Compact Stellarator Development Plan

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FESAC Development Path Workshop
General Atomics
San Diego, CA
January 14, 2002
Outline

• Compact Stellarator (CS) Benefits to MFE Development.

• Current Status of Stellarator Development

• Plan for CS Development Through Proof of Principle (PoP) and Performance Extension (PE) to DEMO
  – Key Milestones, Decisions, and Criteria
  – Cost and Schedule

• Replies to panel questions

• Summary and Recommendation
Compact Stellarators Can Improve The Timetable for Magnetic Fusion Energy

Stellarators solve major problems for MFE:
• Steady state operation with minimal recirculating power.
• Eliminating disruptions.
• Understanding 3D physics.

Compact stellarators (CS) improve on previous stellarator designs:
• Lower aspect ratio ($\leq 4.4$ instead of $> 10$), higher power density.
• Strong physics connection to tokamaks via magnetic quasi-symmetry.
  – CS benefit from tokamak advances in performance and understanding.

CS development strategy to support 35-year Fusion plan at minimum cost:
• Make maximum use of MFE advances in tokamaks and foreign PE stellarators.
• Focus U.S. compact stellarator experiments on 3D physics issues.

Can lead to a U.S. Compact Stellarator DEMO operating in 35 years.
Stellarator Benefits Stem From 3D Geometry

Can obtain up to 100% of the rotational transform from external coils.

- Steady state with no power recirculation for current drive or rotation drive; reduced disruption risk; simpler control.

Can obtain better properties using the extra design freedom afforded by 3D shaping.

Compact stellarators:

- Passive stability at low aspect aspect ratio ($\leq 4.4$) and high beta ($\geq 4\%$).
- Magnetic quasi-symmetry $\Rightarrow$ tokamak-like confinement.
- Reversed shear: no neoclassical tearing modes, reduced turbulence.

Cost: more complex coil and structure geometry.

- PoP research: test physics, quantify benefits vs costs to assess attractiveness.
Stellarators Have Made Impressive Progress

Large Helical Device
(PE w/ S/C magnets - Japan)

\[ \beta > 3\% \]
\[ T_e \approx 10 \text{ keV}, \ T_i \approx 5 \text{ keV}. \]
enhanced confinement.
2-minute pulses.

Wendelstein 7-AS
(PoP- Germany)

\[ \beta > 3\% \]

enhanced confinement.
density control & enhanced performance w/island divertor.

Helically Symmetric Experiment
(CE- U. Wisc.)

- Successful test of quasi-symmetry.
New Stellarators Are Coming

Germany’s Wendelstein 7-X (superconducting PE) is under construction, building components in industry.

- Project delays have occurred due to supplier problems not specific to stellarators. Operation projected to start in ~2010.

U.S. Compact Stellarator design efforts (NCSX and QPS) have led to successful reviews and positive project decisions.

- NCSX and QPS Mission Need (CD-0) approved by DOE in 2001.
- NCSX Acquisition Plan and FY-03 Project Start (CD-1) approved in 2002.

⇒ The U.S. leads in Compact Stellarators.

PoP program accelerated by 1 year relative to current DOE plan.
Compact Stellarator Proof-of-Principle (PoP) Program: CS Attractiveness

FESAC-1999 10-year goal:

“Determine the attractiveness of a compact stellarator by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3D divertor operation.”

U.S. Program Elements

- **NCSX PoP Experiment**
  - Beta limits
  - quasi-axisymmetry
  - transport reduction
  - NTM stabilization
  - Alfvén mode stability
  - divertor-core compatibility
  - disruptions.

Conditions for high-beta, disruption-free operation with no feedback stabilization, current drive, rotation drive, or profile control.

NCSX (PPPL-ORNL)
Compact Stellarator Proof-of-Principle Program

U.S. Program Elements (cont’d.)

- **Stellarator CE Experiments (QPS, HSX, CTH)**
  - Quasi-poloidal symmetry, quasi-helical symmetry, MHD effects with current.
  - Stellarator physics at very low aspect ratio (QPS).

- **Stellarator Physics via Theory and International Collaboration.**
  - Validated physics models, benchmarked tools for physics analysis and design.

- **CS Reactor Design Studies (ARIES)**
  - Reactor optimization, design for adequate alpha confinement, issue identification.

- **2000**
  - International Stellarator PEs
  - Stellarator Physics
  - HSX & CTH CE Exp’ts.
  - QPS CE Exp’t.
  - NCSX PoP Exp’t.
  - Key PoP Milestone
  - Compact Stellarator PE Exp’t.
  - CS Reactor Design Studies
  - Compact Stellarator DEMO

- **2005**
  - Large Helical Device (LHD) - Japan
  - Wendelstein 7-X (W7-X) - Germany

- **2010**
  - Theory, International Collaboration
  - Operate

- **2015**
  - Operate
  - Assess CS attractiveness (FESAC-99 10-Year Goal)
  - CS-PE Mission Need (CD-0)
  - CS-PE Project Start (CD-1)

- **2020**
  - Construct
  - NCSX Transport OK?
  - NCSX Beta OK?
  - CS-PE Design
  - Update

- **2024**
  - Operate
  - Update

**Legend**:
- U.S. - funded Compact Stellarator Projects
- U.S. - funded, but included in Other Program Elements
- Non- U.S. - funded. Shown for Information

**Performance Extension (PE) Program**

Assess CS DEMO relevance

Dsn.
Compact Stellarator Performance Extension (PE)
Program: CS Relevance to DEMO

Key Program Goal

Determine the relevance of compact stellarators to a U.S. DEMO by assessing the benefits, costs, risks, and commercial attractiveness of an optimized compact stellarator design.

- Demonstrate attractive CS characteristics (no disruptions, no current drive) and adequacy of alpha confinement, energy confinement scaling at PE scale.

U.S. Program Elements

- **Stellarator Physics, CS Reactor Design Studies.**
- **CS-PE Experiment (Start Ops in 2017)**
  - Test a CS having reactor-like configuration and plasma parameters.
  - Demonstrate alpha confinement adequacy.
  - Only do what isn’t done elsewhere. (minimize cost)
- **Strong linkages with tokamaks (e.g. ITER) and non-U.S. stellarator PE’s**
  - Acquire key physics and technology information for compact stellarators.
The World’s PE Stellarators and a Tokamak B.P. Experiment Will Provide the Basis for a CS DEMO.

**U.S. CS-PE Provides:**
- Size scaling of 3D, quasi-axisymmetric plasmas.
- 3D physics at reactor-like collisionality, including limited DT.
- Alpha particle confinement, helical Alfvén modes.
- Moderate-pulse plasma control (CS startup).
- Moderate-pulse power/particle handling, while maintaining CS stability advantages.

**Other Large MFE Facilities Provide:**
- Steady-state divertor physics and technology at ≥PE scale. (LHD, W7-X, ITER)
- Superconducting stellarator magnets. (LHD, W7-X)
- Burning plasma physics and technology with Q = 5-10 plasmas. (ITER)
- Size scaling of 2D plasmas to full reactor scale. (ITER)

**Quasi-symmetric stellarators have strong physics overlap with tokamaks.**
- Similar collisionless particle drift orbits.
- Low flow damping, flow-shear stabilization of turbulence.

**Good transfer of understanding from tokamaks to quasi-symmetric stellarators is expected. Will test this on CS PoP and PE experiments.**
U.S. Compact Stellarator PE Experiment Design

CS-PE Requirements

- Reactor-like plasma configuration and parameters.
- Moderate pulse length (JET-like)
- Moderate DT (JET/TFTR-like)

High-leverage design issues

- S/C or normal magnets?
- Aspect ratio?
- Size?

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Key Milestones and Decisions

U.S. - funded Compact Stellarator Projects
U.S. - funded, but included in Other Program Elements
Non- U.S. - funded. Shown for Information

Assess CS DEMO relevance

Assess CS attractiveness (FESAC-99 10-Year Goal)
## Program Milestones, Decisions, Criteria

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<th>Fiscal Year</th>
<th>Event (Major Program Milestones in Red)</th>
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<td>Start CS-PE Preconceptual Design.</td>
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<td><em>Explore configurations and high-leverage engineering issues.</em></td>
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<td>2008</td>
<td>NCSX Transport Assessment</td>
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<td><em>QA optimization, enhanced confinement, density limits OK?</em></td>
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<td><em>If yes, proceed. If not, either modify equipment and iterate, or terminate program.</em></td>
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<td>2010</td>
<td>NCSX Short-Pulse Beta Assessment</td>
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<td><em>Achieved beta = 4%? No disruptions?</em></td>
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<td><em>IF OK, finalize CS-PE configuration, approve CS-PE Mission Need (PE CD-0), start CS-PE conceptual design, and continue with PoP program.</em></td>
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<td>2011</td>
<td><strong>Determine CS Attractiveness (FESAC-1999 10-Yr Goal)</strong></td>
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<td><em>If positive, approve CS-PE Project Start (PE CD-1), plan remainder of the PoP program.</em></td>
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<td>2016</td>
<td>Complete PoP program and update attractiveness assessment.</td>
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<td>2017</td>
<td>Start CS-PE operation (PE CD-4).</td>
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<td>2023</td>
<td><strong>Determine CS Relevance to DEMO</strong></td>
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<td><em>If positive, start design of a U.S. CS-DEMO. If not, re-focus CS program on next-generation design.</em></td>
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Compact Stellarator Development Costs to Support 2023 DEMO Decisions (FY-02 $M)

CS-PE construction peak fills the gap between MFE PE#1 and CTF.
Replies to Panel Questions

• Is an ITER- or FIRE-class CS burning plasma experiment required, or will transfer from tokamaks be sufficient?
  Ans: Transfer from a tokamak b.p.x., in combination with CS-PE, will suffice. Quasi-symmetric stellarator design is advantageous in this regard. Knowledge transfer from tokamaks has been valuable in the PoP design phase and will be validated experimentally on NCSX and CS-PE. Reliable burning-plasma knowledge transfer from tokamaks to stellarators requires that it be pursued as a management priority. For example, integrated simulation spanning configurations is critical.

• What PoP and/or PE-class facilities will be required?
  Ans: The plan requires the PoP program as currently planned, including NCSX. It requires the follow-on CS-PE experiment. It takes advantage of foreign stellarator PE’s, tokamak PE’s, and a tokamak b.p.x. to develop the needed knowledge base in a timely manner at minimum cost.

• Could the CTF be a CS?
  Ans: This has not been analyzed in detail by the stellarator community. A CS could straightforwardly provide the high duty factor required for component testing but might consume too much tritium. This could be analyzed further.
Summary and Recommendation

- Compact stellarators solve important MFE problems and can improve the timetable for MFE development.

- There is a realistic, low-cost CS development plan that could lead to a U.S. Compact Stellarator DEMO in 35 years.

- The sooner CS benefits are understood, the more valuable they will be to the program. Critical assessments can be accelerated and U.S. leadership strengthened by speeding up the PoP program.

Recommendation

- Strengthen the PoP Program to make critical assessments sooner.
  - Improve the quality and timeliness of higher-level Fusion decisions.
## Compact Stellarator Development Costs to Support 2023 DEMO Decisions (FY-02 $M)

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*Note: The table represents the development costs for various projects over a 25-year period, starting from FY-02. The costs are in millions of dollars (FY-02 $M). The values indicate the allocated budget for each year for different projects, including Stellarator Physics, Stellarator CEs, Proof of Principle Experiment (NCSX), Performance Extension Experiment (CS-PE), and CS Reactor Design Studies.*