Critical FNS Activities Required Over the Next Decade to Establish the Scientific Basis for a FNSF

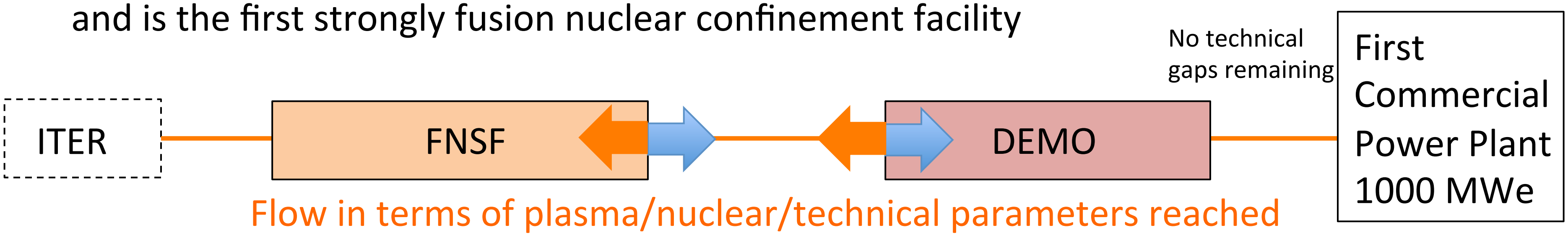
C. E. Kessel (PPPL), J. P. Blanchard, A. Davis, L. El-Guebaly, N. Ghoniem, P. Humrickhouse, A. Khodak, S. Malang, B. Merrill, N. Morley, G. H. Neilson, F. M. Poli, M. Rensink, T. Rognlien, A. Rowcliffe, S. Smolentsev, L. Snead, M. S. Tillack, P. Titus, L. Waganer, A. Ying, K. Young, and Y. Zhai

FESAC Strategic Planning Panel 2014, Public Information, June 3-5, 2014

Washington D.C.

Context for the FNSF and Pre-Requisite Research

The Fusion Nuclear Science Facility (FNSF) is part of the US fusion development view, and is the first strongly fusion nuclear confinement facility

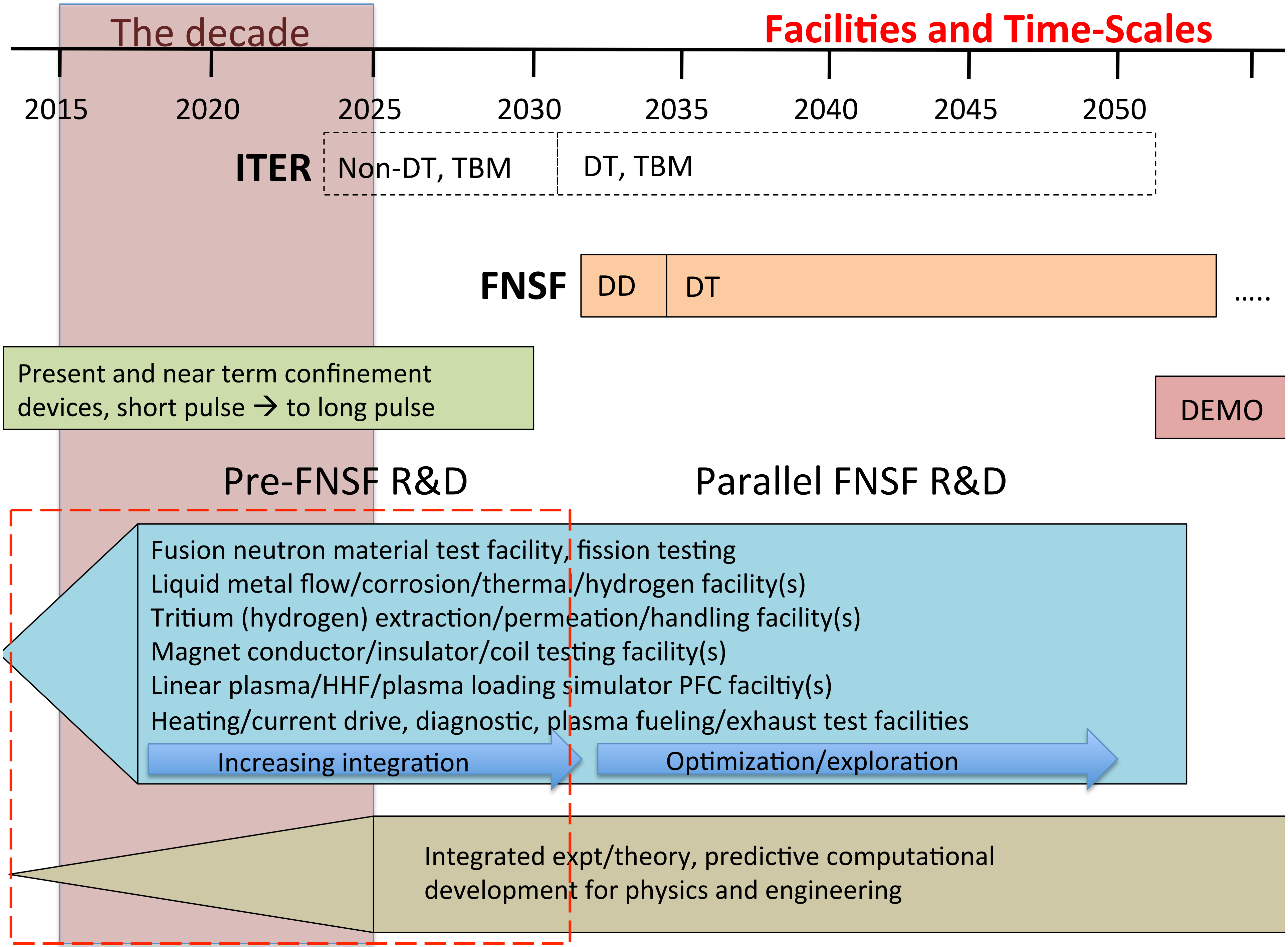


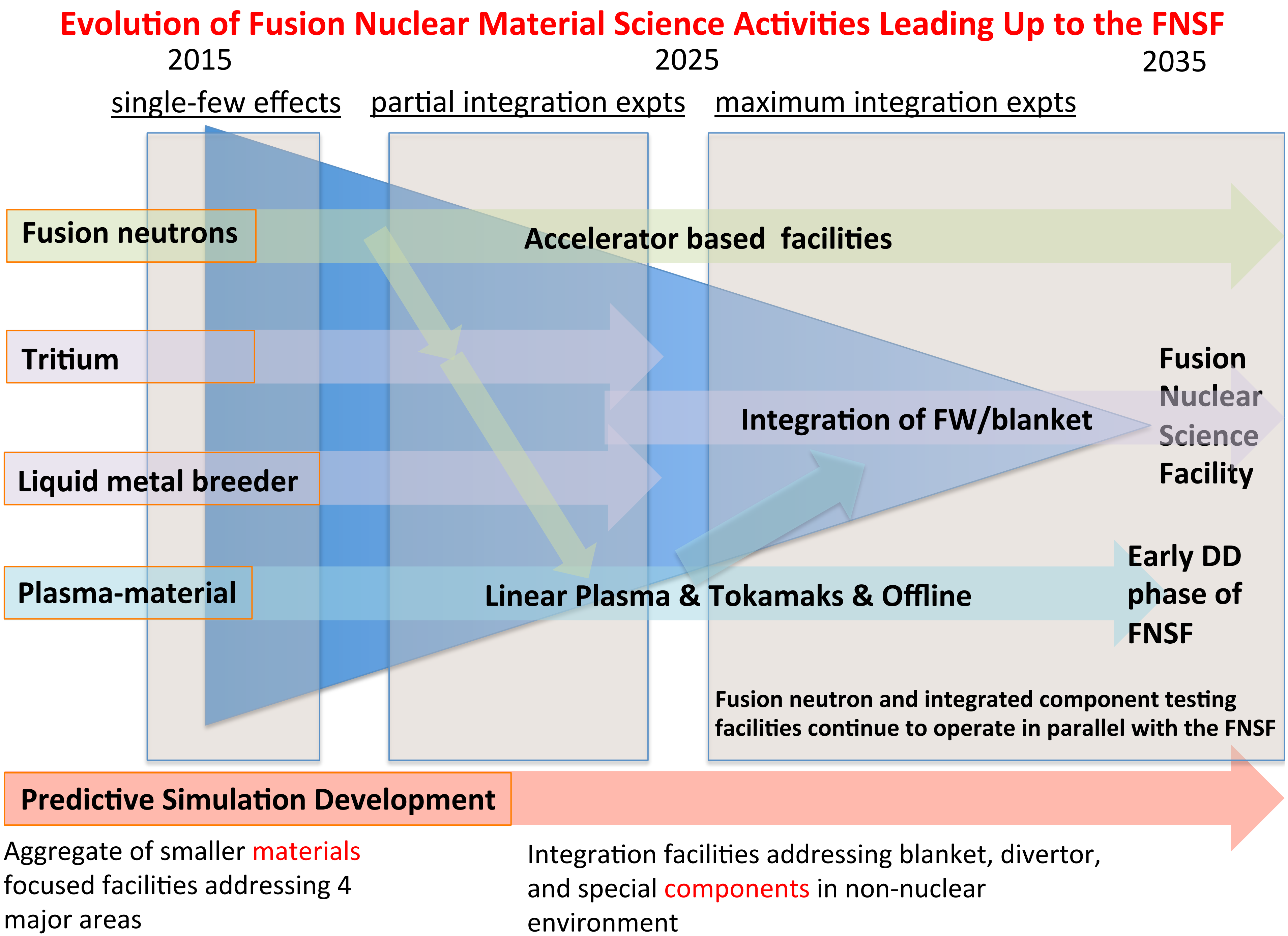
The FNSF is an intermediate step to accommodate the extreme fusion nuclear environment and the complex integration of components and their environment, and the nuclear science and plasma physics

The FNSF will operate with

- a very long pulse fusion neutron producing plasma and very high duty cycles,
- with completely integrated components first wall, blanket, shield, vacuum vessel, divertor, etc.,
- in the fully integrated environment (simultaneous) of fusion neutrons, volumetric and surface heating, hydrogen in materials, strong magnetic fields, pressure/stresses, high temperatures, vacuum interface with plasma, flowing breeder with material interactions, and PMI, all with significant gradients

The FNSF is itself, a materials testing platform in the complete fusion environment


The decade
Facilities and Time-Scales
2015
2020
2025
2030
2035
2040
2045
2050
ITER
Non-DT, TBM
DT, TBM
FNSF
DD
DT
.....
Present and near term confinement devices, short pulse → to long pulse
DEMO
Pre-FNSF R&D
Parallel FNSF R&D
Fusion neutron material test facility, fission testing
Liquid metal flow/corrosion/thermal/hydrogen facility(s)
Tritium (hydrogen) extraction/permeation/handling facility(s)
Magnet conductor/insulator/coil testing facility(s)
Linear plasma/HHF/plasma loading simulator PFC faciltiy(s)
Heating/current drive, diagnostic, plasma fueling/exhaust test facilities
Increasing integration
Optimization/exploration
Integrated expt/theory, predictive computational development for physics and engineering



Evolution of Fusion Nuclear Material Science Activities Leading Up to the FNSF
2015
2025
2035
single-few effects
partial integration expts
maximum integration expts
Fusion neutrons
Accelerator based facilities
Tritium
Integration of FW/blanket
Fusion Nuclear Science Facility
Liquid metal breeder
Early DD phase of FNSF
Plasma-material
Linear Plasma & Tokamaks & Offline
Fusion neutron and integrated component testing facilities continue to operate in parallel with the FNSF
Predictive Simulation Development
Aggregate of smaller materials focused facilities addressing 4 major areas
Integration facilities addressing blanket, divertor, and special components in non-nuclear environment

The Material and Fusion Nuclear Science are Driven by Four Primary Thrusts

1 - Fusion neutrons, are highly energetic particles that produce significant damage and transmutations (generating helium and hydrogen in solids) in all materials

> **ACTION:** Pursue strategy for accelerator/target platform(s) to test materials with fusion relevant neutrons, in US and in coordination with international efforts, to address the multi-decade fusion materials development required to design, construct and operate the FNSF, and to continue to evolve toward higher neutron exposures on the FNSF and beyond.

2 - Tritium is a highly mobile radioactive isotope, which is produced in large quantities to provide the DT fuel, however, it will migrate throughout the fusion core of peripheral systems in the plant

> **ACTION:** Build and operate small scale experiments on critical tritium issues, moving rapidly to more integrated tritium assemblies (T source, T permeation, T extraction, plasma T implantation, high temp…utilizing TPE and other facilities in STAR at INL, ultimately being part of an integrated non-nuclear blanket testing facility
>
> Deuterium would likely serve as a surrogate for most of this research, although tritium would be examined in critical areas such as extraction

The Material and Fusion Nuclear Science are Driven by Four Primary Thrusts

3 - Liquid metal breeder, primarily $Li_{16}Pb_{84}$, is the tritium breeding material, but is a electrically conducting fluid moving through a strong magnetic field

ACTION: Build and operate small scale experiments on critical liquid metal breeder issues including

- PbLi constituency control with impurities and gases;
- Material interactions of PbLi with RAFM, SiC composities, coatings with varying temperature, flows and B-fields;
- PbLi flow assembly for complex 3D thermo-fluid behavior (MHD) at high temperatures, B-fields, with appropriate material contact utilizing MaPLE at UCLA; then moving to higher flow rates, higher temperatures, higher B-fields and larger magnetized test volumes
- PbLi safety science…..

Ultimately being part of an integrated non-nuclear blanket testing facility

The Material and Fusion Nuclear Science are Driven by Four Primary Thrusts

4 - Plasma Material Interactions on the **Plasma Facing Components,** in the ultra-long pulses envisioned for the FNSF, will produce unprecedented material evolution

Existing and *Possible* Facilities include:

- Linear plasma simulators,
- Existing and planned tokamaks, stellarators
  - US tokamaks (~5-10 s)
  - Long pulse tokamaks (~100-1000s)
  - ITER (~500-3000s)
- High Heat Flux facilities
- Liquid Metal PFC testing
- PFC/PMI facility
- DD Phase of the FNSF (~hours to days to weeks)

Develop the technical confidence in divertor component

AND first wall and launcher designs

ACTION:

- Understanding the SOL-divertor plasma, and associated plasma material interactions and coupling to core plasma…existing tokamaks
- Begin to observe the long pulse issues of erosion/redep/migration, dust, and tritium retention….long pulse tokamaks and ITER, W7X, LHD
- Consult FESAC report on Opportunities for Fusion Materials Science and Technology Research (Zinkle), section 3.2, near, medium and long term.

Fusion Neutrons will Produce New Damage Regimes Compared to Fission

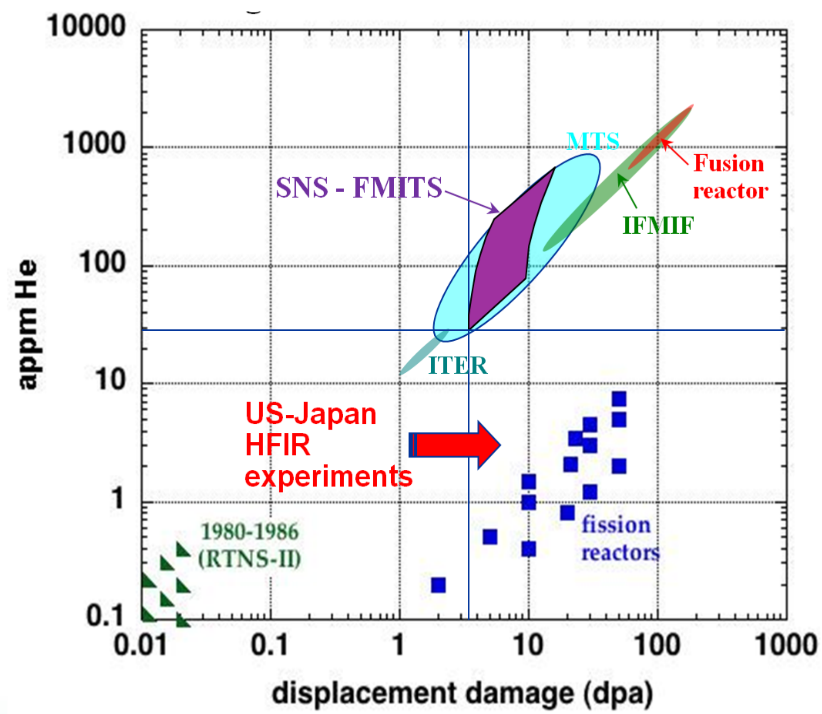
Before the FNSF, we expect to only have fusion relevant neutron irradiation of single materials, in combination with fission neutron exposure

→ Presently the US has no program to provide this testing platform to develop the materials database required for a FNSF

HOWEVER, fusion neutrons are difficult to produce, **accelerators/targets** are used to produce high energy neutrons in the fusion range, beyond the fission neutron energies

Criteria have been established for what is desired by such a facility

- Irradiation volumes
- Neutron flux, damage rate
- Damage, helium/damage, hydrogen/damage
- Availability
- Flux gradients,…



Can we take advantage of a global network of accelerators/targets?

Accelerators/targets are outside FES (BES, HEP, NNSA)

This research requires years to accumulate relevant neutron exposures, it requires iteration with multiple materials, temperatures, and material modifications/developments

Tritium Does Not Need a Crack, Hole or Gap to Move Around, It Moves Right Thru Solids

Tritium will be consumed (and produced) at a rate of 55.6 kg/GW_{fusion}/FPY (full power year), while the average amount released by fission plants is < 0.07 g/year/reactor.

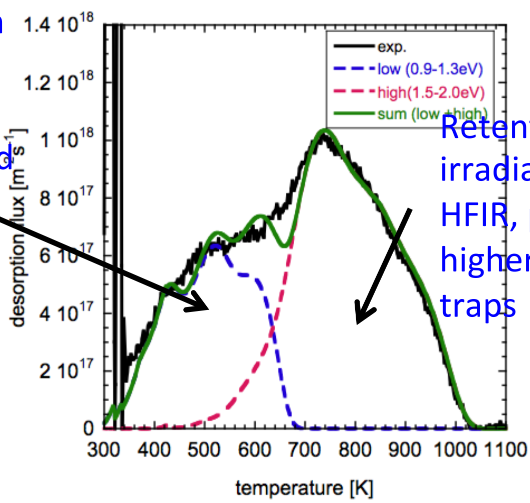
The tritium injected into the plasma chamber, and exhausted is ~ 10x larger than the 55.6 kg/GW_{fusion}/FPY consumption, since the fraction of tritium burned is ~ 10%

Experimental facilities are needed to address many issues associated with tritium behavior from tritium extraction from the breeder, to tritium behavior through multi-materials interfaces, to tritium retention in dust in the plasma chamber

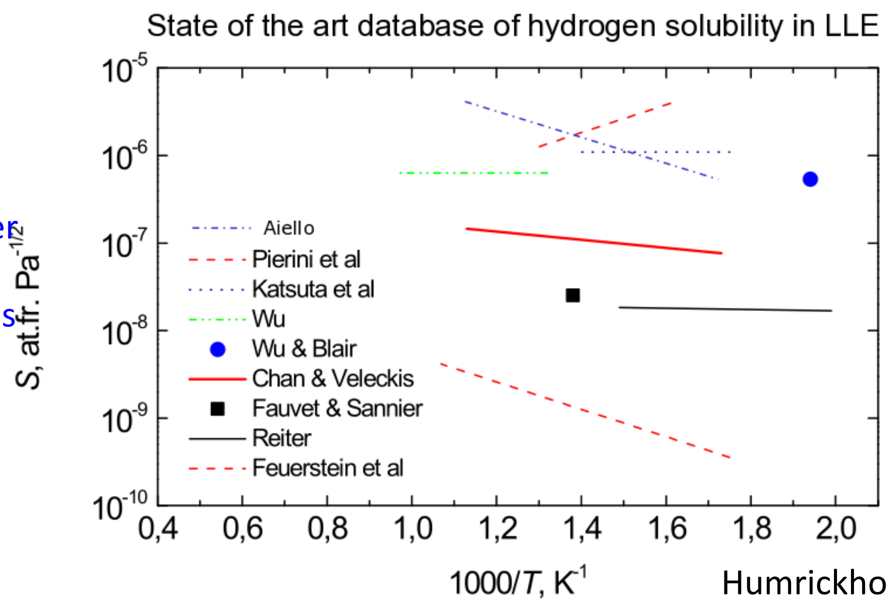
The solubility of hydrogen in LiPb varies by at least 3 orders of magnitude

Hydrogen retention in W matrix, similar to unirradiated

0.025 dpa W, 200C



Retention after irradiation in HFIR, produces higher energy traps



Humrickhouse, INL

Liquid Metal Breeders Will Demonstrate Complex Behavior

PbLi has advantages over pure Li liquid metal and solid breeders

Our knowledge of the PbLi material is still immature to fully predict its behavior due to strong magnetic fields, flow, heating, and liquid-solid interactions

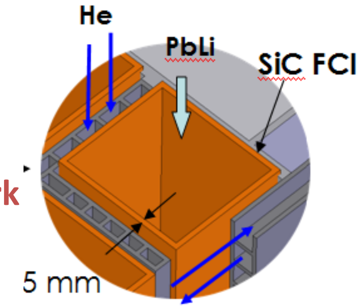
Flowing liquid metal will experience 3D MHD effects, instabilities, buoyancy effects as it crosses and flows parallel to the magnetic field lines

Interaction of RAFM and SiC with PbLi in a magnetic field at high temperatures, leads to new regimes

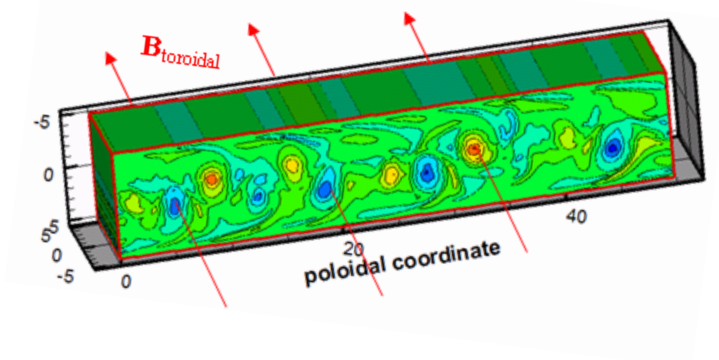
Tritium interaction with helium bubbles, corrosion products and transmutations are unknown

The properties of PbLi in the presence of these pollutants is also not known

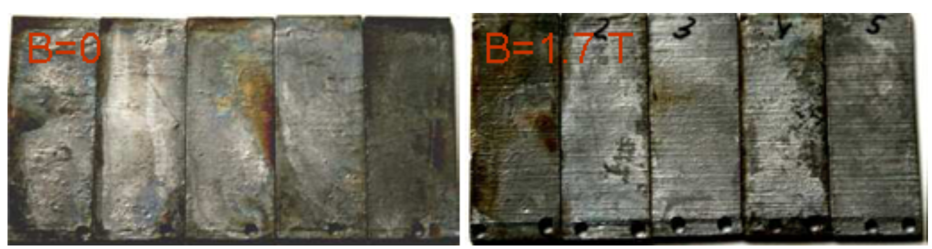
Flow channel insert allows liquid metal concept to work



Quasi-two-dimensional MHD turbulence



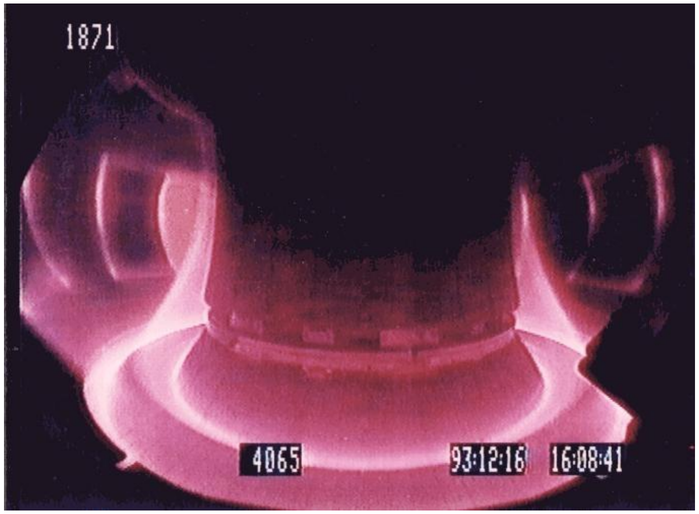
Strong impact of B-field on corrosion



Smolentsev, UCLA

Plasma Facing Components Will Undergo Significant Surface Modification via **PMI**

Plasma facing components include the first wall, divertor, launching structures, and diagnostics



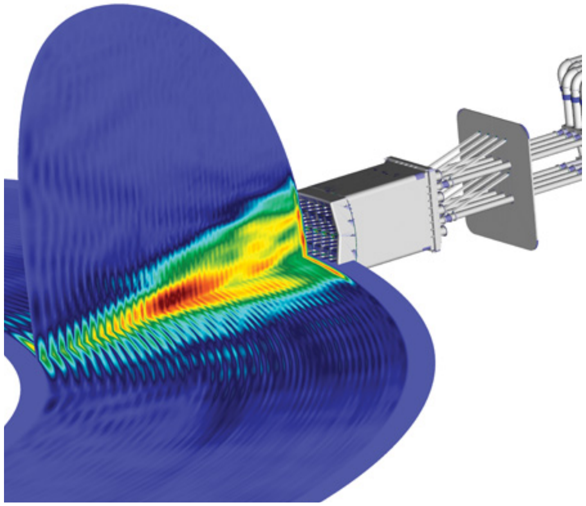
The heat loading, particle loading, erosion, re-deposition, migration, implantation, tritium retention, and dust/debris production must all be understood to a level that allows the design of components for the ultra-long pulses of the FNSF

Linear plasma simulators (like PISCES)

High duty cycle and long exposures, multiple materials, variable plasma species, test irradiated samples

Tokamaks (NSTX-U, DIII-D, C-Mod)

Correct magnetic and PFC geometries, coupled core-SOL-divertor, actual steady and transient plasma loading, able to examine advanced divertors



Offline facilities

High Heat Flux facilities

Liquid metal test facilities

Dust/debris