Fusion Engineering Science

Subgroup A

(Science questions for Materials and Plasma Chamber)

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Subgroup B

(Science questions in technologies for plasma heating, confinement, and control)

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T13: How does the challenging fusion environment affect plasma chamber systems?

T14: What are the operating limits for materials in the harsh fusion environment?

As the US actively seeks opportunities to explore the physics of D-T burning plasma, the importance of establishing the needed material and plasma chamber engineering science knowledge base moves to the forefront of issues.

This knowledge base is required to:

- support the construction and safe operation of ITER
- provide the capabilities for testing blankets in ITER
- demonstrate the feasibility of the D-T fusion fuel cycle in a practical, safe system compatible with plasma operation.

Challenging Environment:

The plasma chamber and its materials must provide simultaneously for:

- Power extraction
- Tritium breeding, extraction, and control
- Structural integrity, high performance, high temperature, reliability, and maintainability

Under extreme conditions of high heat and particle fluxes, energetic neutrons, intense magnetic field, large mechanical and electromagnetic forces and complex geometry

The components and materials surrounding the plasma must be compatible with plasma stability and operation and exhibit favorable safety and environmental features, while *withstanding a fusion environment significantly harsher than any existing nuclear system*

Scientific Phenomena:

Many complex scientific phenomena occur within and at the *interfaces* among coolants, tritium breeders, neutron multipliers, structural materials, conducting shells, insulators, and tritium permeation barriers.

EXAMPLES:

- magnetohydrodynamic reorganization and damping of turbulent flow structures and transport phenomena in conducting coolants
- neutron-induced ballistic mixing of nano-scale strengthening features in structural materials
- fundamental deformation and fracture mechanisms in materials
- surface chemistry desorption and recombination phenomena in tritium breeding ceramics

Integral Part of the Broader Science

Understanding these phenomena requires utilizing and expanding on advances in computational and experimental methods in material science, fluid mechanics, MHD, chemistry, nuclear physics, particle transport, plasma-material interactions, and other disciplines.

RESEARCH APPROACH

Focus on the following Thrusts:

A. Develop plasma chamber systems and materials knowledge to support the construction and operation of ITER, including blanket testing capability in the fusion environment

B. Establish the engineering science base required for the D-T cycle

C. Identify performance limits for materials and plasma chamber technologies

Each thrust has both critical ***experiments*** and ***simulation*** aspects that need to be developed together to achieve understanding of phenomena, resolution of scientific questions, and development of usable components.

Research Thrust A: ***Develop plasma chamber systems and materials knowledge to support the construction and operation of ITER, including blanket testing capability in the fusion environment***

1. **What will be the true Nuclear Environment and machine response in ITER?** ITER as the first large-scale, long-pulse DT burning machine, presents many challenges for safety and nuclear design, some of which still need more accurate predictive capability and more detailed analysis to fully resolve.

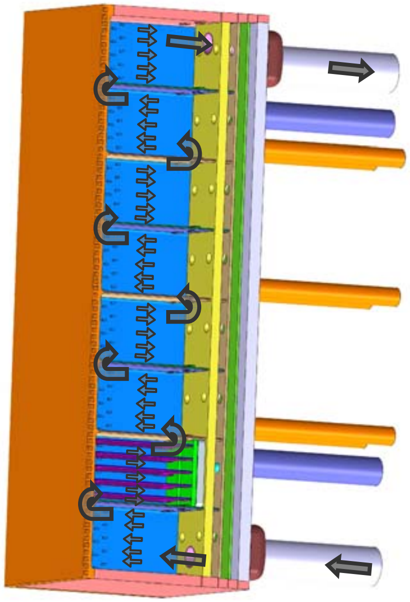
   Improve simulation codes required for more detailed nuclear and safety analysis to support ITER construction and licensing

2. **How will blanket components and materials behave in an Integrated Fusion Environment?** ITER will be utilized as the first integrated nuclear fusion environment for testing of blanket designs and materials.

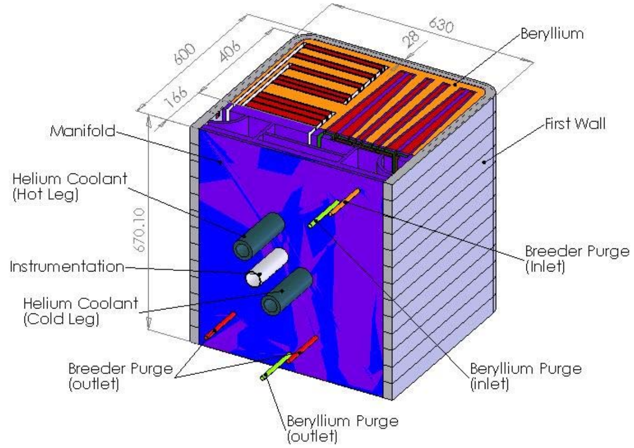
   Provide Scientific and Engineering Basis for ITER Test Blanket Modules (TBM) which will investigate issues such as tritium breeding and recovery, materials interactions, MHD flows, and thermomechanical interactions

Blanket Testing in ITER is one of ITER's Key Objectives

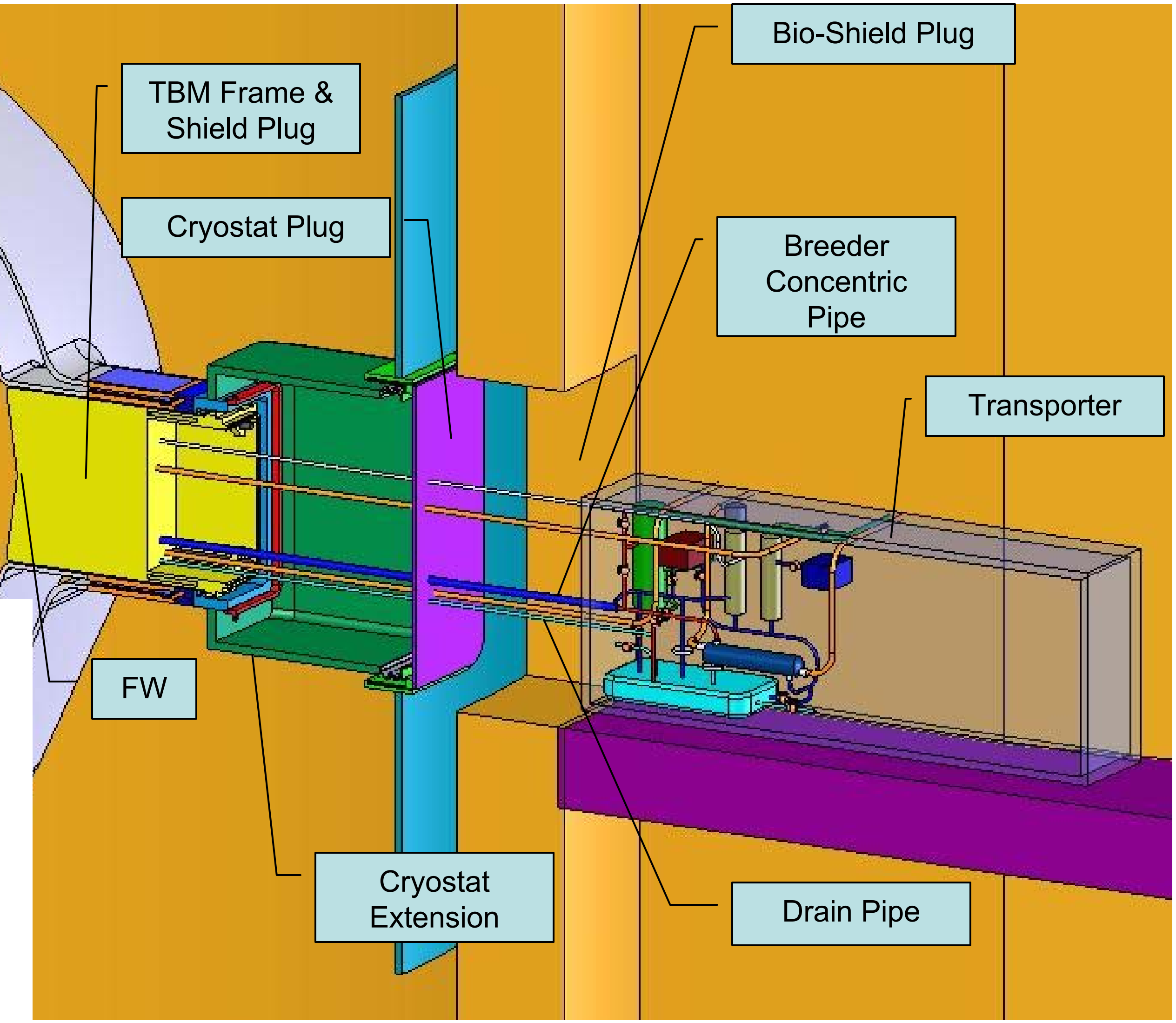
Strong international collaboration among the ITER Parties is underway to provide the science basis and engineering capabilities for ITER TBMs



EU HCLL Test Module



US Solid breeder submodule



Conceptual Liquid Breeder Port Layout and Ancillary equipment

Research Thrust A: ***Develop plasma chamber systems and materials knowledge to support the construction and operation of ITER, including blanket testing capability in the fusion environment (continued)***

Examples of Capabilities Required for ITER Test Blanket Module Experiments:

- Capability for simulation of 3-D magnetohydrodynamic (MHD) forces distribution in liquid breeder flows including effects on drag, turbulent mixing, and flow distribution in complex geometry.
- Experimentally-validated mechanical-property and dimensional stability models of the effects of combined material and environmental variables on the behavior of low activation martensitic steel
- Experiments and phenomenological and computational models to address other key issues for blanket modules such as:
    - behavior of electrical and thermal insulators
    - tritium permeation barriers
    - chemistry control and material compatibility

Research Thrust B: *Establish the engineering science base required for the D-T cycle*

1. **What is the “phase-space” of plasma, nuclear and technological conditions in which tritium self-sufficiency can be attained?**

   Tritium self-sufficiency is affected by all aspects of the fusion system including: the plasma configuration, operation modes and parameters (fractional burn-up, edge recycling, power excursions, disruptions), the control systems for plasma stability, heating and exhaust embedded in the blanket (shells, coils, RF and beam ports, divertors), safety considerations and many other factors in addition to the blanket and tritium processing systems

   Parallel and highly interactive research in plasma physics, plasma control technologies, plasma chamber systems, materials science, safety, and systems analysis is required (significant interactions with many plasma physics thrusts)

2. **Is there a practical blanket system that can exist in this phase-space?**

   A critical element in assessing the engineering feasibility of the D-T cycle in a practical system is the development and testing of blankets and materials that can safely operate in the integrated fusion environment at reactor-relevant neutron and surface heat fluxes for prolonged periods of time at high temperature with sufficient reliability and maintainability.

   Extensive modeling of materials and plasma chamber phenomena along with select experiments in various laboratory-scale facilities and fission reactors will be utilized to supplement ITER testing in providing the scientific and engineering knowledge-base at more demanding environmental conditions.

Research Thrust B: *Establish the engineering science base required for the D-T cycle (cont'd)*

Research focus areas for this thrust include (examples):

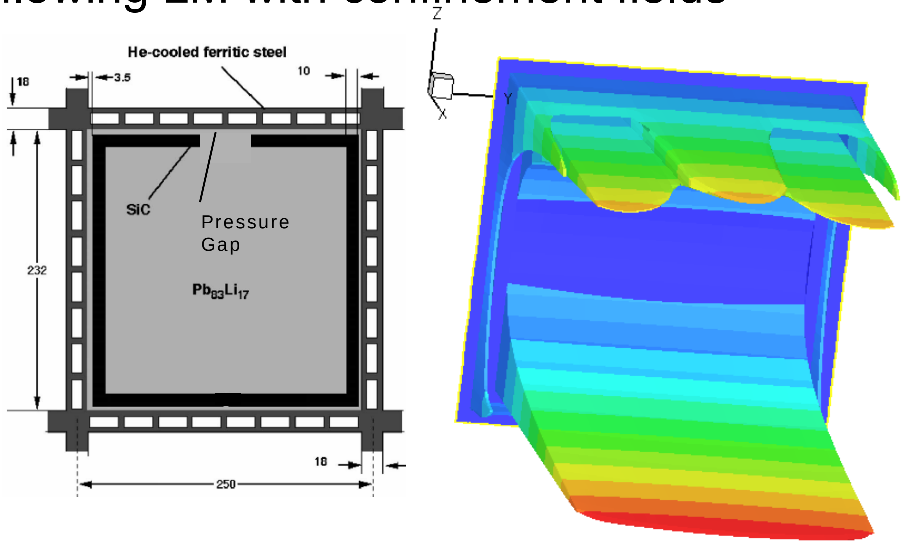
- ☐ Modeling and experimental investigation of the transport, fate, and consequences of fusion-relevant levels of transmutant helium in reduced-activation materials.
- ☐ Physically-based interaction mechanisms studied in experiments with unit cells of breeder/multiplier/coolant/structure/insulators.
- ☐ Experiments and micro-structure models to explore high-temperature radiation-induced sintering and low-temperature tritium diffusion in ceramic breeders and their effects on the allowable operating temperature "window", which is essential to assessing the tritium breeding potential in solid breeders.
- ☐ Novel methods to divert eddy currents generated in liquid metal coolants away from the walls, and hence control the MHD drag and suppress turbulence

This research will be critical in guiding fusion plasma physics research and technology R&D toward the path for a truly "renewable" energy source

Understanding of phenomena is a critical element of Plasma Chamber and Materials research

***Example*: Liquid Metal Magnetohydrodynamics (MHD)**

- Liquid metal blanket designs have the best potential for high power density, but magnetohydrodynamic interactions of the flowing LM with confinement fields leads to:
  - extreme drag leading to high blanket pressure and stresses, and flow balance disruption
  - velocity profile and turbulence distortion leading to severe changes in heat transfer and corrosion
- Pioneering research into highly-parallel multi-scale incompressible MHD solvers is extending the frontiers of problem size and geometric complexity accessible via numerical simulation
- Simulations beginning to shed light on MHD flow features in complex channels of electrically heterogeneous materials at ITER relevant Ha number



3D MHD Simulation of PbLi flow with SiC Flow Channel Insert with $\sigma_{SiC} = 500\ \Omega^{-1}m^{-1}$ shows formation of strong velocity jets even though the pressure drop is tolerable

- Such advances in MHD are of great interest to the broader CFD community

Research Thrust C: *Identify performance limits for materials and plasma chamber technologies*

1. **What are the performance limits of materials and blanket components?**
   Materials and plasma chamber systems will play a critical role in determining the ultimate attractiveness of fusion power because of the need for high power density, high thermodynamic efficiency, high reliability, fast maintainability, long lifetime, and low long-term radioactivity. Meeting these simultaneous demands in the multiple-field, intense fusion environment and complex plasma confinement configurations are a challenge that requires important advances in several scientific fields and engineering applications.

   Continue various long-lead-time aspects of material performance limits and chamber technology research over the next 10 years that could have the largest impact on the ultimate attractiveness of fusion energy

2. **Can innovative material and technology solutions be found that can dramatically improve the attractiveness of and/or shorten the development path to fusion energy?** Innovation in materials and technology research should continue, as more conventional materials and technology approaches may prove to be infeasible or not attractive in the long run. For example, materials with high temperature potential or innovative liquid wall and divertor concepts that can reduce significantly the demands on structural materials are both pathways to enable high power density performance

   Continue work at the fundamental science level on advanced materials and plasma chamber solutions like liquid walls

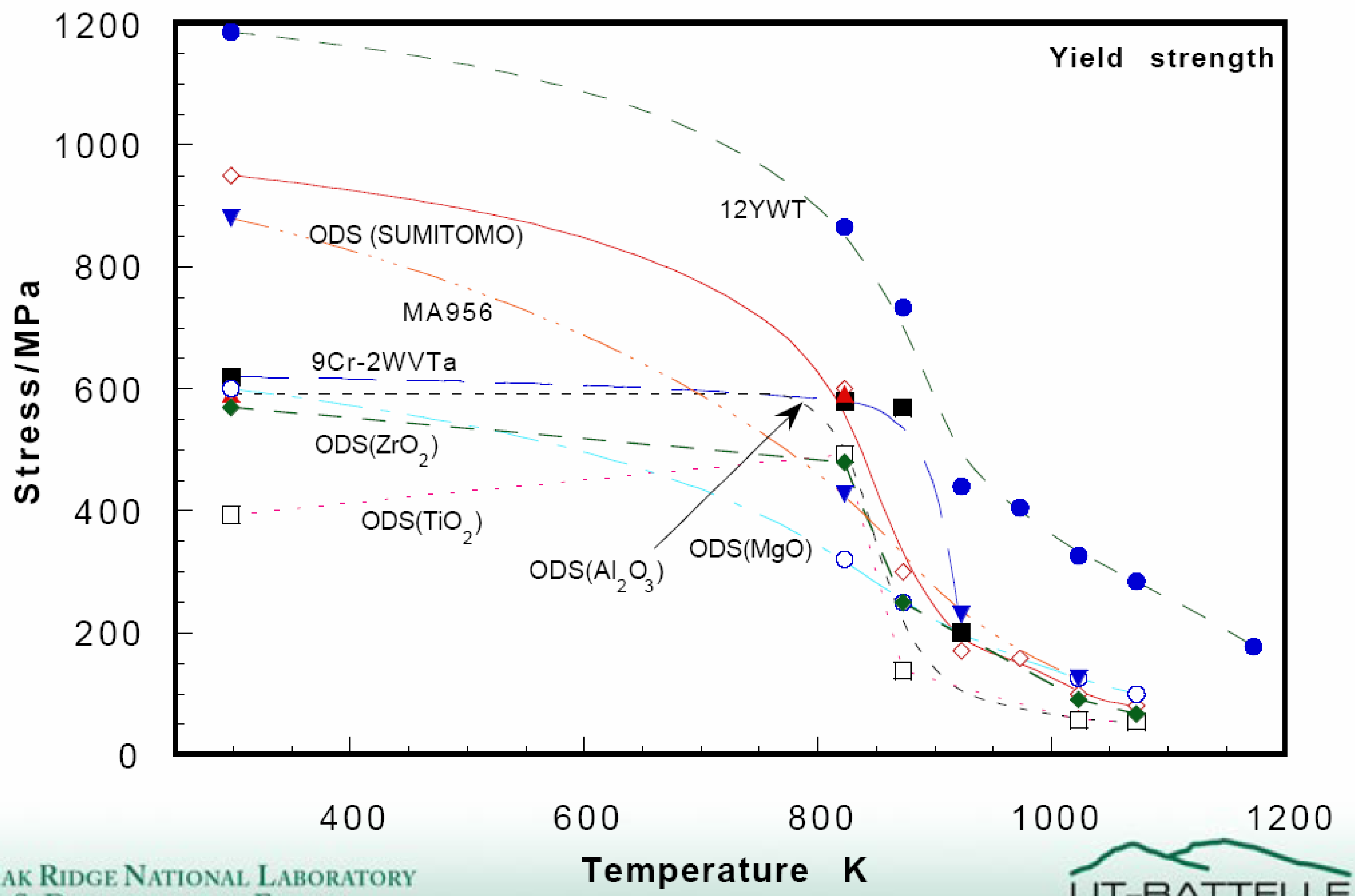
Research Thrust C: ***Identify performance limits for materials and plasma chamber technologies (cont’d)***

In addition to the research described in the Thrusts 1 and 2, which will also aid in advancing aspects of this thrust, **research focus areas for this thrust include (examples):**

- Design of fusion materials that utilize and expand on revolutionary advances in computational and experimental methods to control at the nanoscale level the structural stability of the material during exposure to intense neutron fluxes, high mechanical loads, and corrosive environments.

- Basic research on computational fluid dynamics (CFD) development for turbulent (IFE) and magnetohydrodynamic (MFE) free surface flows to allow simulation and study of phenomena in liquid wall systems
  - free surface vaporization and mass transfer model development will be critical to simulating recondensation rates in IFE
  - coupling to edge plasma physics codes will be necessary in MFE to assess the coupled penetration of impurity vapor and the effect on local heat loads and electrical currents back to the liquid surface

Comparison of tensile strength of 12YWT Nanocomposited Ferritic Steel vs. ODS steels



T15: How can systems be engineered to heat, fuel, pump, and confine steady state or repetitively pulsed burning plasmas? - MFE

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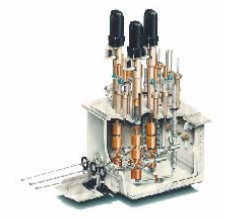

Alcator C-Mod

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Fusion research requires the development and deployment of tools to *create*, *confine*, *understand* and *control* plasmas

- Technologies that heat, fuel, pump shape and confine plasmas are essential and ubiquitous
  - enable all exiting MFE experiments to achieve scientific research and performance goals
  - enable the execution of the U.S.commitment to the construction and operation phases of ITER
  - advances needed to address advanced tokamak and burning plasma challenges and evolution of other concepts

- Plasma technologies impact directly and broadly all three overarching themes: fundamental understanding of plasmas (O1), burning plasma studies (O2) and developing practical fusion energy (O3)

Approach: integrate modeling, development, component construction, testing, and deployment of advanced plasma control tools to support scientific missions

- Two research thrusts address a wide range of *scientific and technological* issues of importance to magnetically confined plasmas
  - together both thrusts ensure that the technologies needed for the study of magnetically confined plasmas will be developed expeditiously.

- *Research Thrust T15-A. Develop long pulse plasma control technologies for tokamaks including ITER.*
  - focuses on developing the technology needed to address key elements of the tokamak development path—long-pulse, advanced operating regimes and burning plasma research
  - technology development is driven by technical challenges and demanding conditions associated with ITER—progresses technologies to an advanced stage of development ie. superconducting magnets and high power density ICRF launchers

T15 (MFE) Research thrusts cont’d.

- *Research Thrust T15-B. Provide plasma control technology support for developing other confinement approaches.*
  - focuses on addressing needs of other concepts at various stages of evolution—Spherical Torus, Reversed Field Pinch, Compact Stellarator etc.
  - addresses a wider range of technologies many of which are at an earlier stage of development such as high temperature superconducting magnets and ICRF launchers for sustaining non-axisymmetric plasmas.

T15 (IFE)

IFE Research Approach:

1. The National Nuclear Security Administration (NNSA) funds R&D on many aspects of laser- and z-pinch driven IFE.

2. The NNSA programs are briefly described in the interim report, but are **NOT** included in the FESAC prioritization process.

3. Key issues for heavy ion drivers are discussed in topic T10.