

Compact Stellarator Program: Cost and Schedule

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**Presentation to:
Fusion Energy Sciences Advisory Committee**

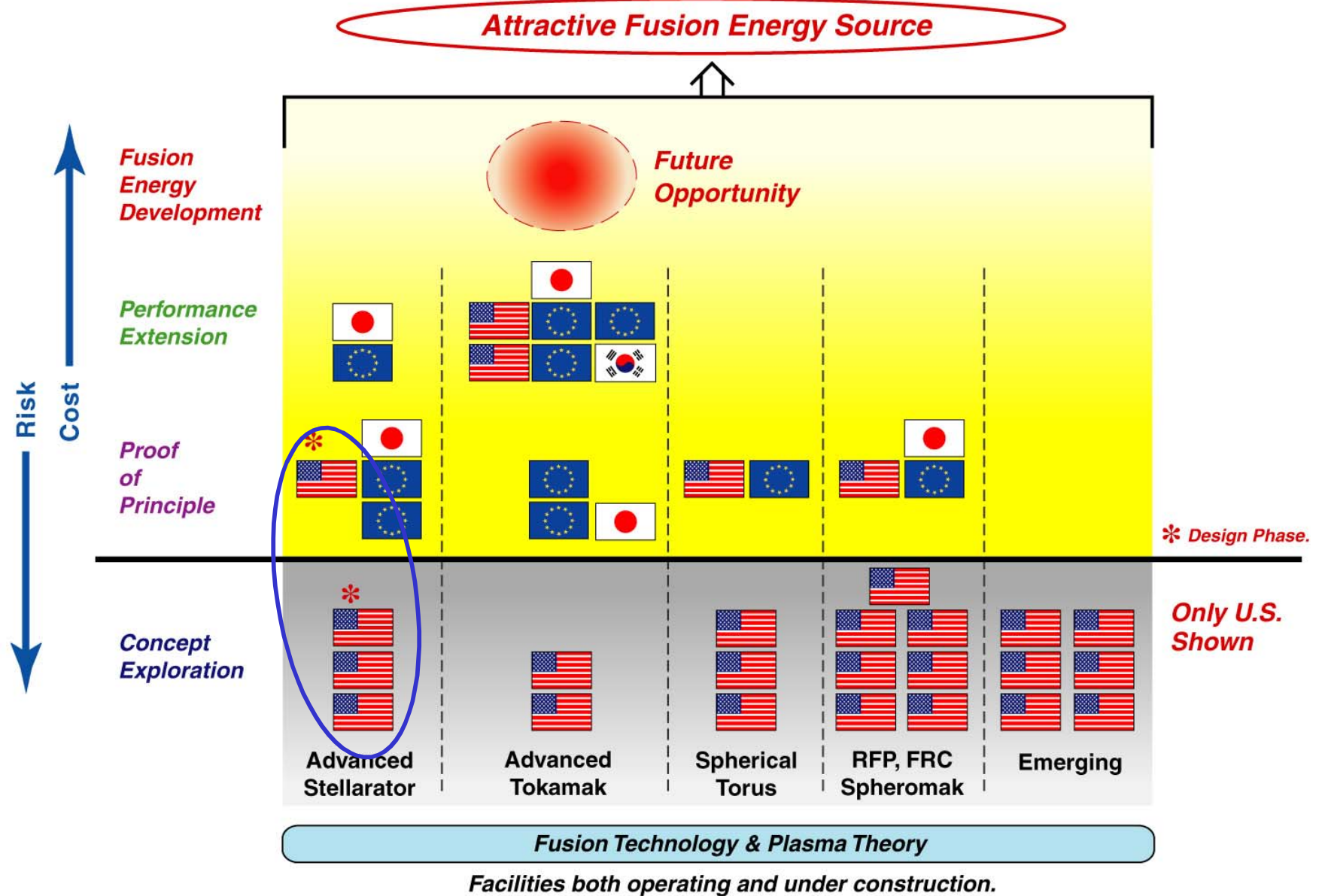
**PPPL
August 1, 2001**

Elements of the U.S. Compact Stellarator Program

FESAC 10 Year Goal:

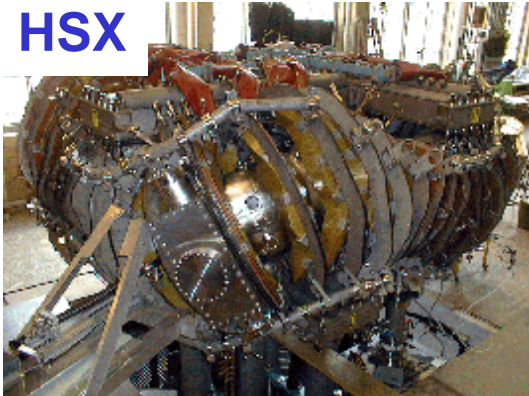
- “**Determine the attractiveness of a Compact Stellarator by assessing resistance to disruptions at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3-D divertor operation.**”
- **CE Experiments, Existing and Under Construction**
 - HSX - Quasi-helical symmetry
 - CTH - Kink and tearing stability
- **Proposed New Projects: NCSX, QPS**
 - NCSX – Low collisionality transport, high beta stability, quasi-axisymmetry, low R/a
 - QPS - Quasi-poloidal symmetry at very low R/a
- **Theory**
 - Confinement, Stability, Edge, Energetic Particles, Integrated Modeling
- **International Collaboration**
 - LHD, CHS, W7-AS \Rightarrow W7-X, Theory
- **Reactor Studies**
 - ARIES team + Stellarator experts

The Magnetic Fusion Energy Portfolio

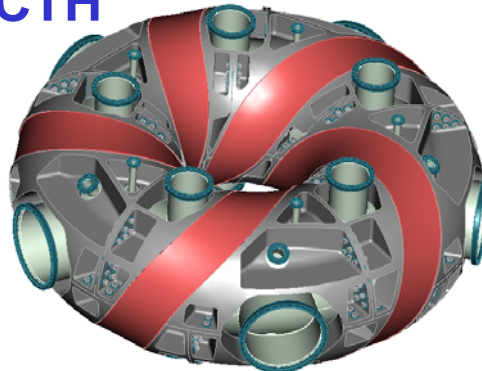


Compact Stellarator Program will Address Key Issues of Fusion Energy Science

HSX



CTH



Microturbulence and Transport:

- Is quasi-symmetry effective in collisionless plasmas?
- Challenge E_r shear understanding via ripple control.

Macroscopic Stability:

- Disruptions - when, why, why not?

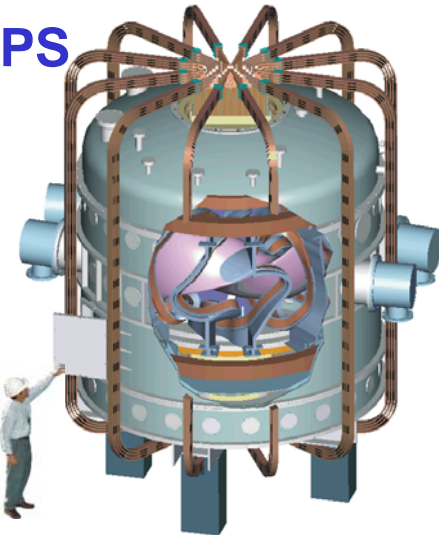
Wave-particle Interactions:

- Do we understand 3-D fast ion resonances, *AE modes in 3-D?

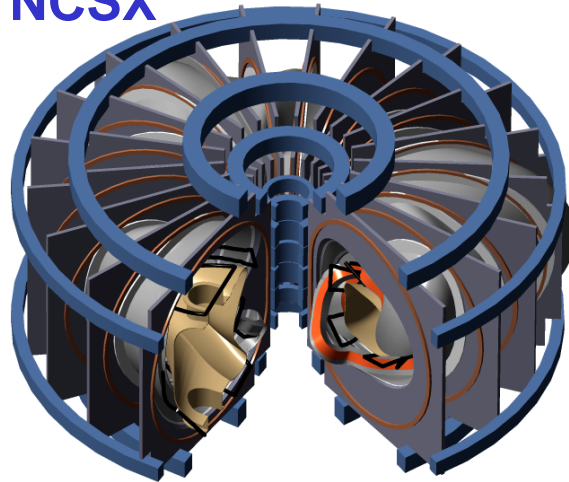
Plasma-boundary interaction:

- Effects of magnetic stochasticity?

QPS



NCSX



Auburn U., Columbia U., LLNL, U. Montana, NYU, ORNL, PPPL, SNL-A, U. Texas, UCSD, U. Wisconsin
Australia, Austria, Japan, Germany, Russia, Spain, Switzerland, Ukraine

NCSX & QPS Physics Validation Reviews

- **NCSX Design is Appropriate for the Central Element of the Compact Stellarator Program**
 - “The consensus of the Panel is that the physics requirements and capabilities of the pre-conceptual design of the NCSX experiment represent an appropriate approach to developing the design of a Proof of Principle scale experiment that is the central element in a program to establish the attractiveness of the Compact Stellarator (CS) Concept.”
- **QPS Combination of Low R/a with Quasi-poloidal Symmetry is an Attractive Stellarator Option**
 - “The Committee feels that the combination of low aspect ratio and quasi poloidal symmetry is an attractive stellarator option. The ORNL-led team has identified the scientific issues of equilibrium, ballooning stability, and transport that should be able to be addressed by the proposed experiment.
 - A clear majority of the Committee feels that these properties fully justify proceeding with the QPS project.”

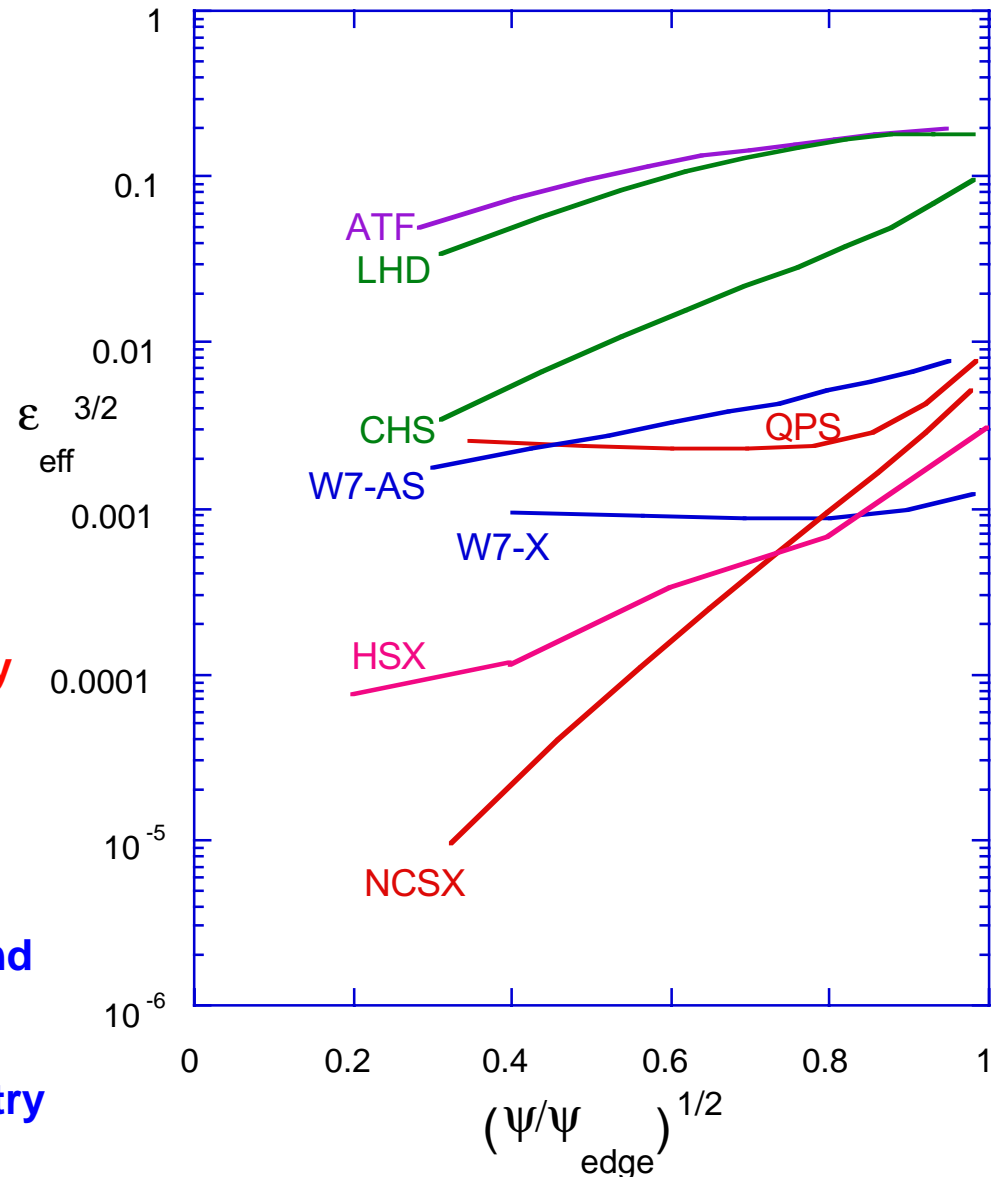
FESAC Approved NCSX for PoP Status

“The NCSX program offers an exciting opportunity in fusion research for several reasons.

- ***First**, a plausible case has been made (for example, at the NCSX Physics Validation Review) that a fusion power system based on a compact stellarator may resolve two significant issues for fusion power systems: **reduction or elimination of plasma disruptions, and provision for steady-state operation.** These gains earn for the compact stellarator an important place in the portfolio of confinement concepts being pursued by the US Fusion Energy Sciences program.*
- ***Second**, the NCSX would **complement research now underway on the advanced tokamak**, which addresses closely related issues by different methods. It also **complements stellarator research outside the US**, which has emphasized different geometries and plasma regimes.*
- ***Finally**, understanding the behavior of magnetized plasmas in **three-dimensional configurations is an important scientific frontier area**, which the NCSX program would advance and strengthen.”*

New Stellarators Test Quasi-Symmetries and Disruption Immunity

- In $1/\nu$ regime, asymmetrical neoclassical transport scales as $\epsilon_{\text{eff}}^{3/2}$
- Low flow-damping
 - manipulation of flows for flow-shear stabilization
 - zonal flows like tokamaks
- Initial (successful!) test in HSX, studies continuing.
- Stability with finite current also a key issue for PoP program:
 - CTH focused on kink & tearing stability with external transform.
- NCSX will test quasi-axisymmetry and current at low n^* and high b .
- QPS will test quasi-poloidal symmetry and current at very low R/a .



NCSX and QPS PVR Construction Costs

	NCSX (\$k FY01)	QPS (\$k FY01)
Fusion Core Systems	\$19,131	\$6,599
Machine Assembly	\$2,961	\$873
Auxiliary Systems	\$2,361	\$551
Power Systems	\$5,123	\$130
Site & Facilities	\$3,994	\$93
Diagnostic Systems	\$2,684	\$205
Central I&C & Data Acquisition Systems	\$3,550	\$271
Project Oversight & Support	\$4,246	\$616
Preparations for Operations	\$470	\$276
Subtotal Without Contingency	\$45,931	\$9,613
Contingency (~26.5%)	\$12,419	\$2,539
TOTAL	\$58,350	\$12,152

Why QPS vs. NCSX Cost Differential ?

- **Three Reasons:**
 - 1) CE vs. PoP scientific scope (factor of ~1/3)
 - 2) Assumed site infrastructure configured to QPS specs
 - 3) Assumed limited initial diagnostics and controls
- **1) Core, Assembly, Auxiliary Systems: QPS is 1/3 of NCSX**
 - Smaller, lower field (1T, 0.9m vs. 1.7T, 1.4m)
 - Initial heating ~ 300 kW ECH vs. 3 MW NBI
 - No internal vacuum vessel, cryogenic coils, PFCs or magnetic trim coils
 - Cheaper (assumed university-based) labor for coil construction
 - Re-using some existing PF coils and most of vacuum tank
- **2) Power, Site and Facilities: QPS is 1/40 of NCSX**
 - Assume power systems moved, operational and configured to QPS specs
 - Assume new building, test cell, control room configured to QPS specs
- **3) Diagnostics and I&C: QPS is 1/14 of NCSX**
 - Initial diagnostic set only
 - Small allocation for control system

Stellarator Community Theory Planning

Future Directions in Theory of 3D Magnetic Confinement Systems ORNL, December 3 – 5, 2001

- *Have a scientific exchange on issues and opportunities for theory of 3D confinement systems and to identify crucial issues not presently being addressed.*
- *Provide a forum for the stellarator experimental projects to communicate needs and priorities to the theory community.*
- *Draw in researchers not traditionally associated with stellarators, but with interests and expertise that could contribute to, and benefit from, such a discussion, for example, the presence of 3D magnetic structures in tokamaks.*
- *Produce a summary document/white paper which would aid researchers in the preparation of proposals for stellarator theory and which would aid OFES in funding such proposals.*

“Lead, but don’t control.”

Current Stellarator Theory Support

	FTE's	\$225k/FTE
Theorists Supported by Non-Project Funds	9.9	\$2,223
<i>National Laboratories</i>	6.5	
LLNL*	0.25	
ORNL	1.7	
PPPL	4.5	
<i>Universities</i>	3.4	
Auburn	0.5	
Columbia	0.75	
Maryland	0.1	
NYU	0.5	
UCSD	0.33	
Wisconsin	1.3	
Theorists Supported by NCSX & QOS Projects	2.7	\$608
PPPL & ORNL	1.6	
Other Collaborators	1.1	
* excludes 1.25 FTE from internal LDRD funds		

What is the Appropriate Level of Stellarator Theory?

- **First Principles Calculation:**

- Non-project fusion Theory and Computation is \$27.5M in FY2001

How much of this is concept specific?
Maybe $2/3 \Rightarrow \$18.3M$??

- Total OFES experimental program is \$152M in FY2001
- Perhaps non-project stellarator theory should be:

$$\$18.3M / \$152M = 0.12 \times \text{experiment} ??$$

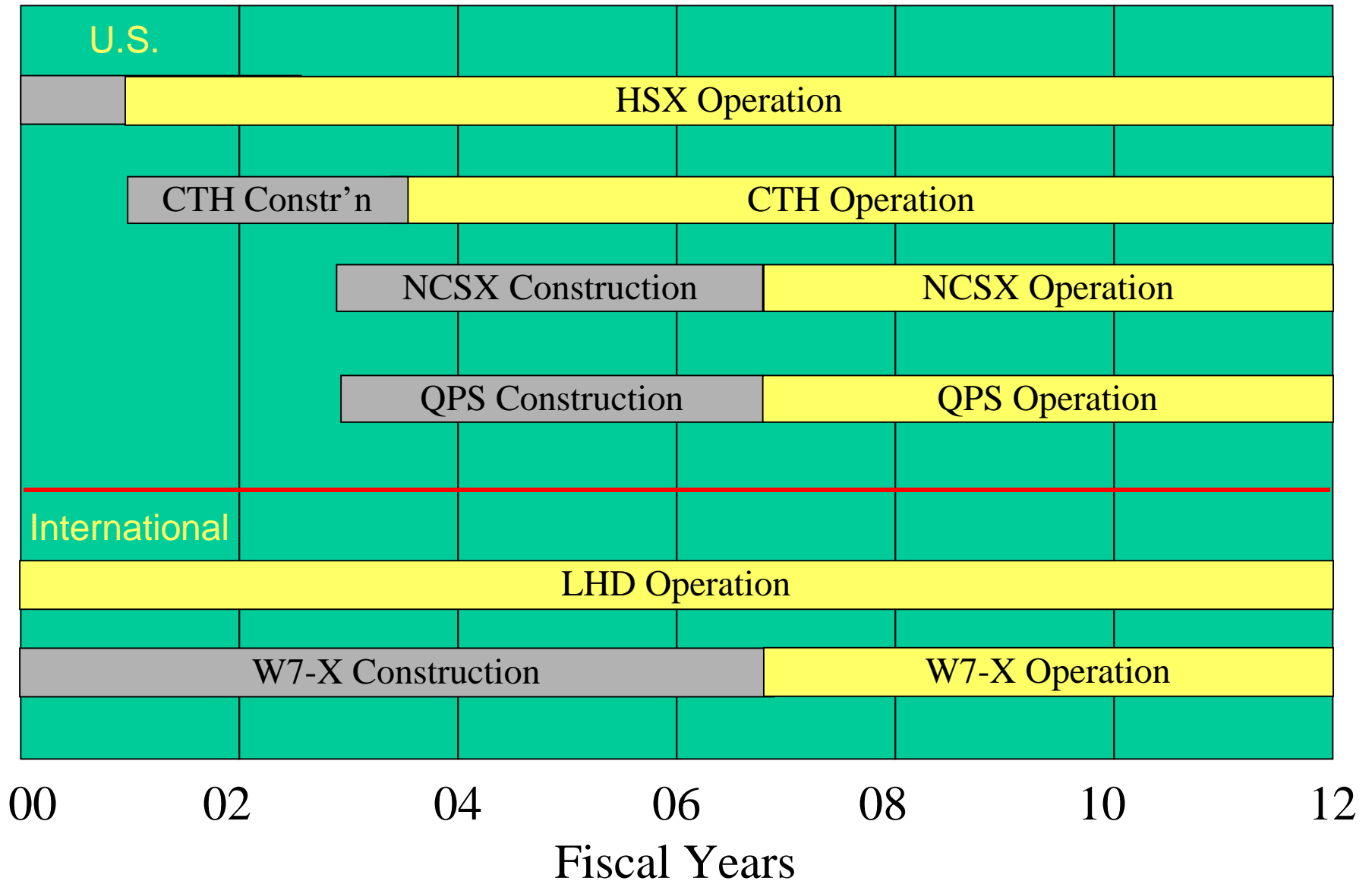
- **Common Sense Check:**

- As stellarator experiment grows, growth in theory will be needed.

Incremental Cost of CS Program is Moderate

	2001	2004	2008	Comments
Existing Activities				
HSX	\$1.6M	\$1.8M	\$2.0M	Return to FY00 level, add RF.
CTH	\$0.5M	\$0.7M	\$0.7M	Comparable to Pegasus, HBT-EP.
Non-Project Stellarator Theory	\$2.2M	\$2.2M	\$2.2M	Levelized by definition (excludes LLNL support).
International Collaboration	\$0.6M	\$0.6M	\$0.6M	Levelized by definiton.
New Projects				
NCSX	\$4.2M	\$15M	\$22M	Increment in 2008 non-PPPL.
Project Theory	\$0.45M	\$0.15M	\$1.1M	
QPS	\$0.5M	\$4.2M	\$4.2M	Site move funded separately.
Project Theory	\$0.15M	\$0.1M	\$0.2M	
Total Incremental Cost	-	\$14.9M	\$22.1M	Incremental cost over FY01, includes HSX & CTH
Redirected Activities				
Additional Non-Project Theory	-	\$0.4M	\$1.3M	Total N-PT = 0.12x exp'tal budget.
Additional International Collab	-	\$0.3M	\$0.3M	Via redirection from JT-60U, ~50% theory.
ARIES Stellarator Study	-	\$1.0M	-	Total cost = \$2.5M, ~20% theory.
Stellarator Community Common Perspectives:				
"Existing Activities" have precedence over "New Projects."				
NCSX is the central element of the Compact Stellarator Proof of Principle program.				
QPS's combination of very low R/a with quasi-poloidal symmetry is an attractive complementary stellarator option.				
"Redirected Activities" depend on moving forward with "New Projects."				
Notes				
\$ FY01				
Credit to NCSX for joint operation with NSTX.				

Schedule of CS Experimental Program



CS Program Integrates well with a Tokamak Burning Plasma Experiment

- **Compact Stellarator completes a broad portfolio base for moving forward with a tokamak burning plasma experiment**
 - Portfolio contains PoP programs from “self-organized” to “externally controlled” (operating or under construction).
 - Demonstrates a clear national commitment to optimization of toroidal fusion systems.
- **Compact Stellarators can benefit particularly well from BP physics in a tokamak**
 - Very similar symmetry, aspect ratio, continuous with tokamak (NCSX).
 - Very similar alpha to Alfvén velocity ratio.
 - Very similar thermal transport issues (NCSX).
 - Very similar technology issues.
 - Closely related macro-stability and edge issues.
- **BP Experiment has reduced burden of proof for approval**
 - Three approaches (AT, CS and ST) can benefit from BP physics & technology
 - Reduced need to validate full AT physics before moving forward

Conclusions

- **The incremental cost of the Compact Stellarator Program is moderate.**
 - The potential science and energy impacts are large.
 - CS program addresses FESAC 10 year goal.
- **The U.S. Compact Stellarator program integrates well scientifically with**
 - the world stellarator program.
 - the world tokamak \Rightarrow burning plasma program.
- **Thoughtful, positively reviewed plans are in place, including plans for a strong stellarator theory program.**
- **Let's proceed!**