Strategies and expectations for Fusion Nuclear Science into the 2020s

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Fusion Nuclear Science has been identified for more than a decade as an important program element

- 2005 FESAC "Scientific Challenges, Opportunities and Priorities for the US Fusion Energy Sciences Program"
  - Identifies key thrusts including fusion materials, systems engineering, fueling, etc.
- 2007 FESAC "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy"
  - Identifies predictive modeling, transients, magnet technology, etc.
- 2009 Research needs for Magnetic Fusion Energy Sciences
  - Major thrust of "Harnessing Fusion Power" includes fuel cycle, power extraction, materials science, etc.
- 2014 FESAC Strategic Planning and Program Priorities Report
  - Identified fusion nuclear science among four high priority areas
- 2015 FES Community workshops focused on three areas with wide community support
  - Transients, whole device modeling, & plasma-materials interface

Current status

- Fusion nuclear science and technology exists as a stable part of the US program
  - An energy program will require a growing investment
  - Program is highly leveraged where possible (NE, BES, University investment, Lab investment, etc.)
  - There are fusion specific challenges that are not funded external to the program (fusion specific, e.g., tritium retention in PFCs, etc.)
- Fusion nuclear science covers many topics
  - The US can't and shouldn't do everything; there is not enough time or budget
  - International collaboration will play a vital role in FNS&T
- Three areas of prime opportunity for the US are *fusion materials*, *fusion fuel cycle*, and *advanced manufacturing*

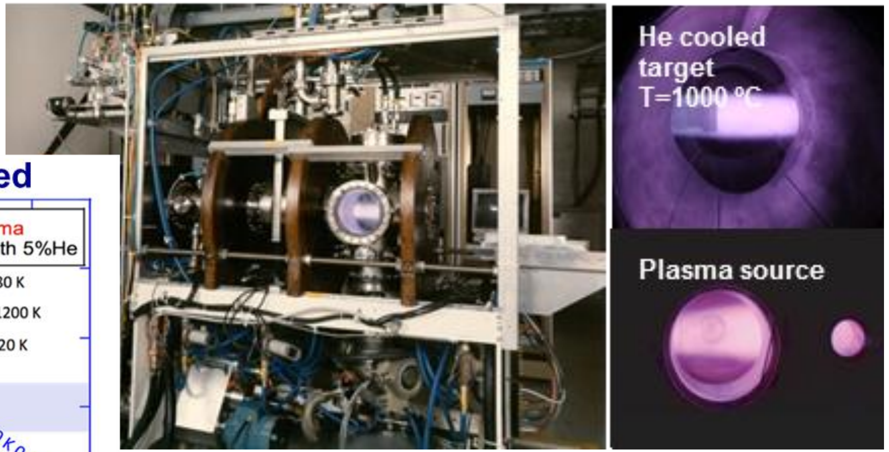
US fusion materials leadership is strong

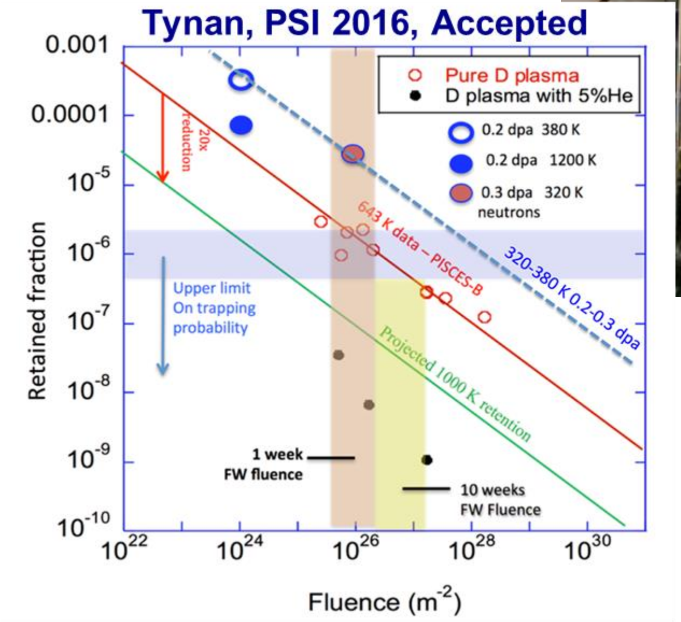
- The US is a leader among the international fusion materials program
  - US-Japan collaboration is more than three decades strong, and continues to make key contributions (PHENIX collaboration becoming FRONTIER)
  - US is executing a structural materials irradiation and PIE for the EUROfusion program (Europe is outsourcing work and recognizing US expertise)
  - Ongoing discussions with the Chinese program
- However, resources are limited
  - With existing budget, prime focus is structural materials and existing materials
  - Not much effort on blanket materials or materials development
  - Even PMI science is not a large program in the US…yet
- Opportunities for leadership include:
  - PMI, fusion relevant neutron source, and modeling & simulation

Three PMI facilities will position the US uniquely to address challenges

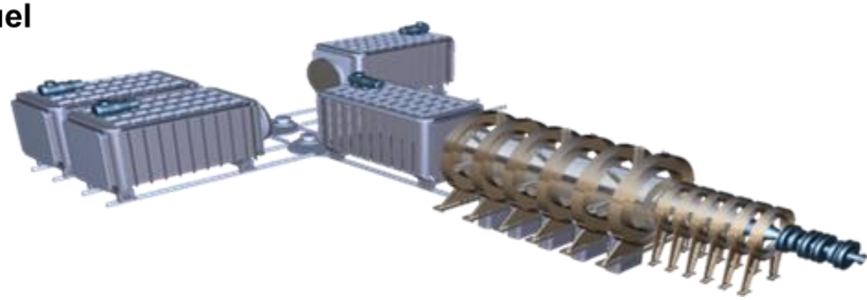
- TPE (INL) addresses tritium retention in damaged samples
- PISCES (UCSD) is a high fluence facility with beryllium capabilities to address ITER challenges
- MPEX (ORNL) will be a DEMO-level fluence device with tilted target & neutron irradiated capabilities

TPE & new external control center



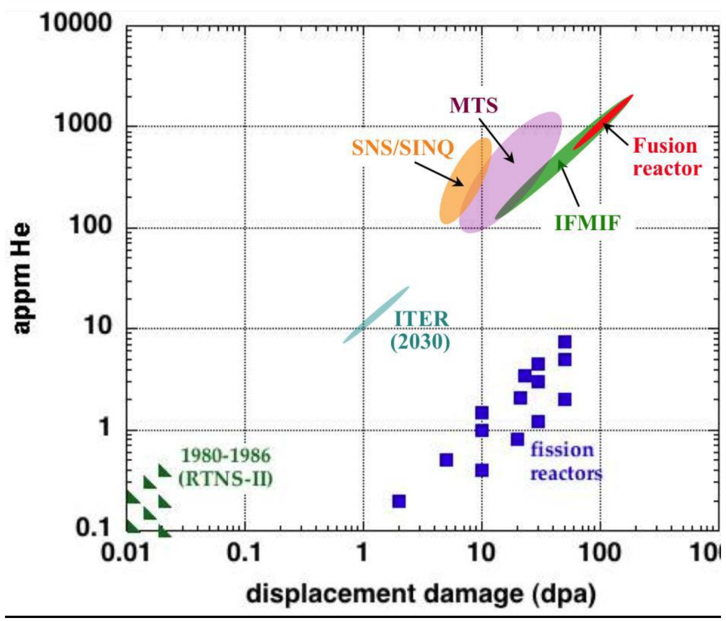


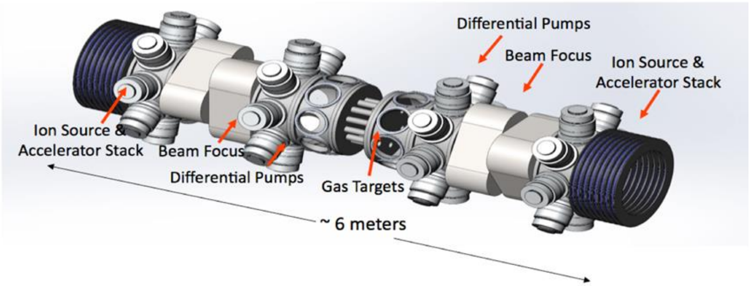
Effect of Radiation damage on Fuel Retention



A fusion relevant neutron source is an international need, and a US opportunity

- High displacement rate irradiations have been carried out in HFIR for decades
- A neutron source with the correct energy spectrum, producing gas synergistically with displacements, is needed for basic scientific understanding as well as materials qualification
- IFMIF has been discussed for decades, and should be built
- DONES is the latest version, with reduced scope but still costing hundreds of millions of dollars
- It is time to consider nearer term, lower cost options with reduced performance
  - A precursor to DONES/AFNS
  - Phoenix Nuclear Labs has a proposal for a DT neutron generator
  - Spallation sources can provide near term data
  - A Gas Dynamic Trap proposal has also been discussed





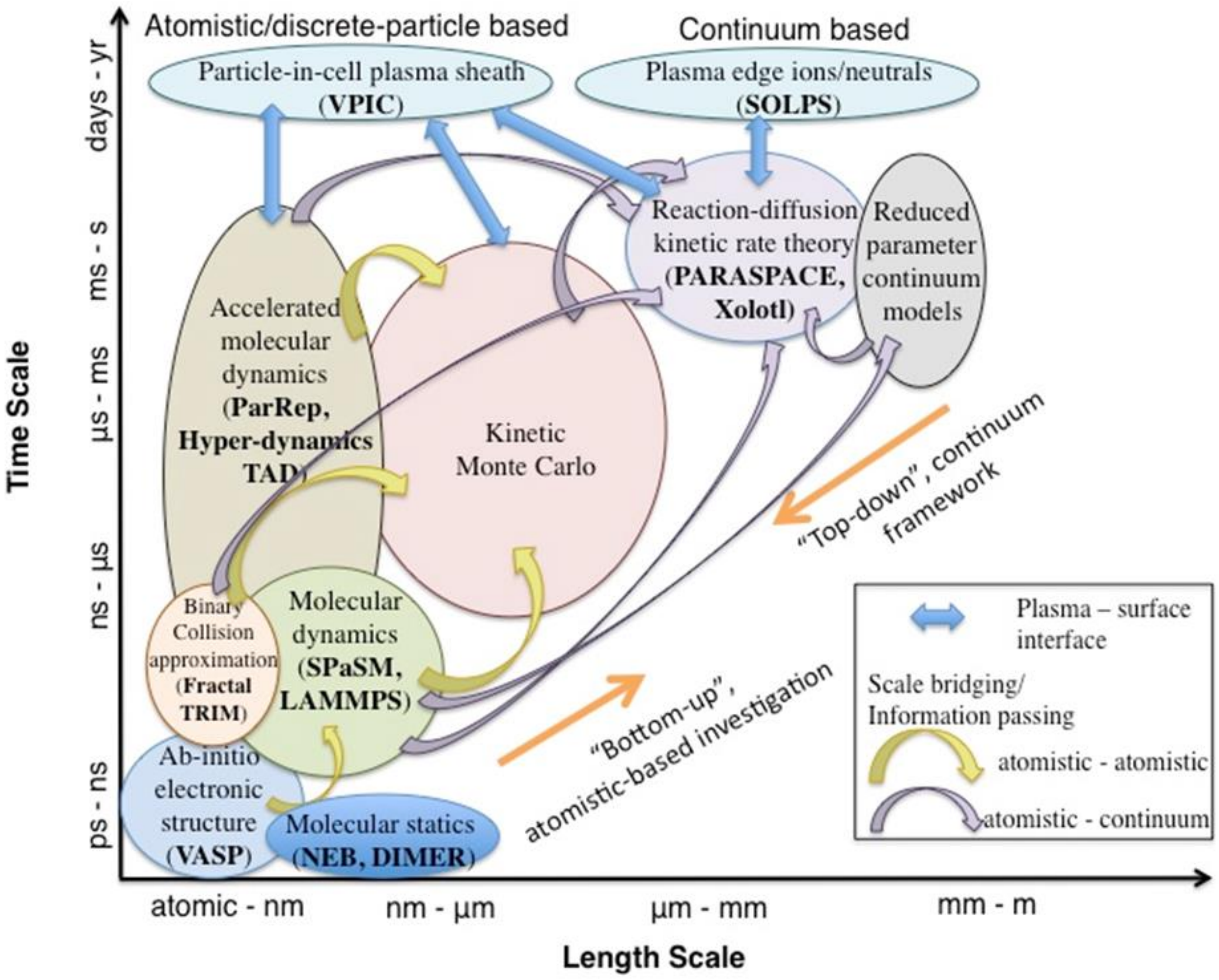
Phoenix Nuclear Labs neutron generator concept

Fusion Prototypic Neutron Source

- Initial discussions between the Virtual Laboratory for Technology (VLT) and FES led to language being inserted into the FY19 budget
- The VLT helped FES organize a workshop around the topic
- 33 members of the US fusion materials community, the VLT, and private industry met August 20-22, 2018, and discussed the possibility of the US developing a Fusion Prototypic Neutron Source (FPNS)
- Initial discussion indicated that the source would be a potential intermediate step to IFMIF/DONES/AFNS
  - The goal is to advance the scientific understanding of fusion neutron damage in prospective structural and blanket materials
  - May provide useful information for the design of DONES/AFNS

Modeling is a critical part of addressing the materials challenge

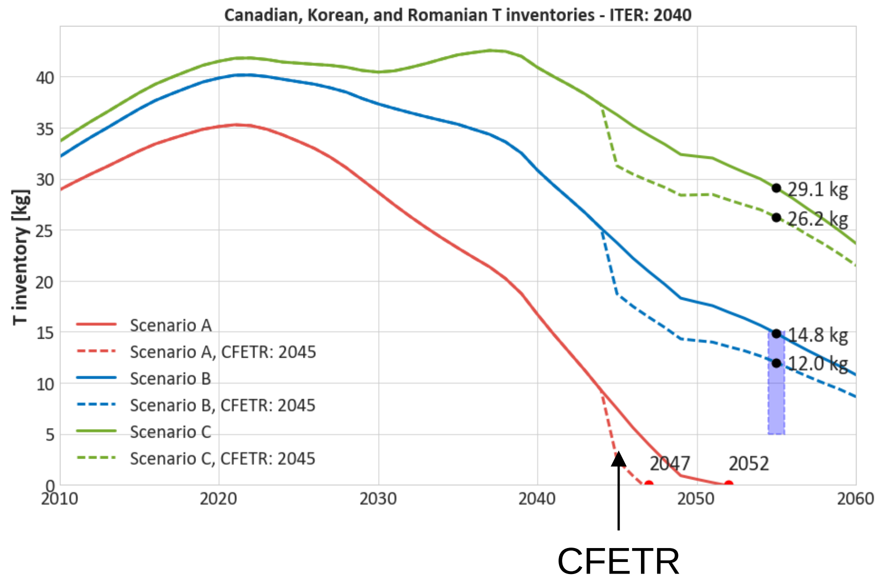
- Experiments help us understand the physics, so we can accurately model a wide range of scenarios
- The PSI SciDAC is making progress on modeling materials challenges from first principles to macroscopic effects, over large length and time scales
- Leverages ASCR/HPC and NE investments



BD Wirth, K.D. Hammond, S.I. Krashenninikov, and D. Maroudas, *Journal of Nuclear Materials* **463** (2015) 30-38.

Closing the fuel cycle is a critical part of fusion energy

- Analysis shows there is likely enough tritium for ITER and possibly one DEMO (startup=5-15 kg)
  - Control of production and consumption is largely outside of fusion community control
  - Without a closed fuel cycle, we need tritium production from fission power plants
    - Why have additional complexity of fusion power plants if fission plants are required?
  - We must close the fuel cycle for any fusion energy system
    - ***Must actually do better than that to start additional plants in the future***



Scenario A:
- Romania does not extract their T
- All HWRs finish their lives ~30y and some HWRs are refurbished +25y
Scenario B:
- Romania extracts their T
- Several refurbishments
Scenario C:
- All known refurbishments go ahead and then some more!
- Romania builds two new CANDUs in the mid-2020s (and refurbishes them)

Tritium inventory & release are significant issues for fusion energy

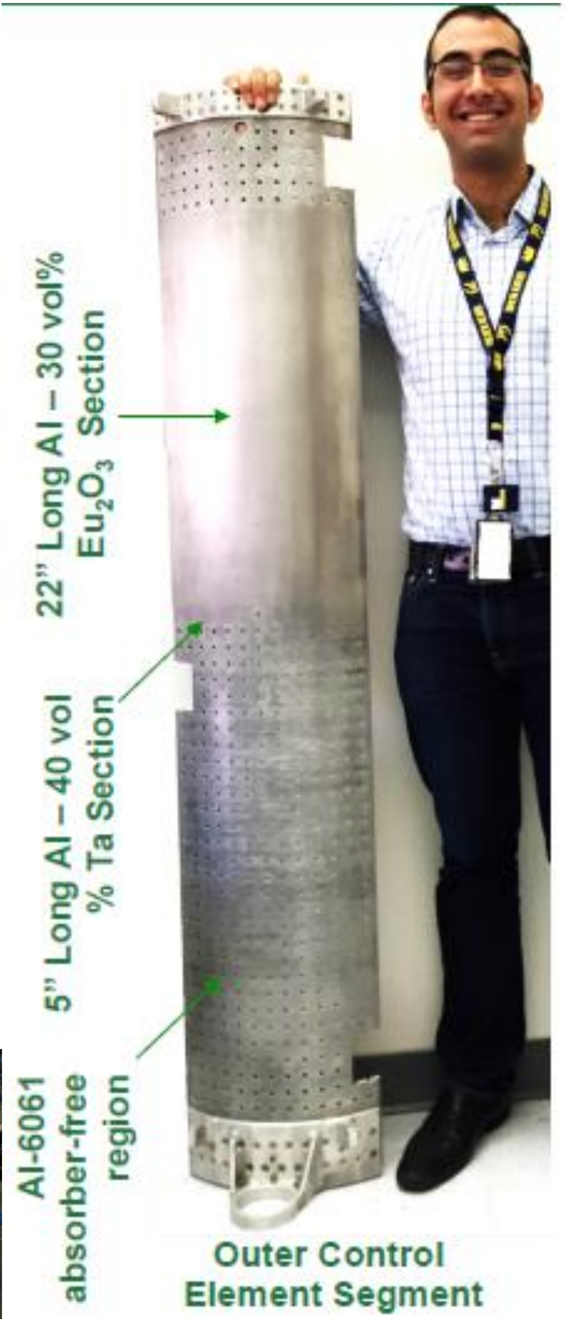
- Fission power reactors (typical annual tritium discharges of 100-800 Ci/GW_e; ~10% of production) are drawing increasing scrutiny for tritium release
- 1 GW_e fusion plant will produce ~10^9 Ci/yr; historic assumed allowed releases are ~0.3 to 1x10^5Ci/yr (<0.01% of production)
  - Public concern about tritium release from *fission plants* suggests actual release may be limited to ~100 Ci/yr (10^{-7} of production)
  - Can fusion achieve 10^6 times better tritium control than operating fission plants?
- Tritium inventory and release pathways in fusion plants are poorly understood
  - Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket structure (tritium inventory issue)
  - Tritium trapping efficacy of precipitates, nanoscale solute clusters and radiation defect clusters (blanket & piping) is poorly understood from a fundamental perspective

Leadership opportunities in fuel cycle research exist

- US has leadership in tritium science and handling due to the activities at defense & nuclear labs (LANL, SRNL, & INL)
- Efficient tritium handling, including extraction in flowing liquids and safety, is a challenge where the US can lead
- Tritium breeding blankets are among the lowest TRLs in fusion energy
  - US (UCLA) has strength in liquid metal modeling and experiments
  - Several international collaborations in blankets
- US leadership in pellet fueling
  - Current plan for installation of a continuous pellet extruder on W7-X
  - Enabling technology for all long pulse devices

Advanced manufacturing has been demonstrated on nuclear components

- HFIR annular control plates used 1960s technology based on the original design
  - Costly, low yield to meet specifications
- A joint project between the nuclear fuel materials group, HFIR staff, and the Manufacturing Demonstration Facility at ORNL was initiated in 2014
- Multiple techniques were tested
  - The cost was less than we initially thought, and was more successful than we could have imagined



OAK RIDGE National Laboratory

Summary

- Fusion nuclear science is an identified need, and an opportunity for world leadership for the US program
- A growing fusion nuclear science program is needed to prepare the US for the next step toward fusion energy
- In the 2020s, the US should lead in
  - Fusion materials
    - PMI, blanket materials, fusion relevant neutron source
  - Areas of the fuel cycle
    - Tritium handling, safety, breeding, and fueling
  - Advanced manufacturing
    - The fusion community must learn to apply it effectively