Argonne National Laboratory Capabilities for INFUSE

For presentation at the FY26 INFUSE Workshop
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ARGONNE FUSION ENERGY WORKING GROUP
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U.S. DEPARTMENT of ENERGY
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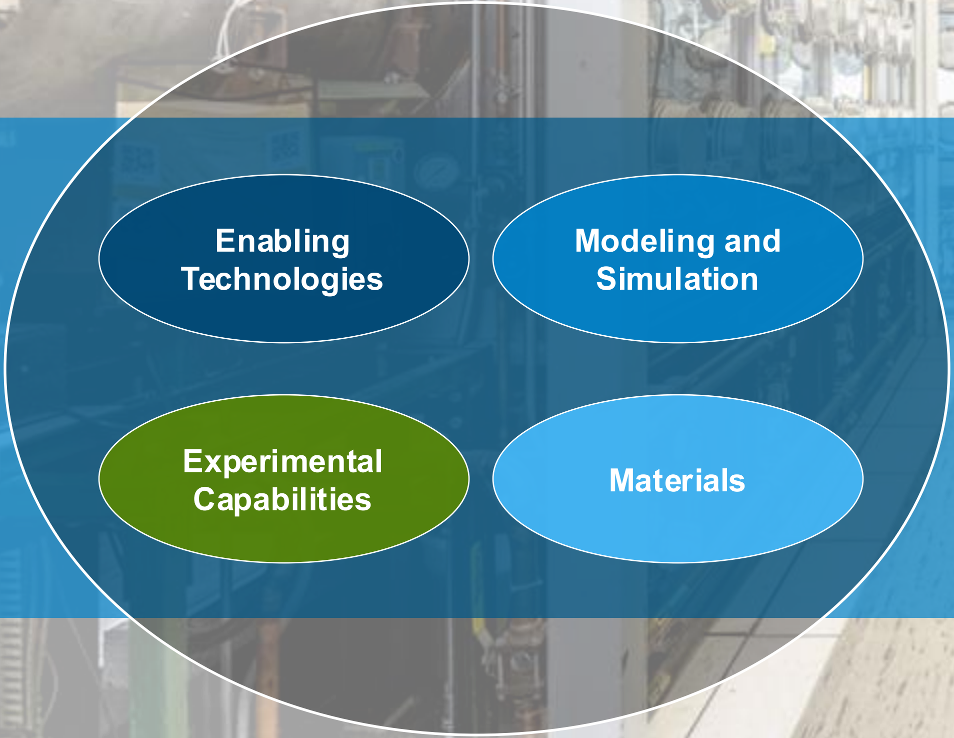


Argonne Fusion Capabilities for INFUSE

Fusion Relevant Experimental Facilities

Enabling Technologies

Experimental Capabilities

Liquid Metal Technologies

Lithium and sodium test loops, instrumentation, component testing

Relevant to liquid metal blanket, divertor surface protection, IFE wetted-wall

Molten Salt Technologies

Molten salt flow systems, material compatibility, chemistry control, corrosion

Applicable to molten salt blanket and IFE thick-liquid-wall chamber

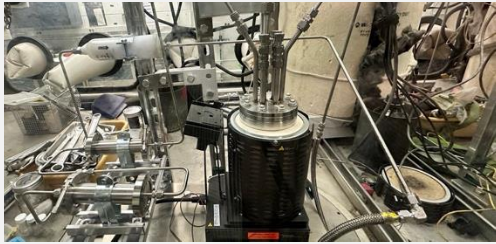
Metal Additive Manufacturing

Fundamental science of metal AM technologies, large-scale defect free products

AM-based tungsten alloys for plasma-facing materials

Heavy Ion Irradiation

Simulates radiation damage in structural materials and protective coatings

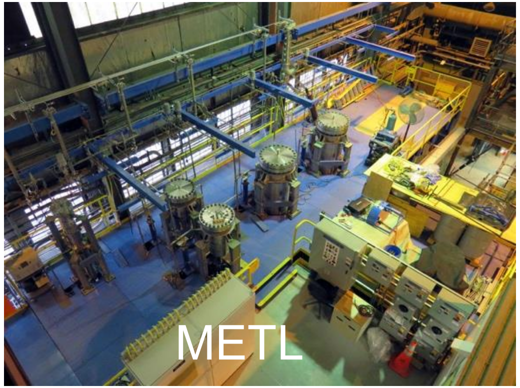


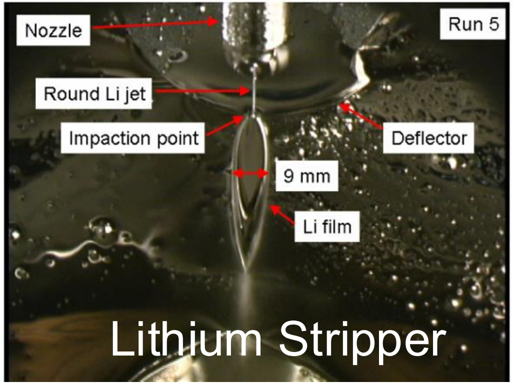
Liquid Metal Technologies

Enabling Technologies

Experimental Capabilities

- **Mechanisms Engineering Test Loop**
  - 2,900-liter system filled with sodium reactor grade sodium
  - Instrumentation and componentry applicable to lithium and lithium-lead blankets
  - Various nuclear reactor fuel handling test articles
- **Sodium Material Test Loops**
  - Forced convection to study material compatibility, corrosion
  - Sodium SCO2 interaction experiment: fluid mechanics, heat transfer
  - Plugging and freeze/melt phenomena
- **Liquid Lithium Thin Film**
  - Liquid lithium film charge stripper for high-power linac application
  - Lithium handling infrastructure
  - Liquid lithium at 300 ^{o}C, 13.9 Mpa through 1-mm diameter nozzle producing velocity > 200 m/s



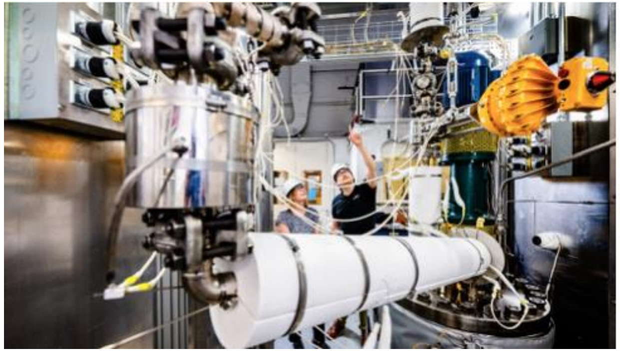


Molten Salt Technologies

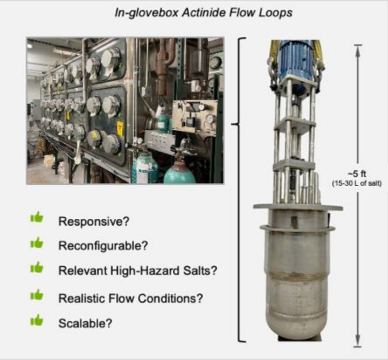
Enabling Technologies

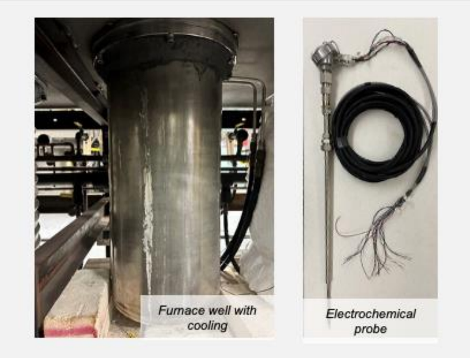
Experimental Capabilities

- **Thermal Hydraulic Loop**
  - Thermal hydraulic studies and molten salt technology demonstrations
  - Operating in both forced flow and natural convection modes
  - Demonstrate combined online chemistry monitoring and control in pilot-scale forced flow system



- **In-glovebox Flow Loops**
  - Rapid, modular molten salt testing
  - Easy handling and operations with beryllium-bearing salts
  - Targeting long-term understanding of chemistry and corrosion
  - Online sampler and optical monitoring
  - Readily scalable & inexpensive





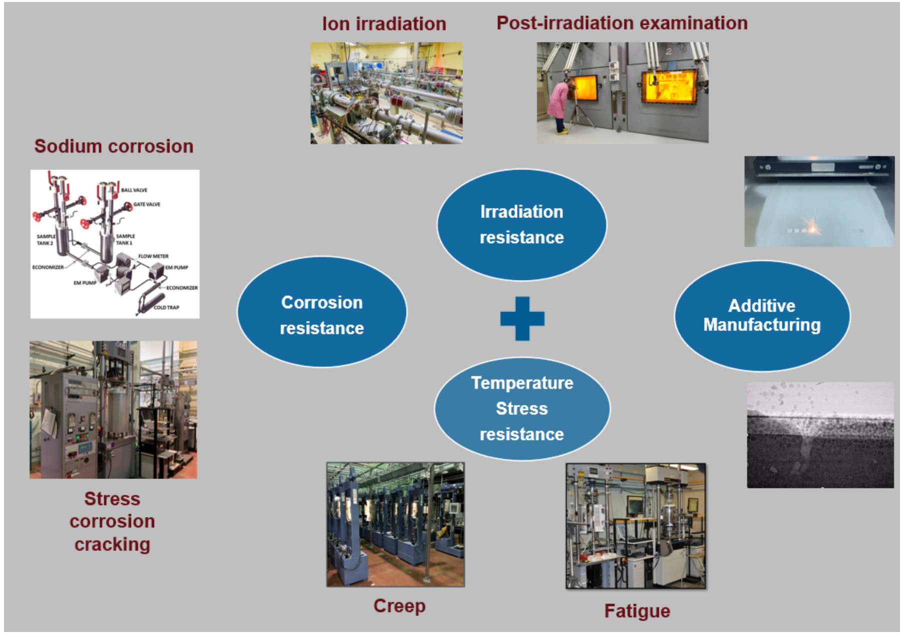
Nuclear Materials Core Capabilities

Experimental Capabilities

Materials

Provide a broad range of capabilities and expertise in advanced manufacturing, radiation damage, corrosion, and mechanical testing and microstructural characterization of reactor structural and cladding materials.

- **Metal Additive Manufacturing**
  - Laser powder bed fusion: AM400
  - Laser direct energy deposition: BeAM Mod 250
- **Radiation Damage**
  - IVEM-Tandem Facility: *in situ* and *ex situ* ion irradiation
  - Post-neutron irradiation-examination (PIE)
    - Irradiated Materials Laboratory (IML): Radiological facility
    - Activated Materials Laboratory (AML): Radiological facility
- **Corrosion**
  - Sodium materials testing
  - High temperature corrosion
- **Mechanical & Environmental Testing**
  - High-temperature mechanical testing
  - Environmental mechanical testing
  - High pressure tube facility
- **Microstructural Characterization**
  - Transmission electron microscopy (TEM), scanning electron microscopy (SEM), metallography, micro-hardness, nano-hardness, synchrotron X-ray techniques



Materials Manufacturing

Enabling Technologies

Additive manufacturing of alloys and ceramics

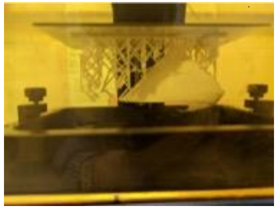
Materials Manufacturing

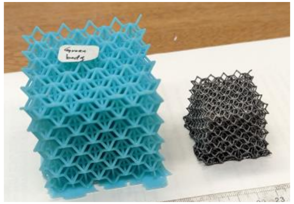
- Additive manufacturing (binder jet, digital light processing)
- Field assisted sintering
- Industrial scale PVD systems coatings
- Melt infiltration

Materials Integration

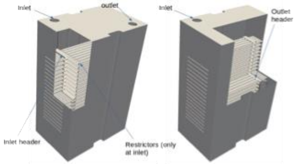
- Joining of dissimilar materials
- Current Activated Ultrafast Reactive Joining (CARUJ)
- Metal/metal, metal/ceramic joining

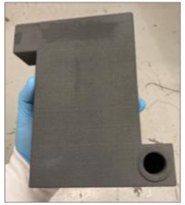
Industrial scale PVD system with multi-targets for depositing HEA materials (alloys, carbides, nitrides, etc.) coatings with wide range of compositions





Digital light processing





Complex shaped silicon carbide component fabricated by additive manufacturing

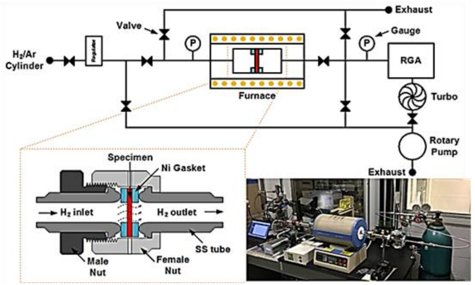
CARUJ test bed to join high-temperature similar an dissimilar materials

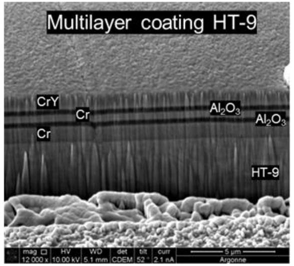
Melt infiltration

Thin Film Synthesis for Fusion Applications

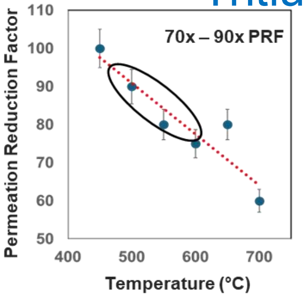
Materials

Hydrogen Permeation Measurement Device at ANL





Tritium barrier coating

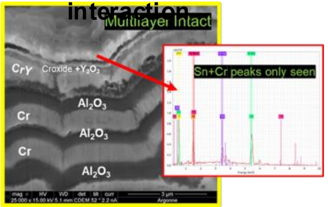


Tritium Management (Breeding Blanket)

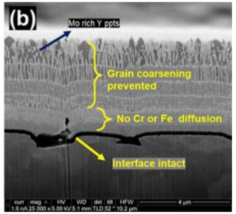
- Cr-Al_2O_3-Y_2O_3 based ^{3}H barrier design
- Thermal shock resistant
- Radiation resistant
- Permeation measurement facility

Enabling Technologies

Multilayer showing good resistance against Sn-Li interaction



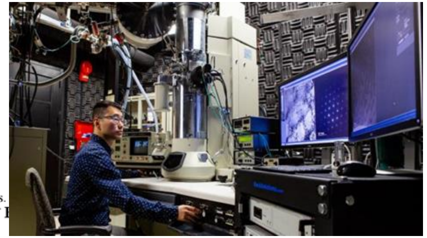
Showing good resistance against Molten salt (FliNaK) interaction



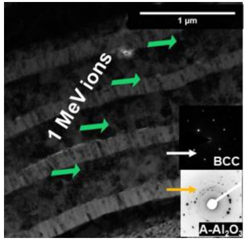
Breeder Material Resistant Coating

- Cr-Al_2O_3-Y_2O_3 design shows good resistance against Sn-17Li system (tested at 550 °C)
- Lithium based molten salt system (tested at 600 °C)

IVEM facility at ANL



Ion irradiation at 600 °C

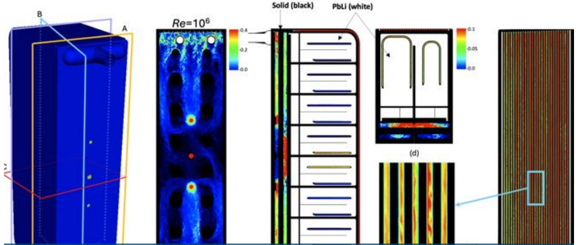


Ion Irradiation Facilities

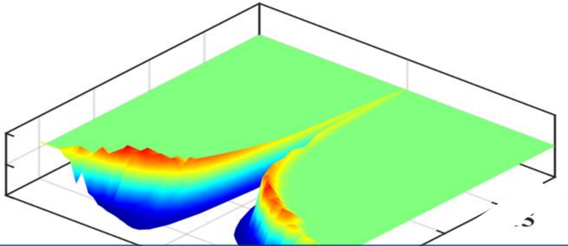
- Access to the IVEM facility (approved for proton use)
    - 5 KeV through 2 MeV proton & heating stage (~1000 °C)
    - In-situ observation of live proton irradiation
    - Future upgrades to include plasma

Modeling, Simulation, and AI

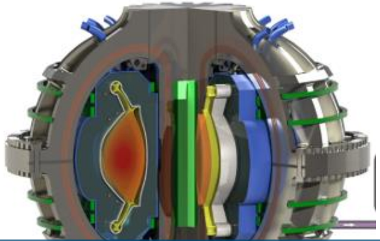
Modeling and Simulation



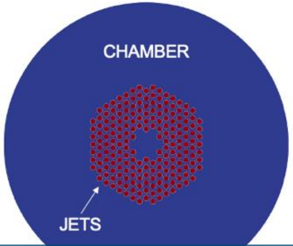
CFD



Plasma Facing Materials

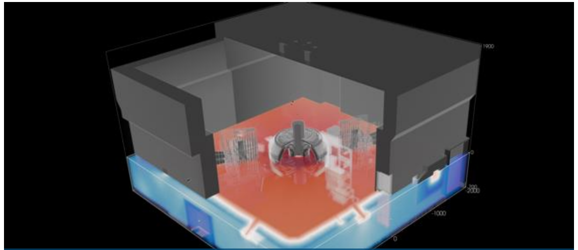


Blanket and First Wall



IFE Chamber

AI Plasma Control



Radiation Transport

Argonne-Developed Mod-Sim Tools for Blankets and IFE Chambers

Modeling and Simulation

SAM
System code for heat and mass transport, including MHD effects

OpenMC
Monte Carlo particle transport code for neutron/photon fluence, nuclear heating, tritium production, radiation damage, dose rate

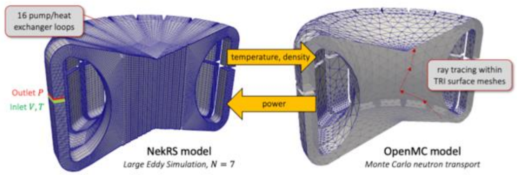
NekRS
CFD code applicable to broad range of fluid dynamics

Moscato
Electrochemistry solver, structural corrosion simulator, and tritium mass transport in molten salts

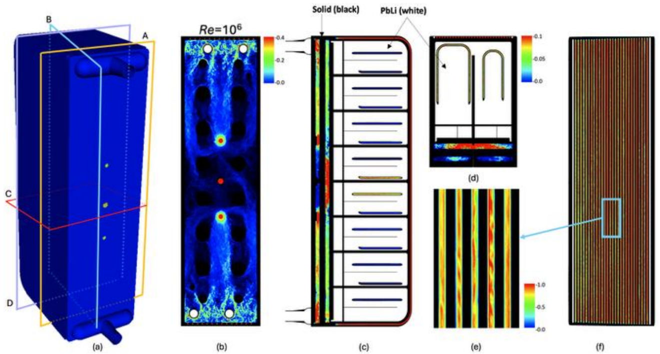
Cardinal
GPU-oriented tool for coupling OpenMC, NeKRS, MOSCATO

PulseFoam
IFE chamber multi-material compressible fluid dynamics


Detailed OpenMC model of ITER



NekRS coupled with OpenMC through Cardinal



NekRS simulations of ITER WCLL test blanket module

Modeling, Simulation, and AI for Fusion at Argonne

OpenMC

2025 R&D 100 WINNER

Enabling Technologies

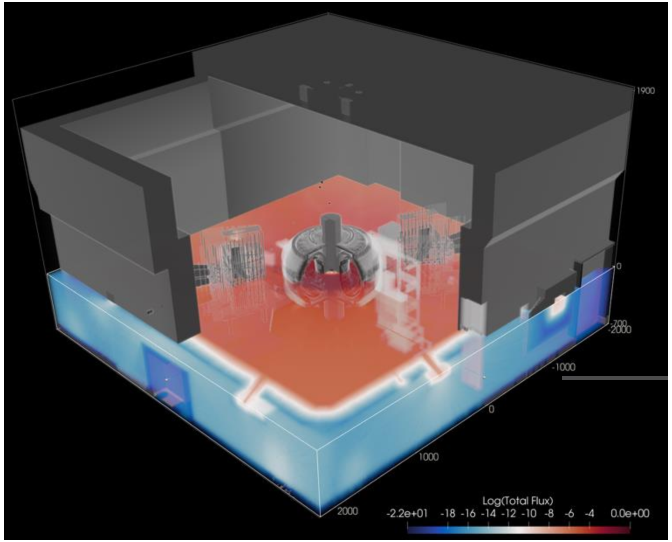
Modeling and Simulation

Modern, open-source, high performance Monte Carlo particle transport code

Rich, extensible Python API enables sophisticated workflows

Integrated capabilities for activation, dose rate evaluation, deep shielding problems, and multiphysics

Has been used for the analysis of ITER, JET, and many industry fusion plant concepts



Powerful new adjoint-based variance reduction techniques in OpenMC allow efficient simulation of complex models like the Joint European Torus (JET)

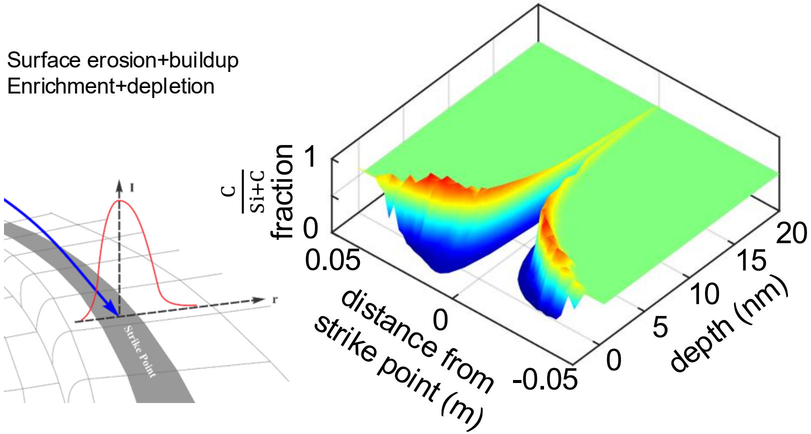
INDUSTRY ADOPTION OF OPENMC

- Type One Energy
- Thea Energy
- Proxima Fusion
- Realta Fusion
- Commonwealth Fusion Systems
- First Light
- Tokamak Energy
- TAE Technologies

Modeling, Simulation, and AI for Fusion at Argonne

Modeling and Simulation

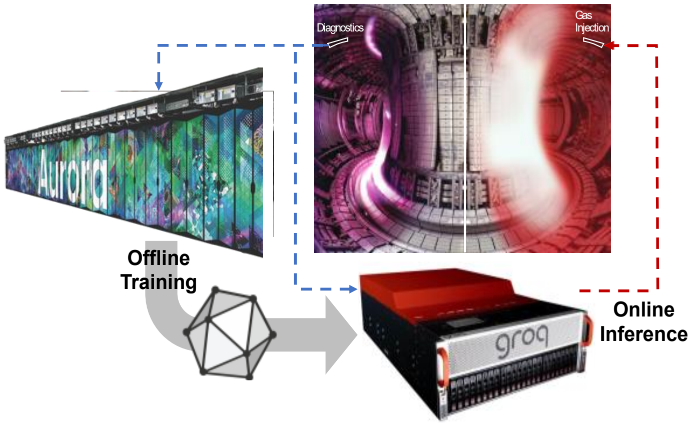
Materials



Plasma Facing Materials

ITMC-DYN, HEIGHTS codes used to model plasma-material interactions in normal operations and instabilities

- Collaboration with DIII-D, Purdue
- Materials erosion, lifetime, structural integrity, plasma contamination



AI for Tokamak Disruption Control

- Collaboration with Princeton, UC Irvine, multiple experiments including DIII-D
- Aurora Early Science Program project

Modeling, Simulation, and AI for Fusion at Argonne

Modeling and Simulation

Computational science support for production projects on Aurora at ALCF

ZAP ENERGY

TYPE ONE ENERGY

tae TECHNOLOGIES

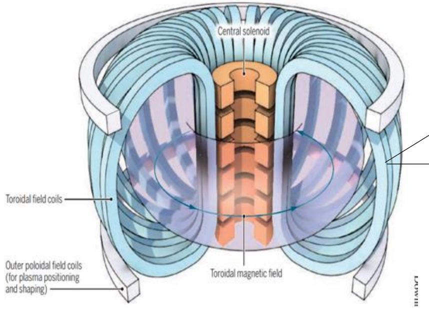
- **Gyrokinetic PIC simulation of tungsten impurity IONS** (*PPPL*, XGC code)
- **Turbulence database** (*General Atomics*, CGYRO code)
- **Z-Pinch modeling** (*Zap Energy*, WARP-X and WARP-M codes)
- **FRC modeling** (*TAE*, WARP-X code)
- **ICF ablator materials modeling** (*U. South Florida*, LAMMPS code)
- **Automatic experimental analyses for DIII-D** (*General Atomics*, CAKE on-demand workflow)
- **AI + simulation for energetic particle control in burning plasmas** (*UC Irvine*, GTC and FRNN codes)
- **Lead-lithium breeder module flow** (*Penn State*, NekRS code)
- **Turbulent stellerator heat/particle transport** (*Type One Energy*; T3D, GX, SFINCS codes)
- **Reactor materials and additive manufacturing** (*LLNL*, LAMMPS code)

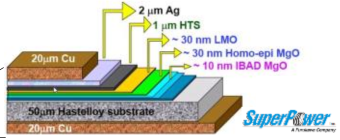
Demonstrations

Critical Current By Design: Boosting Performance of HTS for Tokamaks

Enabling Technologies | Modeling and Simulation | Materials

U. Welp, MSD





2G HTS
Coated Conductors
20 K, 20 T

Compact Tokamak

Challenges

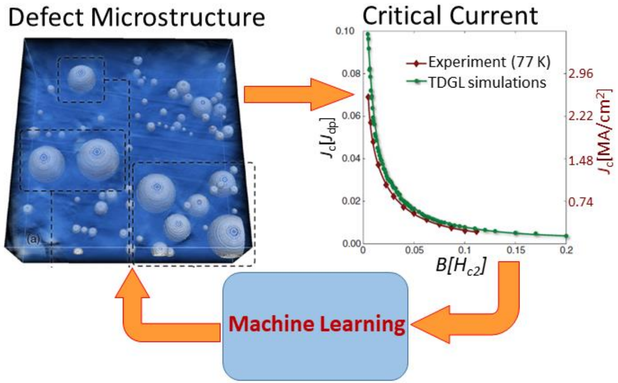
- Long length of uniform HTS wire, ~5000 km
- Cumulative n-irradiation damage: magnet performance drops below threshold

Possible Solutions

- Shielding, but: larger system
- ‘Over-sized’ critical current

Universal AI-based pinning predictor

Determine the optimal defect structure for operation at 20 T, 20 K: highest possible J_c
current conductors are not optimized



- Predict critical current from given defect structure using Time Dependent GL model
- Re-enforcement learning: optimized defects structure

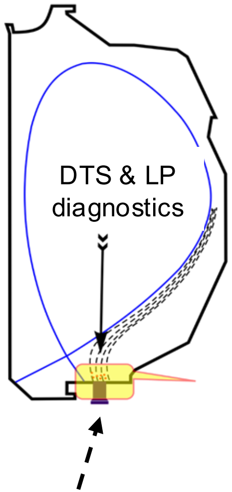
Development of integrated modeling of below & above surface interactions

Modeling and Simulation

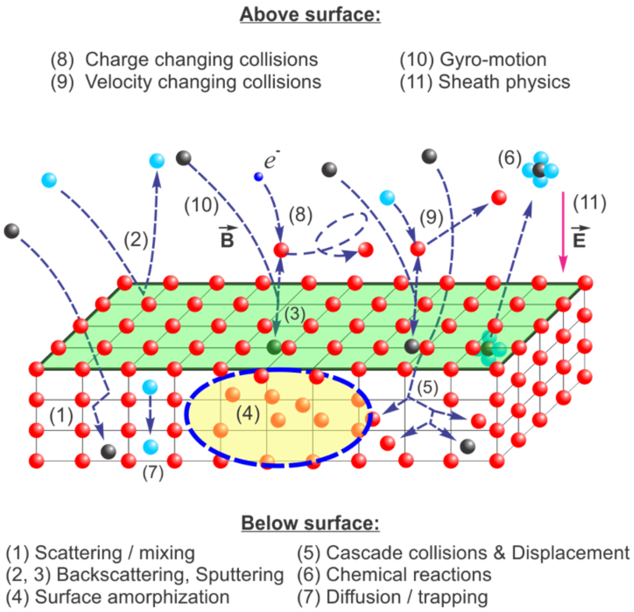
Materials

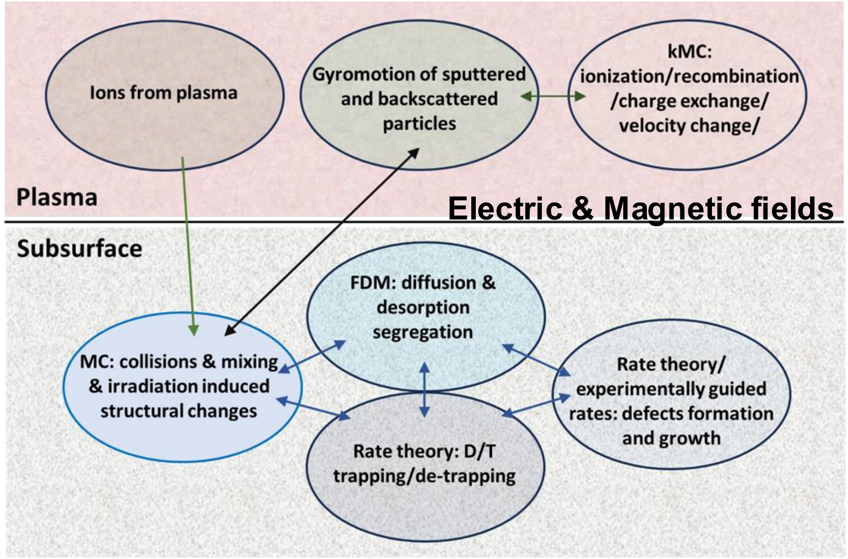
Motivation:

- Reduce averaging and assumptions used in simulations of Plasma and Subsurface domains
- Compare various materials response to plasma: erosion/lifetime, source of impurities, D/T accumulation



DiMES
removable probe,
DIII-D

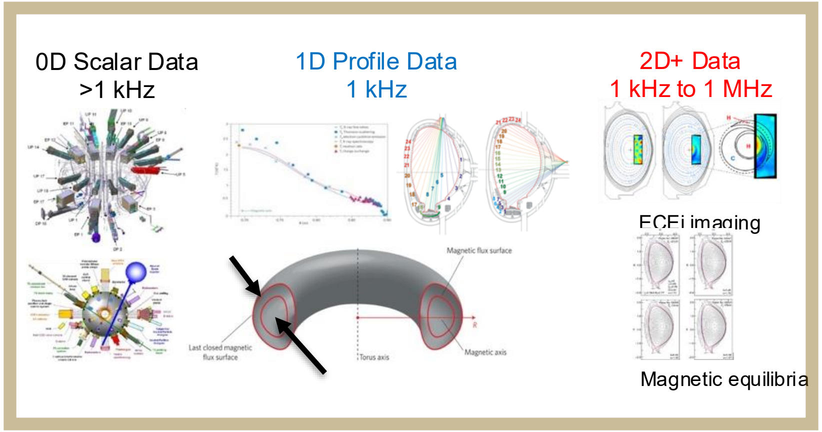


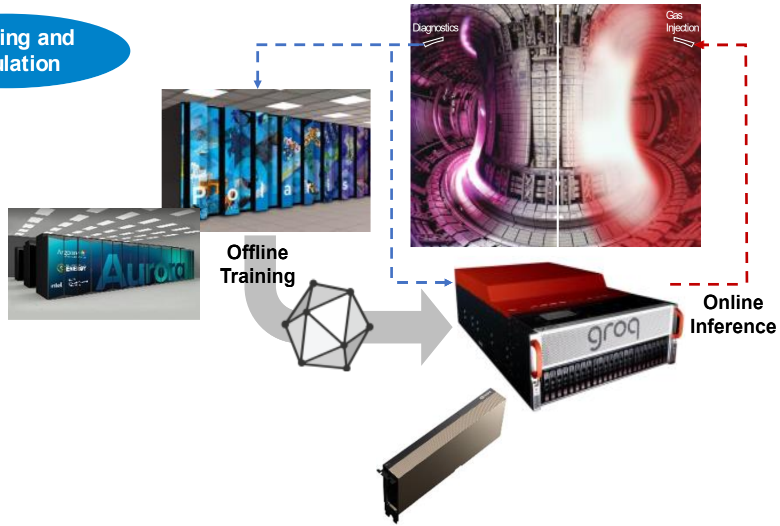


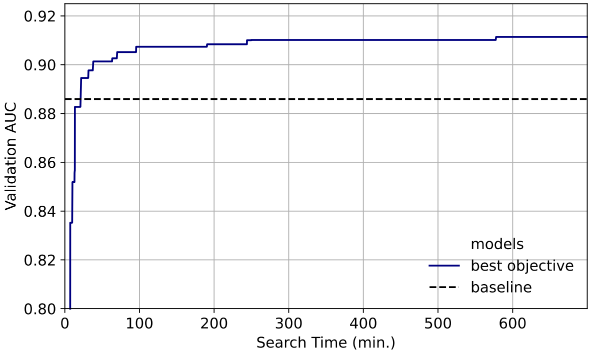
Development of ITMC-DYN+ package: Monte Carlo & deterministic methods

AI for tokamak disruption prediction

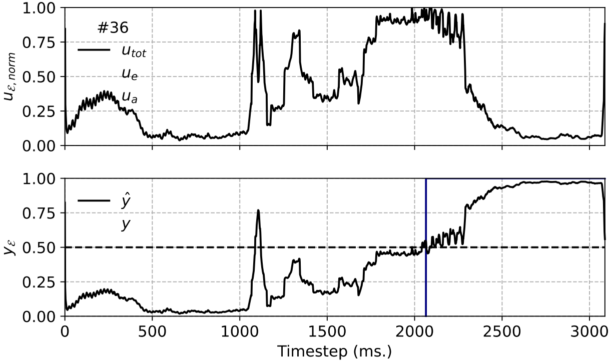
Modeling and Simulation







K. Felker in collaboration with General Atomics

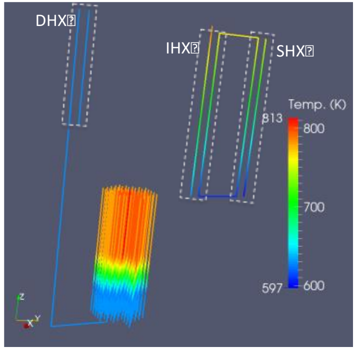


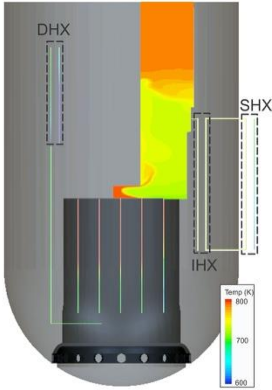
Hundreds of individual networks trained on ThetaGPU and composed into a meta-learner ensemble

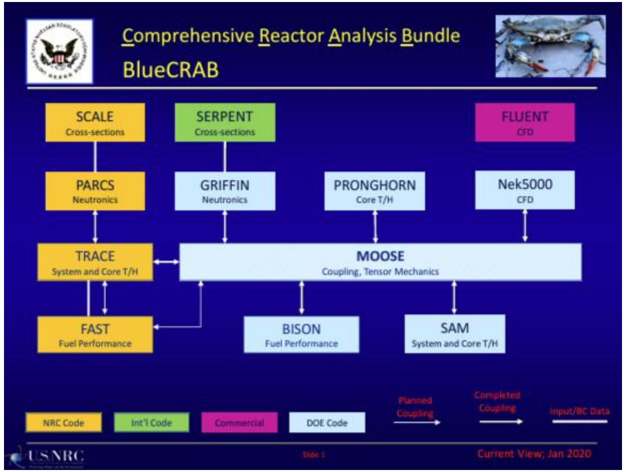
Approx. 1 ms inference latency returns disruption probability and model confidence in real-time, which can integrate with existing instability proximity control systems on DIII-D

SAM Code Capabilities Applicable to Liquid Blankets

- Flow models (single-phase, 1-D, multi-D, …)
- Heat transfer (convective, conduction, thermal radiation, …)
- Liquid metal corrosion
- Liquid metal magnetohydrodynamics (under development)
- Species transport (corrosion products, tritium)
- Special components (pump, heat exchanger, valves…)
- Uncertainty quantification integration
- Multi-scale multi-physics coupling







MOSCATO (Molten Salt Chemistry and Transport)

Enabling Technologies

Modeling and Simulation

MOSCATO is a multiphysics solver that provides salt chemistry simulations for fusion-relevant molten salt systems

- *Simulations include coupled molten salt (FLiBe) and alloy domains*
- *Capabilities for tritium transport*
- *Initial solver written in OpenFOAM has been re-implemented in Nek5000 and NekRS to enable large-scale, highly parallelizable simulations*

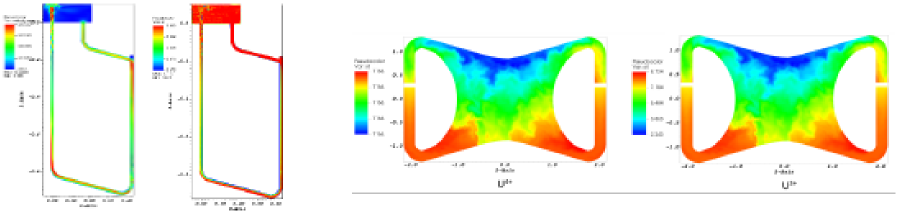
The solver accounts for phenomena including:

- *Heat and mass transfer*
- *Chemical and electrochemical reaction mechanisms*
- *Charge transfer kinetics at alloy/salt interfaces*
- *Ohmic losses*
- *Junction potentials*
- *Mass transfer overpotentials*
- *Gas transport*

The MOSCATO solver can provide crucial capabilities for the fusion reactor systems:

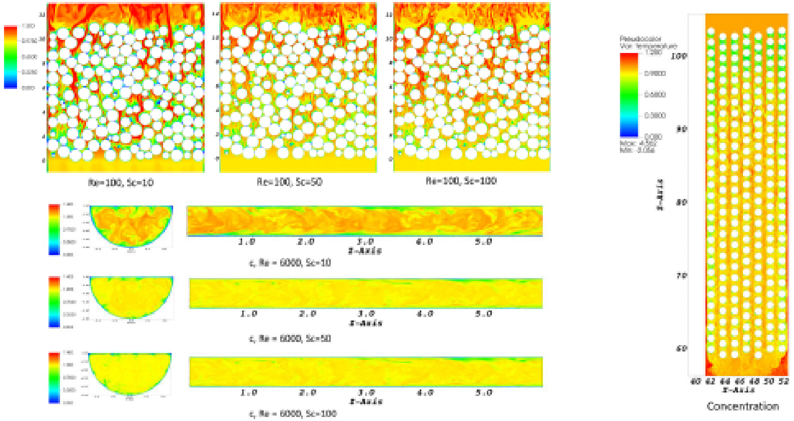
- *Loop- and reactor-scale simulations of large-scale phenomena including thermogalvanic corrosion and gas transport*
- *Component level simulations to provide high-fidelity correlations for reduced-order models*

Full-Scale Thermal Convection Loop and Reactor Core Simulations (MSRs)



Cr^{2+} concentrations in typical TCL geometry and (left), contours of UF_x concentrations (right)

High-Fidelity Component Simulations in Support of Reduced-Order Solvers



Representative results in pebble bed and heat exchanger geometries

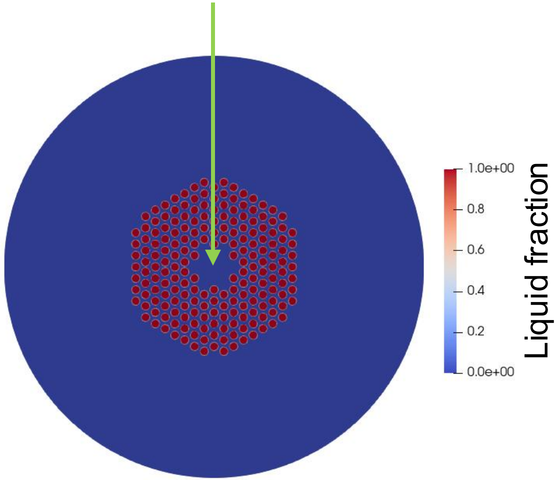
The HYLIFE-I Chamber

PulseFOAM Simulation of post-ignition splashing in HYLIFE-I

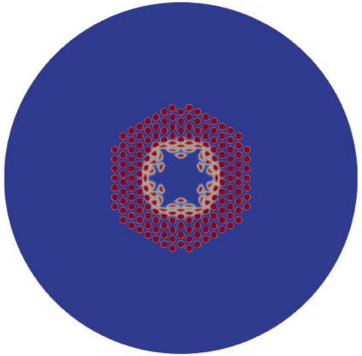
Enabling Technologies

Modeling and Simulation

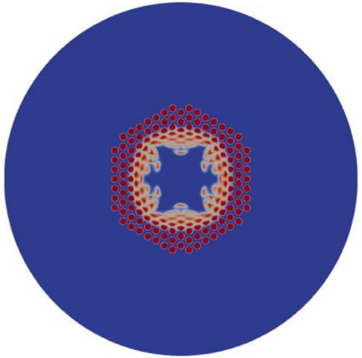
A pressure wave in the center of the chamber is simulated.



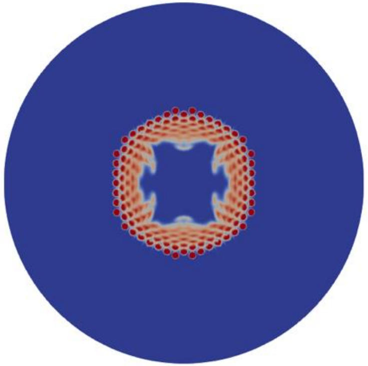
$t = 0$



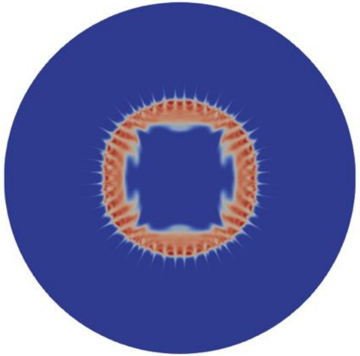
$t = 0.0005\,s$



$t = 0.001\,s$



$t = 0.002\,s$



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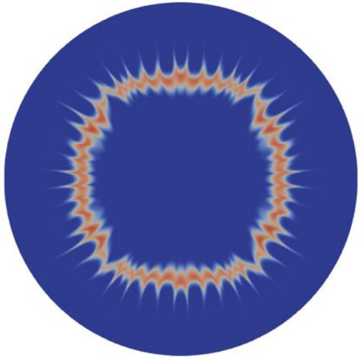

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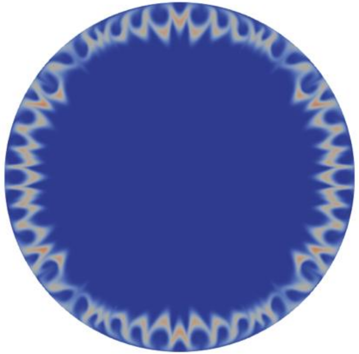


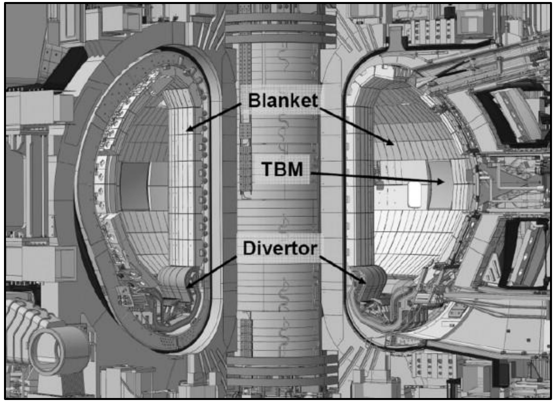
$t = 0.02\,s$

High Throughput Screening via Additive Manufacturing of W-based alloys for Fusion Applications

Materials

ITER plasma facing components

Requirements:
- High melting point
- Low sputtering yield
- High thermal conductivity
- High strength at high temperatures
- Resistance to neutron damage



Materials Suggested

W and alloys:
- Has the highest melting point (>3400C)
- High thermal conductivity even at elevated temperatures (~90 W/m.K)
- High strength at high temperatures (YS up to 300MPa at 1000°C)

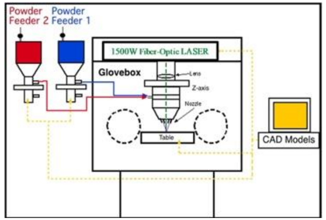
Issues with Tungsten

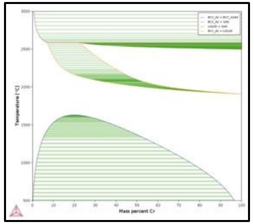
- Highest melting point is also a negative for standard manufacturing techniques
- Poor machinability
- High DBTT (300°C to 400°C)

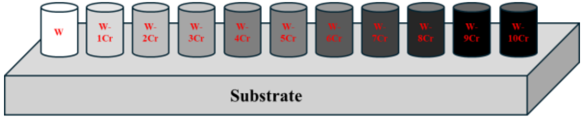
Suggested Solutions

Stage 1: Additive manufacturing of W by employing DED and LPBF techniques

Stage 2: High-throughput screening of W-X compositions for printing (can we lower the temperature requirements and reduce DBTT)







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