Fusion Power Associates Annual Meeting

Fusion Nuclear Science and Technology Research Needed Now for Magnetic Fusion Energy

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Outline

- Introduction
- Nuclear science and technology research needed now to enable the construction and licensing and *utilization* of ITER burning plasmas
  - Basic design and procurement package support
  - ITER TBM program
- Research needed to support innovation in long term efforts to develop materials and components
- Conclusions
  - What we are missing out on by eliminating long term technology programs?
  - Opportunities in the Age of ITER

Technology programs contribute to greater Fusion Science themes

Technology Programs
- Plasma Facing Components
- Plasma Chamber
- Plasma Heating/Fueling/CD
- Safety
- Tritium
- Materials
- Design Studies

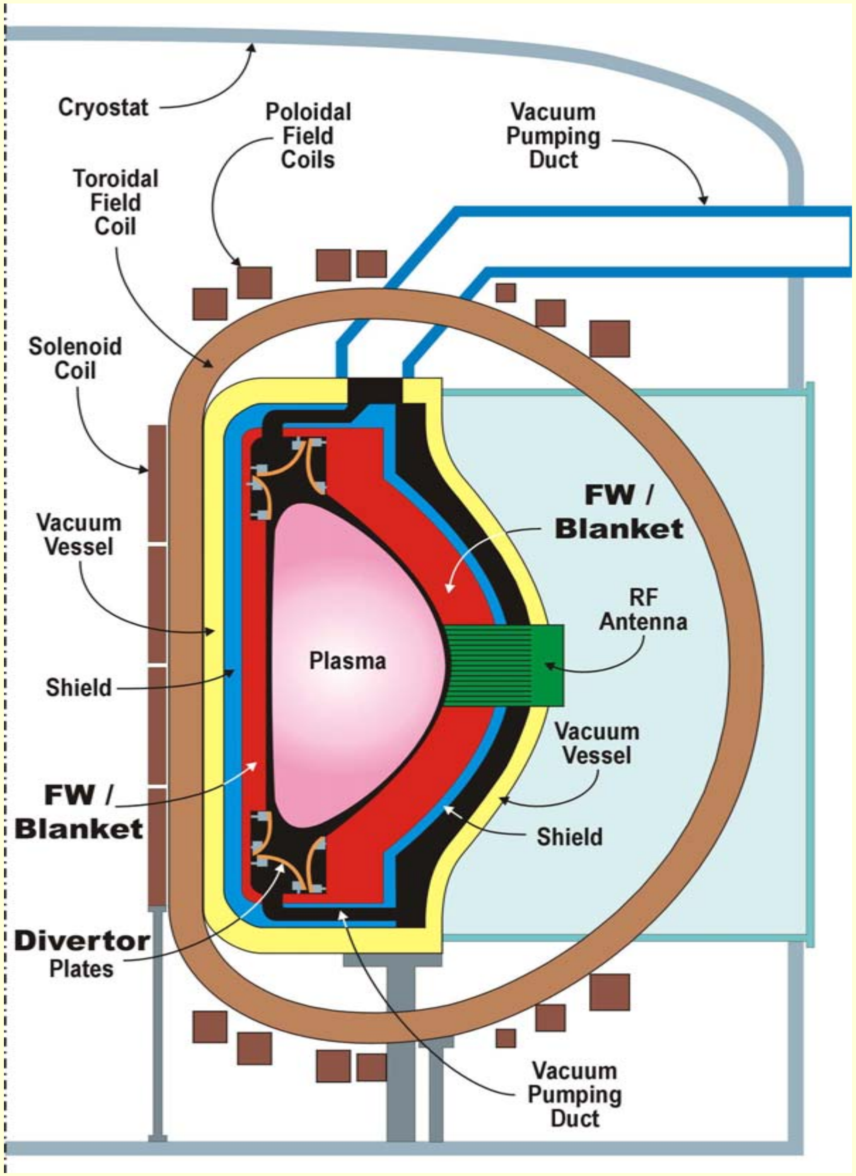
Technology Themes
- ❑ Support of plasma experiments
- ❑ **Exploring underlying engineering and material science phenomena**
- ❑ Explore long term and innovative solutions to challenging fusion problems

Scope of Plasma Chamber Research

Plasma Chamber Research embodies the scientific and engineering disciplines required to understand, design, develop, test, build, and operate safely and reliably the systems that surround a burning plasma.

PC includes all components and functions from the edge of the plasma to the magnets, including:

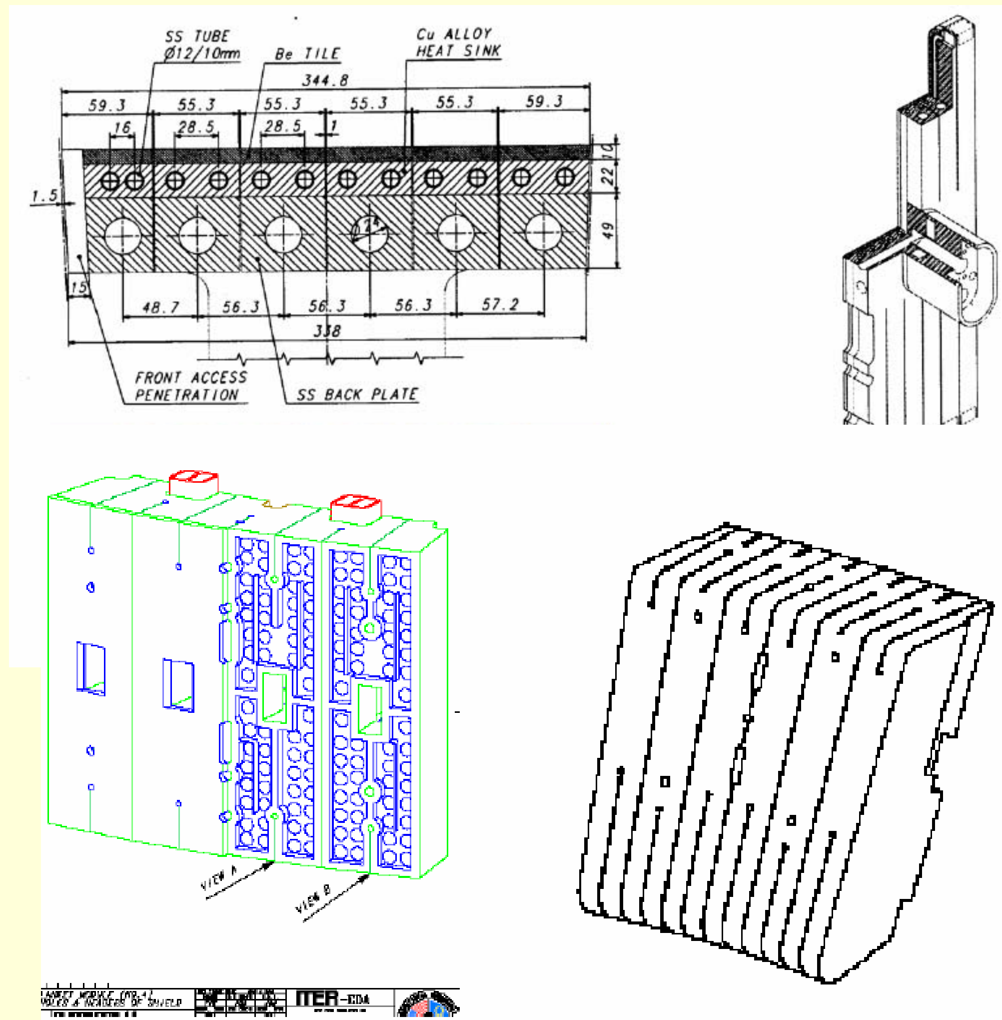
- ❑ first wall
- ❑ blanket (breeding and non-breeding)
- ❑ conducting shells
- ❑ vacuum vessel
- ❑ radiation shielding
- ❑ nuclear part of RF antenna, etc.
- ❑ cooling systems
- ❑ electric/thermal insulators
- ❑ tritium barriers and processing
- ❑ tritium fuel cycle
- ❑ support structure & remote maintenance



PC also includes design and integration for Chamber Components

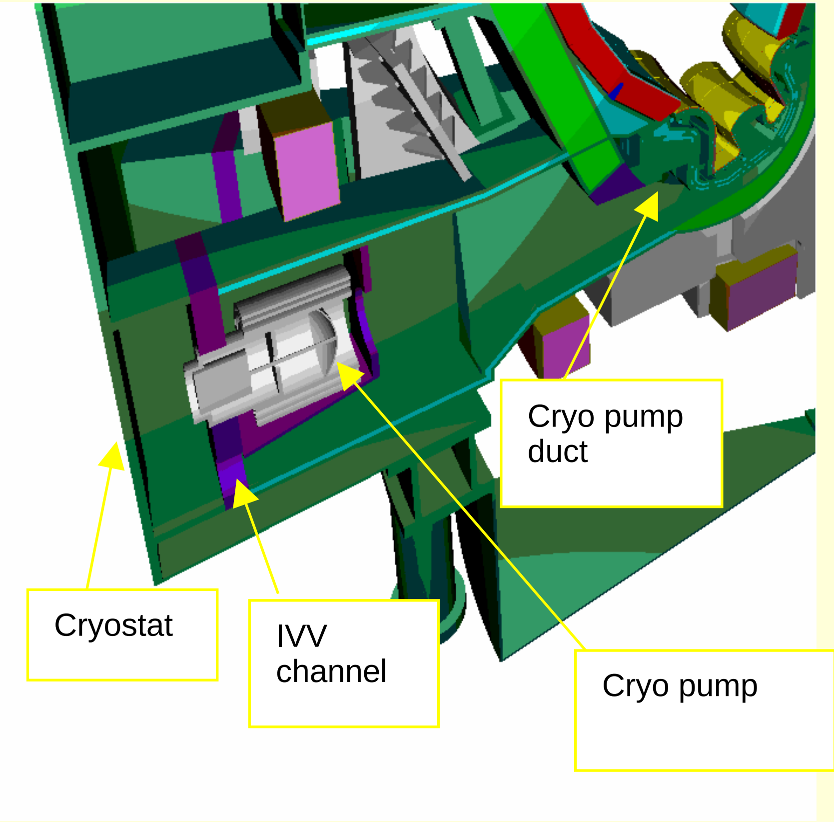
Technology programs are providing major support to preparation of Burning Plasma Experiment, ITER

- Nuclear Science and Engineering Support of the ITER Procurement Packages
  - Module 18
  - Tritium system
  - Diagnostics
- ITER TBM Experiments



“We will do nuclear when we become nuclear” The time has arrived...

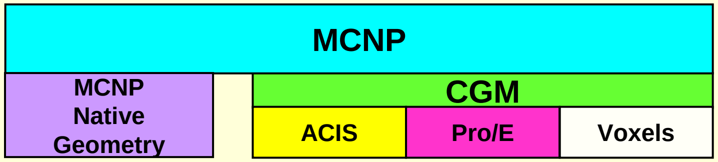
ITER will produce more neutrons than any other nuclear facility ever constructed including all operating fission power reactors. ***I think***



- Detailed Nuclear Analysis is Needed for ITER
  - ITER undergoing major design changes
  - Experience in TFTR, JET, SNS shows that neutronics and radiation environment assessments continue through final design and construction phases
  - ITER licensing will require a strong case to be presented to authorities for radiation doses, operation and maintenance scenarios, accident scenarios, activated inventories, etc.
- NEEDED R&D:
  - **CAD/Neutronics coupling**
  - **Nuclear environment diagnostics**

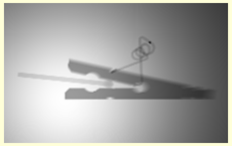
CAD-Based MCNP Development

- **Use Sandia's CGM interface to evaluate CAD *directly* from MCNP**
  - » CGM provides common interface to multiple CAD engines, including voxel-based models

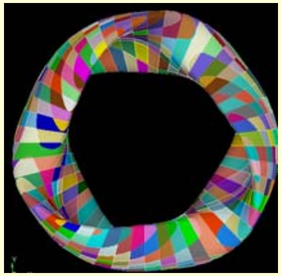


- **Benefits:**
  - » **Dramatically reduce turnaround time from CAD-based design changes**
    - – ***Identified as key element of ITER Neutronics analysis strategy***
  - » **No translation to MCNP geometry commands**
    - – Removes limitation on surface types
    - – Robustness improved by using same engine for CAD and MCNP
  - » **Can handle 3D models not supported in MCNP**

Clothespin, w/helical spring surface



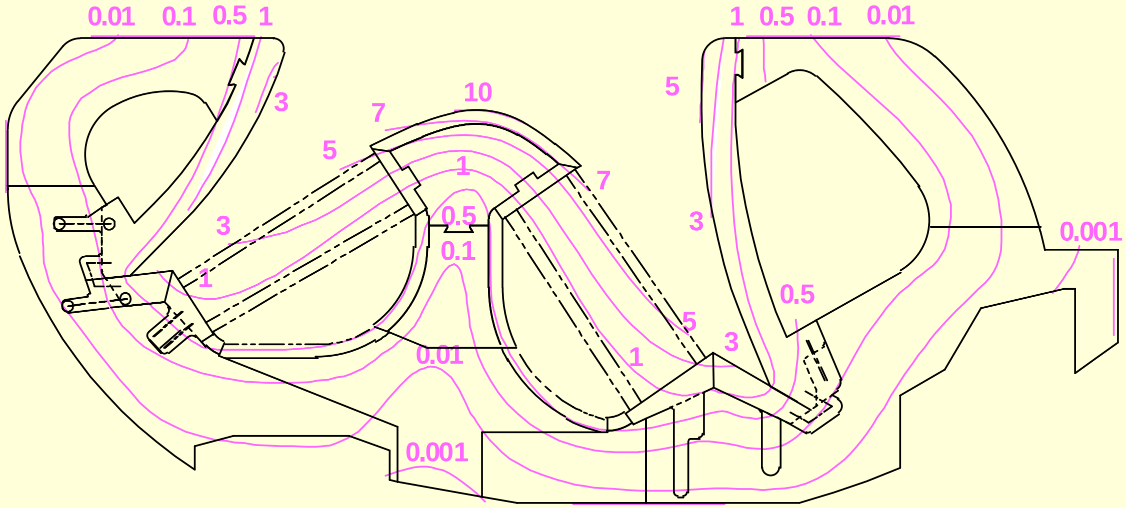
ARIES-CS Plasma



- **Status: prototype using direct CAD query from MCNP**
- **Issues/plans:**
  - Benchmarking the current prototype version of MCNP/CGM for ITER analyses. Explore various approaches to transferring geometry from the ITER CAD design system (possibly CATIA) to the ACIS-based MCNP/CGM
  - The most immediate limitation is that it is slower than MCNP alone. The focus will be to speed up the ray-tracing portion of the code (lots of acceleration techniques possible)
  - ***Goal: speed comparable to MCNP, but using direct CAD evaluation***

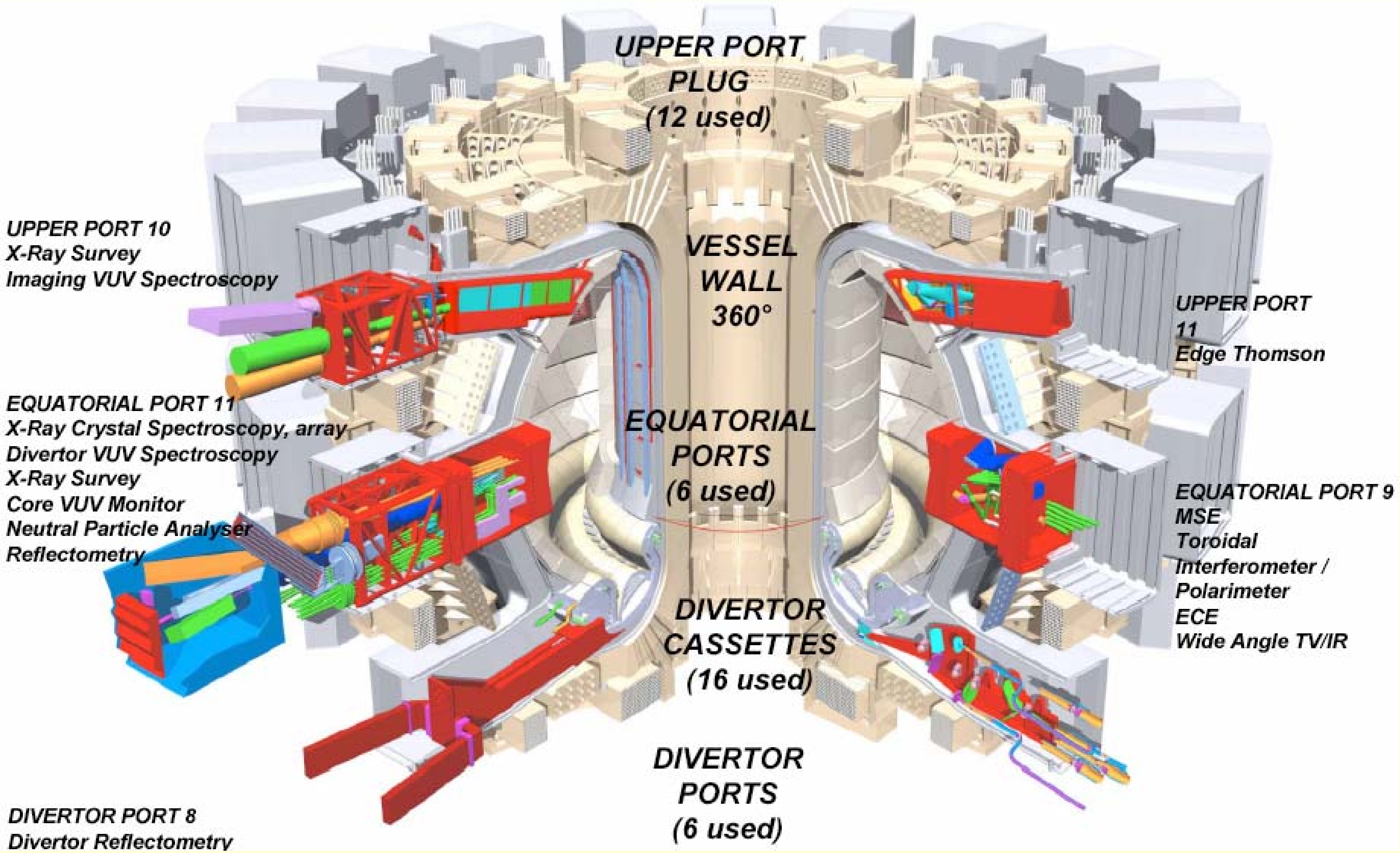
Example:
3-D Nuclear Analysis for Divertor Cassette

- **Determined nuclear heating (W/cm3) profiles in divertor cassette**



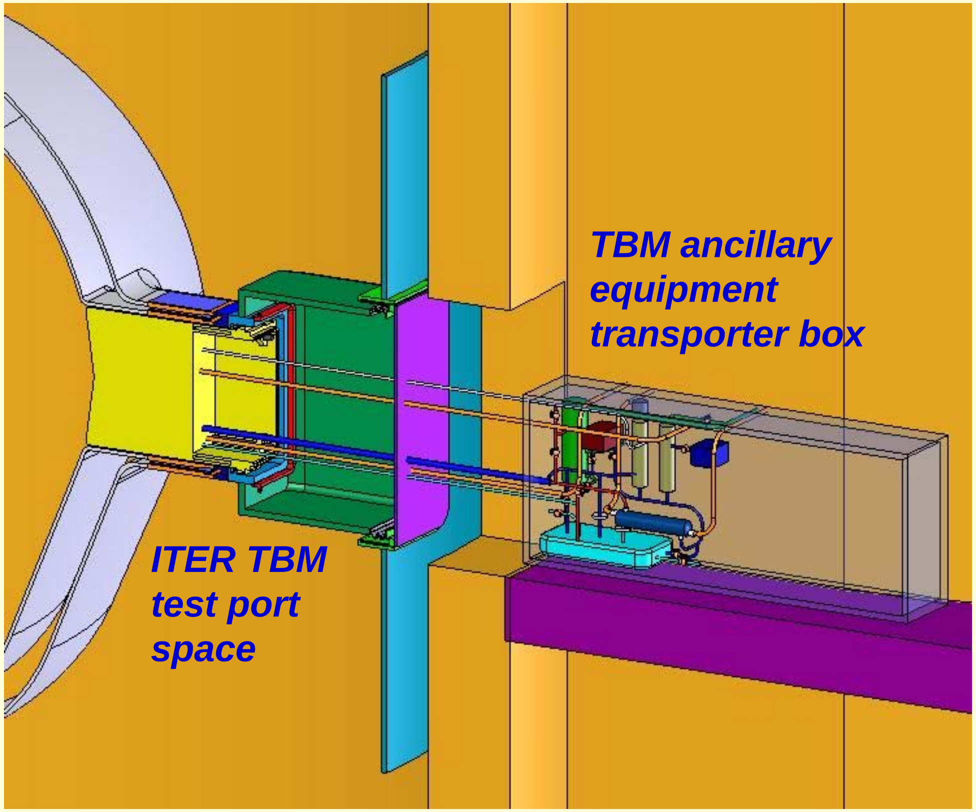
- **Calculated radiation damage in cassette components**
- **Evaluated adequacy of VV and TF coil shielding by calculating hot spot damage, gas production and insulator dose**
- **Performed 3-D divertor cassette pulsed activation calculations to determine radioactive inventory, decay heat, and radwaste level**
- **Assessed neutron streaming effects**

The highly varied diagnostic landscape will all require nuclear analysis



What is the ITER Test Blanket Module (TBM) Program?

Experiments on breeding blanket and first wall phenomena, components, and materials in an Integrated Fusion Environment



- **Test Blanket Modules (TBMs) will be introduced into ITER through specially designed mid-plane ports.**
- **TBM experiments will begin in ITER starting from Day One**
- **Each ITER Party is allocated limited space for testing (Number of Ports reduced to 3. Number of Parties increased to 6).**
- **Each TBM will have its own dedicated systems for tritium and heat extraction, diagnostics etc.**
- **ITER's construction plan needs specifications for TBMs soon because of impacts on space, vacuum vessel, remote maintenance, ancillary equipment, safety, availability, etc.**

Don't throw away the neutron!

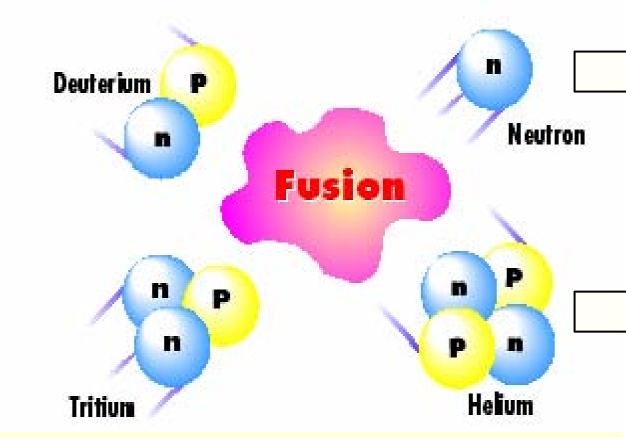
ITER's Principal Objectives Have Always Included Testing Tritium Breeding Blankets

- ***"The ITER should serve as a test facility for neutronics, blanket modules, tritium production and advanced plasma technologies. The important objectives will be the extraction of high-grade heat from reactor relevant blanket modules appropriate for generation of electricity."***

  —The ITER Quadripartite Initiative Committee (QIC), IEA Vienna 18–19 October 1987

- ***"ITER should test design concepts of tritium breeding blankets relevant to a reactor. The tests foreseen in modules include the demonstration of a breeding capability that would lead to tritium self sufficiency in a reactor, the extraction of high-grade heat and electricity generation."***

  —SWG1, reaffirmed by ITER Council, IC-7 Records (14–15 December 1994), and stated again in forming the Test Blanket Working Group (TBWG)



ITER Mission Element:
Integrated environment testing of components and materials

ITER Mission Element:
Long Pulse, burning plasma physics

ITER TBM Experiments are essential steps to establish the conditions governing the scientific feasibility of the D-T cycle

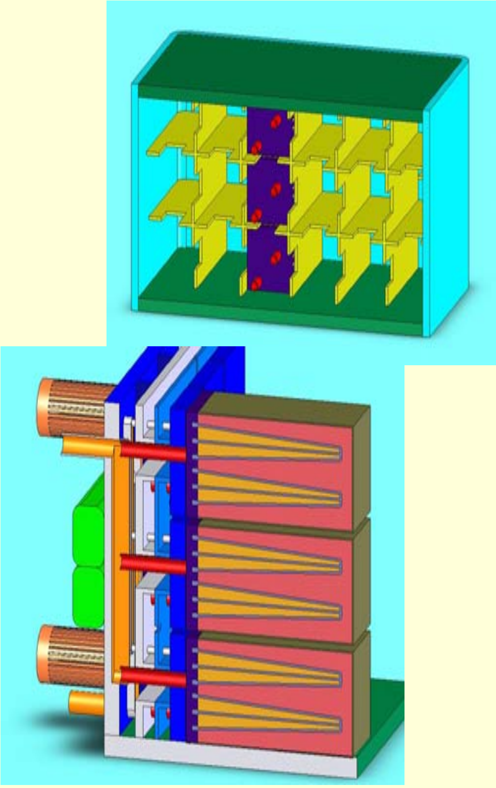
- **The D-T cycle is the basis of the current world plasma physics and technology program. There is only a "window" in the physics and technology "phase-space" in which the D-T cycle is feasible.**
  - **Is tritium self-sufficiency compatible with low plasma-edge recycling or advanced physics modes?**
  - **Is the "temperature window" for tritium release from solid breeders sufficient for adequate tritium breeding?**
  - **Can circulated liquid metal breeders and coolants be used?**
  - **Is there a blanket/material system that can function reliably in integrated fusion environment conditions?**
  - **Are nuclear predictive capabilities (codes, data) adequate to predict accurate TBR in complex geometry heterogeneous systems**
  - **What tritium breeding and recovery technologies will be used for any burning plasma experiments including advanced phases of ITER and beyond?**
- **If the D-T cycle is not feasible plasma, physics and technology research would be very different.**

Redirecting US Plasma Chamber Systems Effort to Support ITER

- **For the past year, a study has focused mostly on assessment of the critical feasibility issues for liquid breeder concepts. Examples of issues are MHD insulators, MHD effects on heat transfer, tritium permeation, corrosion, material choices and compatibility.**

- **Helium-cooled solid breeder concept with ferritic steel structure and neutron multiplier, but without an independent Ancillary Systems.**
  - **Support EU and Japan using their designs, structure and ancillary equipment.**
  - **Contribute unit cell and sub-module test articles that focus on particular technical issues of unique US expertise and of interest to all parties.**

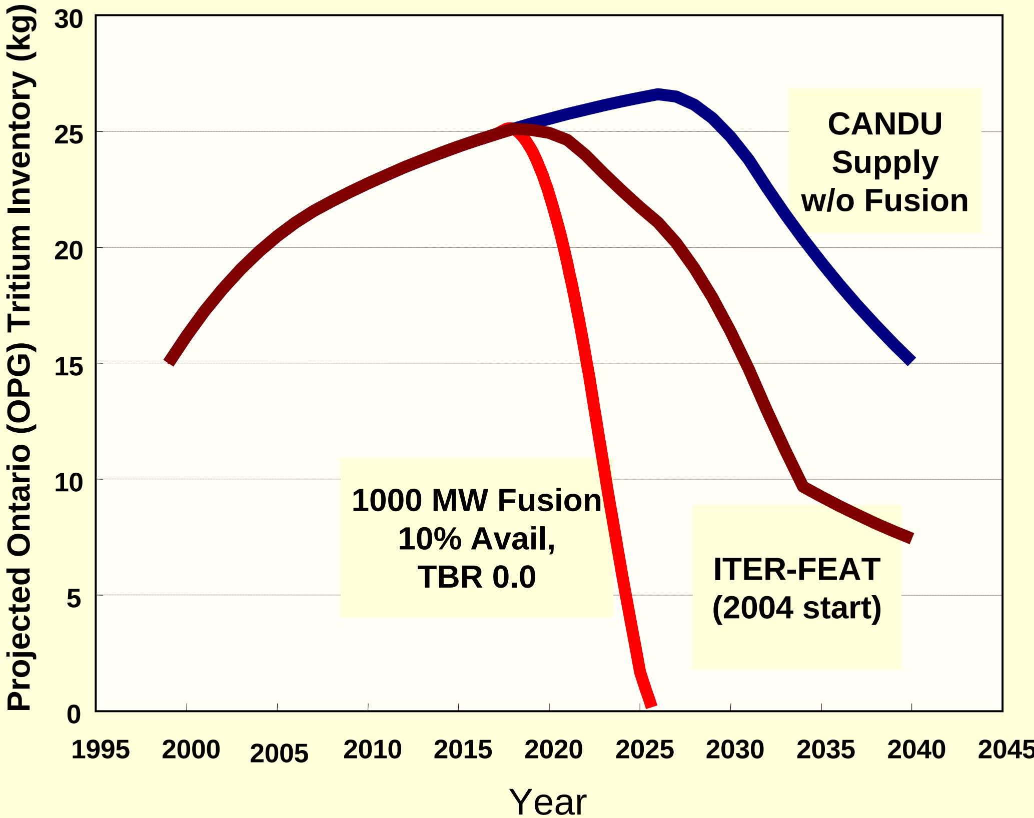
- **Dual-Coolant liquid breeder blanket concepts with potential for self-cooling.**
  - **Primary option: helium-cooled ferritic structure with self-cooled LiPb breeder zone that uses SiC insert as MHD and thermal insulator**
  - **Secondary option: low melting-point molten salt.**



US Solid breeder breeder unit cells in EU FW box

Tritium supply is an issue that time has come to solve; ITER can help us develop the breeding technology through TBM

- ☐ Solid Breeder are the nearest term breeding technology and are being pursued by all parties
  - ☐ Porous ceramic compounds of lithium for tritium breeding
  - ☐ He coolant and purge gas streams for heat and tritium removal
  - ☐ Beryllium for neutron multiplication
  - ☐ RAFS structure



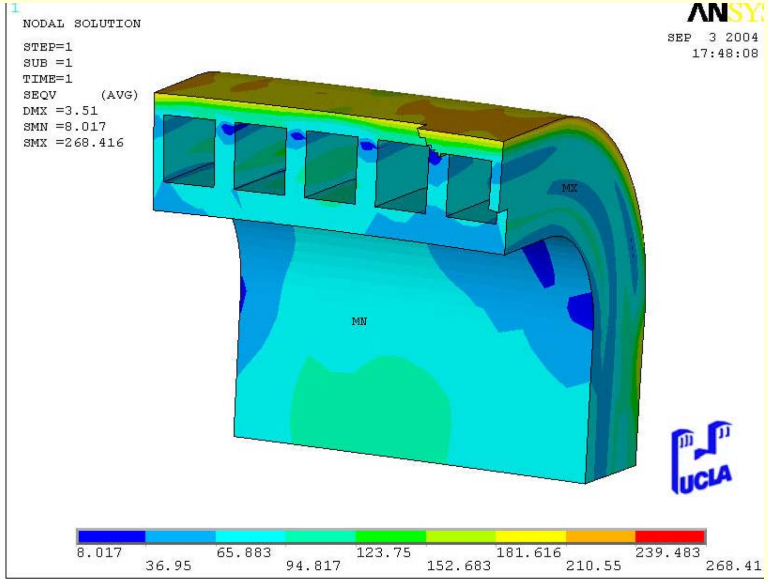
- ☐ **Develop the technology necessary to install breeding capabilities to supply ITER with tritium for its extended phase of operation**

Non-military Tritium Supply *Exhausted by 2025* by ITER at 1000MW at 10% Availability or ITER at 500 MW at 20% Availability

U.S. Solid Breeder R&D Effort Focuses on niche areas of solid breeder blanket material system thermomechanics interactions

Plasma Chamber Research:

- Experiments and modeling development on evaluation of thermomechanical states of blanket element pebble beds under different loading conditions
- Design database on effective thermo-physical and mechanical properties for breeder and beryllium pebble beds
- Engineering scaling analysis for pre-design first ITER TBMs



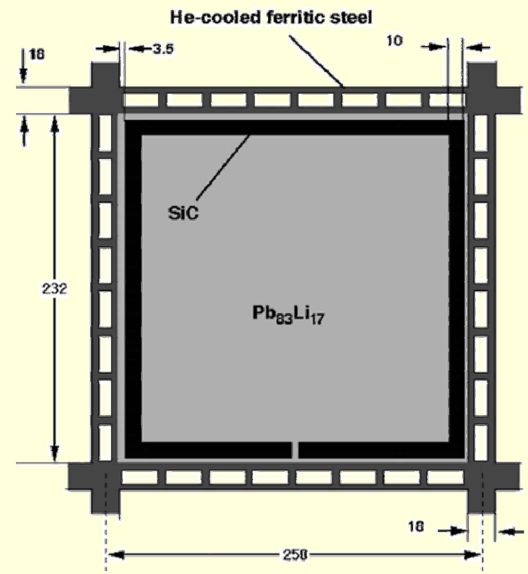
ITER FW stress analysis shows σ_{max} = 268.4 MPa located at the corner of the front inner wall

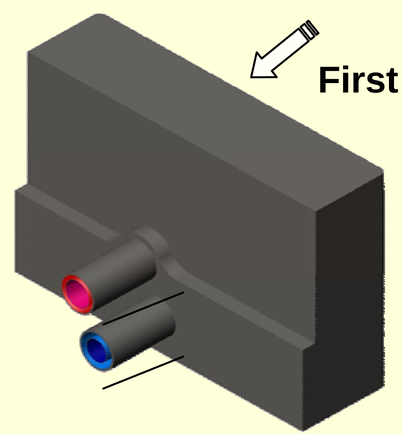
Material/Blanket Experiments Interface:

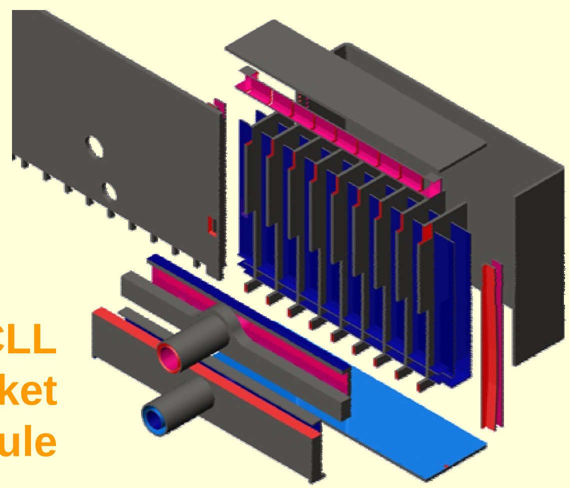
- Development of Web based INTEGRATED FUSION MATERIALS DATABASE
- Construction of VISTA (VIRTUAL INTERNATIONAL STRUCTURAL TESTING ASSEMBLY) modelling tool, to evaluate a range of potential interactions and failure paths (perform “Virtual Experiments”).

Dual Coolant PbLi/Helium blanket concept pushes higher performance with nearer term materials

- ❑ **Cool FW and ferritic steel structure with separate coolant**
- ❑ **Breeding zone is self-cooled Pb-17Li moving at a slow velocity – no separate neutron multiplier**
- ❑ **Use SiC flow channel inserts (FCIs), wherever possible to:**
  - Provide electrical insulation to reduce MHD pressure drop
  - Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall temperature
  - Improve corrosion behavior by provision of stagnant layer



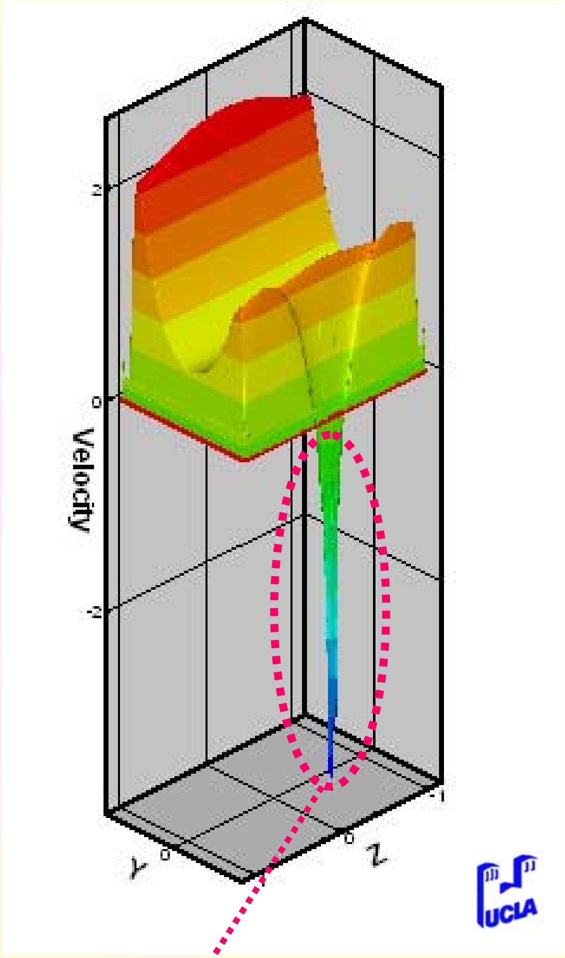




Examples of Knowledge and Capabilities Required for ITER DCLL TBM Experiments

- ❑ Simulation of 3-D magnetohydrodynamic (MHD) force distribution in liquid breeder flows including effects on drag, turbulent mixing, and flow distribution, corrosion, etc.
- ❑ Experimentally-validated mechanical-property and dimensional stability models of the effects of combined material and environmental variables on the behavior of RAFS and SiC for flow channel inserts
- ❑ Other key issues for blanket modules such as:
  - – Safety and accident analyses
  - – behavior of electrical and thermal insulators and tritium permeation barriers
  - – chemistry control and material compatibility

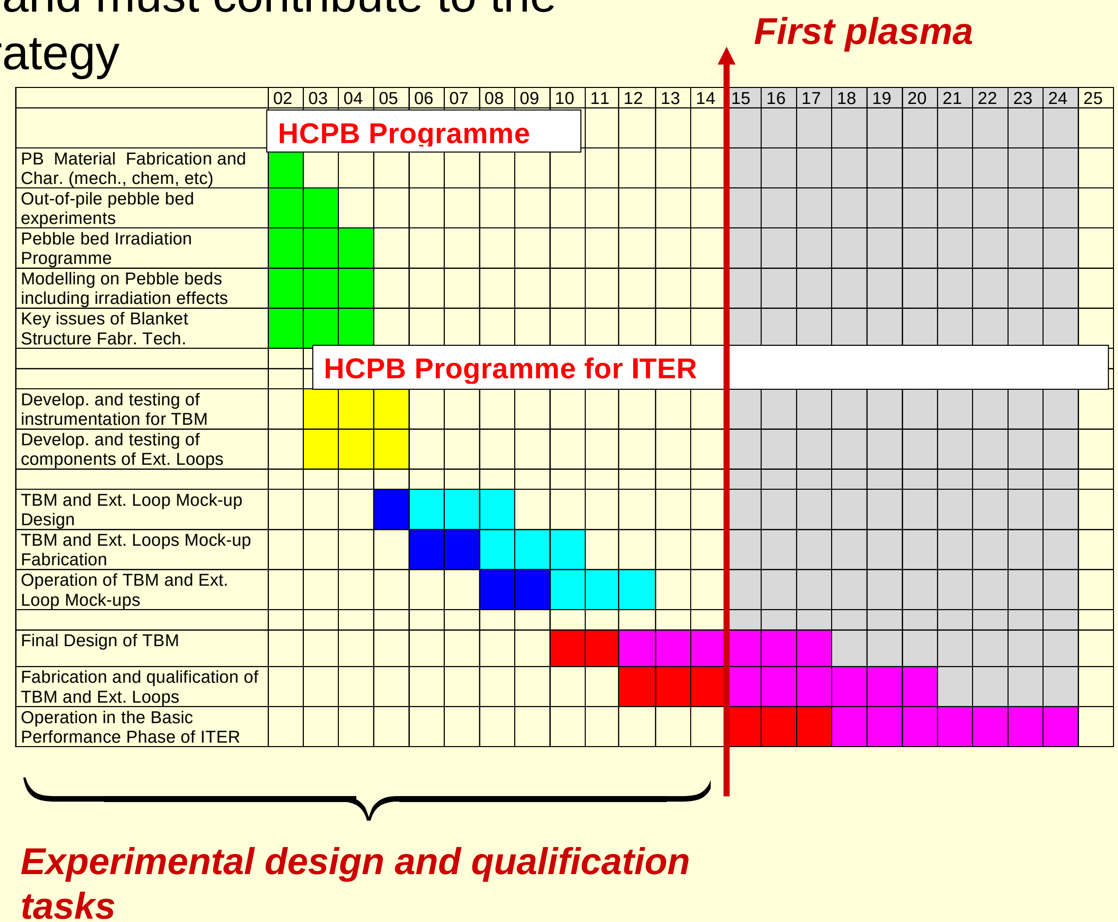
US DCLL velocity profile simulation



Strong negative flow jet near pressure equalization slot not seen in 3D simulation

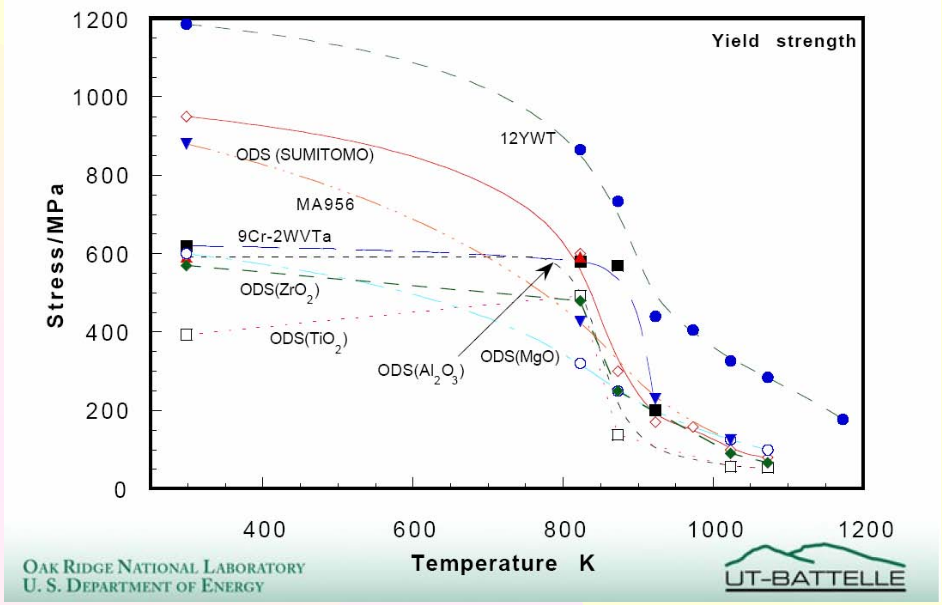
The US is a strong and very much appreciated contributor to TBWG because of *intellectual* leadership scientific testing in fusion facilities

- The international effort on Test Blanket Modules for ITER is coordinated by the Test Blanket Working Group (TBWG)
- ITER TBWG meets quarterly and must contribute to the final **TBWG report** on test strategy
- Near term TBWG Deliverable, the **Design Description Document** containing:
  - **TBMs and ancillary system design**
  - **Fabrication**
  - **Qualification program**
  - **Optimization of TBM system**
  - **Provide initial TBM delivery date**



Support for materials and technology innovation in long term efforts is essential now for a fusion energy future

- 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
  - low long-term radioactivity



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

- Meeting these simultaneous demands in the multiple-field, intense fusion environment and complex plasma confinement configurations are a challenge that requires important advances and long term commitment

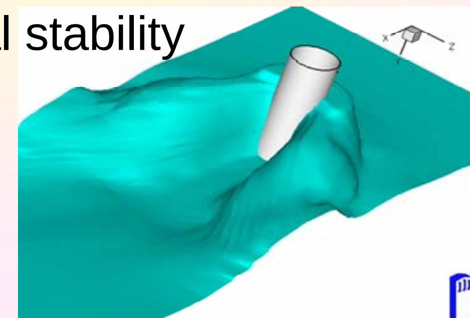
Examples of long term research efforts:

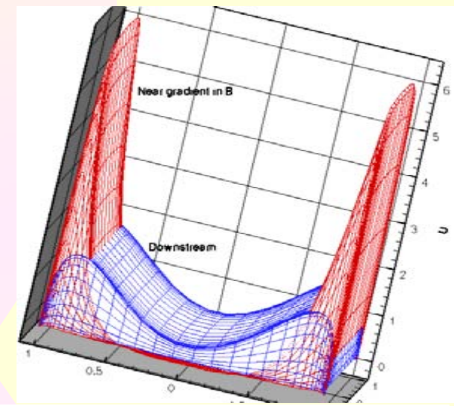
What are the performance limits of materials and blanket components?

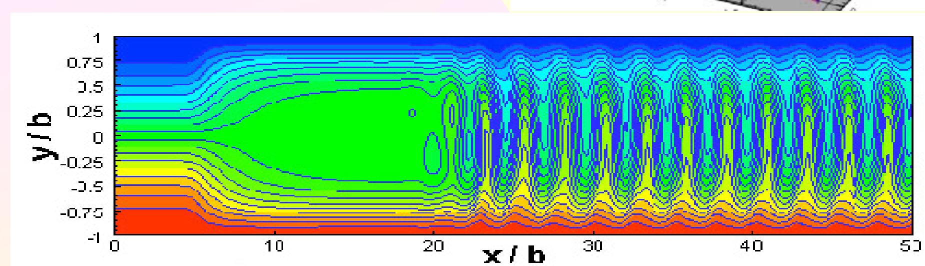
Expand on revolutionary advances in computational and experimental methods to control materials at the nano-scale level to affect structural stability during exposure to intense neutron fluxes, high mechanical loads, and corrosive environments.

Can innovative material and technology solutions be found that dramatically improve fusion or shorten the development path to fusion energy?

Advance basic research on computational fluid dynamics (CFD) for liquid wall systems and coupling to plasma edge and core plasma magnetic behavior



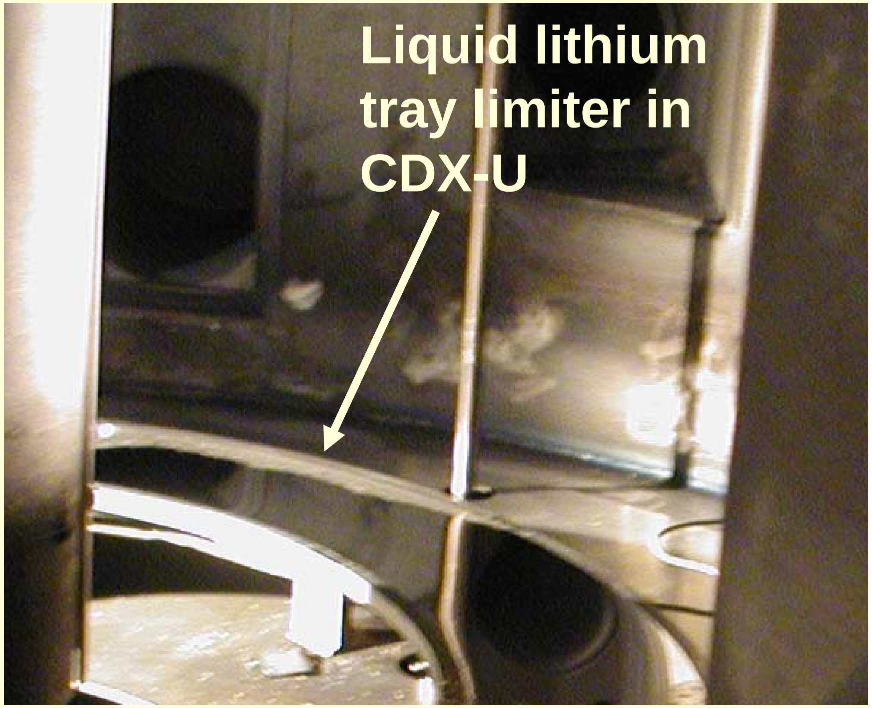




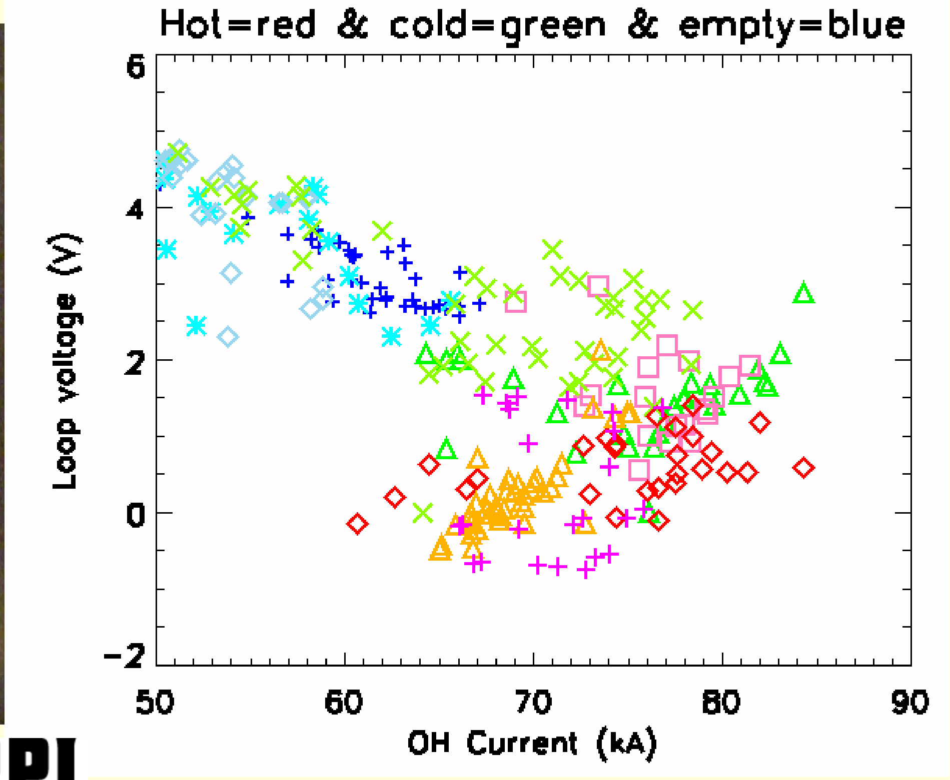
Focus on underlying physics of free surface liquid metal flows during the APEX study led to a dramatic improvement in MHD simulation capabilities

Innovative liquid wall research began as a way to reduce constraints on structural materials, but is now influencing innovative plasma physics program

- First successful test of fully-toroidal liquid lithium limiter in CDX-U performed by partnership of technology community and physicists at PPPL
- Demonstrated dramatic reduction in plasma edge fuel recycling and much less "loop" voltage needed to drive higher plasma currents



Tray after ~40 discharges.

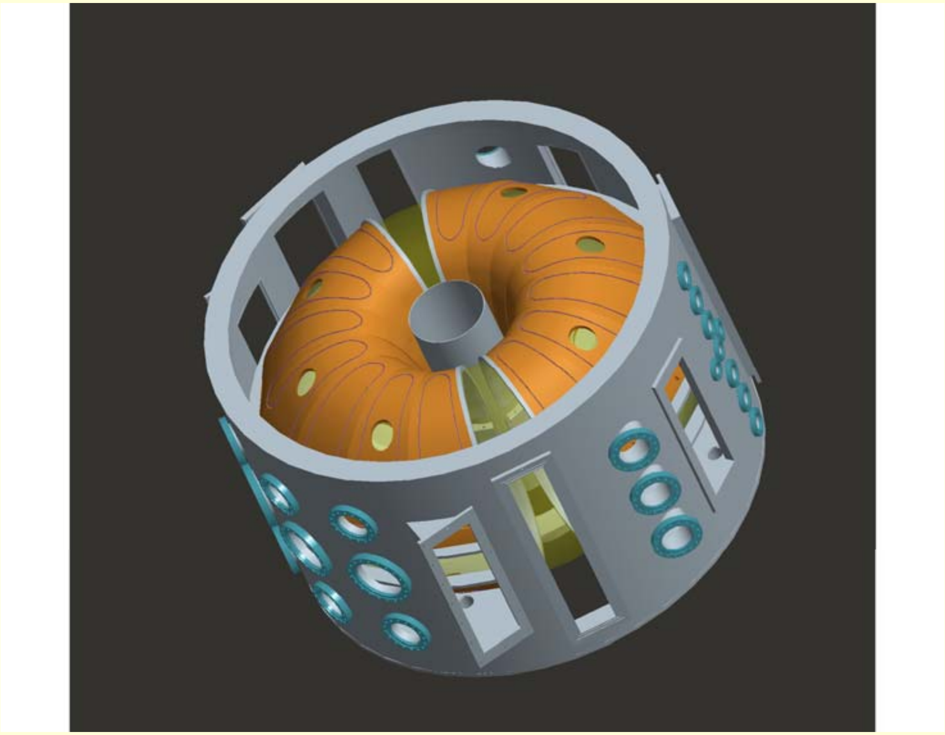


PPPL PRINCETON PLASMA PHYSICS LABORATORY

New Lithium Tokamak eXperiment (LTX) to test transport & profile modification in plasmas with nearly non-recycling walls

- Non-recycling wall permits core fueling for “flat” temperature profile regime in with new transport and MHD properties
- Thin film technology for lithium walls
  - Recoated between discharges
  - Plasma-aligned, heated shell for liquid lithium wall
- Core fueling
  - Pellet injection
  - Supersonic gas injector
- Shell will provide largest possible PFC surface area to minimize deuterium flux/unit area

Goal: <10% recycling



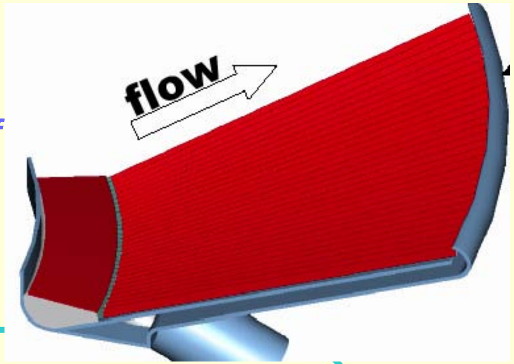
LTX Shell inside CDX-U vacuum chamber

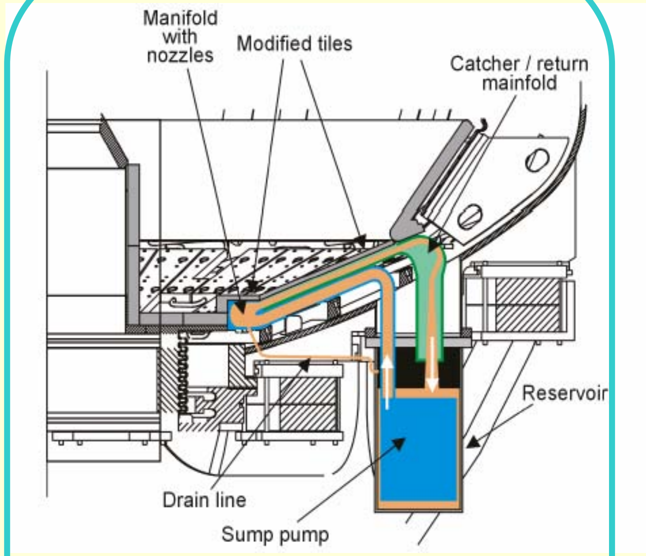
Liquid lithium divertor considered for NSTX to pump particles and control recycling

- **NSTX staged evolution towards Flowing Lithium Divertor Module**
  - This year: Lithium Pellets
  - Module A: thin stagnant liquid Li
  - Decision point
  - Module B: flowing lithium

- **Dominant MHD issues potentially leading to flow disruption must be addressed**
  - Self generated currents in complex magnetic fields
  - Thermoelectric or halo currents at points of plasma contact
  - Time varying fields: startup
  - Lithium safety

Sketches of Li flow module for NSTX





The concept: NSTX Lithium Free Surface Module (ORNL)

What we are missing out on by reducing near term and eliminating long term engineering science and technology programs?

- Loss of Credibility to US fusion program and to any fusion energy plan - Confusing and frustrating message to the International Fusion Programs
- Loss of Technology "headlights" and interaction with other fusion program elements
  - **Enormous risk that roll-forward fusion research may not ultimately bear the fruit of a practical fusion energy source.**
  - **How can we do safety analysis without radioactivity calculations and technologies for tritium containment?**
  - **How do we develop structural materials for the blanket if we do not know what the blanket is?**
- Loss of capability for timely demonstration of tritium self sufficiency – as the premise of fusion as an "inexhaustible" energy source.
  - **Loss of vital expertise needed to design and test in ITER, CTF, DEMO**
  - **Loss of training for the "seed of the future" – graduate students and young researchers.**

Critical *opportunities* for engineering science and technology in the ITER-age

- Heavy involvement of technology community in ITER basic machine
  - Necessary for success and safety of ITER
  - Zeroth level TBM

- Support at the national level for the ITER Test Blanket Module program as a focal point for:
  - advancing understanding of complex physical phenomena, highly heterogeneous and constrained FW and blanket components, and complex systems and processes,
  - integrated research by Plasma Chamber, PFC, Materials, Safety, and Tritium programs
  - international collaboration allowing access to more comprehensive technology programs

- Support at a some moderate level long term research efforts in materials and technologies that:
  - are needed for any burning plasma step beyond ITER
  - provide feedback and synergism with long term physics programs
  - have long lead time but are crucial to the ultimate feasibility and attractiveness of any energy producing system