Overview of the QOS Project

J.F. Lyon, S.P. Hirshman, D.A. Spong, L.A. Berry,
R. Sanchez, J.C. Whitson, B.E. Nelson, M. Cole,
P. Goranson, D. Williamson, D.B. Batchelor

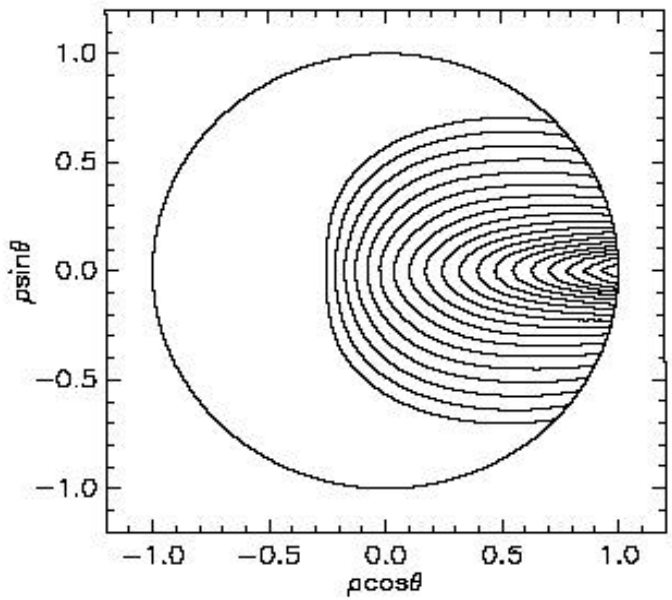
Oak Ridge National Laboratory

US-Japan Workshop on Stellarator/Helical System Concept Improvement

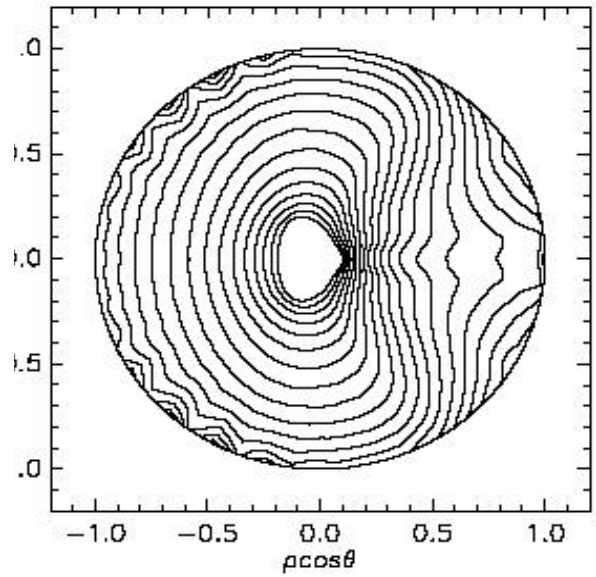
Oak Ridge, Sept. 23-24, 1999

QO Optimization Procedure Improves Confinement of Trapped Particles (at $\beta = 0$)

Open drift surfaces



Closed drift surfaces



- **J*** $\int v_{\parallel} d\varphi$, **approximate second adiabatic invariant; no** E_r
- **Drift surfaces in** $v_{\parallel}/v$ **range where orbits change from trapped to passing are less well confined; these determine the neoclassical transport**

ORNL Is Studying Low-*R/a* Quasi-Omnigeneous (QO) Stellarator Configurations

- Goal is a proposal within a year for an experiment to study QO optimization at low aspect ratio
- QOS physics studies are exploring different aspects of low *R/a* QO configurations
- 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

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TOPICS

- **Issues for Low-Aspect-Ratio Quasi-Omnigeneous Stellarators**
- **Physics and Coil Optimization for the QOS Reference Configuration**
- **Reference Configuration Properties**
  - **Magnetic Configuration (B_{mn})**
  - **Confinement and Heating**
  - **Beta Limits and Bootstrap Current**

Low-*R*/*a* QO Stellarators Have Advantages

- Lower aspect ratio (*R*/*a* ~ 3 to 4) has advantages
  - larger plasma size for a given cost experiment
  - lower cost for a given fusion power in a reactor
- Quasi-omnigeneity has advantages
  - Approximate alignment of bounce-averaged drift orbits and magnetic surfaces
    - reduced neoclassical transport, orbit losses
  - Low bootstrap current (~1/10 current in tokamak)
    - configuration insensitive to increasing beta
    - robust against current-driven modes
  - Magnetic well and stellarator shear out to plasma edge
  - Allowing multiple helicities provides flexibility to
    - obtain low aspect ratio
    - vary finite-β bootstrap current cancellation
    - change transport and ballooning stability limits

Issues -- are good QO properties kept at low *R*/*a*?

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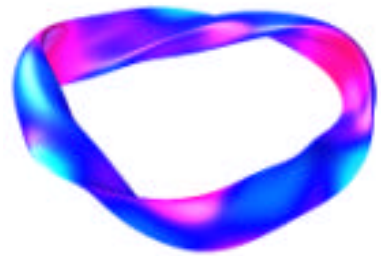
Optimization Loop Determines Outer Flux Surface Shape. Coils to Produce This Shape Are Then "Reverse-Engineered".

Initial configuration
(large aspect ratio)



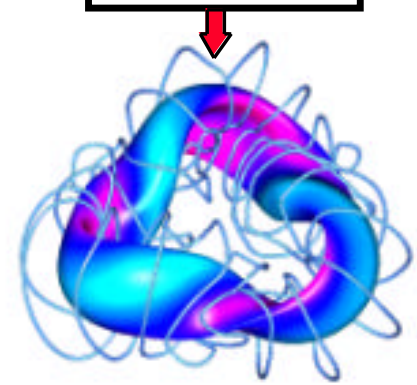
Final optimized configuration

Adjust boundary shape + profiles

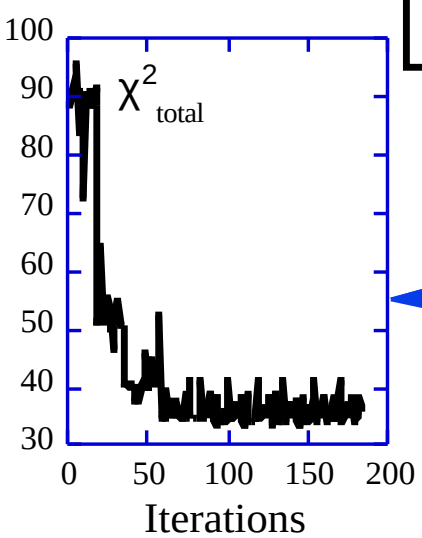
Solve VMEC equilibrium

Calculate physics targets, χ^2

NESCOIL COILOPT



Levenberg-Marquardt Minimize χ^2



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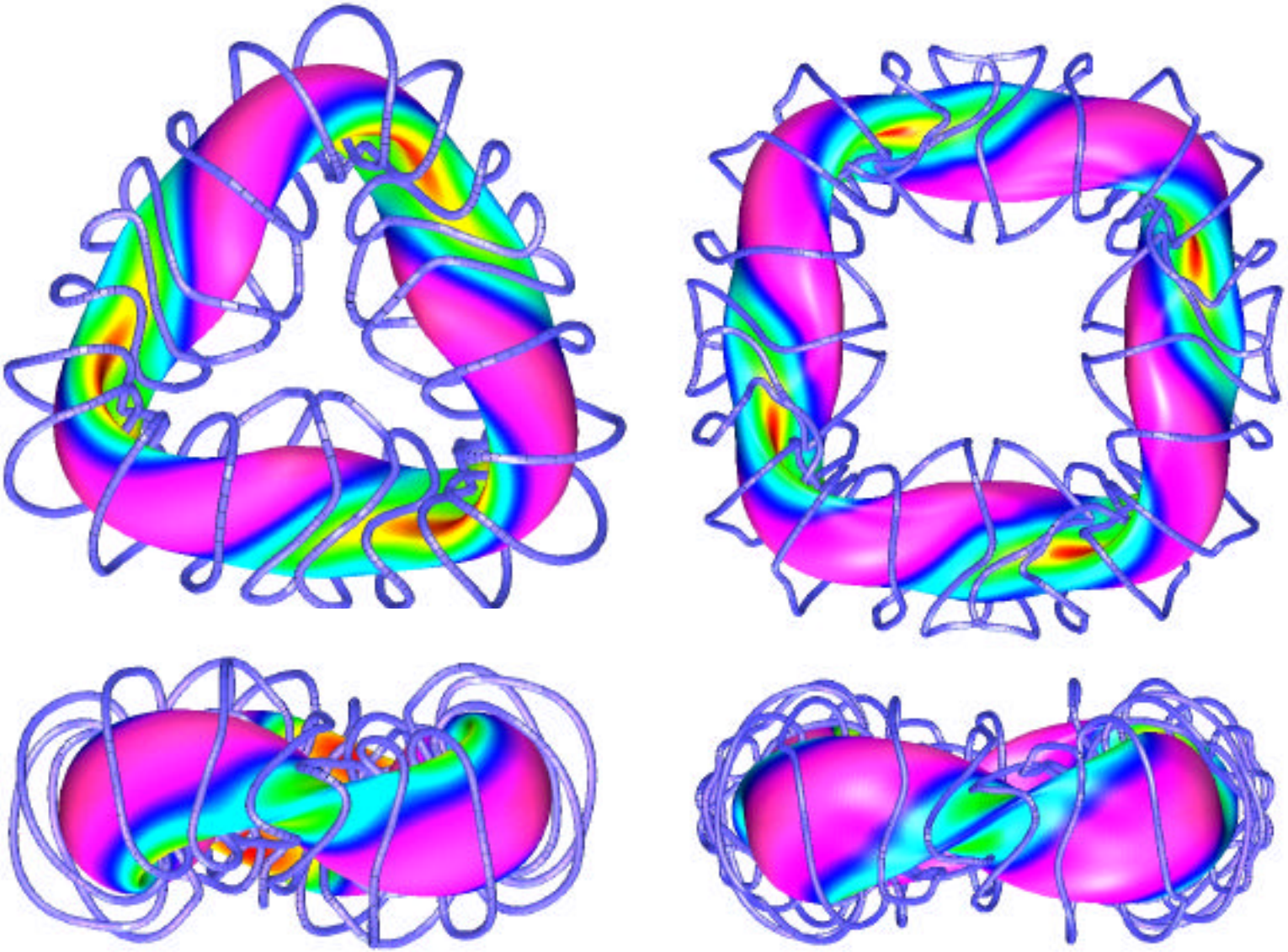
Optimization Process Integrates a Wide Range of Physics Criteria in χ^2

Targets (Physics/Engineering)	Example	
Bounce-average omnigeneity (drift surfaces and flux surfaces aligned)	$B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$ $J^* = J^*(\psi)$	Transport
Trapped, passing orbits	Replace J* with J	
Local diffusive transport	D, χ from DKES	
Current profile	monotone increasing $I(\psi)$ **self-consistent I_{BS}**	Equilibrium
Limit maximum plasma current	e.g., $I_{max} < 40$ kAmps	
Iota profile	$i(\psi) = 0.5$ $(\rho = 0)$ to 0.8 $(\rho = a)$	
Magnetic Well, Mercier	**$V'' < 0$, $D_M > 0$ over cross section**	Stability
Ballooning stability	**$\langle\beta\rangle \sim 4\%$**	
Aspect ratio	$R_0/a \approx 3$ to 4	Geometry
Limit outer surface curvature	avoid strong elongation/cusps	

<u>Control variables:</u> shape (40-50 Fourier harmonics R_{mn}, Z_{mn}) for LCFS + profile parameters

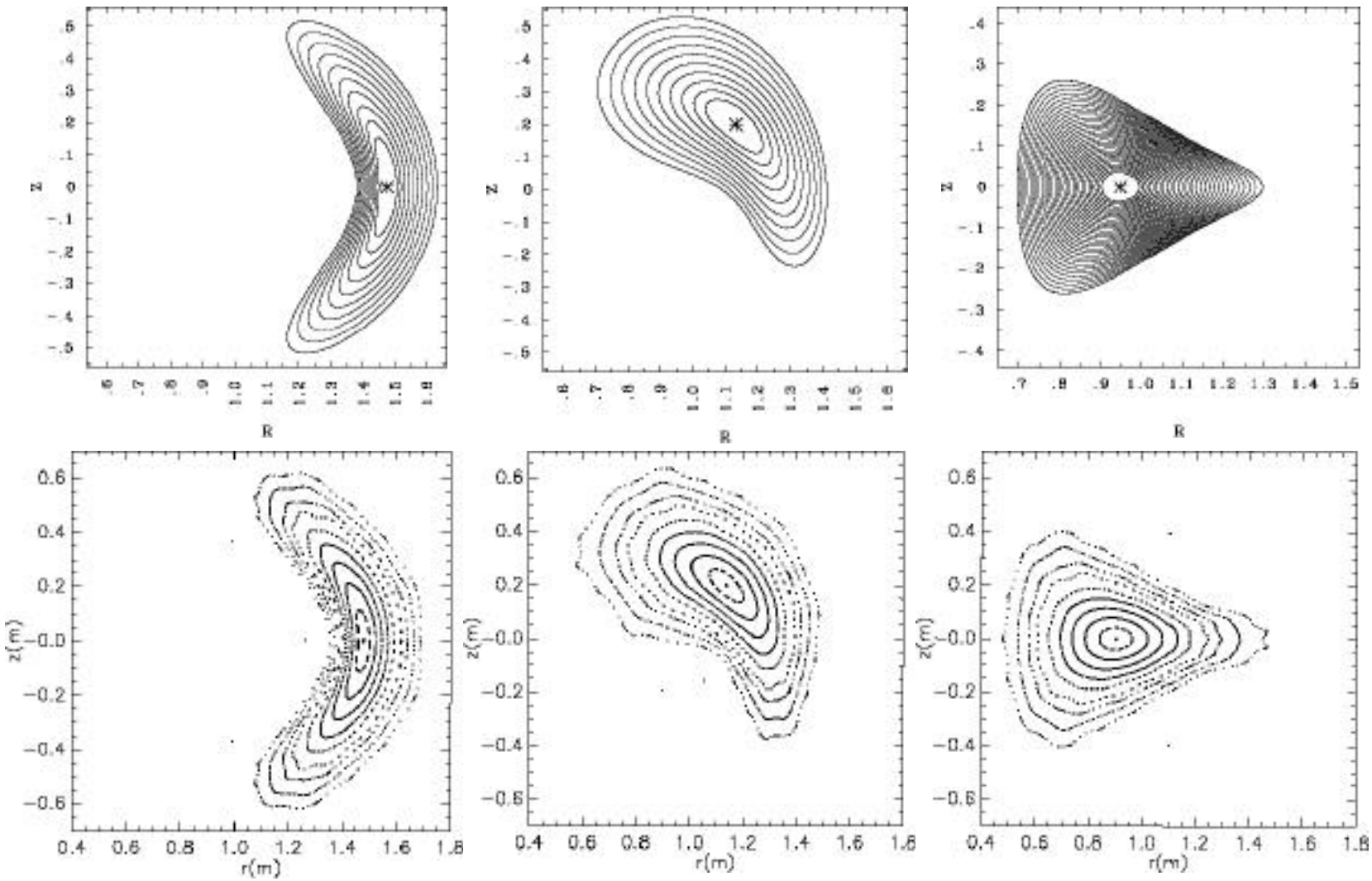
Three and Four Field Period QO Configurations Have Been Analyzed

<R>/<a> = 3 to 4.8



colors indicate contours of constant |B|

Excellent Flux Surface Reconstruction Is Obtained Using Modular Coils Generated by the COILOPT Code



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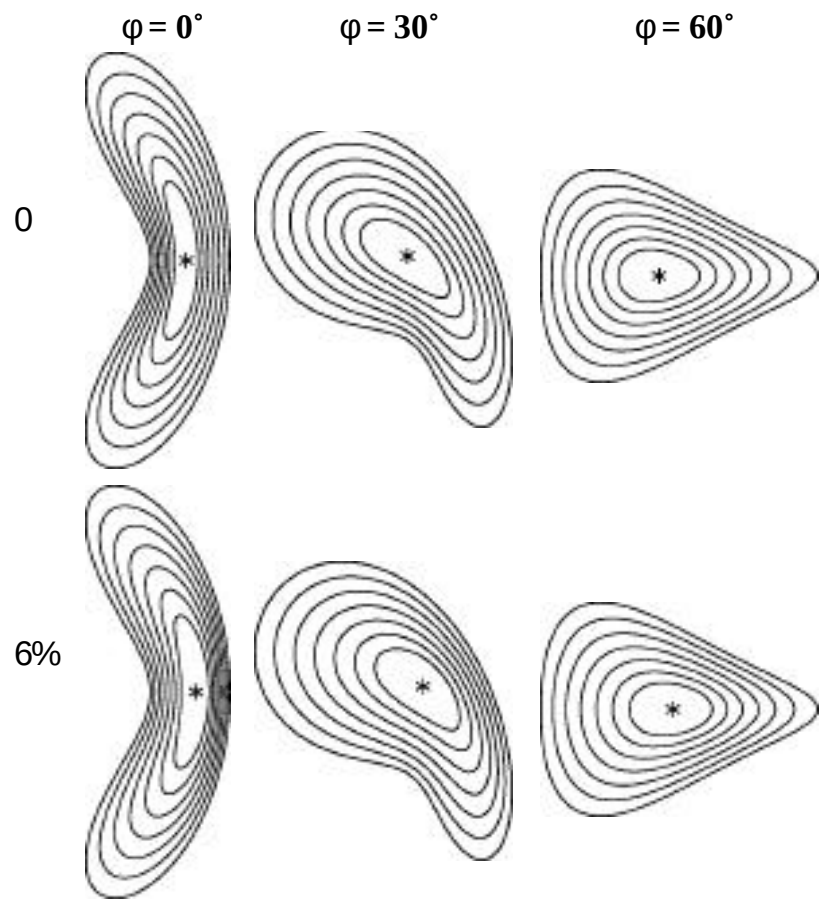
QO Configuration Is Insensitive to Increasing β

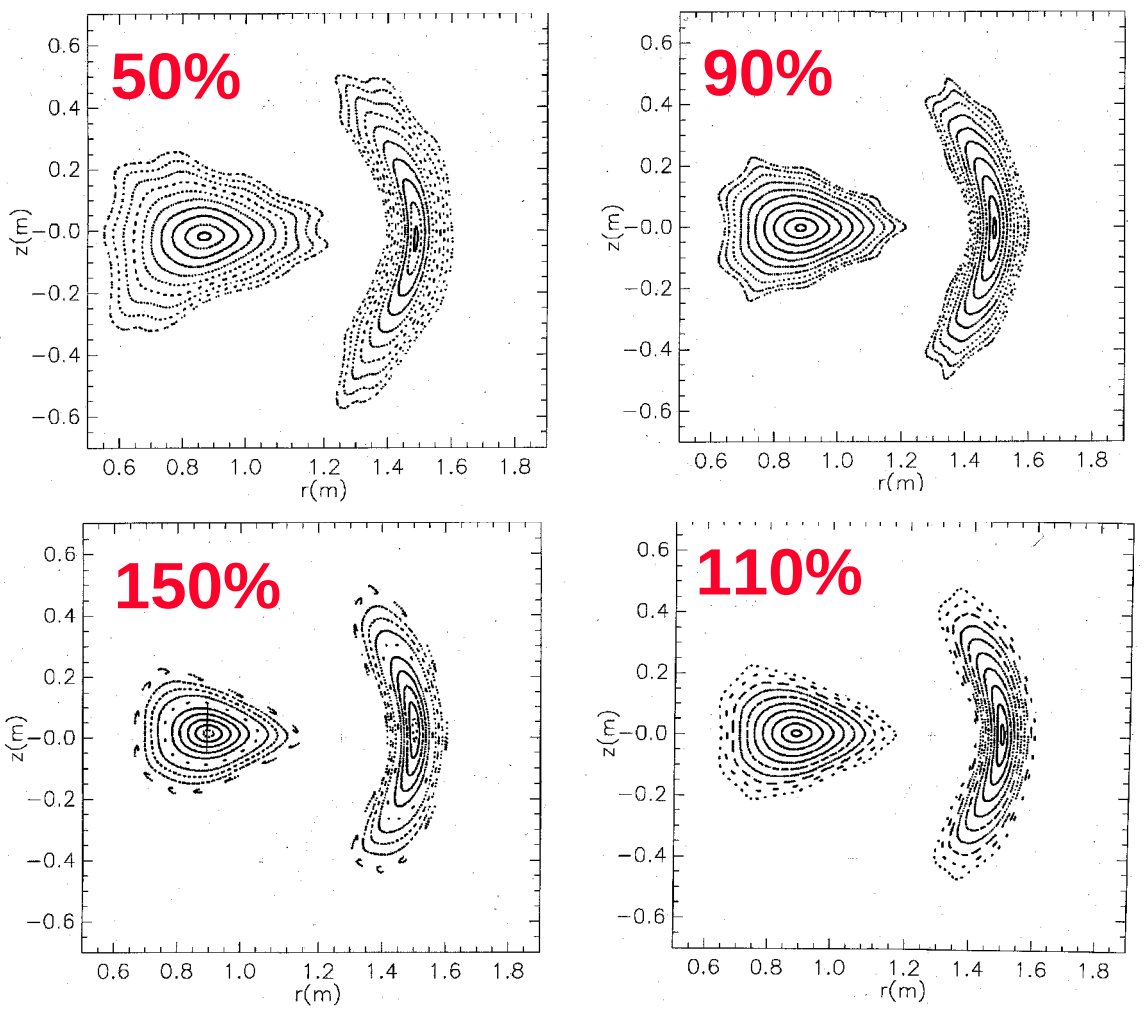
- Little outward magnetic axis shift between 0 and 6% β
- Small bootstrap current produces only ~10% change in the rotational transform



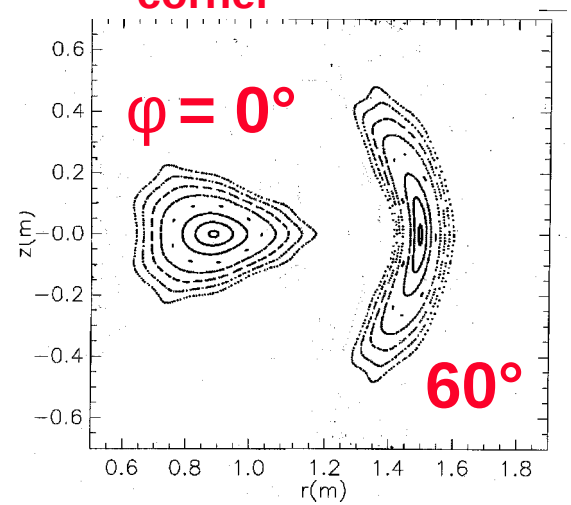
Path from vacuum to full β should be robust

QOS Modular Coils Allow Configuration Flexibility, Show Robustness

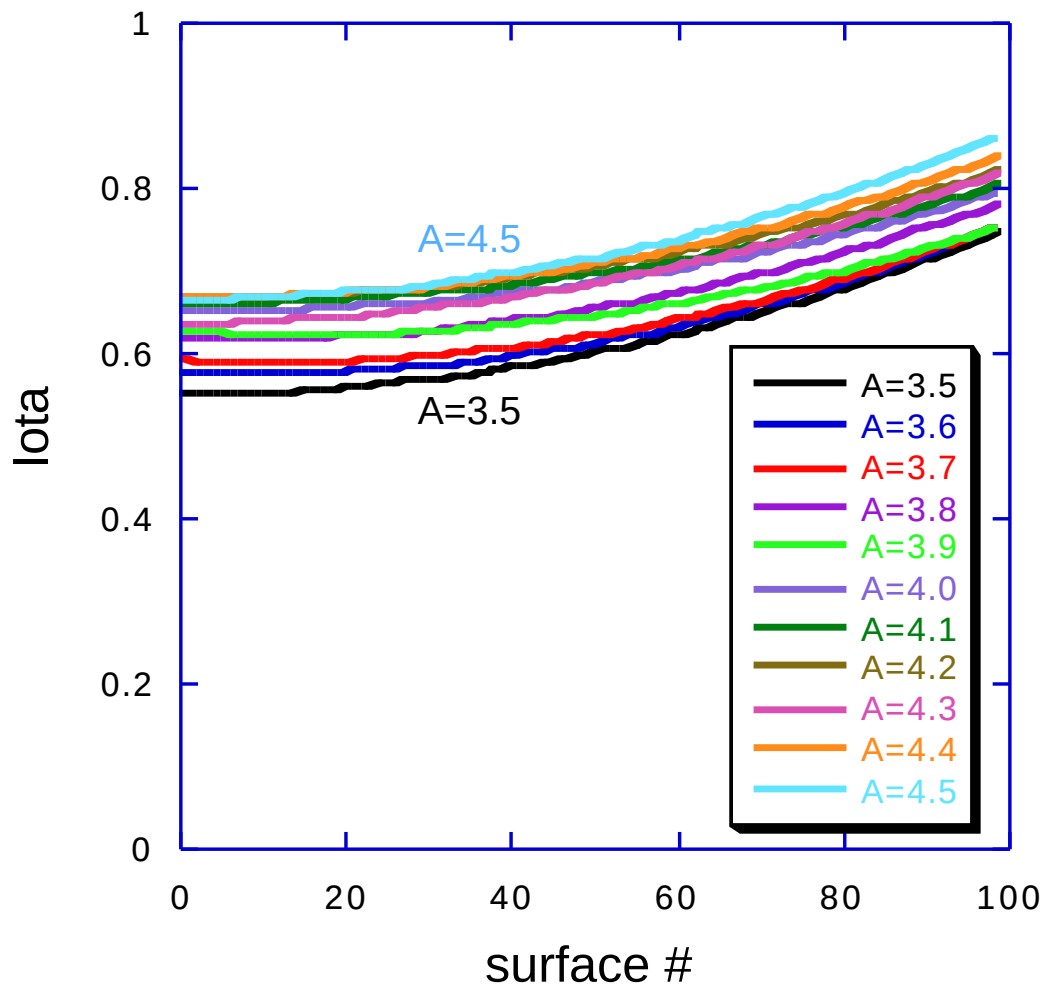
- No variation yet in VF coil currents or TF coils or β
- 10% change in a single coil introduces some islands



I_{corner} = 100%



Recent QOS Designs Have Focused on Aspect Ratios $R_0/\langle a \rangle$ = 3.5 to 4.5 and Rotational Transform 0.55 to 0.9



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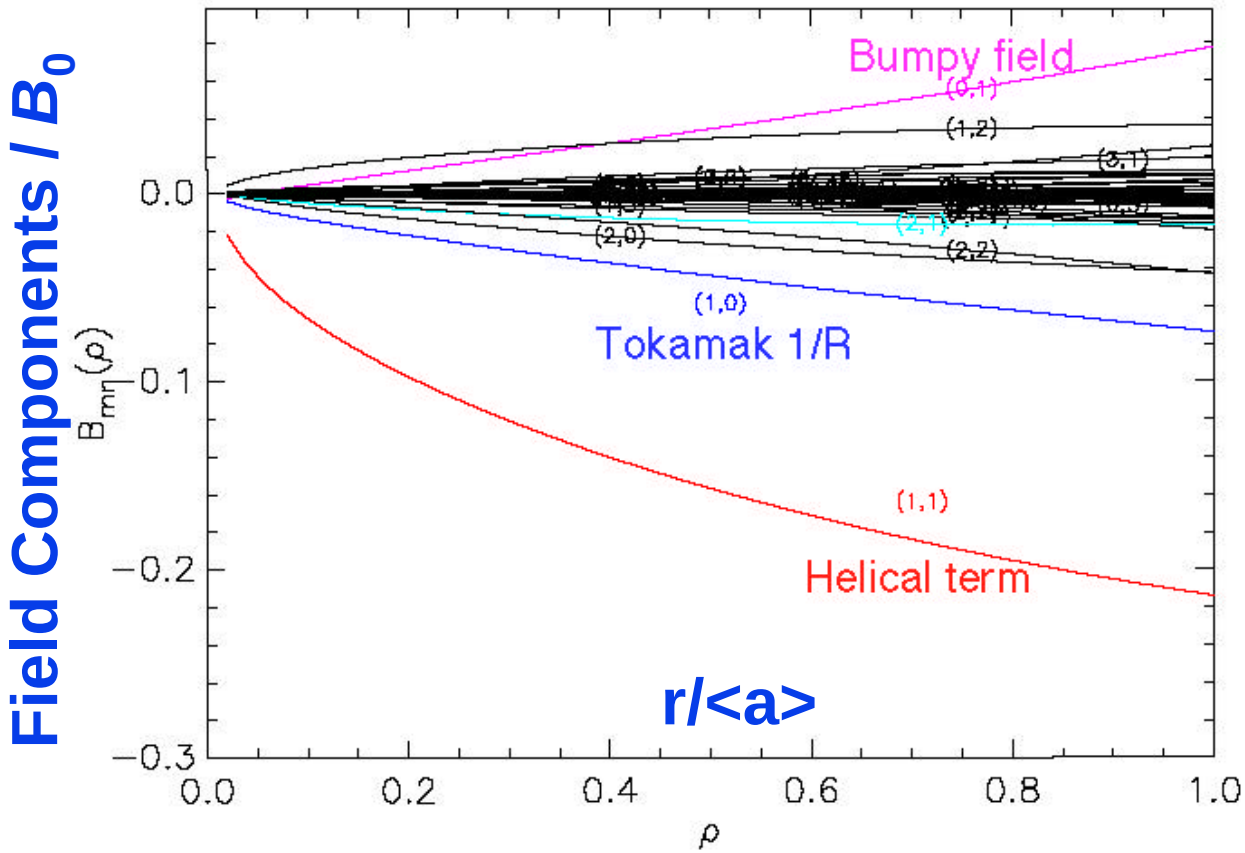
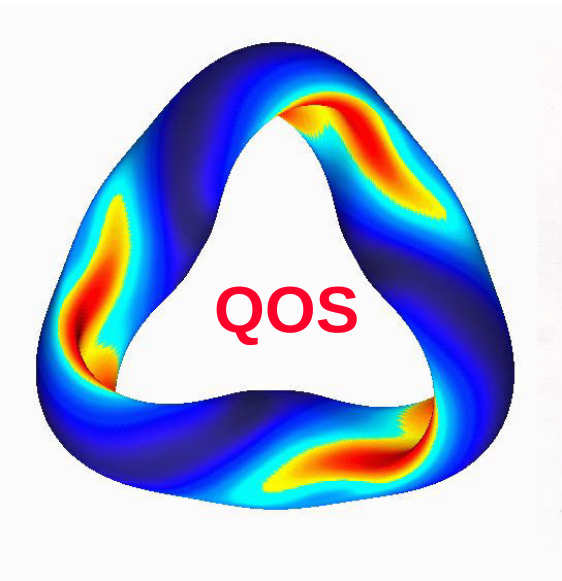
Spatial Harmonic Spectrum of a QO-Optimized Magnetic Field

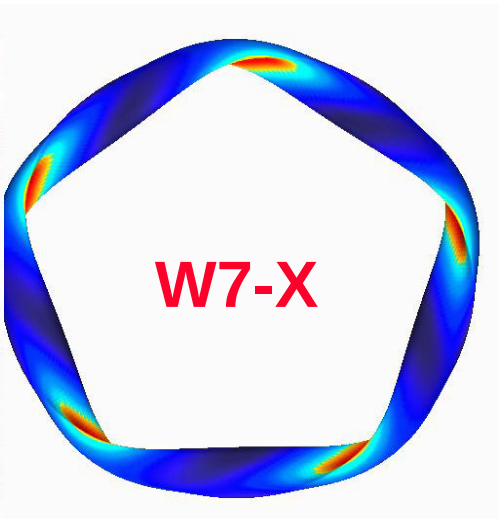


- **Helical shaping, axisymmetric 1/<R> term (a factor 4 less than in a comparable tokamak), and mirror field are dominant terms**
- **Compensating smaller terms needed to satisfy physics criteria**

QOS Configuration Complements W7-X and HSX

B(m,n) component	QOS	HSX	W7-X
Aspect ratio R/<a>	3.6	8	11
Helical (1,1)/B(0,0) at r = a (in %)	-22	-14.5	-7.6
1/R (1,0)/B(0,0) at r = a (in %)	-3.5	0.25	-4.3
Mirror (0,1)/B(0,0) at r = a (in %)	+8.6	+9.1[a]	+11.3
Mirror (0,1) at center/B(0,0) (in %)	0	+7.7[a]	+10.1





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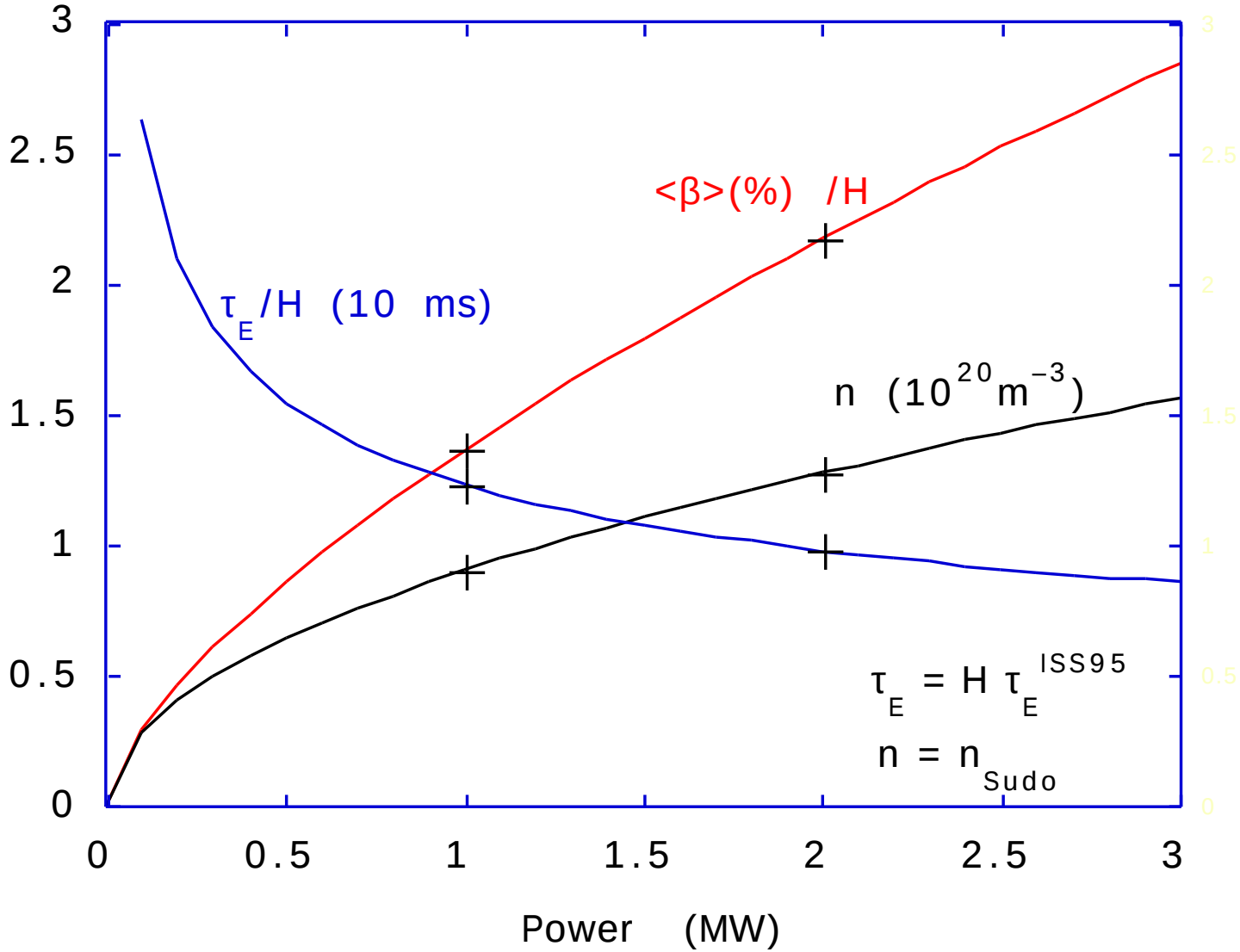
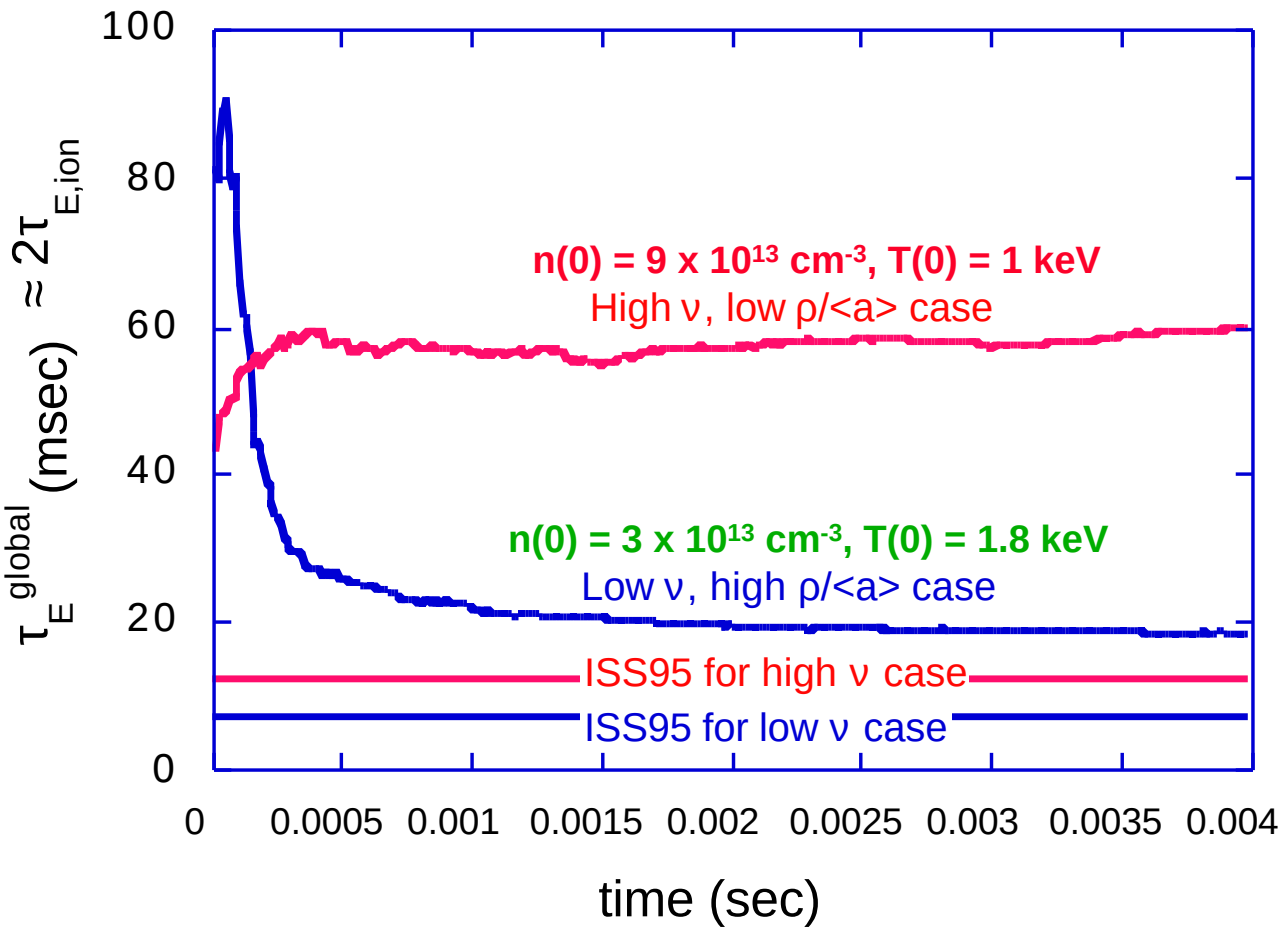
Projected QOS Plasma Performance

τ_E and β for ISS95 scaling; double for 2 x ISS95



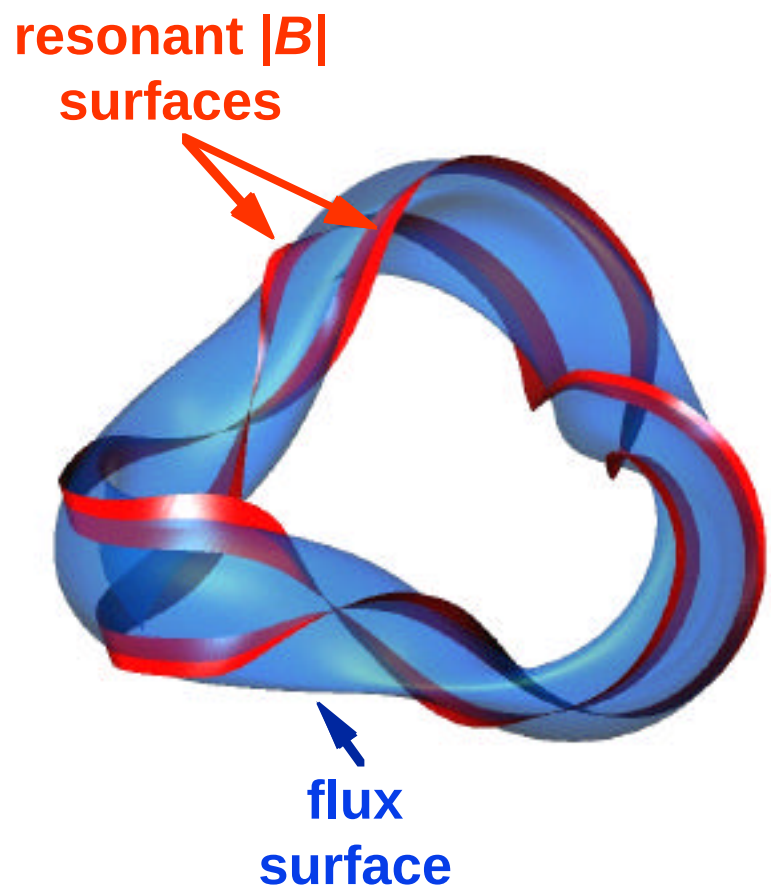
Full Radius Particle Transport Simulations Show QOS Global Transport Energy Lifetimes Are Not Dominated by Neoclassical Losses

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



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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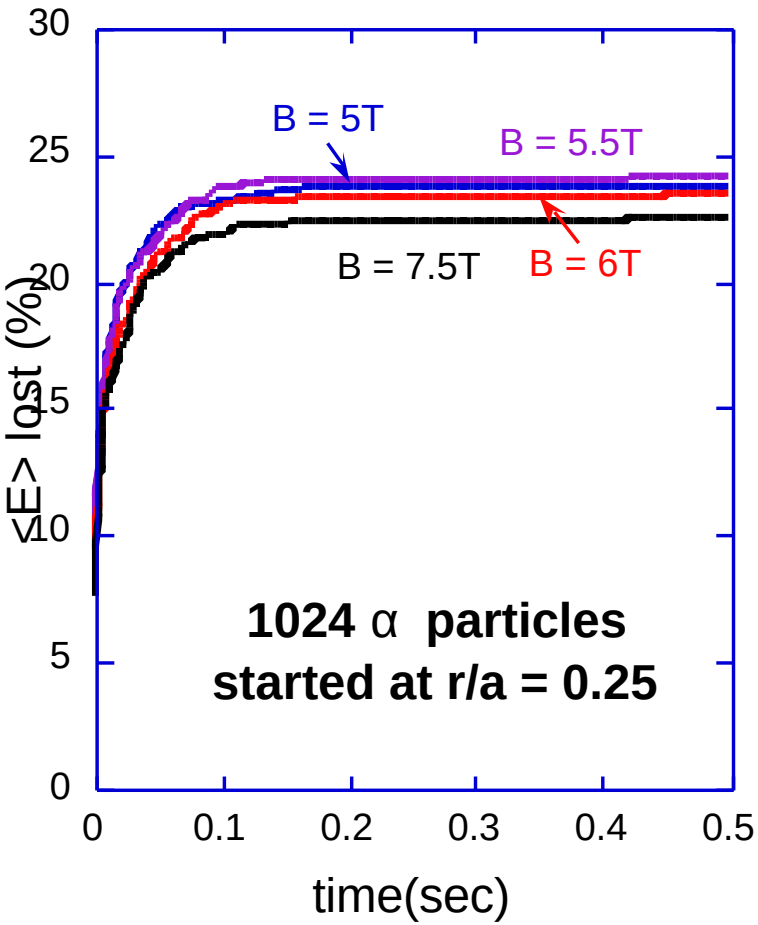
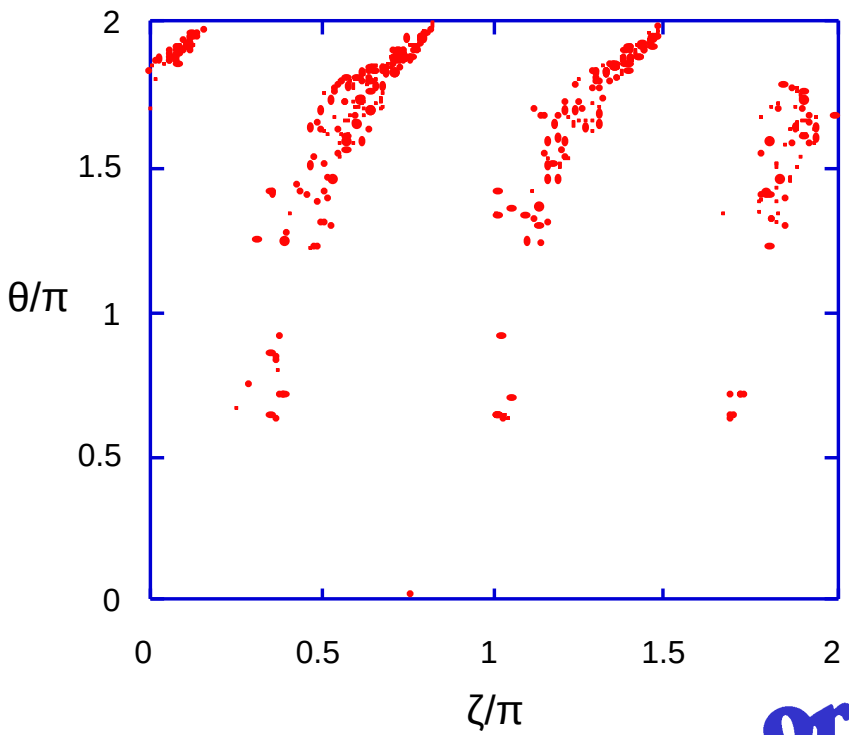
QO Devices Have Not Yet Been Optimized for a Reactor

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



Alpha loss locations on outermost closed flux surface



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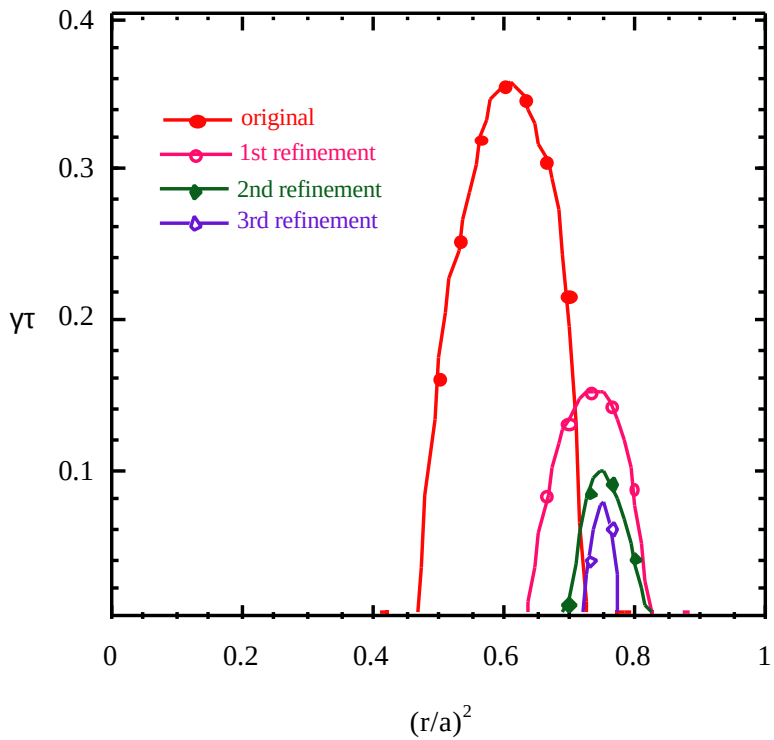
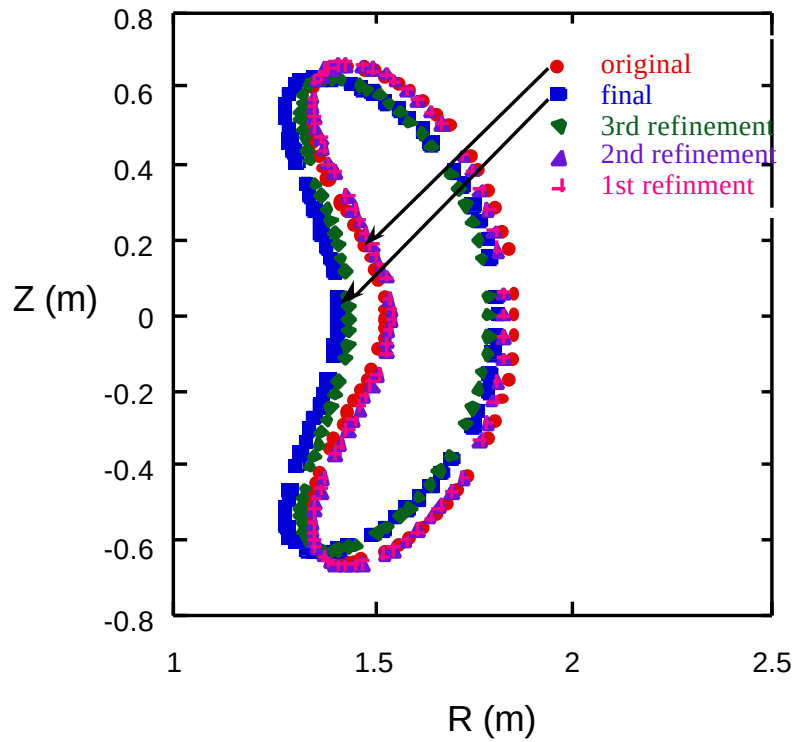
Fast Ballooning Calculation Allows Shape Optimization for Higher-β Configurations





- ~10 speedup in 3-D ballooning stability calculation allows incorporation in the optimization loop
- Original configuration, unstable at β = 3%, was stabilized by small plasma boundary shape changes
- Pressure profile modifications then raised stable β to 4%

Bootstrap Current Reduction Is an Important Feature for QOS Design and Operation

- **The bootstrap current affects plasma properties at a fundamental level with changes in**
  - **equilibrium -- transform, shifts, surface quality, etc.**
  - **stability -- ballooning, kink, and resistive modes**
- **Operationally, it is difficult to control because**
  - **the total current is roughly proportional to the plasma pressure and the profile is sensitive to the configuration**
  - **the collisionallity regime is important**
  - **the current response to changes is on the L/R time scale**
- **Avoid problems by minimizing bootstrap current**

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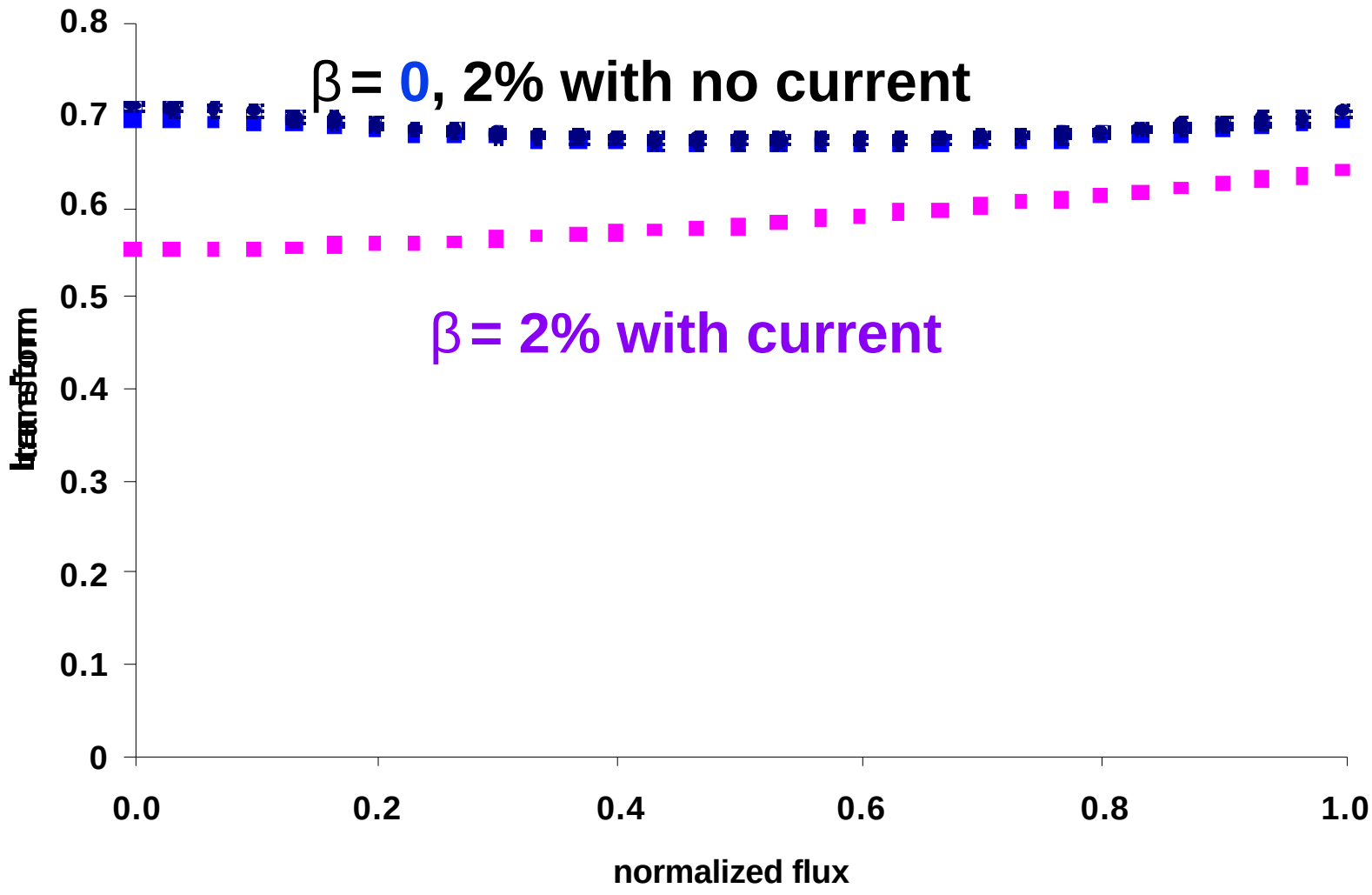
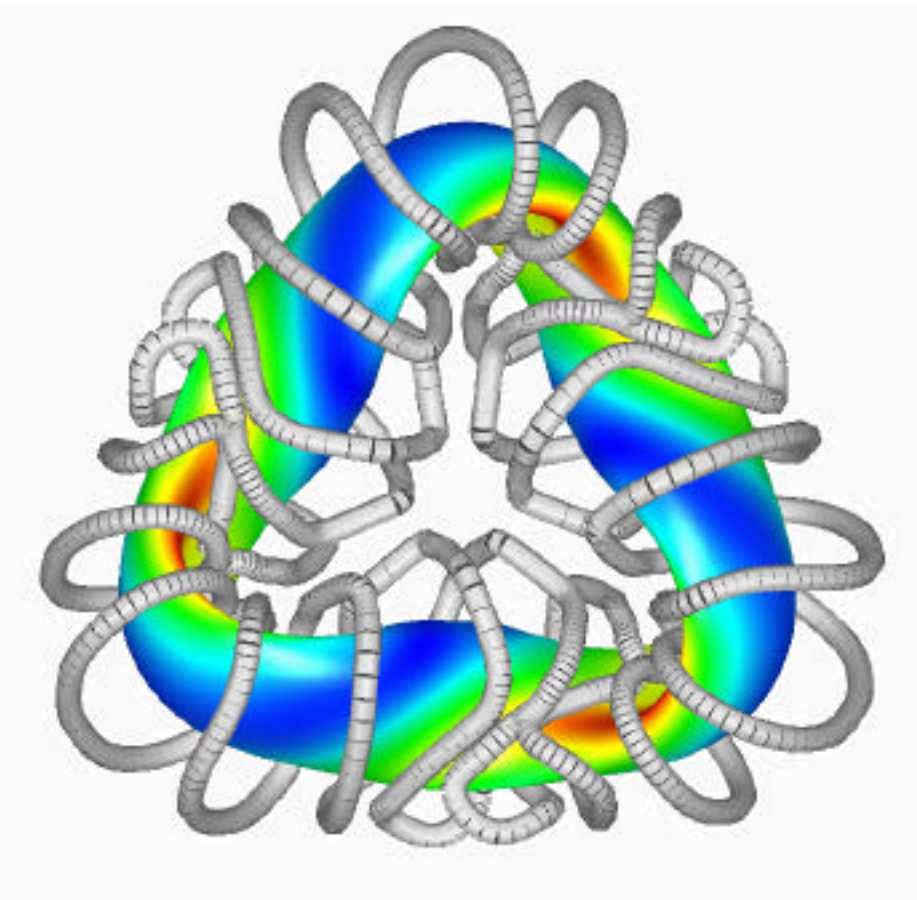
Bootstrap Current Contributes About 10% of the Net Transform Based on Equilibrium Calculations



Quasi-Omnigenous Stellarator



Scoping Study Parameters

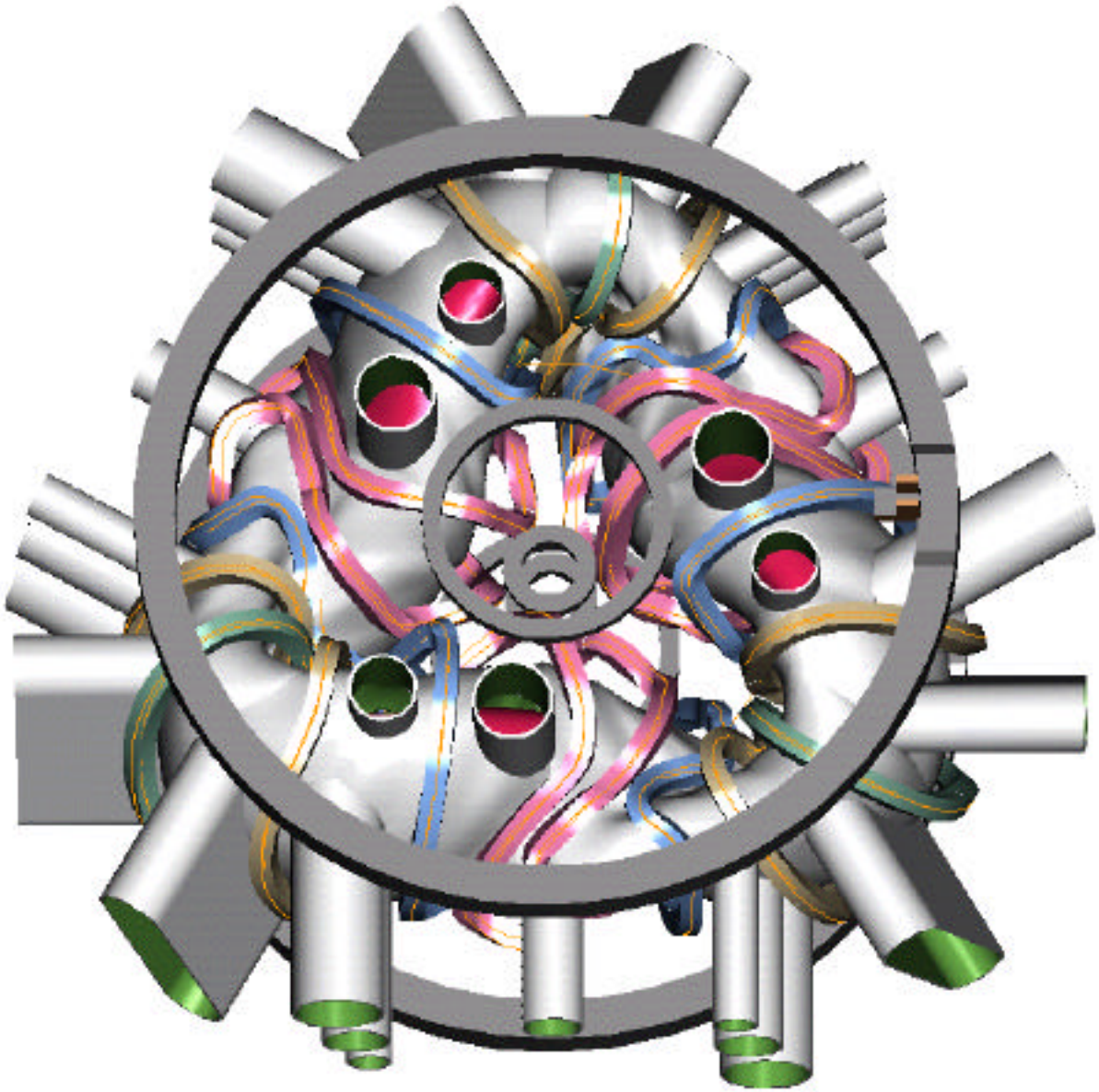
- R_0 1 m
- $\langle a \rangle$ 28 cm
- $R_0/\langle a \rangle$ 3.6
- B_0 1 T

Plasma Heating Available

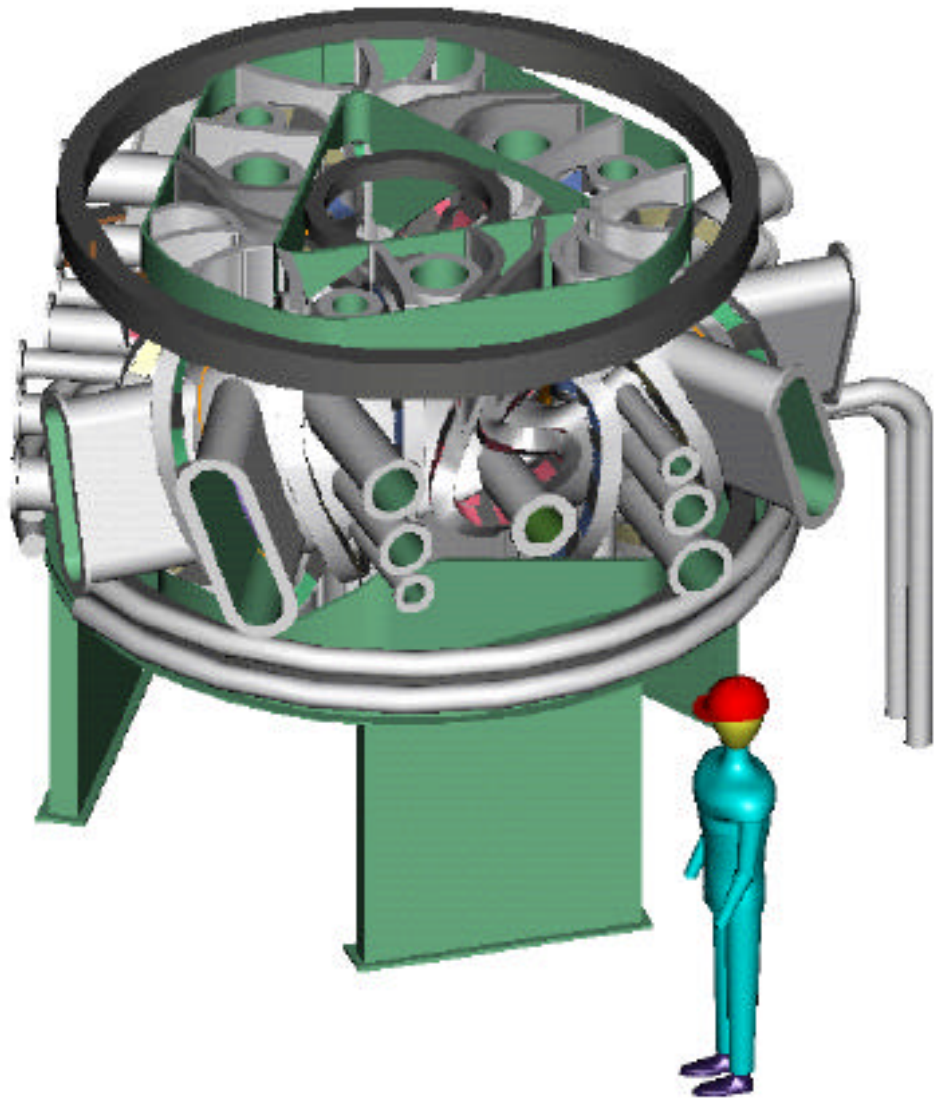
- 0.6 MW ECH
- 3 MW ICRF

Partnership with Univ. of Texas; collaboration with PPPL et al.

QOS LCFS, Vacuum Vessel, and Coils



View of QOS without Top and Side Plates



QOS Design Features

- **Pre-assembled unit, consisting of vacuum vessel, modular coils, PF coils, and structure**
- **Modular coil concept to minimize cost**
  - **Flexible conductor wound by hand on integral support structure**
  - **Molded winding cavity avoids expensive contour machining**
  - **Coils threaded over six identical vessel segments**
- **Machine designed for maximum access**
  - **Ports include: 6 with ~20 cm x 70 cm access, 12 with ~20 cm diam., +18 other ports**
  - **Coil structure does not interfere with access ports**
- **Maximum use made of existing equipment and facilities**
  - **Power supplies, control room, safety enclosure, cooling system**
  - **ECH and ICRF heating, fueling and vacuum pumping systems**
  - **Diagnostics**

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Issues for a Low-*R*/*a* QO Experiment

- **Fragility of magnetic surfaces as β increases**
  - **good surfaces in vacuum, ability to adjust as β increases?**
- **Control of the bootstrap current**
  - **minimization, reversal, effect on tearing modes?**
- **Increasing the beta limit above 2%**
  - **deep magnetic well, Mercier curvature term stabilizing?**
  - **ballooning stability limited by corners?**
- **Reduction of neoclassical transport, orbit losses**
  - **confinement >> ISS95 scaling?**
  - **compatibility with efficient ICRF heating?**
  - **adequate aplha-particle confinement for a reactor?**
- **Access to improved confinement modes?**
- **Compatibility with divertor**
  - **modular coils allow access to exiting flux bundles?**
- **Coil-plasma spacing leads to a compact reactor?**

Some Issues Can *Not* Be Addressed in an R = 1 m, B = 1 T , t = 1 s QOS Experiment

- **Heating power does not allow exploring $\beta \approx 4\%$**
  - **can only test robustness, stability to $\beta < 2\%$**
- **True steady-state operation not available**
  - **can only test bootstrap current equilibrium in 1-s pulse**
- **Full divertor operation not available**
  - **can only study power in diverted flux bundles exiting between coils and hitting wall**

    (modify using biased targets and varying coil currents)
- **LHD and W7-X will address these issues**

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SUMMARY

- **Progress has been made in the preliminary design phase for a compact QO concept exploration experiment**
  - **Low aspect ratio, $R/\langle a \rangle = 3.6$**
  - **Bootstrap current << current in tokamak for same size and ι**
  - **Self-consistent with bootstrap current profiles**
  - **Good neoclassical transport ($\tau_{E,neo} \approx 2\text{-}3 \times \tau_{E,ISS95}$), $\iota \approx 0.7$**
  - **Ballooning optimization achieves $\beta \approx 4\%$**
- **Start has been made on coil and engineering design**
  - **7 modular coils per period - good flux surface reconstruction**
  - **Good access for heating and diagnostics on all sides**
- **Further work is needed**
  - **Better optimization of the magnetic configuration**
  - **Better optimization of the modular coils**
  - **Refinement of the engineering studies, costing**
  - **Reactor optimization studies**

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