Oak Ridge National Laboratories Fusion Development Capabilities

Arnold Lumsdaine
Fusion Energy Division

FY2023 INFUSE Workshop

October 19, 2022

ORNL Capabilities Summary

Modeling and Simulation

- Whole device integrated modeling – Integrated Plasma Simulator (IPS)
- Fusion Energy Reactor Models Integrator (FERMI)
- Multi-physics engineering simulation
- Radiation transport modeling
- World-leading high-performance computing platforms

Facilities and Technology Development

- World-leading neutron science irradiation facilities
- Pellet fueling technologies
- RF research testing
- Magnet and cable R&D
- Helium flow loop experiment
- Activated materials characterization
- Material corrosion testing
- Plasma facing component design and testing
- Remote handling

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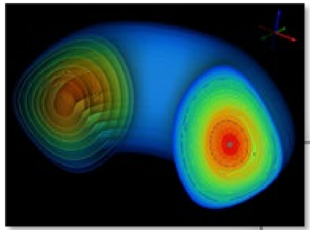
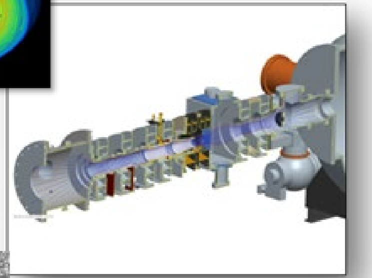
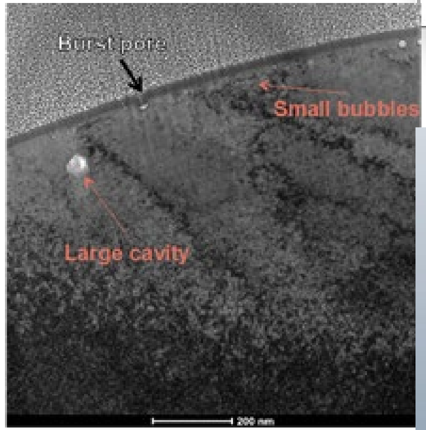
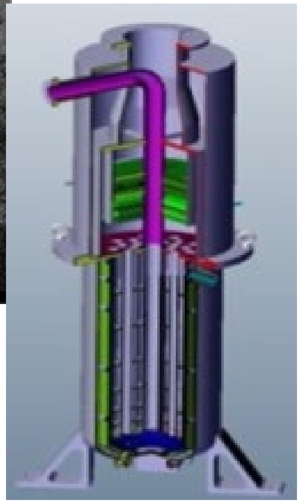
Five high-level thrusts provide growing capabilities

- Develop a fusion ***whole device modeling capability*** leveraging ORNL high-performance computing expertise and commitment to advanced computing
- Build the Material Plasma Exposure eXperiment (***MPEX***), a world-leading capability to test plasma facing materials
- Develop the next generation of ***fusion plasma facing and structural materials*** leveraging the largest materials program in the Office of Science, LM-PFCs
- Provide a solution to the problem of ***power and particle exhaust*** compatible with high duty cycle operation
- Develop ***fuel cycle and blanket technology***



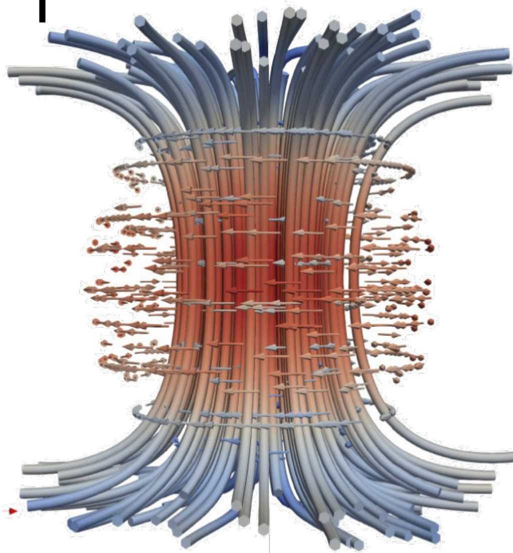


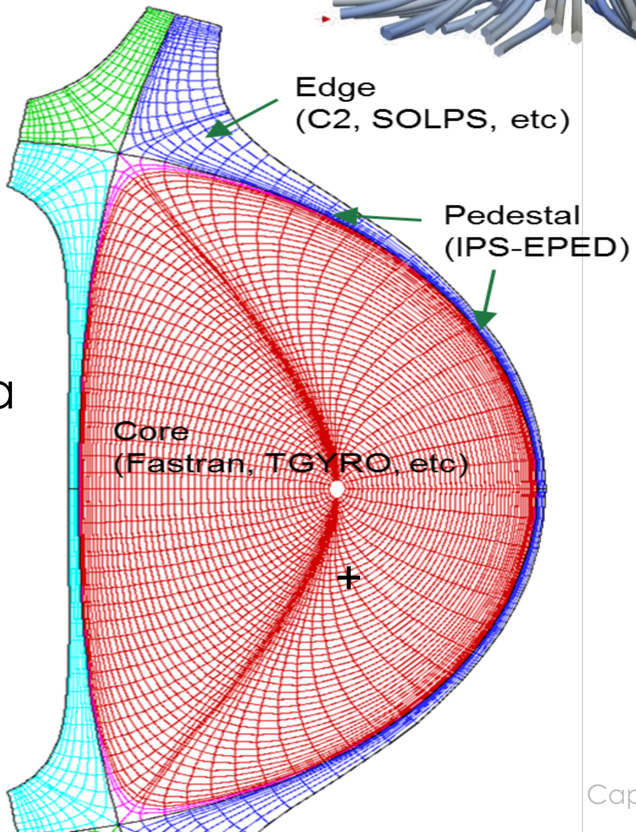




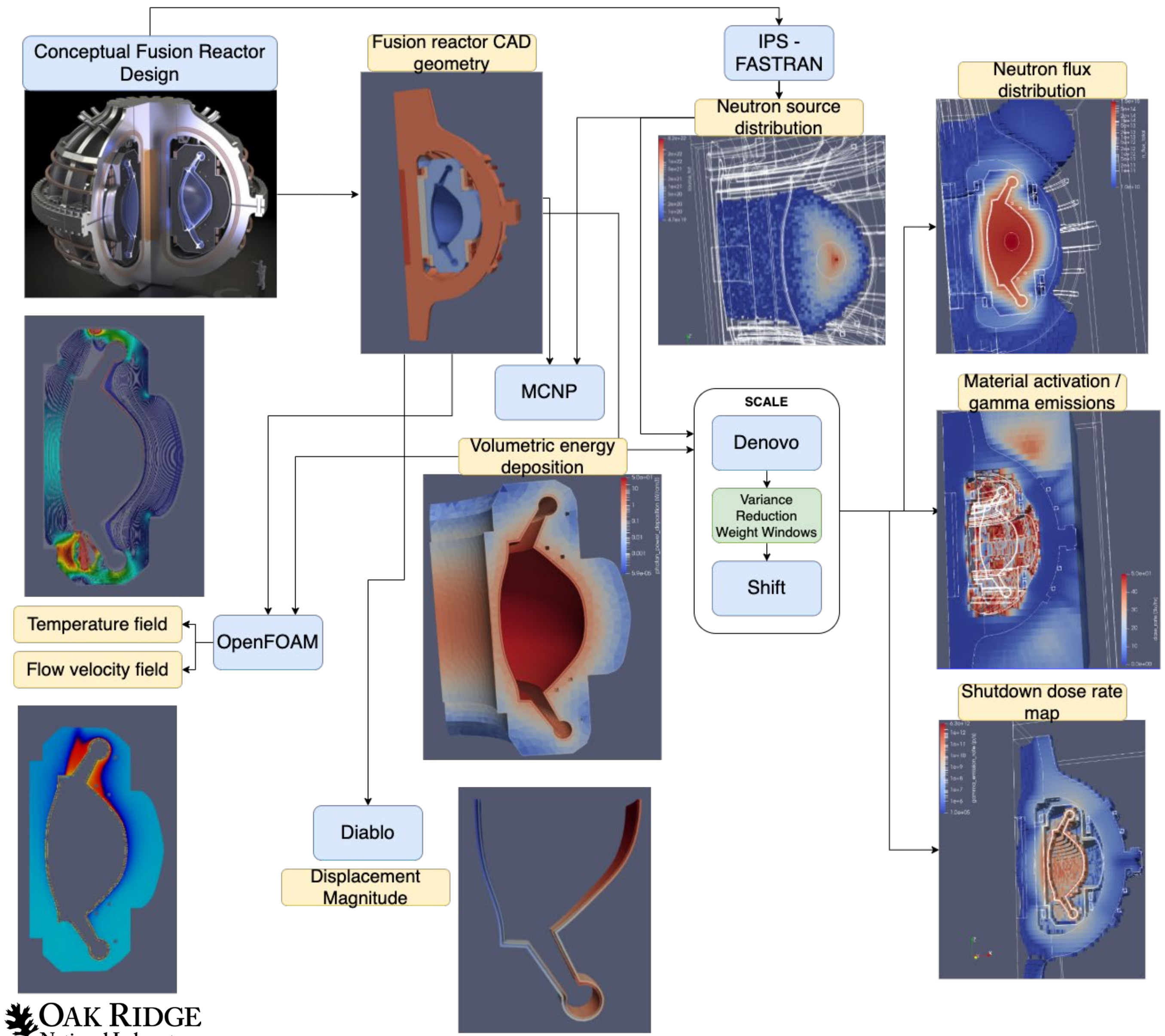
Fusion Whole-Device Modeling Capability for FPP

- **Present efforts:** AToM SciDAC, LDRD projects on integration and pedestal-boundary physics
  - Using ORNL's "Integrated Plasma Simulator" (IPS) to integrate models and optimize performance
    - High fidelity HPC simulations, analytic theory, and AI/ML to develop and enhance reduced models, which are systematically validated on multiple existing devices
  - Core-pedestal modeling well-developed, initial pedestal-boundary (EPED-SOLPS) coupling developed
  - Systems code integrated into IPS, initial physics-engineering coupling and optimization
- **Near-term goal**: FPP integrated design capability
  - Systematic prediction and optimization of coupled full plasma (core-pedestal-boundary) system
  - HPC enabled integration of **plasma**, **neutronics**, and **engineering** components
  - Pre-conceptual reference designs to highlight key integration issues and high impact optimizations





Fusion Energy Reactor Models Integrator (FERMI)



PI: Vittorio Badalassi
Team: ORNL, LLNL, CFS, MIT, Hypercomp, NVidia
ARPA-E GAMOW Award

Technology Summary

- *Development of a virtual reactor*
- *Integrated plasma physics, PMI, shielding, structural/ thermal, MHD, fluids, UQ models*
- *Validation on available data and results*

Technology Impact

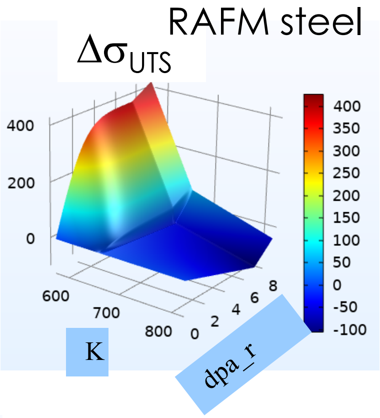
- Speeds up the overall design development by 30 times
- Exceptional fidelity of the engineering calculations
- Enables the development of a commercial fusion reactor

Proposed Targets

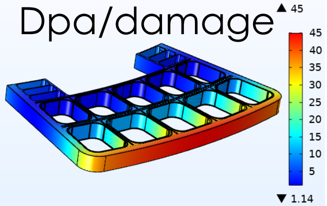
Metric	State of the Art	Proposed
Coupled Multiphysics First Wall and Blanket Simulation	*No existing capability*	*FERMI integrated simulation environment*
FliBe cooled/breed FW & Blanket Proof of Concept	*TRL = 3*	*TRL = 6*
Conceptual Design time	*9 Years*	*3 months*
Design team number and design iterations	*20 engineers and 3 iterations*	*3 engineers and 6 iterations*

ORNL FED Multi-Discipline Fusion Engineering Simulation

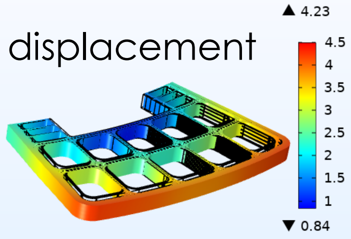
Thermo-Mechanical with Irradiated property evolution



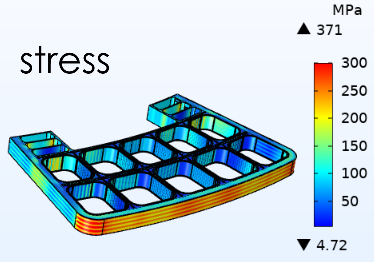
Dpa/damage



displacement

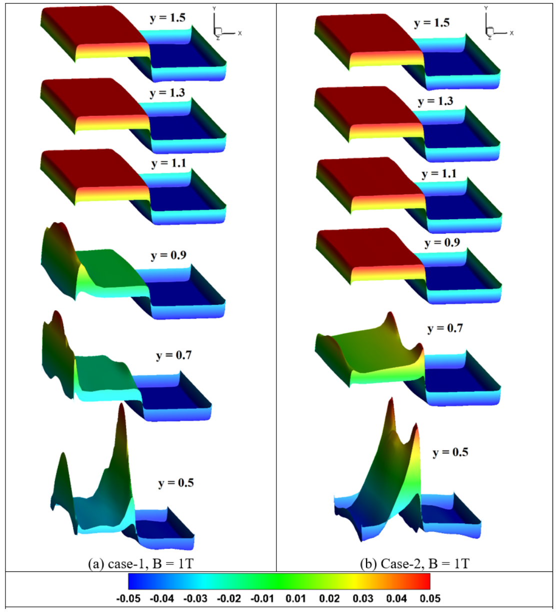


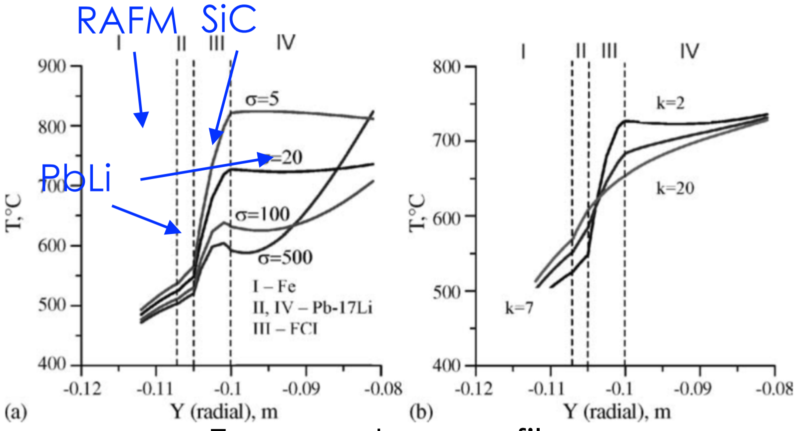
stress



Liquid Metal MHD/CFD

Velocity profiles

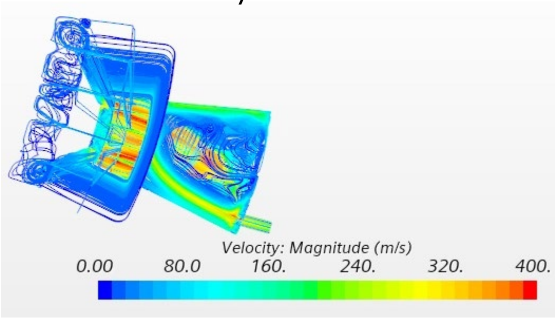


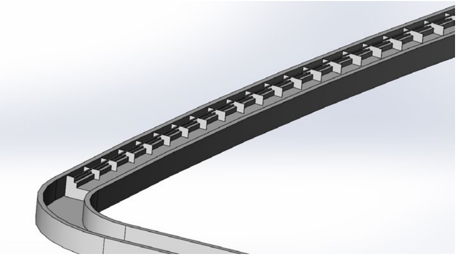


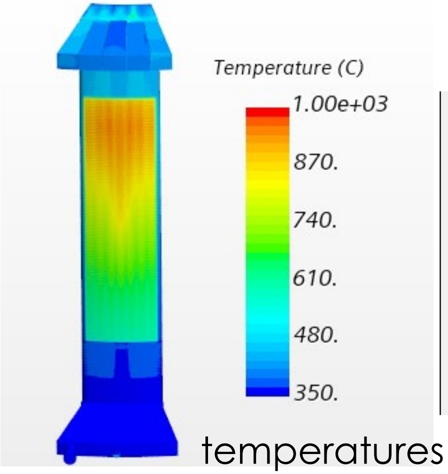
Temperature profiles

Helium CFD

Velocity streamlines



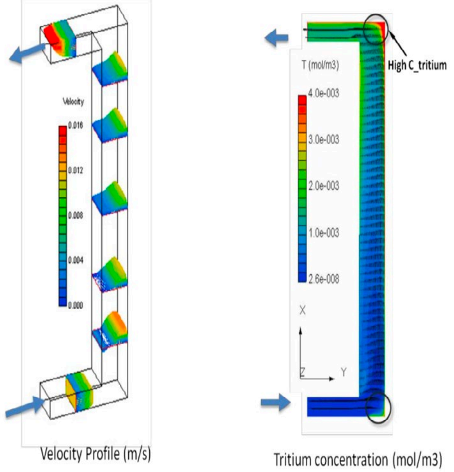




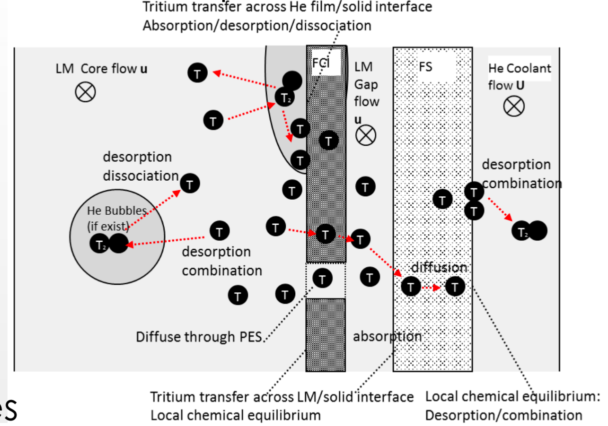
temperatures

Tritium Migration

Tritium in fluid



Tritium permeation



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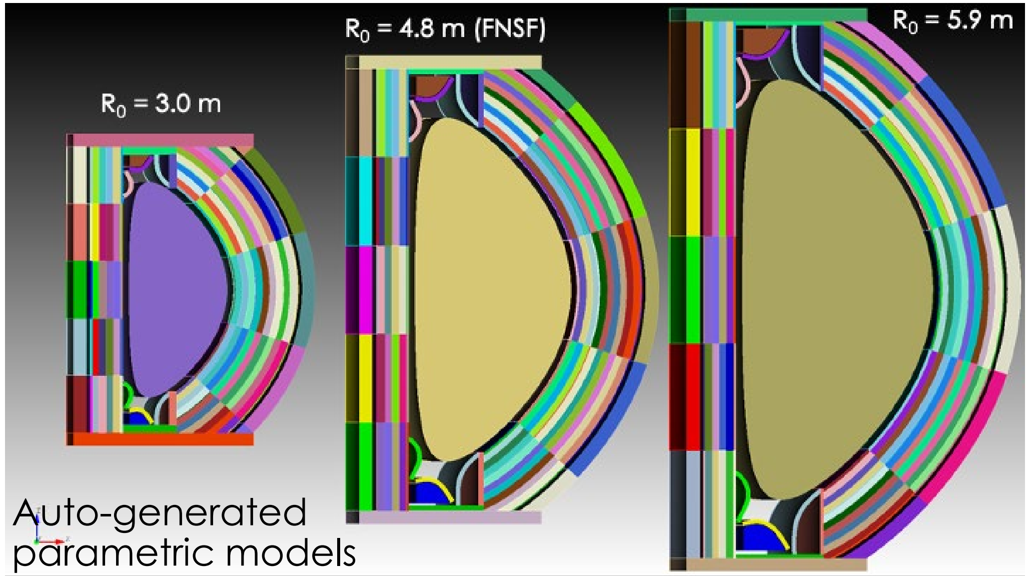
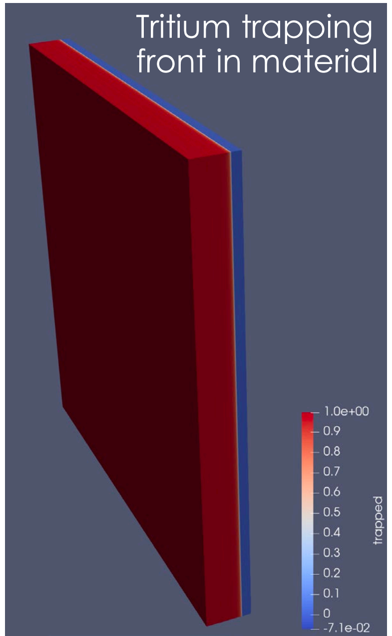
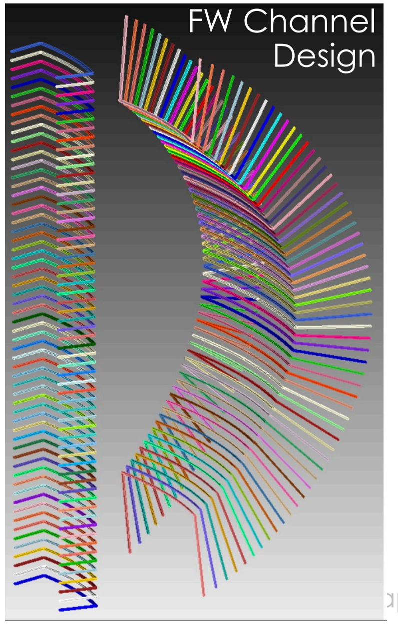
Multiphysics modeling of blankets & ancillary systems

- Parametric design and automatic CAD generation using python/Cubit
- Neutronics modeling with MCNP
- Heat, tritium generation profiles from neutronics coupled to 1/2/3D models of:
  - Heat transfer
  - Thermal hydraulics
  - Tritium transport

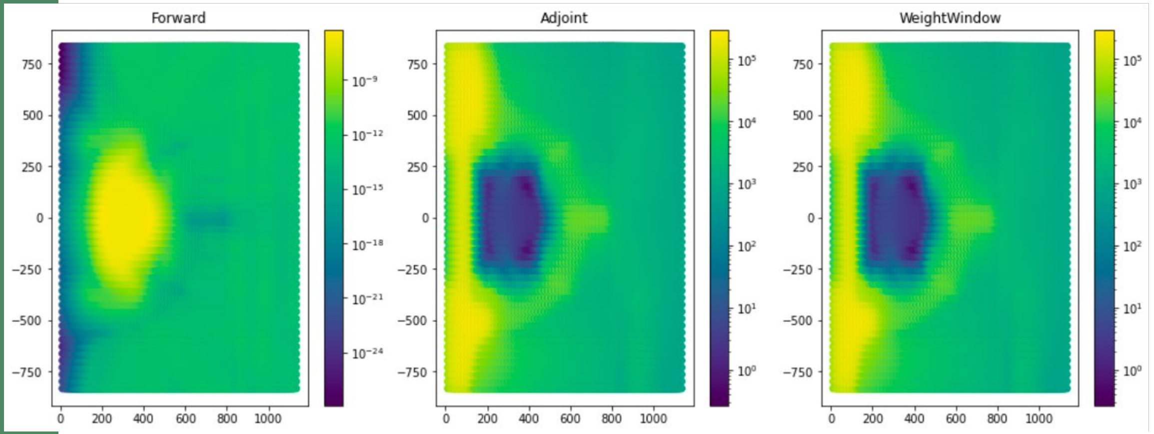




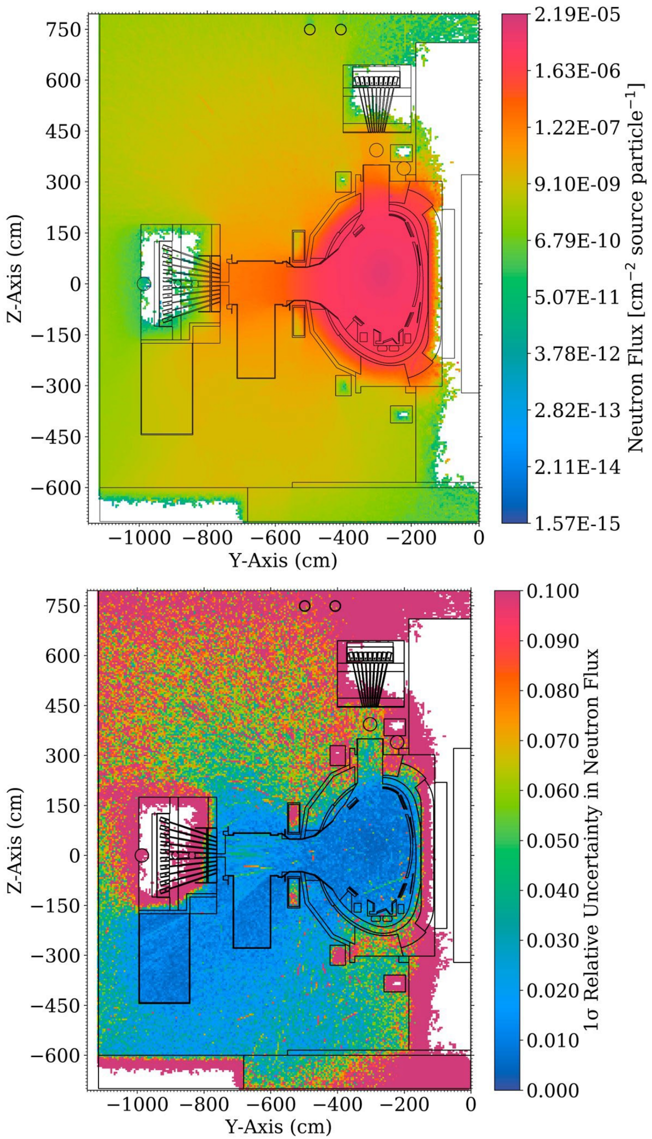


ORNL Fusion Radiation Transport Analysis Capabilities

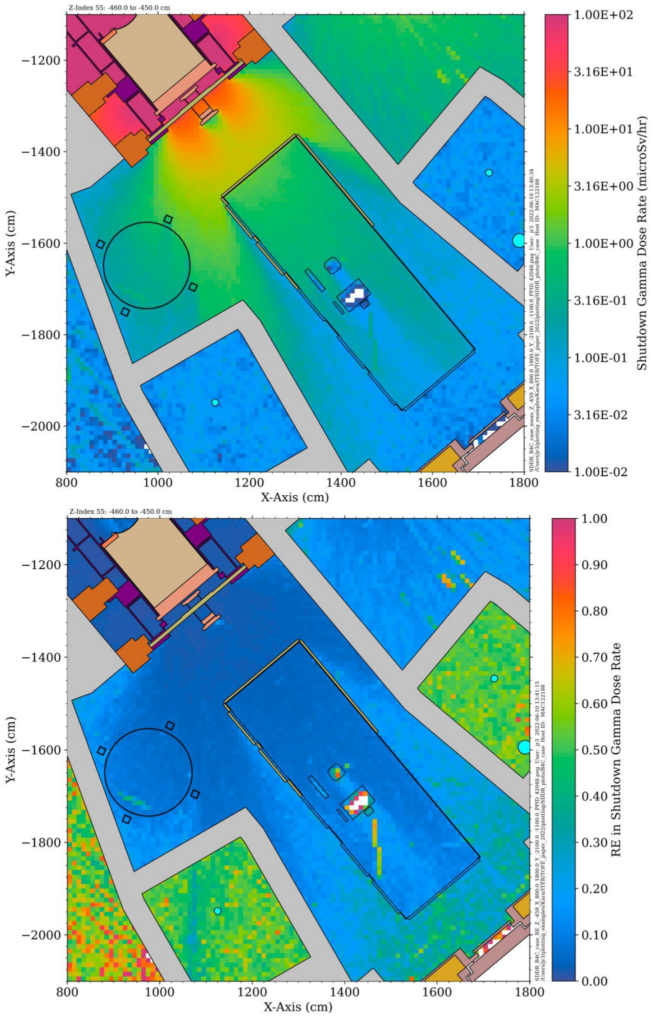
- **ORCS** for Shutdown Dose Rate (SDDR)
  - *ORNL Rigorous Two-Step (R2S) Code Suite*
  - *Monte Carlo neutron and photon radiation transport with variance reduction and activation*



Reactor concept design variance reduction using Shift and DAGMC directly on CAD model (FERMI)



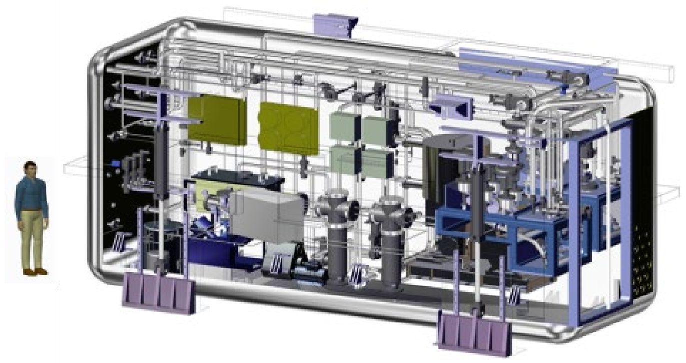
JET Oct 1 neutron flux with RE



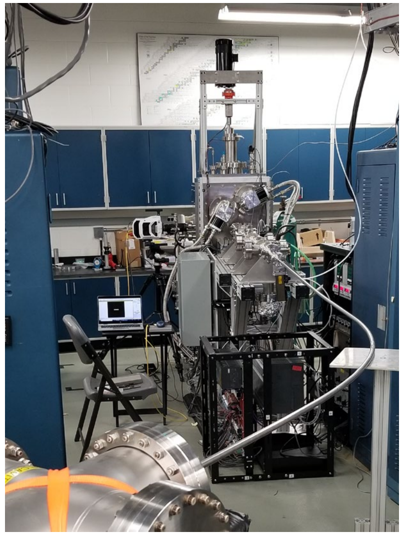
ITER LP 16 SDDR with RE
10^6 s after shutdown

Steady-State Pellet Fueling Systems

- The future fusion energy reactor will require a true steady-state pellet fueling system.
- ORNL has been developing a steady-state pellet injector for ITER based on twin-screw extruder (TSE) and gas gun technology.
- A prototype using this same technology is being developed to provide steady-state fueling for W7-X without the complication of tritium.
- Deployment on W7-X is helpful for ITER to gain experience with the technology.



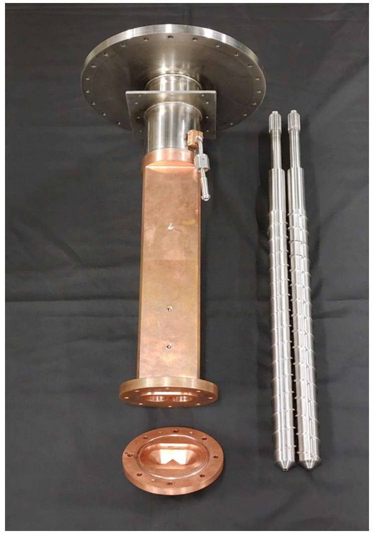
ITER Pellet Injection System Conceptual Design



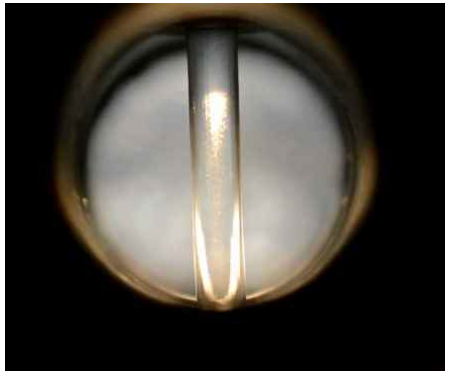
W7-X Continuous Pellet Fueling System

ORNL Pellet Fueling Technology

- The pellet source for a reactor fueling system will be based on a continuous cryogenic extruder.
- ORNL has been developing a steady-state extruder for ITER.
- Extension of this technology to achieve higher flow rates and tritium compatibility needed for ITER and beyond are under development



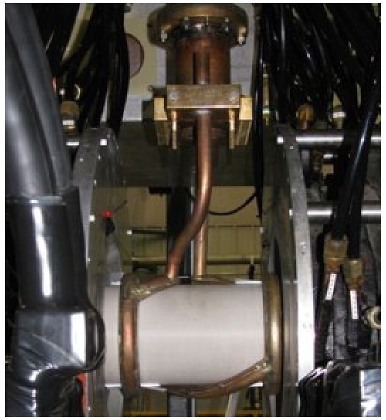
Twin-screw extruder



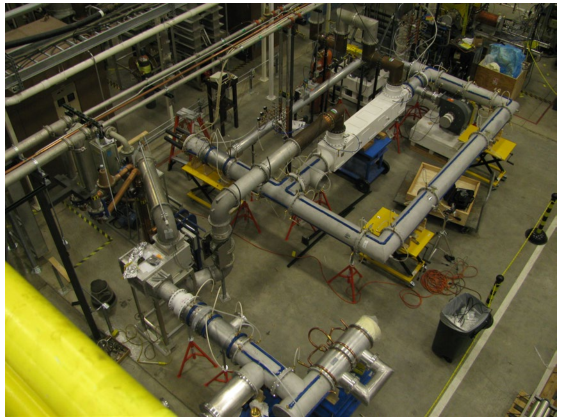
3 mm solid H_2 continuous extrusion

ORNL Enabling Technology - RF R&D & Capabilities

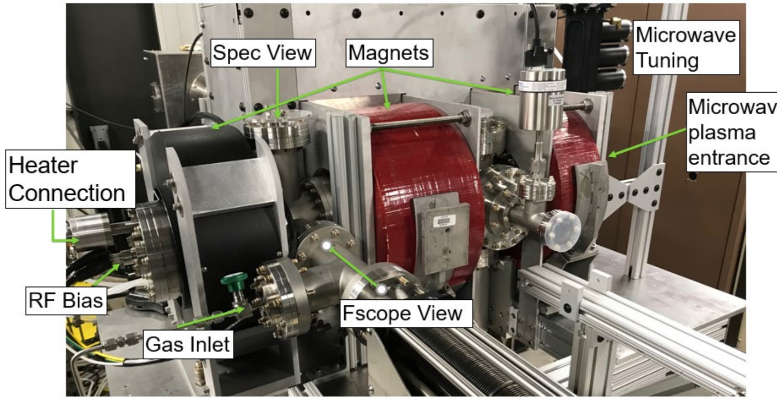
- Key contributor to ITER ECH and ICH technology and controls demonstration and development
- High-powered microwave sources & infrastructure
  - 28 GHz (200 kW), 53 GHz (200 kW), 104/140 GHz (100/40 kW) gyrotrons
  - FMIT (340kW)
  - FRT-85 : 3-30 MHz, 20 kW CW
  - Sairem Transmitter : 100 kW at 13.56 MHz
- Design and building MPEX rf heating technologies for utilization in MPEX
- RF Plasma Interaction Experiment (PIE) with RF Breakdown Testing material
  - Advanced understanding of reactor-relevant rf material degradation in high-temperature environment (W, SiC, BN, SiN)
  - Platform for diagnostic development that support emission and erosion characterization
  -



Helicon Window on proto-MPEX



6 MW resonant ring and line for U.S. ITER



RF Plasma Interaction Experiment (PIE)*

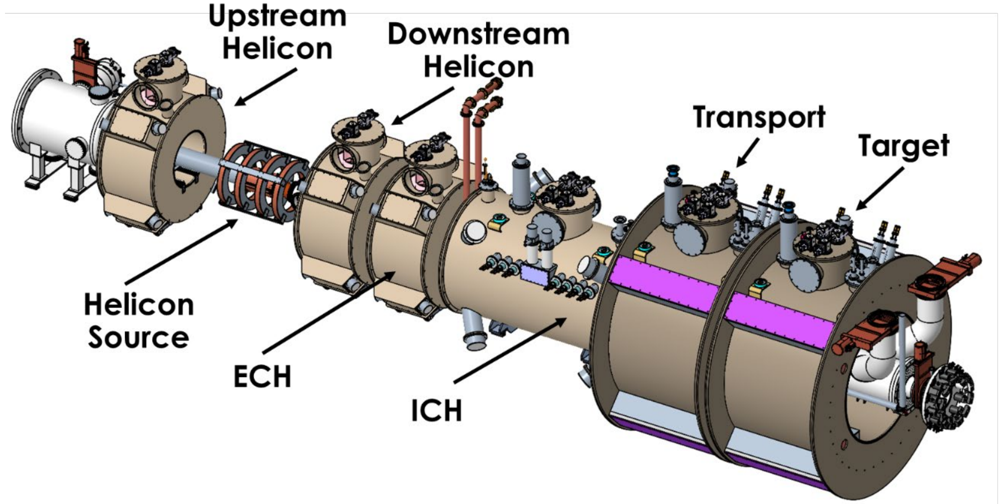
John Caughman (caughmanjb@ornl.gov)
Robert Duckworth (duckworthrc@ornl.gov)

ORNL Enabling Technology – Magnet and Cable Capabilities and R&D

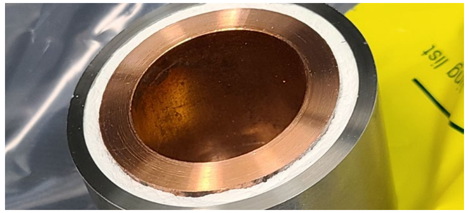
- Working with Tesla Engineering to complete fabrication and acceptance testing MPEX magnet system
- Design support for high-field magnets for plasma separation processing & instrumentation upgrades at SNS
- Irradiation of in-vessel cables for ITER
- Electrical characterization of components for advanced fission and fusion reactor systems

Robert Duckworth (duckworthrc@ornl.gov)

HFIR Gamma Irradiation Facility (GIF)



MPEX Magnet System Delivery to ORNL in 2023



Cross section of IVC to be irradiated at HFIR GIF

Fusion insulation test specimen

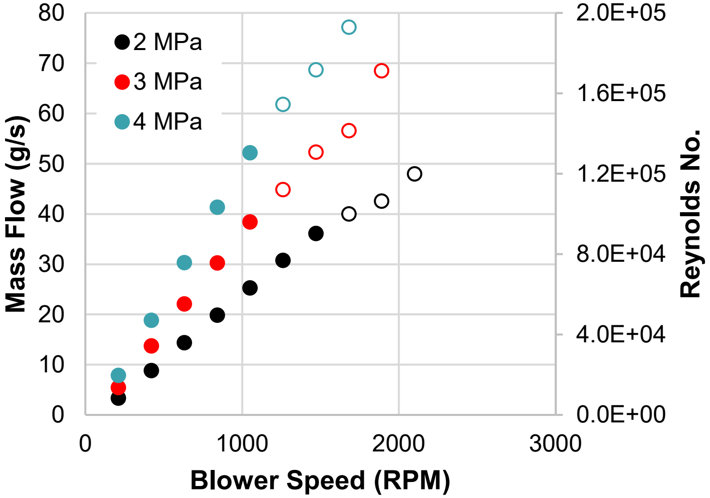
Paschen test fixture

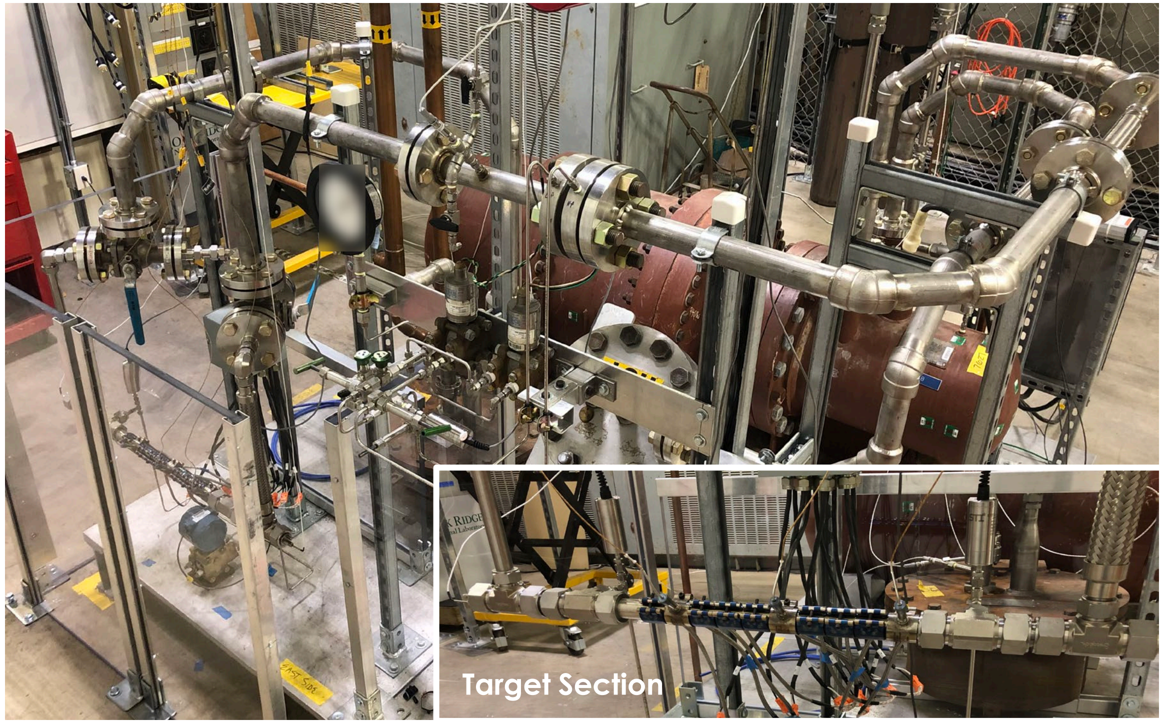
Helium Flow Loop Experiment

HFLE designed, constructed, and commissioned for thermal hydraulic testing of AM components[1].

April 2022 Commissioning

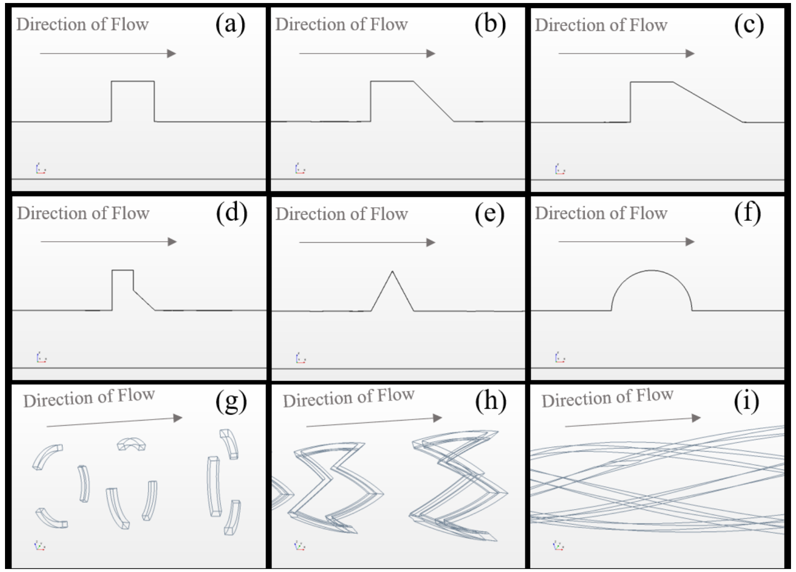
Confirmed operation up to 4 MPa, stable mass flow up to 80 g/s (Re=200k)

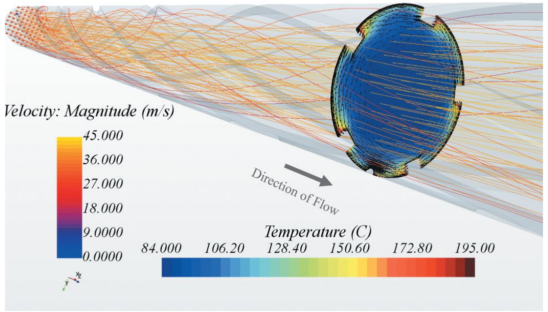




Gen 1 Test Sections

AM 316L SS, various ribbed surfaces, studying heat transfer performance





Geometries matching simulations performed by Gehrig et al[2]

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[1]Wiggins et al, TOFE 2022, Anaheim, CA.
[2]Gehrig et al 2021, *Fus. Sci. Technol*, **77**.

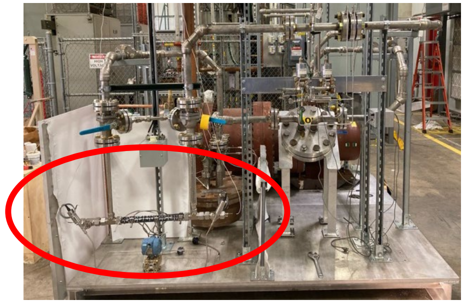
We do foundational R&D for blankets & PFCs

Testing helium cooling strategies for blankets

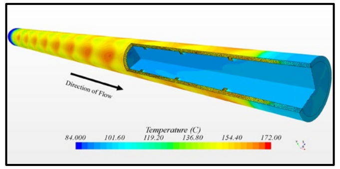
Advanced Manufacturing

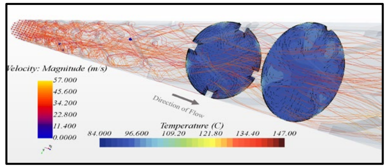
Test section

He loop:
4 MPa, ~100 gram/s, up to ~300 C



Ribbed surface enhances heat transfer

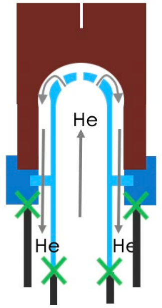




FY23 planned addition

Test helium cooled PFC component under transient heat loads

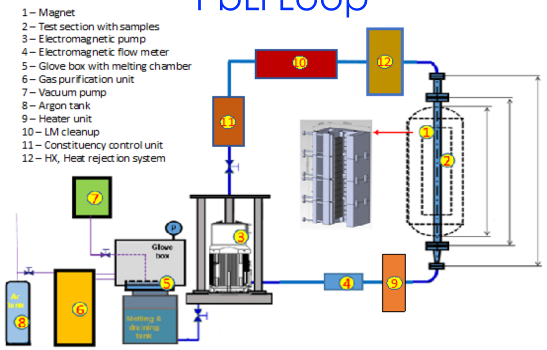
Additive Manufacturing



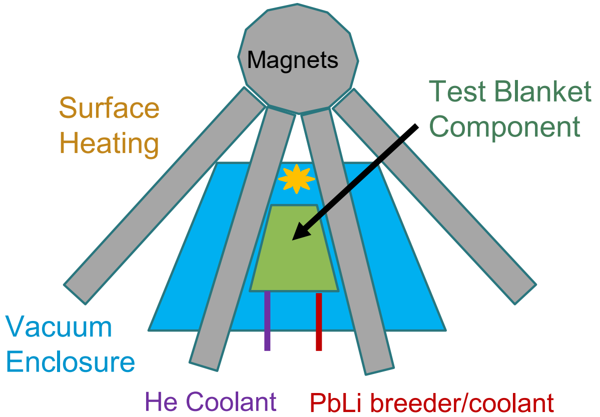
high heat flux source

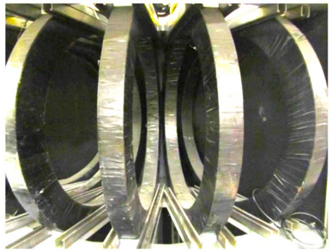
PbLi Loop

Testing PbLi Compatibility with Ferritic Steel in Thermal Convection Loops



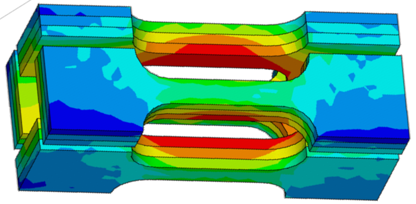
Develop the basis, design, construct, and operate a Blanket Component Test Facility (BCTF)



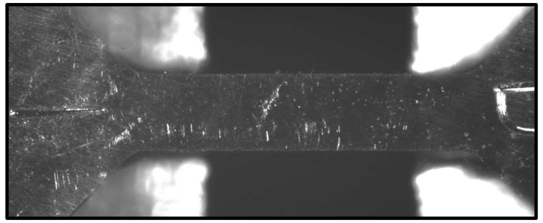


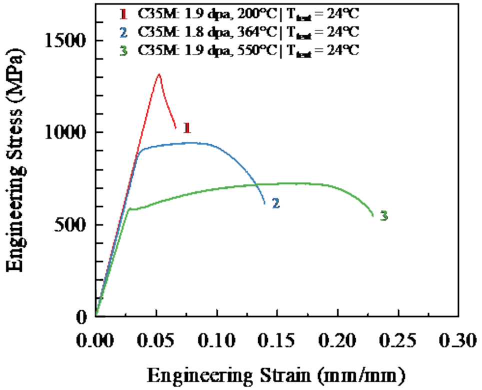
Idea/Mission

Irradiation Capsule Design & Fabrication

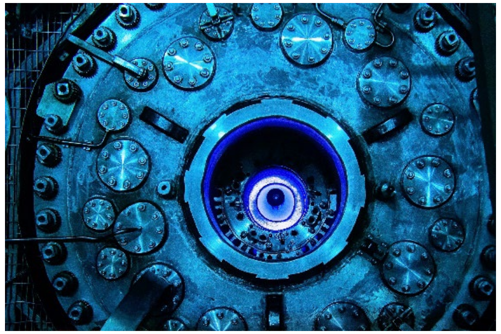


Hot Cell Handling & Mechanical Testing

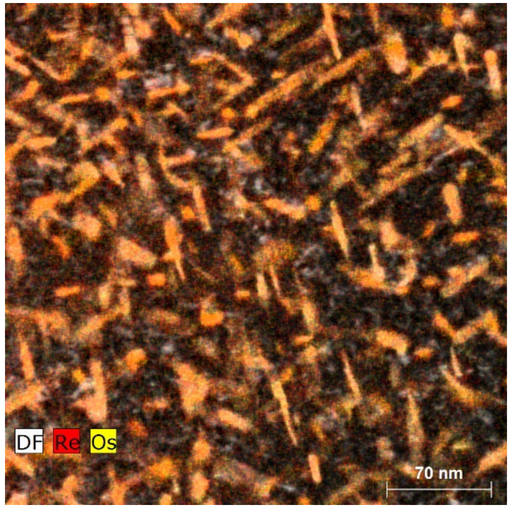




Irradiation



Microstructure Characterization



Data Analytics/Publications

Neutron Science irradiation facilities at ORNL

Spallation Neutron Source

SNS is an accelerator-based neutron source that will provide the most intense pulsed neutron beams in the world for scientific research and industrial development. When ramped up to its full beam power of 1.4 MW, SNS will be eight times more powerful than today's best facility. This versatile scientific tool will give researchers more detailed snapshots of the smallest samples of physical and biological materials than ever before possible. The diverse applications of neutron-scattering research will provide opportunities for experts in practically every scientific and technical field.

https://www.ornl.gov/file/neutron-science-fact-sheet-0/display

https://www.ornl.gov/file/high-flux-isotope-reactor-fact-sheet/display

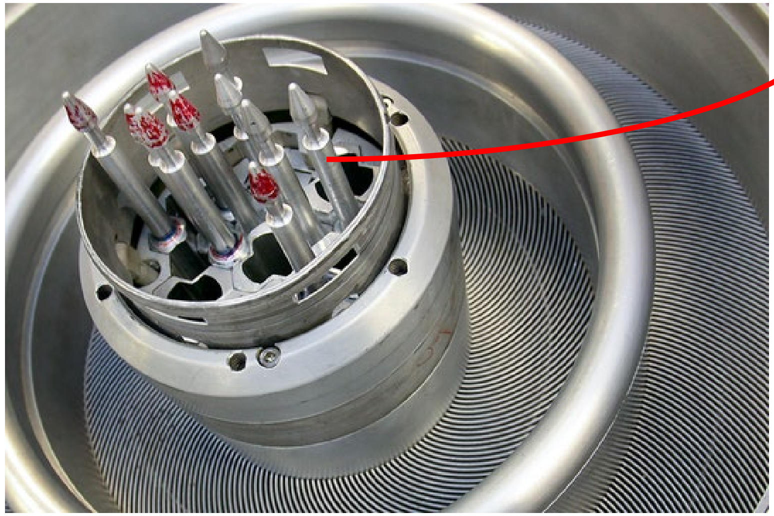
https://www.ornl.gov/file/spallation-neutron-source-fact-sheet/display

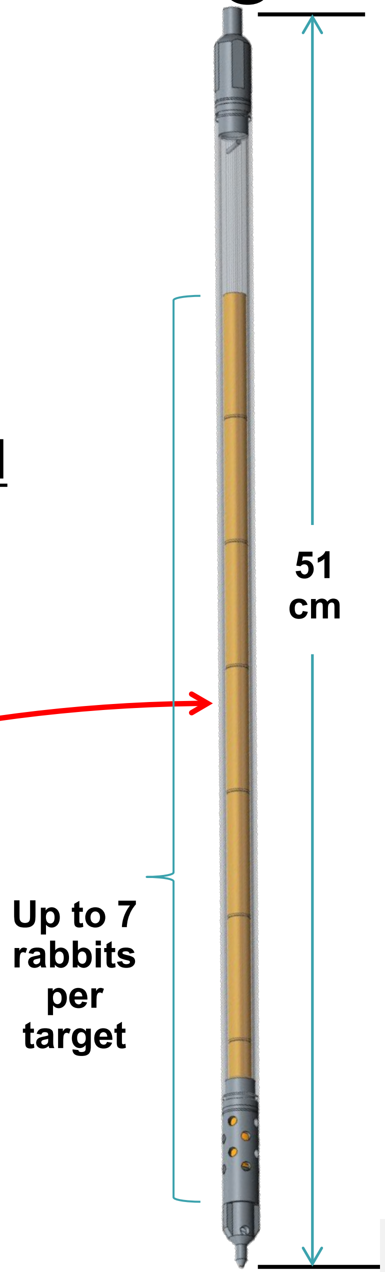
High Flux Isotope Reactor

HFIR is the highest flux reactor-based source of neutrons for condensed matter research in the United States. Thermal and cold neutrons produced by HFIR are used for studies in a variety of scientific fields. The neutron scattering capabilities of this facility provide knowledge about the molecular and magnetic structures and behavior of materials, including high-temperature superconductors, polymers, metals, and biological samples.

Flux Trap Experiments – Rabbits and Targets

- **High fast flux**: 1.1 × 10^{15} n/cm^2/s
- **High thermal flux**: 2.0 × 10^{15} n/cm^2/s
- **Small diameter**: Ø9.5–11.3 mm
- **12.6 dpa/CY** (steel, assuming 7 cycles)
- ~150 available rabbit positions, none instrumented
- ~15 target positions, 2 instrumented
- Single temperature (60°C–1200°C)
- **Low cost:** $30K~$400K





Rabbits inside target rod holder

https://nsuf.inl.gov/File/pfwg%20Petrie%20-%20Oak%20Ridge%20National%20Lab%20NSUF%20Partner.pdf

LAMDA – Low Activation Material Development and Analysis Laboratory

LAMDA is a world-class, multipurpose **radiological materials science facility** for the evaluation of materials of low or no radioactivity. It consists of four laboratory suites containing specialized instrument for materials testing and characterization.

Thermal/physical properties

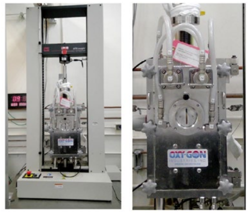
Thermal expansion

Thermal transport

Electrical/ Seebeck

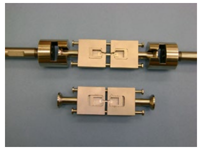
Mechanical properties

Torsion



High Temp Frames

Impact



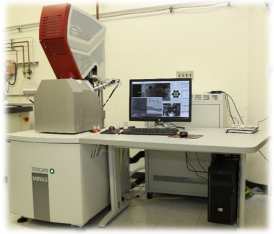
Small Specimen Test Technology

Creep

Microstructural characterization

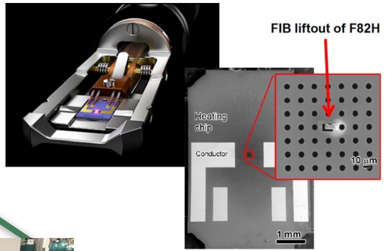
Dual beam FIB

TEM



SEM/EBSD

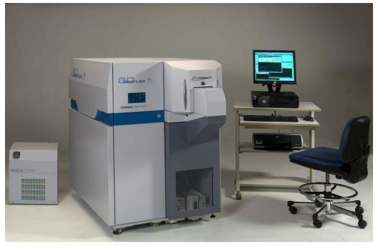
STEM



In-situ - various

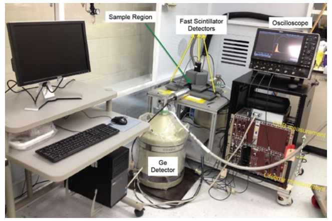
Chemical analysis

LECO O&H

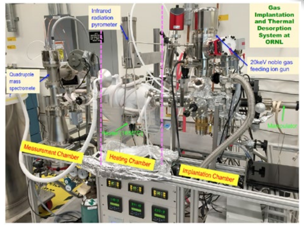


GD-OES

Specialized instruments



Positron Annihilation



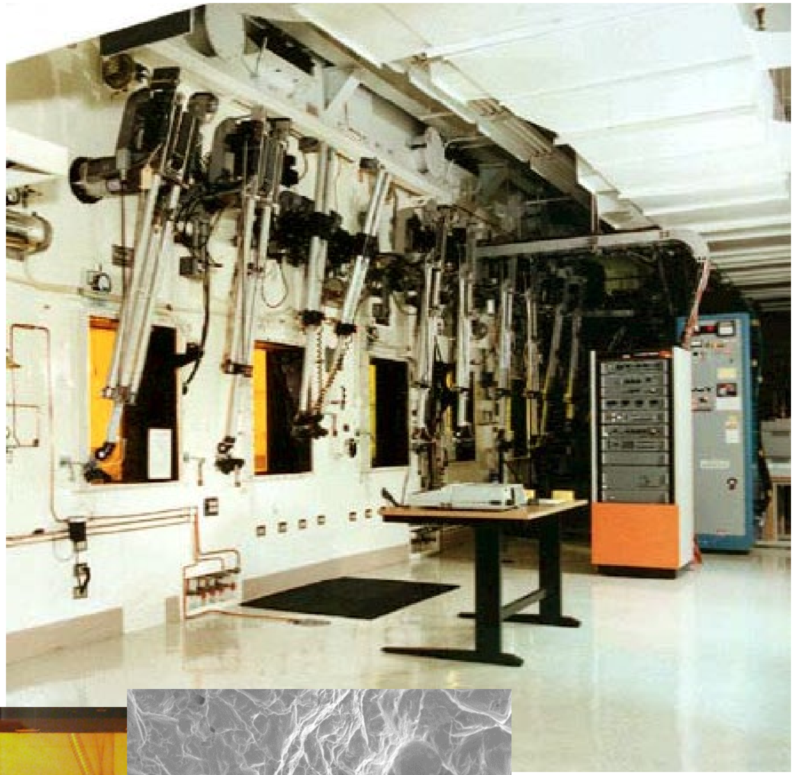
Thermal Desorption Spectrometry

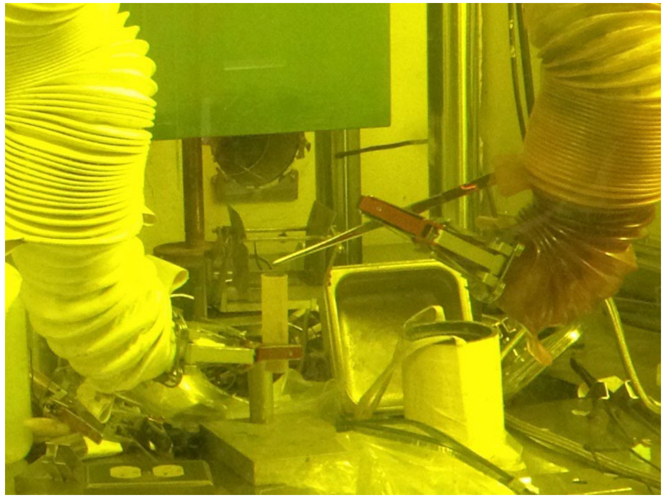
Gas Permeability

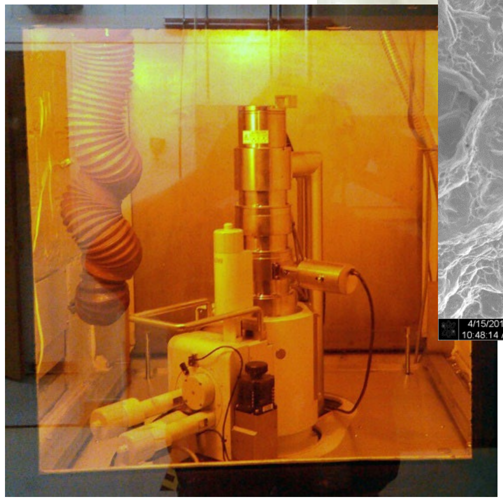
OAK RIDGE National Laboratory

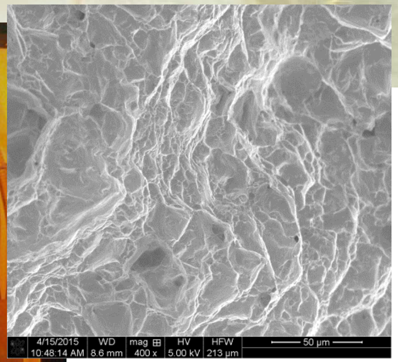
Overview of IMET

- Six interconnected steel-lined examination cells containing 30 m^2 of workspace.
- Cells 1~3 focusing on mechanical testing
- Low alpha contamination facility (<70 dpm / 100 cm^2).
- Irradiation capsule disassembly, mechanical testing (tensile, fracture testing, microhardness), density measurement, SEM, general characterization (optical, video documentation).









In-cell JEOL 6010LA and fractograph from irradiated tensile specimen

Corrosion Science & Technology Group Mission:

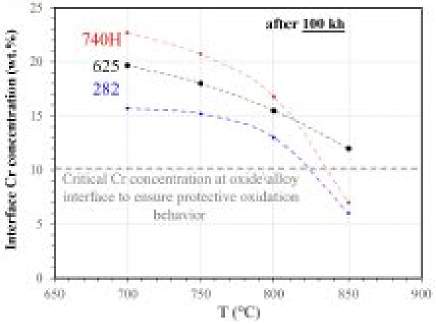
Develop corrosion solutions for all forms of power generation and transportation

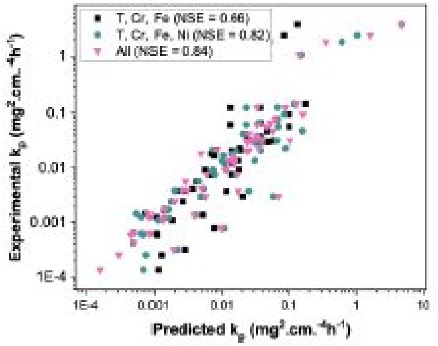
Thermal convection loops determine compatibility in flowing salts or liquid metals

(1st FLiBe loop in 40+ years)

Thermal cycling simulates turbine and automotive duty cycles to evaluate new alloys or coatings

Unique: cycling in controlled gas up to 1500°C



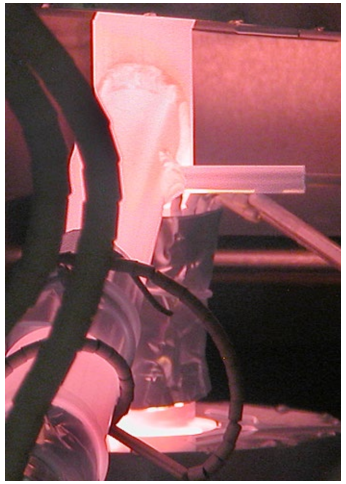


Machine learning and thermo-kinetic models being employed to predict performance

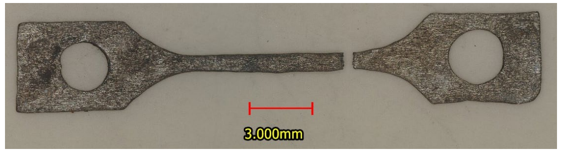
- Expertise covers aqueous and high temperature corrosion
- Solutions include material selection, lifetime modeling, process modification and new alloy or coating development

ORNL Corrosion group studies fission/fusion compatibility

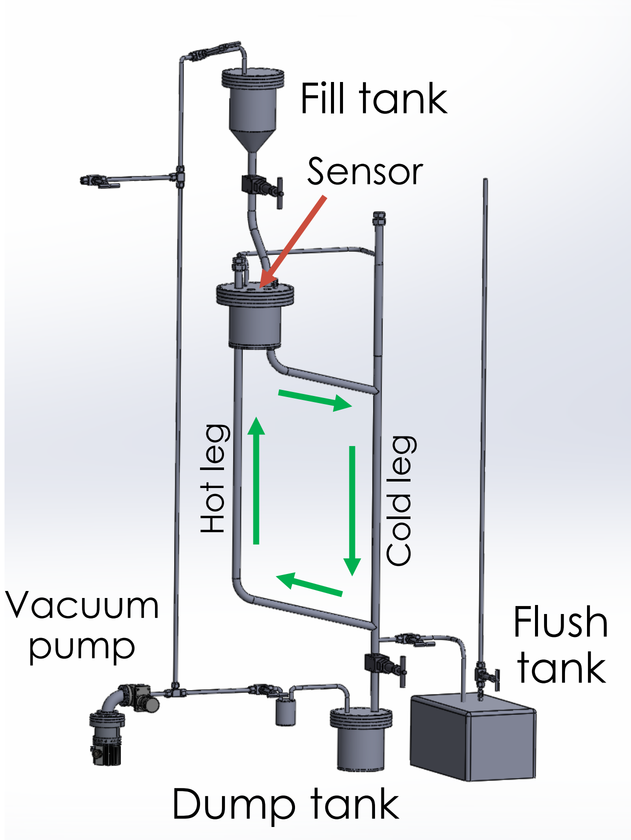
- Recent experience with liquid metals and molten salts
  - Liquid Metals
    - Pb-Li (and Pb)
    - Li
    - Sn
  - Molten salts
    - NaCl-$MgCl_2$
    - FLiNaK (FLiBe surrogate)
    - FLiBe (separate Be-only facilities)
- Static capsule experiments
  - Welded shut to minimize impurity uptake
  - Ex: ORNL funded FY23 project to study Be-X in FLiBe
- Flowing thermal convection loop (TCL)
  - Flow (~1-2cm/s) without pumps or valves
  - ~100°C temperature gradient: **study mass transfer**
  - 1/10 cost of pumped loop ~$125K + salt/metal



V-4Cr-4Ti Li loop at 700°C through chamber viewport



ODS FeCrAl dissolved in flowing Pb-Li at ~690°C

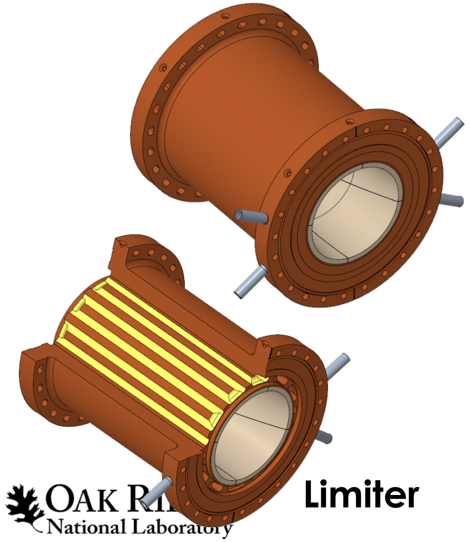


FLiBe TCL (2021 operation)

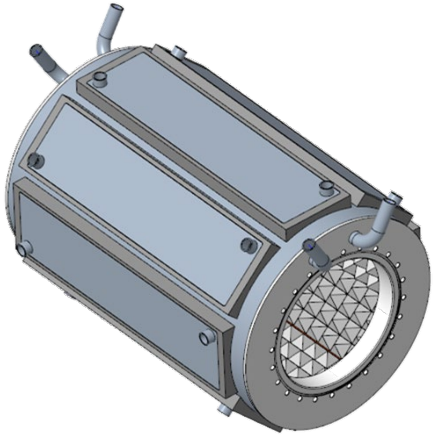
Steady-state PFC development and testing

- The MPEX device will operate in steady-state (up to 10^6 second pulse) requiring actively cooled plasma facing components.
- Components were tested at the Applied Research Lab at Penn State.
  - E-beam deposited prototypic MPEX heat-flux across the entire area of interest.
  - The thermal response was measured with a front-facing IR camera.
  - The test article then undergoes UT at ORNL.

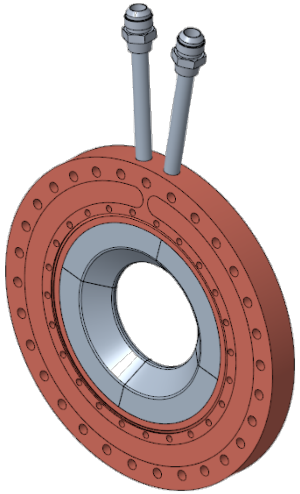
Electron Beam (EB) Facility at ARL-PSU with MPEX Microwave Absorber Test Article



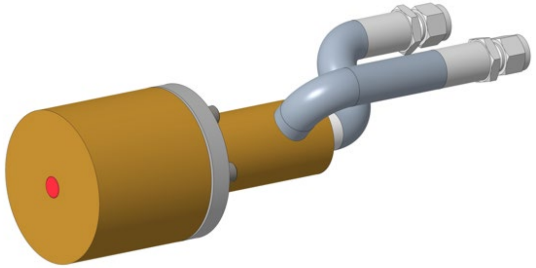
Limiter



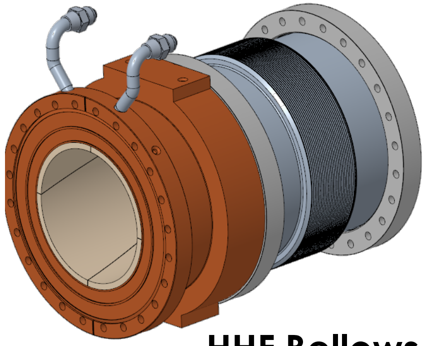
Microwave Absorber



Skimmer



Target



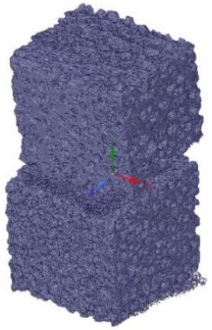
HHF Bellows

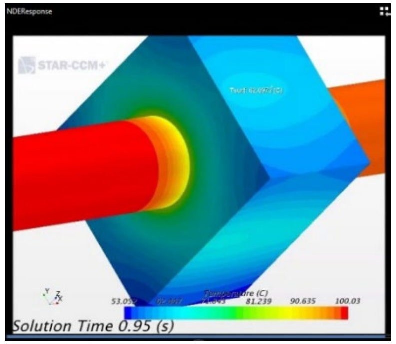
Power Handling Challenges / PFC Development

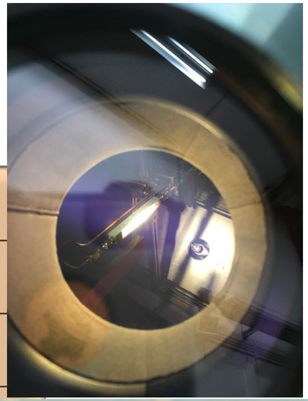
Achievement
- Demonstrated that a *nearly isotropic high-conductivity, low-Z plasma facing material* is possible by combining pyrolytic graphitic ligaments with an isotropic-engineered microstructure

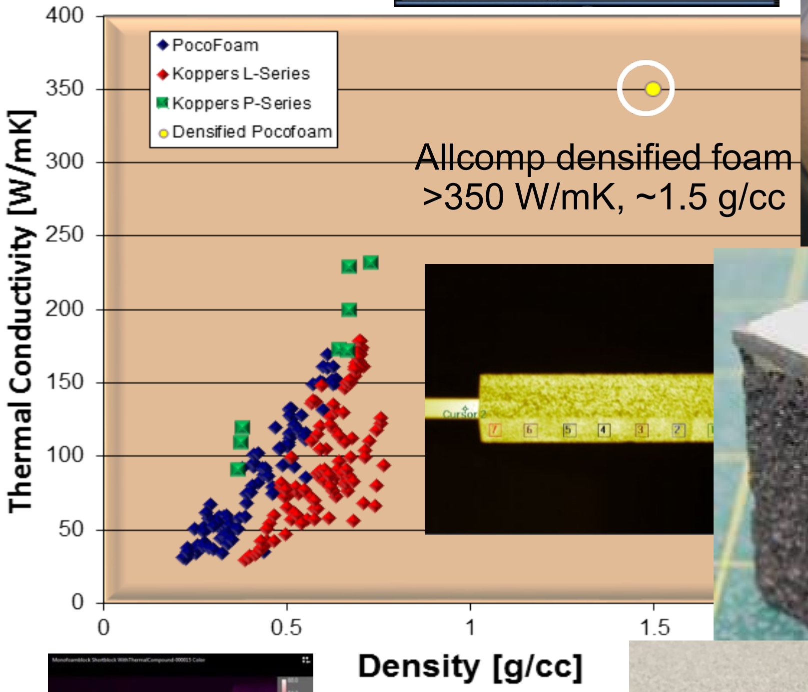
Significance and Impact
- For the first time, the thermal efficiency of low-Z armor is *comparable to the copper heatsink*
- Max Planck IPP interested in fielding the monoblock in the *W7-X stellarator for potential* use in divertor scraper element

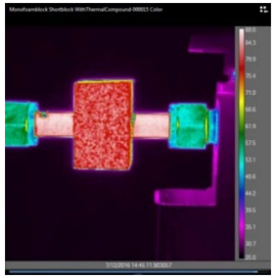
Research Details
- Densified graphitic foam and mock-ups produced
- Thermal properties measured, *k=265 W/mK to date*, expect 350 W/mK
- *Robust braze joint* obtained on CuCrZr tubes
- Hot water IR thermography showed that using no braze joint actually delivers best thermal performance
- W-coated monoblocks in development











D. Youchison, A. Lumsdaine, J. Klett, R. Dinwiddie, P. Bingham

Arnold Lumsdaine (lumsdainea@ornl.gov)

Remote Handling at ORNL

- ORNL Remote Systems Group specializes in designing, analyzing, fabricating, and testing equipment's that go into hazardous environment
- With 50ft high ceilings, Two 10T hoists on a 20T crane, 3 bridges, and a 30ft pit area, RSG can accommodates the needs of many large experiments.
- The Highbay is 130 ft. x 60 ft. in dimension with added capability to lower equipment to the basement that is 2 floors below.

ORNL HighBay

Army Automation

SNS Operator Station

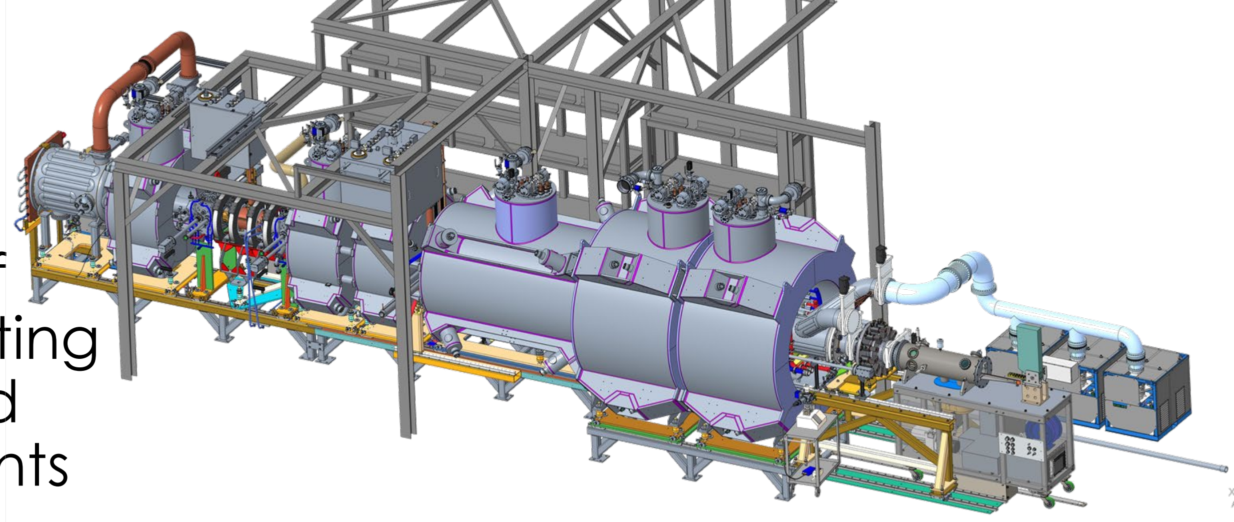
Andros Robot

SNS Hot Cell

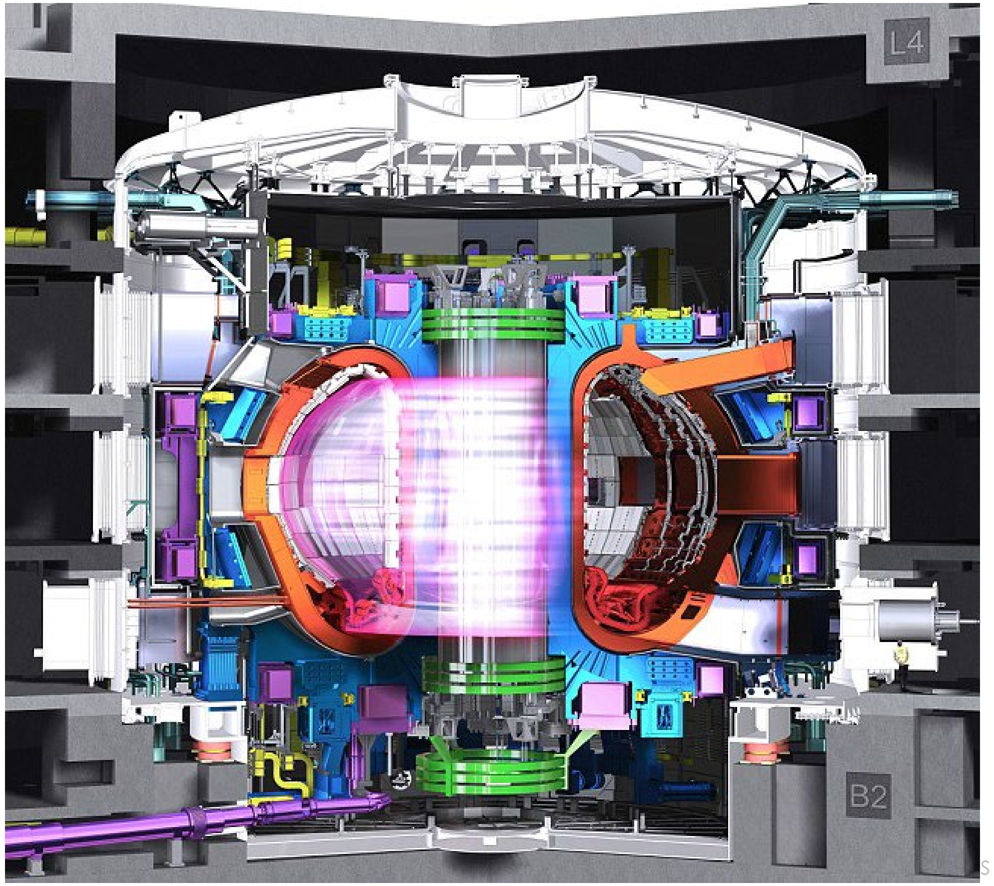
ASM Manipulator

Venu Varma
(varmavk@ornl.gov)

Systems Engineering



- Systems engineering (SE) is the process of defining requirements for systems, allocating to sub-systems, identifying interfaces, and validating and verifying those requirements through procurement and installation.
- It is an important practice for building large, complex facilities.
- ORNL has experience designing and constructing large fusion (and similar world leading scientific facilities).
- Many fusion start-ups have little experience with SE. Industries with SE experience don't understand the fusion enterprise. National labs could help bridge this gap.



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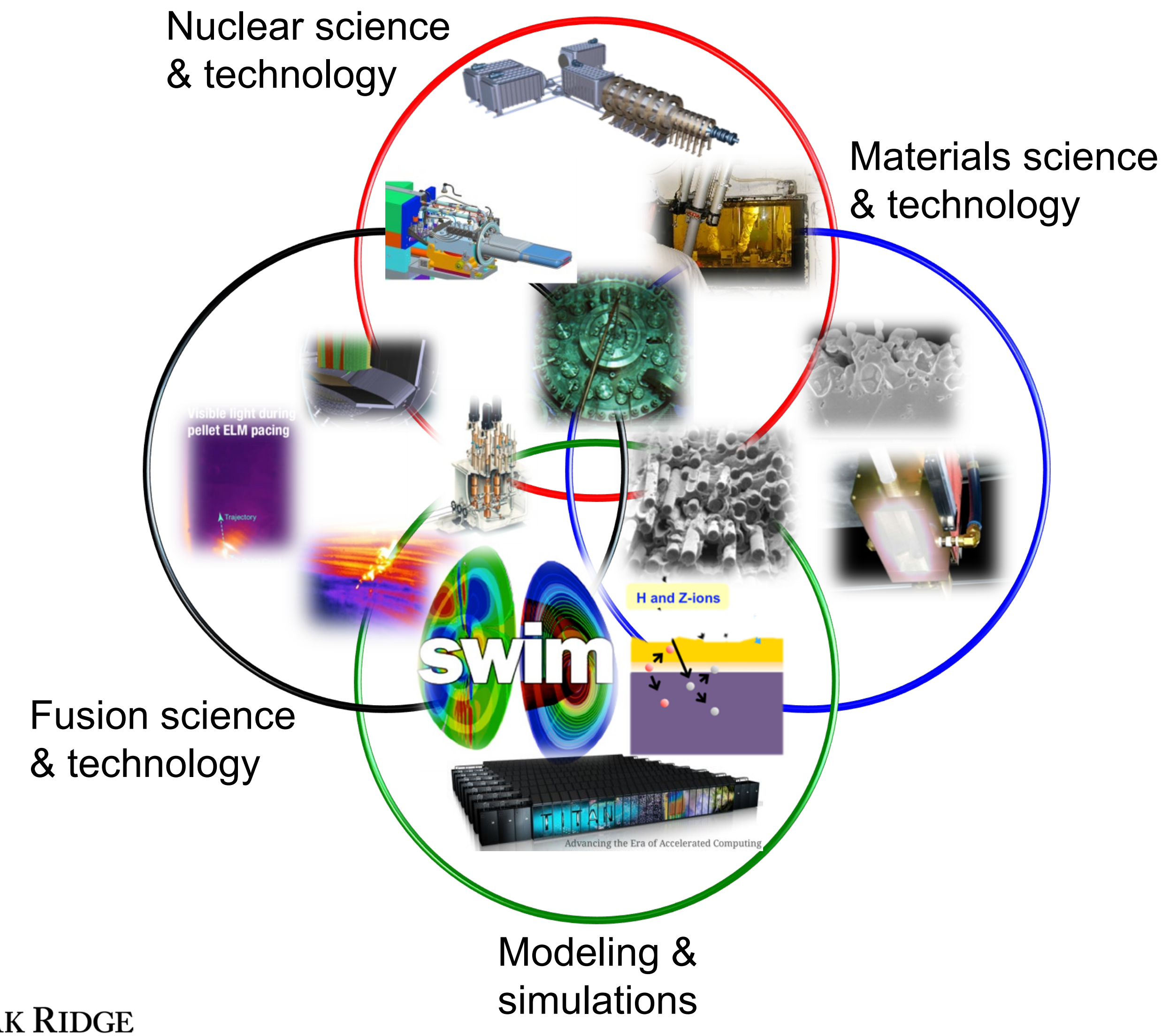
SUMMARY

ORNL has PIs covering many areas of **Expertise** & World-class **Capabilities** in Fusion Energy



- ORNL Leadership
  - Fusion materials
  - Fusion technology
  - Boundary physics
  - Plasma theory & modeling
- Maintain & grow collaborations
  - Long-term staff at DIII-D & NSTX-U
  - JET, W7-X, KSTAR, EAST, WEST, etc.
- Expand ORNL fusion S&T impact
  - MPEX
  - ITER Research
  - Advanced modeling & simulations

ORNL Capabilities Summary

Modeling and Simulation

- Whole device integrated modeling – Integrated Plasma Simulator (IPS)
- Fusion Energy Reactor Models Integrator (FERMI)
- Multi-physics engineering simulation
- Radiation transport modeling
- World-leading high-performance computing platforms

Facilities and Technology Development

- World-leading neutron science irradiation facilities
- Pellet fueling technologies
- RF research testing
- Magnet and cable R&D
- Helium flow loop experiment
- Activated materials characterization
- Material corrosion testing
- Plasma facing component design and testing
- Remote handling