Report of the Toroidal Alternates Panel

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FESAC Toroidal Alternates Panel

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Charge to FESAC From DoE Under Secretary for Science

- **Focus on Four Toroidal Confinement Concepts**
  - Spherical Torus, Stellarator, Reversed-Field Pinch, Compact Torus(FRC & spheromak)

- **For those concepts that are seen to have promise for fusion energy, please identify and justify a long-term objective for each concept as a goal for the ITER era.**
  - ITER era: when ITER operates (~ next 15-20 years)
  - Panel addressed all four
  - Iterative process with community to identify ITER-era goal
  - Reasonably ambitious and focused goals

- **With that[goal] in mind, I ask that FESAC:**
  1. critically evaluate the goal chosen for each concept, and its merits for fusion development;
  2. identify and prioritize scientific and technical questions that need to be answered to achieve the specified goal;
  3. assess available means to address these questions; and
  4. identify research gaps and how they may be addressed through existing or new facilities, theory and modeling/computation.

- **Identify and prioritize the unique toroidal fusion science and technology issues that an alternate concept can address, independent of its potential as a fusion energy concept.**

Community Input

- **Panel sought advice from the broader fusion community**
  - Website provided opportunity for open input (only filtered for spam)
  - Invitation to participate sent to USBPO, UFA, ICC, FPA, and experiments
  - Invited 15 page submissions by concept advocates and researchers
  - Maintained an interactive process (not an exam): Q&A from panel to community
- **ITER-era goals provided by concept advocates with panel feedback**
- **Concept presentations to the Panel (6/30–7/2 @ DFW Wyndham)**
  - Invited speakers addressed questions sent from panel working groups
  - 2 hr blocks for each concept (60min presentation, 60min discussion)
  - 1 hr for brief public comments each day by request
  - Presentations were open to the public (23 external participants)

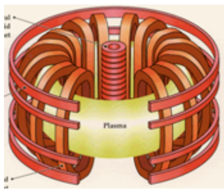
View all input at http://fusion.gat.com/tap/community

Research on Toroidal Alternates Seeks to Reduce the Size, Cost and Complexity of the Fusion Power Core

Stellarator

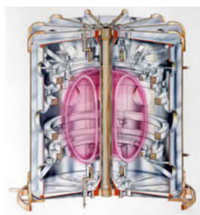
3D coils,
no current drive

Tokamak



Nested sets of
planar coils

Spherical Torus



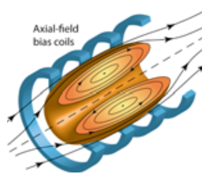
Smaller OH
transformer

Reversed-field
pinch

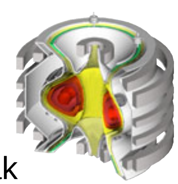
Reduced
TF coils

Compact Torus

Field-reversed configuration



Spheromak



No TF coils

Steady-state “current-free” plasma configuration maintained by external coils

↓

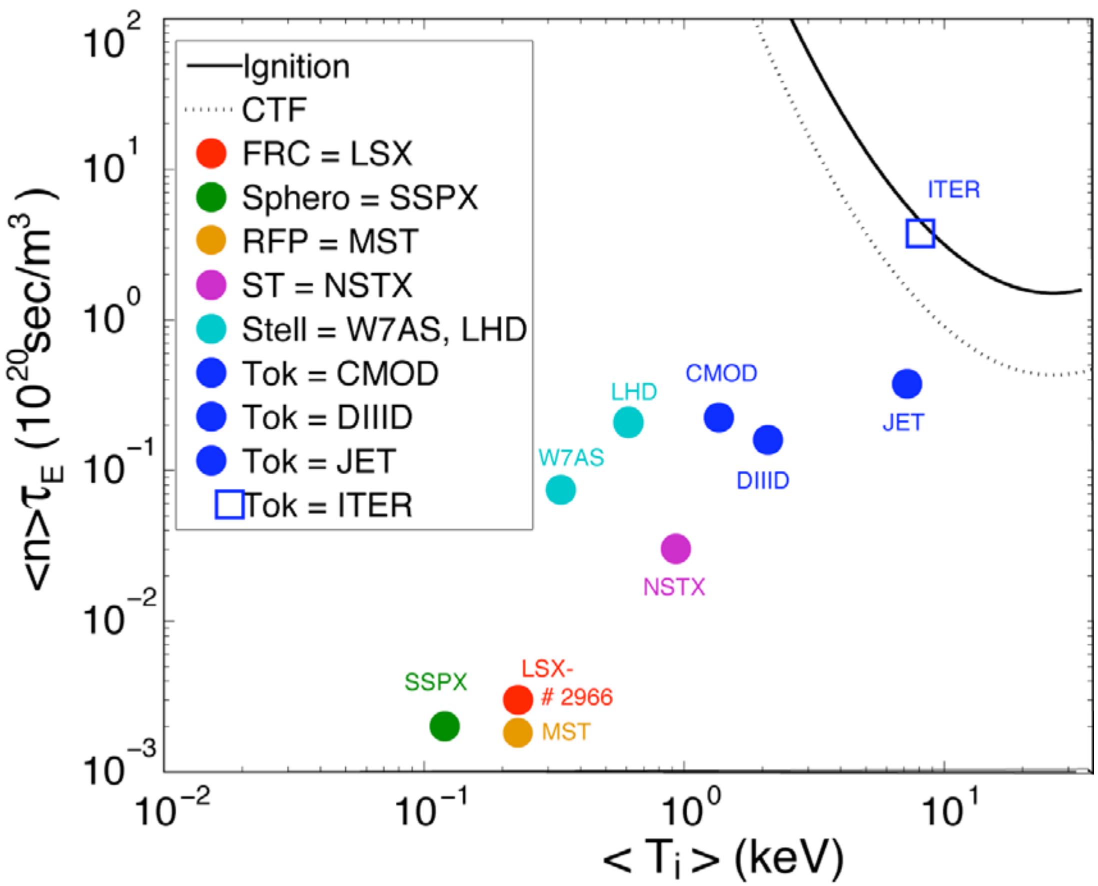
Increasing role of plasma currents in providing confining magnetic fields

↓

Self-organized plasma configuration with internal currents maintaining the fields

Simply-connected plasma chambers

All Approaches to Magnetic Confinement Must Satisfy Lawson Criteria: Some Are Closer Than Others



Must overcome transport and Bremsstrahlung losses for ignition

$$nkT\,\tau_E > 8.3 \text{ atm-sec at } \langle Ti \rangle = 15\text{keV}$$

Fusion power density $\propto \beta^2 B^4$

$$\beta = \frac{2\mu_0 (nkT)}{B^2}$$

Motivates operation at high field and high β. Also note: $\tau_E \propto B$.

MHD stability limits β

Coil engineering constraints limit B, so ratio of B to B_{mag} is important.

General Findings

1. The overall quality of the science in toroidal alternates research is excellent, with broad benefit to the U.S. fusion program and to general plasma sciences including applications to other disciplines. The work is strongly focused on developing scientific understanding as the path forward to achieving ITER-era goals.

2. Alternate Concepts research provides significant benefit to the broader U.S. fusion and plasma science program by effectively recruiting and training bright young people to be our nation's next generation fusion scientists.

3. Predictive simulation plays a central and increasingly visible role in toroidal alternates research, in many cases pushing the state-of-the-art computational capability.

4. Alternate concept research requires similar tools to other parts of the fusion program, but it has uniquely urgent needs in two areas: (1) theory and simulation, which which are particularly challenged by complex 3D resistive MHD physics, kinetic effects, and anomalous transport seen in these experiments; and (2) diagnostic capability, which is especially vital for the less mature concepts. These areas deserve priority emphasis and support within the alternates program to strengthen scientific contributions and solidify projections to next step experiments.

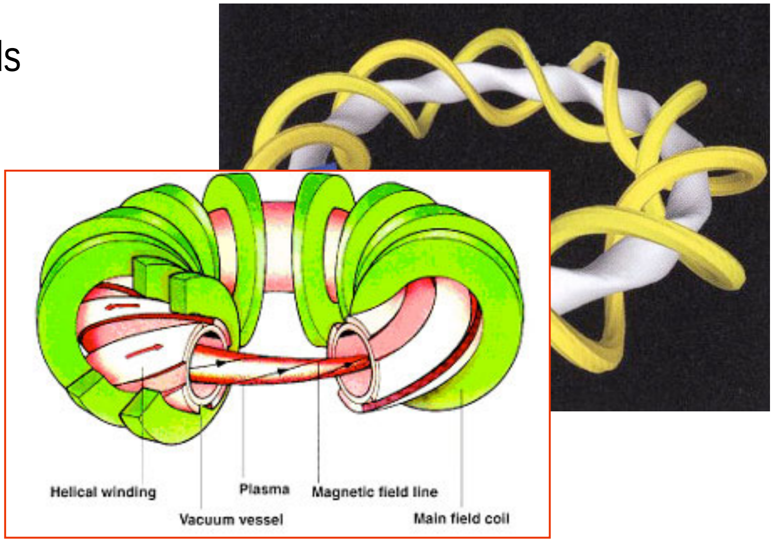
5. <u>Promise for Fusion Energy:</u> Some of the four concepts we have considered are much more highly developed than others, yet all of them require further development and investigation before any definitive assessment of their fusion energy capabilities is possible.

ITER-era Goal for the U.S. Stellarator Research

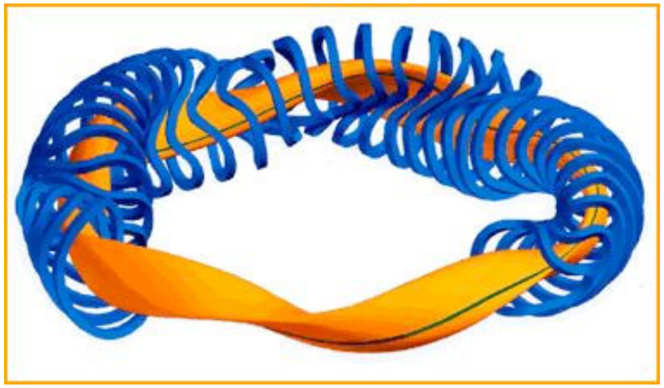
- The Stellarator uses external coils to generate the confining fields and rotational transform, providing steady-state operation with little or no plasma current, no disruptions. Can have large neoclassical transport due to variation in |B|and significant particle trapping. Complex coil geometry, 3D power handling.

- <u>ITER-era goal:</u> *Develop and validate the scientific understanding necessary to assess the feasibility of a burning plasma experiment based on the quasi-symmetric (QS) stellarator.*

- <u>Evaluation Synopsis</u>: *This ITER-era goal addresses critical scientific and technical issues for quasi-symmetric stellarator configurations. Achieving the goal will advance the knowledge of steady-state confinement, but requires significant extrapolation in plasma parameters to demonstrate the benefits of the quasi-symmetry, as well as a design strategy that addresses both robust flux surfaces and manufacturing constraints.*



Modular coils: W7-X
(Germany-under construction)



Highest Priority Issues, Gaps, and Initiatives for Stellarator Research

1. Simpler coil systems with acceptable field errors and manufacturing tolerance
   Gap: No design studies planned for quasi-symmetric stellarators
   Possible Initiative: Systematic study to examine simplified QS designs and error-field correction.

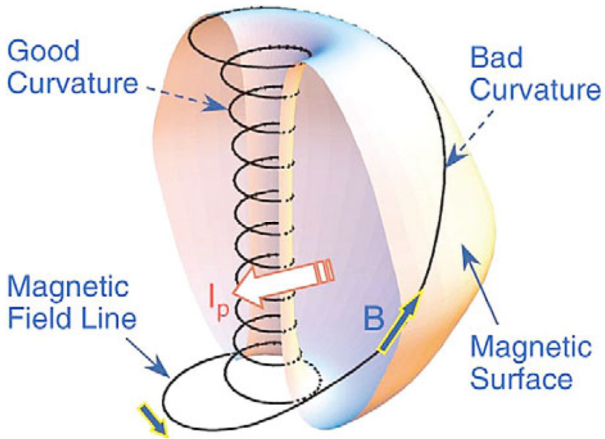
2. High-performance integration of quasi-symmetric optimized stellarators
   Gap: No quasi-symmetric stellarator Proof-of-Principle experiment, no similar compact stellarator.
   Possible Initiative: QS stellarator of sufficient size & power to achieve high beta at low collisionality.

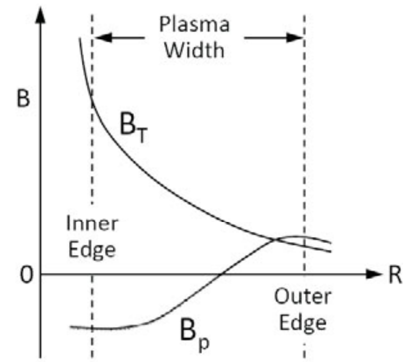
3. Predictive capability for confinement
   Gap: Integrated nonlinear models for 3D turbulent transport and stability.
   Possible Initiative: Integrated modeling and validation program for 3D plasmas (including tokamak).

4. 3D divertor power handling for quasi-symmetric configurations
   Gap: Integrated divertor and core-plasma solution for QS stellarators .
   Possible Initiative: Validate 3D divertor design models with high-power QS stellarator experiment.

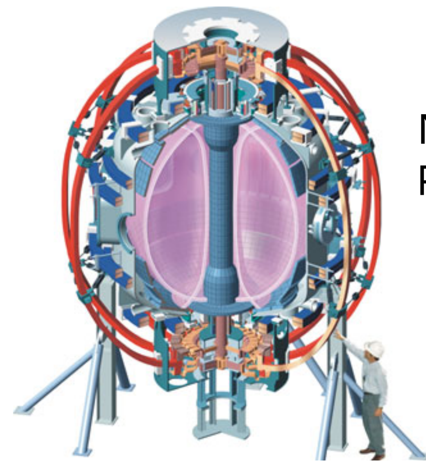
It is clear that to achieve the ITER-era goal a quasi-symmetric experiment of sufficient scale needs to be undertaken within this time frame to demonstrate, in an integrated fashion, that the benefits of quasi-symmetry seen at the Concept Exploration level can be extended to high performance, high beta plasmas.

ITER-era Goal for U.S. Spherical Torus Research





R/a~1.3–1.8, κ=2, q_a=12



NSTX at PPPL

- The Spherical Torus pushes the tokamak to its low-aspect ratio limit: higher beta, smaller unshielded center post, high surface area to volume ratio may enable a facility for testing fusion components. Requires non-inductive current ramp-up and sustainment and has high-current single-turn TF return in nuclear environment.

- <u>ITER-era goal:</u> *Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demonstration fusion power plant.*

- <u>Evaluation Synopsis</u>: *The ITER-era goal is clear, well motivated, and tied tightly to the overall fusion energy roadmap. Achieving this goal will advance knowledge of low-aspect ratio tokamak confinement, but entails significant extrapolation in non-inductive current drive, electron transport, power handling, and magnet technology.*

Highest Priority Issues, Gaps, and Initiatives for Spherical Torus Research

1. Start-up and ramp-up to multi-MA toroidal currents in over-dense plasmas
   Gap: Upgrades to existing experiments will likely achieve ≤ 1 MA toroidal currents.
   Possible Initiatives: New experiments testing scaling to Ip > 2MA.

2. Normal and off-normal divertor heat flux at high power
   Gap: Must test divertor solutions at 6x higher power density with appropriate geometry.
   Possible Initiatives: Divertor, power upgrades to existing exps, new experiments, edge models.

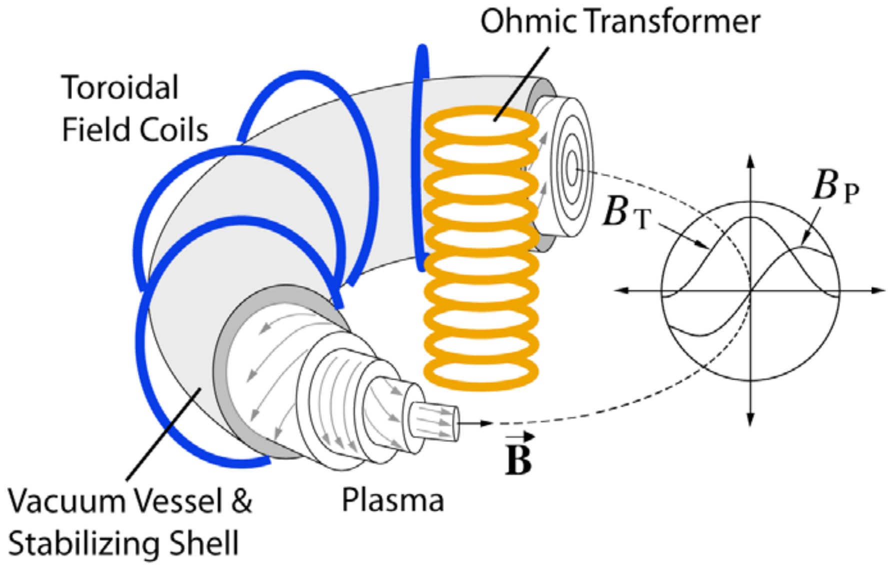
3. Electron energy transport at high temperature and low collisionality
   Gap: Electron transport scaling and modeling at 10x higher Te with low collisionality.
   Possible Initiatives: Upgrades to existing experiments, new experiments, validated simulations.

4. Reliable center post magnets and current feeds with high neutron fluence
   Gap: Demonstration of single-turn TF return with B_m ~ 8Tesla and radiation-resistant insulators.
   Possible Initiatives: Engineering R&D on appropriate magnet technologies.

The ITER-era goal requires significant extrapolation in plasma performance and the level of knowledge required. In some areas there is a sound technical basis for extrapolation but in many others the science is incomplete or untested. Achieving the ST goal is likely to require very significant resources.

ITER-era Goal for U.S. Reversed-Field Pinch Research

- The Reversed-Field Pinch uses internal currents to produce most of the toroidal magnetic field with sufficient ohmic current to drive q below unity. High field in plasma relative to field at the coils. Internal magnetic fluctuations or "plasma dynamo" sustains current, but opens field lines via reconnection. Steady-state requires non-inductive current drive in over-dense plasma.



- <u>ITER-era goal:</u> *Establish the basis for a burning plasma experiment by developing an attractive self-consistent integrated scenario: favorable confinement in a sustained high beta plasma with resistive wall stabilization.*

- <u>Evaluation Synopsis</u>: *The ITER-era goal is clear and addresses critical scientific and technical issues for the RFP approach. Achieving this ambitious goal would establish the possibility for a low-external field approach to magnetic fusion. Significant challenges in establishing current sustainment with good confinement will need to be overcome to realize this goal.*

Highest Priority Issues, Gaps, and Initiatives for Reversed-Field Pinch Research

1. Confinement scaling and transport mechanisms

   Gap: 3x smaller ρ^* in experiment and Lundquist number >10x smaller in both simulation and experiment

   Possible Initiatives: Advanced PoP-level experiments with longer pulse and higher current; new experiment; faster simulations

2. Current sustainment by oscillating field current drive (OFCD) or long-pulse inductive operation

   Gap: Higher plasma temperatures and fields to increase OFCD efficiency (>10x higher Lundquist number)

   Possible Initiatives: Long pulse, high temperature experiment to demonstrate 100% OFCD.

3. Integration of current sustainment and good confinement at high Lunquist number ($\tau_R/\tau_A \propto I_p T_e^{3/2}\sqrt{n_e}$)

   Gap: Higher plasma temperatures and RWM control are needed to achieve 100% OFCD without large perturbations

   Possible Initiatives: Initial tests in advanced PoP-level experiment followed by new PE experiment achieving multi-MA, multi-keV temperatures with RWM control and OFCD; new or upgraded two-fluid and gyrokinetic codes.

Achieving the ITER-era goal requires significant increase in plasma parameters; risk could be mitigated by a step-wise approach involving research on current experiments, proceeding to an advanced Proof-of Principle experiment, and finally to a Performance Extension experiment as results warranted.

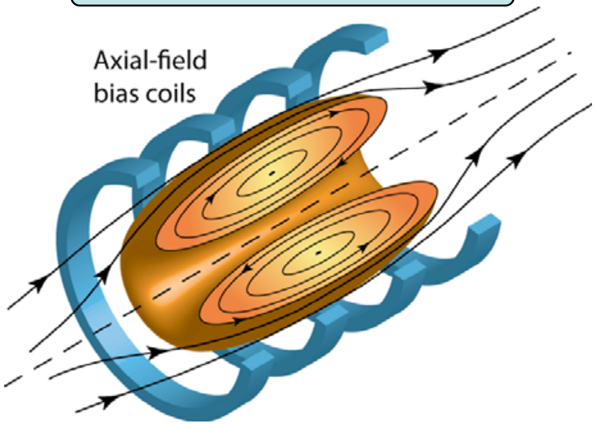
ITER-era Goal for U.S. Compact Torus Research

- Compact torus configurations use self-organized internal plasma currents to produce the confining magnetic field. The CT program involves the spheromak and the field reversed configuration (FRC). The FRC has no toroidal field, diamagnetic currents only, β~1 stabilized by finite Larmor radius effects. Spheromak has toroidal and poloidal currents sustained by magnetic fluctuations.

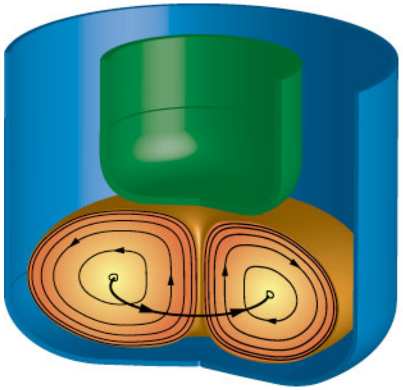
- ITER-era goal: *To demonstrate that a compact toroid with simply connected vessel can achieve stable, long-pulse plasmas at kilovolt temperatures, with favorable confinement scaling to proceed to a pre-burning CT plasma experiment.*

- Evaluation Synopsis: *The ITER era goal for the CT is clear and aims for critical progress toward fusion energy with self-organized plasmas; achieving this goal would advance and validate magnetic confinement in a simply-connected chamber with no external toroidal field. However, the goal is highly ambitious, requiring a large extrapolation in stability, confinement, and sustainment, and there is limited theoretical or experimental basis for prediction.*

Field Reversed Configuration



Spheromak inside flux conserver



Highest Priority Issues, Gaps, and Initiatives for Compact Torus Research

1. MHD stability of the FRC at low collisionality with large-s ($a/\rho_i \geq 30$)
   Gap: Experimental demonstration with s ≥ 10; MHD calculations showing stability with s ≥ 10
   Possible Initiatives: New experiments with higher field and larger radius

2. Efficient spheromak formation techniques to achieve multi-Tesla magnetic fields
   Gap: Experiments achieve 1 Tesla or less with limited flux amplification
   Possible Initiatives: Extensive resistive MHD simulations, new experiments to test formation techniques

3. Efficient sustainment with good confinement (FRC and Spheromak)
   Gap: FRC: 10x increase in plasma current Spheromak: Efficient sustainment at multi-MA currents
   Possible Initiatives: Larger size RMF facility or tangential neutral beam (FRC); Flexible multi-pulse spheromak.

4. Transport (FRC and Spheromak)
   Gap: FRC: Transport properties are unknown. Spheromak: Large uncertainties in ohmic input power.
   Possible Initiatives: Profile measurements in the FRC, auxiliary heating in the spheromak.

Although it would require a major increase in CT funding to significantly advance CT research, this would have only a modest impact on the overall fusion budget. A combination of improved diagnostics, theory and simulation is needed to show how either concept can solve its difficult physics problems before making a large new step.

Summary

- ITER-era goals have been identified and evaluated for each concept
  - All are ambitious, some more so than others.
  - Working towards these goals will yield important benefits to fusion science
  - Reaching these goals would be a significant achievement for fusion energy development
- Scientific and Technical issues have been identified and prioritized
  - Strong consensus on the most important issues, which are clearly motivated by ITER-era goals
  - Resolving these issues requires coordinated effort in theory and experiment for fundamental understanding
  - Should clearly inform follow-on DoE strategic planning process (ReNeW)
- Assessed existing capabilities (including upgrades) and identified gaps
  - Upgrades to existing facilities, codes, and diagnostics can in many cases yield important new information
  - Significant extrapolation in plasma parameters are required to validate physics basis for ITER-era goals
  - Ultimately, achieving ITER-era goals will require new capabilities (simulation and experiment) for all concepts
- Identified broad scientific benefits for research on these toroidal magnetic alternate concepts
  - Many shared issues among alternates (and the tokamak) mean shared tools, approaches, and relevant results
  - Effective vehicle for recruiting and training bright young scientists for the U.S. fusion program