COMPACT STELLARATOR

RESPONSES TO

“PROGRAM EVALUATION CRITERIA”

QUESTIONS

0. QUALITY OF SCIENCE

- Is the proposed research program of very high quality?
- Does it have scientific and technical credibility?
- Is it based on an understanding appropriate for its stage of the program?

Reply:

The Physics Base Needed for the Compact Stellarator PoP Program Is Well Established

- Theoretical understanding of MHD equilibrium and stability, neoclassical transport, and divertor topology is well developed and incorporated in 3-D codes that are used as design and analysis tools
- High-*R*/*a* stellarators with plasma current do not disrupt at density limit, β limit, or at low q (inductive) when fraction of rotational transform generated externally is >20%
- Control (and reversal) of the bootstrap current and its agreement with theory has been demonstrated
- >1-hour operation on ATF

Cont'd...

0. QUALITY OF SCIENCE (cont.)

The Physics Base Needed for the Compact Stellarator PoP Program Is Well Established, cont'd.

- 3-D neoclassical transport and energetic orbit confinement is understood well enough to optimize experimental design
- Global confinement scaling based on data sets from the world stellarators also fits tokamak data
- Improved confinement modes, 2.5 x τ_E^{ISS95}, and τ_E = 0.26 s has been achieved in stellarators
- Enhanced confinement techniques developed on tokamaks can be applied to stellarators (esp. QA)
  - edge control, flow shear
- Divertors have been demonstrated on CHS and will be further tested on W7-AS and LHD

0. QUALITY OF SCIENCE (cont.)

Present Stellarator Performance Is Part of the Confidence Base for Compact Stellarators

- **LHD (<*a*> = 60 cm): τ_E up to 0.26 s with 1.5 x ISS95 scaling; quasi- steady-state operation up to 22 s with NBI in *initial* experiments.**
- **W7-AS (<*a*> = 18 cm): τ_E up to 55 ms, 2.5 times τ_E^{ISS95} scaling**
  - **T_e = 5.7 keV, T_i = 1.5 keV, n_e = 3 x 10^{20} m^{-3}, $\langle\beta\rangle$ = 1.8% (not simultaneously)**
  - **demonstration of access to the electron root of the electric field ambipolarity condition**
  - **ICRF heating and plasma sustainment with no increase in density or impurities**
- **CHS (<*a*> = 20 cm): $\langle\beta\rangle$ = 2.1% and demonstrated**
  - **large parallel viscous damping in a non-symmetric configuration**
  - **radial electric field control**
  - **ICRF heating of the bulk plasma**
  - **enhanced pumping with a local magnetic island divertor**

0. QUALITY OF SCIENCE (cont.)

Technical Credibility:

- **Re-uses major pieces of equipment and infrastructure which have previously operated**
- **Conventional materials (e.g., copper coils, inconel vacuum vessel, carbon armor)**
- **Preconceptual design by experienced fusion engineers, experience base from ATF, W7-AS, HSX, LHD, many tokamaks**

0. QUALITY OF SCIENCE (cont.)

May 1998 DOE PoP Review Panel replied to similar questions

- **‘The panel members conclude that the stellarator community is ready for a PoP program with a lead experiment based on the "quasi-axisymmetric (QA) stellarator," which is a concept based on a new direction, rather than a refinement of more standard directions.’**
- **‘In endorsing the technical merit of the proposed lead experiment, the National Compact Stellarator Experiment (NCSX), the panel members recognized: (a) the significant innovative components of the proposal, (b) the strong theoretical basis for the design, (c) the experimental relationship to the tokamak which has a large data and theoretical basis, and (d) the strengths of the stellarator team in physics and engineering.’**

1. CONFIDENCE FOR NEXT STEP

Does the proposed program provide reasonable expectation to develop the knowledge base required to proceed to the next stage?

Reply:

The proposed PoP program provides the necessary knowledge base through a combination of NCSX, QOS, supporting experiments, theory, international collaboration, and system studies

The knowledge base needed for the next step consists of

- **operation at β ~ 5% with plasma currents and externally-generated transform without disruptions (*NCSX*)**
- **suppression of neoclassical islands and tearing modes by bootstrap current and stellarator magnetic shear (*NCSX, theory*)**
- **understanding β limits and the limiting mechanisms (*NCSX, theory*)**
- **reduction of neoclassical transport to a low level by configuration design (*NCSX, QOS, HSX, theory*)**
- **control of turbulent transport (e.g., by flow shear control), leading to enhanced global confinement (*NCSX, QOS, theory)***
- **assessment of quasi-omnigeneous approach *(QOS, W7-X)***
- **development of practical particle and power handling (*Int'l. collab.; NCSX, QOS)***
- **development of attractive reactor configurations (*System studies, theory)***

2. PLASMA SCIENCE/TECHNOLOGY BENEFIT

- What is the benefit to the advancement of plasma science?

Reply:

- magnetohydrodynamics
  - * confirming compact stellarator stability to external kink modes, ballooning, neoclassical tearing modes; vertical instability tests
  - * understanding of 3-D systems
- transport and turbulence
  - * understanding transport in fully 3-D sytems
- wave-plasma interactions
  - * understanding ion cyclotron heating mechanisms in systems with mixed toroidal and helical symmetries
- plasma-material interactions
  - * understanding magnetic structure in the edge of hybrid configurations

3. ISSUE RESOLUTION

Is the proposed research likely to resolve key issues and provide the basis for a decision

* **to advance to the next stage?**
* **to re-direct within a stage?**
* **to terminate the concept?**

Reply:

To control risk, the proposed program is planned in phases, with milestones to test goals and make decisions.

- **NCSX Transport assessment -- 2 years after 1st plasma. Assess confinement optimization and density limits at moderate beta.**
- **Decision:**

a **If confinement is adequate, proceed to high-beta campaign**

b **If confinement is marginal, modify equipment and continue efforts to improve**

c **If confinement is poor (worse than present data base), test a more promising configuration or terminate program**

3. ISSUE RESOLUTION (cont.)

- **NCSX short-pulse beta-limit assessment** -- 3-4 years after 1st plasma. Assess short-pulse, disruption-free operation at β-limit (4%).
- **Decisions:**

a If expected β limits $\approx$4% are achieved in short pulse without disruptions; proceed with full PoP mission -- control, power & particle handling compatibility, longer pulses. At that time, define the milestones and decision points leading to next-step (Performance Extension) decisions.

b If β limited due to inadequate confinement enhancement; modify equipment and continue to improve confinement or heating

c If β limited due to much lower than expected stability limits; modify equipment and continue search for acceptable regime

d If $\beta \leq$ 2% or can't avoid disruptions; modify configuration to respond if possible, or terminate program

3. ISSUE RESOLUTION (cont.)

– **QOS assessment.** 2 years after 1st plasmas.

– **Decisions: does QOS satisfy goals?**

- Reduction of energetic orbit losses and transport in low-A, non-symmetric configurations
- Control and reduction of the bootstrap current
- Reduction of anomalous transport $\Rightarrow$ H > 2

– If all goals met, decide whether to promote QO to PoP level

– If goals not met, terminate experiment

3a - 1. Does the proposed program address the physics requirements, and does it contribute to the physics (theory and experiment) basis in the following areas?

Replies:

The proposed facilities will include diagnostics and design features needed to be able to document the physics results and compare them with theoretical predictions. Theoretical understanding and models will be updated, guided by the experimental data obtained in the course of the program.

Exploring macroscopic equilibrium and stability limits

* **NCSX has the magnetic configuration, heating power, and machine performance to study disruption immunity at high beta with plasma current and 3-D shaping**
* **NCSX will study stabilization of external kinks and vertical instabilities without a close conducting wall**
* **QOS will study configuration invariance to beta and minimization of bootstrap current at low beta**

3a - 1. Does the proposed program address the physics requirements, and does it contribute to the physics (theory and experiment) basis in the following areas? (cont'd.)

Replies:

Generating reliable confinement data at relevant temperatures

- Program will generate data, where none currently exists, on confinement scaling and its improvement at these low aspect ratios
- a range of heating systems (NBI and RF) with MW-level heating power is available for NCSX and QOS to reach keV temperatures and low collisionality

Examining methods of particle and power exhaust

- Will collaborate with foreign stellarator programs on divertor studies
- Compatibility of the NCSX and QOS configurations with divertors will be examined

Examining methods of plasma sustainment

- Program will test the suitability of sustainment by a combination of bootstrap current and external transform at low aspect ratio

3b. Does the proposed program address the technology requirements and does it contribute to the technology basis?

Reply:

- The PoP program relies, as far as possible, on proven technologies used in fusion experiments (e.g., liquid-nitrogen- and water-cooled copper coils, carbon plasma-facing components, existing plasma heating equipment, diagnostics, instrumentation and controls, data acquisition systems). To the extent that R&D and prototyping are required to validate machine-specific design and manufacturing approaches, they are included in the proposed program budgets.
- New plasma technologies that might be needed to meet special requirements of the concept or a new operating mode (e.g., launchers, controllers, fuelers, etc.) would be developed by the technology program as appropriate.
- Reactor system studies will be addressed by the ARIES group in collaboration with scientists and engineers from the compact stellarator program.
- One area in which the program will contribute to the technology base for future compact stellarators is in the development of computational tools for physics and engineering design.

4. LEADING EDGE RESEARCH

In which areas would the proposed research contribute at the leading edge in the context of the national and international fusion programs?

Reply:

- **Test beta limits and disruption avoidance in stellarators at $\langle\beta\rangle \geq 4\%$ (vs 2% now attained in stellarators)**
- **Stellarators with plasma aspect ratio 3-3.5 (vs >6 elsewhere)**
- **Stellarators with bootstrap current as part of the optimization strategy**
- **Test stability to external kink modes and vertical instability without a close conducting wall or feedback**
- **Test of quasi-axisymmetric (NCSX) and low-aspect-ratio quasi-omnigeneous (QOS) stellarator optimization**

4. LEADING EDGE RESEARCH (cont.)

In which areas would the proposed research be behind the leading edge?

Reply:

- Power and particle handling
- Long-pulse/steady-state operation
- Use of superconducting coils

What are the opportunities for leveraging broad knowledge bases?

Reply:

- Theoretical design tools in collaboration with Germany, Japan, Switzerland
- Experimental results from large-aspect-ratio stellarators
  - Beta limits and transport improvement in LHD, and W7-X*
  - Magnetic island divertor studies on LHD, W7-AS, and W7-X*
  - Steady-state operation in LHD, and W7-X*
  - Superconducting coil experience from LHD, and W7-X*
- Experimental results from tokamaks
  - Confinement improvement techniques (e.g., flow shear control)
  - Beta limits and limiting mechanisms
  - Divertor studies

* W7-X operation is not planned until ~2006

5. ENERGY VISION

What is the overall attractiveness of the energy vision for this concept?

Reply:

* **steady-state operation without external current drive**
* **disruption immunity at the beta limit**
* **stability against external kinks and vertical instability without close conducting wall or active feedback systems**
* **stable neoclassical magnetic islands**

Have the important issues been identified?

Reply:

* **key issues identified for the proposed PoP program are beta limits, disruption avoidance at the beta limit, and confinement improvement**

5. ENERGY VISION (cont'd.)

Can the issues be addressed in the context of the broader national and world programs?

Reply:

* **the PoP program will rely on the world stellarator program to resolve steady state and particle and power handling issues and not duplicate those efforts**
* **the PoP program fills a niche not occupied by the existing U.S. and world program of tokamaks and large-aspect-ratio currentless stellarators**

What is the proposed activity to contribute to this effort?

Reply:

* **systems studies to clarify reactor design issues and influence research directions**
* **international collaboration to obtain needed data not not being generated in the U.S. Program**
* **International collaboration on concept optimization and theory**

5. ENERGY VISION (cont.)

What is the potential for energy applications?

Reply:

* **reliable steady-state MFE fusion power plants**

What is the definition and impact on development pathway: costs, schedule and risks?

Reply:

* **the next step in the development pathway (performance extension) would be to extend compact stellarators to steady state and larger size**
* **the PoP program makes it possible to include compact stellarator solutions in the design of an optimized MFE system**
* **reduces risk by providing alternative solutions (i.e., 3-D shaping) to those being pursued by the advanced tokamak**

6. PROGRAM ISSUES

What are construction & operating costs and their basis?

Reply:

* **NCSX:** Construction cost = 44 M$ in constant FY-99 $
* Basis: preconceptual design information, a 5-year construction schedule (2000-2004), experience with similar projects, and detailed knowledge of the PBX systems.
* Operating costs are 20 M$ per year, including facility operations, enhancements, and physics research
* During the construction years, operating costs of 5 M$ expected for experimental preparation activities

* **QOS:** Construction cost assumption ≈8 M$ in constant FY-99 $
* Basis: QOS scoping studies and comparisons with HSX and ATF
* Total budget rising to ≈4 M$ per year after first plasma

6. PROGRAM ISSUES (cont.)

Are there adequate resources to accomplish proposed program goals?

Reply:

* **NCSX:** All of the required financial resources are identified in either the construction project or the research program. The construction project budget includes the device modifications, adaptation of the four PBX-M neutral beam lines, and facility modifications to operate at B = 1.2 T with a basic diagnostic set. The research program budgets include physics research, facility operations, and facility enhancements after first plasma.

* **QOS:** A similar division will be made. The construction project budget will include the device itself, adapting the ATF ECH system, and facility modifications to operate at B = 1T with a basic diagnostic set. The research program budgets include physics research, facility operations, and facility enhancements after first plasma.

6. PROGRAM ISSUES (cont.)

Are there opportunities to be a national research facility?

Reply:

* **NCSX is a national facility. The research program will be led by PPPL and ORNL, with many other institutions collaborating. Currently the University of Texas at Austin, Columbia, Auburn, and Wisconsin are collaborating in the design.**
* **QOS is a joint ORNL - UT-Austin program with PPPL as the main collaborator; other university participants (e.g., Auburn, UT-Knoxville) are expected.**

Are there opportunities to leverage existing facilities?

Reply:

* **NCSX and QOS will use existing facilities from previous experiments.**
* **HSX will provide the first information on quasi-symmetry for NCSX**
* **CAT-Upgrade with OH current will provide some information on kink stability**
* **W7-AS collaborations are providing information on magnetic island divertors**
* **LHD collaborations will provide information on ion confinement scaling and divertors**

7. PORTFOLIO BALANCE

Does the proposed program maintain a balanced portfolio of research opportunities?

Reply:

The compact stellarator program will add needed breadth to the U.S. portfolio of innovative fusion concepts. It will use 3-D shaping to attack critical issues for steady-state, high-beta, disruption-free operation of toroidal confinement systems, complementing the existing world programs in stellarators and advanced tokamaks

Within the proposed program itself, there is also balance:

- **NCSX addresses quasi-axisymmetric optimization with sufficient size, field, and power to test beta limits, disruption immunity, and transport reduction**
- **QOS addresses quasi-omnigeneous optimization with adequate size, field, and power to test bootstrap current reduction, configuratioin invariance with beta, and transport reduction**
- **HSX tests quasi-helical symmetry**
- **CAT-U tests effects of plasma current**

7. PORTFOLIO BALANCE (cont'd.)

- **International collaboration on W7-AS, LHD, and W7-X used to address issues complementary to those in US Compact Stellarator program**
- **Theory focused on concept development and providing a framework for interpretation of experimental results and projections to future devices**

8. SCIENCE/TECHNOLOGY GOALS

How does the proposed program contribute to broad-based national science and technology goals?

Reply:

- **The program's main benefits are primarily of a scientific nature, and primarily within fusion**
- **Stellarators drive the development of 3-D plasma physics, which will aid the understanding of 3-D phenomena such as resistive wall modes and field error effects. These limit performance in nominally 2-D systems like tokamaks and RFPs.**

How does the proposed program contribute to educational opportunities?

Reply:

- **NCSX and QOS would support students from many universities**
- **Numerous MS and PhD theses from PPPL and ORNL experiments**

9. KEY PROGRAM MILESTONES

How does the proposed program contribute to broad-based national science and technology goals?

Reply:

Program milestones and decisions after first plasma were addressed in Question 3. Issue Resolution. Project milestones leading up to first plasma are:

NCSX:

- **Physics Validation Review in September 1999**
- **Conceptual Design Review in March, 2000**
- **1st Plasma in Sept. 2004 with 3.5 M$ increment in FY 2000**
- ***1st Plasma in Sept. 2005 with 0.65 M$ increment in FY 2000***

QOS:

- **Physics Validation Review in April 2000** ***(June 2000)***
- **Conceptual Design Review in Sept. 2000** ***(Dec. 2000)***
- **1st Plasma in June 2003 with 1.3 M$ increment in FY 2000**
- ***1st Plasma in Sept. 2003 with 0.65 M$ increment in FY 2000***