# Report of the Toroidal Alternates Panel

David N. Hill (Panel Chair) Lawrence Livermore National Laboratory

**FESAC Toroidal Alternates Panel**

| | | |
|---|---|---|
| David Anderson | University of Wisconsin | dtanders@facstaff.wisc.edu |
| Jeff Freidberg | MIT | jpfreid@mit.edu |
| Martin Greenwald | MIT | g@psfc.mit.edu |
| Houyang Guo | RPPL @ U. Washington | guo@rppl.aa.washington.edu |
| Rich Hazeltine (VC) | U. Texas | rdh@physics.utexas.edu |
| Dave Hill (Chair) | LLNL | hilldn@fusion.gat.com |
| Bick Hooper | LLNL | hooper1@llnl.gov |
| Hantao Ji | PPPL | hji@pppl.gov |
| Tim Luce | General Atomics | luce@fusion.gat.com |
| Dale Meade | FIRE | dmeade@pppl.gov |
| Jon Menard | PPPL | jmenard@pppl.gov |
| Martin Peng | ORNL | pengym@ornl.gov |
| John Sarff | U. Wisconsin | jssarff@facstaff.wisc.edu |
| John Sheffield | ISSE @ U. Tennessee | jsheffi1@utk.edu |
| Xianzhu Tang | LANL | xtang@lanl.gov |
| Ed Thomas | Auburn U. | etjr@physics.auburn.edu |
| Mike Zarnstorff | PPPL | zarnstorff@pppl.gov |

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

# 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

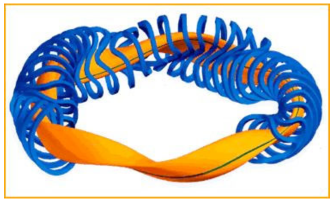
- **ITER-era goals provided by concept advocates with panel feedback**

- **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**

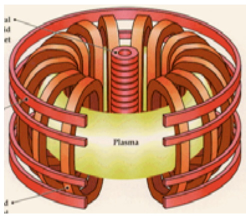
# Research on Toroidal Alternates Seeks to Reduce the Size, Cost and Complexity of the Fusion Power Core

Stellarator



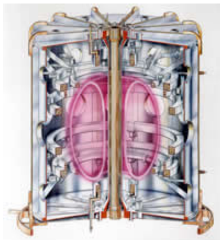
3D coils,
no current drive

Tokamak



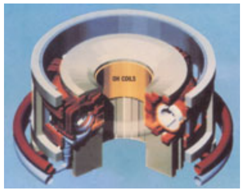
Nested sets of planar coils, some current drive

Spherical Torus



Smaller OH transformer

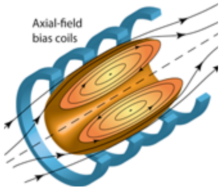
Reversed-field pinch



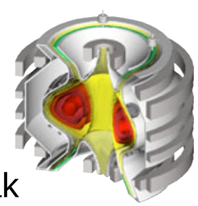
Reduced TF coils

Compact Torus

Field-reversed configuration




Spheromak



No TF coils

Steady-state "current-free" plasma configuration maintained by external coils

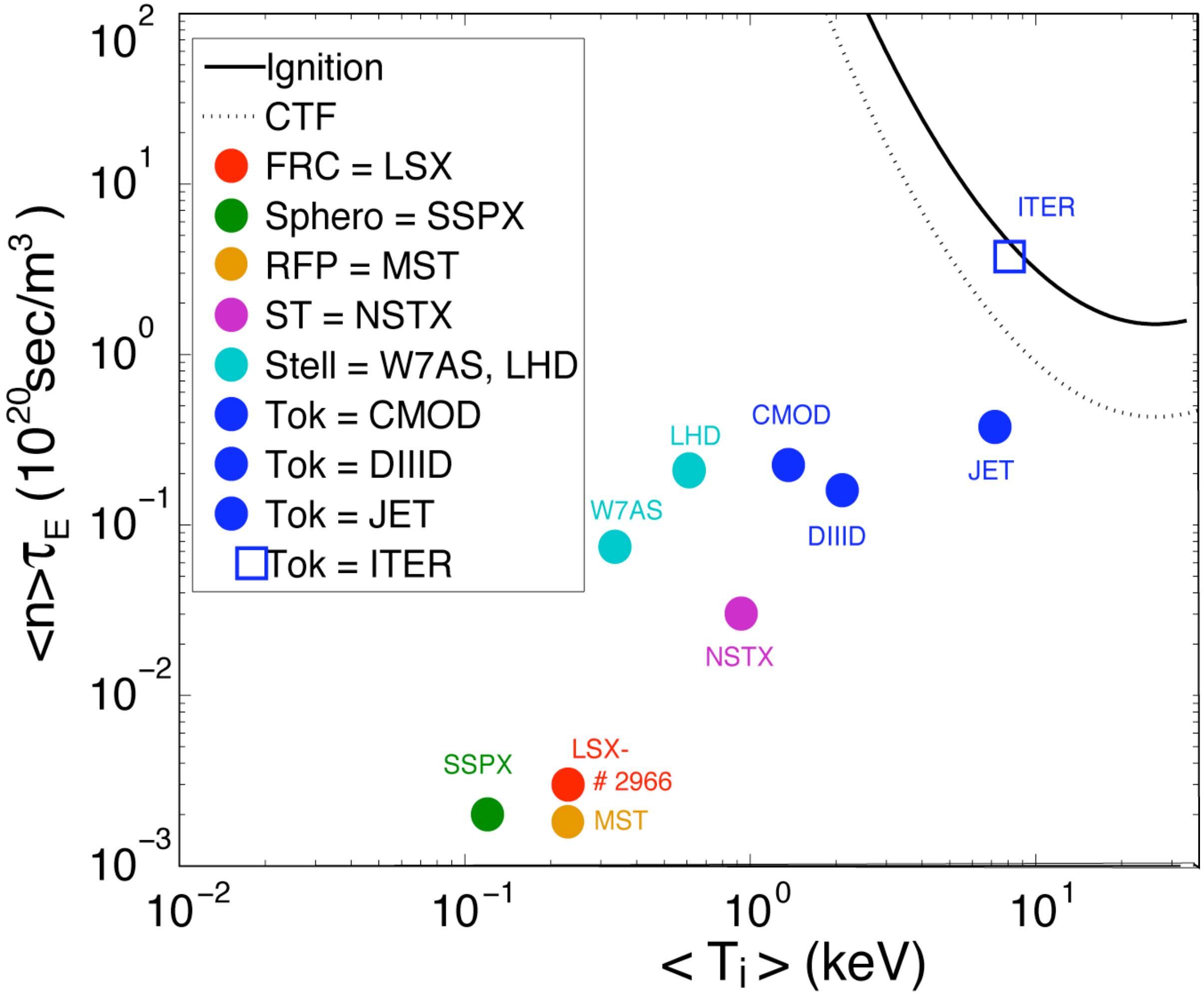
Increasing role of plasma currents in providing confining magnetic fields

Self-organized plasma configuration with internal currents maintaining the fields

Simply-connected plasma chambers

Adapted from slide provided by John Perkins of LLNL

# 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 $\beta$. Also note: $\tau_E \propto B$.

MHD stability limits $\beta$

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

# Five General Findings Regarding Alternate Concepts

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.

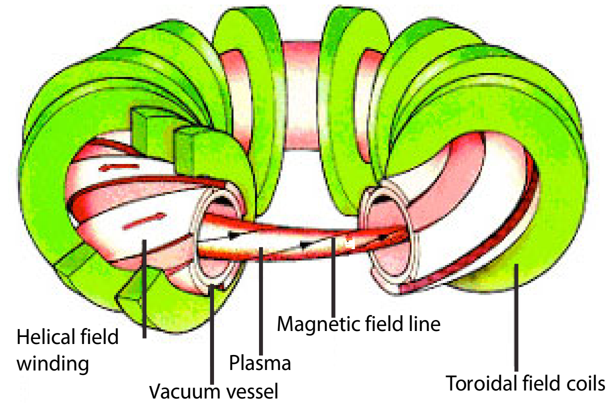
3. Predictive simulation plays a central and increasingly visible role in toroidal alternates research, in many cases pushing the state-of-the-art computational capability.

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.

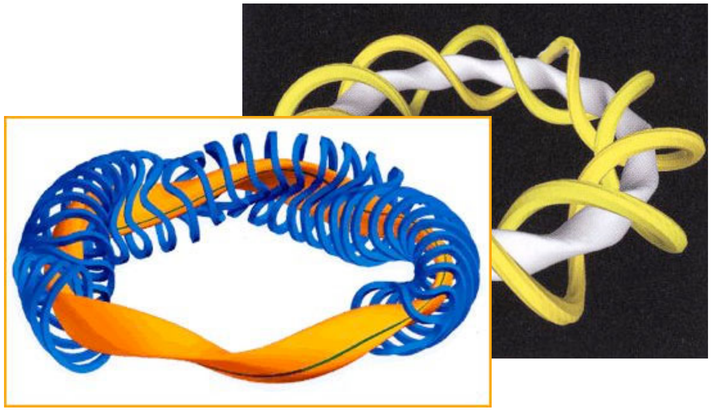
5. Promise for Fusion Energy: Some of the four concepts we have considered are much more highly developed than others, yet all of them require further development and investigation before any definitive assessment of their fusion energy capabilities is possible.

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

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

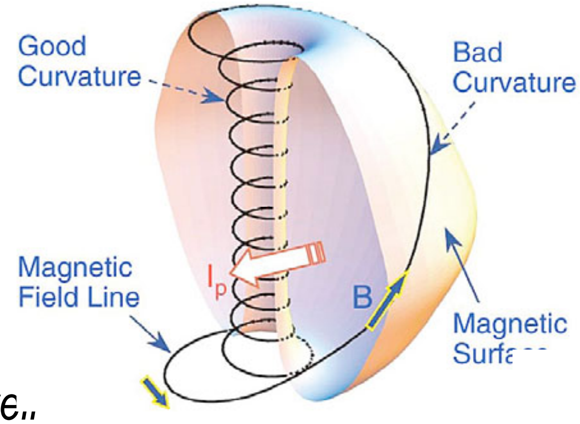


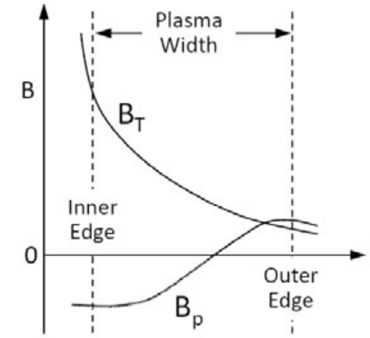

- Panel Evaluation Synopsis: *This ITER-era goal addresses critical scientific and technical issues for quasi-symmetric stellarator configurations. Achieving the goal will advance the knowledge of steady-state confinement, but requires significant extrapolation in plasma parameters to demonstrate the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



- Highest Priority Scientific Issues
  - Simpler coil systems: *Can we find ways to reduce the fabrication risk of optimized high performance stellarators?*
  - High performance integration: *Can improvements observed in smaller experiments be carried over to a high performance level device and what are its required attributes?*
  - Predictive capability: *Can a predictive capability for quasi-symmetric systems be developed by building upon the work in the tokamak program coupled with a smaller experimental database?*
  - Power handling: *Can a divertor solutions be found for a 3D stellarator system compatible with quasisymmetry?*

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

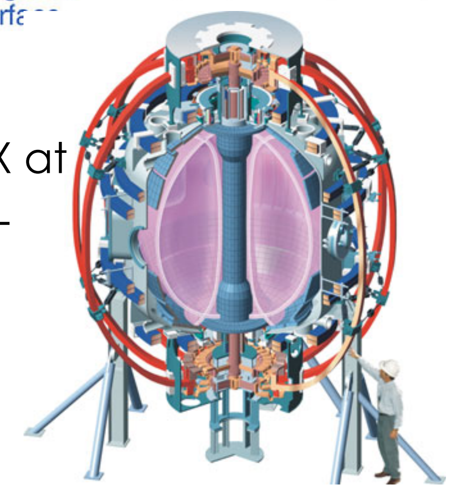



- <u>ITER-era goal:</u> *Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demonstration fusion power plant.*

- <u>Panel Evaluation Synopsis</u>: *The ITER-era goal is clear, we.. 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.*

NSTX at PPPL



- <u>Highest Priority Scientific Issues</u>

  Startup and ramp-up: *Is it possible to start-up and ramp-up the plasma current to multi-MA levels using non-inductive current drive with minimal or no central solenoid?*

  First-wall heat flux: *What strategies can be employed for handling normal and off-normal heat flux consistent with core and scrape-off-layer operating conditions?*

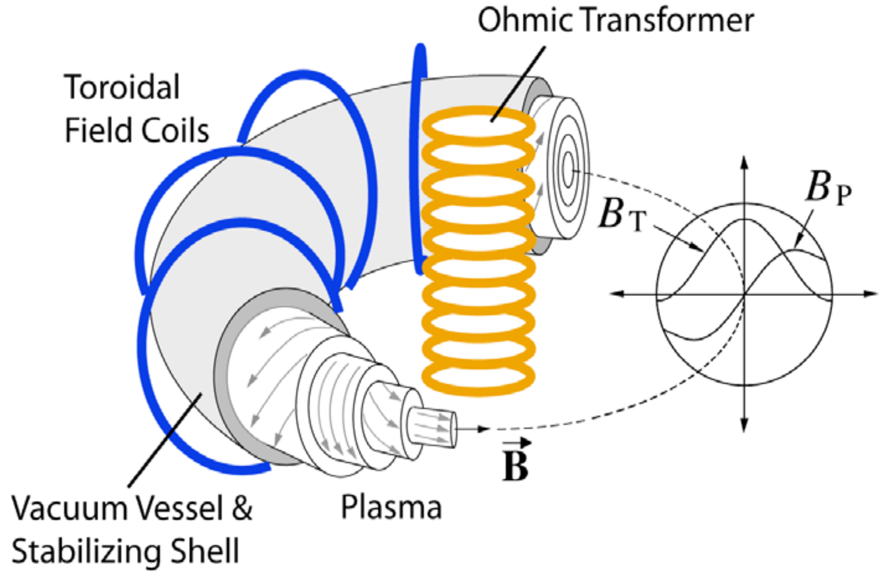
  Electron transport: *What governs electron transport at low-aspect ratio and low collisionality?*

  Magnets: *Can we develop reliable center post magnets and current feeds to operate reliably under substantial fluence of fusion neutrons?*

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

- ITER-era goal: *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.*

- Panel Evaluation Synopsis: *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 Scientific Issues

  Confinement and Transport: *What governs transport when magnetic fluctuations are reduced and how does energy confinement depend upon Lundquist number?*

  Current sustainment: *Can Oscillating Field Current Drive sustain the RFP configuration with high efficiency as compared to long-pulse induction?*

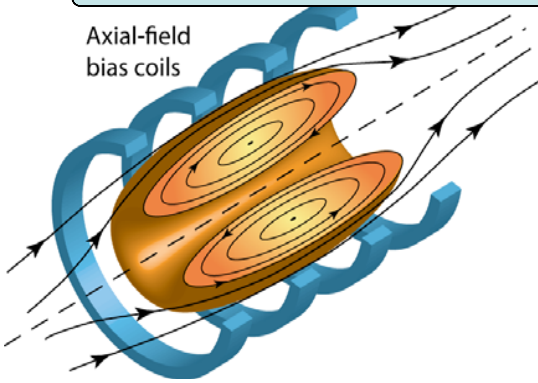
  Integration: *Is good confinement compatible with current sustainment at high Lundquist number?* $(\tau_R/\tau_A \propto I_p T_e^{3/2}\sqrt{n_e})$

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

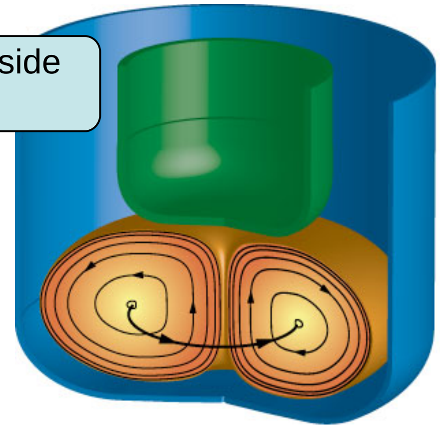
- <u>ITER-era goal:</u> *To demonstrate that a compact toroid with simply connected vessel can achieve stable, long-pulse plasmas at kilovolt temperatures, with favorable confinement scaling to proceed to a pre-burning CT plasma experiment.*

- <u>Panel Evaluation Synopsis</u>: *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



- <u>Highest Priority Scientific Issues</u>

FRC – Stability: *Is global stability possible at large-s ($a/\rho_i$)in low collisionality FRCs?*

Transport: *What governs energy transport and can it be reduced at high temperature?*

Sustainment: *Is energy-efficient sustainment possible at large-s and is it compatible with good confinement?*

Spheromak– Sustainment: *Can efficient time-averaged current drive be maintained with good confinement?*

Formation: *Can formation and buildup techniques be developed to achieve fusion relevant magnetic fields?*

Transport: *What mechanisms govern transport and confinement in low collisionality spheromak plasmas?*

# Toroidal Alternates Research Provides Significant Benefit to the Broader US Fusion Program

- **Unique capabilities for scientific research on important topics with broad impact**
  - Dynamos, Reconnection Physics, and Resistive MHD (astrophysics, disruptions, tearing modes)
  - Symmetry and 3D Field Effects (ELM control, rotation, flows, and error fields)
  - Neoclassical transport (confinement scaling, ELMs, tokamak pedestal)
  - Magnetic and electrostatic turbulent transport (pedestal, error fields )
  - Power Handling and Particle Control (pushes limits, isolates geometric effects)
  - Non-Inductive Current Drive (startup, rampup, and sustainment, profile control)
  - Magnetic Self-Organization (astrophysics, MHD stability, transport)

- **Concept development must address common issues for magnetic fusion energy**
  - Plasma Energy confinement, transport, and overall energy balance
  - Configuration sustainment (e.g., current drive)
  - Operating limits (e.g., absolute plasma pressure for given coil limits)
  - Plasma thermal loads and PFC lifetimes (e.g. divertors)
  - Plasma exhaust particle control, overall tritium cycle
  - Wall neutron loading

# 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