The World Stellarator Program

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Stellarators and Tokamaks Have Similar Performance

- Plasma parameters are comparable for the same plasma volume, field, power

  T_e = 10 keV

  T_i = 4-13.5 keV

  τ_E = 0.3 s

  $\langle\beta\rangle$ = 4.5% in LHD

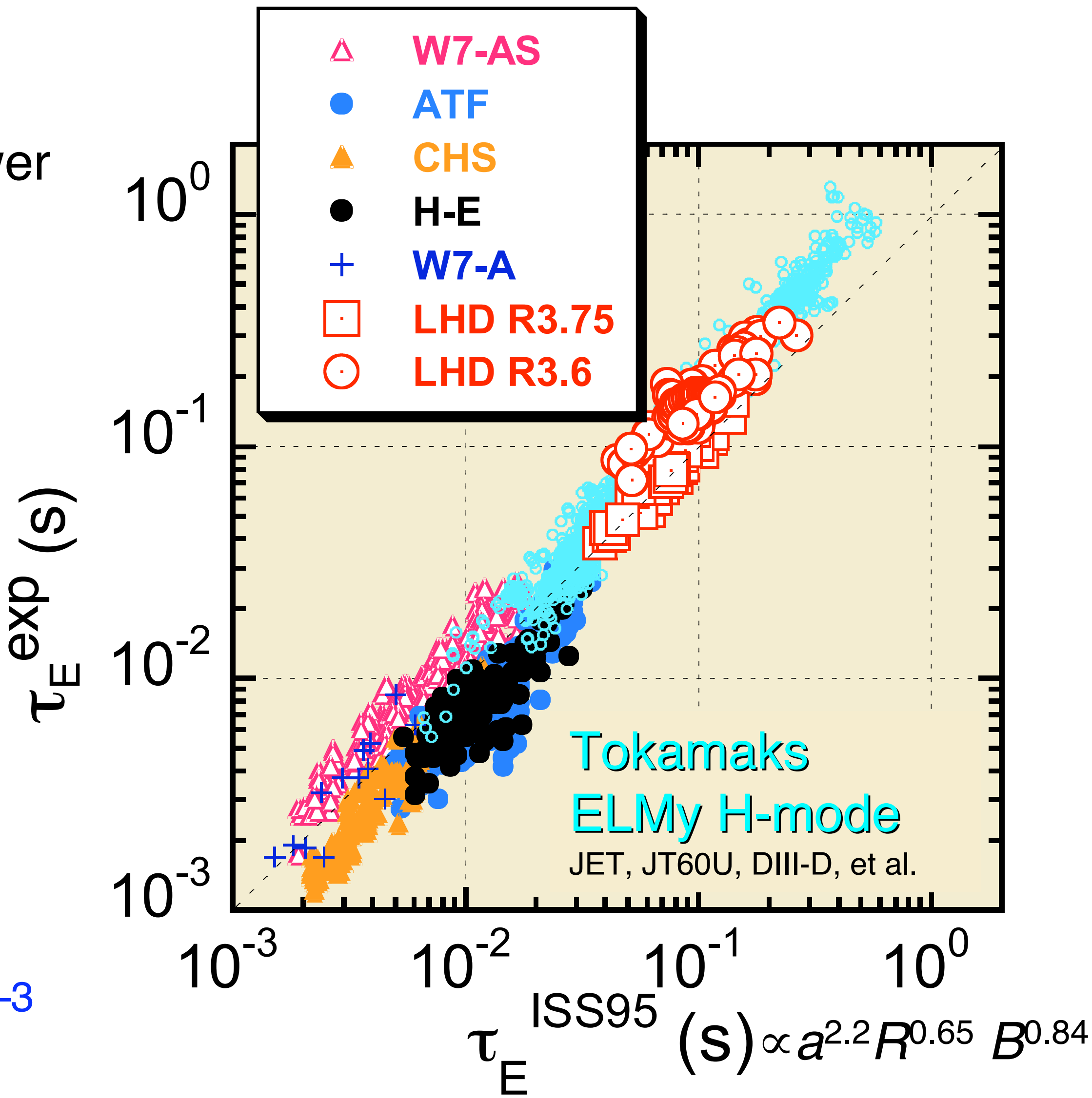
- A consistent parameter set for LHD

  $n = 4.5 \times 10^{20}\ m^{-3}$

  T = 0.85 keV

  P = 10 MW

  $nT\tau = 4.4 \times 10^{19}$ s-keV-m^{-3}



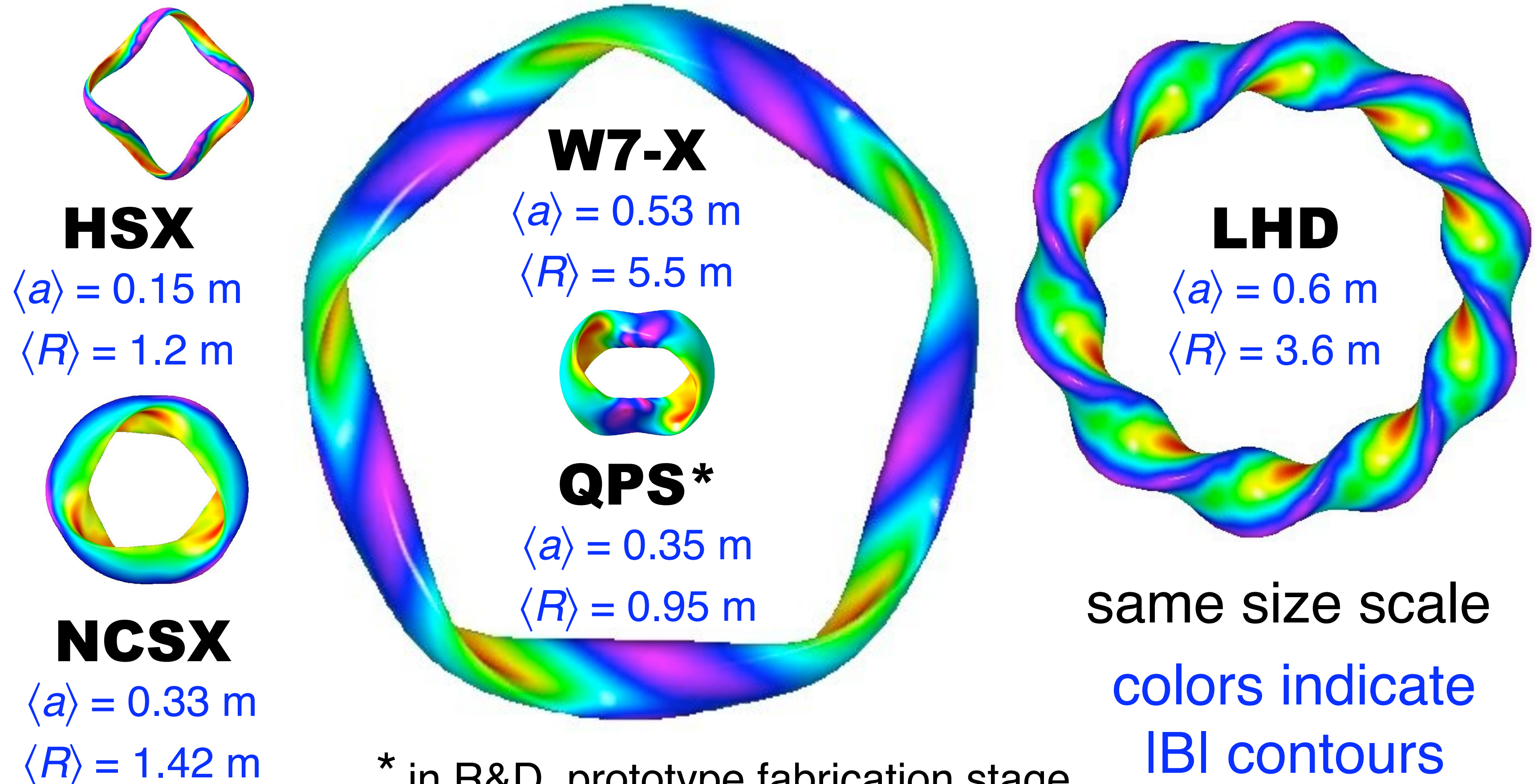
Stellarators Complement Tokamaks

- Both have poloidal + toroidal fields, but in stellarators
  - confining poloidal field produced by external coils
  - no/small plasma current avoids disruptions, VDEs
  - good flux surfaces, even in vacuum
  - globally reversed shear, NTMs stable
- 3-D nature allows changing magnetic configuration properties over a wide range to illuminate toroidal confinement physics
  - aspect ratio, shape of last closed flux surface
  - magnetic axis topology, $q(r)$ value and sign of the shear
  - degree and type of symmetry, flow damping

Stellarators Reduce Program Risk

- Inherently steady-state (no disruptions, no current drive constraints)
  - P = 490 kW for > 54 minutes ⇒ 1.6 GJ in LHD so far
  - near-term goal: P = 3 MW for 1 hour ⇒ 11 GJ
- Densities (4.5 x 10^{20} m^{-3}) many (5–10) times Greenwald limit with improved performance, lower impurity level, eases divertor constraints
  - density “limit” (stored energy decreases with increasing density) set by impurity radiation, not disruptions
- Beta (4.5%) set by available power and equilibrium surfaces, not by instabilities, even though ballooning modes were expected
  - stong self-stabilization for interchange modes (magnetic well, axis shift with beta)
  - kink stability (low current, can avoid major resonances)
  - second stability for ballooning modes (different character in stellarators)
- **BUT so far have large plasma aspect ratio ⇒ large devices**
  - compact stellarators solve this problem

New Quasi-Symmetric Stellarators NCSX and QPS Have Much Smaller Aspect Ratio

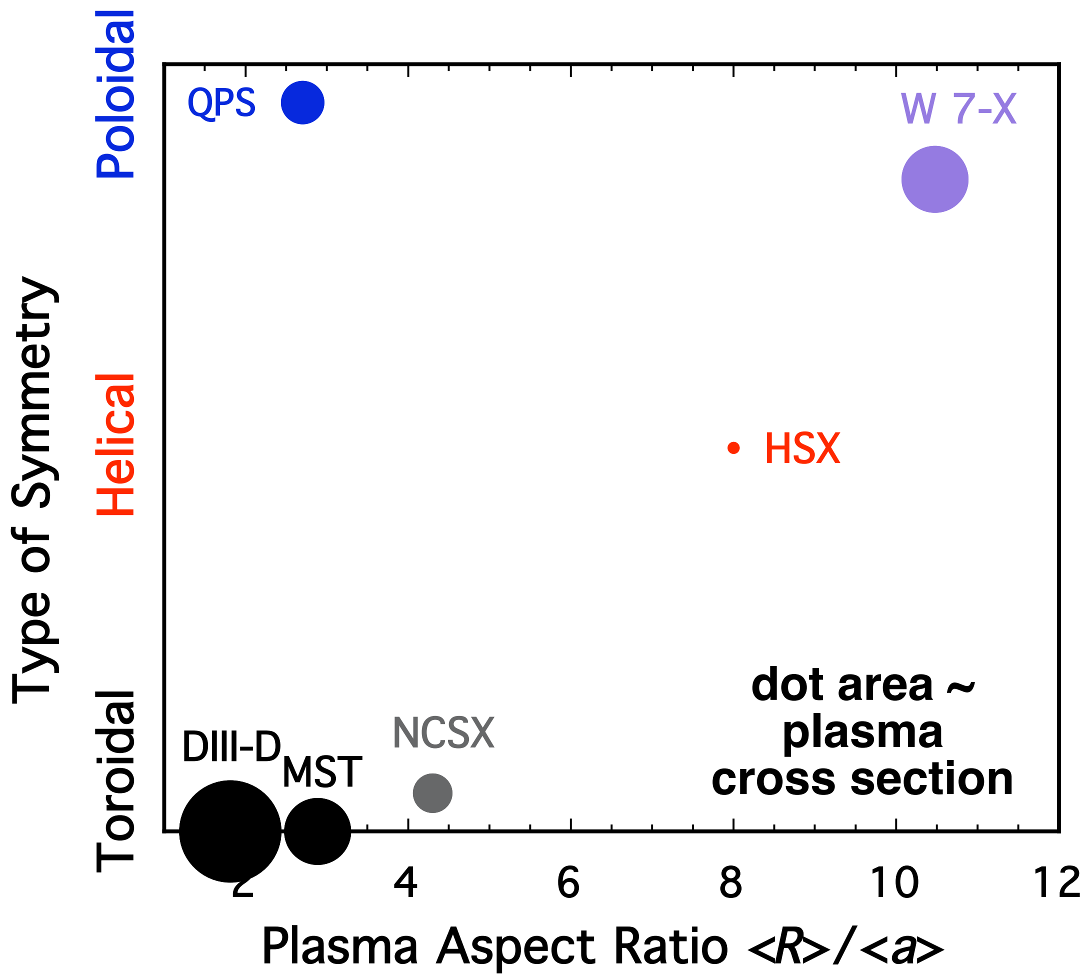


* in R&D, prototype fabrication stage

- |**B**| geometry determines plasma flow magnitude and direction and resulting transport and stability properties

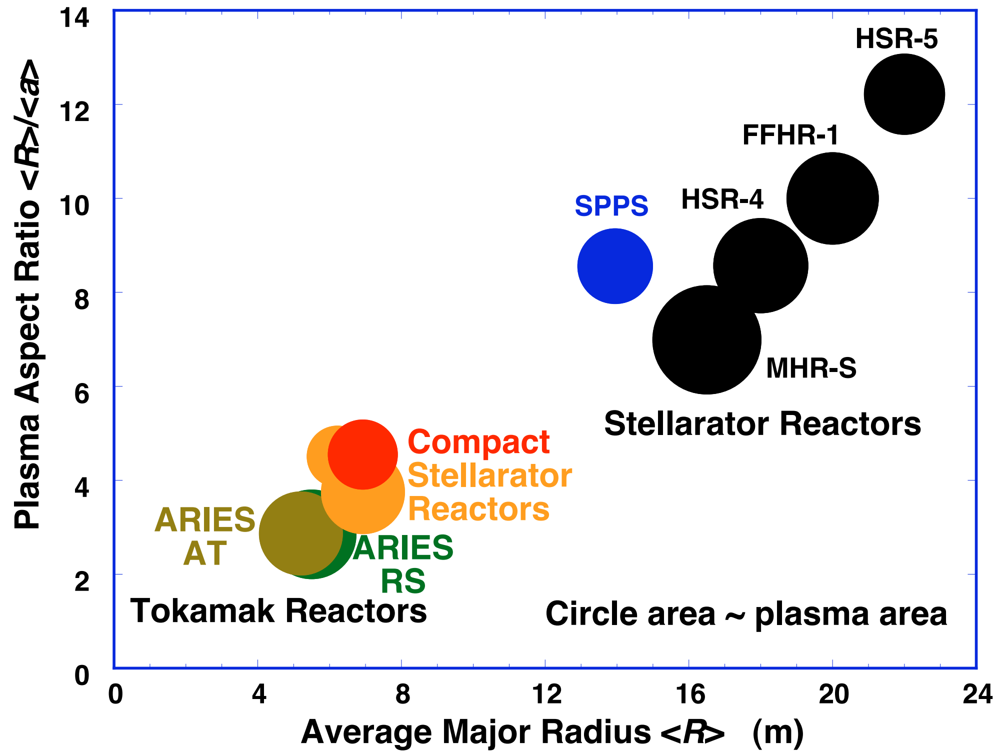
Magnetic Field Symmetry and Plasma Aspect Ratio Are Important

- Quasi-symmetry
  - small |B| variation in a symmetry direction
  - low flow damping in symmetry direction allows large flows (and shear) for breakup of turbulent eddies
- Low effective field ripple also reduces neoclassical transport
- Compactness means less cost for a given plasma performance and a more competitive reactor

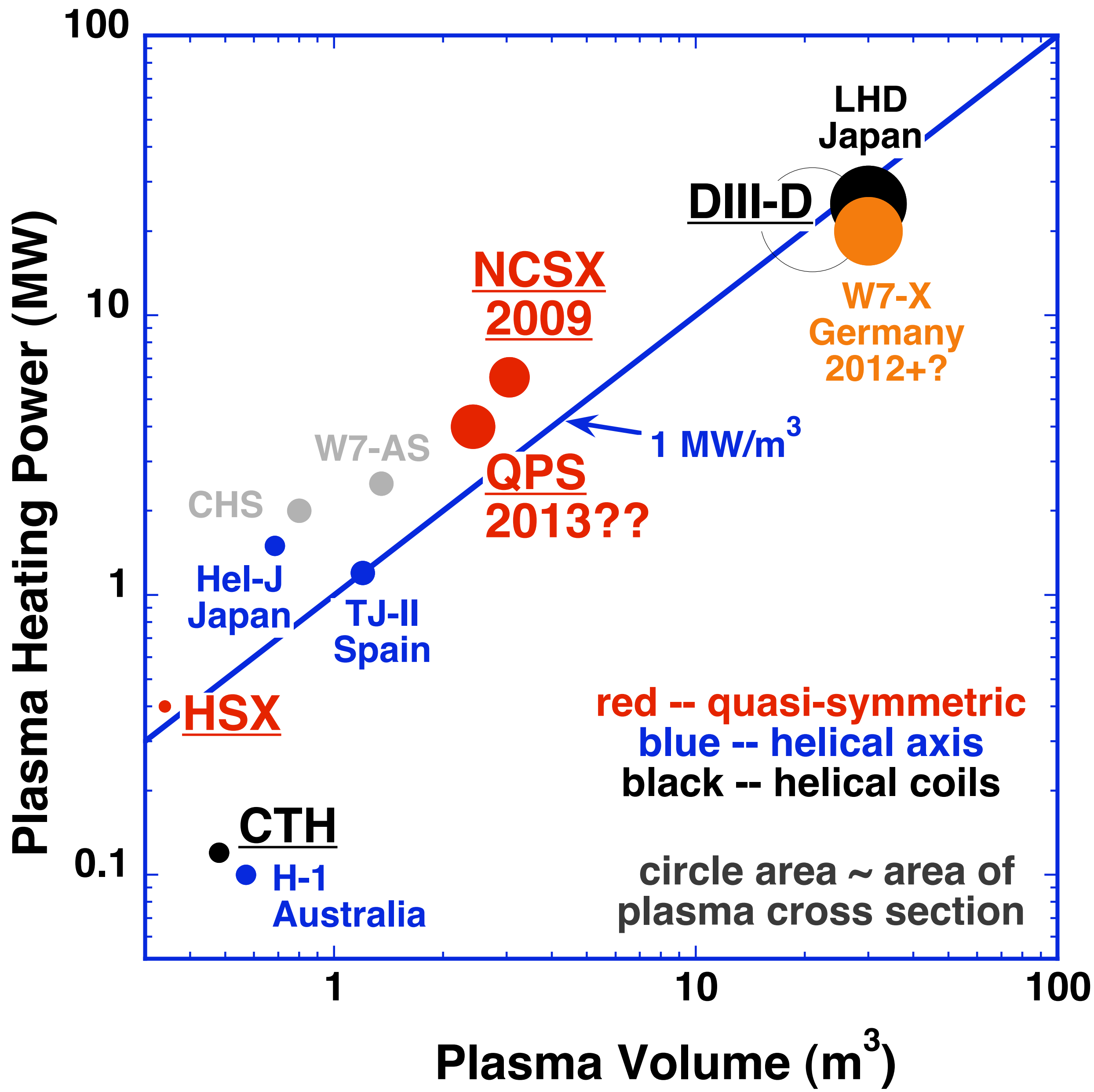


An Improved Stellarator Reactor Vision

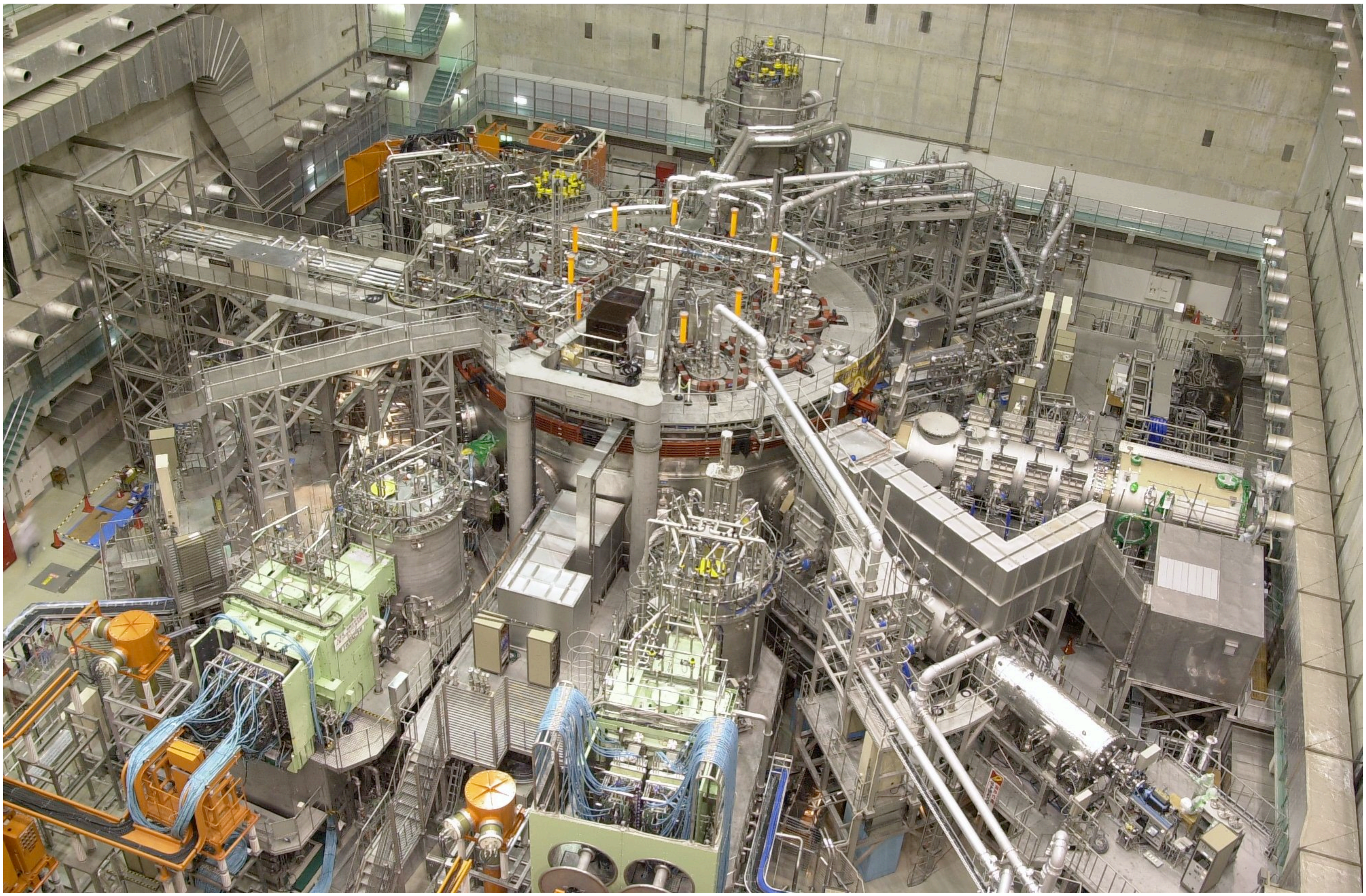
- Compact stellarators could combine the best features of
  - tokamaks (good confinement, moderate aspect ratio) and
  - stellarators (disruption immunity, very high densities, low/no plasma current, steady-state operation, no feedback systems)
- ARIES group is studying ARIES-CS as a reactor
- Study shows that stellarator reactors can be comparable to tokamaks in compactness
  - $\langle R_{axis} \rangle = 7.75$ m
  - $\langle B_{axis} \rangle = 5.7$ T



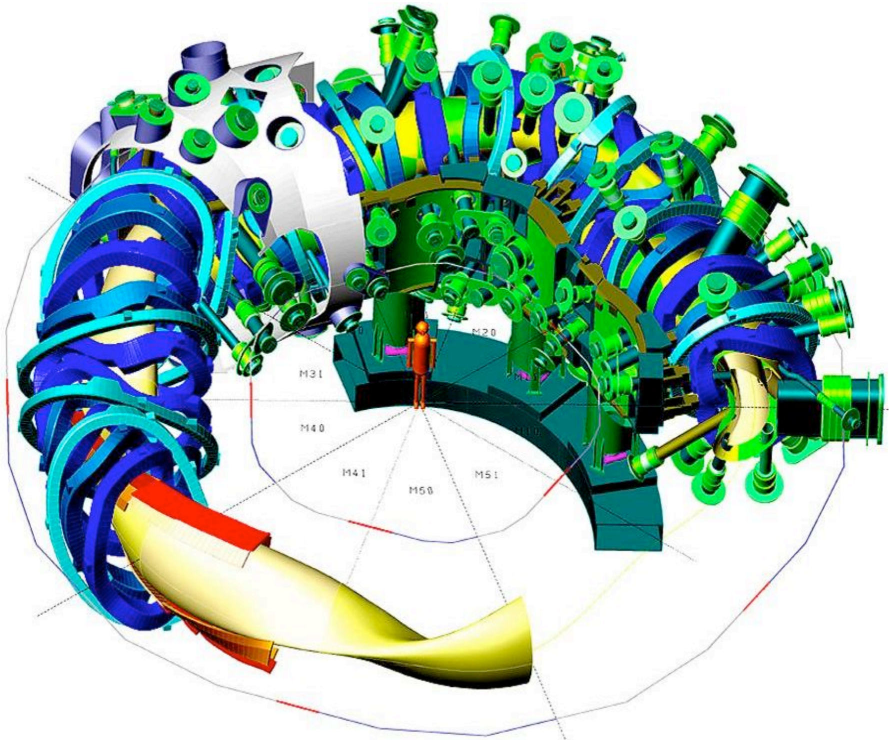
World Stellarators Vary Widely in Capability

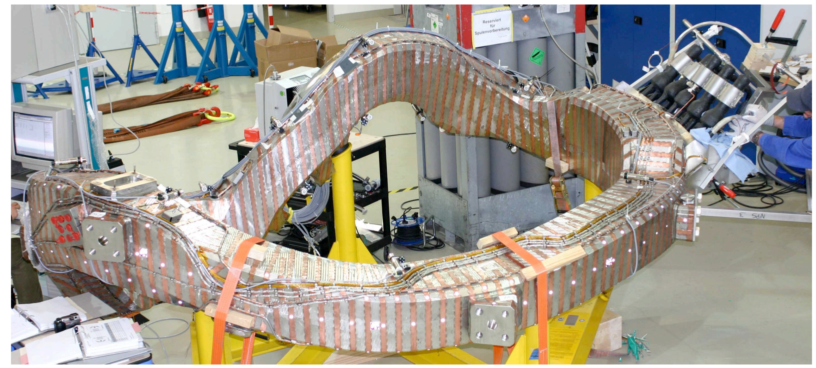


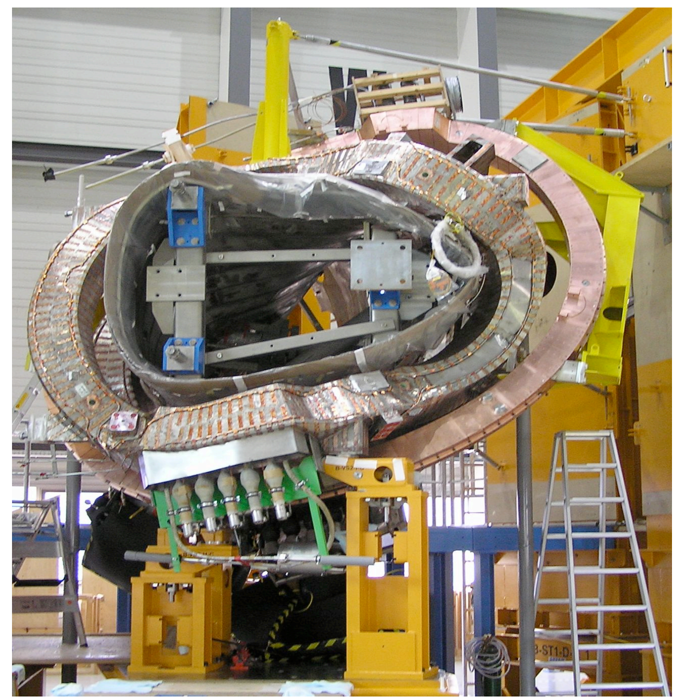
The Largest is LHD: Superconducting Coils, V_{pl} = 30 m^3
R_{axis} = 3.5-3.9 m, a_{pl} ~ 0.5-0.6 m, B = 3 T, $P_{heating}$ = 20-25 MW



W 7-X is under Construction: Supercond. Coils, V_{pl} = 30 m^3
R_{axis} = 5.5 m, a_{pl} = 0.53 m, B = 3 T, $P_{heating}$ = 15–30 MW





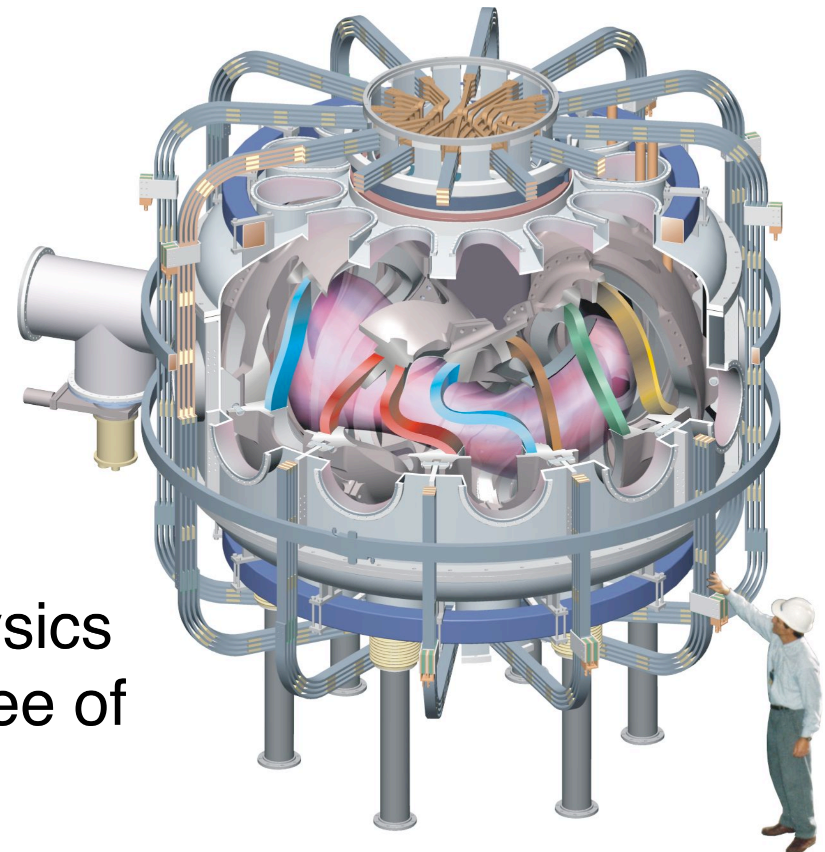


Operation 2012+ due to coil quality problems (defective HV insulation and interturn faults)

Speedup measures considered:
2nd coil test facility and 2nd assembly line

QPS Exploits Poloidal Symmetry

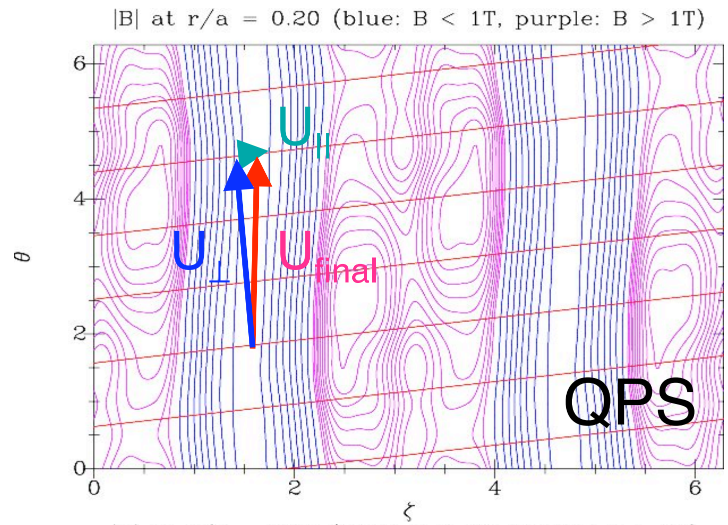
- Allows large poloidal flows that most effectively break up turbulent eddies that cause anomalous transport
- Also reduces neoclassical transport to a very low level
- Coil sets allow varying key physics features by factor 10–30; degree of
  - quasi-poloidal symmetry, poloidal flow damping, neoclassical transport
  - stellarator/tokamak shear
  - trapped particle fraction

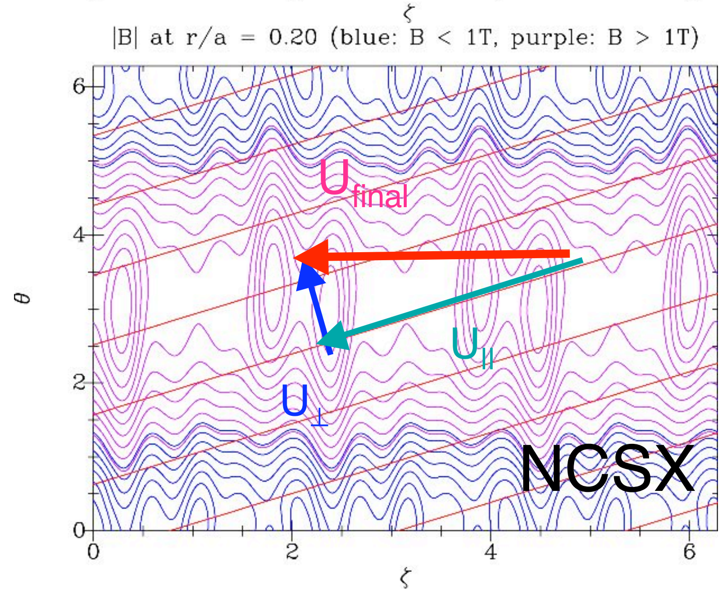


- $\langle R \rangle = 0.95$ m
- $\langle a \rangle = 0.3\text{-}0.4$ m
- $\langle R \rangle / \langle a \rangle > 2.3$
- $B = 1$ T, 1.5-s pulse
- $P = 3\text{-}5$ MW

NCSX and QPS Are Two *Different Types* of Magnetic Configurations

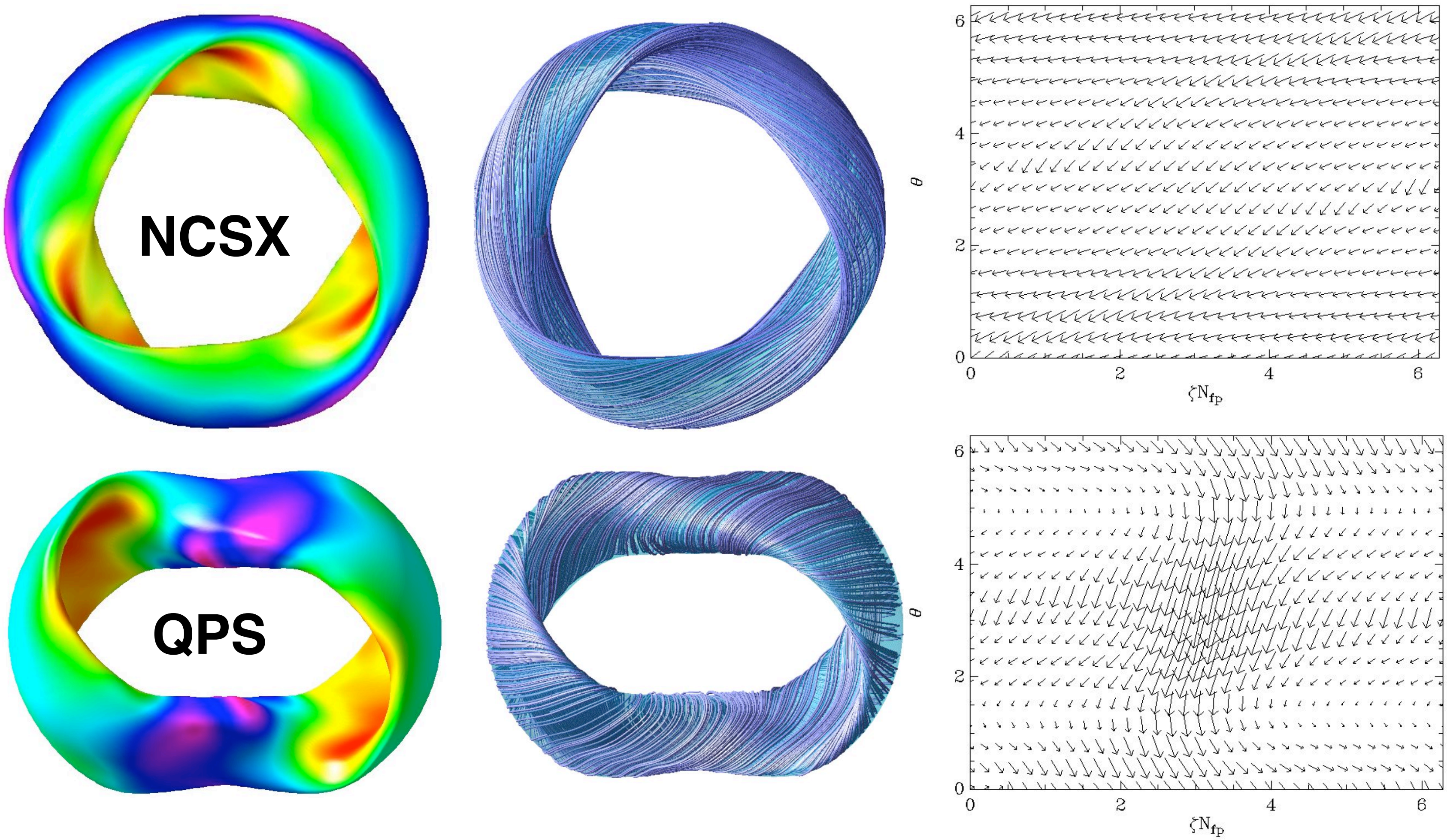
- QPS broadens magnetic configuration space explored by compact stellarators to more than a single symmetry
  - poloidal flows to suppress turbulence and flow shearing to improve stability
  - NCSX relies on toroidal flows
- Together they complete physics basis for demonstrating attractiveness of compact stellarators
  - will generate the physics and design basis and confidence to decide what form a larger, follow-on experiment would take
  - give credibility to the stellarator DEMO vision





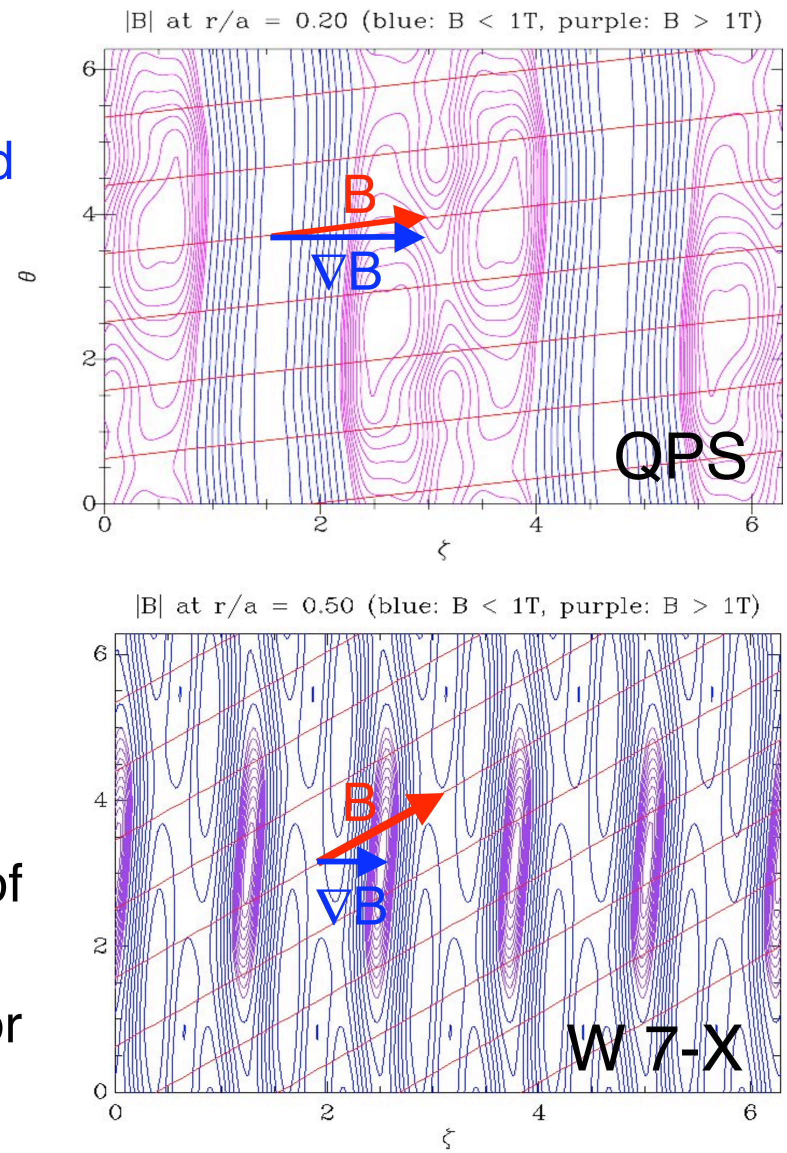
NCSX Relies on Toroidal Flows and QPS on Poloidal Flows to Improve Confinement

|**B**| contours | flow lines | flows on surface



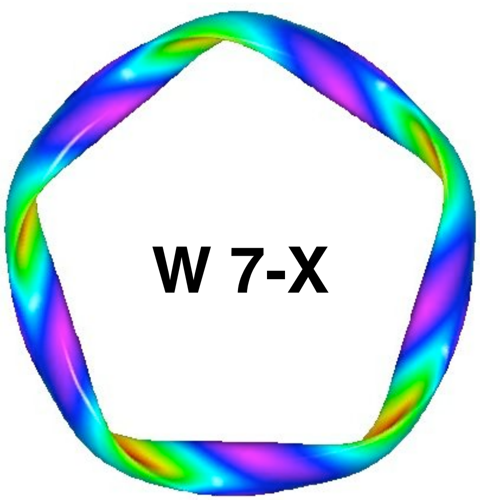
QPS & W 7-X Explore *Different* Approaches

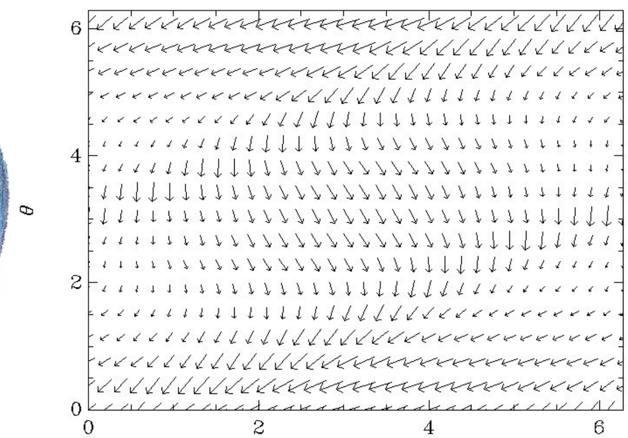
- *Different* transport minimization approaches to reduce **B** x ∇B drifts
  - QPS reduces angle between **B** and ∇B -- possible at low *R*/*a*
  - W 7-X reduces ∇B in a surface -- possible at high *R*/*a*
- Low bootstrap current and quasi-poloidal symmetry in QPS at very low aspect ratio
- W 7-X currentless at four times QPS's aspect ratio.
- The complementarity and synergism of the two experiments is needed for concept improvement similar to that for tokamaks and spherical tori.

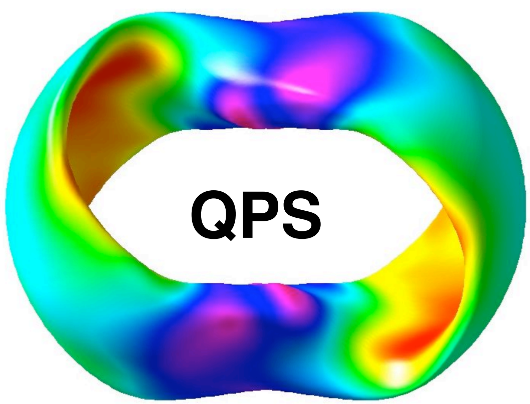


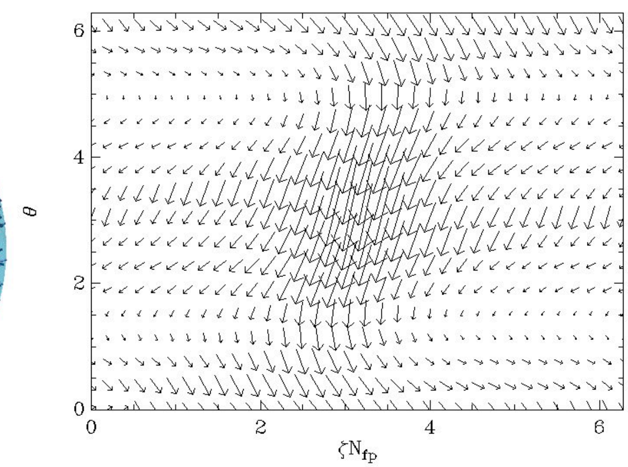
QPS Has Large, Sheared Poloidal Flows Compared to W 7-X

|**B**| contours | flow lines | flows on surface



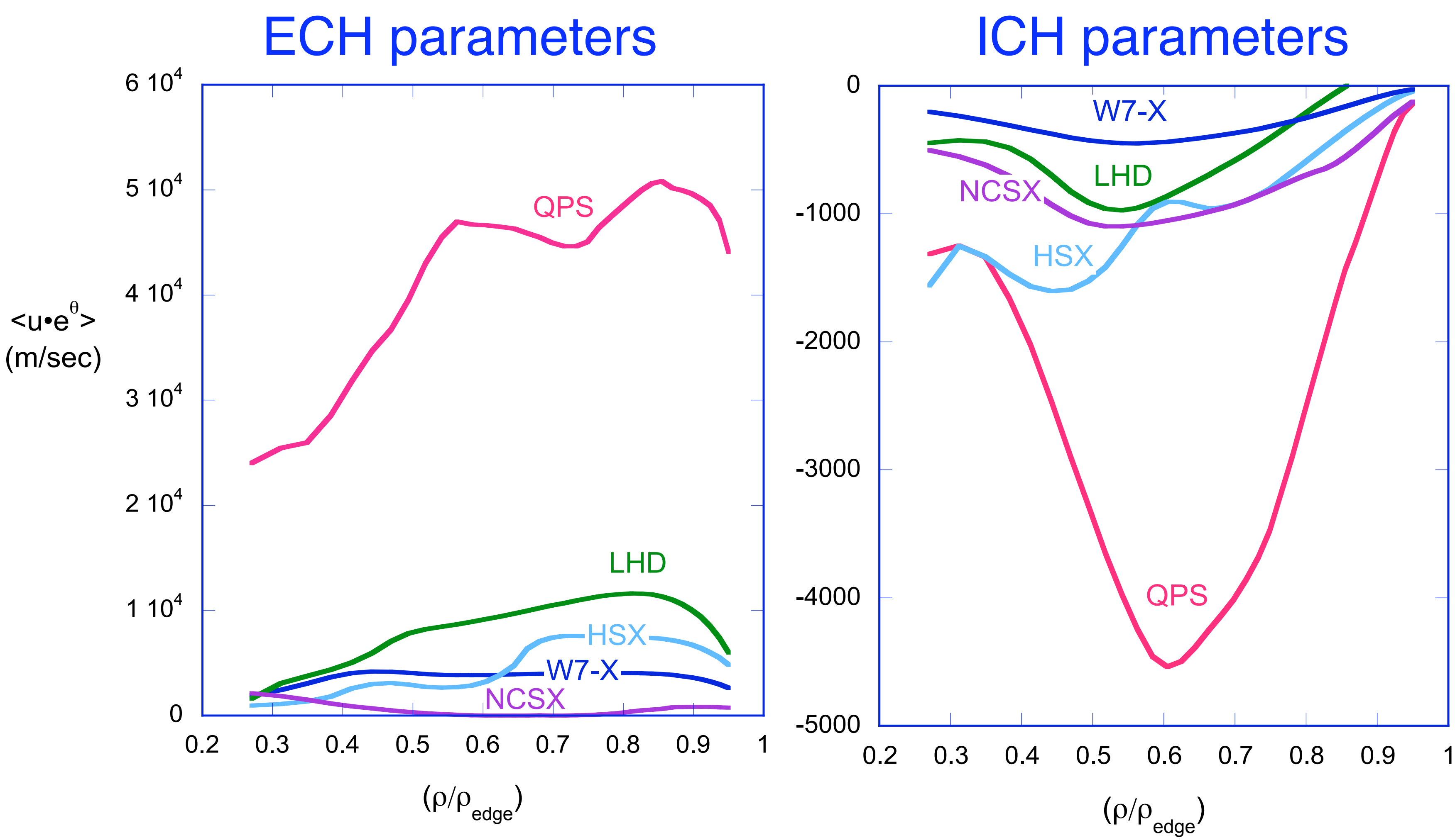






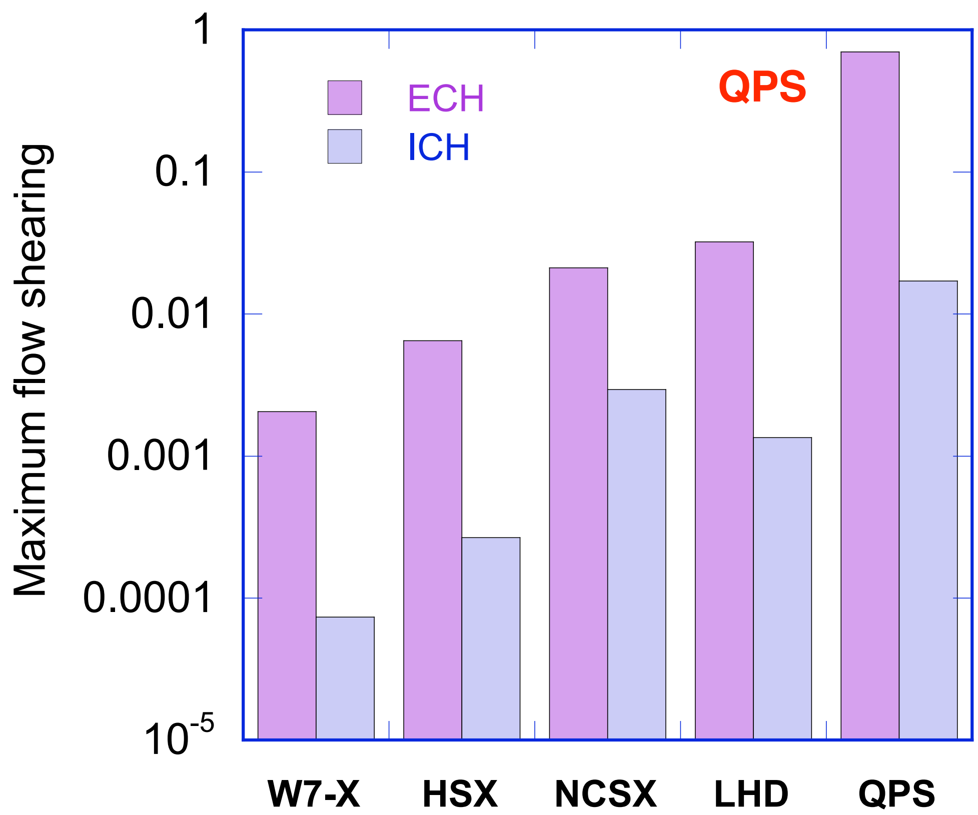
QPS Has Largest Poloidal Flows

- Important for breakup of turbulent eddies

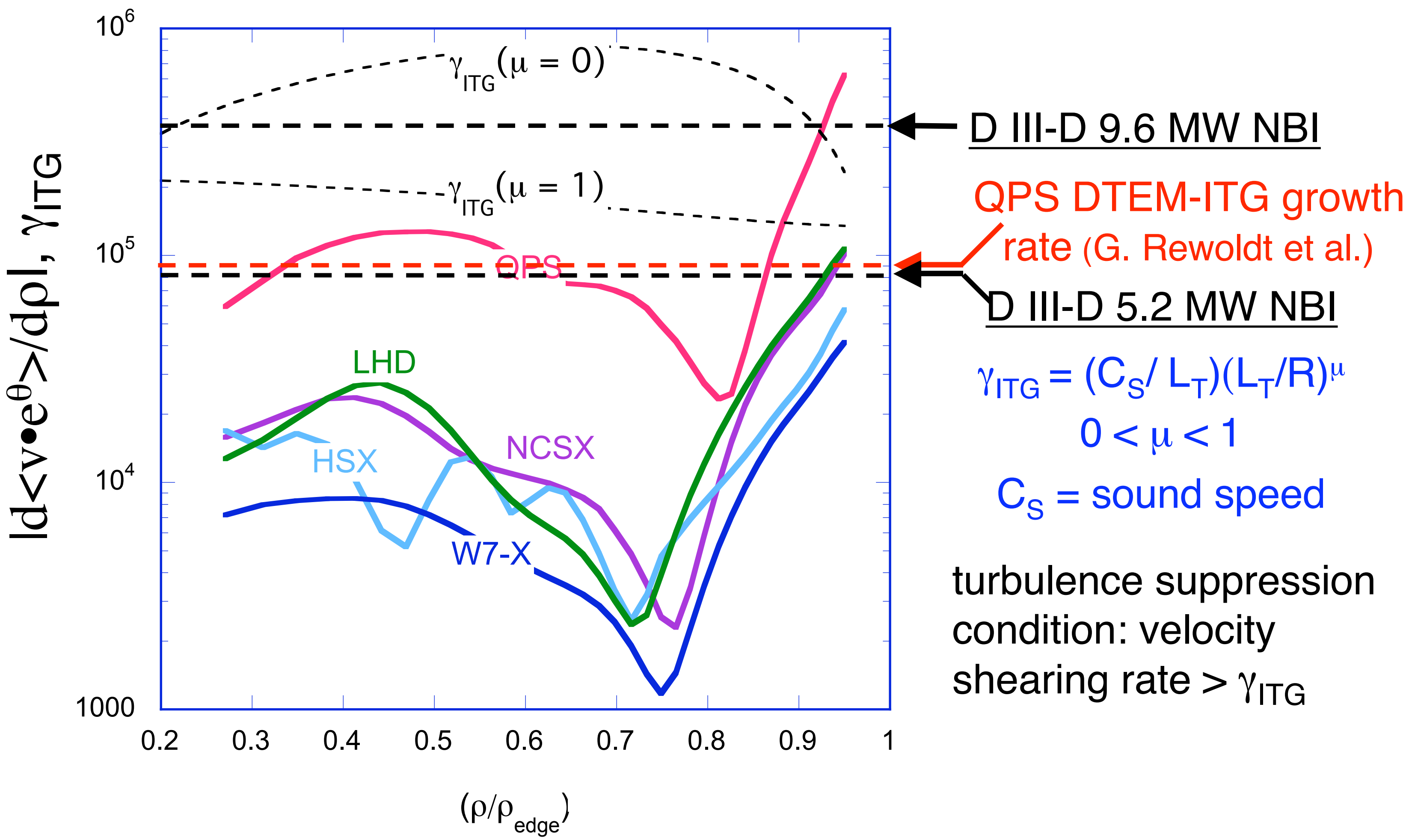


Flow Variation within Flux Surfaces Impacts MHD Ballooning/Interchange Thresholds

- Maximum parallel flow shearing rates in QPS are ~0.5 of Alfvén time
- Could influence MHD stability thresholds (ballooning, resistive tearing, etc.)



QPS Has Highest Velocity Shearing Rates, Comparable to ITG Growth Rates



$\gamma_{ITG} = (C_S/ L_T)(L_T/R)^{\mu}$

$0 < \mu < 1$

C_S = sound speed

turbulence suppression condition: velocity shearing rate > γ_{ITG}

SUMMARY

- Stellarators complement tokamaks and reduce programmatic risk
- World stellarators vary in capabilities (power, size) and magnetic configuration properties
- Newer concepts (NCSX, QPS) feature compactness and quasi-symmetry to further improve performance
- IBI geometry determines plasma flow direction, magnitude and shearing rate, hence resulting transport and stability properties
- QPS has the largest poloidal flow and flow shearing for suppression of instabilities
- ARIES-CS study shows stellarators can be comparable to tokamaks in compactness