The World Stellarator Program

J. F. Lyon, ORNL

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Stellarators and Tokamaks Have Similar Performance

- Plasma parameters are comparable for the same plasma volume, field, power
  
  \[ T_e = 10 \text{ keV} \]
  
  \[ T_i = 4-13.5 \text{ keV} \]
  
  \[ \tau_E = 0.3 \text{ s} \]
  
  \[ \langle \beta \rangle = 4.5\% \text{ in LHD} \]

- A consistent parameter set for LHD
  
  \[ n = 4.5 \times 10^{20} \text{ m}^{-3} \]
  
  \[ T = 0.85 \text{ keV} \]
  
  \[ P = 10 \text{ MW} \]
  
  \[ nT\tau = 4.4 \times 10^{19} \text{ s-keV-m}^{-3} \]
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)
  – $P = 490 \text{ kW}$ for $> 54 \text{ minutes} \Rightarrow 1.6 \text{ GJ}$ in LHD so far
  – near-term goal: $P = 3 \text{ MW}$ for 1 hour $\Rightarrow 11 \text{ GJ}$

• Densities ($4.5 \times 10^{20} \text{ m}^{-3}$) 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
  – strong 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 $\Rightarrow$ large devices
  – compact stellarators solve this problem
New Quasi-Symmetric Stellarators NCSX and QPS Have Much Smaller Aspect Ratio

- **HSX**
  - $\langle a \rangle = 0.15 \text{ m}$
  - $\langle R \rangle = 1.2 \text{ m}$

- **NCSX**
  - $\langle a \rangle = 0.33 \text{ m}$
  - $\langle R \rangle = 1.42 \text{ m}$

- **W7-X**
  - $\langle a \rangle = 0.53 \text{ m}$
  - $\langle R \rangle = 5.5 \text{ m}$

- **QPS***
  - $\langle a \rangle = 0.35 \text{ m}$
  - $\langle R \rangle = 0.95 \text{ m}$

- **LHD**
  - $\langle a \rangle = 0.6 \text{ m}$
  - $\langle R \rangle = 3.6 \text{ m}$

* in R&D, prototype fabrication stage

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

same size scale colors indicate $|B|$ contours

- in R&D, prototype fabrication stage
Magnetic Field Symmetry and Plasma Aspect Ratio Are Important

- **Quasi-symmetry**
  - small IBI 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
  – $\langle R_{\text{axis}} \rangle = 7.75 \text{ m}$
  – $\langle B_{\text{axis}} \rangle = 5.7 \text{ T}$
World Stellarators Vary Widely in Capability

Plasma Heating Power (MW) vs. Plasma Volume (m³)

- NCSX 2009
- LHD Japan
- DIII-D
- W7-X Germany 2012+
- CHS
- CTH
- HSX
- Hel-J Japan
- TJ-II Spain
- H-1 Australia
- Hel-J Japan
- QPS 2013??

Key:
- red -- quasi-symmetric
- blue -- helical axis
- black -- helical coils

Circle area ~ area of plasma cross section
The Largest is LHD: Superconducting Coils, $V_{pl} = 30 \, m^3$

$R_{axis} = 3.5-3.9 \, m$, $a_{pl} \sim 0.5-0.6 \, m$, $B = 3 \, T$, $P_{heating} = 20-25 \, MW$
W 7-X is under Construction: Supercond. Coils, $V_{pl} = 30 \text{ m}^3$, $R_{\text{axis}} = 5.5 \text{ m}$, $a_{pl} = 0.53 \text{ m}$, $B = 3 \text{ T}$, $P_{\text{heating}} = 15–30 \text{ MW}$

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

- $\langle R \rangle = 0.95 \text{ m}$
- $\langle a \rangle = 0.3-0.4 \text{ m}$
- $\langle R \rangle/\langle a \rangle > 2.3$
- $B = 1 \text{ T, 1.5-s pulse}$
- $P = 3-5 \text{ MW}$
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
QPS & W 7-X Explore *Different* Approaches

- *Different* transport minimization approaches to reduce $\mathbf{B} \times \nabla \mathbf{B}$ drifts
  - QPS reduces angle between $\mathbf{B}$ and $\nabla \mathbf{B}$ -- possible at low $R/a$
  - W 7-X reduces $\nabla \mathbf{B}$ 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
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 \( \sim 0.5 \) of Alfvén time
- Could influence MHD stability thresholds (ballooning, resistive tearing, etc.)
QPS Has Highest Velocity Shearing Rates, Comparable to ITG Growth Rates

\[ \gamma_{\text{ITG}}(\mu = 0) \]
\[ \gamma_{\text{ITG}}(\mu = 1) \]

\[ \gamma_{\text{ITG}} = \left( \frac{C_S}{L_T} \right) (L_T/R)^\mu \]
\[ 0 < \mu < 1 \]
\[ C_S = \text{sound speed} \]

\[ \frac{d}{d \rho} \frac{\langle v\cdot e \rangle}{\rho} \]

D III-D 9.6 MW NBI
D III-D 5.2 MW NBI

QPS DTEM-ITG growth rate (G. Rewoldt et al.)

turbulence suppression condition: velocity shearing rate > $\gamma_{\text{ITG}}$
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

• $|B|$ 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