Compact Stellarator Development Plan

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General Atomics

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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:

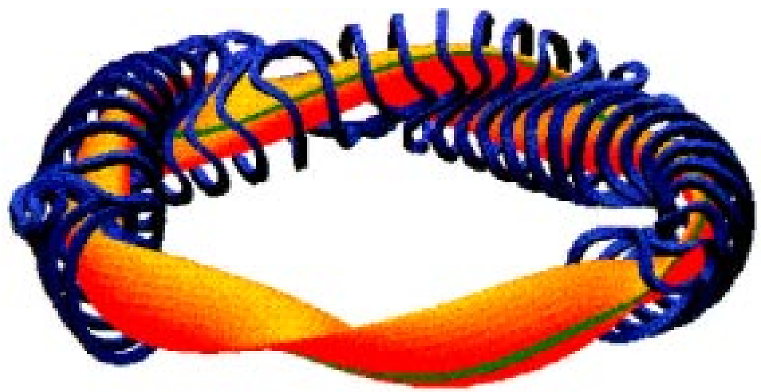
- Make maximum use of MFE advances in tokamaks and foreign PE stellarators.
- Focus U.S. compact stellarator experiments on 3D physics issues.

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.



Wendelstein 7-X (Germany)
A= 11

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

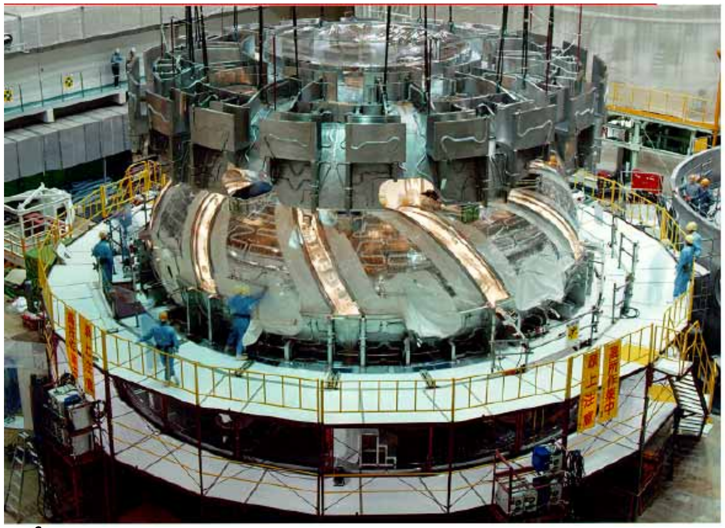
Compact stellarators:

- Passive stability at low aspect aspect ratio (≤ 4.4) and high beta (≥4%).
- Magnetic quasi-symmetry ⇒ 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



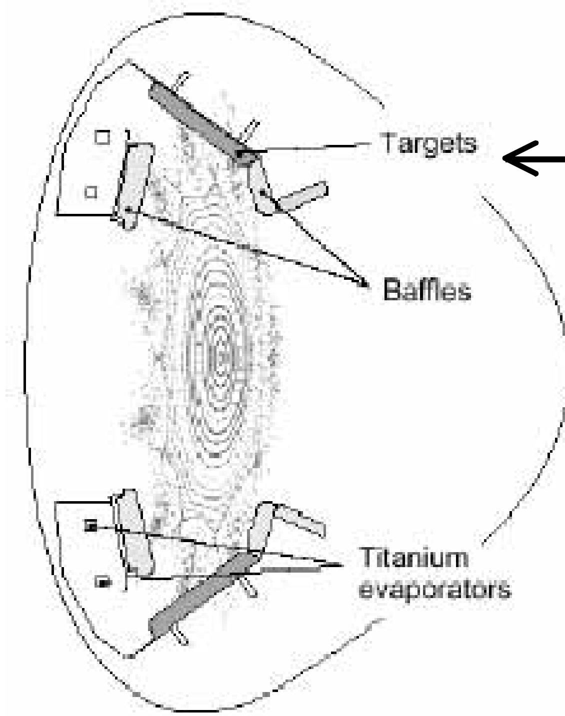
Large Helical Device
(PE w/ S/C magnets - Japan)

β > 3%.

$T_e \approx$ 10 kev, $T_i \approx$ 5 keV.

enhanced confinement.

2-minute pulses.

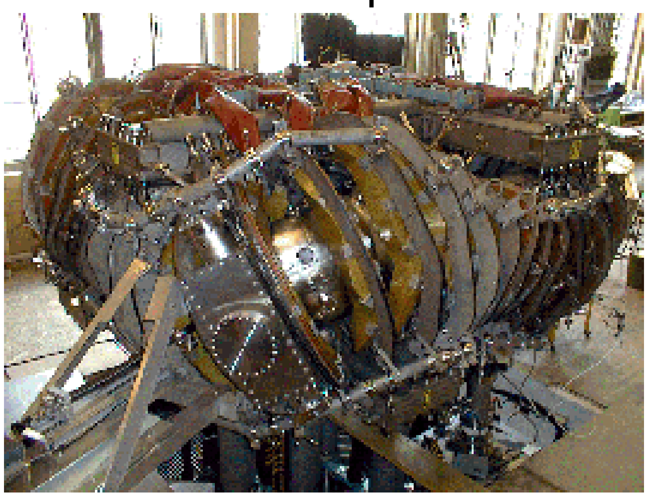


Wendelstein 7-AS
(PoP- Germany)

β > 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.

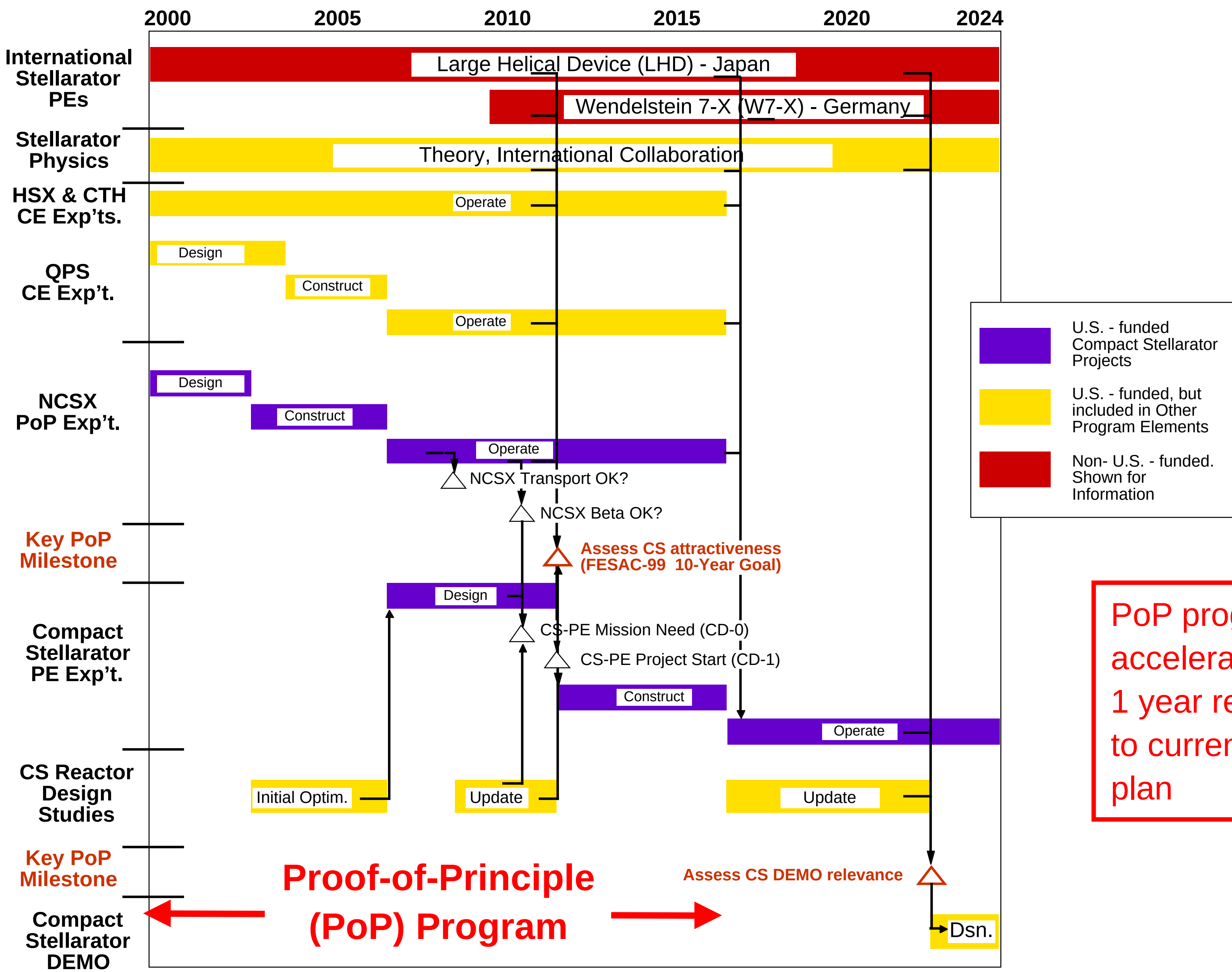
- Project delays have occurred due to supplier problems not specific to stellarators. Operation projected to start in ~2010.

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

- Compact Stellarator PoP designation approved by FESAC in 2001.
- 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.

CS Development Plan Supports DEMO Design Start in 2023.



PoP program accelerated by 1 year relative to current DOE plan

Compact Stellarator Proof-of-Principle (PoP) Program: CS Attractiveness

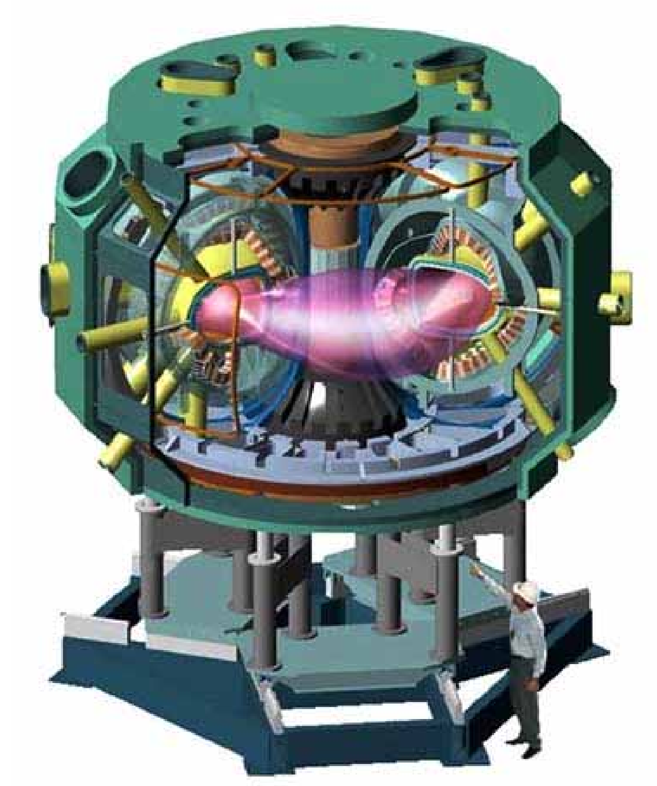
FESAC-1999 10-year goal:

"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.

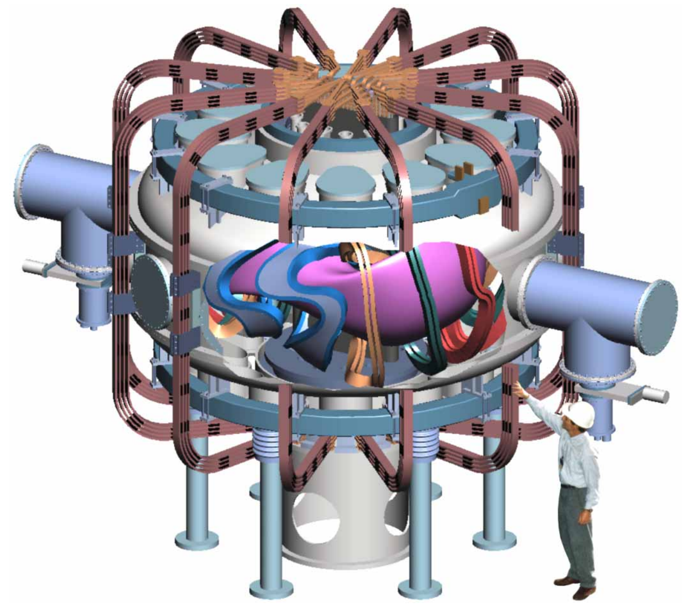


NCSX (PPPL-ORNL)

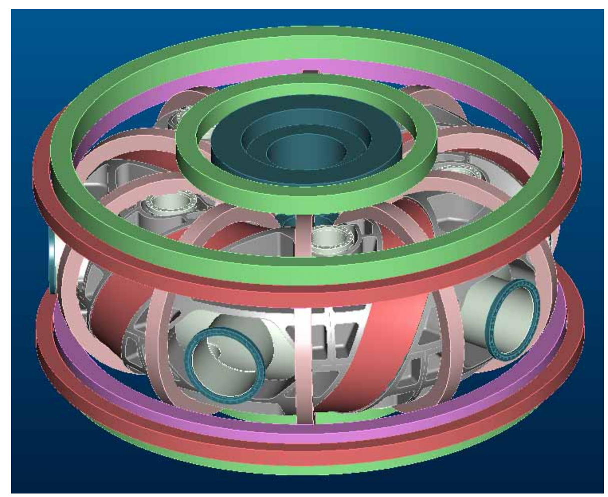
Compact Stellarator Proof-of-Principle Program

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.

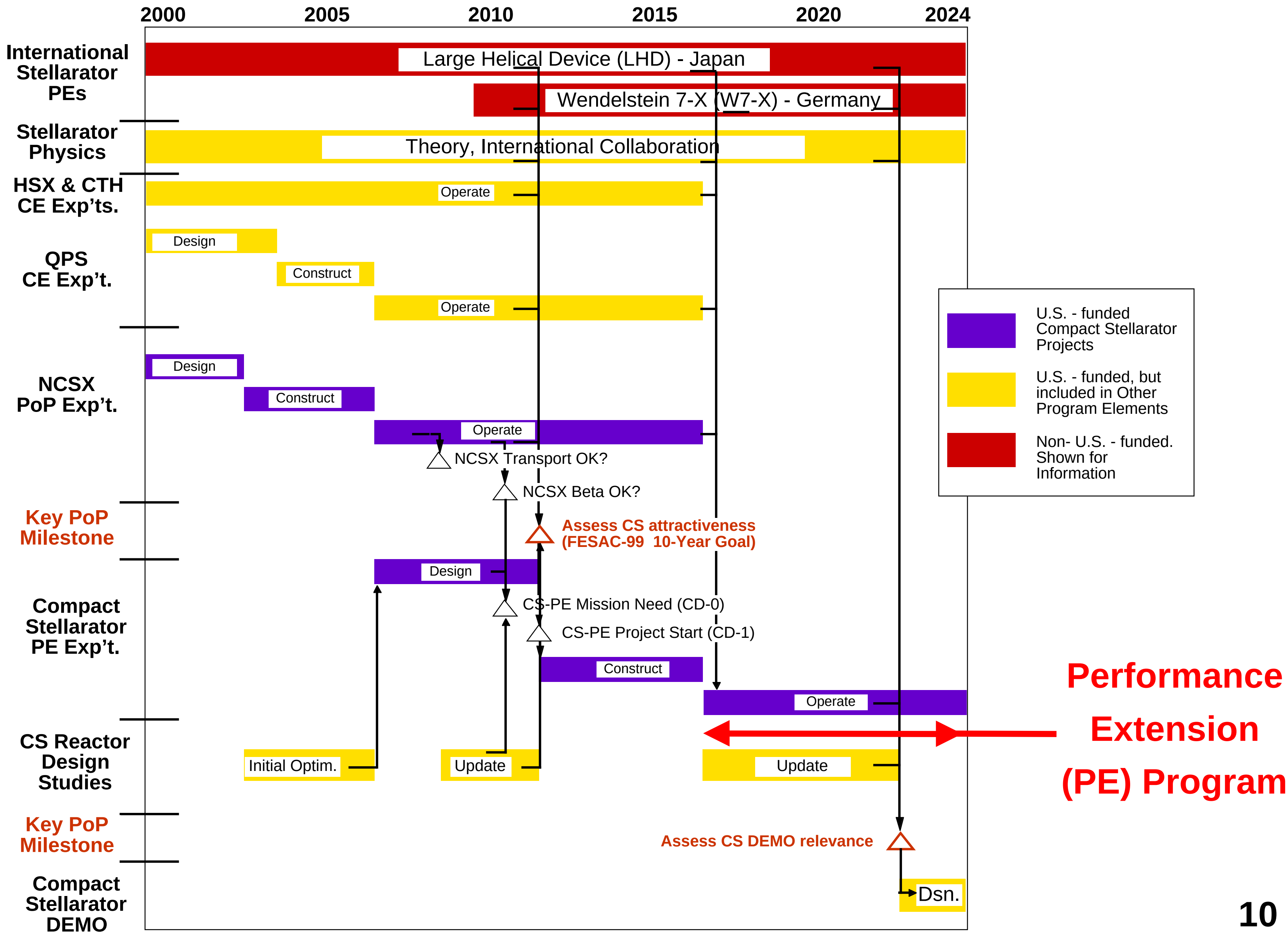


QPS (ORNL)



CTH (Auburn U.)

CS Development Plan Supports DEMO Design Start in 2023.



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

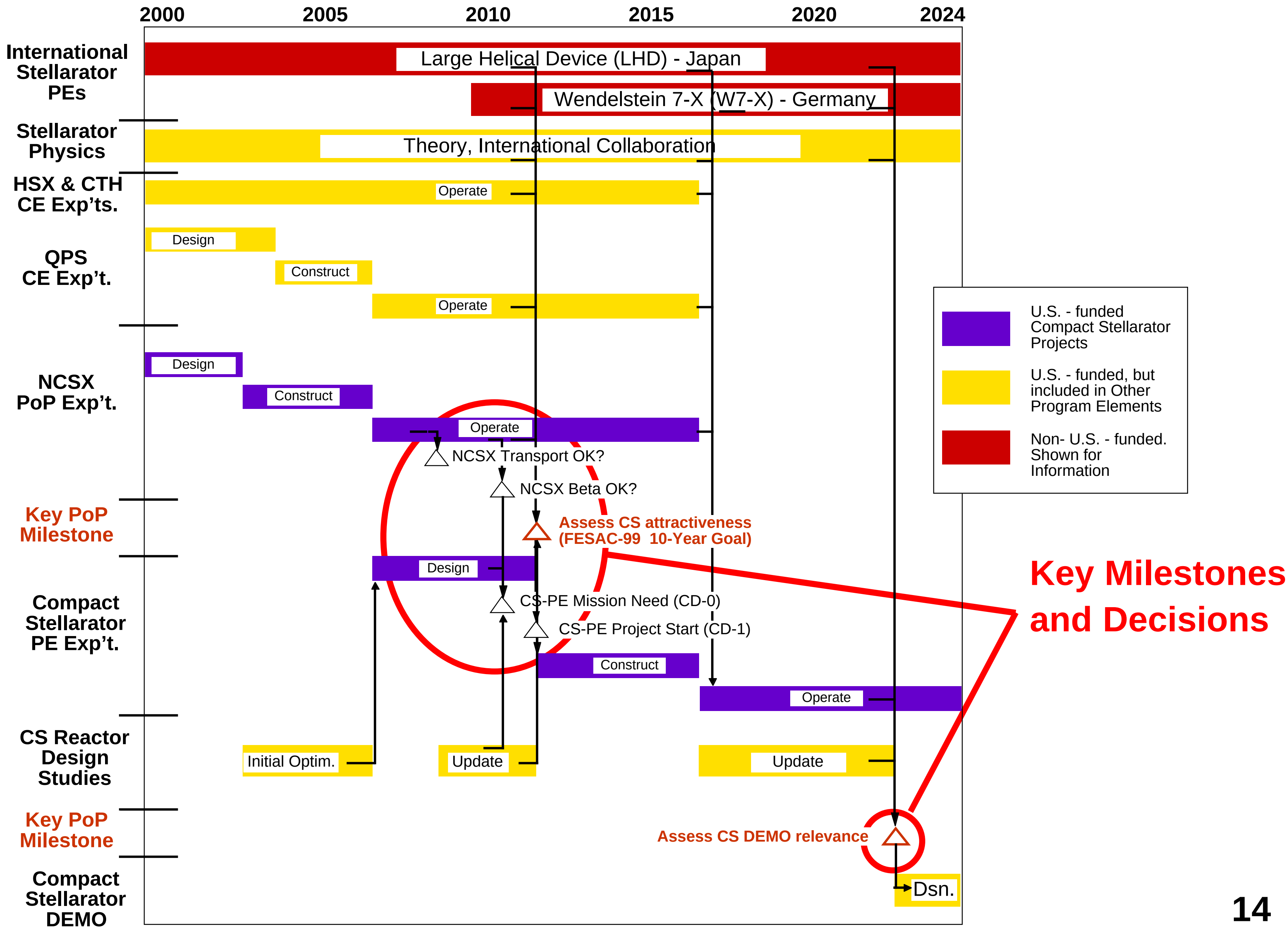
- Reactor-like plasma configuration and parameters.
- Moderate pulse length (JET-like)
- Moderate DT (JET/TFTR-like)

High-leverage design issues

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

Parameter	CS-PE	Reactor12	Reactor14
R (m)	2.9	8.1	6.6
$R / \langle a \rangle$	4.4	4.4	4.4
B_{axis} (T)	4	5.7	6.6
B_{coil} (T)	8.5	12	14
P_{fus} (MW)	25	1,700	1,700
Q	1	ignited	ignited
$\langle \beta \rangle$ (%)	4.8	4.9	4.8
$\langle \beta_\alpha \rangle$ (%)	0.2	0.17	0.17
τ_E/τ_{97P}	2.0	1.5	1.5
τ_E (s)	0.4	1.6	1.2
ν_I^*	0.02	0.11	0.12
T_0 (keV)	13	13	13
n_e (10^{20} m^{-3})	1.2	2.7	3.6
t_{pulse} (s)	~50	st. state	st. state
Cost ($M)	600		

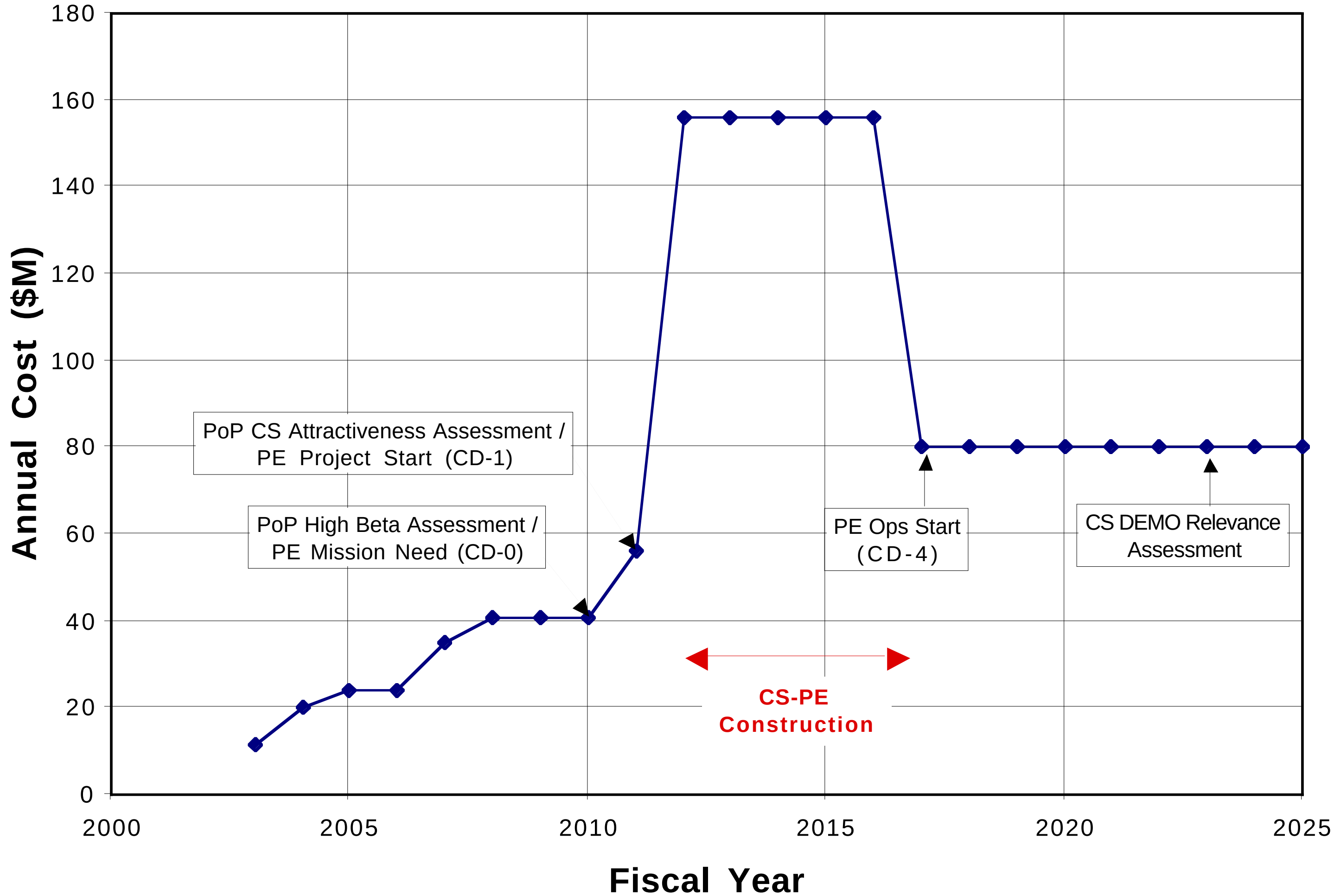
CS Development Plan Supports DEMO Design Start in 2023.



Program Milestones, Decisions, Criteria

Fiscal Year	**Event** (Major Program Milestones in **Red**)
2006	Start NCSX Operation. (PoP CD-4). Start CS-PE Preconceptual Design. *Explore configurations and high-leverage engineering issues.*
2008	NCSX Transport Assessment *QA optimization, enhanced confinement, density limits OK?* *If yes, proceed. If not, either modify equipment and iterate, or terminate program.*
2010	NCSX Short-Pulse Beta Assessment *Achieved beta = 4%? No disruptions?* *IF OK, finalize CS-PE configuration, approve CS-PE Mission Need (PE CD-0), start CS-PE conceptual design, and continue with PoP program*
2011	**Determine CS Attractiveness (FESAC-1999 10-Yr Goal)** *If positive, approve CS-PE Project Start (PE CD-1), plan remainder of the PoP program.*
2016	Complete PoP program and update attractiveness assessment.
2017	Start CS-PE operation (PE CD-4).
2023	**Determine CS Relevance to DEMO** *If positive, start design of a U.S. CS-DEMO. If not, re-focus CS program on next-generation design.*

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)

		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Stellarator Physics																								
	Theory & Int'l Collaboration	Costs Included in Other Program Elements																						
Stellarator CEs																								
	HSX, CTH, QPS	Costs Included in Other Program Elements																						
<u>Proof of Principle Experiment</u>																								
NCSX																								
	Design																							
	Construction	11	19	20	14																			
	Res. Prep / Upgrades /Ops	1	1	4	10	30	36	36	36	36	36	36	36	36	36									
<u>Performance Extension Experiment</u>																								
CS-PE																								
	Design					5	5	5	5	20														
	Construction										120	120	120	120	120									
	Operations															80	80	80	80	80	80	80	80	80
CS Reactor Design Studies		Incl. in Other						Incl. in Other								Incl. in Other								
CS Projects Total		11	20	24	24	35	41	41	41	56	156	156	156	156	156	80	80	80	80	80	80	80	80	80