Design of the QPS Reference Configuration

Presented at QPS PVR

(April 24-25, 2001) by

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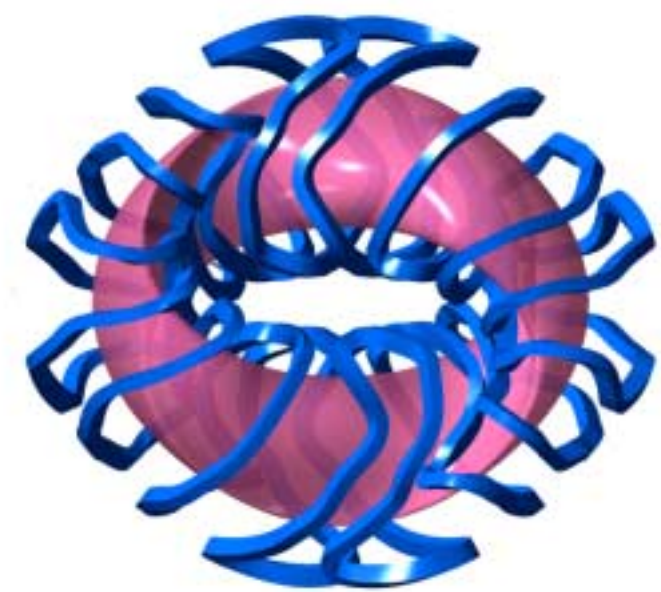
QPS Nomenclature

- **QPS – Quasi-Poloidal Stellarator**
- **N - number of field periods (toroidal translational invariance $\varphi \rightarrow \varphi + 2\pi/N$)**
- **ι - mean $d\theta/d\varphi$ ("pitch") of a magnetic field line on a flux surface**
- **A - aspect ratio, R/<a>, based on surface area and volume (stellarator definition)**
- **$\theta(u)$, $\varphi(v)$ – poloidal, toroidal angles**

Summary of Geometry and Physics of the QPS Reference Design

- **N = 2, A ~ 2.6 compact stellarator**
  - **Explores ultra-low A, <R> ~ 0.90 m, <a> ~ .35 m**
- **Dominant Quasi-Poloidal symmetry of |B| spectrum**
  - **Linked mirror (similar to W7-X)**
  - **Finite (but small) I_{bs}**
- **Moderate ballooning stable β ~ 2- 2.5%**
  - **Kink, vertical, neoclassical tearing mode (NTM) stability**



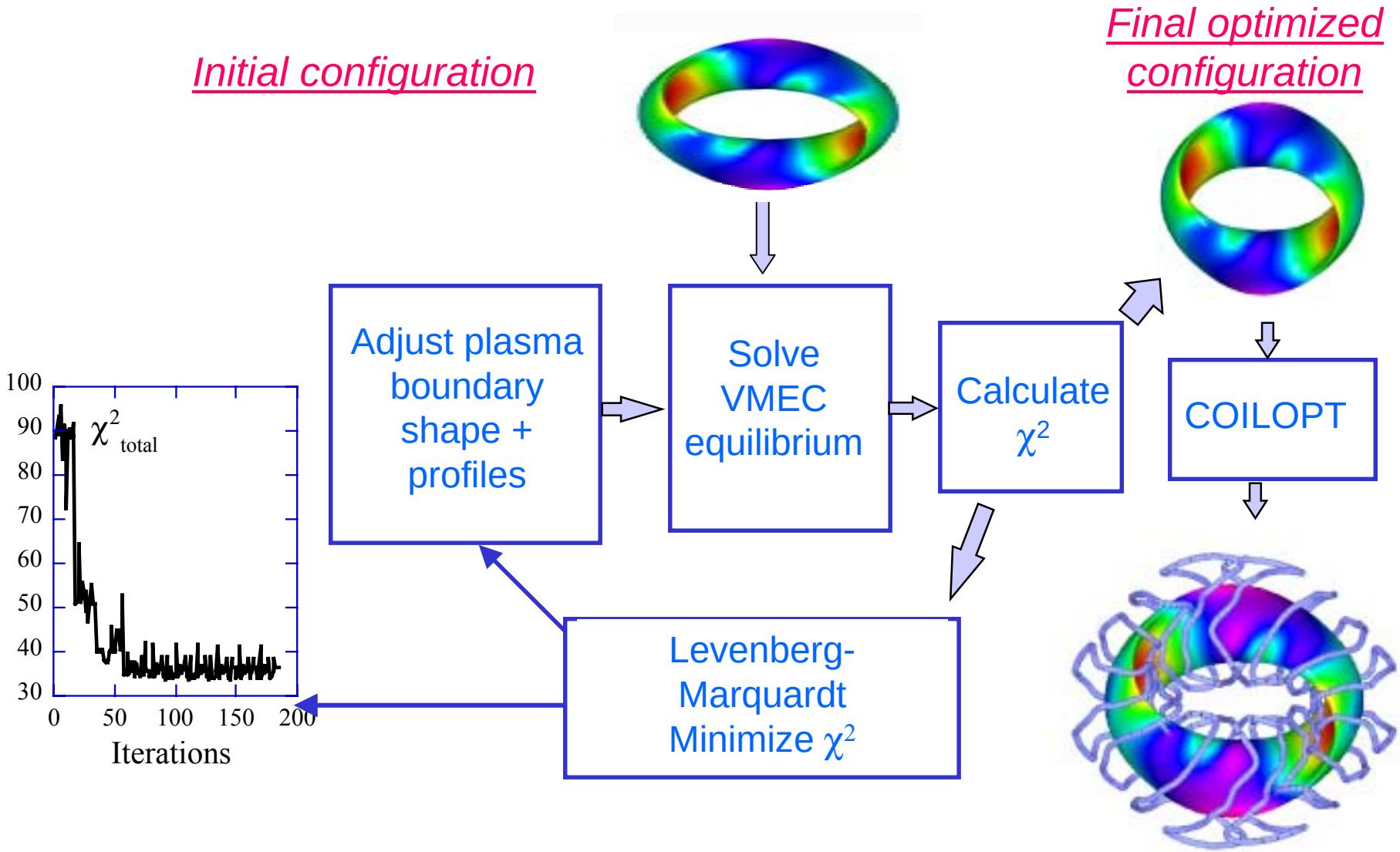
Motivation for the QPS Reference Configuration

- **Compact (low A)**
  - **Niche in world program which may eventually lead to a smaller, economical stellarator reactor**
- **Exploit Quasi-Poloidal (QP) symmetry**
  - **Reduce transport losses in low collisionality regime ($1/\nu$)**
    - **Finite β in experiment**
    - **Close to relevant regime for reactor**
  - **Reduce boostrap currents**
    - **Configuration invariance with β**
    - **Passively stabilize external kinks, vertical modes**
- **Develop coil set with flexibility to explore low β (<3%) access to eventual high β (~7-15%) QPS "reactor vision" regime**

Design Process for the Reference Configuration GB4

- **Same codes were developed and applied to optimize designs of QPS and NCSX**
  - **Two step optimization process (reverse engineering)**
  - **Physics Optimization (ORNL STELLOPT code)**
    - **Uses MPI + VMEC (equilibrium) + PIES (island healing) + sophisticated physics stability and transport modules**
  - **Coil Optimization (ORNL COILOPT code)**
    - **Design feasible modular coils**

Compact Stellarator Optimization Procedure



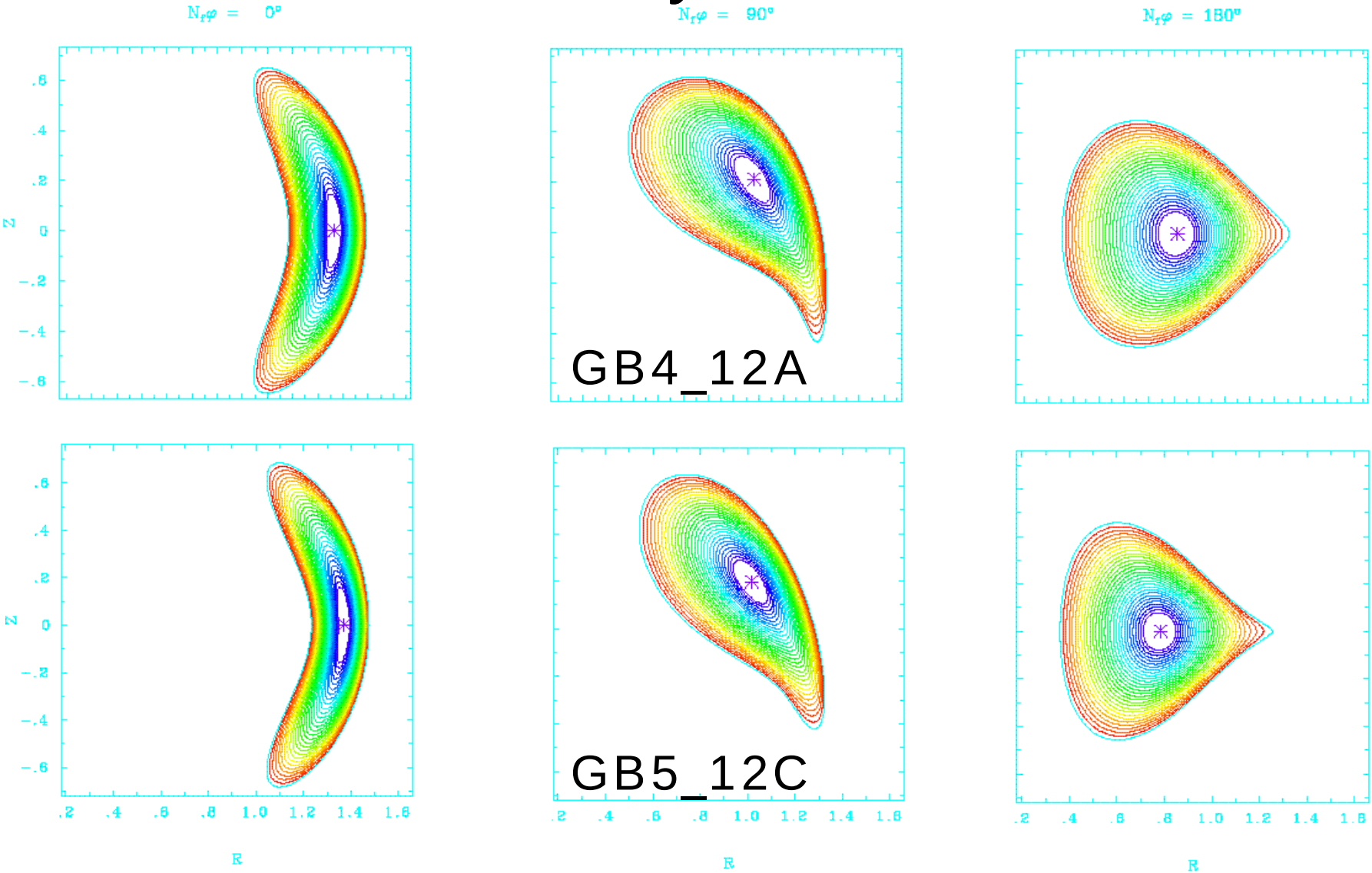
A Variety of Physics and Engineering Targets Is Used in the Optimization

Category	Targets (Physics/Engineering)	Examples
TRANSPORT	Bounce-average omnigeneity (drift surfaces and flux surfaces aligned)	$B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$ $J = J(\psi)$
	Target nearby quasi-symmetries	Minimize B_{mn} if $m \neq 0$ (QP), or if $m/n \neq 1$ (QH)
	Local diffusive transport	D, χ from DKES
CURRENT	Current profile	self-consistent I_{BS}, $I(\psi)$ goes to 0 at edge
	Limit maximum plasma current	e.g., $I_{max} < 80$ kA
	Iota profile	$\iota(\psi) \sim 0.25 - 0.4$ ($\rho = 0$, a)
STABILITY	Magnetic Well, Mercier	$V'' < 0$, $D_M > 0$ over cross section
	Ballooning, Kink, Vertical stability	$\langle\beta\rangle \sim 2$-4%
GEOMETRY	Aspect ratio	$R_0/a \sim 2.5$ to 3.5
	Adequate shielding of neutrals	Minimum "waist" thickness
	Fit within vacuum bell jar	$R_{max} < 1.5$ m
COILS	NESCOIL targets/feasible coil design	Coil complexity, B_{err}, Max. current density

GB4 vs GB5 Reference Design: A Clarification

- **GB4 (1/01) preceded GB5 (3/01)**
  - **Picked for engineering reference design work to begin in time for PVR**
- **GB5 supercedes GB4**
  - **Essentially same stability properties, bootstrap current and coils, but *significantly* improved neoclassical transport compared to GB4**
  - **Engineering and complete stability scan not yet completed**

GB5 Is Closely Related to GB4



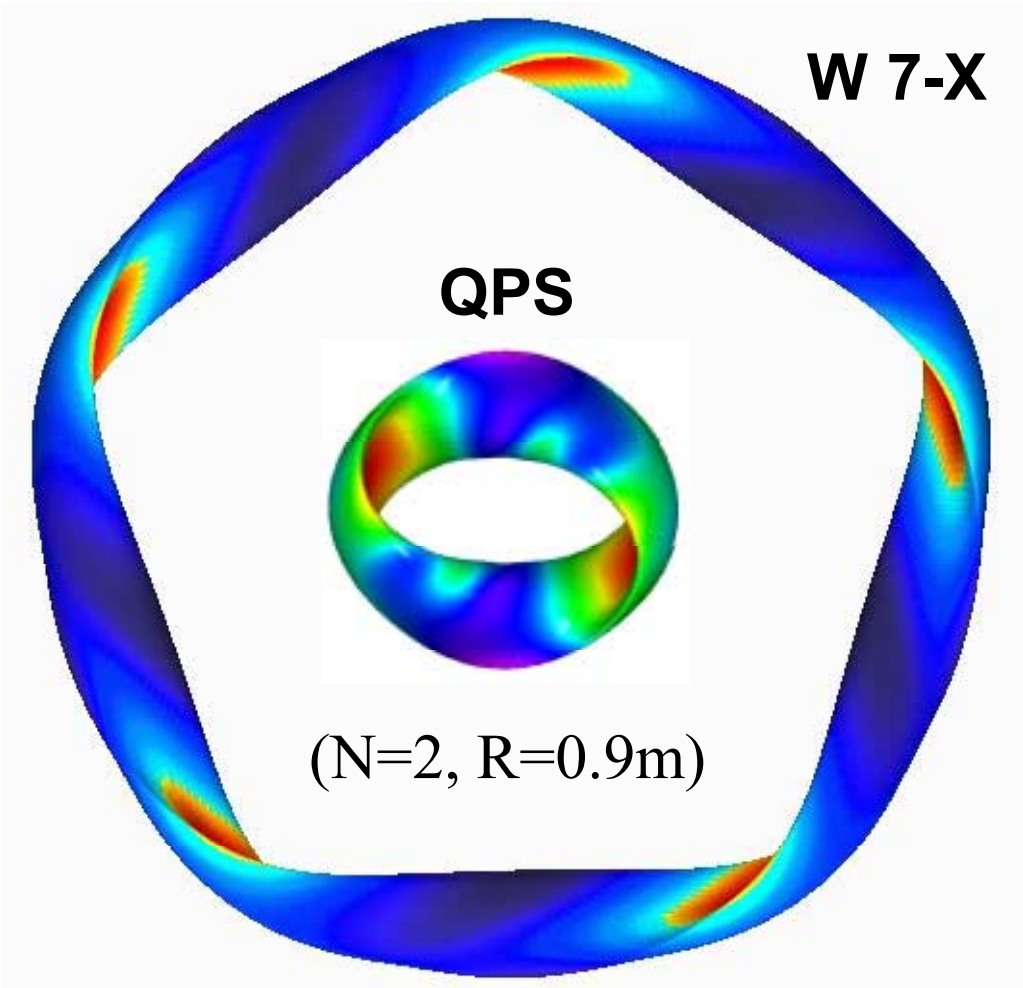
Remainder of Presentation Uses GB5 (Whenever Available)

- **Following physics properties of GB5 reference configuration will be described**
  - **Equilibrium**
    - **Geometry and transform**
    - **|B| structure and approximate "poloidal symmetry"**
  - **Transport**
    - **Reduction of ε_{eff} ($1/\nu$, low collisionality transport)**
    - **Bootstrap current**
  - **Stability**
  - **Reconstruction from coils**

Equilibrium Properties of QPS Reference Configuration

- **Very Low Aspect Ratio A ~ 2.6**
  - **Much smaller than W7-X (A ~ 11) or any planned or existing stellarator**
  - **Potential for compact stellarator reactor**
- **Low Number of Field Periods**
  - **N = 2 allows good field penetration, smoother coils**
  - **Achieves scaleable coil-plasma separations**

QPS Is Compact: $A_{W7\text{-}X} \sim 4\ A_{QPS}$



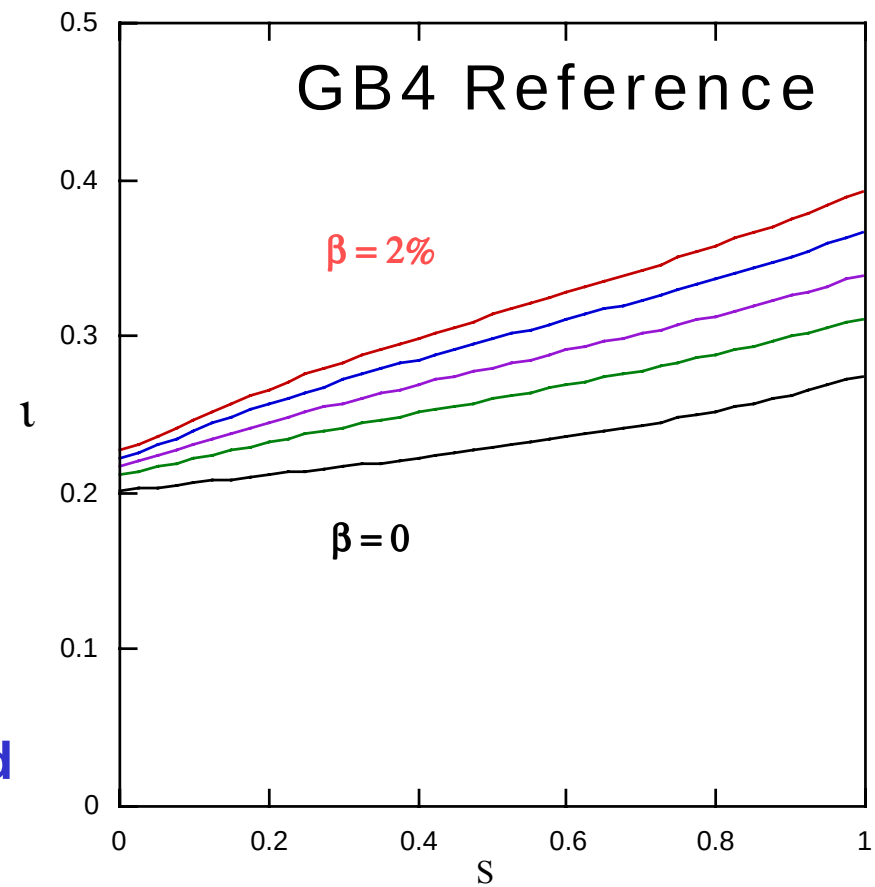
(N=5, R=5.95m)

Shown here norm-alized to same <a>

Rotational Transform (ι) in QPS

(A. Ware)

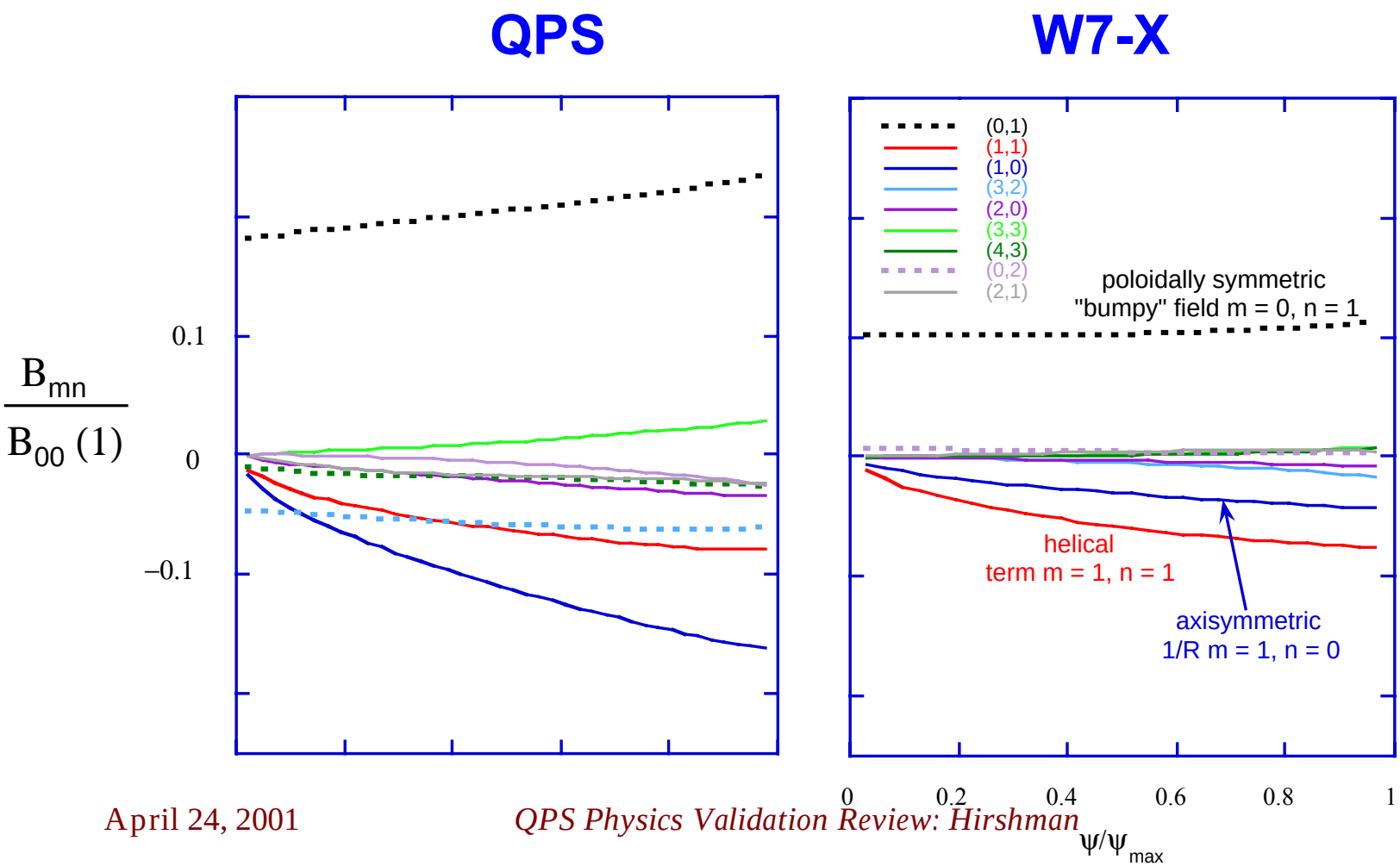
- **0.25 < ι < 0.40 at β = 2%**
  - **Lower than NCSX and W7-X**
  - **About same ι /N**
    - **Coils equally complex**
  - **Avoids m=5, N=2 resonance (ι = 0.40)**
- **Stellarator profile**
  - **J_{bs} * ι'/ ι > 0: consistent with ntm stability/island "healing"**



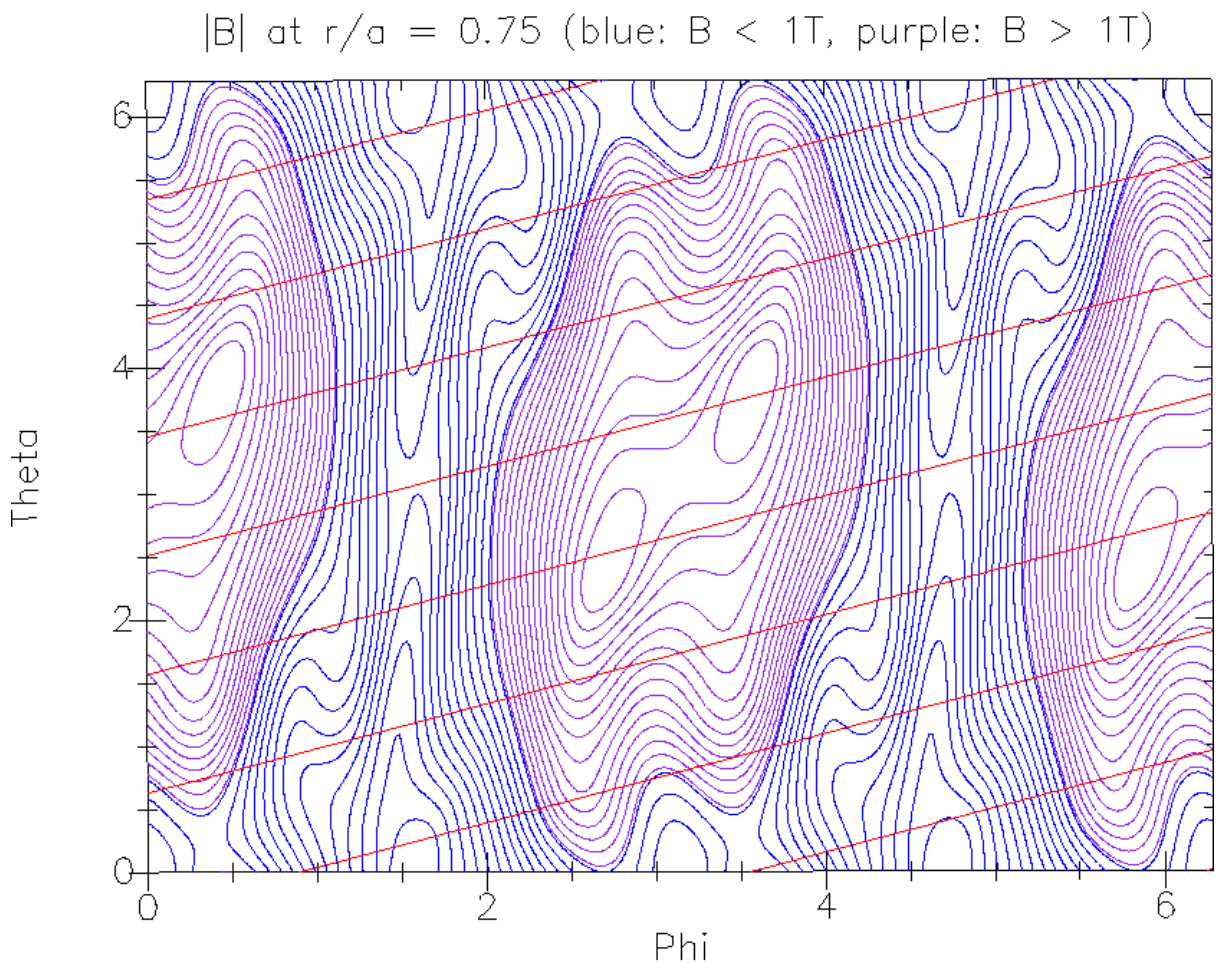
QPS Physics: Symmetry and Transport Consequences

- **Quasi-Poloidal Symmetry**
  - **Dominant symmetry of |B| in drift Hamiltonian [$|B| \approx |B|(\Psi,\varphi)$, only angular dependence in H]**
    - **"Linked mirror": $|B|_{m=0,n=1}/B_{00}$ largest harmonic**
    - **P_θ is approximate invariant – confines orbits**
  - **Excellent $1/\nu$ confinement achievable**
  - **Possibility of lowered poloidal viscosity allow external control of flows for exploration of Internal Transport Barriers (ITBs)**
  - **Near edge, omnigeneity improves particle orbit and energy confinement**

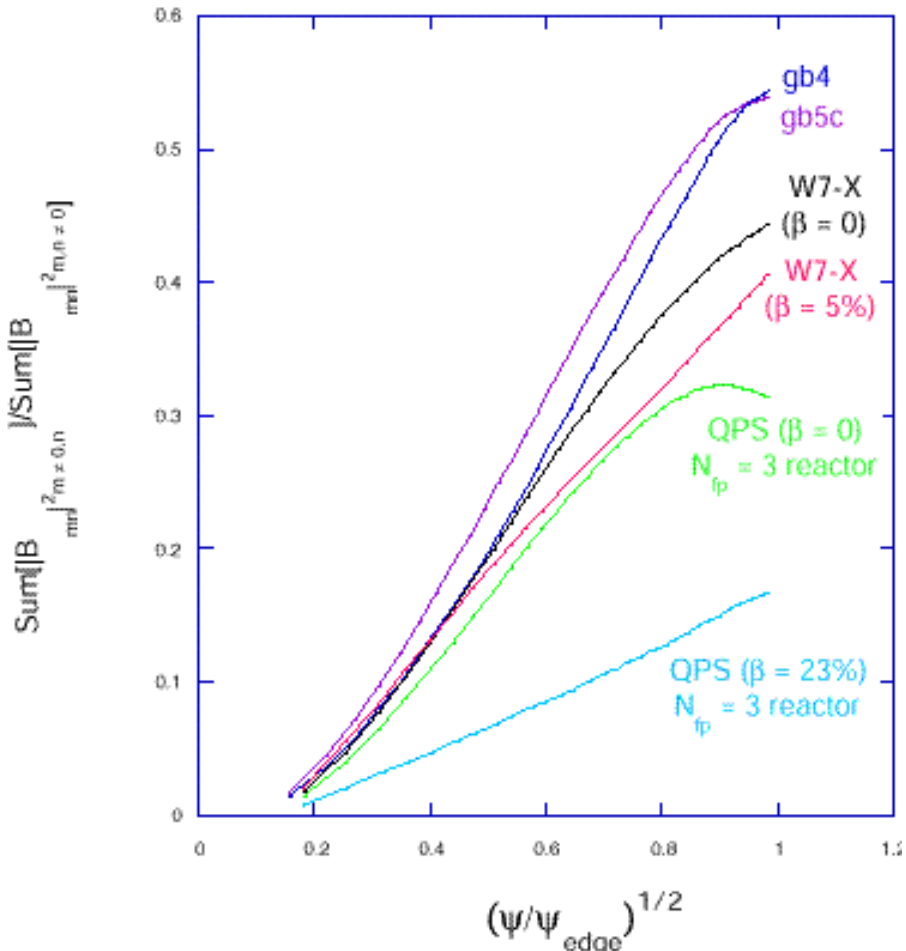
Linked Mirror Characteristic of |B| Spectra in QPS and W7-X



|B| Contour For GB4 Show Approximate Poloidal Banding



Degree of Quasi-Poloidal Symmetry Varies with Radius in QPS Stellarators



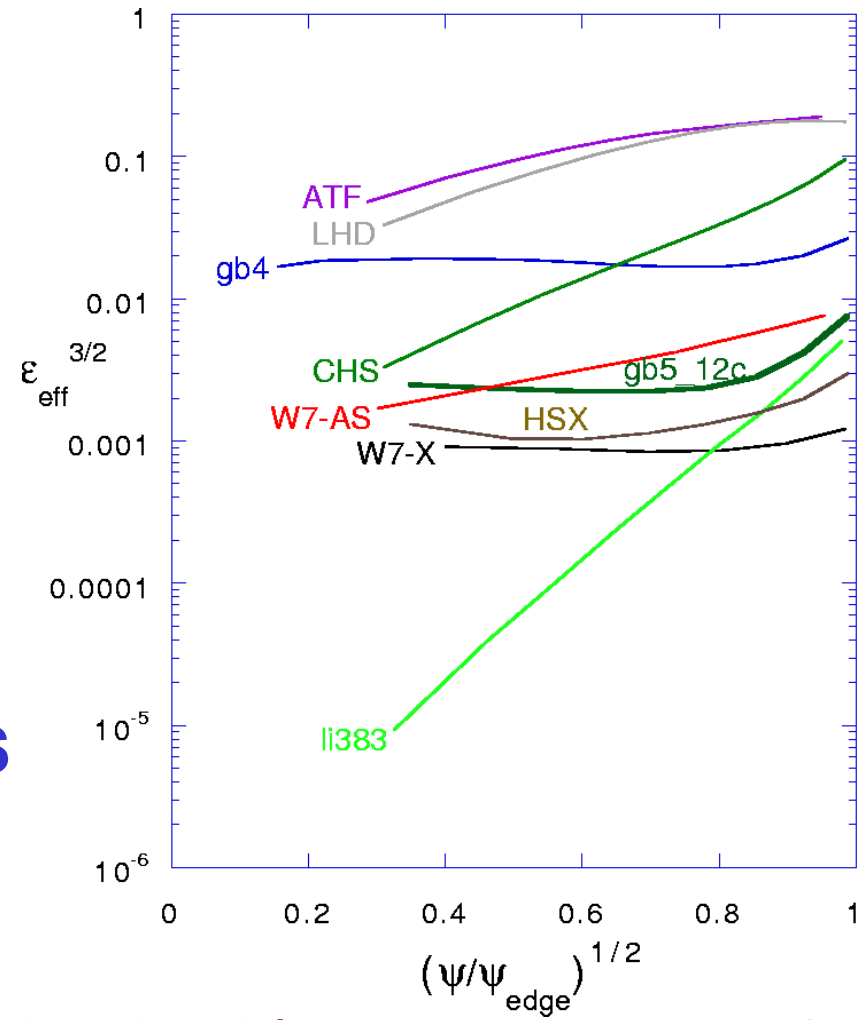
- **In all designs, QP-ness improves away from edge**
- **GB4 is actually a little more symmetric than GB5 (although transport worse)**
  - **Omnigeneity playing a role?**
- **Reactor QPS has highest QP-symmetry**

Diffusion in 1/ν Regime

(D. Spong)

- **Diffusivity $\chi \sim \varepsilon_{eff}^{3/2}$**
- **Calculated using NEO code (Kernbechler, Nemov) and confirmed with DKES**
- **GB5 within factor of 2 of HSX, comparable to NCSX (li383) at edge**
- **$\chi < 0.01$ required for QPS**

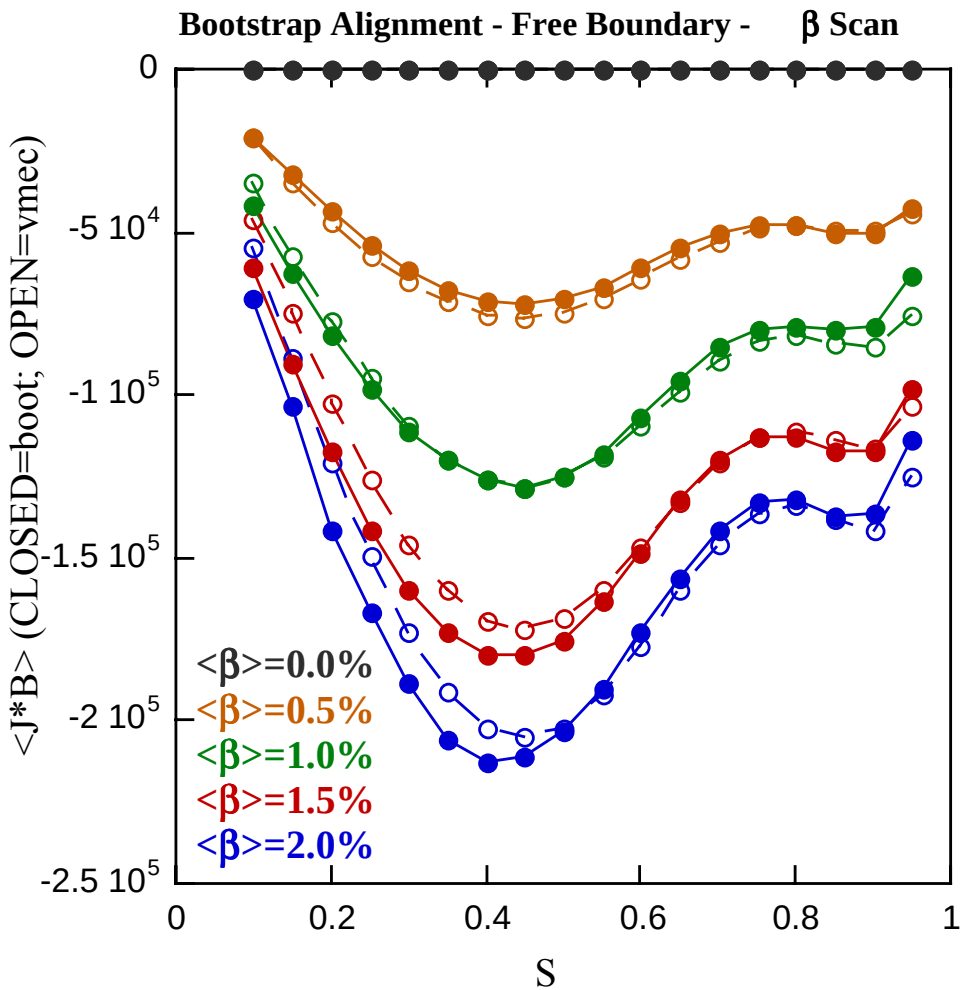
$\tau^{nc} > \tau^{ISS95}$



QPS Physics: Bootstrap Current
(A. Ware)

- **At finite β, internal parallel current**
  - **Low compared to axisymmetric plasma at same value of rotational transform**
  - **Configurational invariance**
    - **Large fraction of external transform**
    - **Possibility to avoid low order rational surfaces for range of β**
  - **Current-driven stability limits achieved in absence of conducting walls for β > 4%**
  - **Some "internal" transform eases design of coils**

Bootstrap Current Consistent With Equilibrium Current (Free Boundary GB4)

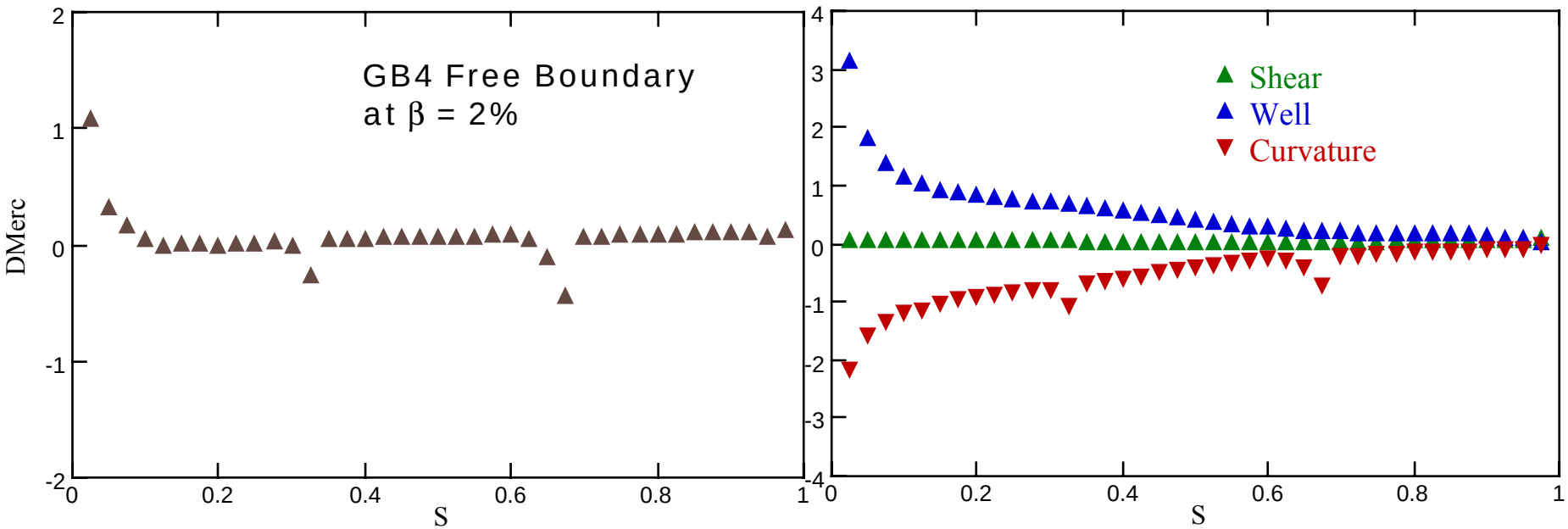


QPS Physics: Stability Properties

(A. Ware)

- **Ballooning stability limits β ~ 2-2.5%**
  - **Low field period N = 2 gives small field bending stabilization (consequence of low A)**
  - **High-β QPS "reactor vision" with β ~ 7-15% has been explored**
    - **2nd ballooning stability regime**
    - **Stable to kink and vertical modes**
    - **Bootstrap consistent with tokamak-like ιs**
- **Good Mercier, kink, vertical stability properties (well, low internal current)**

QPS Well Stabilizes Local Interchanges (A. Ware)



QPS Can Explore Exciting Physics At Low A

- **Neoclassical "1/ν" losses small enough to heat (electrons), tail ions to test QP optimization – D. Spong**
  - **Sufficient heating available with RF (electron β~3%) to test ballooning stability and bootstrap current theoretical predictions**
  - **Explore physics of ITB formation in QPS**
    - **Consequences of low poloidal viscosity**

QPS Physics Exploration (cont'd)

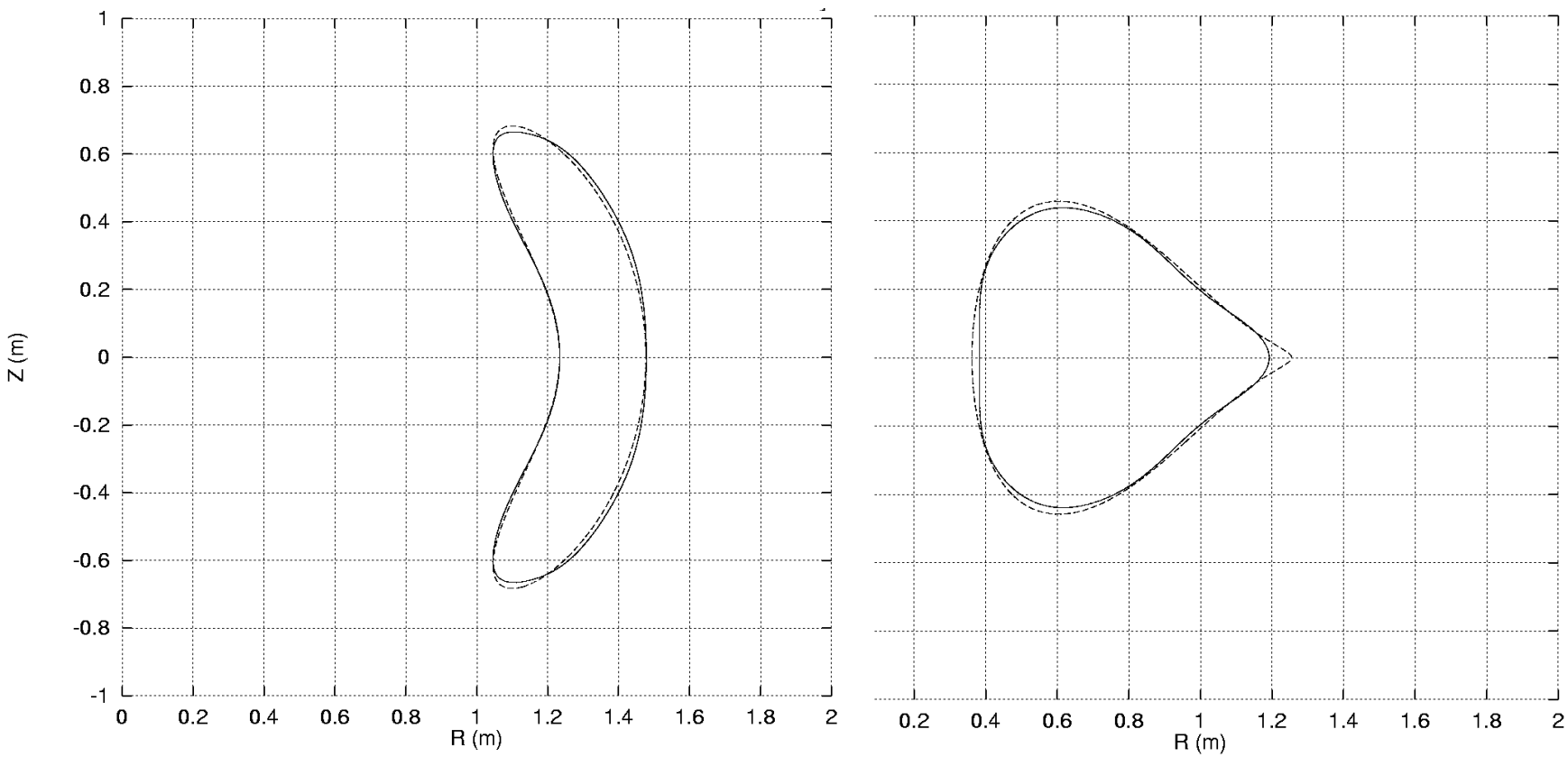
- **Magnetic Surface Quality at Low A (L. Berry)**
  - **Persistence of surfaces (and A) with β**
  - **Explore robustness and flexibility of configuration in regime of strong geometric (helical + toroidal) coupling**
- **Investigate ballooning β limits**
  - **Can high-n mode β limit be exceeded?**
    - **LHD suggests "YES!", but at much higher A**

Reconstruction of QPS Using Coils Determined by COILOPT Code

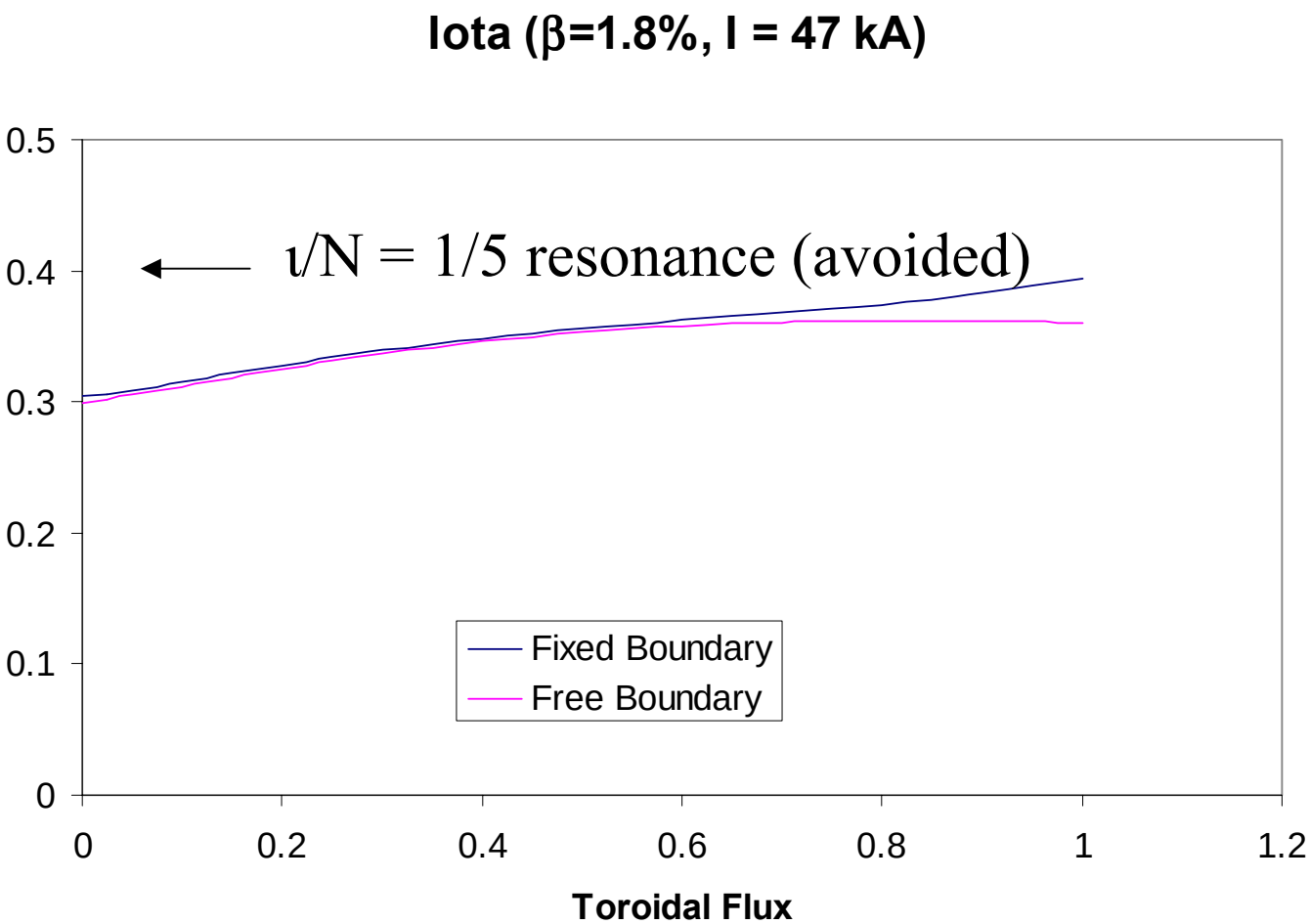
(L. Berry)

- **Boundary reconstruction errors are larger (compared to NCSX coil set)**
  - **$BNORMAL_{max}$ errors ~ 8-12% ($\langle B_{err} \rangle$ ~ 1.4%), which is 2-3 times NCSX errors**
- **Nevertheless, QPS coils are adequate to reproduce physics properties**
  - **In case of transport, original target is even improved (lower transport)!**

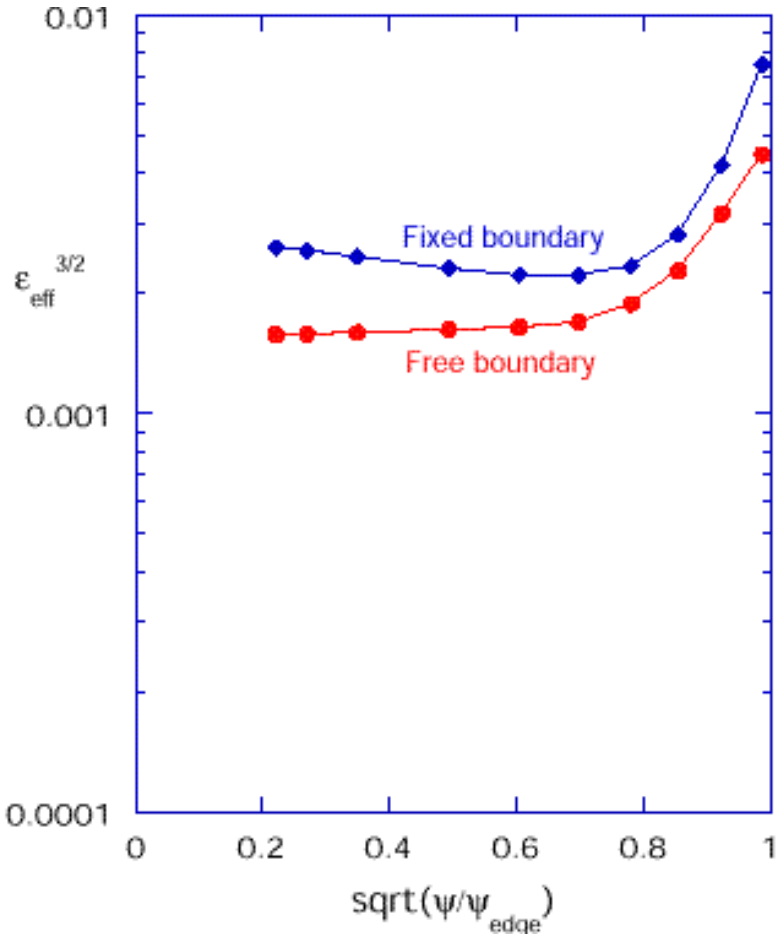
Plasma Boundary Reconstruction from GB5 Coils



GB5 Coils "Preserve" ι Profile



GB5 Coils Substantially *Improve* Transport



- **Internal *and* edge ripple reduced (~ 2x)**
- **"Free-boundary" behavior different than observed in NCSX design process**

Reference Coils Preserve Other Physics Properties

- **Status of Free-boundary Stability**
  - **GB4 stability has been verified**
  - **GB5 stability needs to be confirmed**
    - **Same ballooning β limit expected**

- **Paradox of Lower Transport in Free-Boundary GB5**
  - **Coils (free boundary), compared to original optimization, uses more modes**
    - **"accessibility" to lower χ^2 state**

Reconstruction Using PIES Code (Work in progress - D. Monticello and S. Hudson)

- **To assess importance of magnetic islands, PIES (Princeton Iterative Equilibrium Solver) code is being used**
- **Free-Boundary PIES Reconstructions are in progress for QPS Reference GB4**
  - **Convergence not complete**
  - **Error correction calculations unfinished**
- **Fixed-Boundary PIES results at β = 2% show good surfaces exist for QPS (GB4)**

Conclusions

- **A low aspect QPS reference configuration has been designed with:**
  - **A ~ 2.6**
  - **Approximate quasi-poloidal symmetry**
  - **Low collisionality transport nearly as good as in much higher A devices (HSX, W7-X)**
  - **Predicted ballooning β limits (~2-2.5%) comparable to best existing stellarators**
  - **Coils that have acceptable engineering and physics reconstruction properties**