Answers to Questions Posed to Stellarator Community

prepared for Toroidal Alternates Panel
June 30, 2008

1. *Can a more specific primary goal be formulated in terms of the international stellarator program, and more specifically, how the US efforts and goals could contribute in a significant fashion toward that vision?*

- Develop basis for **steady-state** fusion **without disruptions**, compatible with **ignited or high Q** operation
  - Includes 3-D divertor
  - Good alpha particle confinement

- Unique US contributions
  - Physics of quasi-symmetric configurations
  - Development of compact configurations with aspect ratios substantially lower than the LHD and W7-X experiments
  - Configuration design optimization, including physics and engineering constraints.
  - Reactor-design studies and optimization
  - 3D equilibrium modeling and analysis

2. *A second goal in the document focuses on understanding of 3D effects in toroidal confinement. What are more specific objectives and their measurable outcomes?*

- Develop predictive understanding of plasma confinement by stellarator configurations

- Apply understanding and models developed from stellarators to 3D magnetic fields in other magnetic configurations, including equilibrium, stability, and transport properties

- Use experiments with 3D magnetic fields on all configurations to challenge and validate stellarator models and understanding.

3. *The cancellation of NCSX necessitates a revision in the US stellarator program. The committee would like to see an initial cut at a "scientific roadmap" to accomplish these revised goals in the "ITER era" timeframe.*

Community is developing a new map for US stellarator research

Investigation and experimental testing of key scientific and engineering issues

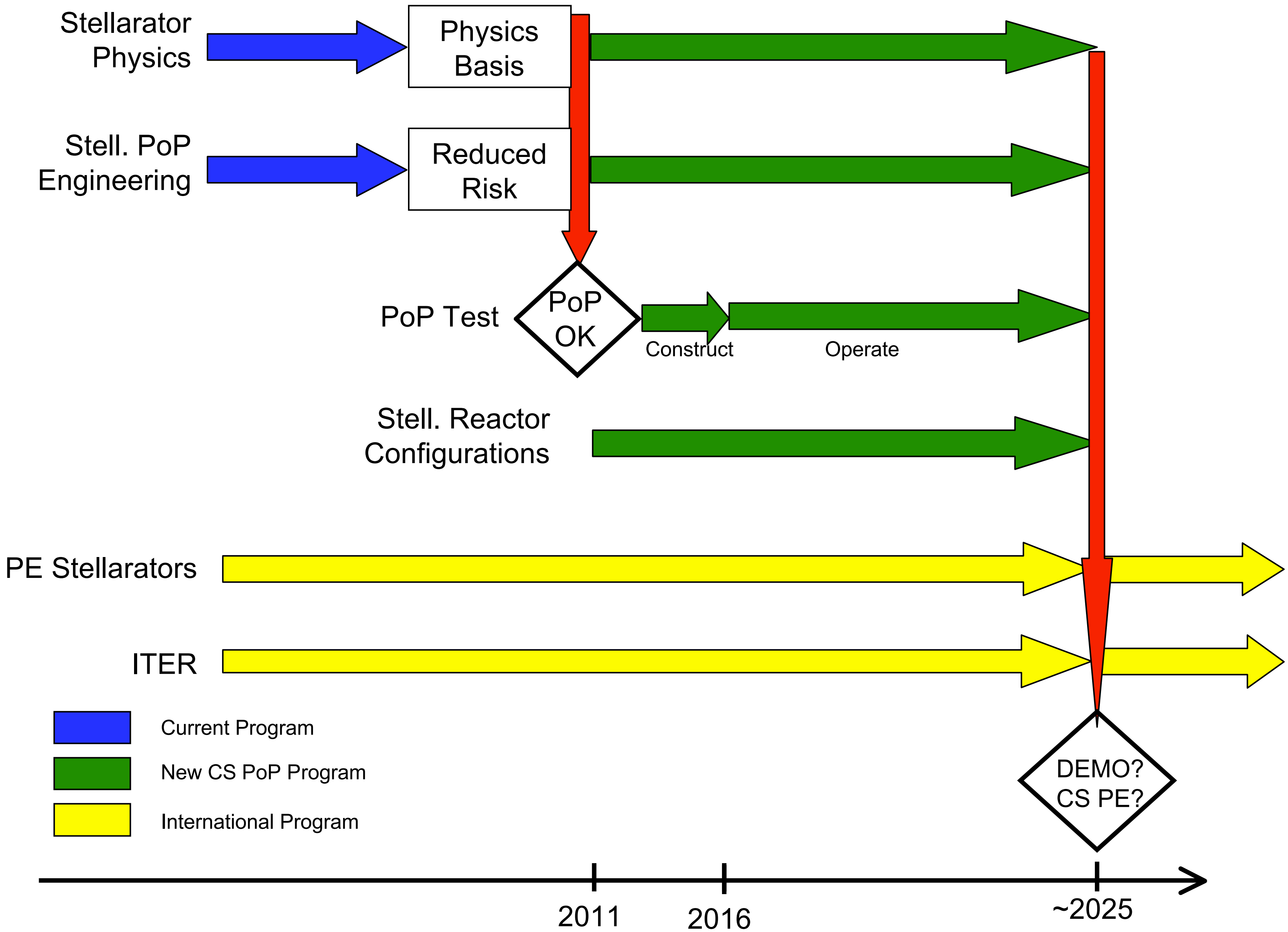
strengthening of stellarator theory, modeling, and international collaboration

Community workshops following TAP will address development of new road map.

Scientific elements of plan

- Understanding of beta limiting mechanisms
- Evaluation of 3-D divertor design and peformance
- Understanding of anomalous transport (particularly ions) in QS plasmas
- Impurity transport in hot dense QS plasmas
- Energetic ion stability and confinement in QS plasmas
- Sensitivity of operating limits to heating profiles
- Engineering issues of high performance QS stellarators

US Stellarator Roadmap



4. The document expressed a view that the stellarator might go straight to DEMO without a specific stellarator-based DT experiment. This step would be based upon ITER results, confidence in predictive modeling, and results from the PE experiments and other experimental data. Under what conditions would this be a credible option? Where is the decision point?

- Any step to DEMO based on verified predictive modeling from ITER

- DT experiments provide information on:
    1. ρ^* scaling
    2. alpha-driven instabilities and losses
    3. effect of fast alpha on plasma-facing components
    4. relation of alpha heating to plasma profiles and thus operational limits

- ITER could provide sufficient information on all in combination with stellarator PE (German vision)
    Stellarators not strongly sensitive to profiles
- Decision point during ITER DT operation.

5. *Divertors are difficult even in an axisymmetric geometry, especially at high power levels. A discussion of divertor problems and options, and their possible resolution within the overall stellarator program would be appreciated.*

- Area of active research in international program (W7-AS, LHD, W7-X)
- 3-D Island divertor -> primary option for optimized modular stellarators
- Impurity screening and detachment observed in high density diverted discharges
- EMC3/EIRENE SOL modeling codes show reasonable agreement with experiment

6. The panel would appreciate hearing a brief discussion of the following physics topics:

- *Can flux surface be made sufficiently robust to field errors and plasma currents?*
  We believe so (iota control, trim coils, configuration optimization)
- *What amount of plasma current is acceptable for disruption elimination?*
  Not known for sure. Stellarators stabilized against kinks by iota control and 3D shaping
- *What is the present understanding of beta limits in stellarators?*
  Soft beta limits observed. Not related to MHD, but likely to transport
- *High density operation as proposed for a reactor: Does this scenario exceed the beta limits or provide excessive divertor loads?*
  No. T is lower.
- *Can sufficient alpha-particle confinement and stability to EPM's be achieved?*
  QS allows low levels of prompt loss (≤ 5% in ARIES-CS). High n, low T predicted to reduce level of AE/EPM
- *How will impurity accumulation issues be addressed without ELM's?*
  High density, radiative divertor.is primary approach, QS may help temperature screening

7. Stellarators require optimization, at a minimum, to reduce collisionless neoclassical transport. Optimization targets are based on our predictive understanding of critical issues and features desired in the configuration. What are these issues, our level of understanding, and what needs to be done to refine our understanding of these targets?

- See white paper

8. Due to their 3D nature stellarators have additional complexity. Simplified coils and constructability were put forth as an issue needing investigation. What were the main problems in coil fabrication and assembly experience from W7X and NCSX and how will more simplified designs be approached? What is desirable versus required?

- See recent submissions to TAP web site for information on W7-X and NCSX construction issues

- Goal of predictable and cost-effective fabrication through experience, and
    - Relaxed physics constraints, e.g. MHD limits
    - Greater use of trim coils (increased construction tolerances)
    - Improved engineering optimization targets (maintainability, acceptable coil distortion levels).
    - Improved physics targets (alpha-particle losses, resonant fields, divertor fluxes, and turbulent transport).
    - Improved strategies for 3D coil construction and system assembly.
    - Continued exploration of 3D shaping possibilities

9. NCSX was designed as a compact device. The ARIES-CS study was based upon a scale up of this design. What are the lessons learned from this study, especially in regard to the level of compactness needed or beneficial for the stellarator? What other problems/issues were identified in this study?

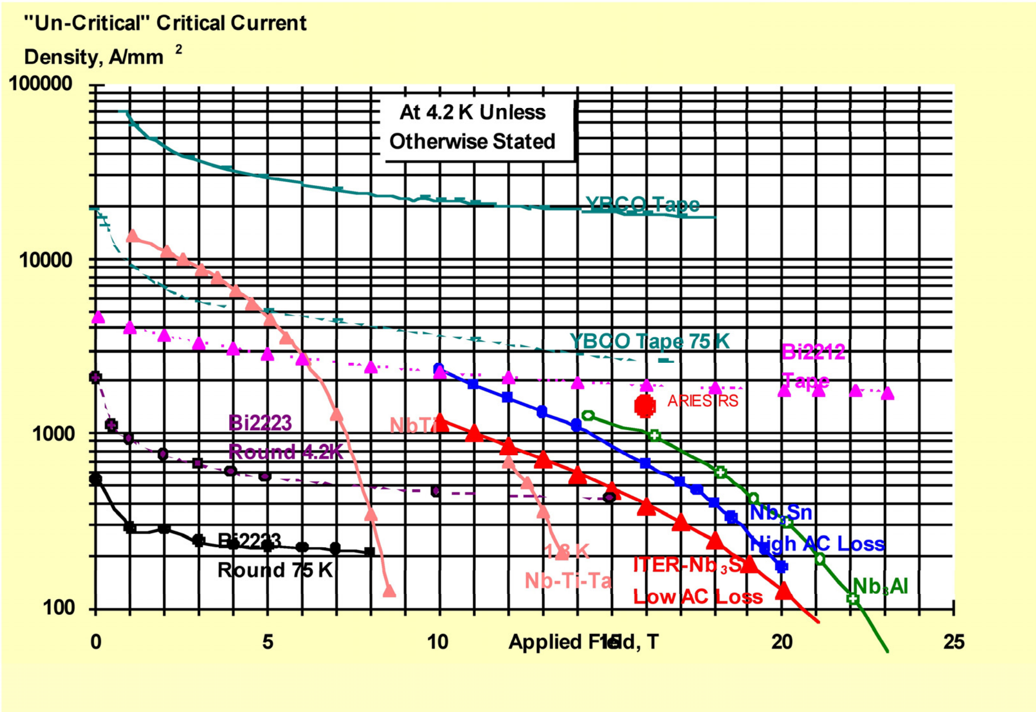
- Compact stellarator power plants feasible
  - increasing machine size relative to Aries-CS provides more engineering margin with small cost penalty.
  - irregular shape of components requires 3D analyses and high degree of integration between analyses and design.

9 ARIES-CS (continued)

- Major R&D needs
  - Development and demonstration of configurations with reduced alpha particle losses, particularly alphas > 10 keV
  - Understand beta limits in stellarators
  - Demonstrate achievement of desired iota profile, with I_{BS}
  - Demonstration of adequate divertor geometries in compact stellarators with highly radiative plasmas
  - Demonstration of plasma startup scenarios and the path to ignition
  - Development of high-field 3D superconducting magnets with required shapes
  - Engineering accommodation of lost alpha particles.
  - Demonstration of methods to fabricate, assemble, and maintain large superconductor stellarators free of resonance-inducing field errors

10. The document supports increased research into use of high temperature superconductors for stellarator applications. Is this a credible step in the near-term? What are the critical fields, bend radii, needed temperatures; what are the specific advantages/disadvantages and opportunities with respect to stellarator applications?

- HTS magnets most likely avenue for steady-state experiments in US program in ITER era
- HTS finding increasing use in power applications(strong ORNL participation)
- Stellarator HTS magnet development path required.



Reproduced from Bromberg, 2006 US/Japan workshop presentation on stellarator magnets

Priorities

11. *The panel would appreciate a discussion of the relative priorities assigned to the various scientific and technical issues raised in the white paper or in response to this request*

Basis for selecting priorities to gaps and opportunities similar to Greenwald Panel Report:

- What is urgency of specific problem?
- What is the state of progress or level of expected effort being devoted to the problem? In what sense is it a gap rather than an ongoing research activity?

- Gaps and opportunities concern US and international program
  - Cancellation of NCSX leaves significant gap in US program
  - Ordering of priorities largely reflect US program needs

Primary Priorities

contribution to goal essential, with comparatively limited work to date

- Predictive capability; validation of models with experiment
  - Predictive understanding coupled with experimental validation vital to effective configuration optimization of stellarators
- Configuration optimization
  - Central to stellarator improvement
  - QS unique element of US program
- Operational limits
  - Limiting behavior, or lack, must be understood to allow optimization for correct physics
- Simpler coil construction
  - Need predictable, cost-effective constructability

Secondary Priorities

contribution to goal highly important, with considerable work performed or underway

- 3-D divertor
  - Essential for steady-state vision
  - Strong pursuit in international program (but not at DEMO scale)
- Transport
  - Energetic ion confinement must be adequate
  - Relation of anomalous transport to underlying configuration
- Impurity accumulation
  - Very important to stellarators in particular
  - QS, HDH mode are approaches with promise
- Advanced coil technologies
  - HTS magnets facilitate US steady-state stellarators

Tertiary Priorities

contribution to 20-year goal significant but not essential, solutions envisioned to be mostly in hand

- Disruptions
  - Not observed in most stellarators
  - Lower priority with cancellation of NCsx
- Start-up/profile control
  - Strong control of profiles not required to access high beta regime; ramp-up requirements minimal
- ITBs
  - Stellarator confinement adequate for BP scenarios
- Maintenance/remote handling
  - Issue dealt with as part of configuration optimization