Compact Stellarators

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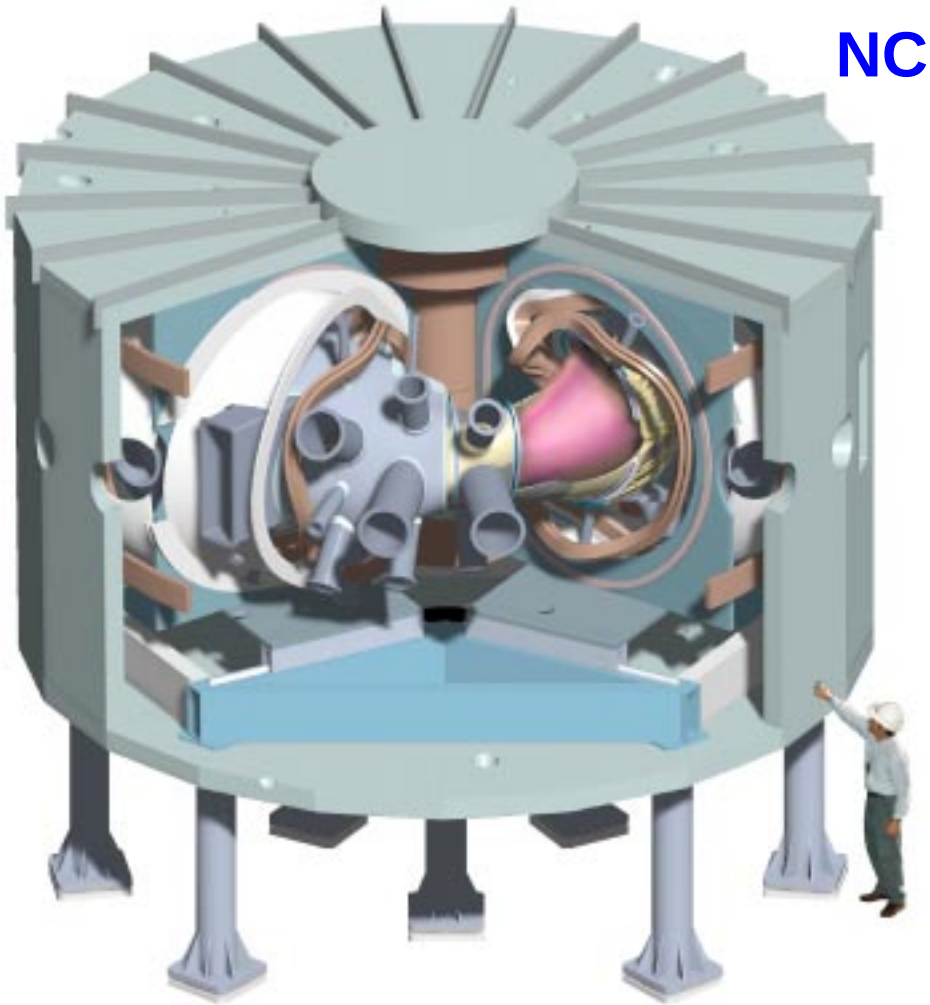
MPIPP, Garching June 25, 2002

Topics

- Compact Stellarators
- QPS
- NCSX
- Reactor Studies

The US is Planning Two Compact Stellarators

Different configuration and design approaches are used



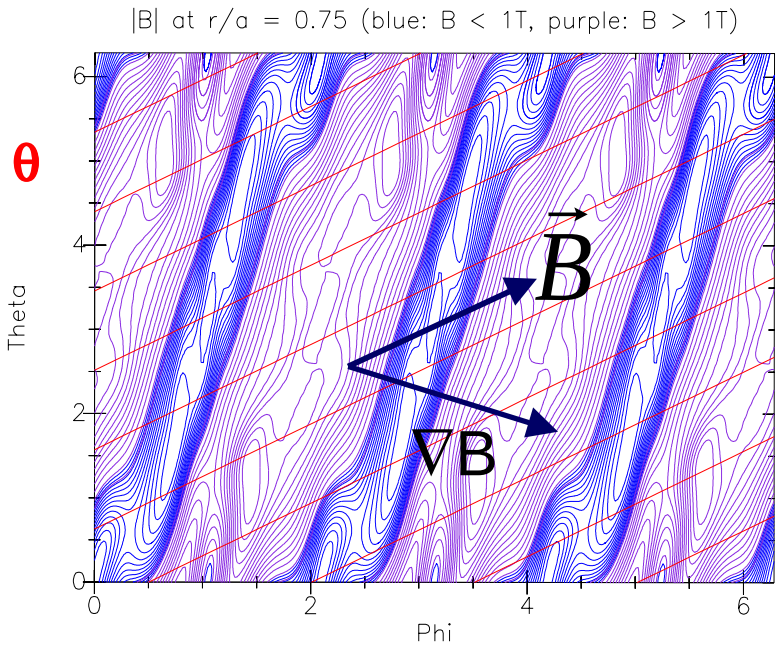
NCSX

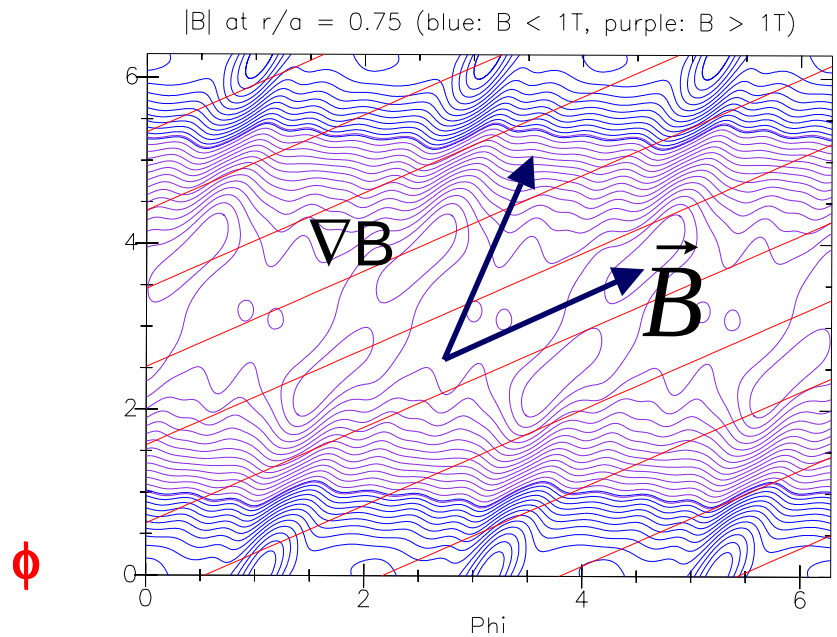
Q PS

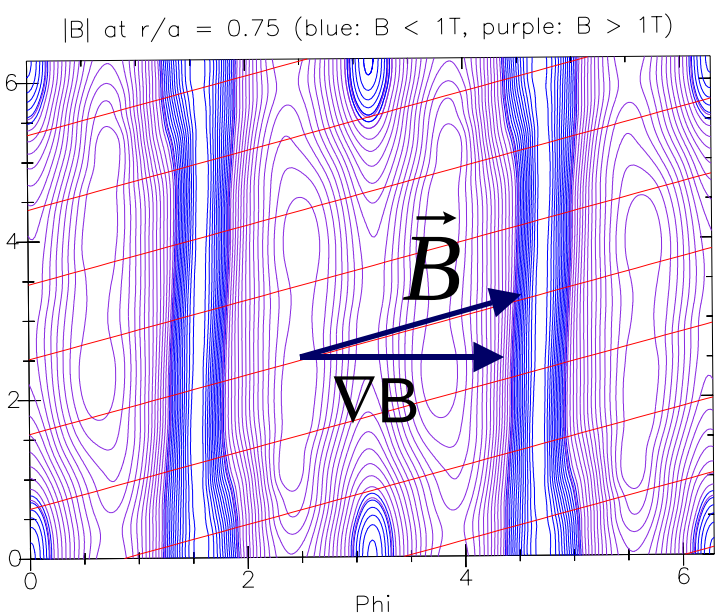
NCSX and QPS Are Complementary

	NCSX	QPS
Magnetic geometry	Quasi-axisymmetric	Quasi-poloidal
Major radius <R>	1.4 m	0.9 m
Plasma radius <a>	0.33 m	0.33 m
Aspect ratio <R>/<a>	4.3	2.7
Number of field periods	3	2
Magnetic field	2.0 ± 0.5 T for 0.2 s	1.0 ± 0.2 T for 1 s
Plasma current	450 kA	150 kA
Heating power (initial) (upgrade)	3 – 6 NBI 6 MW ICRF	0.6 – 1.2 ECH/EBW 1 – 3 ICRF
Modular coils	3 types, 6 each, LN cooled	4 types, 4 each, gas cooled
Vacuum vessel	interior to coils	exterior to coils
Location	PPPL	ORNL
Estimated cost	72 M$	15 M$
First operation	June 2007	Sept. 2007

US Stellarator Approach Features Quasi-Symmetry

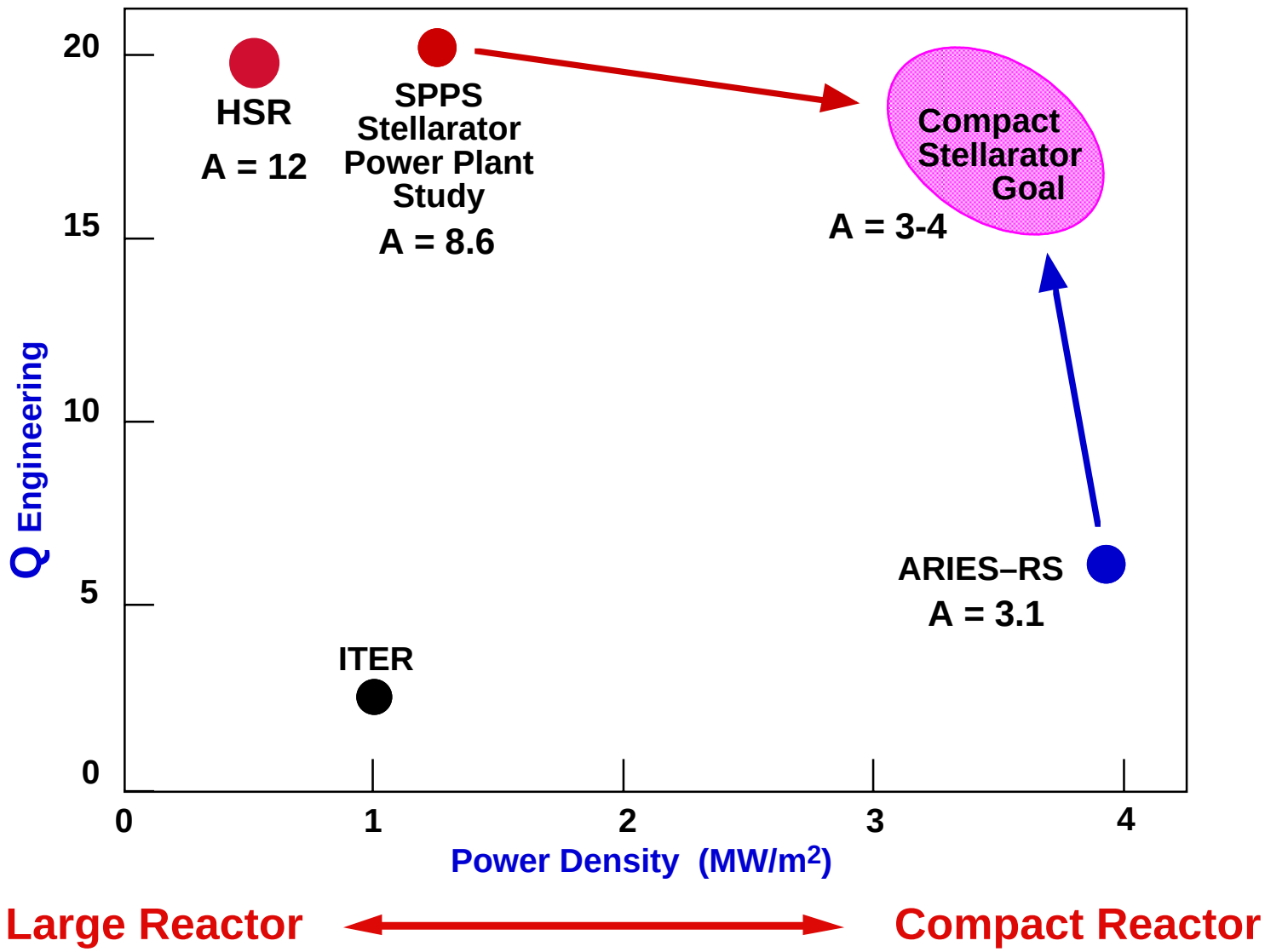




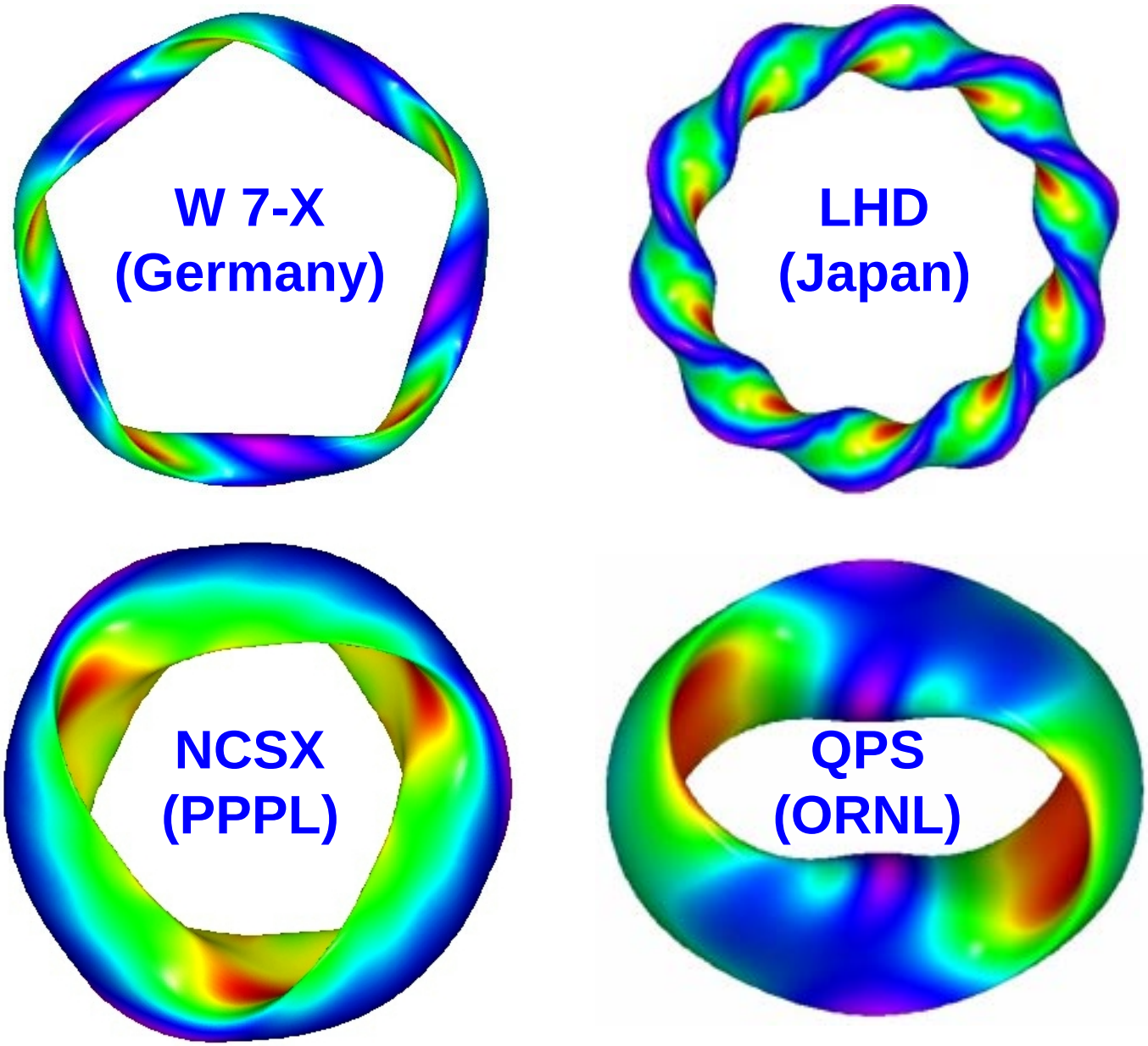


- **Quasi-helical**: |B| like large *R*/*a* stellarator. HSX (*R*/*a* = 8) will test this concept.
- **Quasi-axisymmetric: |B| like a tokamak. NCSX (*R*/*a* = 4.3) will test this concept.**
- **Quasi-poloidal: |B| like toroidally linked mirrors. The *B* x ∇B drift can be made very small in this approach. QPS (*R*/*a* = 2.7) will test this concept.**

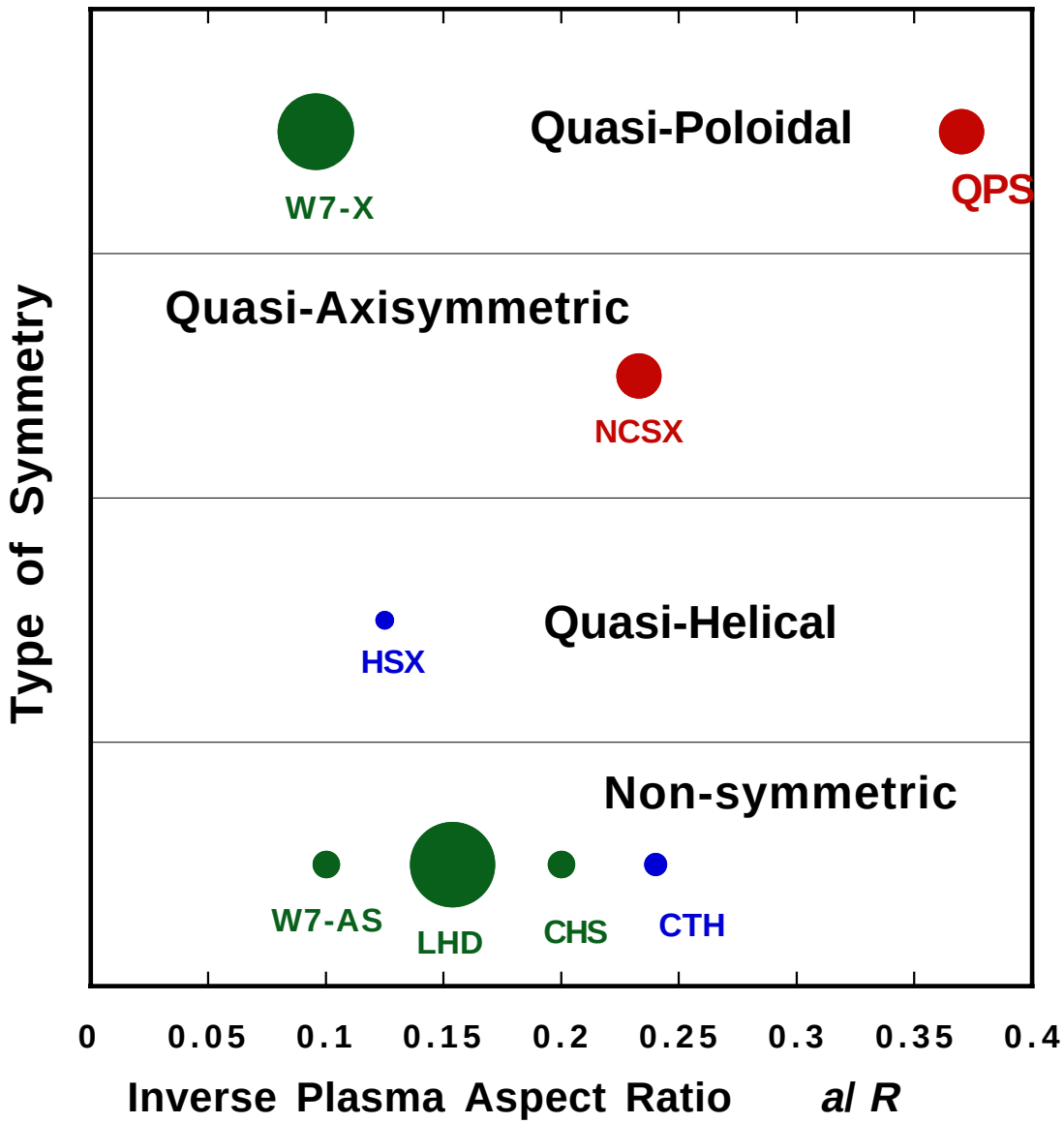
A Compact Stellarator Could Combine the Best Features of Tokamaks and Stellarators!



Compact Stellarators Allow Larger Plasmas



Compact Stellarators Complement Other World Stellarators

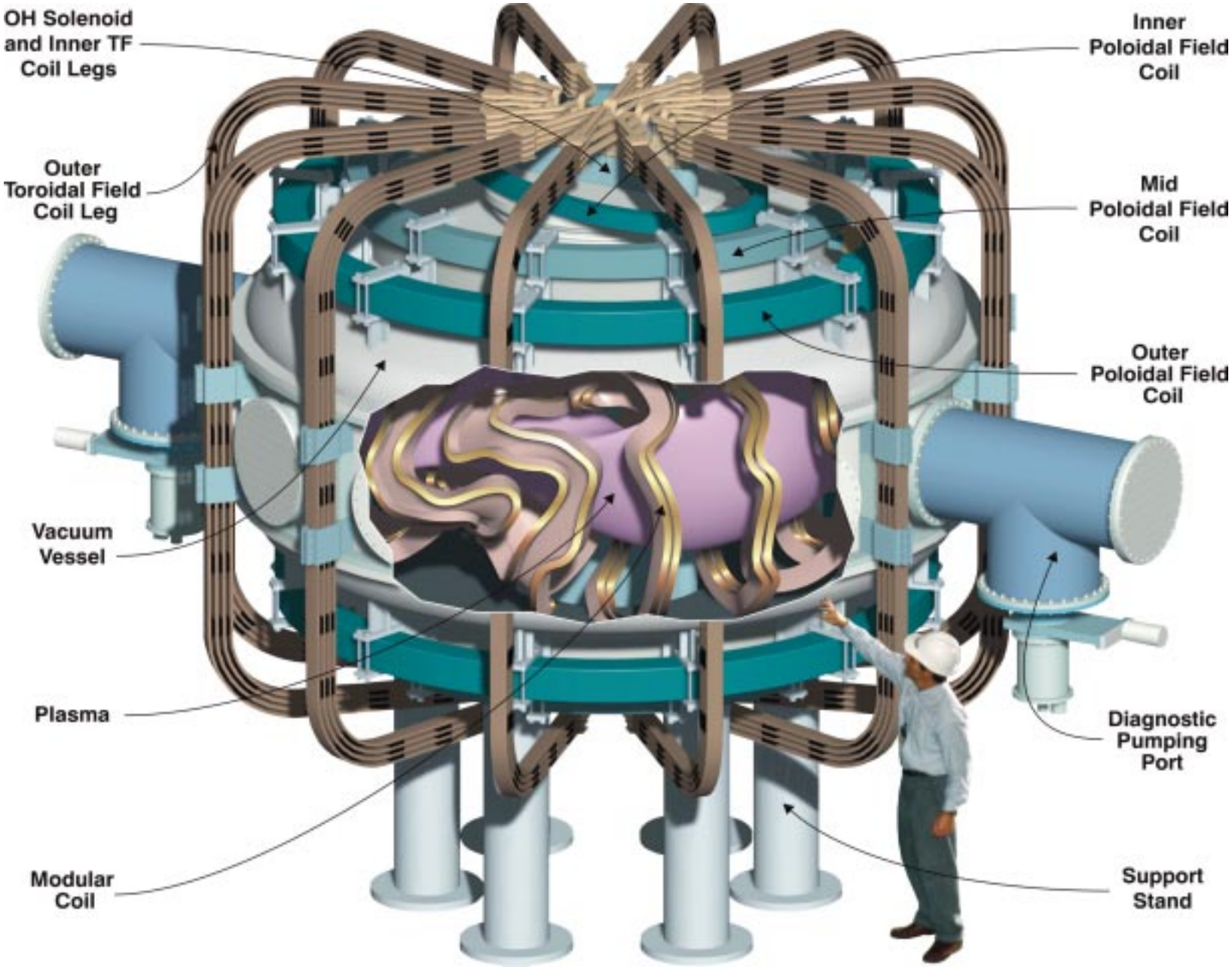


Radius of circles
Is proportional to
the average
plasma radius

Multi-Laboratory QPS Team

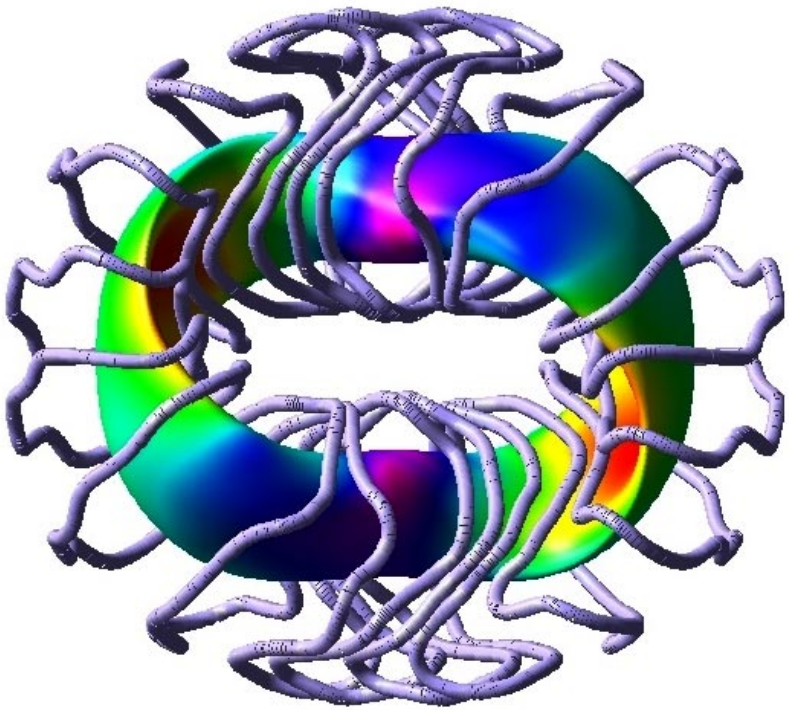
- **ORNL – D.B. Batchelor, L.A. Berry, M.J. Cole, R.H. Fowler, P. Goranson, E.F. Jaeger, S.P. Hirshman, J.F. Lyon, P.K. Mioduszewski, B.E. Nelson, D.A. Rasmussen, D.A. Spong, D.J. Strickler, J.C. Whitson, D.E. Williamson**
- **U. Texas at Austin – W.H. Miner, jr., P.M. Valanju**
- **U. Montana – A. Deisher,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

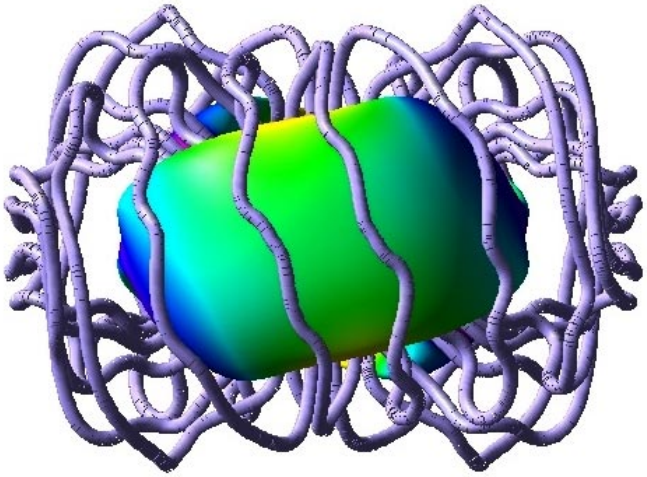
QPS

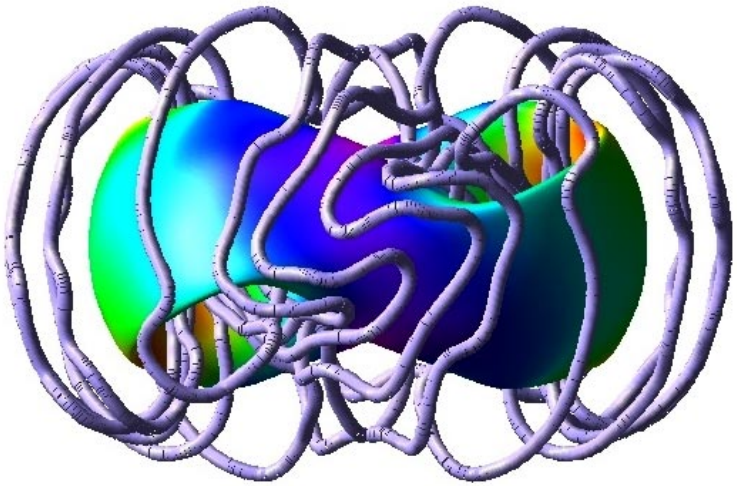

OH Solenoid and Inner TF Coil Legs
Outer Toroidal Field Coil Leg
Vacuum Vessel
Plasma
Modular Coil
Inner Poloidal Field Coil
Mid Poloidal Field Coil
Outer Poloidal Field Coil
Diagnostic Pumping Port
Support Stand

QPS Plasma and Coil Configuration

- ***R*/*a*** **= 2.7, waist 23 cm**
- **ι(0) = 0.29, ι(a) = 0.36**
- **transport similar to W 7-X, but at 1/4 *R*/*a***
- **large plasma-coil, coil-coil spacings and minimum bend radius**
- **good access between coils for diagnostics and heating**

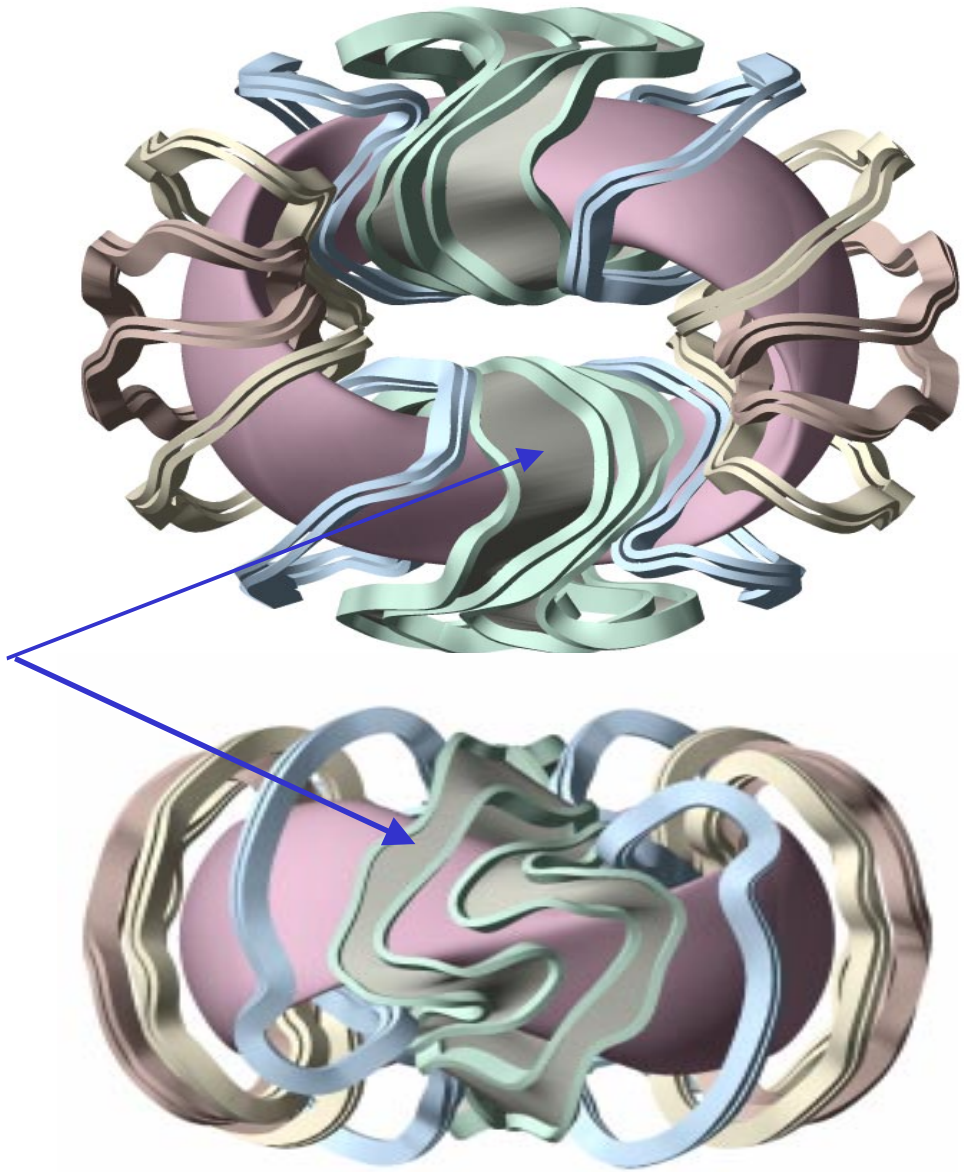






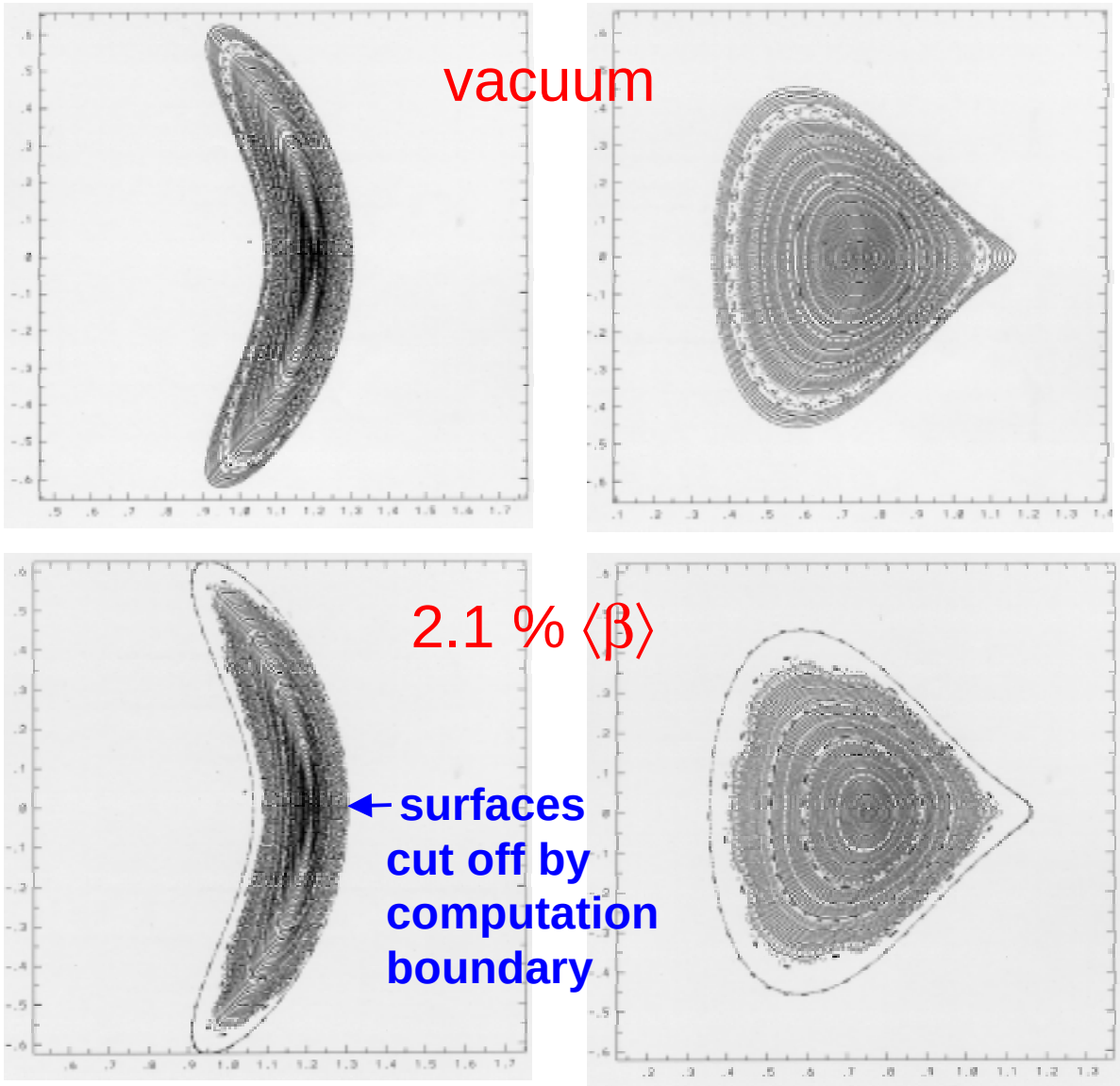
QPS Coil Configuration

- **Central coils are split to better match the desired plasma configuration**

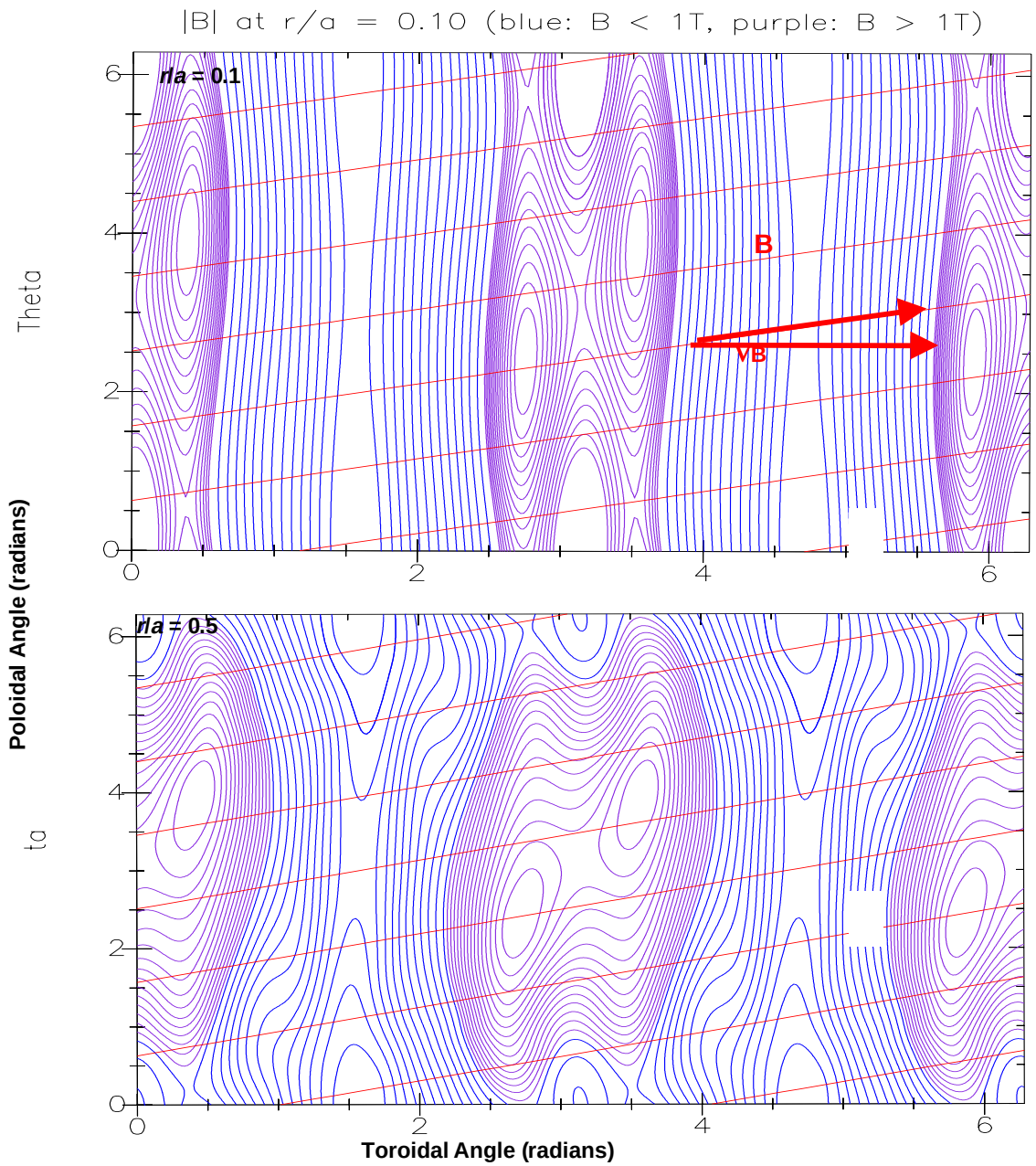


QPS Flux Surfaces Do Not Require Healing

- **PIES show only small islands which plasma should cure**



|B| Contours illustrate Quasi-poloidal Structure

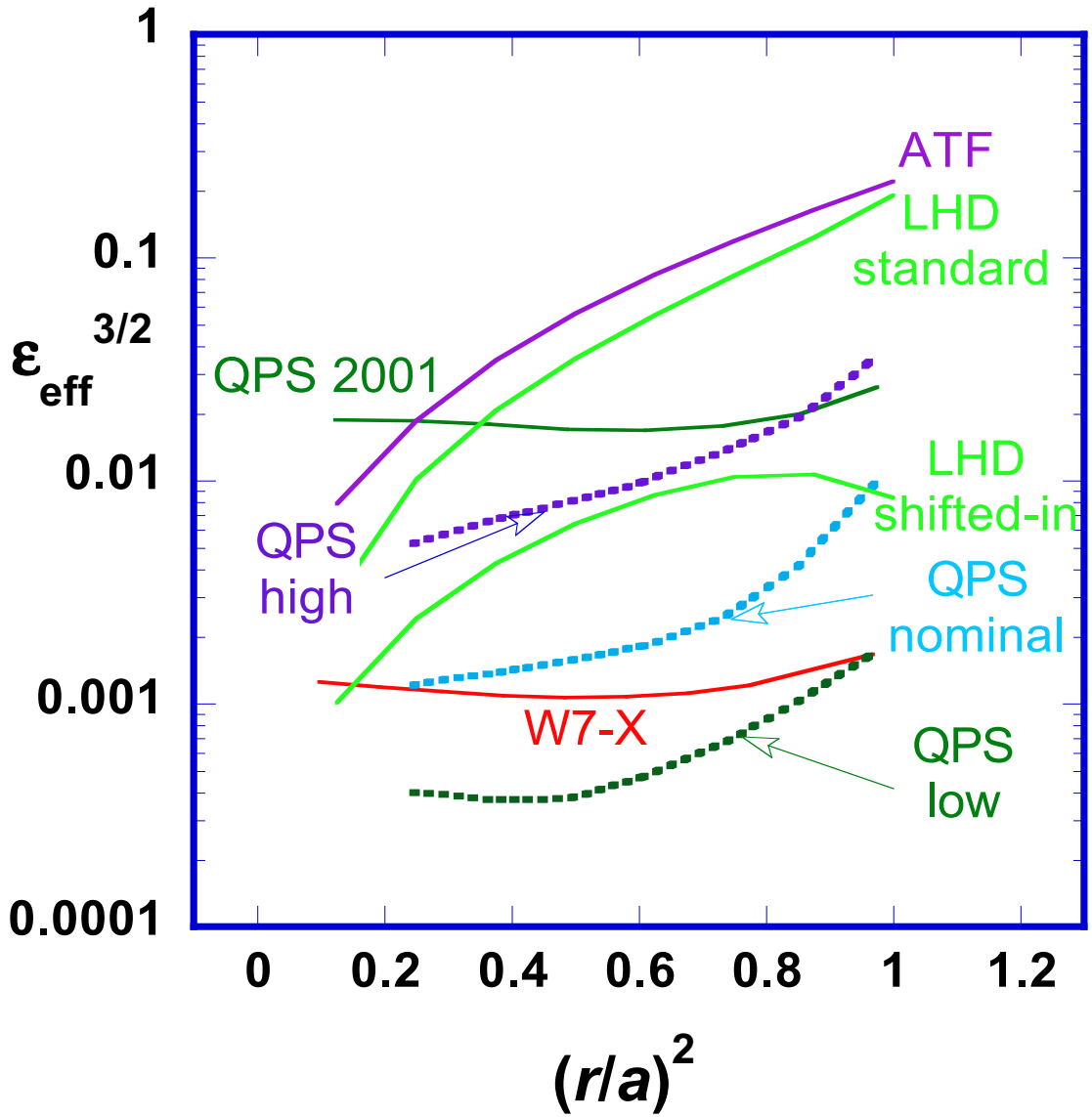


Unique Features of Quasi-Poloidally Symmetric Stellarators

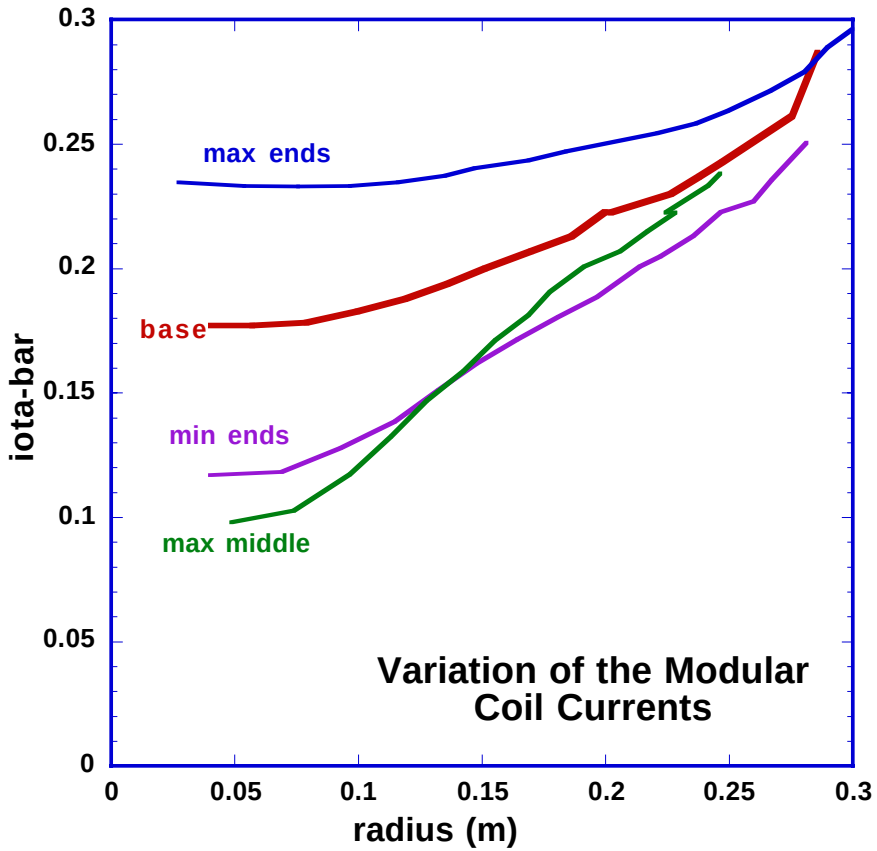
- **Closer alignment of B and ∇B than is possible with other forms of symmetry - reduces radial drift and banana thickness**
- **Minimum flow damping in the direction of E_r x B**
  - ***tokamaks*** **have minimum flow damping in toroidal direction - flow shear requires weak driving force (e.g., beams, RF)**
  - ***QP stellarators*** **have minimum flow damping in poloidal direction - flow shear is potentially self-sustained through internally generated E_r driven by plasma ambipolar diffusion**
- **Trapped particles are localized in low curvature regions**
  - **potential improvements to dissipative trapped electron mode stability**
- **Properties improve with increasing β**
  - **access to a second stability region**
  - **omnigeneity, thermal and fast ion confinement**
  - **configuration relatively insensitive to increasing β**
  - **bootstrap current relatively independent of β**

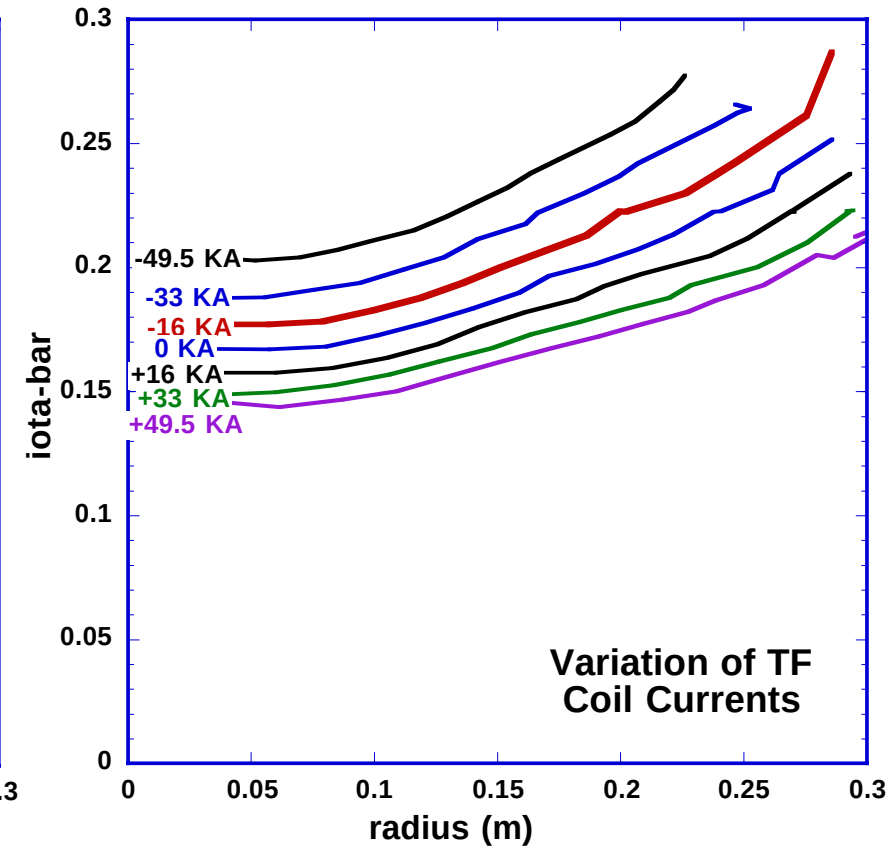
QPS Coil Set Allows Testing Neoclassical Transport

- Changing currents in QPS coils varies neoclassical trans-port by factor 8-20
- Can change from neoclassical being dominant over plasma core to not being significant
- Base QPS is a factor 10 better than 2001 version, ~ W 7-X value



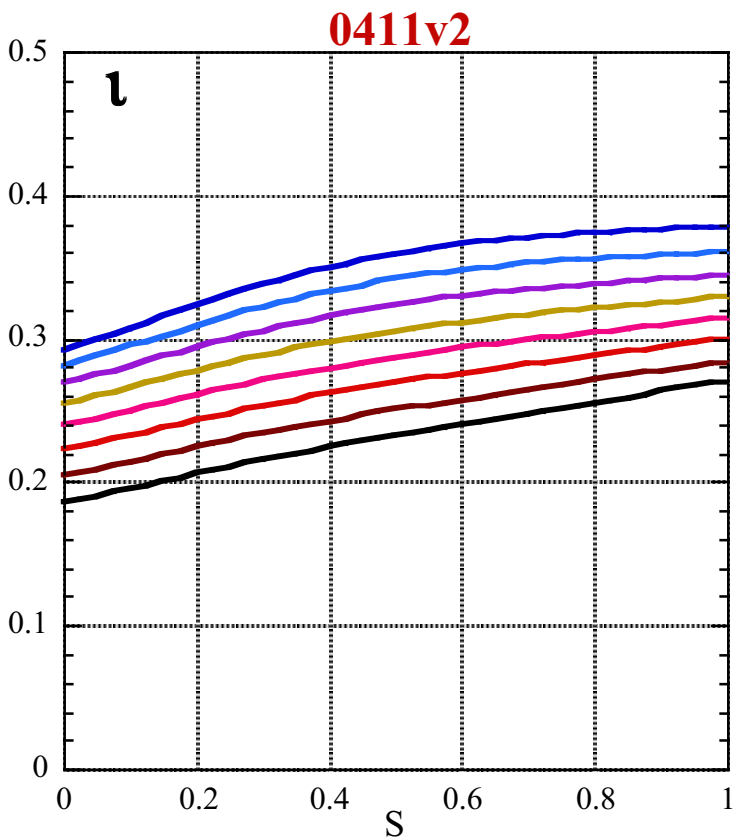
QPS Coils Allow Variation of Rotational Transform and Shear

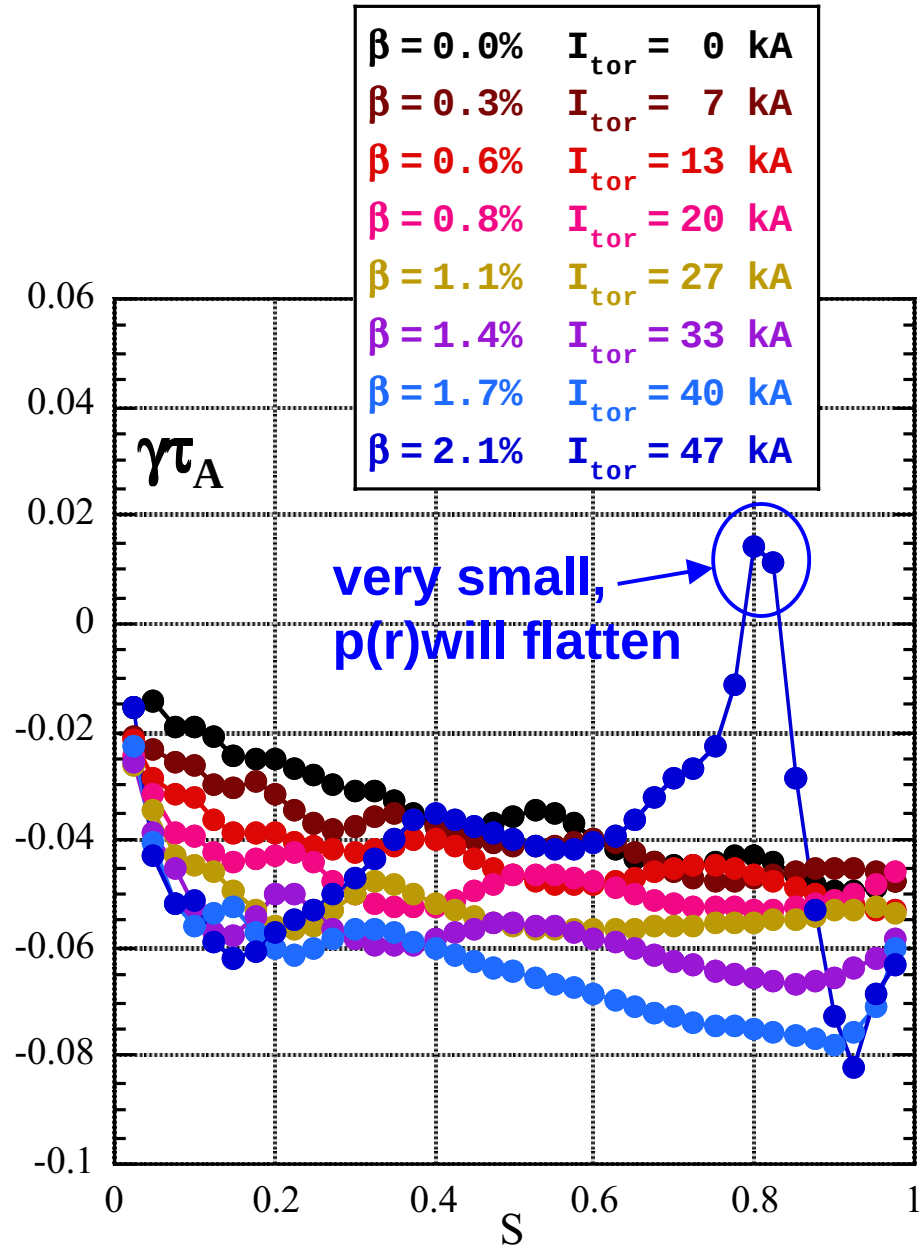




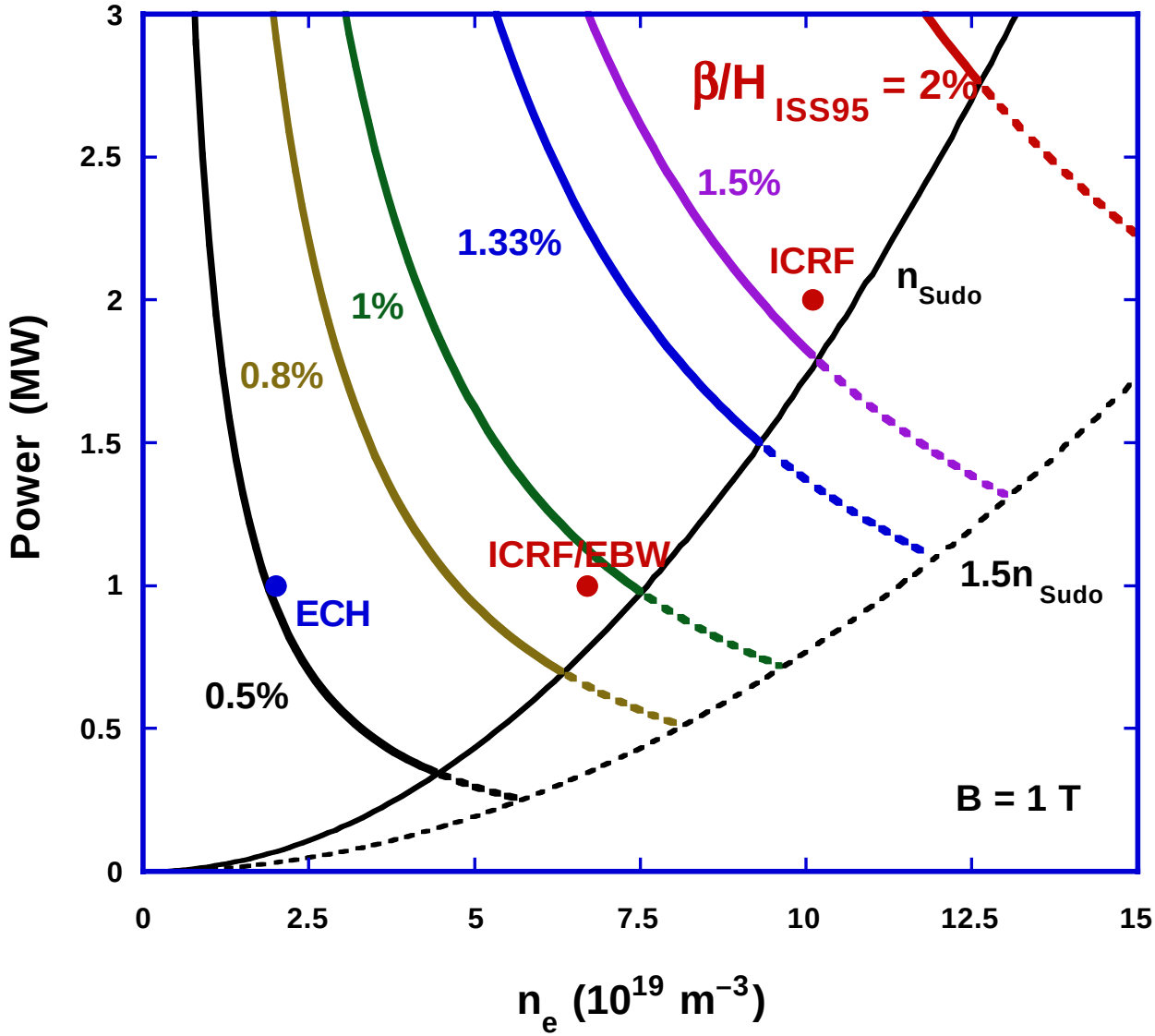
A Stable Path Exists from Vacuum to β = 2.1%

- **Infinite-n ballooning growth rates vs. S = (*r*/*a*)²**
- **Fixed (unoptimized) plasma pressure profiles**





P = 1-3 MW Gives Parameters Needed for the QPS Objectives



Multiply contour values by H_{ISS95} (= 1-2.5 in experiments)

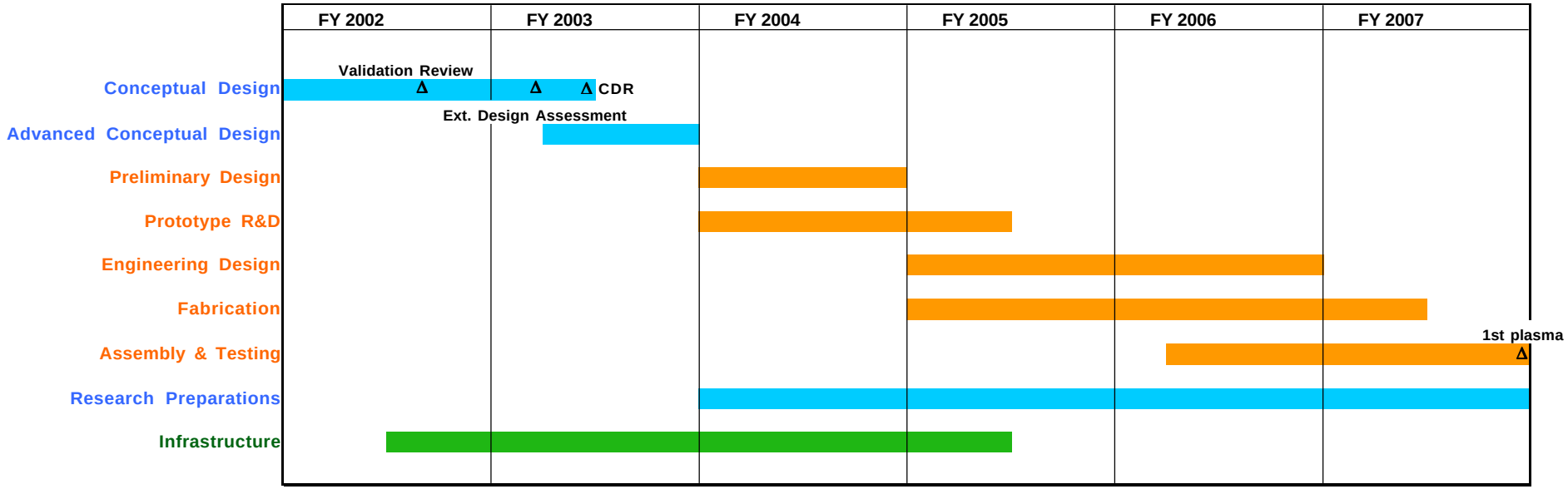
QPS parameter space for *B* = 1 T

QPS Program Objectives

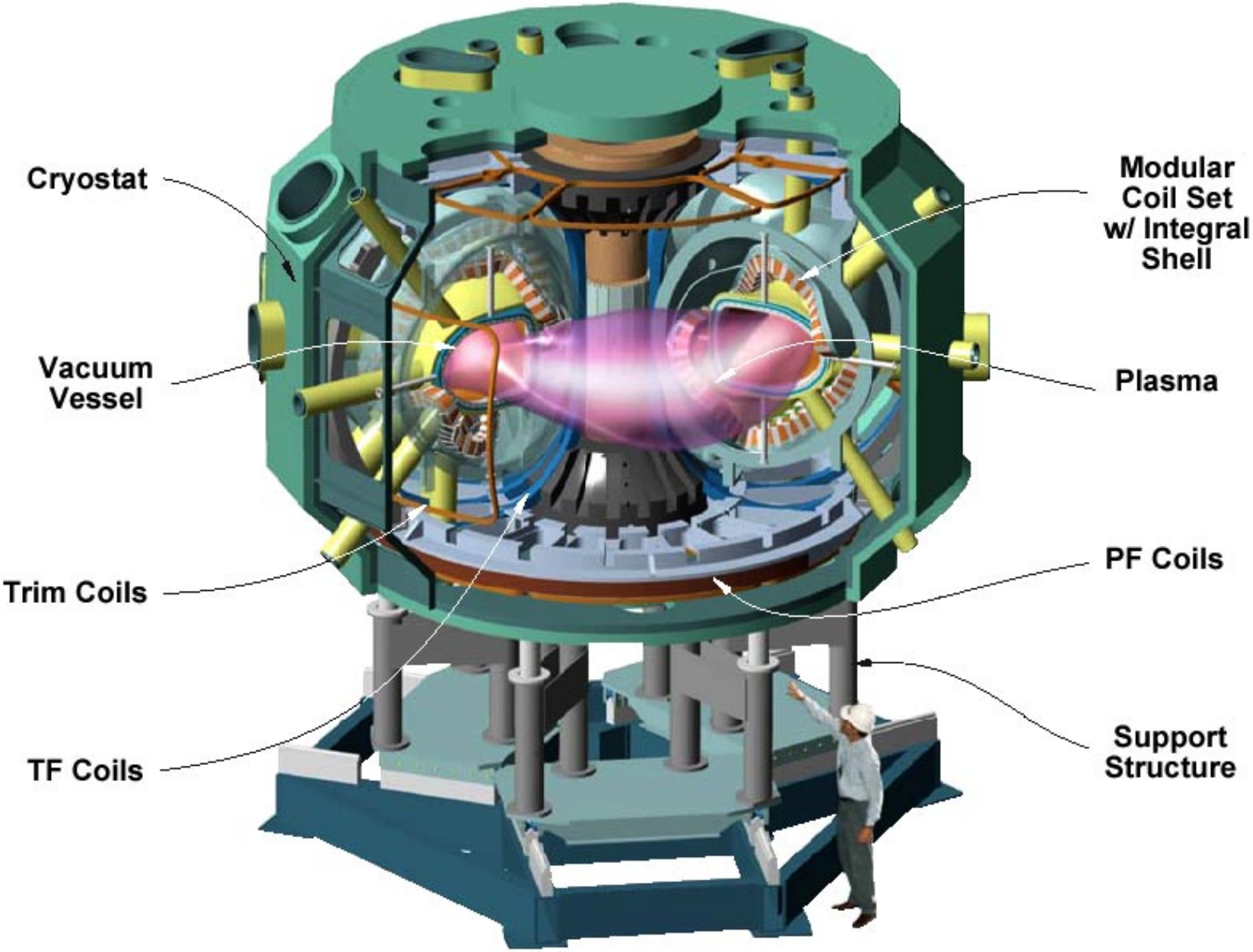
- **Confinement understanding**
  - anomalous transport, internal transport barriers, and flow shear in low-*R*/*a* configurations with quasi-poloidal symmetry
  - reduction of neoclassical transport due to near alignment of *B* and ∇B
  - impact of poloidal flows on enhanced confinement
  - equilibrium quality (islands, ergodic regions) and its repair at *R*/*a* ~ 2.7; robustness with β and dependence of bootstrap current on configuration properties
  - understand β limits and limiting mechanisms for quasi- poloidally symmetric configurations at very low *R*/*a*
- **Explore physics not obtainable from other stellarators and theory**
  - effect of strong toroidal coupling
  - significant bootstrap current in quasi-poloidal geometry
  - different neoclassical transport reduction mechanism
- **Study issues common to low-β and high-β quasi-poloidal stellarators**
  - scaling of the bootstrap current with β
  - reduction of H-mode power threshold
  - flux surface robustness as beta increases due to reduced parallel bootstrap current
  - ballooning instability character and limits

Status and Plans

- Successful Physics and Project Validation reviews
- Complete assessment of QPS physics properties
- Improve engineering design and cost estimate
- April 2003: Design, Cost & Schedule Review
- 2003-2007: R&D, design and construction
- Sept. 2007: First plasma

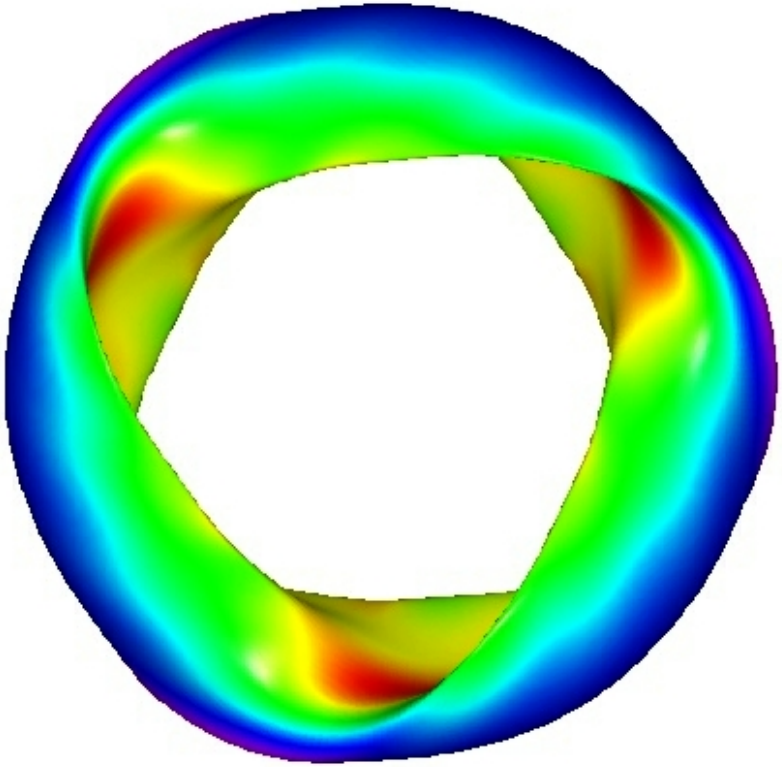


NCSX

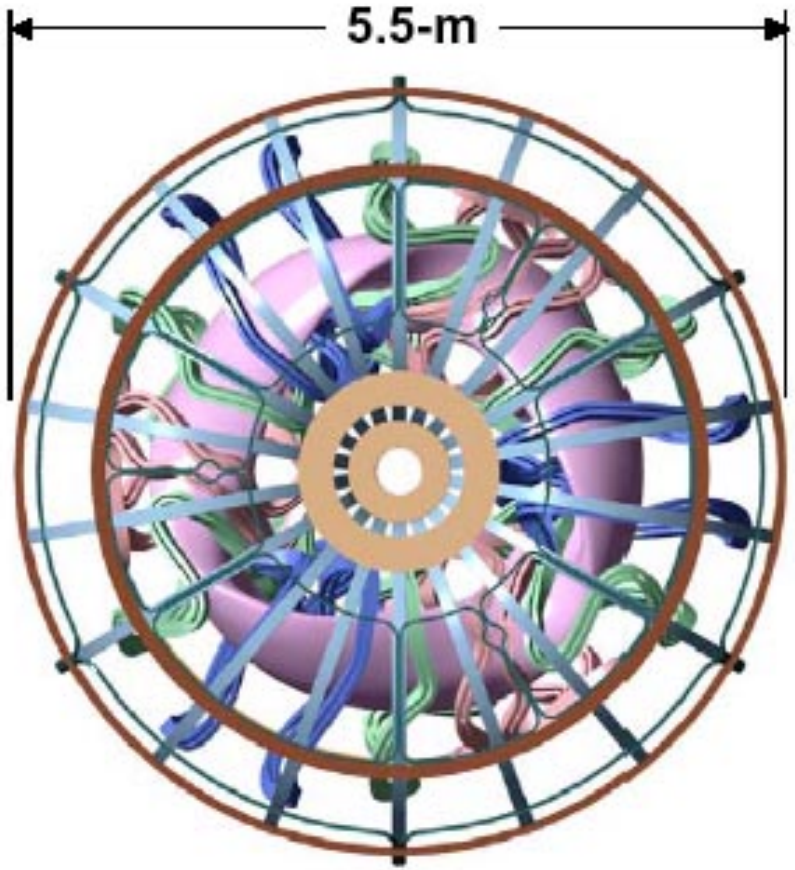

Cryostat
Vacuum Vessel
Trim Coils
TF Coils
Modular Coil Set w/ Integral Shell
Plasma
PF Coils
Support Structure

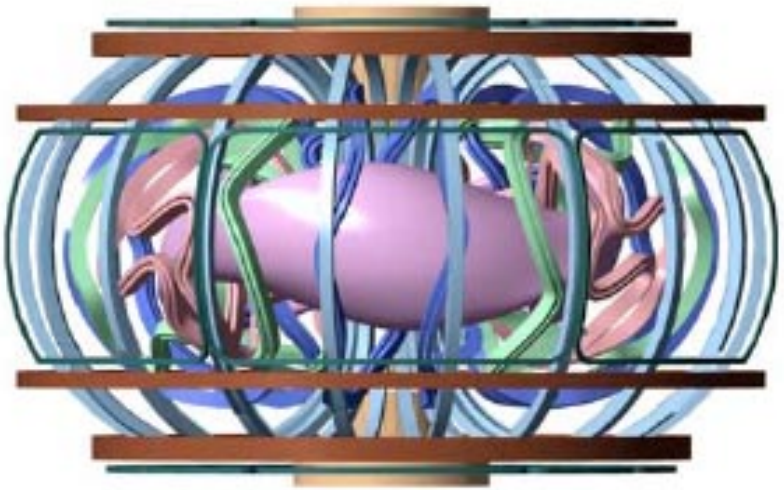
NCSX Plasma Configuration Has Attractive Physics

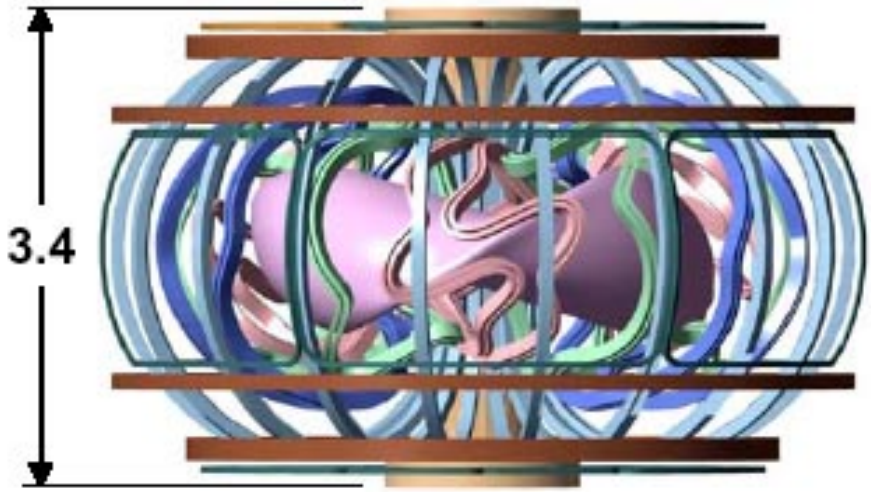
- 3 periods, $R/\langle a \rangle = 4.4$, $\langle \kappa \rangle \sim 1.8$
- Quasi-axisymmetric: low helical ripple transport, low flow damping
- Passively stable at $\beta = 4.1\%$ to kink, ballooning, vertical, Mercier, neoclassical-tearing modes; without conducting walls or feedback systems.
- Steady state without current-drive
- 18 modular-coils (3 shapes)
  Full coil set includes PF coils & weak TF coil for flexibility
- Coils meet engineering criteria:
  Bend radii & Coil-coil separation distance



NCSX Plasma and Magnets

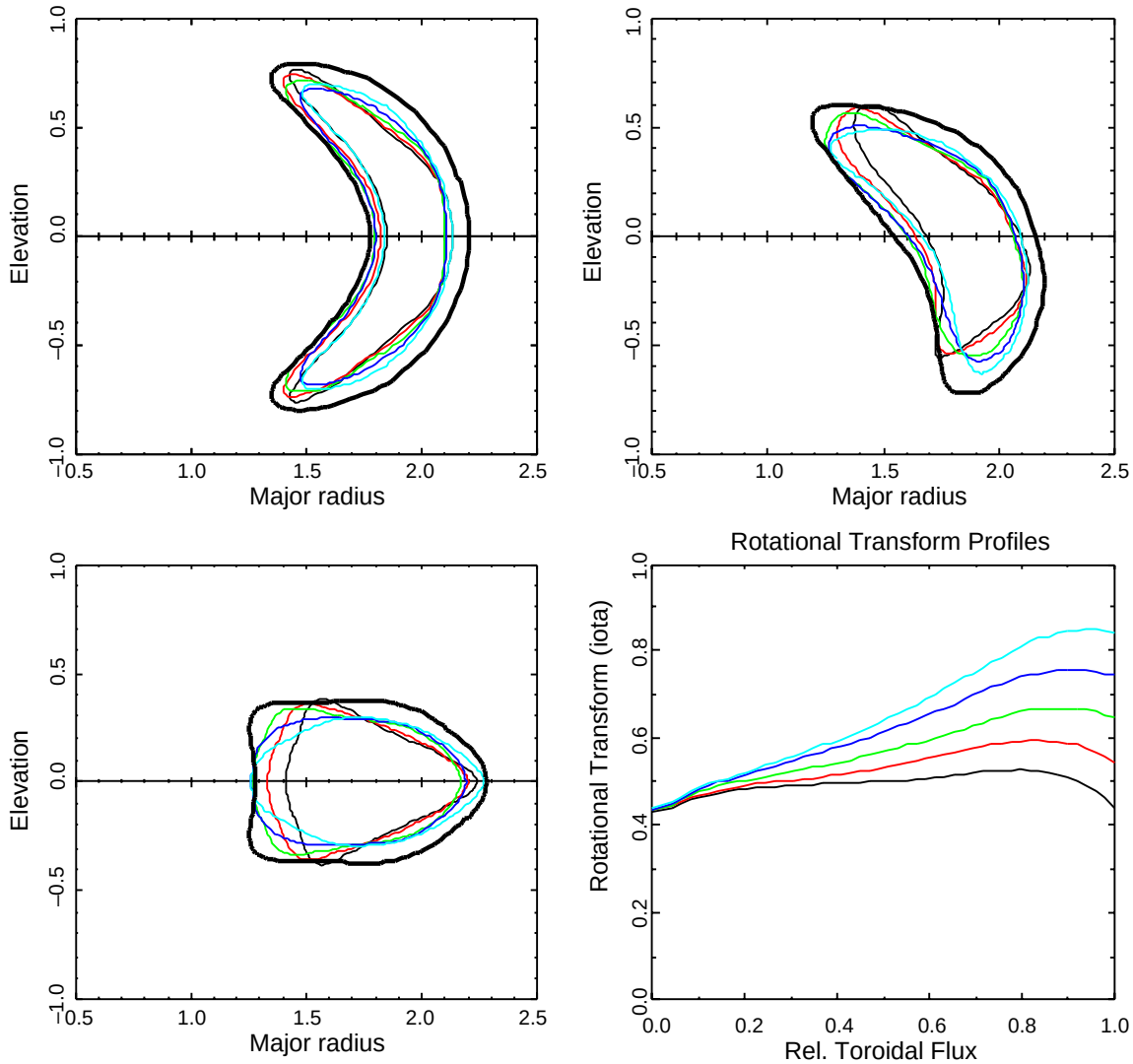






Modular Coils are Flexible

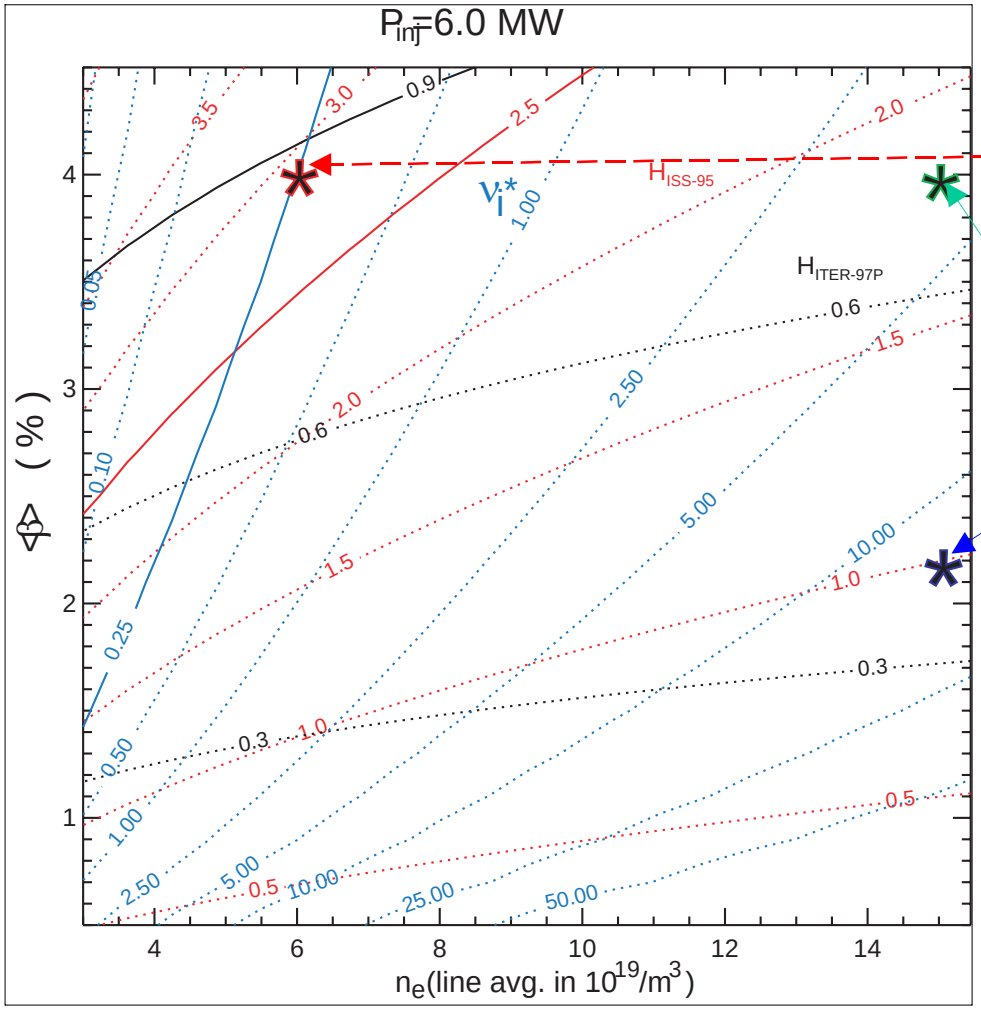
- Can control magnetic shear at fixed plasma current and profiles to study kink-stabilization physics, etc.
- Can also vary shear at fixed edge iota



β = 0, full current

Wide Range of Plasmas Accessible

Contours of H_{ISS95}, $H_{ITER\text{-}97P}$, and min ν_{*i}



B = 1.2 T, 6 MW

- * β = 4%, ν_{*i} = 0.25 requires H_{ISS95} = 2.9, $H_{ITER\text{-}97P}$ = 0.9
- * β = 4% at Sudo 'density-limit' requires H_{ISS95} = 1.8
- * H_{ISS95} = 1.0 gives β = 2.2% sufficient to test stability theory
- 3 MW gives β = 2.7%, ν_{*i} = 0.25 with H_{ISS95} = 2.9;
- β = 1.4% with H_{ISS95}=1.0 sufficient to test stability theory

LHD and W7-AS have achieved H_{ISS95} ~ 2.5

PBX-M obtained β = 6.8% with $H_{ITER\text{-}97P}$ = 1.7 and H_{ISS95} ~ 3.9

NCSX Mission

Acquire the physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3-D fusion science.

Understand…

- Beta limits and limiting mechanisms in a low-A current carrying stellarator
- Effect of 3D fields on disruptions
- Reduction of neoclassical transport by QA design.
- Confinement scaling; reduction of anomalous transport by flow shear control.
- Equilibrium islands and neoclassical tearing-mode stabilization by choice of magnetic shear.
- Compatibility between power and particle exhaust methods and good core performance in a compact stellarator.
- Explore 3D Alfvenic-mode stability in reversed shear compact stellarator

Demonstrate…

- Conditions for high-beta, disruption-free operation

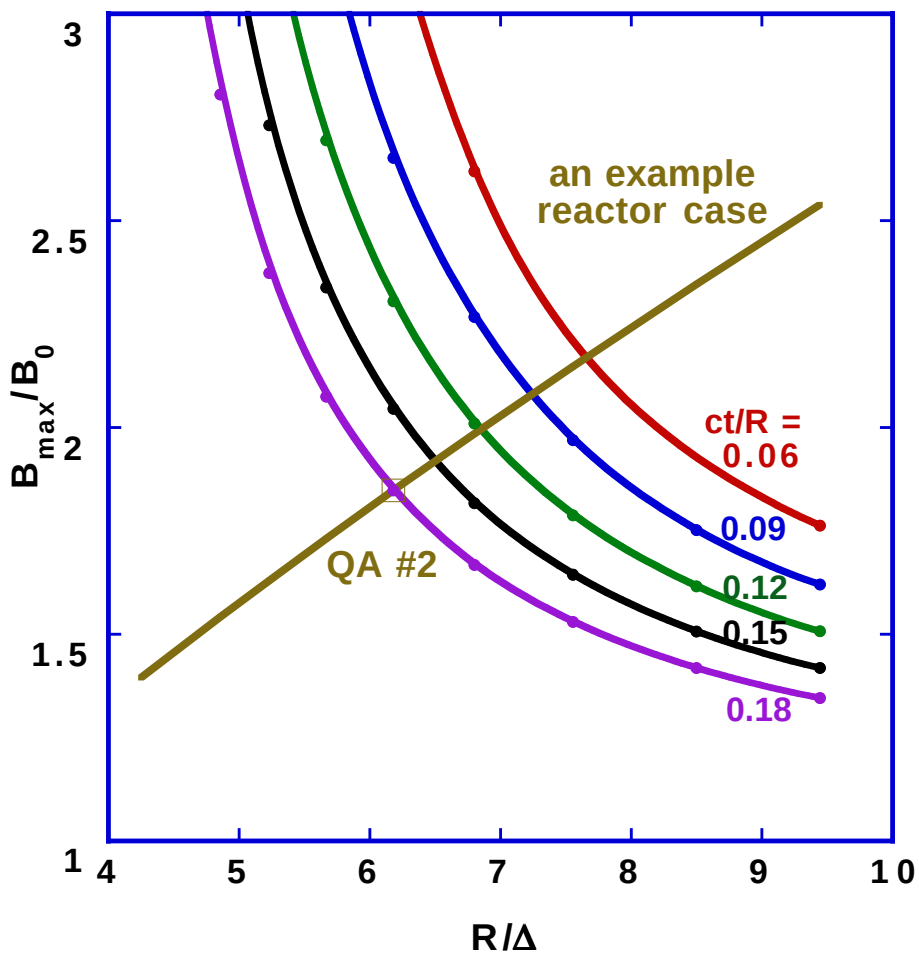
Approach and Assumptions

- The coils are characterized by $A_\Delta = R/\Delta$ and B_{max}/B_0 where Δ is the minimum distance between the plasma edge and the centerline of the coils for a given R, and B_{max} is the maximum field on the coils
- $R_{min} = A_\Delta(d + ct/2)$ where d is the limiting (inboard) space needed for the plasma-wall distance (pw), first wall (fw), blanket (bl), shield (sh), vacuum vessel (vv), and assembly gaps; ct is the radial depth of the modular coils
  - $ct/2 = A_\Delta B_0/(16 N_{coil}\, j_{coil} k)[1 + \{1 + 32\, N_{coil}\, j_{coil} k d/(A_\Delta B_0)\}^{1/2}]$
  - N_{coil} = number of coils, j_{coil} = current density averaged over the coil cross section in kA cm^2, and k = (toroidal width)/(radial depth) of the coils
- d is 1.12 m (pw = 5 cm, fw = 2 cm, bl = 28 cm, sh = 49 cm, vv = 20 cm, and 5 cm for gaps), similar to that in the ARIES-AT study
- The corresponding value for d on the outboard side is 1.30 m with pw = 5 cm, fw = 2 cm, bl = 63 cm, sh = 25 cm, vv = 30 cm, and 5 cm for gaps
- The other reactor assumptions are similar to the ARIES-AT study
  - thermal conversion efficiency η = 59% and B_{max} = 12 T

Determination of Reactor Size

- **The minimum value for *R* was calculated for M = 2 and 3 QA and QP reactors subject to several constraints**
  - $P_{electric}$ = 1 GW, $\Gamma_n \leq 4$ MW m^{-2}, a plasma-coil distance ≥ 1.11 m, $j_{coil} \leq 3$ kA cm^2, H-95 ≤ 3.5, $\langle n \rangle / n_{Sudo} \leq 1$, $\langle \beta \rangle \leq 5\%$
  - H-95 = τ_E / τ_E^{ISS95} where $\tau_E^{ISS95} = 0.79 a_p^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{-0.4}$
  - $n_{Sudo} = (1/4)[PB/Ra^2]^{1/2}$
- **The minimum values for *R* and H-95 and maximum Γ_n are obtained with $\langle n \rangle / n_{Sudo} = 1$**

Scaling Model Used for Reactor Size



- NESCOIL code was used to calculate B_{max}/B_0 at a distance ct/2 radially in from a current sheet (at a distance Δ from the plasma edge) that reproduced the last closed flux surface
- B_{max}/B_0 was increased by 15% to simulate effects due to a smaller number of coils
- Minimizing B_{max}/B_0 increases the field in the plasma for a given B_{max} on the coils
- Minimizing R/Δ allows a smaller R for a reactor with a given d
- B_{max}/B_0 needed for a given $P_{electric}$ and d is proportional to $(R/\Delta)^{3/4}$

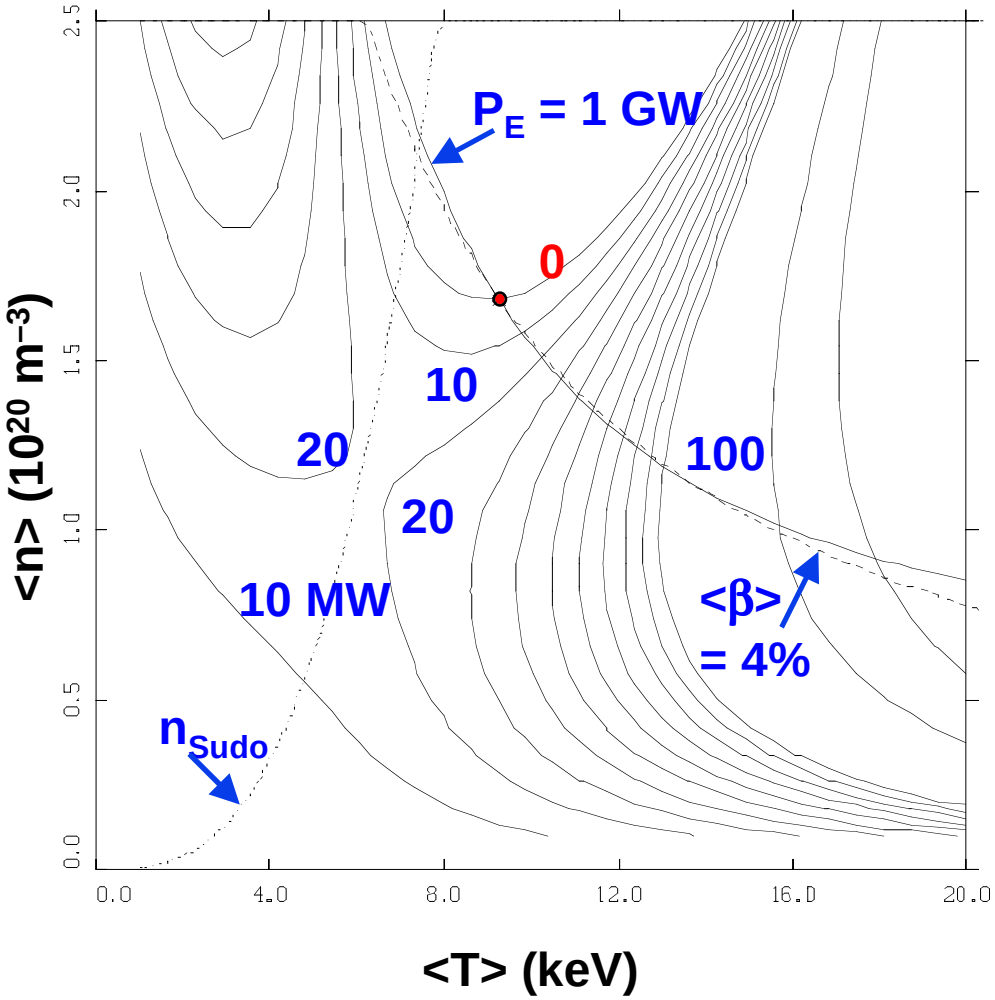
Scaled 1-GW Compact Stellarator Reactors with B_{max} = 12 T, $\langle\beta\rangle \leq \beta_{limit}$, H-95 ≤ 5

	QA#1	QA#2	QP#1	QP#2
Plasma aspect ratio R/a_p	2.96	4.4	2.70	3.70
Volume average β limit $\langle\beta\rangle_{limit}$ (%)	4	4.1	10	15
Average major radius R (m)	**8.22**	**9.93**	**7.34**	**7.84**
Average plasma radius a_p (m)	2.78	2.26	2.72	2.12
Plasma volume V_{plasma} (m^3)	1250	1000	1040	690
On-axis field B_0 (T)	**5.41**	**5.65**	**5.23**	**5.03**
τ_E/τ_E^{ISS95} multiplier H-95	**2.65**	**2.62**	**3.61**	**4.42**
Volume average beta $\langle\beta\rangle$ (%)	**4**	**4.1**	**4.6**	**6.2**
Energy confinement time τ_E (s)	2.69	2.41	2.49	2.01
Vol.-ave. density $\langle n\rangle$ (10^{20} m^{-3})	1.31	1.50	1.40	1.70
Density-average $\langle T\rangle$ (keV)	11.1	10.8	11.3	11.5
Neutron wall load Γ_n (MW m^{-2})	**1.34**	**1.37**	**1.54**	**1.85**

Scaled 2-GW Compact Stellarator Reactors with B_{max} = 12 T, $\langle\beta\rangle \leq \beta_{limit}$, H-95 ≤ 4

	QA#1	QA#2	QP#1	QP#2
Average major radius R (m)	**10.35**	**12.51**	**7.34**	**7.85**
Average plasma radius a_p (m)	3.50	2.84	2.72	2.12
Plasma volume V_{plasma} (m^3)	2500	2000	1070	700
τ_E/τ_E^{ISS95} multiplier H-95	**2.07**	**2.04**	**3.56**	**3.94**
Volume average beta $\langle\beta\rangle$ (%)	**4**	**4.1**	**6.5**	**8.75**
Energy confinement time τ_E (s)	2.69	2.41	1.76	1.42
Vol.-ave. density $\langle n\rangle$ (10^{20} m^{-3})	1.31	1.50	1.62	2.40
Neutron wall load Γ_n (MW m^{-2})	**1.69**	**1.72**	**3.07**	**3.68**

Operating Space for a QA#1 Reactor



R = 7.1 m, B_0 = 5.4 T

- **Operating Point**

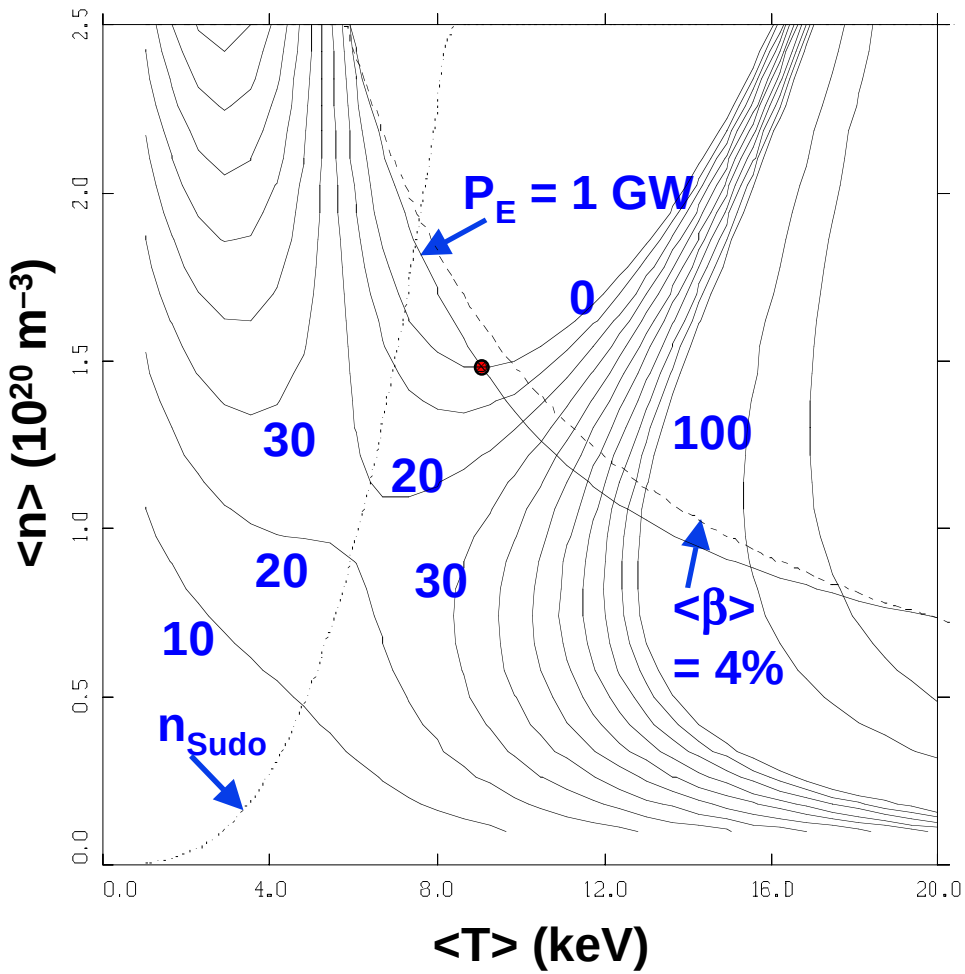
$\langle n \rangle = 1.7 \times 10^{20}$ m^{-3}, $\langle T \rangle = 9.3$ keV
$\langle \beta \rangle = 4.04\%$, for H-95 = 2.9
$n_{DT}/n_e = 0.82$, $Z_{eff} = 1.48$

- **Saddle Point**

$\langle n \rangle = 0.9 \times 10^{20}$ m^{-3}, $\langle T \rangle = 5.4$ keV
$\langle \beta \rangle = 1.4$ %, and $P_{aux} = 20$ MW

Assumes ARIES-AT n(r/a) and T(r/a), α losses = 0.1, $\tau_{He}/\tau_E = 6$
$B_{max} = 12$ T

Operating Space for a 1-GW QP#1 Reactor



R **= 7.3 m, B_0 = 5.2 T**

- **Operating Point**

<*n*> = 1.5 x 10^{20} m^{-3}, <*T*> = 9.1 keV
<*β*> = 3.74%, for H-95 = 2.95
n_{DT}/n_e = 0.82, Z_{eff} = 1.48

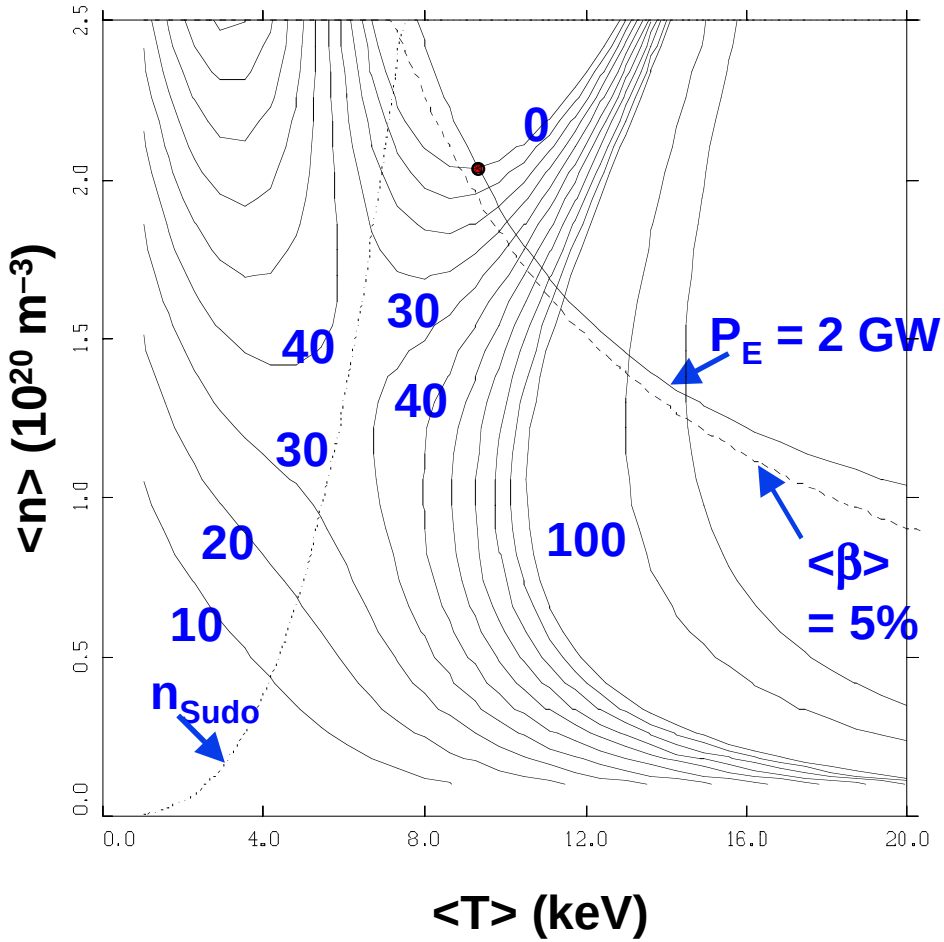
- **Saddle Point**

<*n*> = 0.9 x 10^{20} m^{-3}, <*T*> = 5.4 keV
<*β*> = 1.4 %, and P_{aux} = 20 MW

The 10% β limit allows reducing B_{max} from 12 T to 8.5 T. This requires increasing H-95 from 2.95 to 4.1 for 1-GW operation

<*β*> = 8.4 % at operating point
<*β*> = 3.4 % at saddle point

Operating Space for a 2-GW QP#1 Reactor



R **= 7.3 m, B_0 = 5.2 T**

- **Operating Point**

<*n*> = 2.0 x 10 ^{20} m^{-3}, <*T*> = 9.3 keV
<*β*> = 5.28%, for H-95 = 2.65

- **Saddle Point**

<*n*> = 1.3 x 10 ^{20} m^{-3}, <*T*> = 5.4 keV
<*β*> = 1.4 %, and P_{aux} = 39 MW

Comparison with Other Stellarator Configurations

- **The same assumptions were used with the plasma and coil configurations corresponding to the HSR, MHR-S, and SPPS stellarator reactors**
- **The modified "HSR*" had R = 17.4 m (instead of 22 m because B_{max} was increased from 10.6 T to 12 T), H-95 = 3.06, $\langle\beta\rangle$ = 4.9%, and Γ_n = 1.24 MW m^{-2}**
- **The modified "MHR-S*" had R = 18.6 m (instead of 16.5 m because of the ARIES-AT blanket and shield assumptions), H-95 = 2.87, $\langle\beta\rangle$ = 5%, and Γ_n = 0.62 MW m^{-2}**
- **The modified "SPPS*" had R = 20.8 m (instead of 14.0 m because B_{max} was decreased from 16 T to 12 T), H-95 = 3.13, $\langle\beta\rangle$ = 5%, and Γ_n = 0.60 MW m^{-2}**
- **For the same modeling assumptions, the compact stellarator configurations lead to reactors with a factor of 2 to 3 smaller major radius and a factor of 1.4 to 3 higher wall power loading**

ARIES Compact Stellarator Reactor Study

- The ARIES group plans to carry out a compact stellarator reactor study starting next year
- The first 1 1/2 years will be spent working with US stellarator group on tools and coil optimization
- The last year will be spent on a point reactor study

Summary

- The US is starting a new confinement program -- compact stellarators
- QPS will test the quasi-poloidal approach
- NCSX will test the quasi-axisymmetric approach
- Compact stellarators may lead to an attractive reactor concept