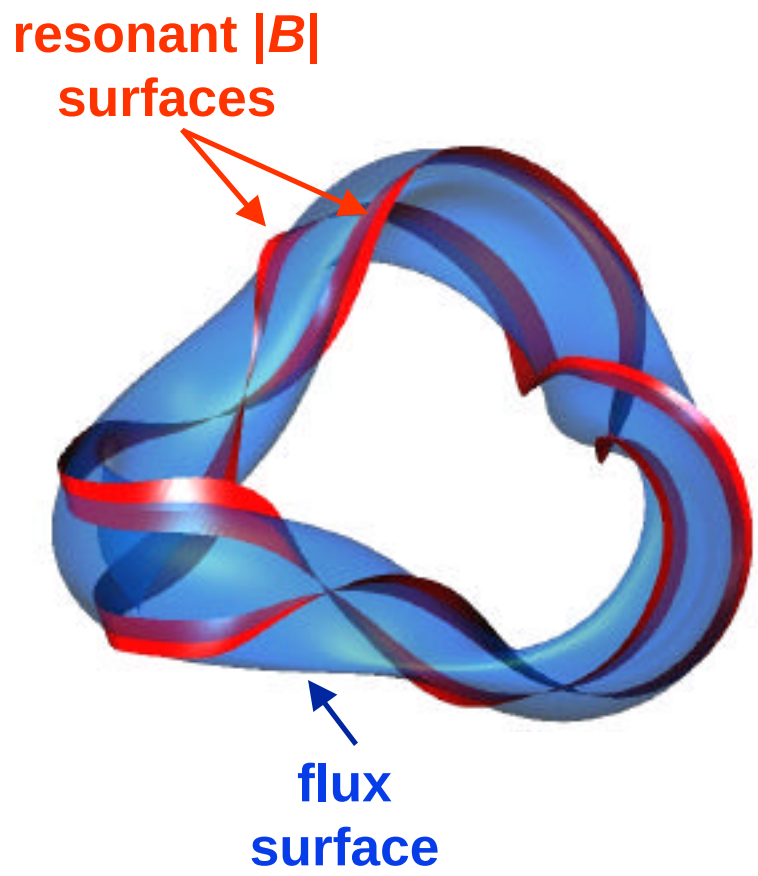



**Alpha loss locations on outermost closed flux surface**



# 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

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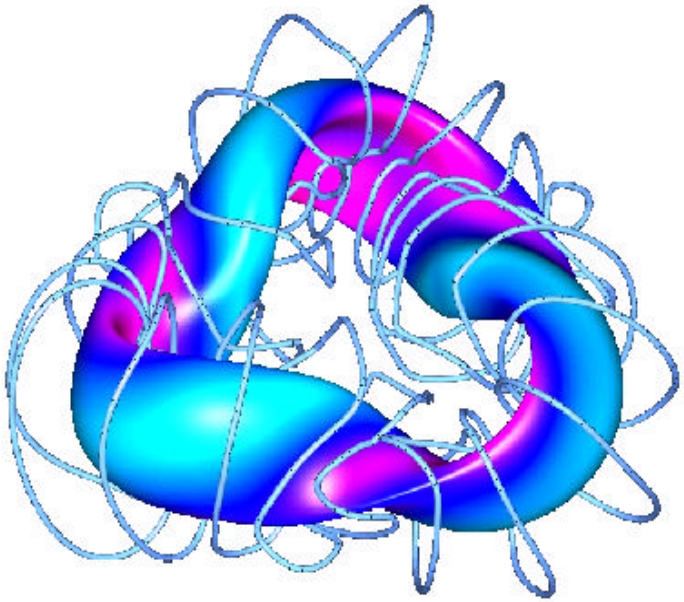
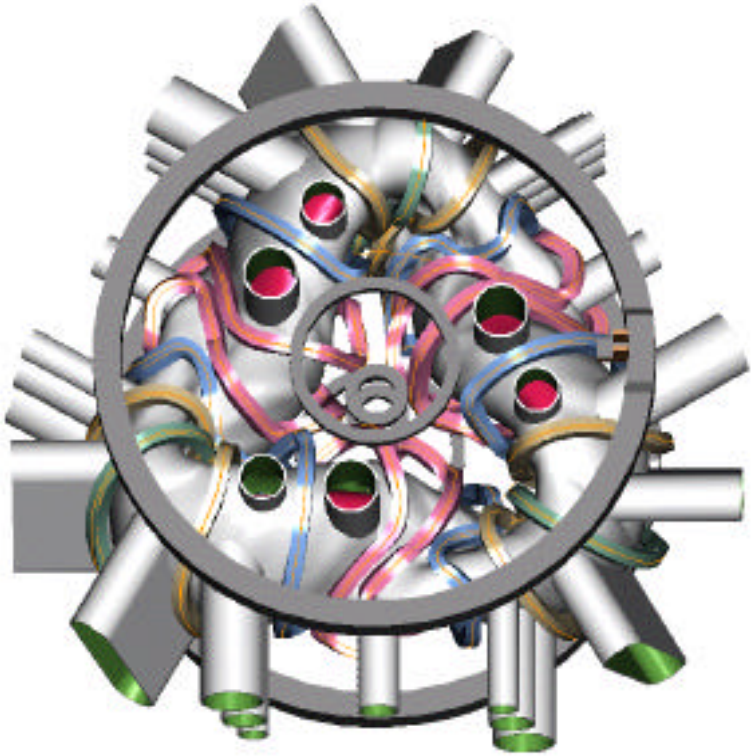
# Reference QOS Properties

- 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 $\beta$
- Bootstrap current < 1/10 current in similar tokamak
- Shaped plasma surface gives ballooning $\beta$ 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 ±50% changes R/<a> from 2.9 to 4.6

# Transformation from Physics to Engineering





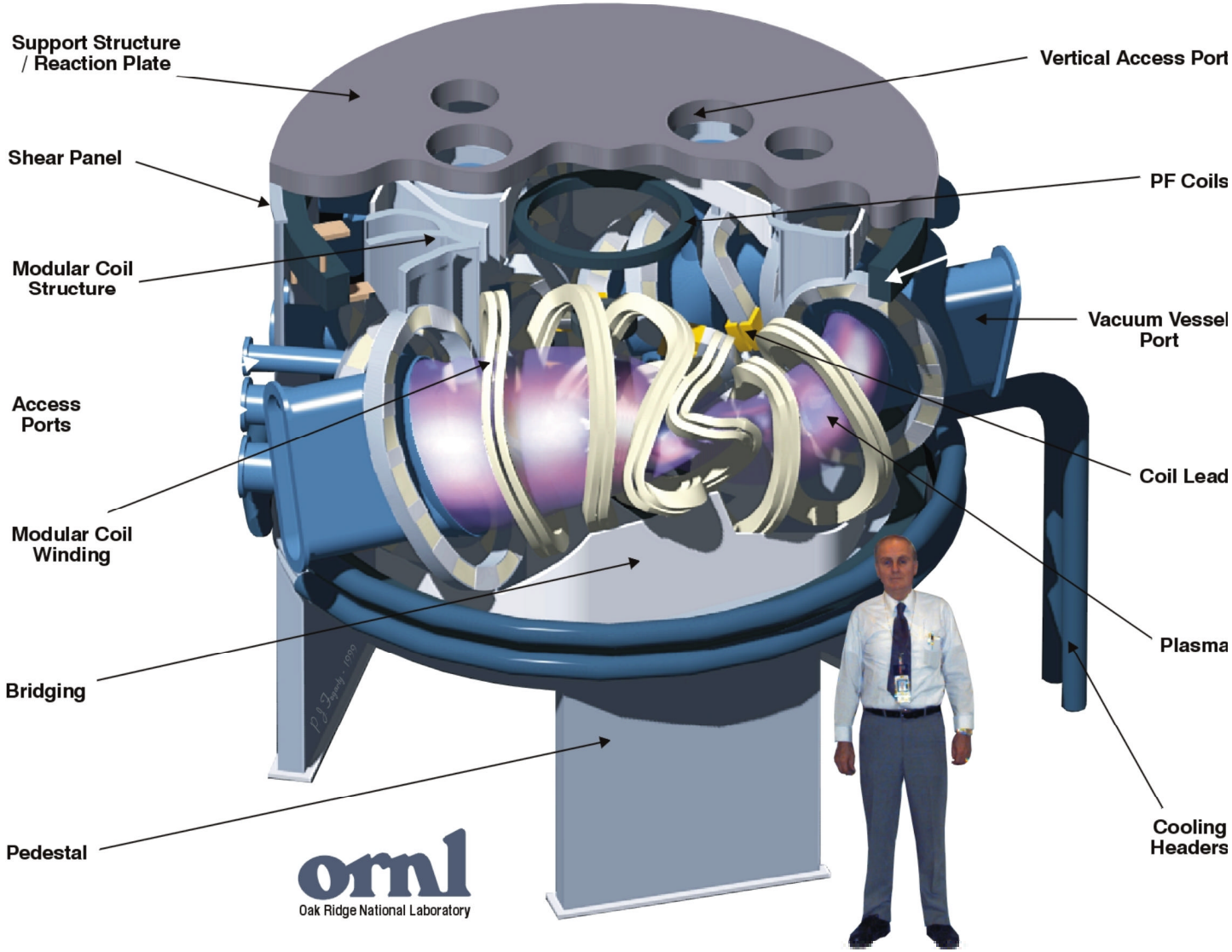
**Scoping Study Parameters**

- $R_0$ = 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

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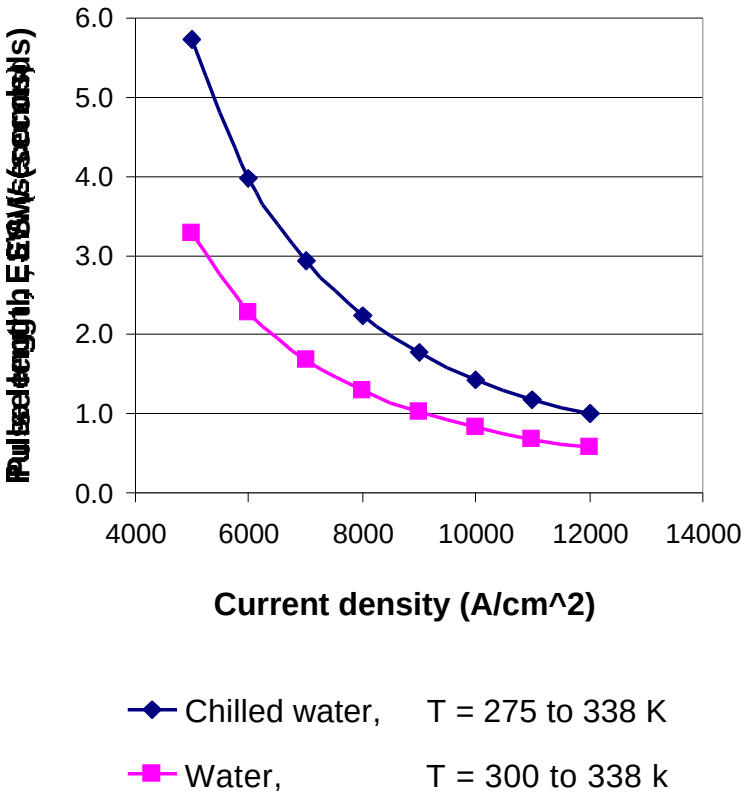
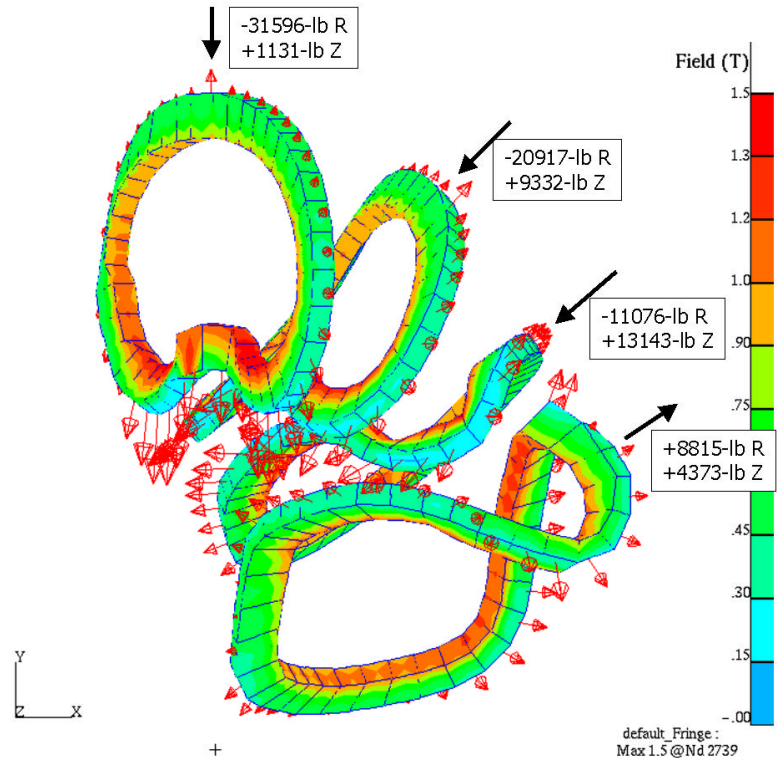
# Initial Examination of QOS Modular Coils

## Pulse Length

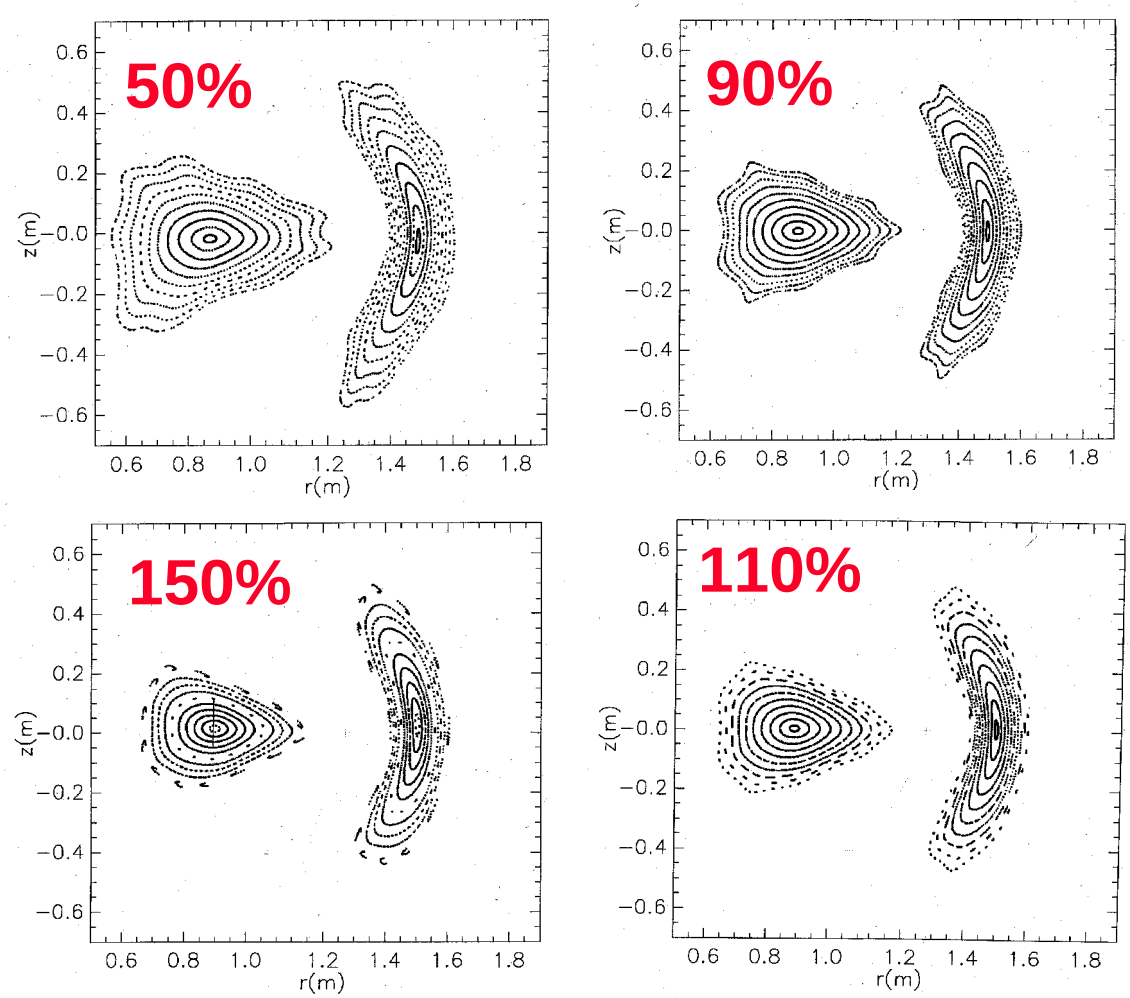


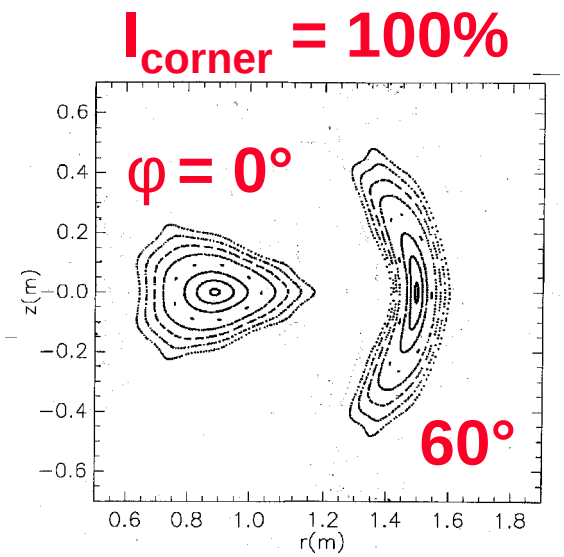

## Forces



# 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



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

# Higher-$I_{BS}$ QO Stellarator Features

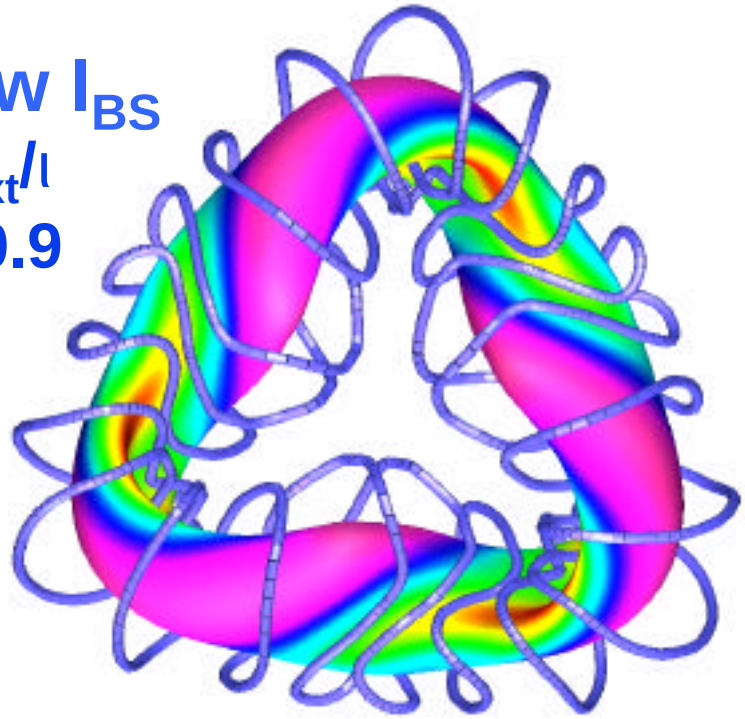
- **Tokamak-like shear ($d\iota/dr < 0$)**
  - $\iota(0) \approx 0.47$ ($q > 2$) and $\iota(a) = 0.12$ ($q \approx 8$)
- **Bootstrap current ≈1/4 that of equivalent tokamak**
  - ≈40% of the edge transform comes from the coils
- **Ballooning stable at $\beta = 23\%$**
  - smoother corners lead to high ballooning beta limits
  - stable to Mercier modes and internal kinks
  - smaller j and j near edge external kink limit >10%?
- **Less helical axis excursion**
  - simpler modular coils easier fabrication, lower cost?
- **More mirror-like |B| variation on a flux surface**
  - larger plasma-coil separation possible? 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

low $I_{BS}$

$I_{ext}/I$

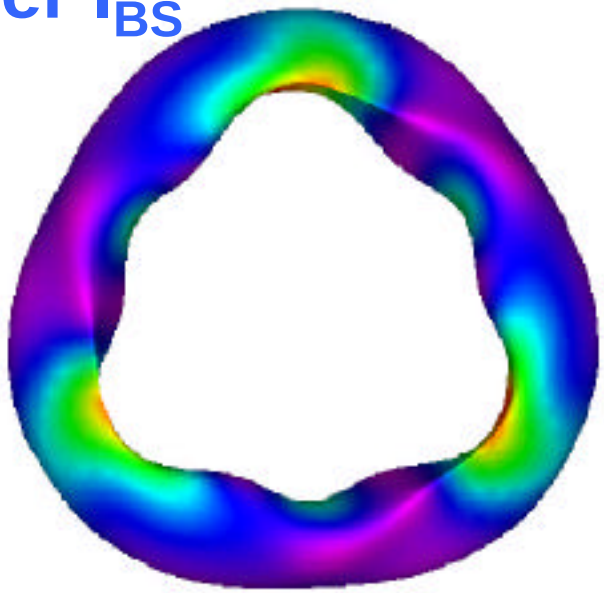
~0.9

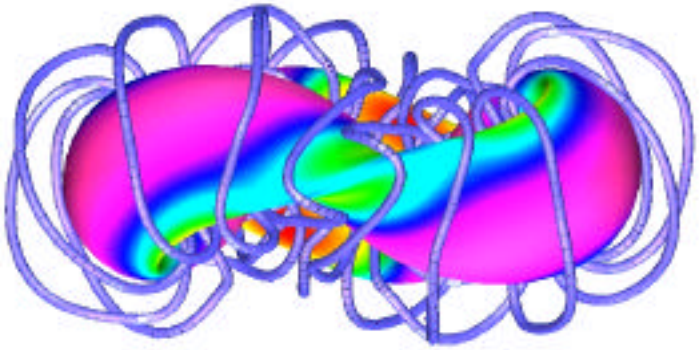


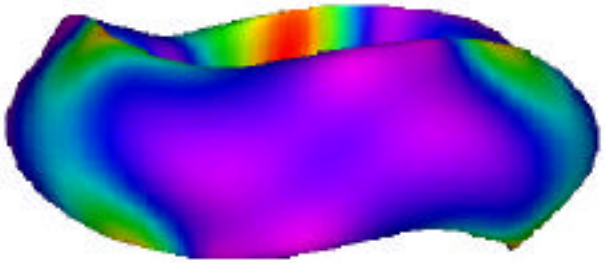
higher $I_{BS}$

$I_{ext}/I$

~0.4



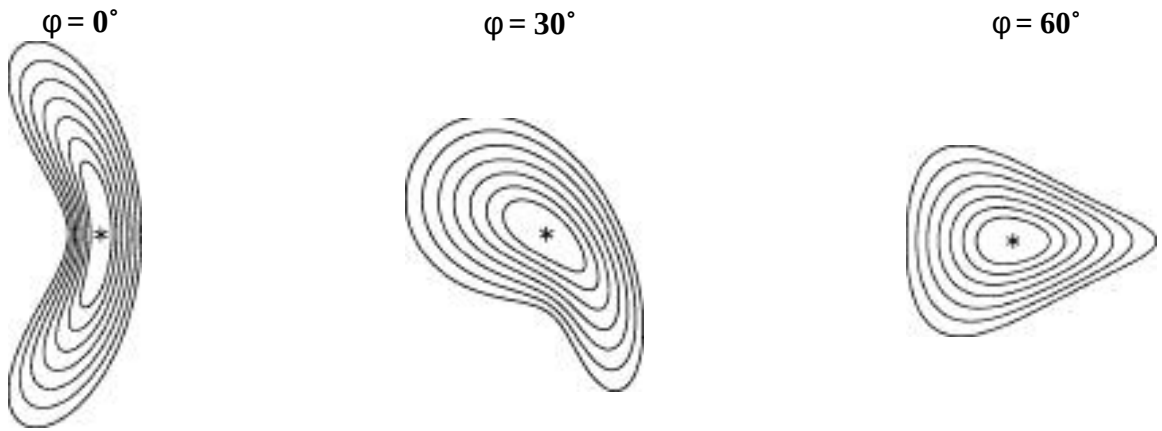




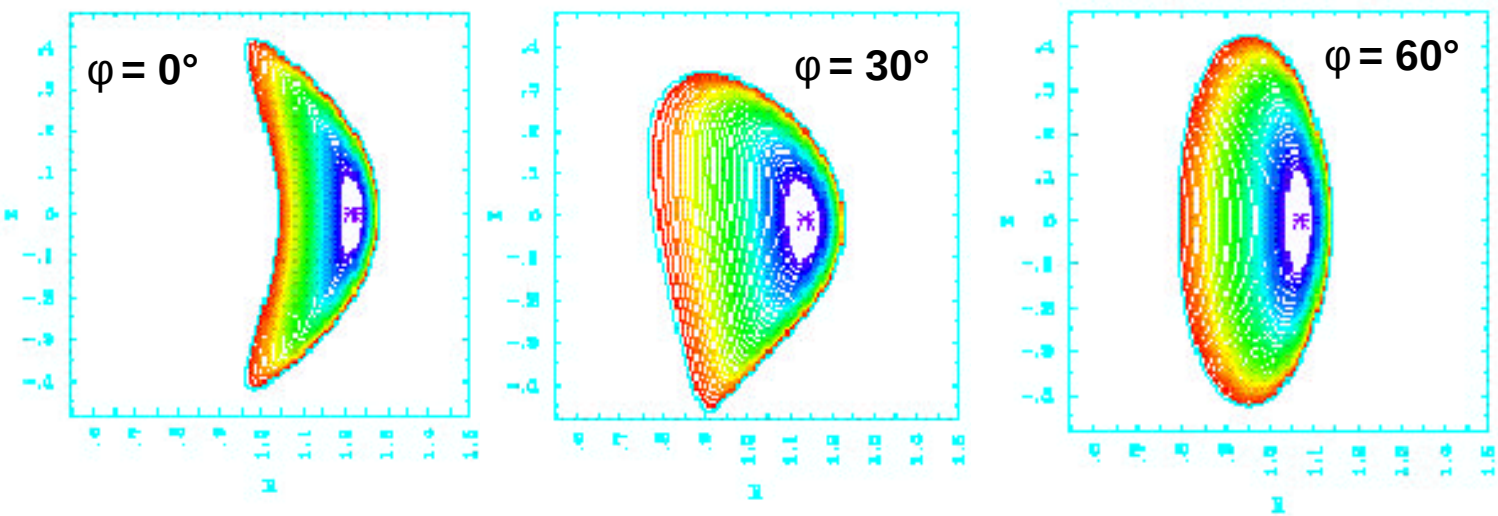
colors indicate contours of constant |B|

# 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>, $\beta \sim 4\%$**

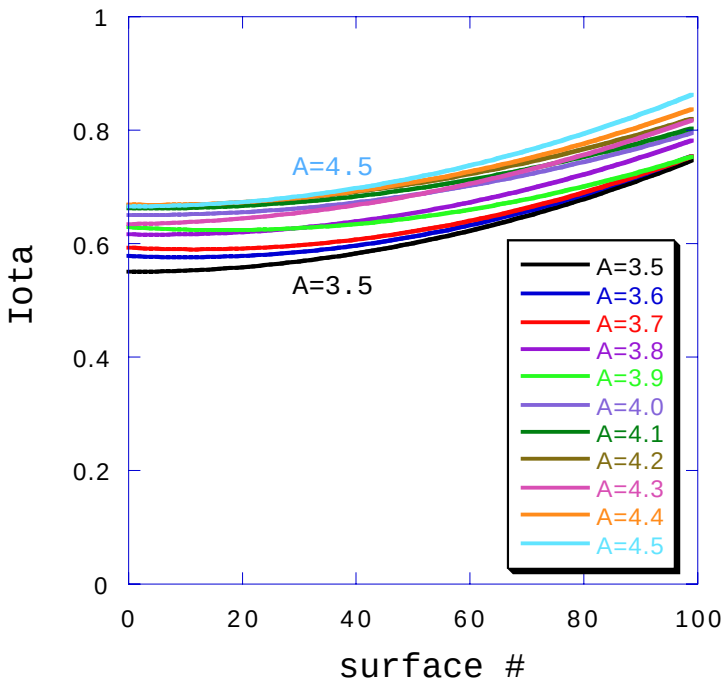



**Higher-$I_{BS}$ , $d\iota/dr < 0$; <u>nearly planar axis</u>, $\beta \sim 15\%$**

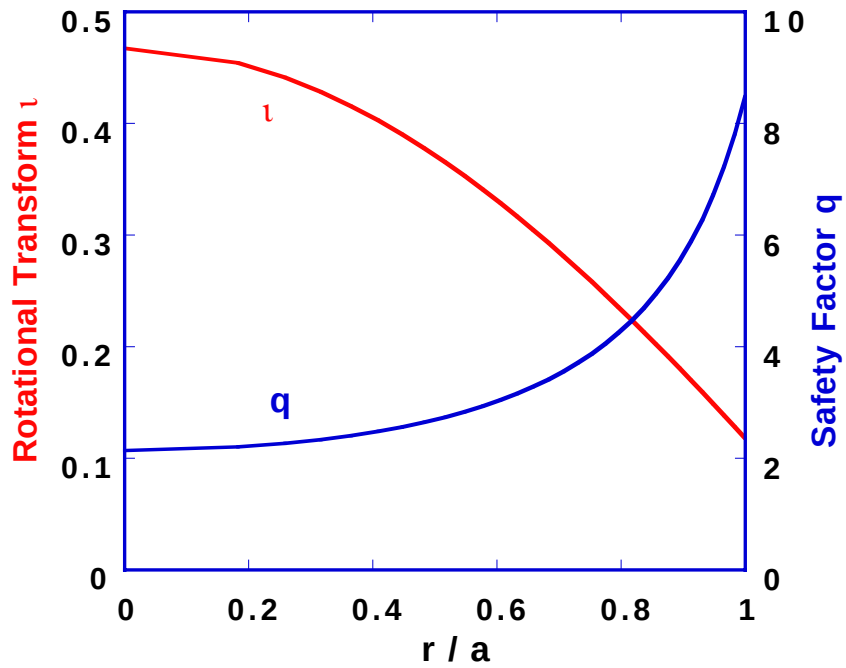


# Rotational Transform Profiles Are Very Different for the Two QO Types

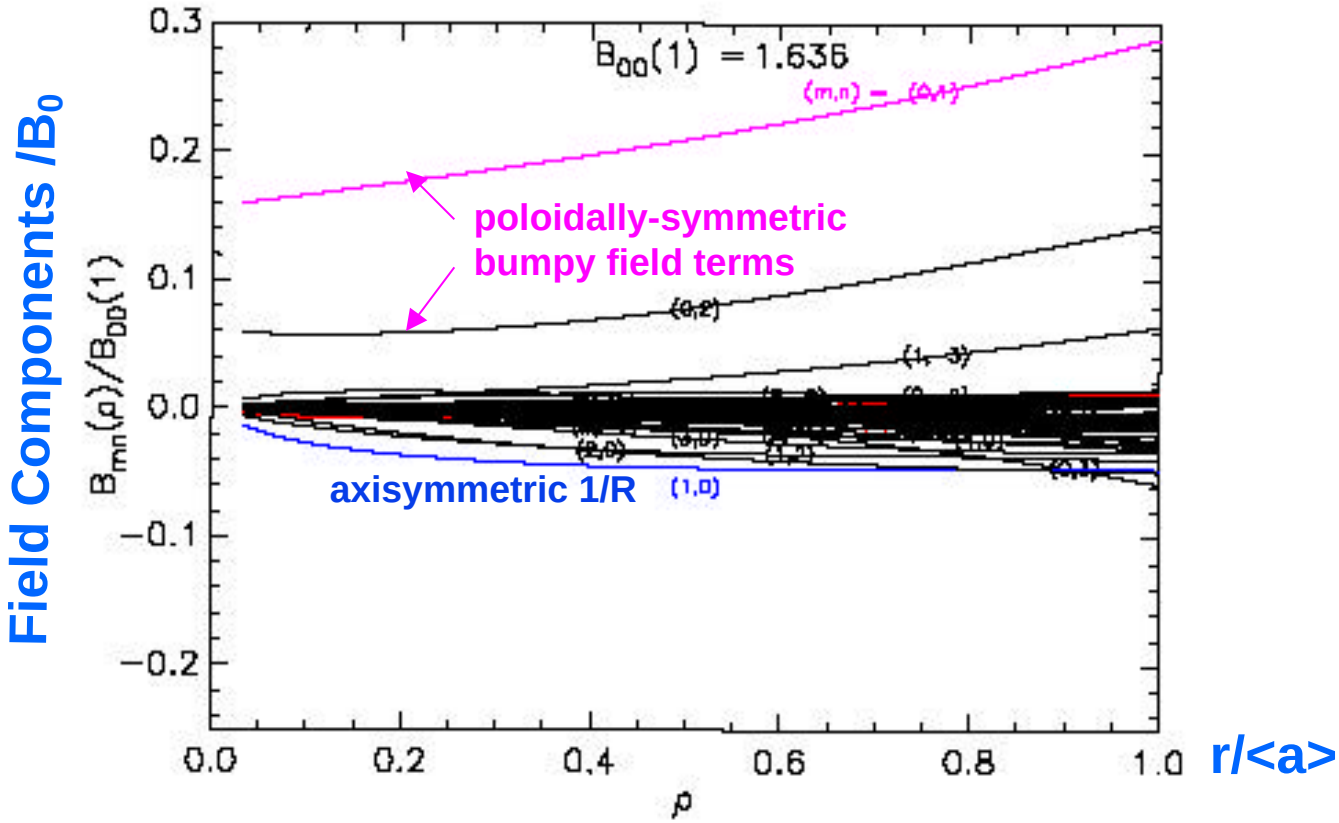
## Low-$I_{BS}$ QO cases




## Higher-$I_{BS}$ QO cases



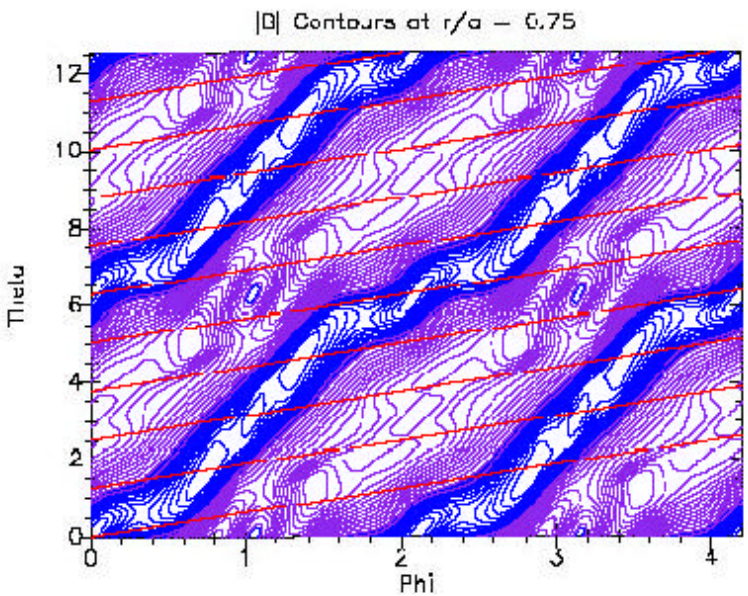
# The Higher-$I_{BS}$ QO-Optimized Magnetic Field Has Different Spatial Components



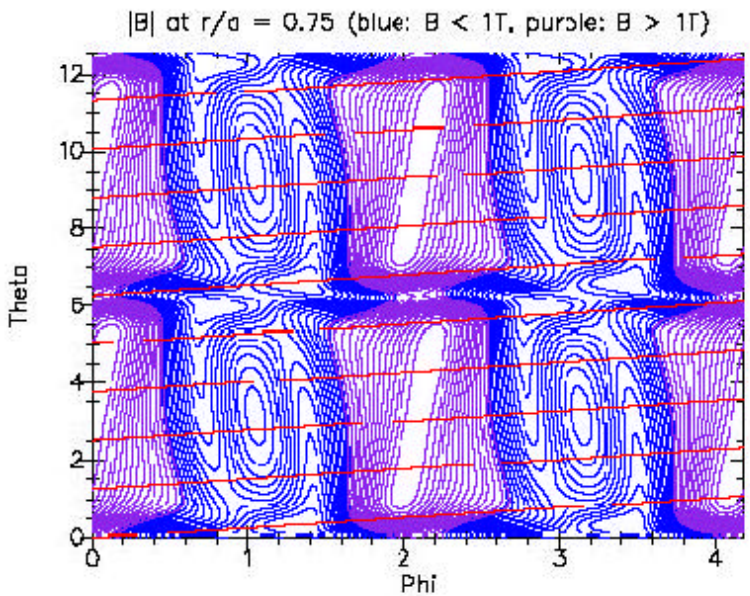

- Dominant poloidally-symmetric terms >5 times larger
- Small axisymmetric 1/R term reduces toroidal curvature drift
- Helically-symmetric terms >20 times smaller

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

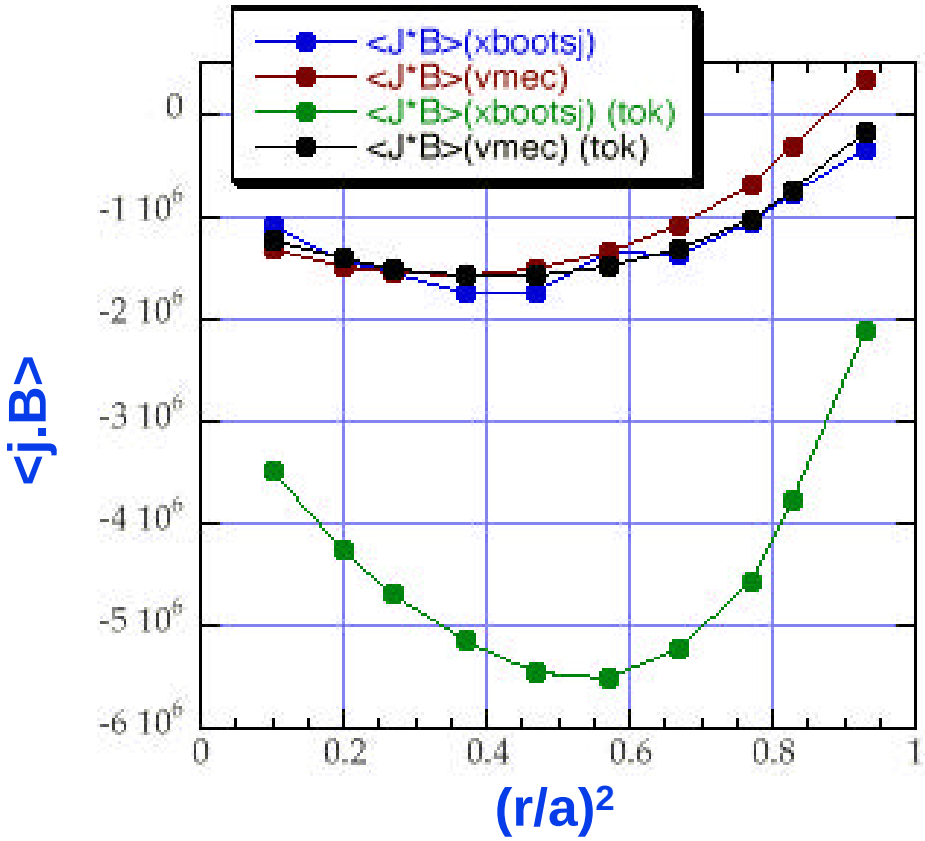
**earlier near quasi-helical**
**$\beta$ = 2% QO case**




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



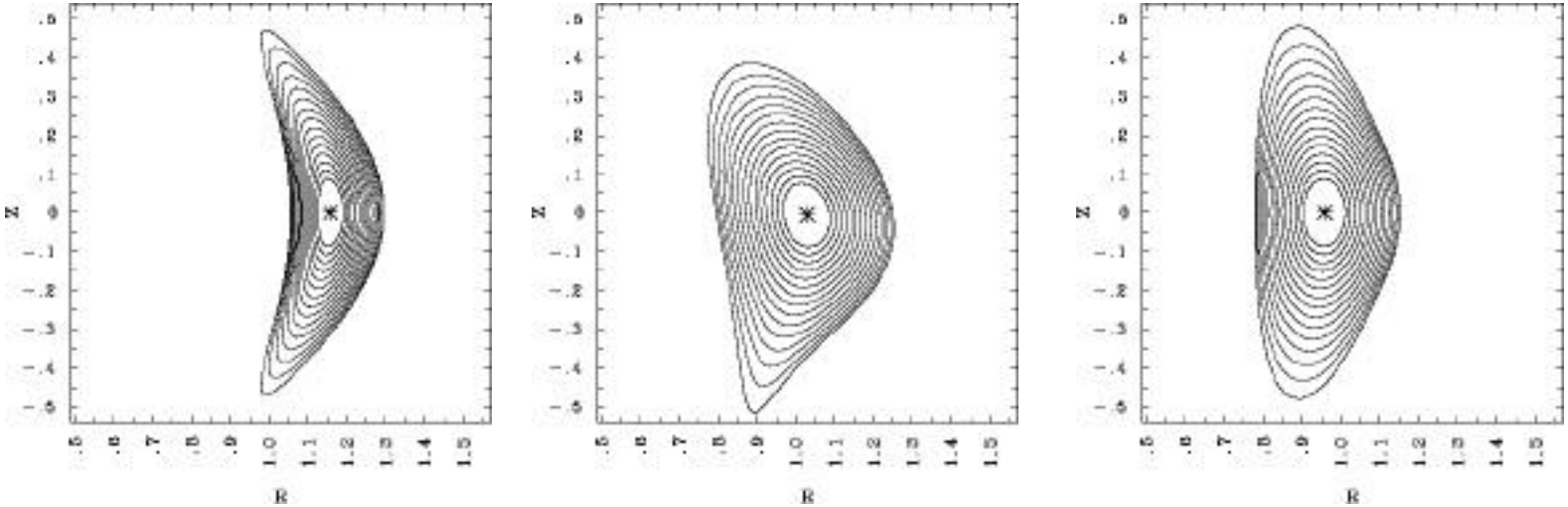
# β = 15% QO Configuration Has 1/4 the Bootstrap Current of Equivalent Tokamak



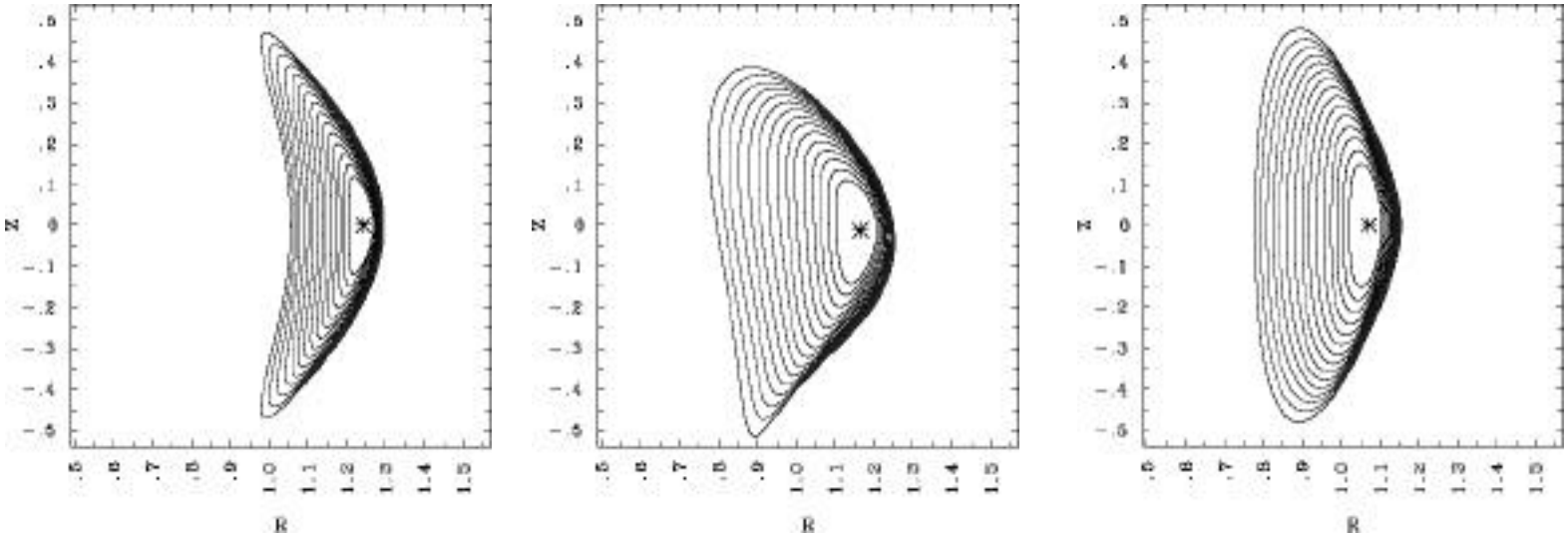

- QO case has self-consistent bootstrap current
- $I_{BS}$ 4x larger in an equivalent tokamak; large opposing driven current needed for self-consistent equilibrium

# Magnetic Well Increases with β

## β = 0

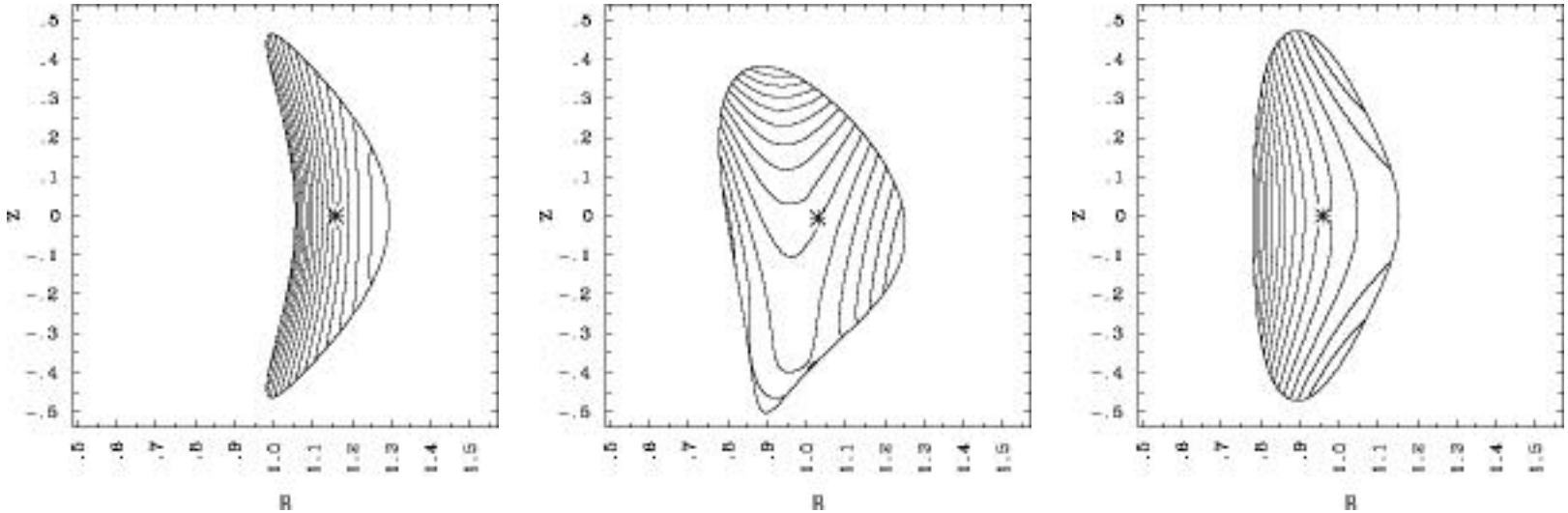



## β = 23%

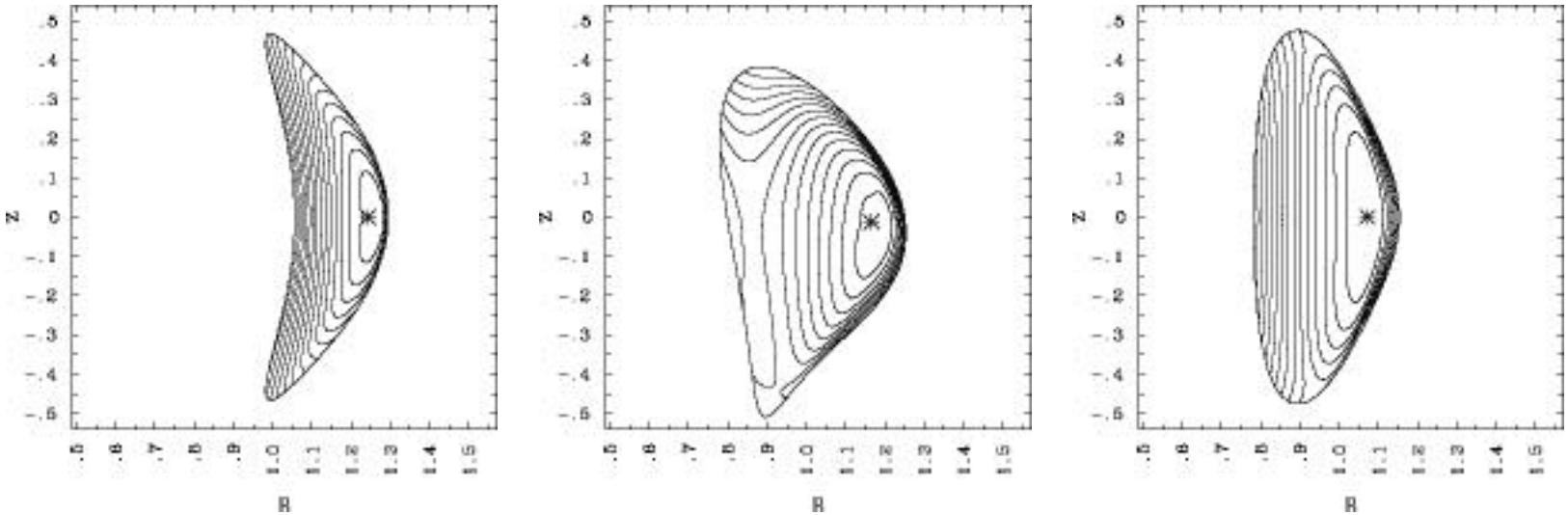


# |B| Contours Close with Increasing β

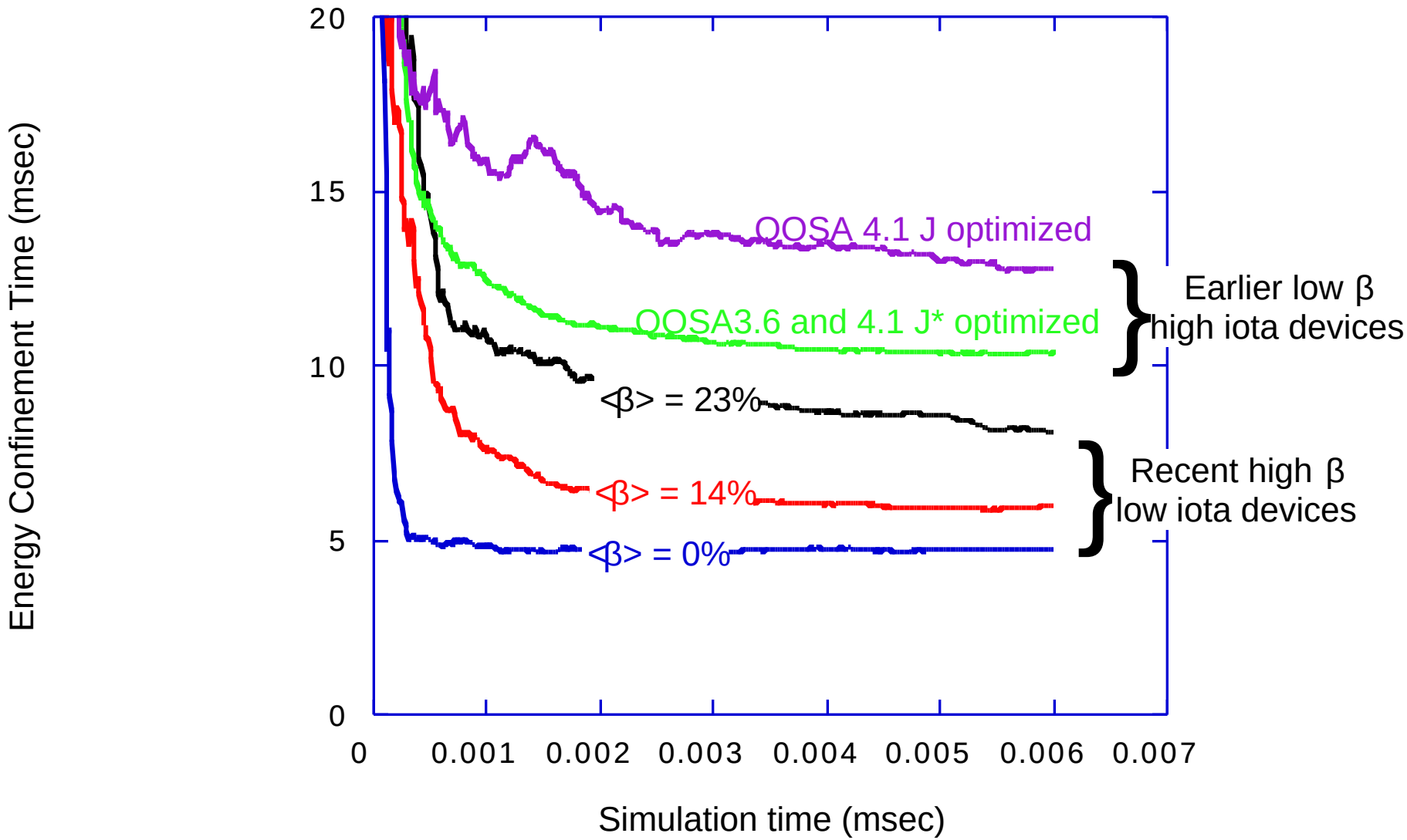
## β = 0




## β = 23%

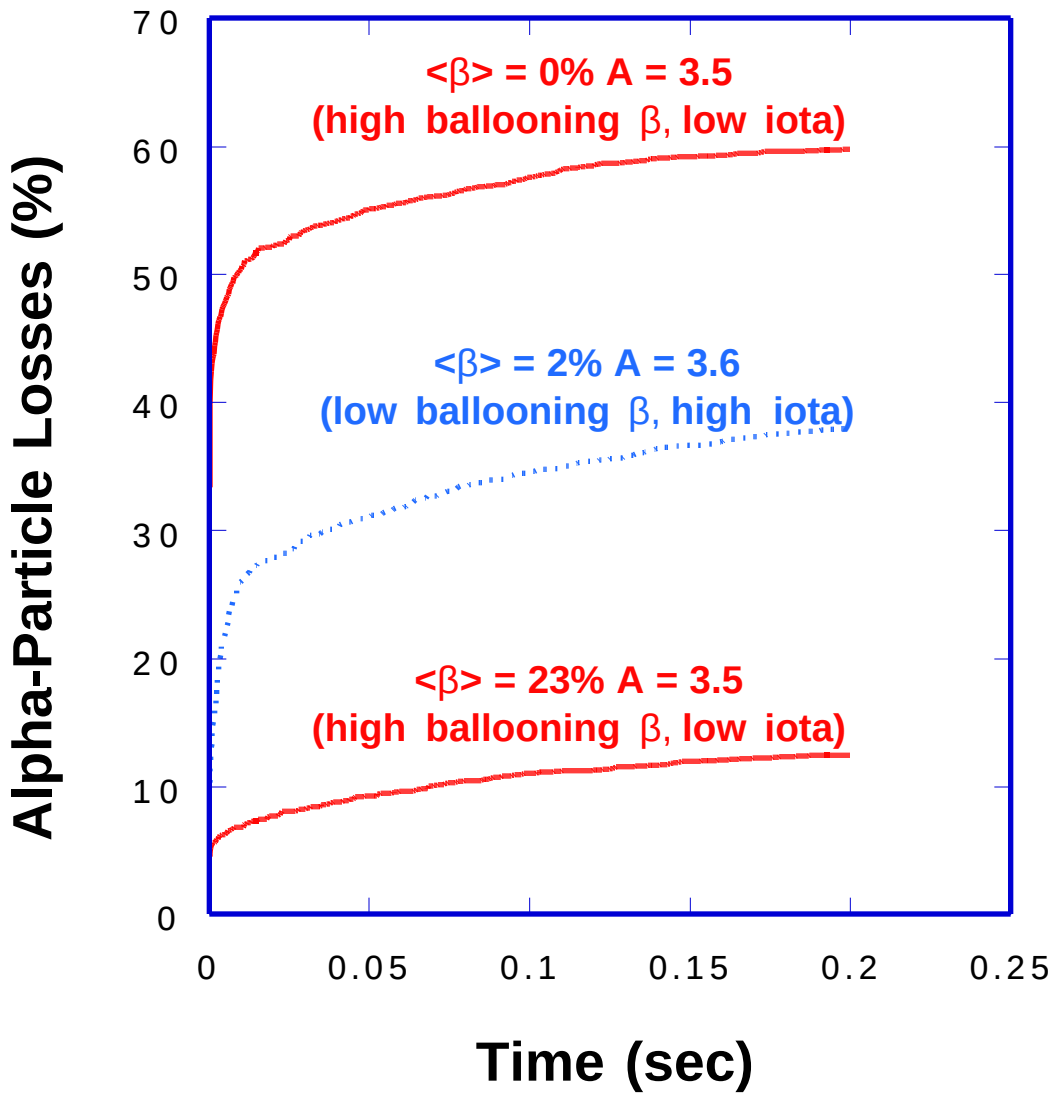


# Confinement Improves with Increasing β



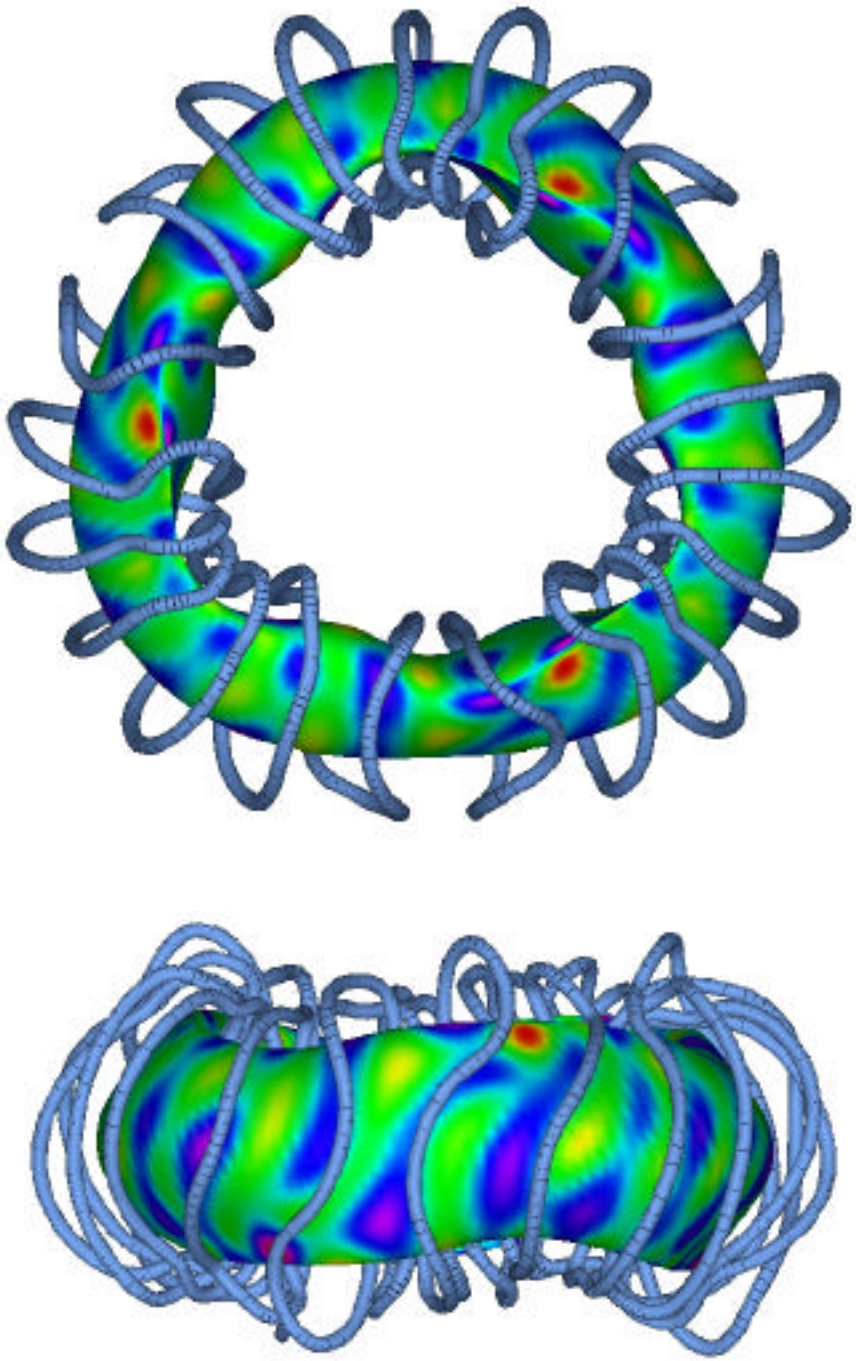

- **Low-$I_{BS}$ configurations factor ~2 better confinement**

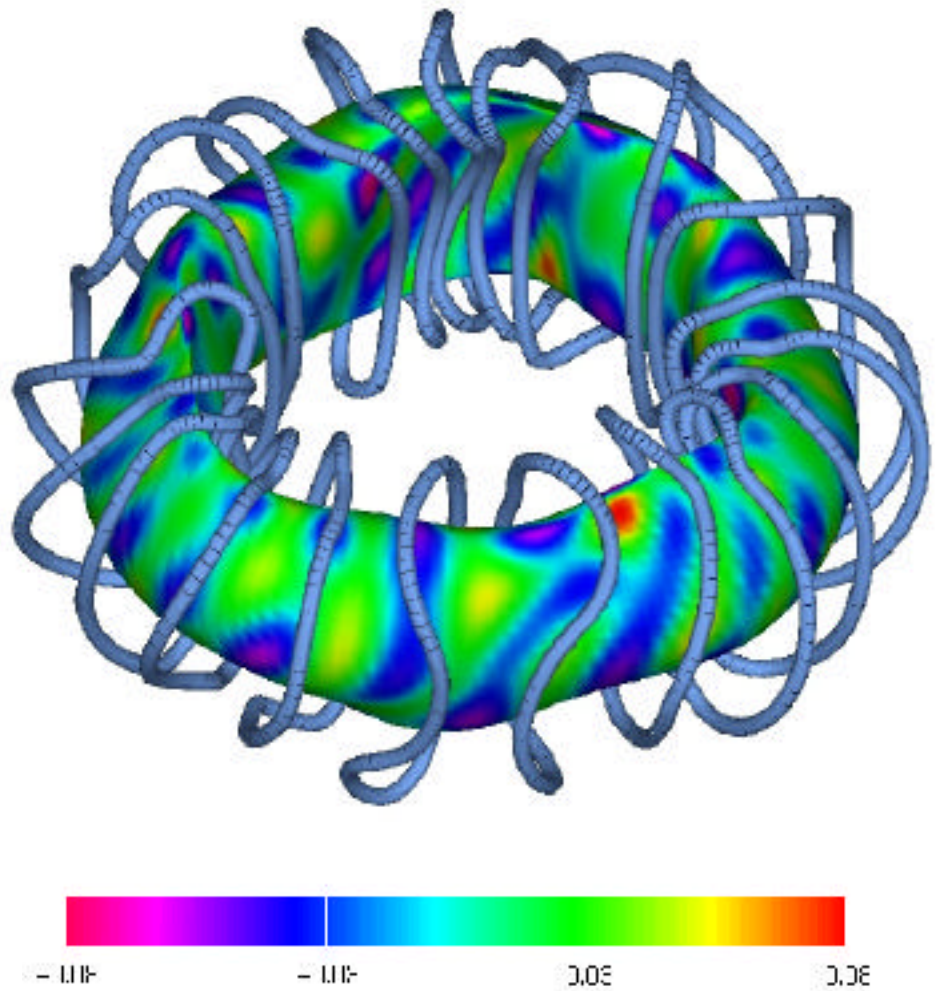
# α Confinement Improves with Increasing β




- **Low-$I_{BS}$ configurations have better confinement at low β**

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





# Plans

- **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
- **Complete assessment of higher-$I_{BS}$ configuration**
  - kink stability and flux surface fragility at $\beta > 10\%$
  - confinement and stability from low $\beta$ to high $\beta$
- **Improve energetic and thermal ion confinement**
- **Improve coil configuration**
  - small saddle coils in corners for high-$I_{BS}$ case
  - look at finite cross section modular coils for high-$I_{BS}$ case
  - improve plasma-coil and coil-coil spacings for low-$I_{BS}$ case
- **Assess low and high $I_{BS}$ configurations as reactors**

# SUMMARY

- **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 È**
  - **good neoclassical transport ($\tau_{E,neo} \approx$ 3-5 $\times \tau_{E,ISS95}$), ι ≈ 0.7**
  - **ballooning stable at β ≈ 3-4%**
- **An engineering assessment has started**
  - **coil calculations and preliminary cost estimate**
- **Work has started on a higher-β QO configuration**
  - **ballooning stable up to β ≈ 23%; also kink stable at β ≈ 10%**
  - **configuration may allow simpler modular coils and smaller reactor**
  - **neoclassical confinement still needs to be improved**