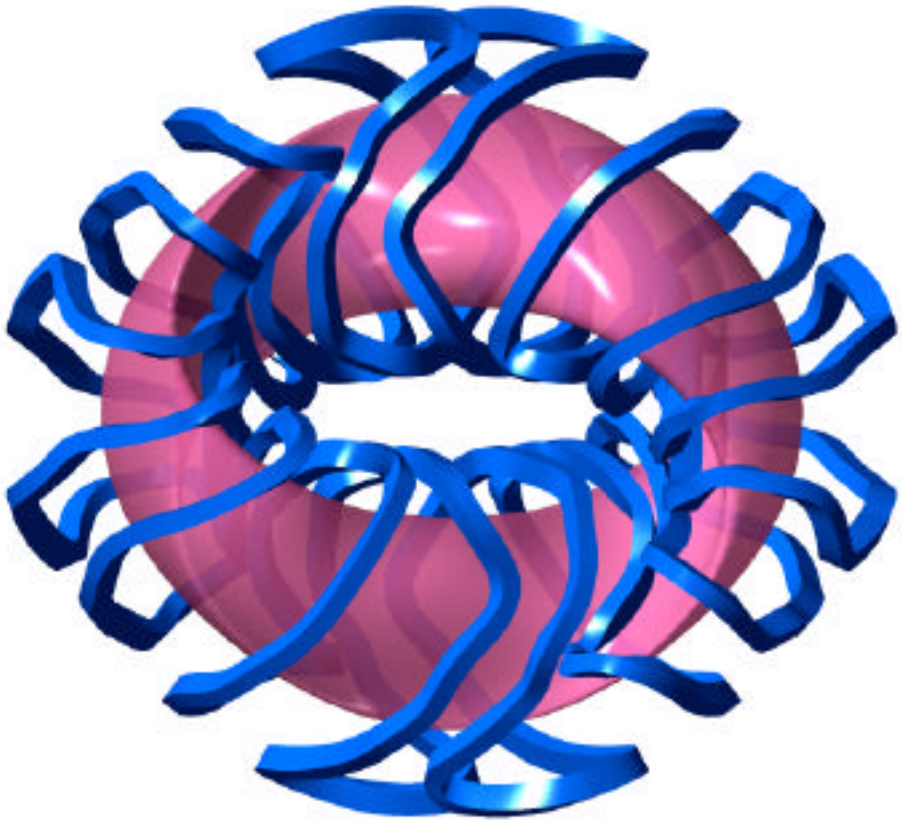
# QOS Status



**J.F. Lyon for the QOS Team**

**OFES Seminar, Feb. 20, 2001**

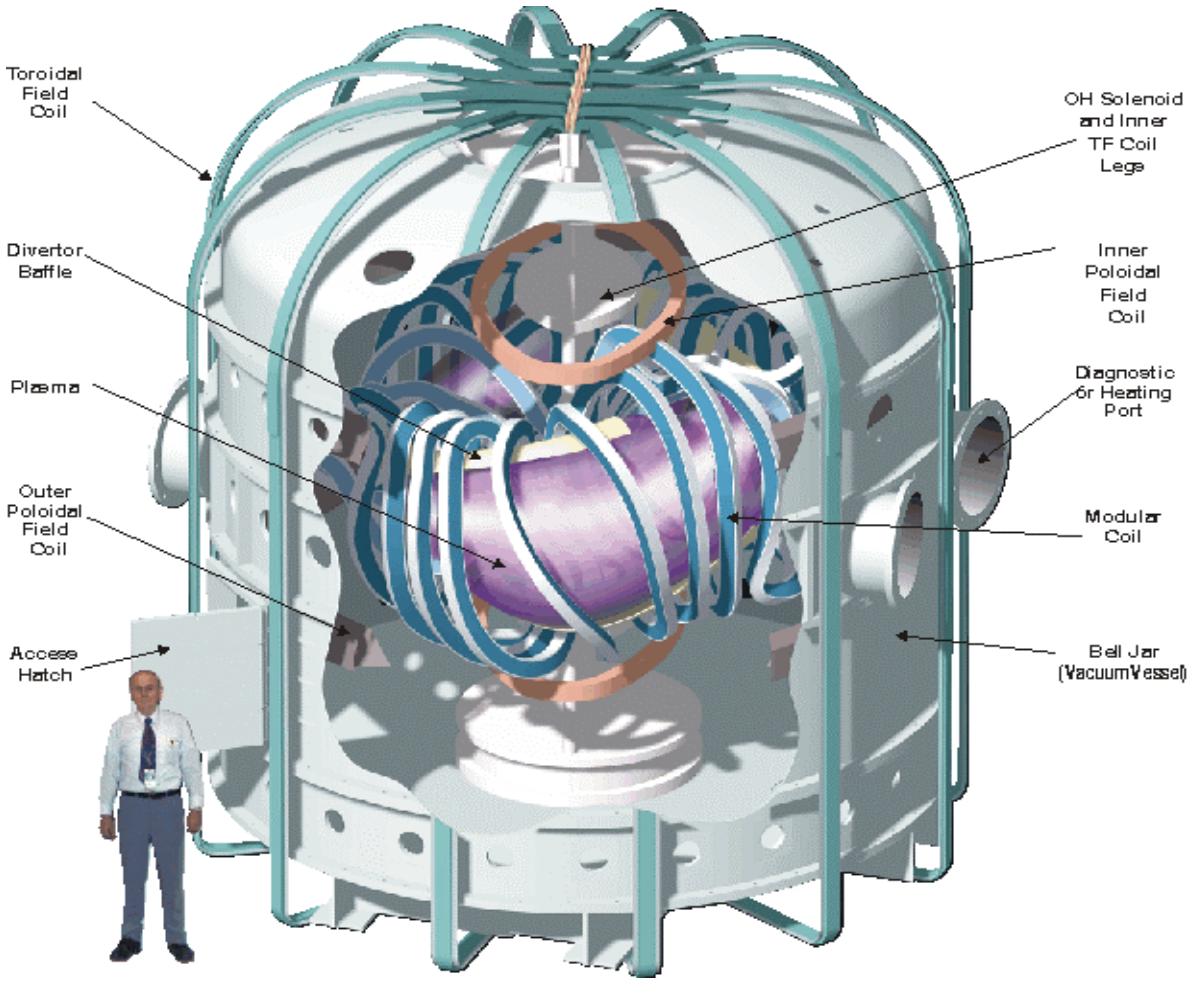
# Multi-Laboratory QOS Design Team Builds on NCSX Base

- **ORNL – D.B. Batchelor, L.A. Berry, M.J. Cole, R.H. Fowler, P. Goranson, E.F. Jaeger, S.P. Hirshman, J.F. Lyon, P.K. Mioduszewski, B.E. Nelson, D.A. Rasmussen, D.A. Spong, D.J. Strickler, J.C. Whitson, D.E. Williamson**
- **U. Texas at Austin – W.H. Miner, jr., P.M. Valanju**
- **U. Montana – A. Deisher, D. Heskett, A.S. Ware**
- **PPPL – G.Y. Fu, D.A. Monticello**
- **U. Tennessee – T. Shannon**
- **Universidad Carlos III de Madrid, Spain – R. Sanchez**

**Tools & experience developed by NCSX-QOS team applied to QOS**

# QOS

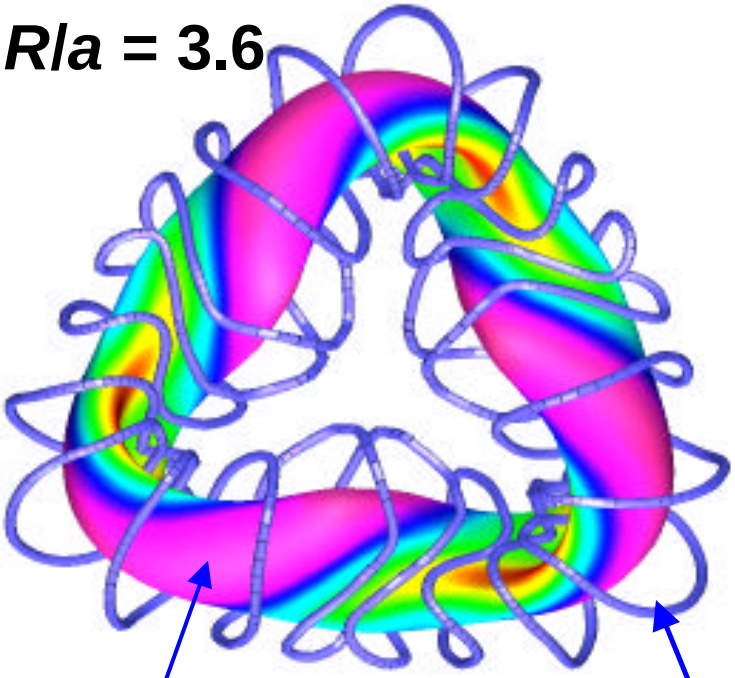
## a Low-R/a Quasi-Poloidal Stellarator




- **$\langle R \rangle$ = 0.95 m**
- **$\langle a \rangle$ = 0.37 m**
- **$\langle R \rangle / \langle a \rangle$ = 2.6**
- $V_{pl}$ = 2.5 m$^3$
- **$\iota_0$ = 0.26, $\iota_a$ = 0.39**
- **$B_{mod}$ = 1 T (0.5 s)**
- $B_T$ = ± 0.15 T
- $I_p \leq$ 70 kA
- **$P_{ECH}$ = 0.6-1.2 MW**
- **$P_{ICRF}$ = 1-3 MW**

# QOS Configuration Has Evolved to a Larger, More Compact System

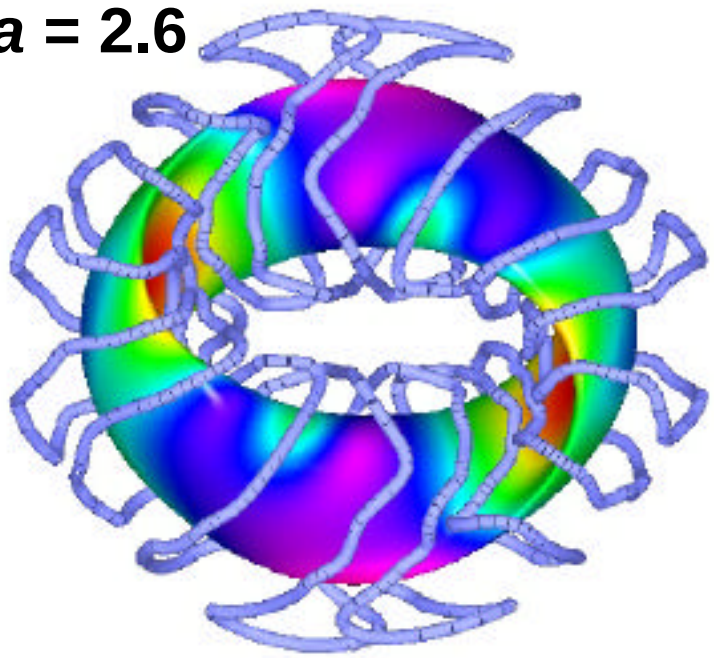
*Rla* = 3.6



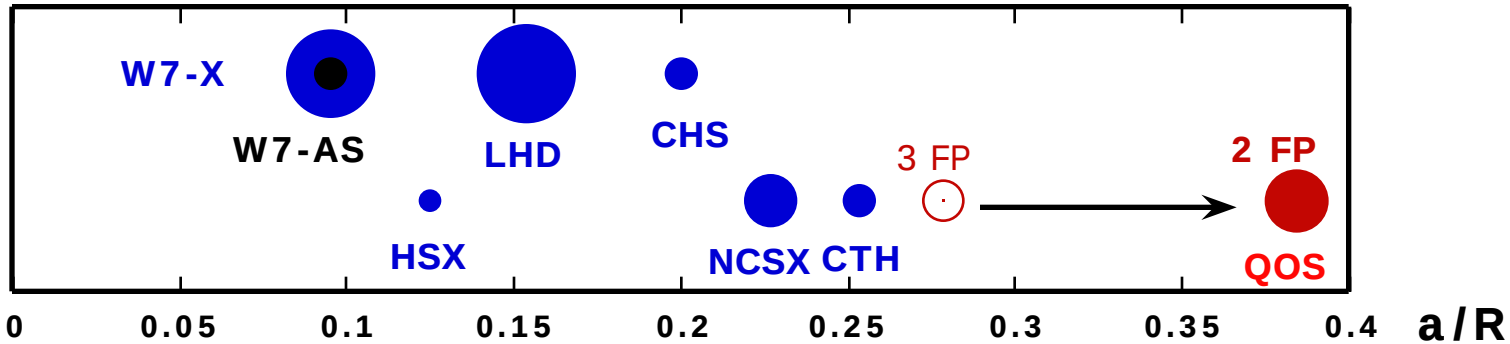
Plasma surface

Coil Set

*Rla* = 2.6



Colors show contours of constant |*B*|

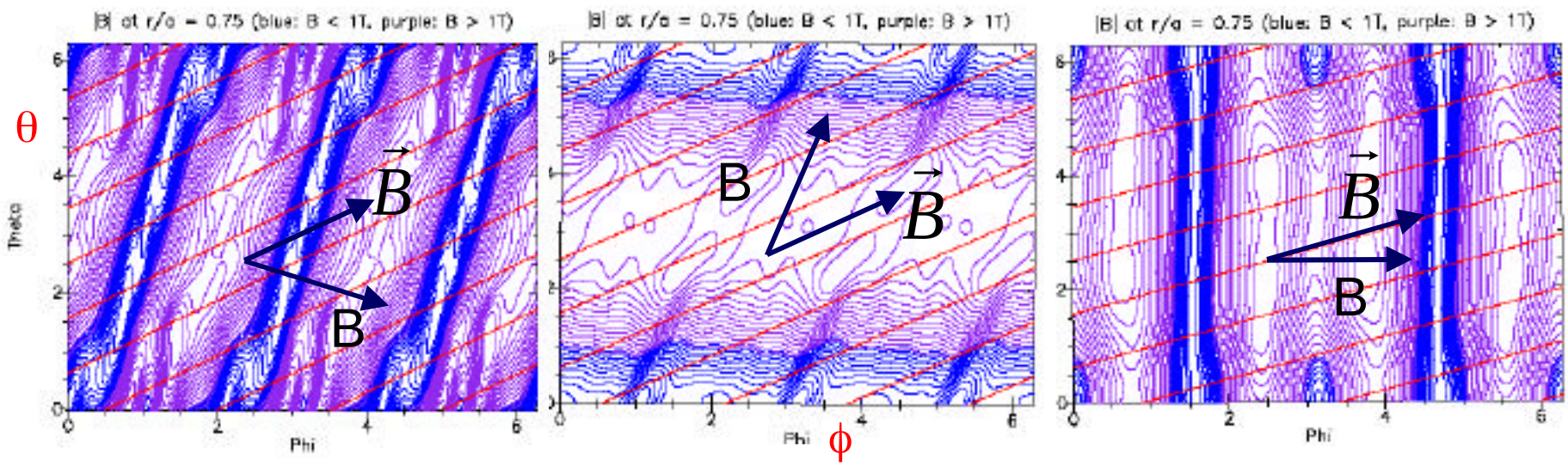


# Stellarator Concept Optimization Employs Quasi-Symmetry

**As R/a becomes smaller, the magnetic field structure employs a dominant symmetry in the magnetic field to obtain good neoclassical confinement**

- **$|B| = \sum B_{mn}(\psi) \cos(m\theta - n\phi)$; $\theta$ and $\phi$ poloidal and toroidal angle variables**

**Quasi-Helical** **Quasi-Axisymmetric** **Quasi-Poloidal**




- Quasi-helical: |B| like very large *R/a* stellarator. HSX (*R/a* = 8) will test this concept.
- Quasi-axisymmetric: |B| like tokamak. NCSX (*R/a* = 4.4) would test this approach.
- **Quasi-poloidal: |B| like toroidally linked mirrors. The *B* x B drift can be made very small in this approach. QOS (*R/a* = 2.6) would test this concept.**

# Motivation for Quasi-Poloidal Symmetry

- **Quasi-poloidal symmetry for QOS originally motivated by quasi-poloidal high-$\beta$ (10-15%) reactor-relevant configurations**
- **Unique features contribute to toroidal physics understanding**
  - **neoclassical confinement improvement due to near alignment of *B* and B**
  - **configuration robustness: small change at low $\beta$ due to low bootstrap current compared to tokamaks**
  - **presence of trapped particles at the magnetic axis permits non-zero bootstrap on axis with no seed current needed**
  - **direction of bootstrap current + sign of shear should decrease size of magnetic islands and stabilize neoclassical tearing modes**
  - **compensation for toroidal effects at very low *R*/*a*, ~1/2 that of existing stellarators**
  - **possible impact of poloidal flows on enhanced confinement**

# QOS Mission

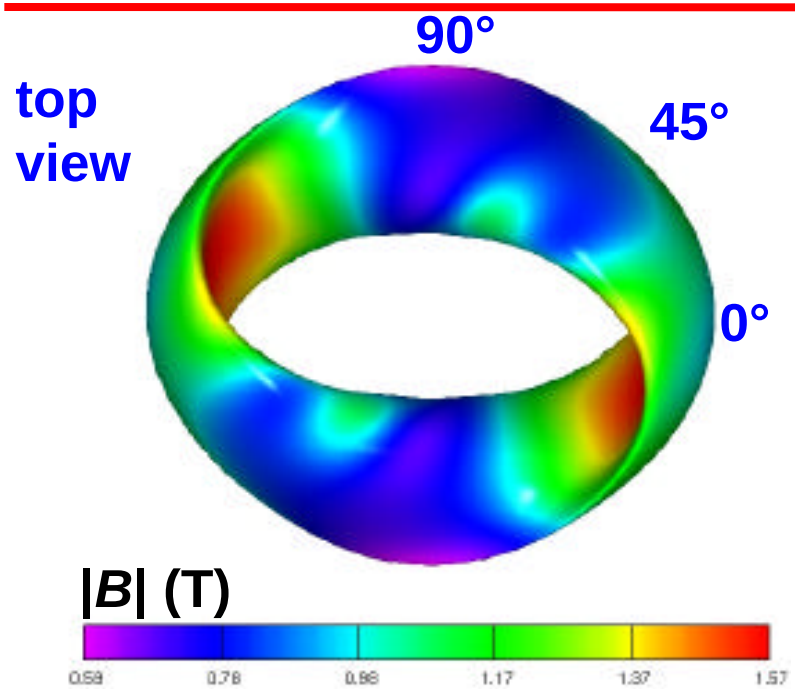
- **Broaden understanding of toroidal magnetic configurations -- quasi-poloidal symmetry**
- **Explore very low aspect ratio (~2.6)**
- **Develop understanding of key issues for a low-*R*/*a* quasi-poloidal approach to a high-β (•β®= 10-15%) compact stellarator concept**
- **Complement NCSX in completing the knowledge base needed for advancing the development of the compact stellarator concept to the next stage**

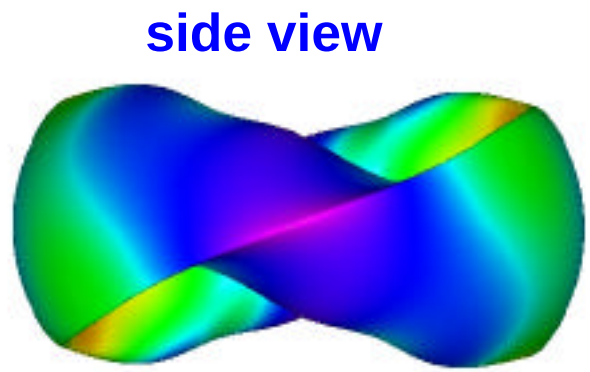
**QOS would determine the optimum mix of quasi-poloidally symmetric components of the magnetic field for a compact stellarator configuration**

# Topics

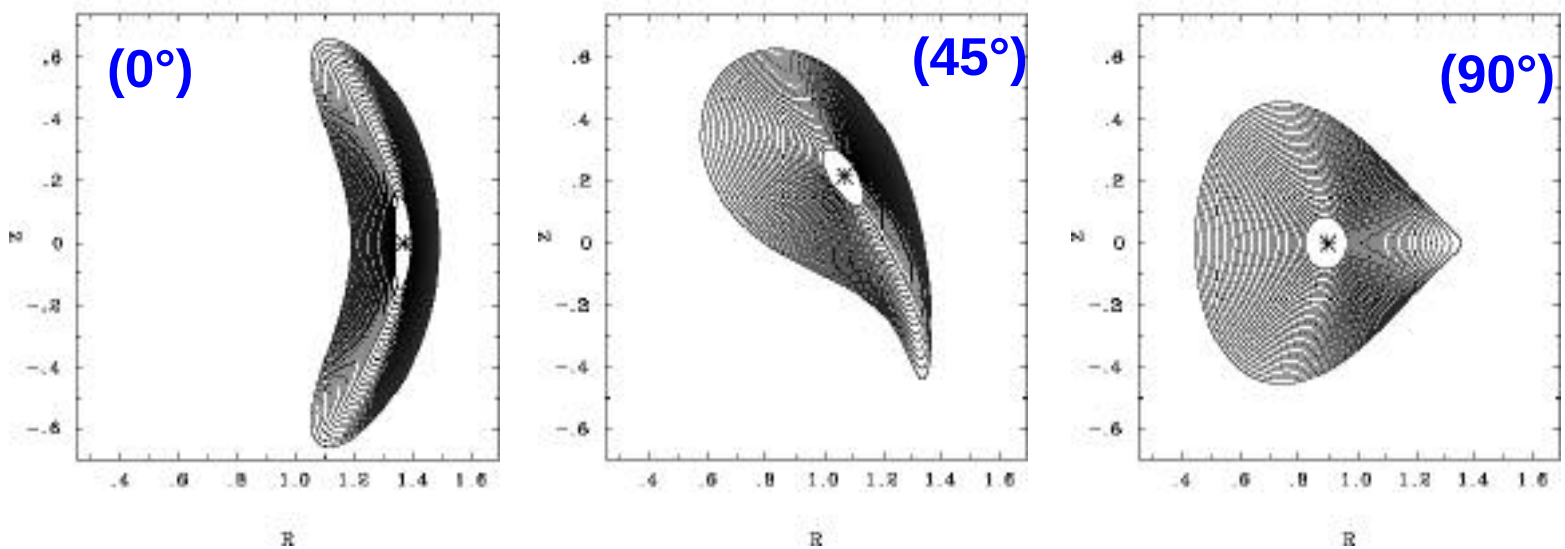
- Quasi-poloidally symmetric magnetic geometry
- Equilibrium and stability, bootstrap current
- Neoclassical confinement
- Engineering design
- Experimental objectives
- Plans

# QOS Magnetic Configuration

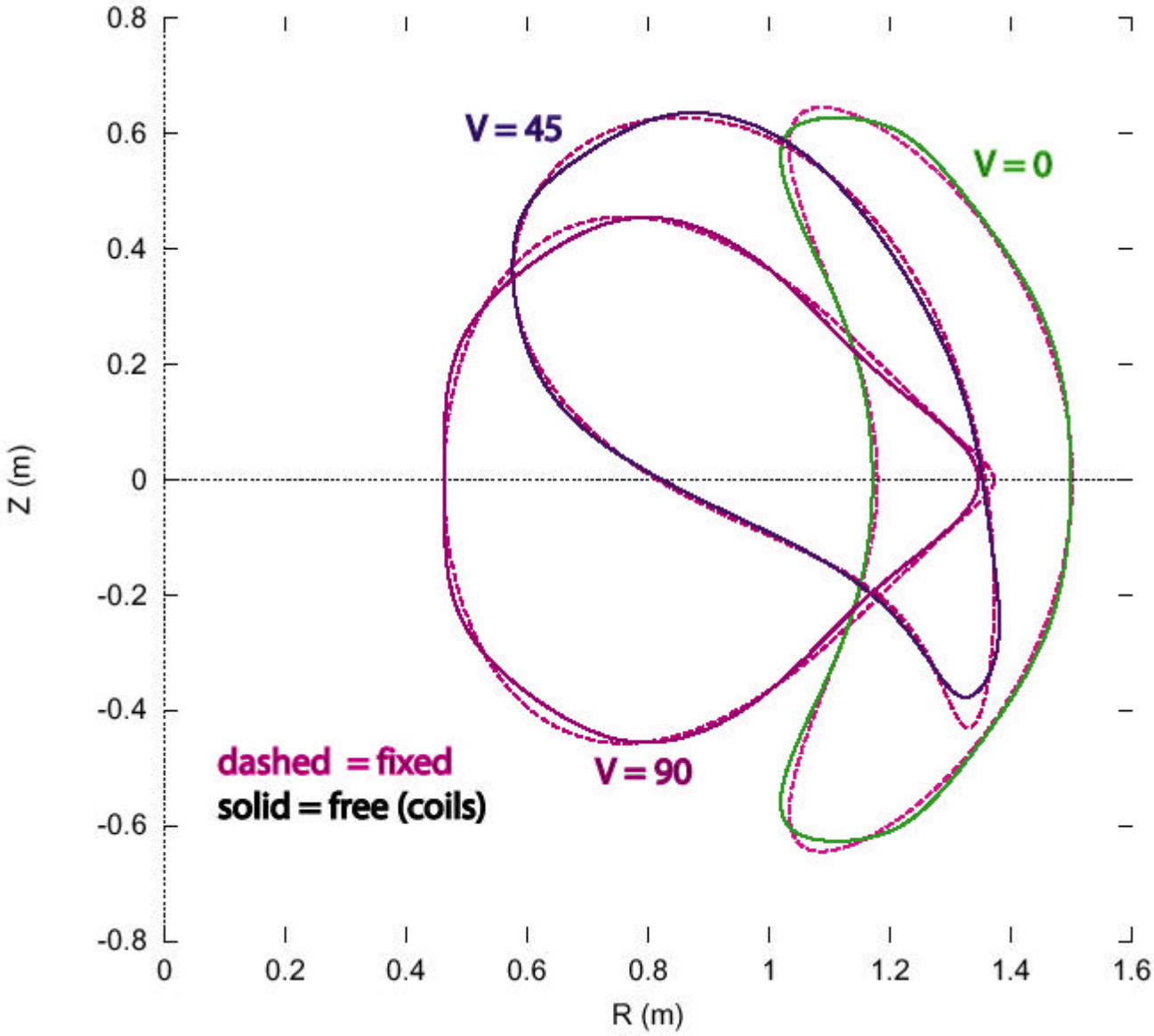



•β®= 2%, $I_{bs}$ = 63 kA

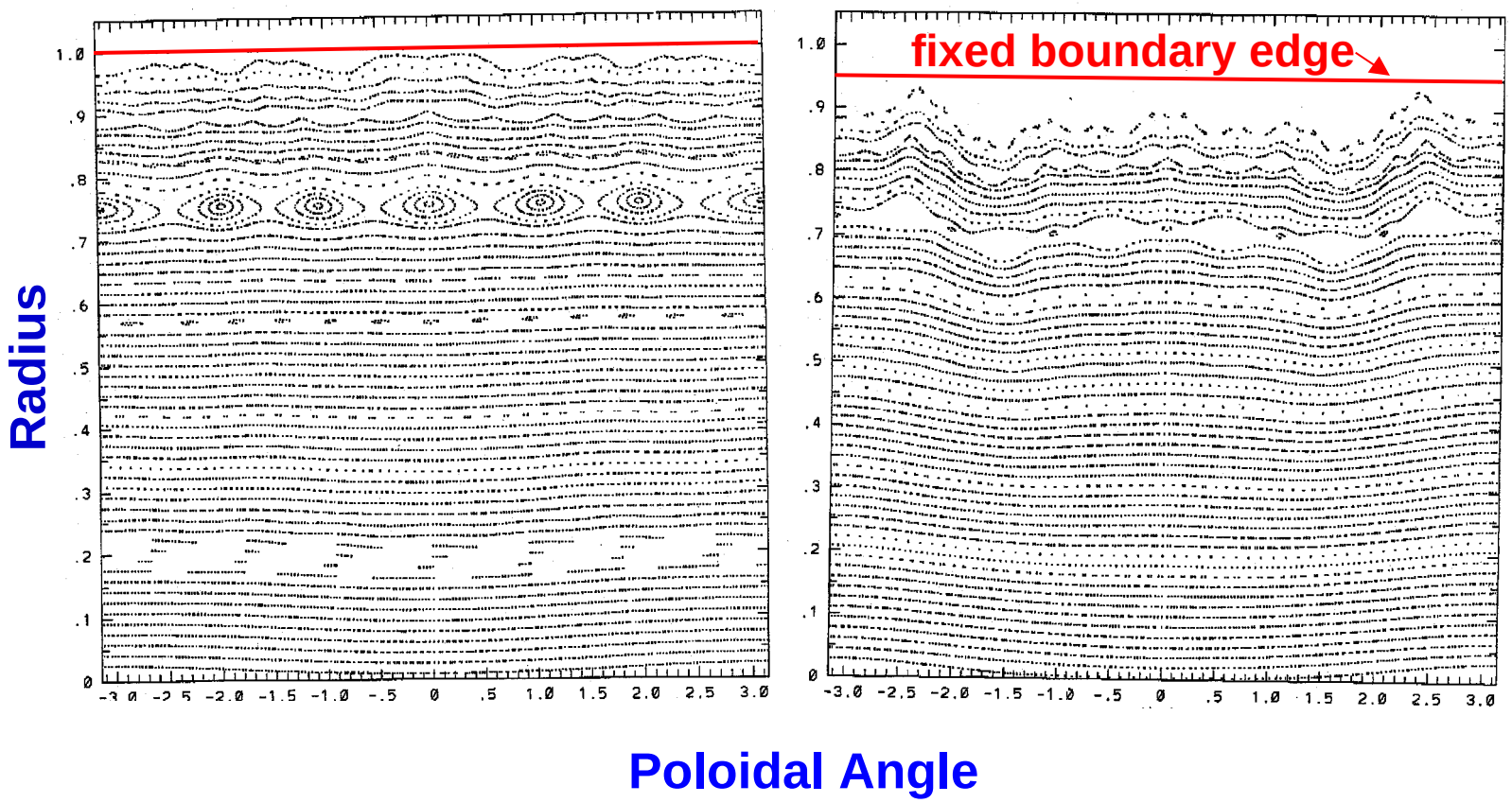


# Modular Coils Reconstruct the Original Physics-Optimized Configuration



# PIES Reconstruction Has Not Been a Problem

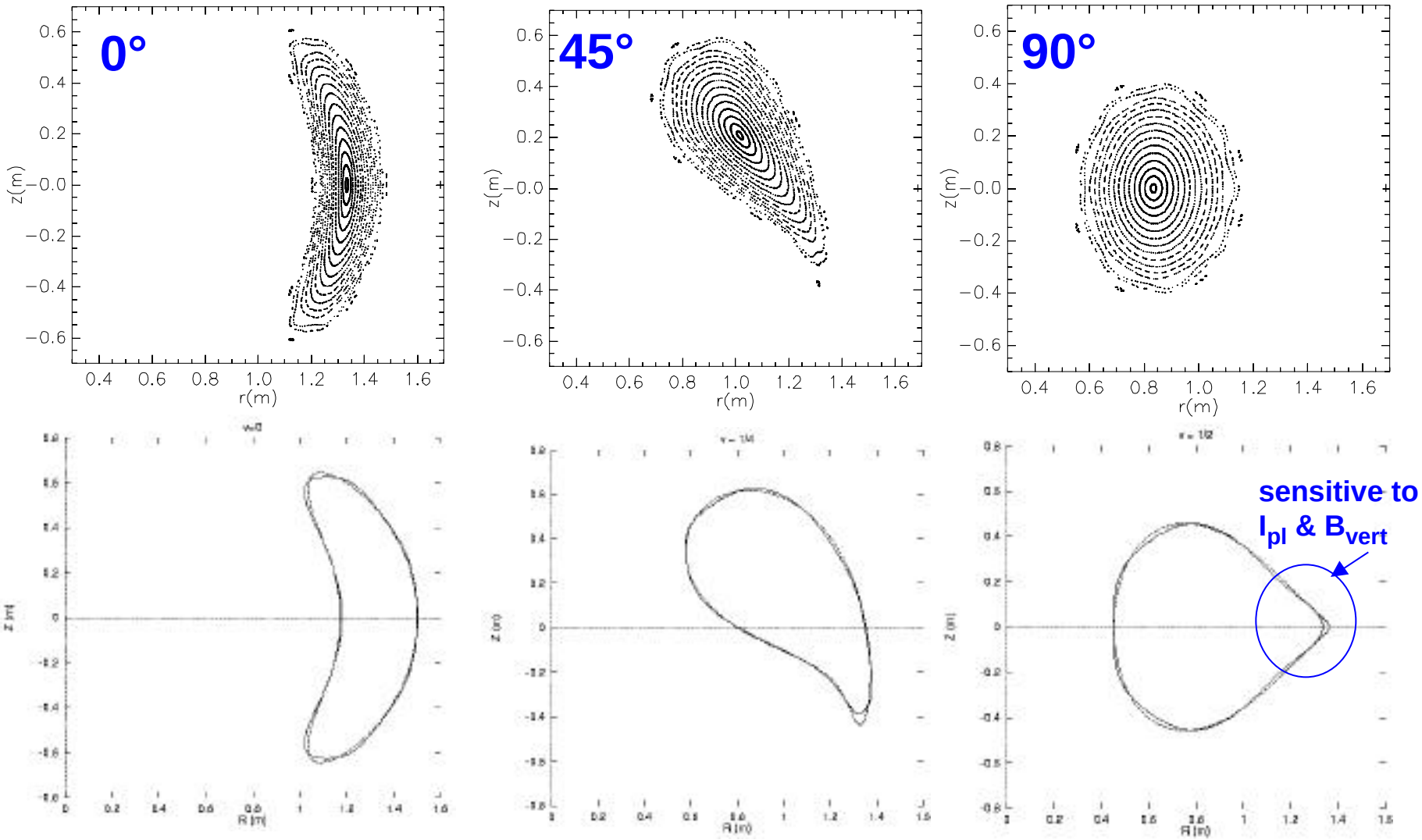
**Fixed Boundary** **Free Boundary**



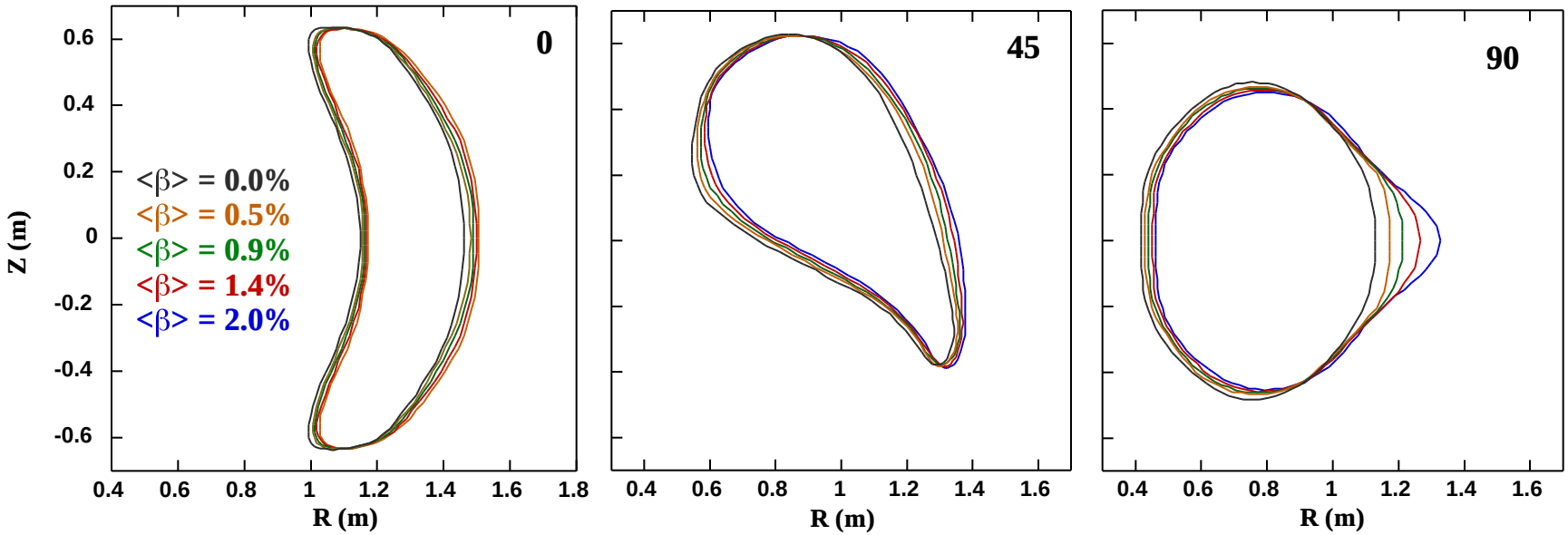

•β®= 1.6%

D. Monticello

# Vacuum Flux Surfaces Match Equilibrium Surfaces

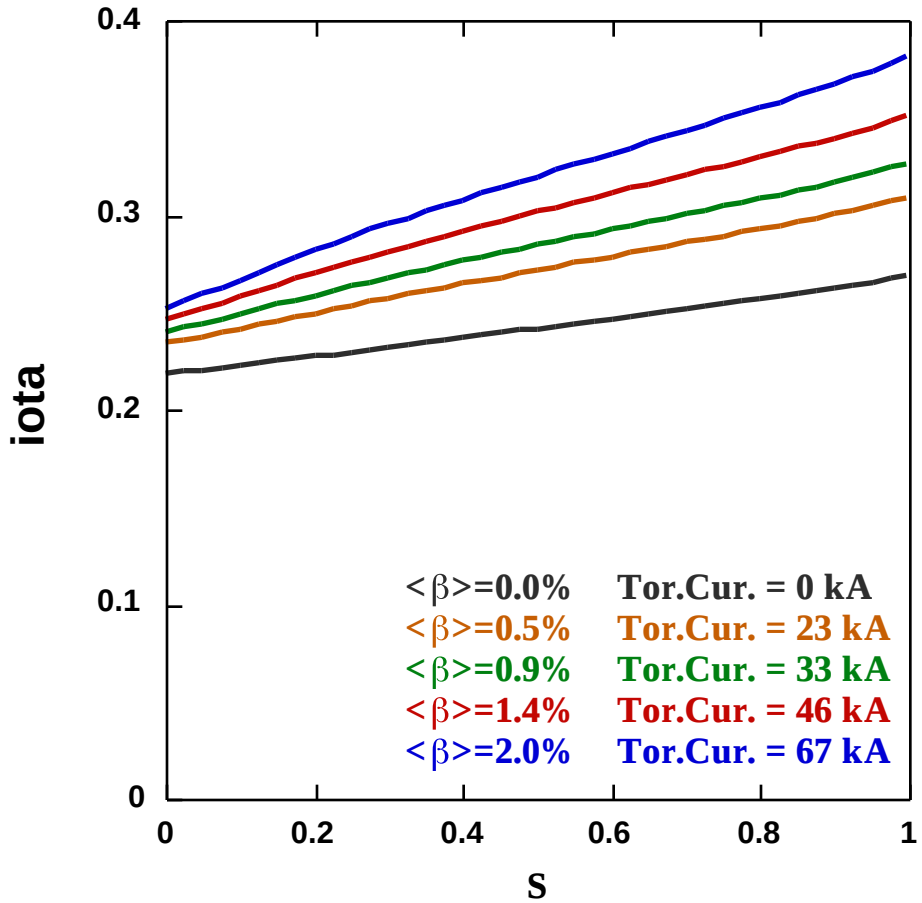


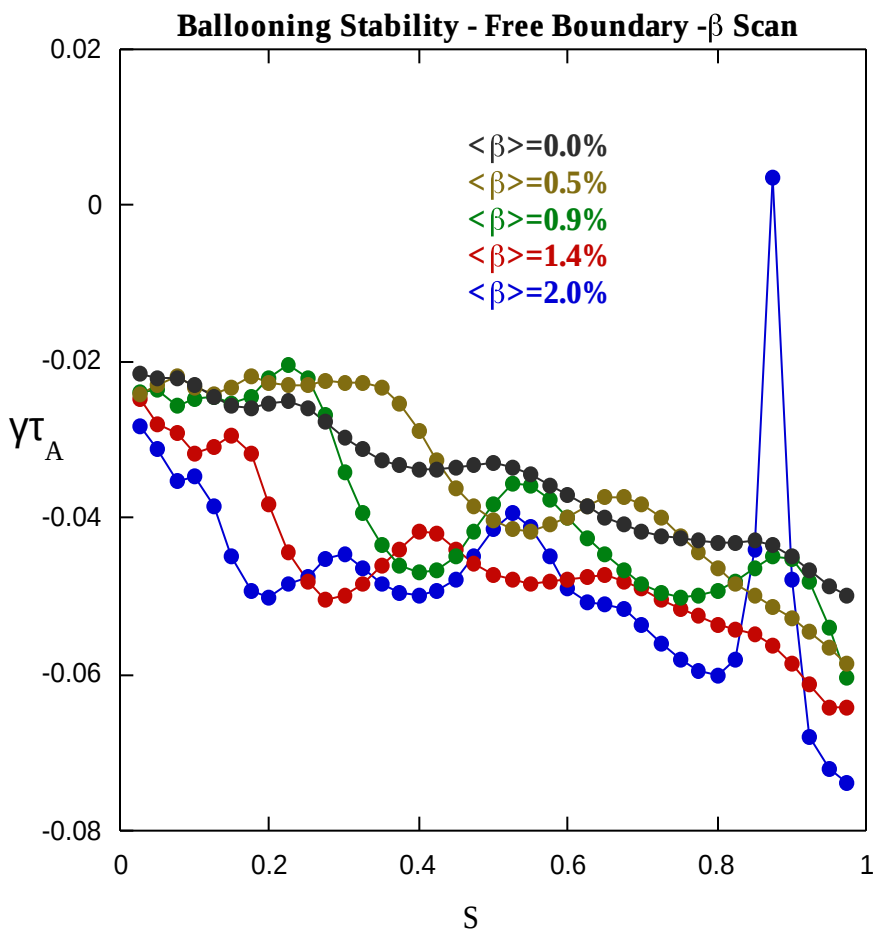
# Plasma Boundary Shifts Slightly Outward with •β®




- β varied for same p(r), self-consistent $I_{bootstrap}$

# Free Boundary Equilibria Stable up to •β®= 2.5%




**S = normalized flux ~ $(r/a)^2$**

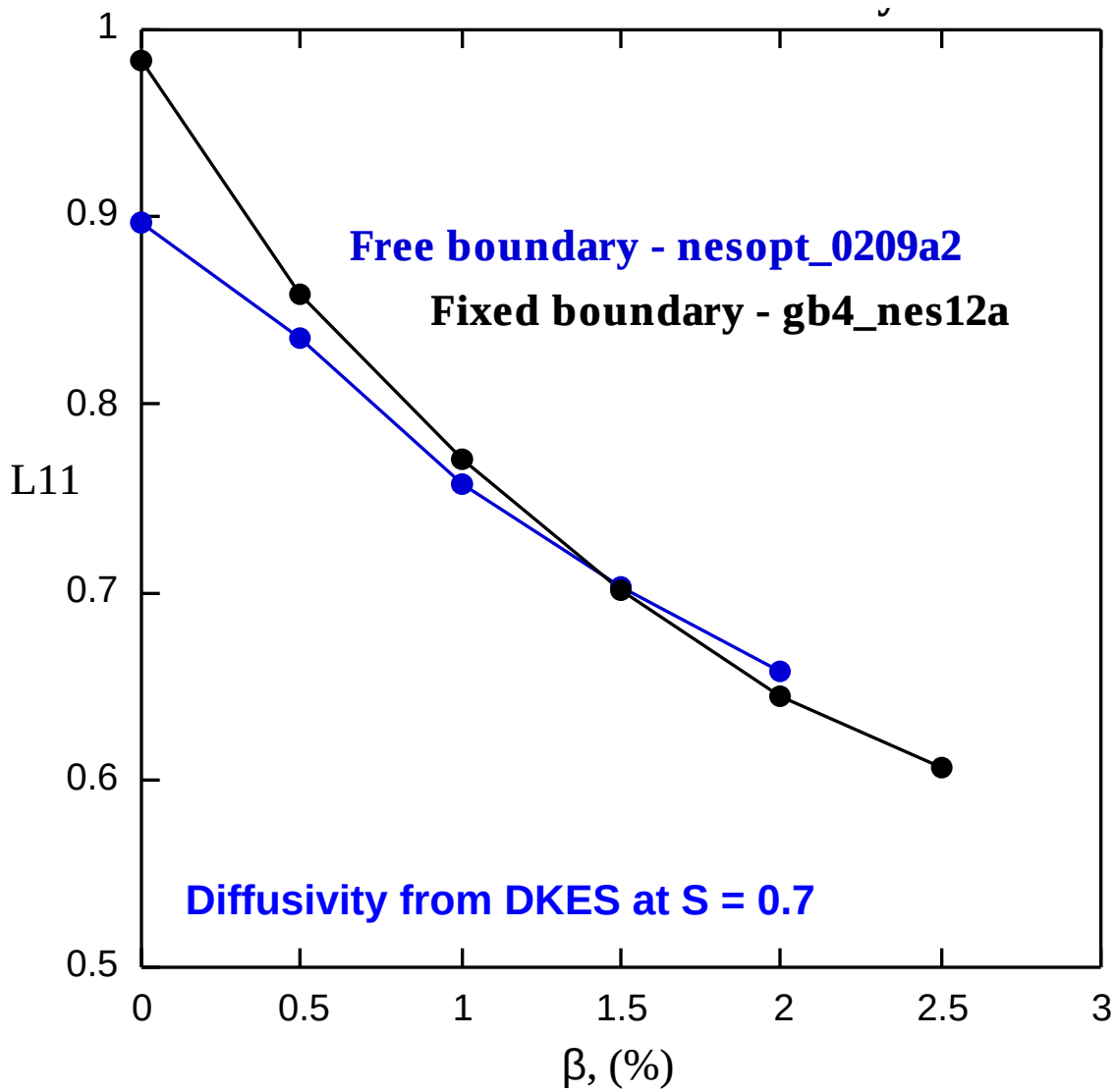
# Fixed and Free Boundary Equilibria Meet Stability Goals

| VMEC Equilibrium | Mercier Mode | High-n Ballooning Mode | External Kink/ Vertical Mode | Neoclassical Tearing Mode |
|---|---|---|---|---|
| Fixed Boundary | $\langle\beta\rangle > 2\%$ [(a)] | $\langle\beta\rangle = 2.5\%$ | $\langle\beta\rangle > 3\%$ | stable [(b)] |
| Free Boundary | $\langle\beta\rangle > 2\%$ [(a)] | $\langle\beta\rangle = 2\%$ | $\langle\beta\rangle > 2\%$ | stable [(b)] |

(a) Stability from deep magnetic well, not shear; should be stable against resistive tearing modes

(b) $B \cdot j_{BS} \times \iota'/\iota > 0$

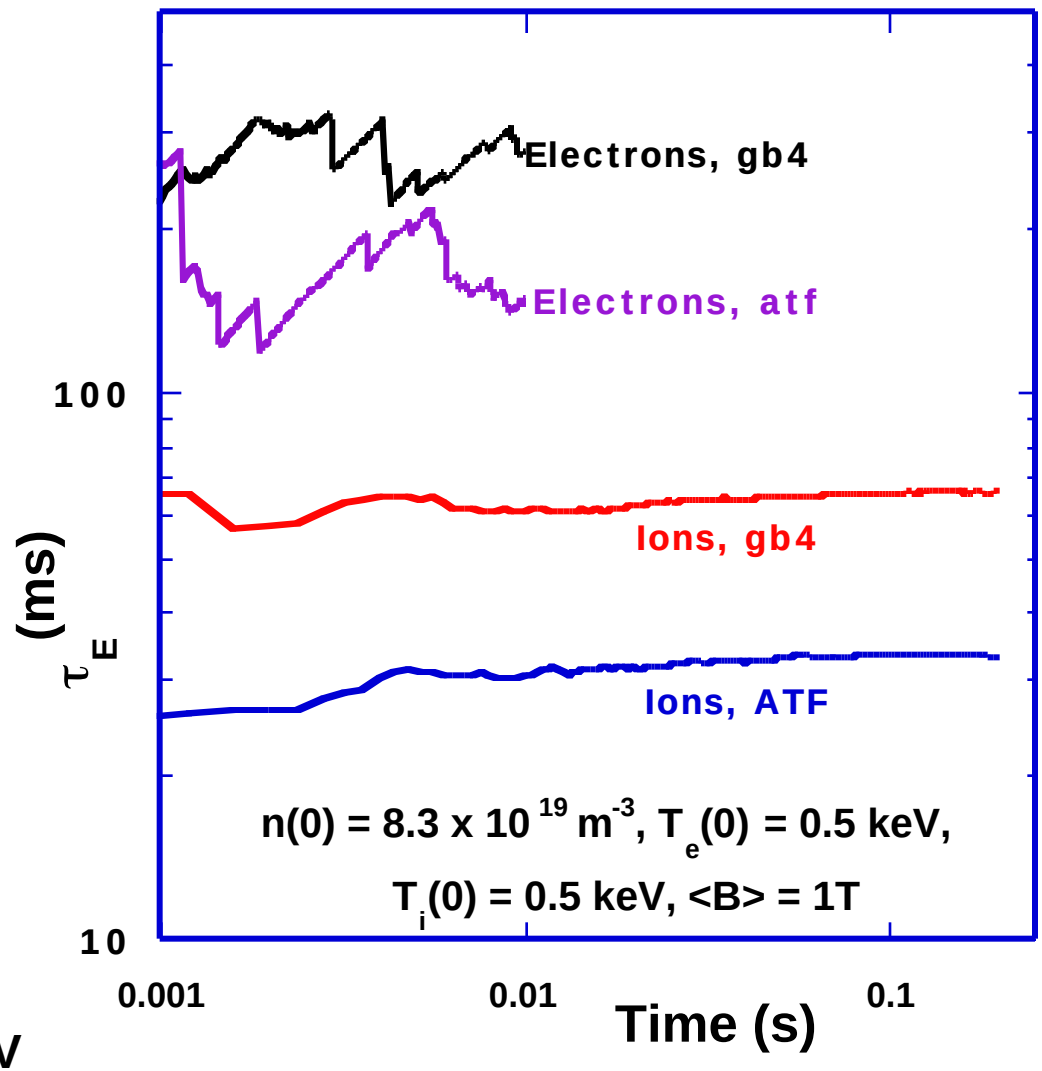
# Confinement Improves with •β®




- Same trend seen up to •β®= 23% in quasi-poloidal reactor configuration
- Free boundary and fixed boundary behavior the same

# QOS Neoclassical Ion Confinement ~2 x Better than in ATF with $E_r = 0$

- $\tau_E$ should be much worse than in ATF, but is 2 x better due to quasi-poloidal symmetry
- Confinement improves more with ambipolar electric field
- Neoclassical transport is not a limitation




Monte Carlo calculation for $n = 8.5 \times 10^{19}$ m$^{-3}$, $T = 500$ eV

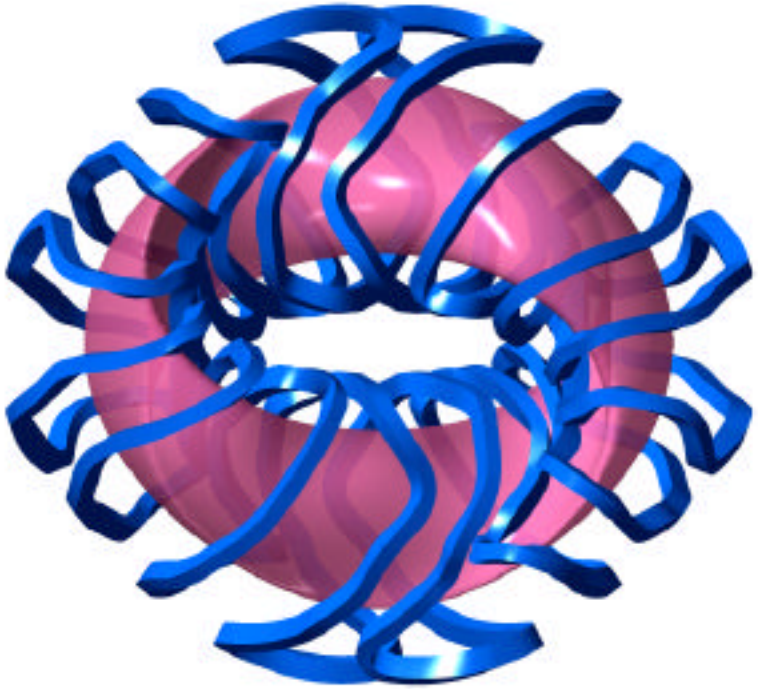
# Available Heating Power Allows Parameters Needed for Physics Objectives

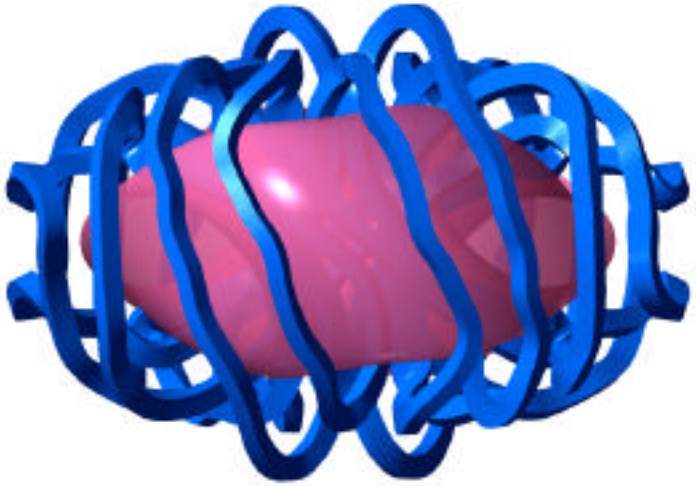
| B (T) | P (MW) | RF | $n_e$ ($10^{19}$ $m^{-3}$) | $T_e$ (keV) | $T_i$ (keV) | $\tau_E$ (ms) | $\langle\beta\rangle$ (%) |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 28 GHz ECH | 0.48 | 2.1 | 0.2 | 3.3 | 0.44 |
| 1 | 1.5 | 28 + 53 ECH | 1.9 | 2.1 | 0.4 | 9.4 | 0.94 |
| 0.5 | 1 | 28 GHz EBW | 7.5 | 0.3 | 0.3 | 13.4 | 1.8 |
| 1 | 1 | 28 + 53 EBW/ICH | 10.5 | 0.45 | 0.45 | 28.5 | 1.9 |
| 1 | 2 | 28 + 53 EBW/ICH | 14.9 | 0.50 | 0.50 | 22.6 | 3.0 |
| 1 | 3 | 28 + 53 EBW/ICH | 18.2 | 0.54 | 0.54 | 19.7 | 4.0 |

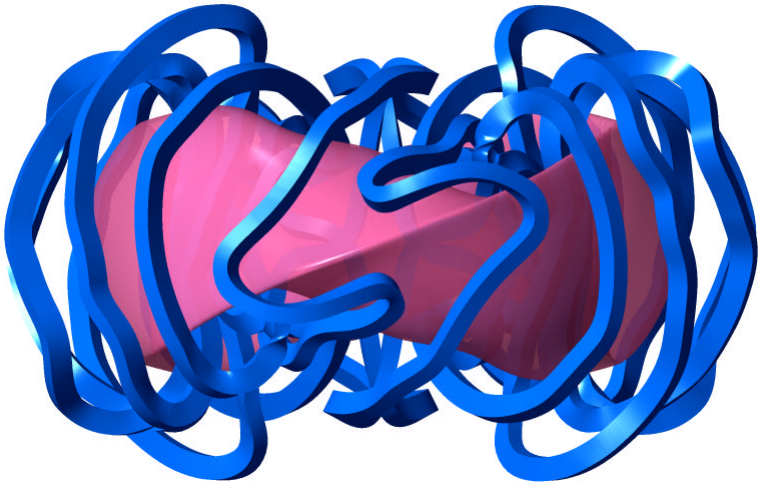
**Assumed H = 1.5 x ISS-95, 1.5 x $n_{Sudo}$; $\tau_E$, $T$ and $\beta \propto$ H**

# QOS Coil Set Also Optimized for Engineering Criteria

- Adequate coil-coil spacing, plasma-coil spacing, minimum bend radius
- 16 coils of 4 different types
- Good access between coils for heating and diagnostics
- Room in center for TF coil legs and OH solenoid

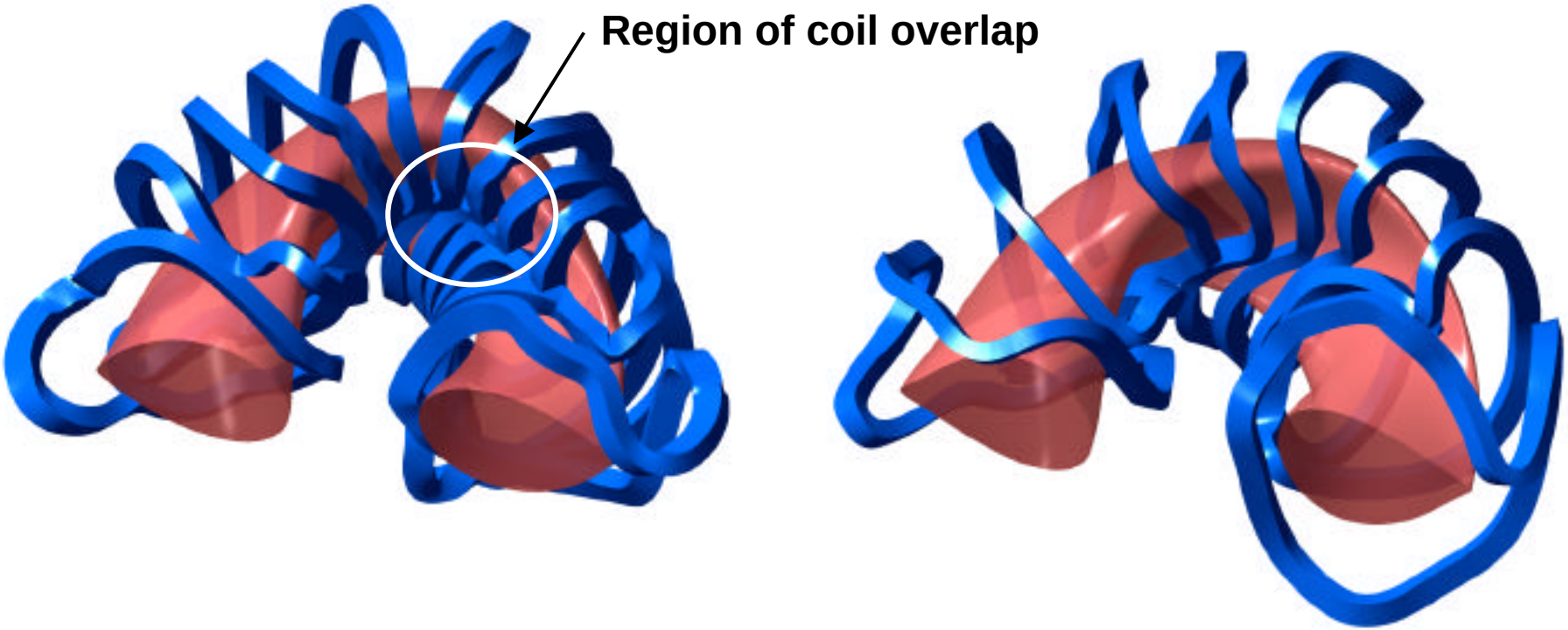






# Coil-Coil Spacing is Now Feasible

**Earlier 22 coil version** **Present 16 coil version**

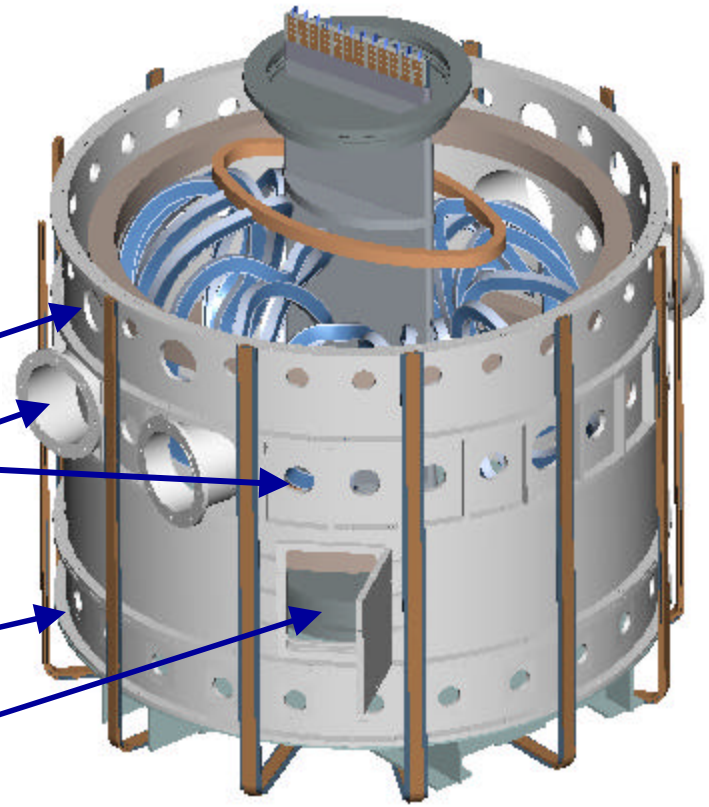



**Smaller *R* would require cryogenic coils and interior vacuum liner**

# Existing Vacuum Tank Provides Access for Diagnostics, Heating and Maintenance

- eliminates complex and costly interior vacuum vessel
- allows larger plasma scrapeoff, larger range of plasma shapes, smaller less complex modular coils, and *much* simpler assembly
- allows good access to plasma and possibility of cooling the coils for extended performance

Lid and sides can be removed



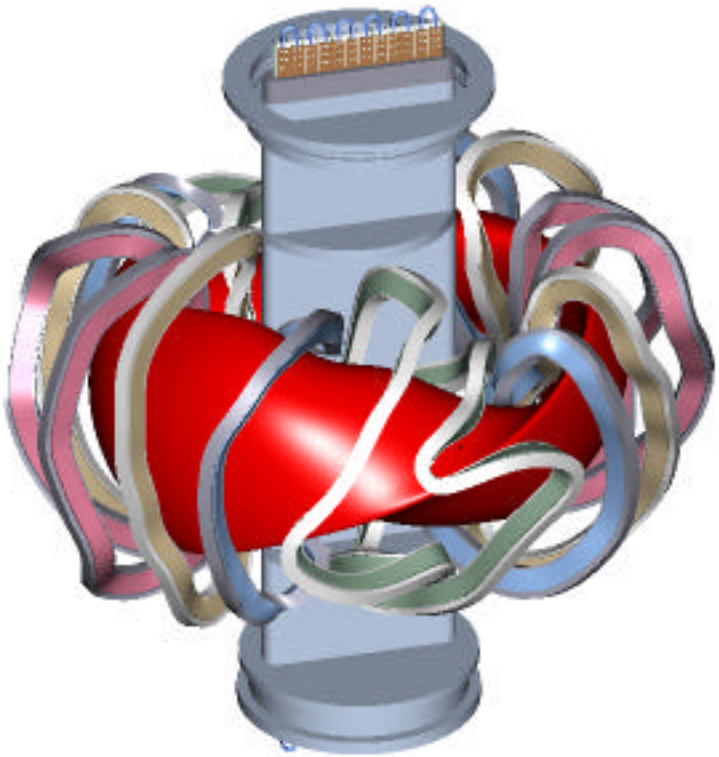
18 - 8” diam., 6 -12” diam., 23 - 6” diam. ports

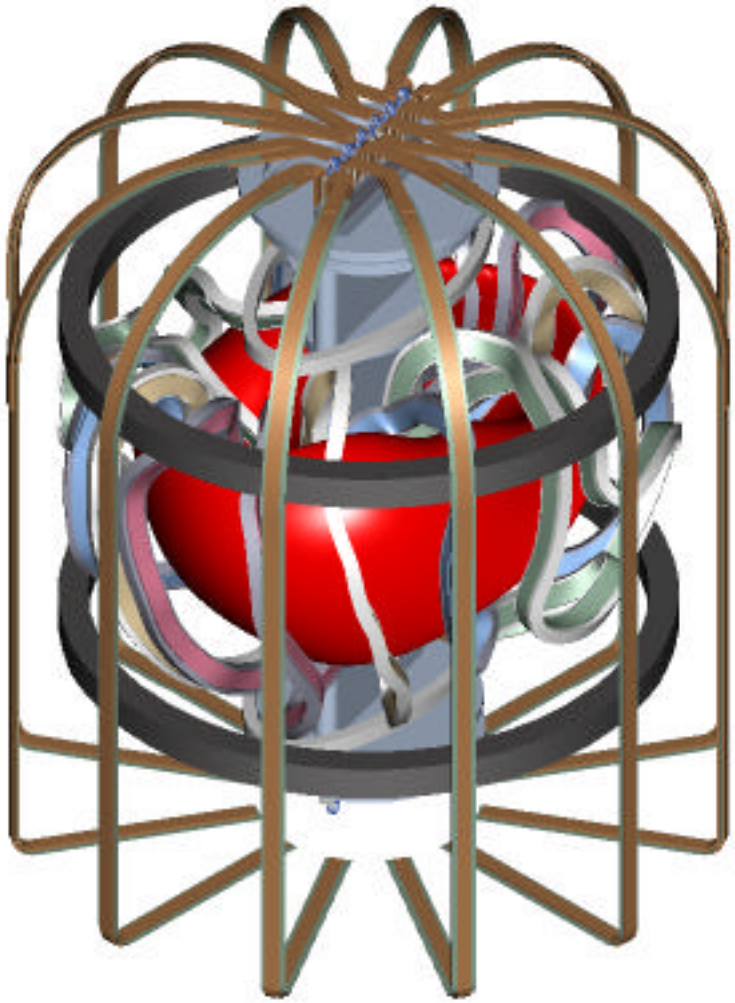
4 -22” diam. ports

24 x 6” ports for coil leads, coolant feeds, etc.

Personnel access door

# TF, VF and OH Coils for Flexibility



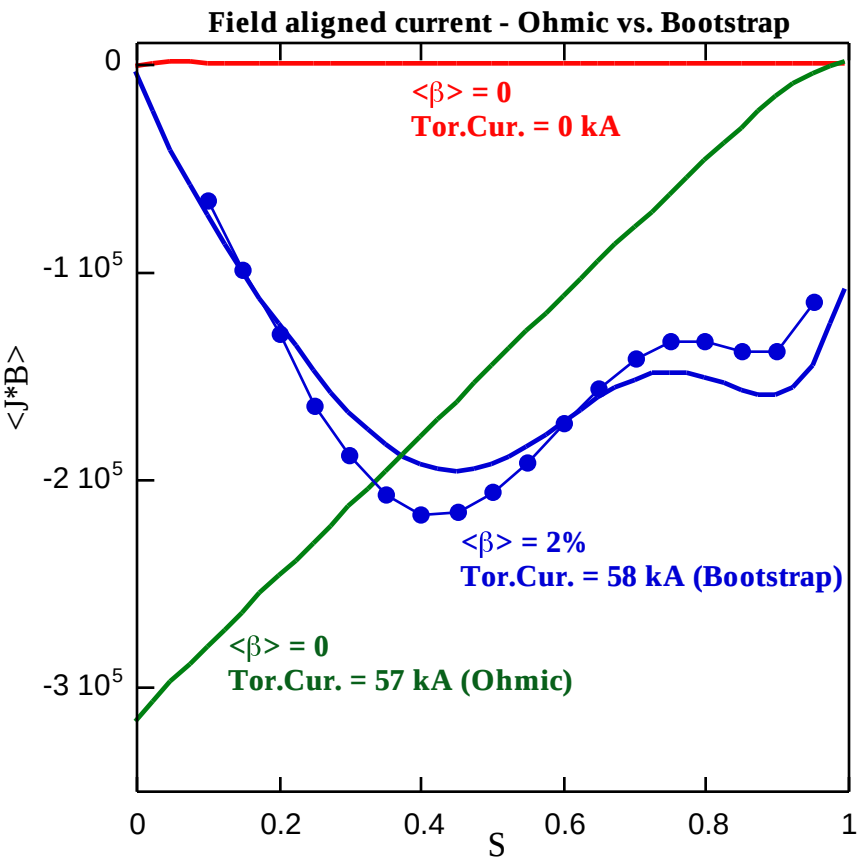


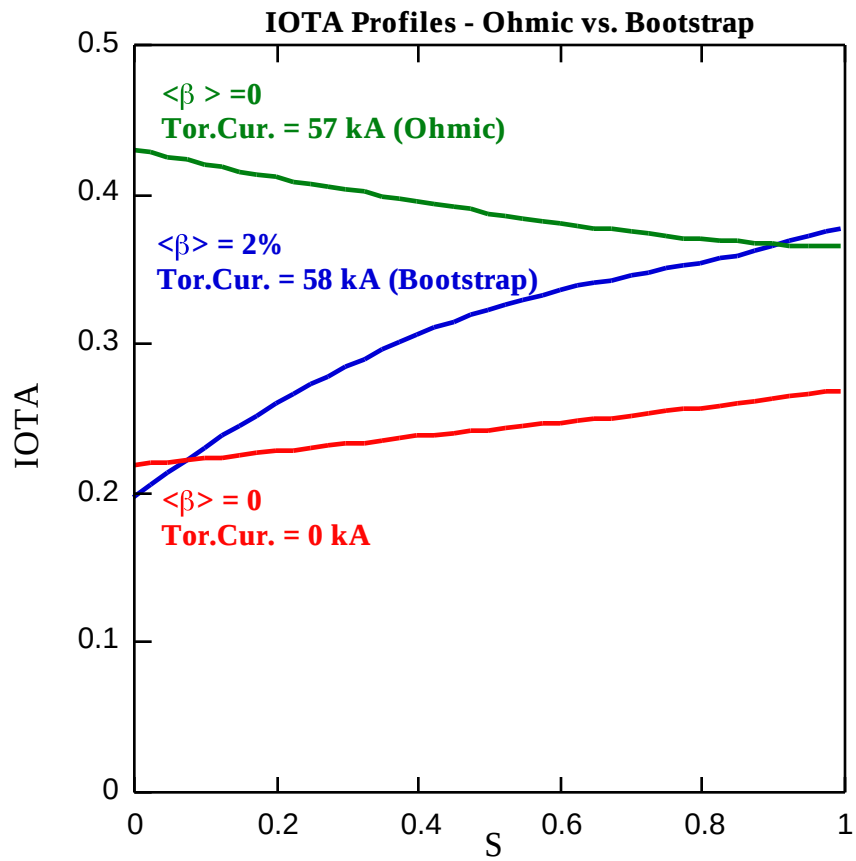
**Centerstack assembly contains inner TF legs and OH current solenoid**

# TF, VF Coils and OH Solenoid Provide Flexibility

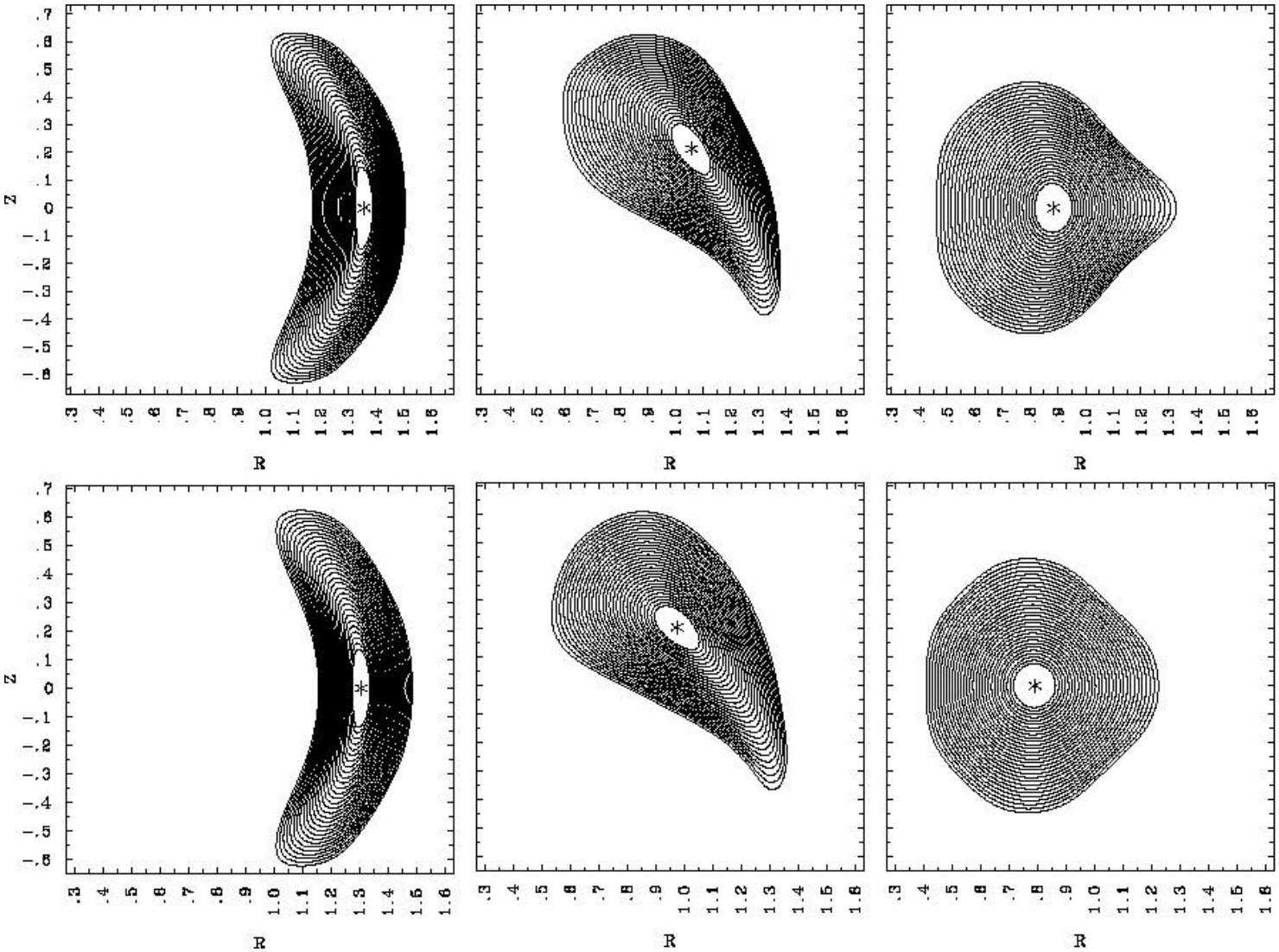
- Need to modify $B_{mn}$ spectrum to study effect on equilibrium quality, MHD stability, and neoclassical transport
- Different currents in the modular coils allow changing $\iota$ & shear, helical axis excursion, mirror field component, plasma shape, and *R*/*a*
- VF coils can shift axis and shape the plasma surface
- TF coils (±0.15 T) can change $\iota$ and shear
  - repair outer surfaces due to magnetic islands
  - change the aspect ratio a factor of 2
  - use magnetic islands to bound the plasma or for divertor studies
- OH solenoid (±0.1 V-s) can drive plasma current and change/reverse shear
  - test reducing magnetic islands and stabilizing tearing modes

# Ohmic Current Allows Changing ι and Shear



# $I_{OH}$ Free Boundary Surfaces Similar to •β®= 2% $I_{bs}$ Surfaces




**Bootstrap**
**β = 2%**

**Ohmic**
**β = 0%**

**Modification with VF, TF, or different currents in modular coils not explored yet**

# QOS Presents Opportunities for Extension of Toroidal Confinement Studies into a New Area

## Low-*R*/*a* quasi-poloidally symmetric plasmas

- Reduction of neoclassical transport due to near alignment of *B* and B; less dependence on $E_r$
- Study equilibrium quality (islands, ergodic regions) and its repair at *R*/*a* ~ 2.6; robustness with $\beta$ and dependence of bootstrap current on configuration
- Understand $\beta$ limits and limiting mechanisms for quasi-poloidally symmetric configurations at very low *R*/*a*
- Extend study of anomalous transport, internal transport barriers, and flow shear to low-*R*/*a* configurations with quasi-poloidal symmetry
- Impact of poloidal flows on enhanced confinement

# QOS Objectives Address Key Scientific Issues -- 1

- **Transport and Turbulence** -- ***What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled?***
  - **Reduce neoclassical transport through optimizing the quasi-poloidally symmetric components of the magnetic field**
  - **Extend study of anomalous transport, internal transport barriers, and flow shear to low-R/a configurations with quasi-poloidal symmetry**

- **Plasma Fluid Behavior and Macrostability** -- ***What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems?***
  - **Study equilibrium quality and configuration dependence of the bootstrap current at low R/a**
  - **Reduce magnetic island widths and control neoclassical tearing modes at low R/a through rotational transform, magnetic shear, and reduction of the plasma current**
  - **Understand $\beta$ limits and limiting mechanisms for quasi-poloidally symmetric configurations at very low R/a**

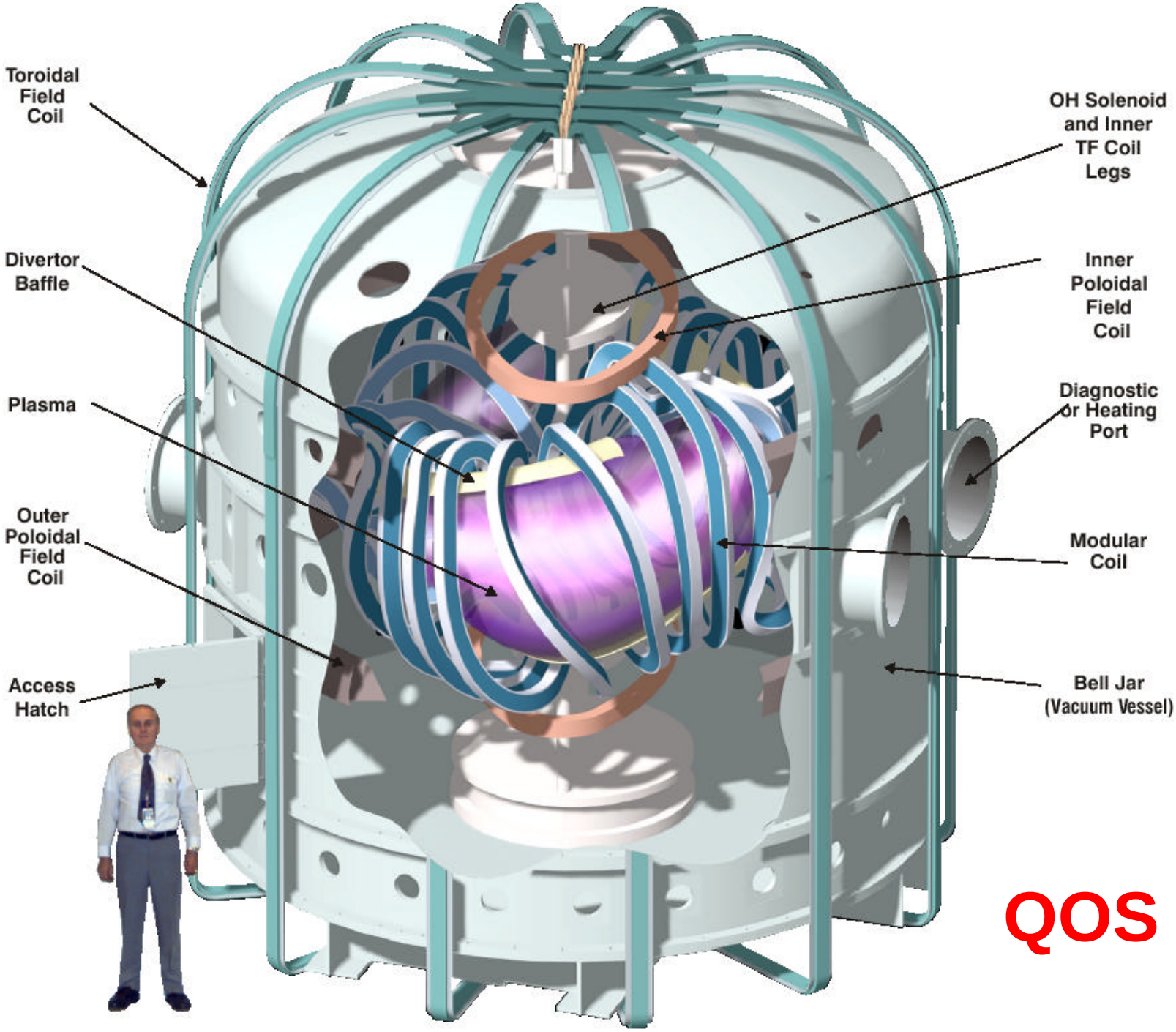
# QOS Objectives Address Key Scientific Issues -- 2

- **Wave-particle Interaction** -- ***What are the fundamental causes and nonlinear consequences of wave interactions with thermal and non-thermal particles?***
  - **ECH/EBW and ICRF to reach higher $\beta$**
- **Plasma-wall Interaction** -- ***What are the fundamental processes occurring near the boundary of a confined plasma and how can the interaction between the plasma and material surfaces be controlled ?***
  - **Study power and particle exhaust in a low-aspect-ratio stellarator with an open divertor geometry**

- **These objectives contribute to the ten-year goal to "determine the attractiveness of a Compact Stellarator" identified by the FESAC Panel on Priorities and Balance**
  **and the DOE Report of the Integrated Program Planning Activity that states that critical scientific issues for the stellarator include the identification of optimal configurations for the magnetic field and the confinement and stability of stellarator plasmas.**

# Plans

- Community QOS Project Meeting Feb. 28
- Further refine the reference plasma and coil configuration
- Complete assessment of QOS physics properties
- Assess flexibility obtained with VF, TF, and OH solenoid
- Refine engineering design and cost/ schedule estimates
- April 24-25 Physics Validation Review
- April 2002 Design, Cost & Schedule Review


Toroidal Field Coil
Divertor Baffle
Plasma
Outer Poloidal Field Coil
Access Hatch
OH Solenoid and Inner TF Coil Legs
Inner Poloidal Field Coil
Diagnostic or Heating Port
Modular Coil
Bell Jar (Vacuum Vessel)

QOS