US Strategies for an Innovative Stellarator-Based FNSF

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For the US Stellarator Steering Committee

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Context

**FNSF:** fully integrated fusion plasma and technological environment
- Long-pulse, high duty factor
- Integration testing and validation; tritium breeding

**Stellarators:** helical magnetic field torus, like tokamaks
- full field from 3D coils, 3D plasma shaping
Stellarators Already Provide Advanced Characteristics

**Steady-state:** field from 3D coils, not plasma current

- No disruptions.
- No current drive $\Rightarrow$ potential high fusion gain, higher reliability
- Quiescent high-beta $\geq$ 5%,
- Energy confinement similar to tokamaks.
- Very high density limit $\Rightarrow$ potential higher fusion reactivity
  - colder edge, for easier divertor
  - reduced fast-ion instability drive

- No need for feedback stabilization $\Rightarrow$ simplify plasma control,
  - reduce diagnostics needed in fusion environment

Closes some technical gaps, reduces some R&D needs.
Simplifies FNSF and DEMO designs.
Need to demonstrate these capabilities can be simultaneous
Stellarator Research is Active World-wide

Large international programs:
• LHD, R=3.7m superconducting, partially optimized (Japan, 1998)
• W-7X, R=5.5m superconducting, quasi-omnigenous (Germany, 2015)

US:
• Historically, strong theory program.
  – Methods to optimize confinement in 3D
  – quasi-symmetry (QS): tokamak-like transport
• Pioneering novel Concept Exploration experiments, e.g.
  – HSX, quasi-helically symmetric
  – CTH, disruption onset thresholds
• NCSX project: partially built mid-scale experiment
  – study sustainable high performance, quasi-axisymmetric
  – synergy: tokamak-like transport and stellarator stability.
**QS Stellarator FNSF has Moderate Size**

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<thead>
<tr>
<th></th>
<th>R (m)</th>
<th>( &lt;a&gt; ) (m)</th>
<th>B (T)</th>
<th>( \beta ) (%)</th>
<th>Pfus (MW)</th>
<th>Neut. Wall load. (MW/m²)</th>
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<tbody>
<tr>
<td><strong>W7-X-like</strong></td>
<td>18</td>
<td>2.1</td>
<td>4.5</td>
<td>3.6</td>
<td>1500</td>
<td>0.9</td>
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<tr>
<td>H.Wobig et al, NF 43 (2003) 889</td>
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<tr>
<td><strong>ARIES-CS-like</strong></td>
<td>4.75</td>
<td>1.05</td>
<td>5.6</td>
<td>6</td>
<td>529</td>
<td>2</td>
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<tr>
<td>J.Menard et al, NF 51 (2011) 103014</td>
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<tr>
<td><strong>LHD-like</strong></td>
<td>14.4</td>
<td>2.5</td>
<td>4.7</td>
<td>5</td>
<td>3000</td>
<td>1.5</td>
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<tr>
<td>A. Sugara et al, FED 87 (2012) 594</td>
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All target FNSF neutron flux. All are ignited or very close to ignition.

Similar to power plant designs -> prototype reactor integration issues directly

All are high gain. Would produce net power: can be pilot plants.
Lack of Current Drive Has Practical Benefits

- Minimizes wall penetrations & blocking of breeding blankets

- Relieves engineering constraints. Provides design margin on performance. Makes design easier.

- Simplifies sub-systems and control

- Strongly reduces recirculating power. Allows net power production at lower fusion power.

For stellarator DT experiments:
Component Test Facility = High $Q_{DT}$ = Pilot-plant
Stellarator R&D Gaps to FNSF

- Integrated high performance of QS-optimized stellarators
  - Simultaneous high beta, high confinement, without disruptions. Benign ELMs.
  - Requires experimental validation

- Simplified coil design, via new coil strategies or simpler shape

- Predictive capability for plasma behavior and operation
  - Operating limits
  - Validation of theoretical models; including relationship to tokamak physics understanding.

- Effective divertor design, compatible with high performance

- Impurity and fusion ash accumulation control
US Stellarator Initiative is Needed (1)

1. Strong international collaboration with W7X, LHD (G. Wurden)
   — W-7X will be the first large, fully-optimized 3D experiment
   — Long-pulse, high-power, high-beta capabilities. Divertor program.
   — But, not quasi-symmetric – hard to connect with ITER.
   — Project to very large FNSF or DEMO.

2. US mid-scale QS experiment (J. Harris)
   — Integrated high performance for QS; divertor; impurity accumulation; predictive understanding
   — QUASAR using NCSX components (~4 years)
     Theory-based design for this mission
   — Managed as National & International collaboration.
US Stellarator Initiative is Needed (2)

3. Targetted exploration experiments (O. Schmitz)
   - Divertor design development
   - Simpler coils
   - Tests of turbulence optimization

4. Strengthened theory & computation program (M. Landreman)
   - Predictive understanding and modeling
   - Configuration optimization & improvement
   - Simpler coil design
   - Design of next-step experiments
• Major reviews of Initiative in
  
  ~2015 (start)
  
  ~2024 (progress)
  
  ~2029 (readiness for next steps, decision on approaches)
Summary

• Stellarators can be a game-changer. Provide many of the needed characteristics for a FNSF and an advanced DEMO.
  – No disruptions. No current drive. High beta.
  – Stellarator FNSF is high gain, can be a pilot-plant.

• US opportunity to lead QS-optimization strategy
  – close connection to tokamak understanding; ITER results
  – can result in similar system scale as tokamaks.

• Need US Initiative to close remaining gaps
  – Strong collaboration with large international facilities
  – Mid-scale QS experiment: integrated performance
  – Concept exploration experiments on specific topics
  – Strong theory and modeling program.