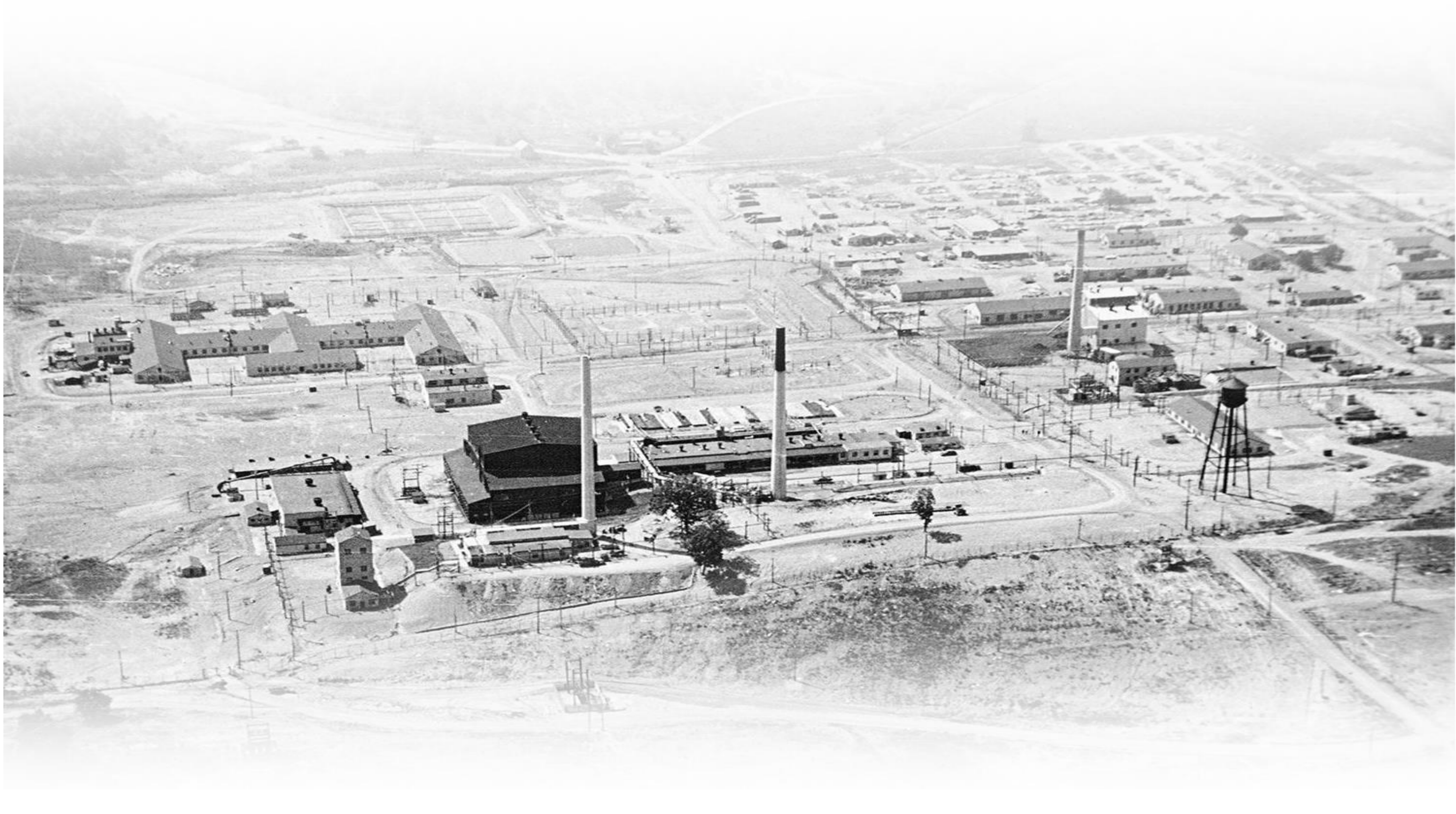
Oak Ridge National Laboratory Fusion Research Capabilities

D. Youchison (Fusion Energy Division)

2020 INFUSE Workshop

November 23, 2019

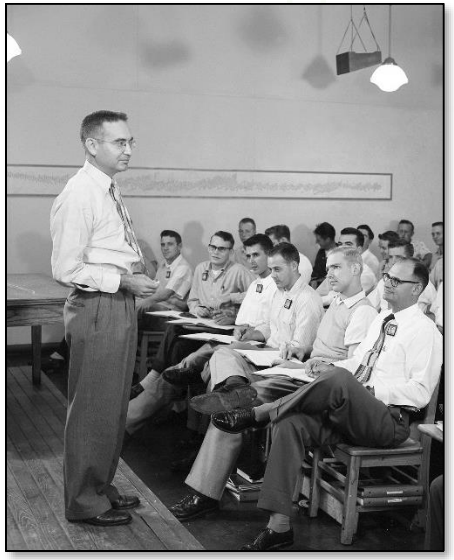
ORNL (X-10) began as a nuclear reactor laboratory specializing in isotope production in 1943



Oak Ridge National Laboratory

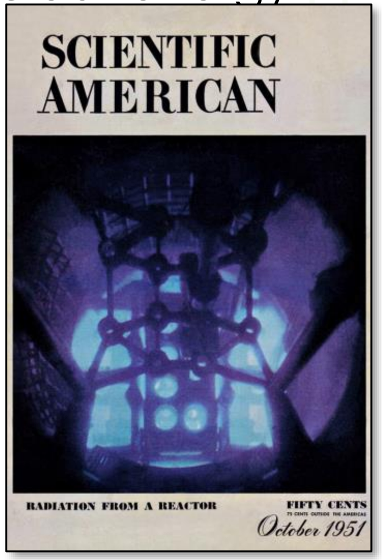
ORNL grew into a leading nuclear science laboratory

- Trained nuclear engineers at the Oak Ridge School of Reactor Technology
- Contributed to the design of naval nuclear propulsion systems
- Examined the safety, environmental, and waste disposal challenges of nuclear energy
- Designed, built, and operated 13 experimental reactors
- Developed techniques for nuclear fuel reprocessing



ORSORT established by Alvin Weinberg and Hyman Rickover, 1950

ORNL's Geneva reactor exhibited at UN conference on the Peaceful Uses of Atomic Energy, 1955



ORNL's Low Intensity Test Reactor–First visible Cerenkov glow, 1950

ORNL's Bulk Shielding Reactor, 1950–1991

OAK RIDGE National Laboratory

~4600 staff members

Oak Ridge National Laboratory

Thomas Zacharia, Laboratory Director

Michelle Buchanan
Deputy for Science and Technology

Jeff Smith
Deputy for Operations

Partnerships: TBD
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Office of Research Excellence: Moody Altamimi

Communications: David Keim
Counterintelligence: Selin Warnell
Internal Audit: Gail Lewis
General Counsel: David Mandl
Office of Integrated Performance Management: Brian Weston

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Jeff Nichols
Assoc Lab Director

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- **Computer Science and Mathematics Division:** Barney Maccabe
- **National Center for Computational Sciences Division:** James Hack

Energy and Environmental Sciences
Moe Khaleel
Assoc Lab Director
Renae Speck, COO

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- **Environmental Sciences Division:** Stan Wullschleger
- **Electrical and Electronics Systems Research Division:** Rick Raines
- **Energy and Transportation Sciences Division:** Xin Sun

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Assoc Lab Director

- **Cyber and Data Analytics Division:** Shaun Gleason
- **Field Intelligence Element Division:** Kendall Card
- **National Security Emerging Technologies Division:** Budhendra Bhaduri
- **Nuclear Nonproliferation Division:** Cecil Parks

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Assoc Lab Director
Ann Weaver, COO

- **Neutron Scattering Division:** Hans Christen
- **Neutron Technologies Division:** Mark Wendel (Interim)
- **Research Accelerator Division:** Fulvia Pilat
- **Research Reactors Division:** Tim Powers
- **Proton Power Upgrade Project:** John Galambos

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Assoc Lab Director

- **Fusion Energy Division: John Canik (interim)**
- **Nonreactor Nuclear Facilities Division:** Mike Pierce
- **Isotope and Fuel Cycle Technology Division:** Brad Johnson
- **Reactor and Nuclear Systems Division:** Jeremy Busby
- **Transformational Challenge Reactor Program:** TBD

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David Dean
Assoc Lab Director

- **Center for Nanophase Materials Sciences:** Karren More
- **Chemical Sciences Division:** Phil Britt
- **Materials Science and Technology Division:** Sean Hearne
  - **-Fusion Materials** Yutai Katoh
- **Physics Division:** Marcel Demarteau

Exascale Computing Project
Doug Kothe
Director

- **Deputy Project Director:** Lori Diachin (LLNL)

Second Target Station Project
Graeme Murdoch
Interim Director

- **Project Manager:** Graeme Murdoch
- **Technical Director:** TBD

US ITER Project
Suzanne Herron
Interim Director

- **Deputy Project Director:** Suzanne Herron
- **Technical Systems Division:** Graham Rossano

- Fusion S&T n=135
- Plasma S&T
- Confinement Experiments
- Theory & Modeling
- Remote Systems

Business Services
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- **Business Operations Division:** Debbie Mann
- **Contracts Division:** Brooks Baldwin
- **Information Technology Services Division:** Kris Torgerson

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John Powell, Director

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- **Environmental Protection Division:** David Skipper
- **Health Services Division:** Bart Iddins, MD
- **Nuclear and Radiological Protection:** Mike Stafford
- **Office of Technical Training Division:** Jeff Ullian
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- **Integrated Operations Support Division:** Kim Jeskie
- **Laboratory Modernization Division:** Jim Serafin
- **Laboratory Protection Division:** Bill Manuel
- **Logistical Services Division:** Cheri Cross (Interim)
- **Utilities Division:** Bob Baugh

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Mardell Sours, Director

- **Compensation:** Mark Keck
- **Diversity and International Office Division:** Deborah Bowling
- **Employee Benefit Programs Division:** Scott McIntyre
- **Employee and Organizational Development Division:** Carla Agreda
- **Information and Process Management:** Jeff Ault
- **Labor Relations Division:** Patrick Bocian
- **Talent Acquisition Division:** Gary Worrell

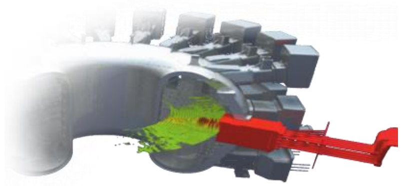
ORNL aligned with FES strategic plans

FES strategic plan submitted to Congress identifies:

- ***Massively parallel computing*** with the goal of validated whole-fusion-device modeling
- ***Material science*** as it relates to plasma and fusion sciences
- Research in the prediction and control of ***transient events***
- ***FES user facilities*** will be kept world-leading
- Continued stewardship of ***discovery in plasma science***

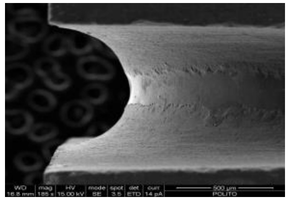
ORNL engagement in the major themes

Leadership-class computing
HPC at ORNL



Whole device modeling

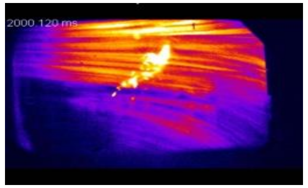
ATоM SciDAC
RF SciDAC
GSEP SciDAC
PSI SciDAC
SCREAM SciDAC
Exascale app project



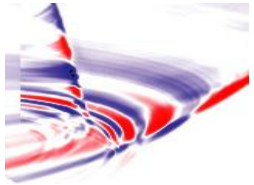
Material mechanical testing

Low Activation Materials & Development (LAMDA) Lab

Fusion materials program
Proto-MPEX
PHENIX collaboration (Japan)
EUROfusion project



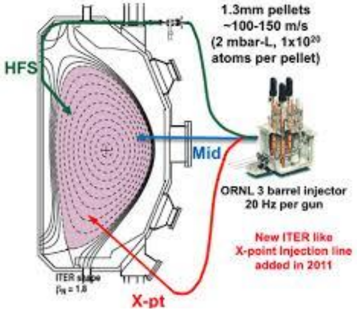
Shattered Pellet Injection



ELM Suppression

Shattered pellets for disruption mitigation
ELM pacing
Pellet fueling

NSTX-U

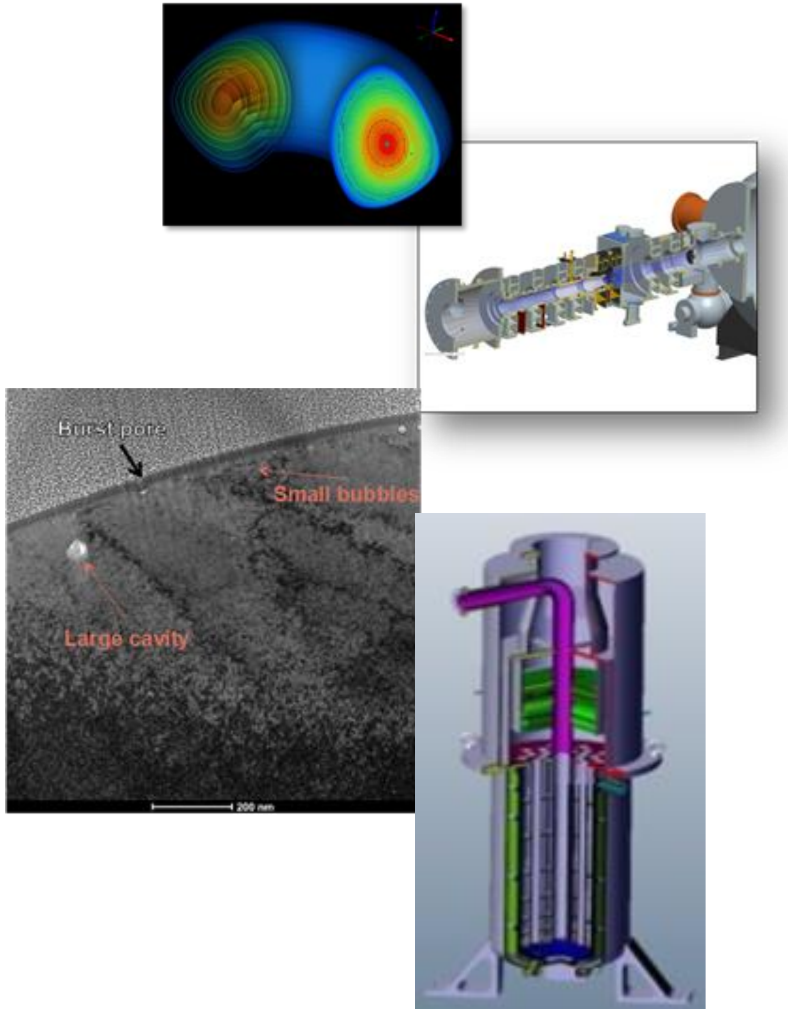


DIII-D

W erosion & migration studies
Transient studies
Plasma heating

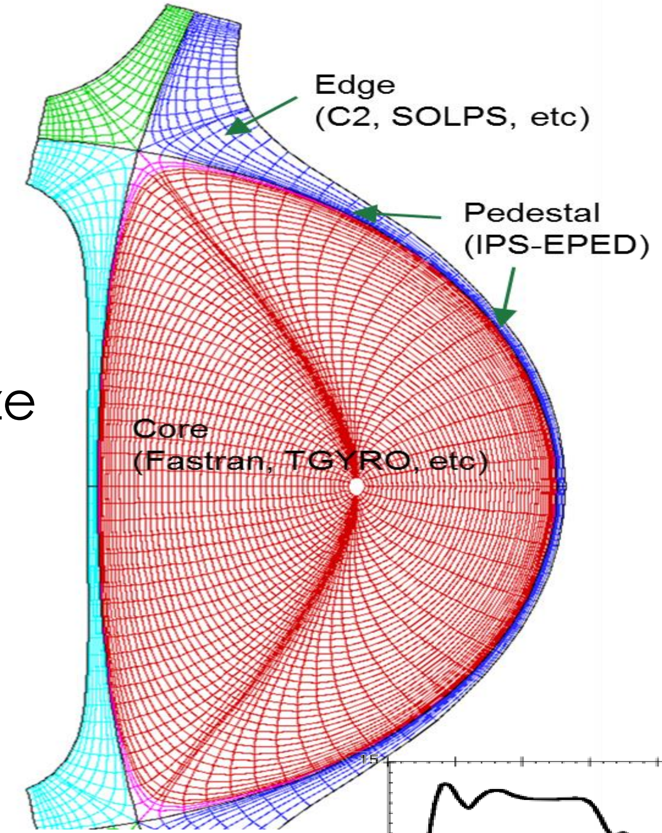
Five high-level thrusts provide growing capabilities

- 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 – Fusion Energy System Studies
- Develop ***fuel cycle and blanket technology***

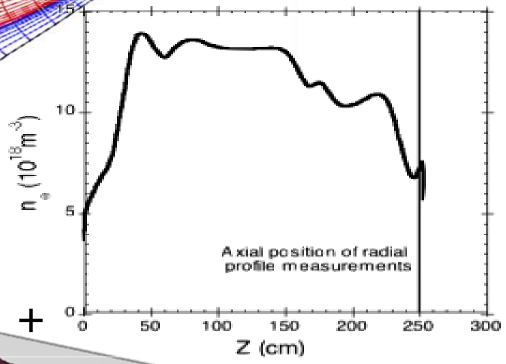


Building Towards Fusion Whole-Device Modeling Capability

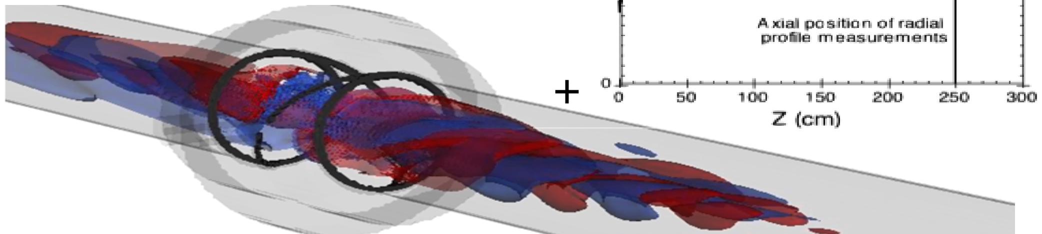
- **Present efforts:** AToM SciDAC collaboration
  - Focus on integrating models/codes that will form the plasma component
  - Using ORNL's "Integrated Plasma Simulator" (IPS) to optimize plasma performance
  - The challenge is integrating an edge plasma model onto the well established core model



- **Long-term goal**: FNSF integrated design capability
  - HPC enabled integration of **plasma**, **neutronics**, and **engineering** components



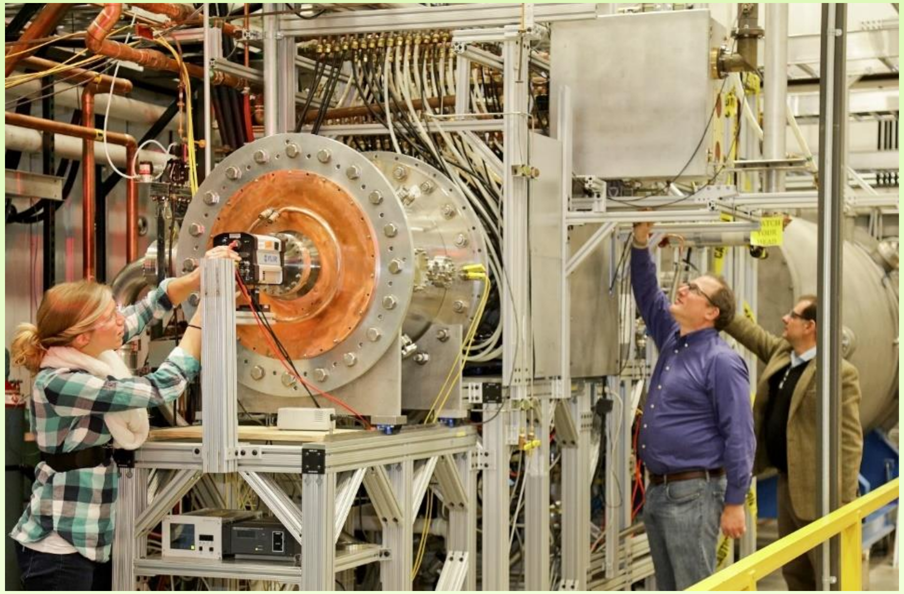
- **New effort:** Integrate RF heating with plasma transport simulation for optimization of Proto-MPEX performance



Simulation :
Titan 3-D full-wave simulation

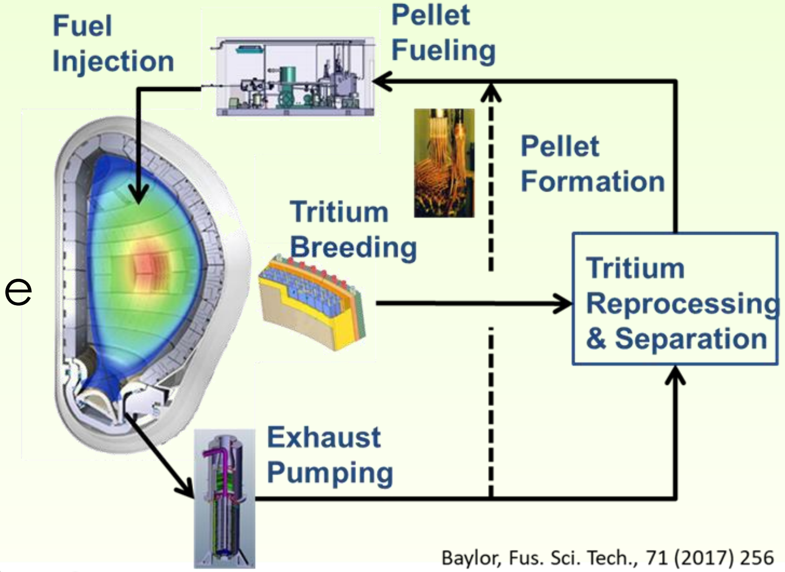
Advancing fusion nuclear science

Proto-MPEX



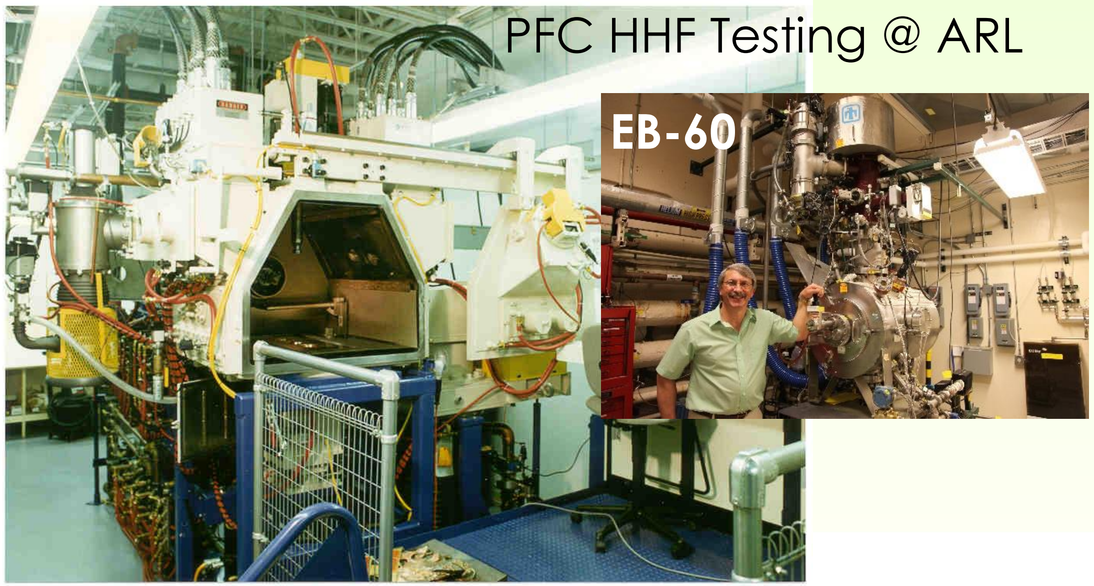
Pellet-Lab

Fuel Cycle



Baylor, Fus. Sci. Tech., 71 (2017) 256

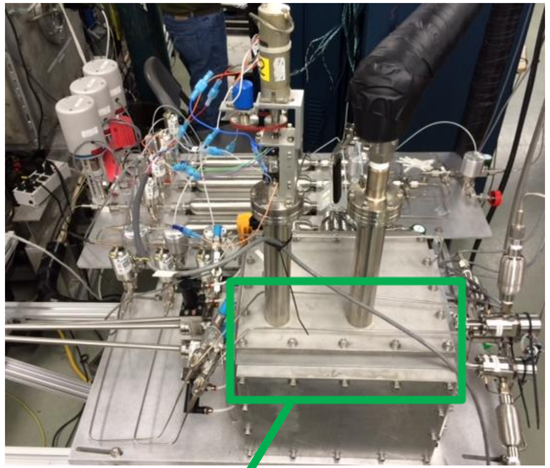
PFC HHF Testing @ ARL

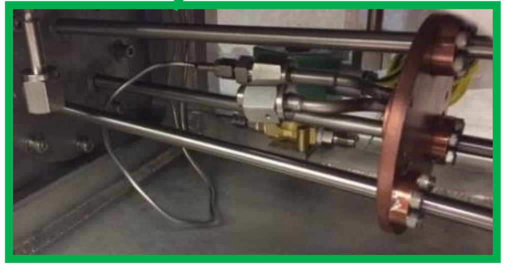


Transient Mitigation using Pellet Technology

- Disruption Mitigation
  - Shattered pellet injector (SPI) experiments on DIII-D deliver deep penetration and assimilation to maximize dispersal of plasma energy into radiation to spread out the heat over greatest area possible
  - Large High-Z (Ar, Ne) pellets developed for thermal mitigation and runaway electron dissipation
  - SPI experiments on JET and KSTAR are planned in support of ITER DMS
- ELM Pacing
  - Experiments on DIII-D demonstrated peak heat flux deposited in the divertor per ELM decreases with increasing injection frequency

SPI-II with Gas Manifold





Three cryogenically cooled barrels inside the guard vacuum

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.

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.

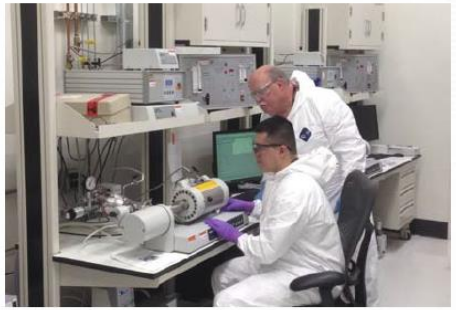
LAMDA

<100 mR/hr

Low Activation Materials Development and Analysis Laboratory (LAMDA)

Description

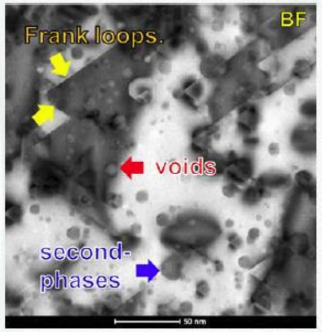
The LAMDA facility is a multipurpose laboratory for evaluation of materials with low radiological threat without the need for remote manipulation. The LAMDA laboratories are equipped for analysis of samples at < 100 mR/hr at 30 cm. This mode of operation allows for more precise and delicate sample handling than in traditional hot cells. LAMDA is also an ideal setting for collaborative work with sponsors and partners.



Work within the thermo-physical properties test suite

The LAMDA laboratory typically utilizes small, compact samples to allow researchers to leverage cutting-edge characterization and test equipment to study materials phenomenon not possible at a hot cell facility. Post irradiation examination capabilities in the LAMDA lab are focused on three main categories: mechanical testing, physical properties and microstructural characterization. The dedicated LAMDA equipment, along with the "open lab" analytical capabilities, provides an unparalleled resource for irradiated materials science.

When combined with the ORNL hot cells, these facilities provide complimentary capabilities for high and low-dose samples. This unique suite of tools allows for "right-sized" post-irradiation examination and provides the most cost and time efficient analysis possible for irradiated materials.

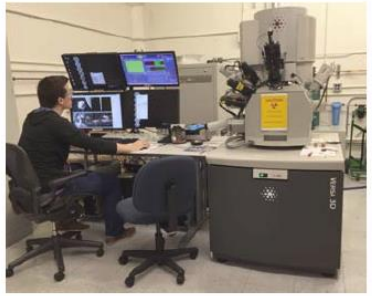


Transmission electron microscopy bright field image of irradiated SiC (9 dpa at 1440 °C)

Applications

LAMDA contains a broad set of equipment including testing capabilities for:

- Mechanical testing in multiple configurations and environments
- Measurement of physical properties
- Measurement of electrical and thermal properties
- Specimen cleaning facilities
- High resolution optical imaging
- Scanning electron microscopy
- Transmission electron microscopy
- Cutting, grinding, and polishing capabilities
- CNC milling capabilities
- Annealing and heat treating
- Other capabilities can be introduced on demand



Focused ion-beam preparation of samples

Contact

Josh Schmidlin
LAMDA Manager
Materials Science and Technology Division
865.574.6231
schmidlinje@ornl.gov

Keith Leonard
Technical Advisor, LAMDA
Materials Science and Technology Division
865.576.3687
leonardk@ornl.gov

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Date: April 2017, R2

Liquid Salt Test Loop

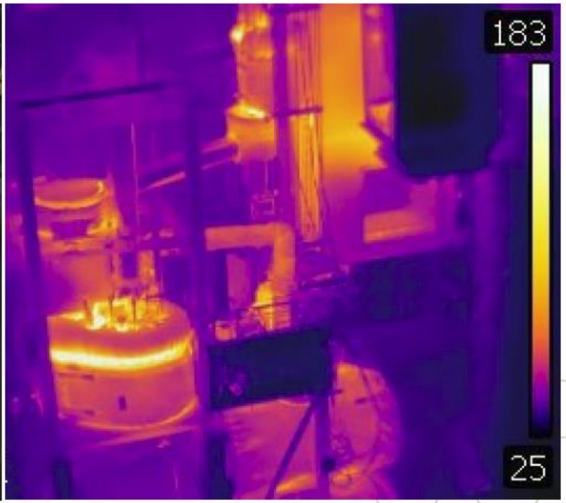
Description

The liquid salt test loop (LSTL) is a versatile facility for the development and demonstration of high-temperature fluoride-salt technology. It is made from a high nickel alloy and operates at up to 700°C. The major components include a centrifugal pump to circulate the salt, a salt-to-air heat exchanger, three tanks, pressure control and trace heating systems, and associated instrumentation. The loop builds on Oak Ridge National Laboratory's historic leadership and expertise in fluoride salt technology.

The LSTL is being used to develop and demonstrate technology for high-temperature fluoride salt systems through a number of planned tests. For example, one test includes heat transfer measurements in a heated pebble bed using a 200 kW induction heater. This testing demonstrates the use of a 1.07 m (42 in.) silicon carbide (SiC) tube as a structural component. The next phase of testing will focus on characterizing the pump performance. During these early tests, instrumentation (salt pressure, level, temperature, flow rate) will also be evaluated. Future testing may be conducted on new flanges and valves, instrumentation such as that used for optical diagnostics, heat exchanger performance, and other heat transfer experiments.

Near term goals	Provide infrastructure (operational knowledge and equipment) to test high-temperature salt systems
	Develop a nonintrusive, inductive heating technique that can be used for thermal/fluid experimentation
	Measure heat transfer characteristics in a molten salt-cooled pebble bed
	Demonstrate the use of SiC as a structural material for use in molten salt systems

Overview image of the LSTL

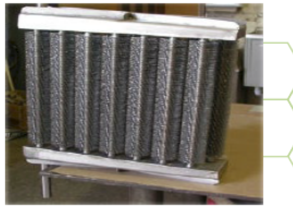


Thermal image of the loop during operation

Liquid Salt Test Loop

Specifications	
Salt	FLiNaK
Operating temperature	≤ 700 ºC
Flow rate	≤ 4.5 kg/s ~3.5 m/s (1 in. pipe)
Operating pressure	Near atmospheric
Construction material	Inconel 600, SiC
Operating run time life	2+ years
Primary piping ID	2.67 cm (1.05 in.)
Loop volume	75 L
Heating	~20 kW trace heating 200 kW test section
Thermocouples	~92 (7 in bed)
Pressure gauges	1 in salt (0–0.34 MPa) 4 in gas spaces
Flow rate	Ultrasonic flow meter
Vibration accelerometers	6 on pump
Salt level	1 radar level 3 heated thermocouple arrays

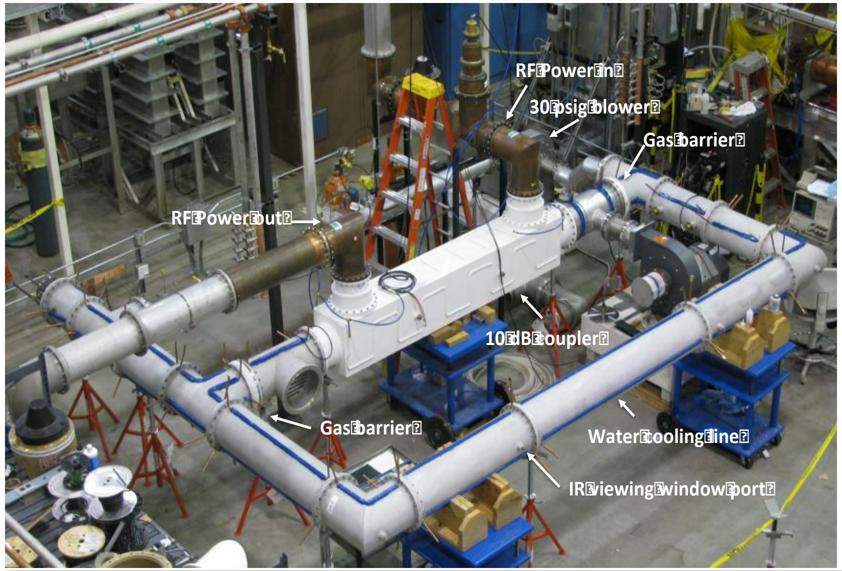
Pump impeller and volute



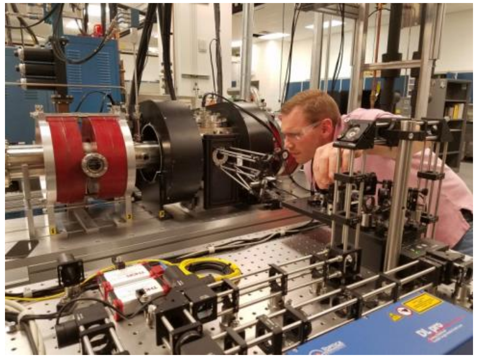
Salt-air heat exchanger

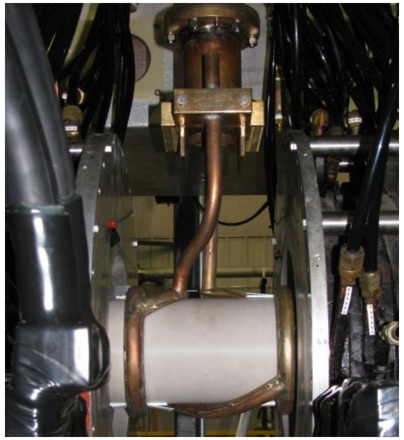
Enabling Long Pulse operation, PMI Research, and Plasma Processing with RF and Microwave Technology

- We have broad range of capabilities to support research in a variety of areas
  - Numerous CW higher power transmitters
    - FMIT system for high power RF transmission line component testing (1.5 MW, 40-80 MHz)
    - RF and Gyrotron power for Proto-MPEX plasma source development
      - 100 kW at 13.56 MHz
      - 100 kW and 30 kW at 3-30 MHz
      - 100 kW at 28 GHz, 53 GHz, and 140 GHz
  - Several plasma processing systems for plasma-assisted physical vapor deposition, RF sheath studies, and diagnostic development
- Continuity of graduate student and intern program commitments
- Developing new diagnostics to advance understanding of the antenna environment and RF sheath through development of Doppler Free Saturation Spectroscopy (very accurate/non-pertubative)
- Modeling capability of fields and plasmas (COMSOL, GENRAY, AORSA)



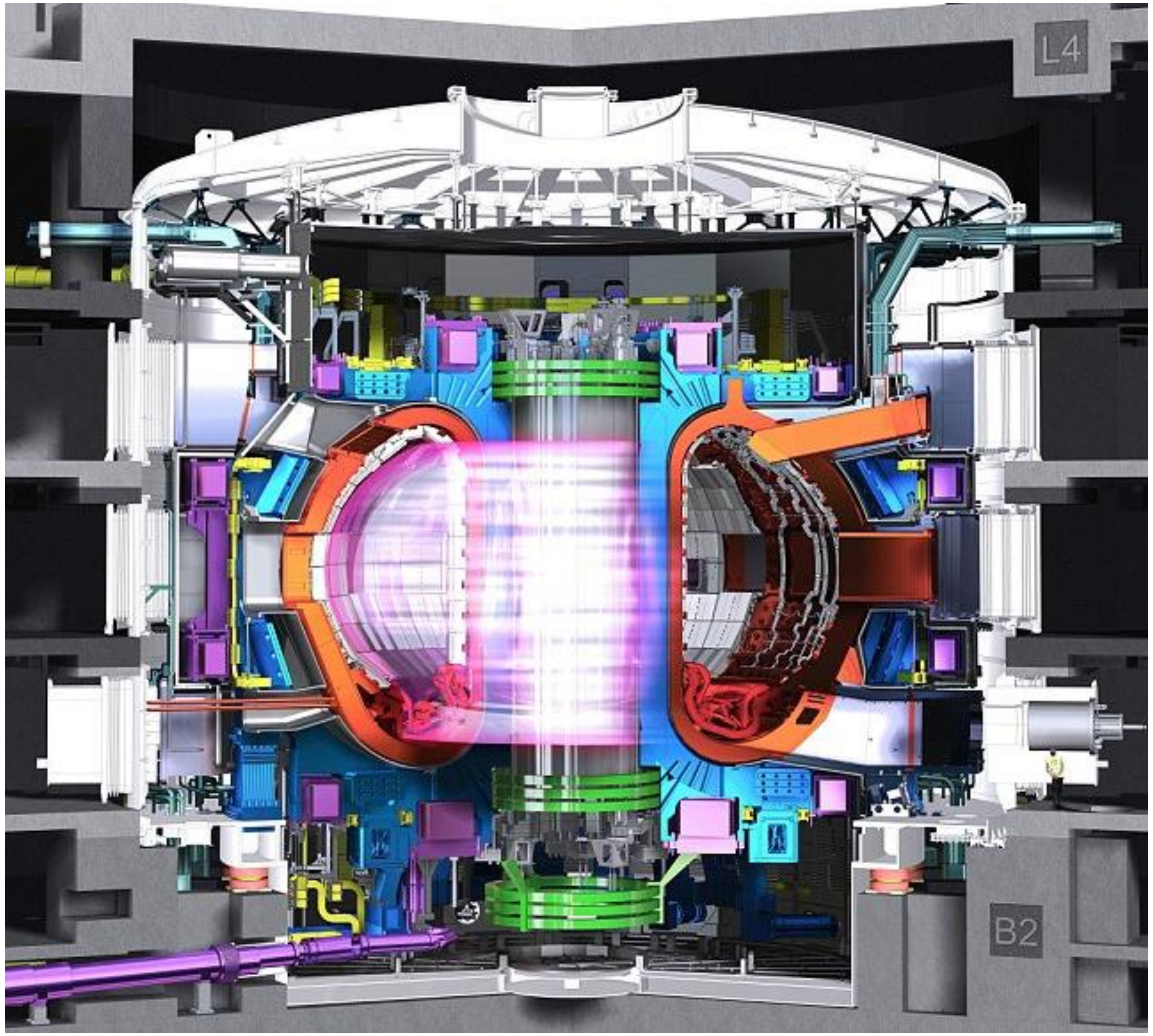
Resonant Ring testing of RF transmission line components for 1 hour at 6 MW proves component performance




100 kW Helicon Antenna on Proto-MPEX

ORNL: Fusion Plasma Facing and Structural Materials

- High temperatures, plasma bombardment, and hard-spectrum neutrons
- Not a single material currently exists that can meet specifications for a fusion energy device
- Structural materials (steels, silicon carbide, etc.) require significant advances over fission materials
- ORNL leads the US and an international effort in fusion materials
- ORNL is a world leader in Advanced Manufacturing at the Manufacturing Demonstration Facility



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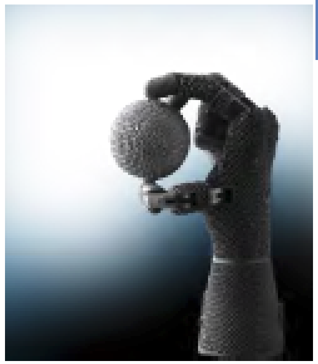
Advanced Manufacturing R&D Ecosystem for Technologies

MDF
Manufacturing Demonstration Facility

Additive Manufacturing
- Metal Powder Bed Consolidation
- Direct Metal Deposition
- Polymer Extrusion
- Ultrasonic Consolidation



Carbon Fiber
- Precursor to Filament
- Filament to Carbon Fiber
- Carbon Fiber to Composite Material

Advanced Materials & Processing
- Lightweight Metals
- Roll-to-Roll
- Low-Temperature
- Transient Field

Automation & Controls
- Modeling and Simulation
- Sensing, Tracking and Measurement
- Communicating Wirelessly

Manufacturing Demonstration Facility → **Market**

Technology Impacts:
- Market Driven Adoption of New Materials and Processes
- Transformational and Cross-Cutting for Next-Generation Products

Working with ORNL's MDF

Manufacturing Demonstration Facility

- Identify opportunities aligned with ORNL's MDF technology thrust areas
- Discuss ideas with MDF director
- Jointly pursue funding to support collaborative activity

	Assess	Assist	Collaborate
Type of Agreement	User Agreement (Non Proprietary)	Work for Others Agreement (Proprietary)	Cooperative Research & Development Agreement
Length of Engagement	Up to 12 months	As defined by agreement	Longer-term basis of a year or more
Cost to Company	NO COST	Full cost recovery	Cost-share required
Intellectual Property Rights	Each party owns its own inventions. Jointly developed inventions will be jointly owned.	Companies own intellectual property made or created using corporate funds as a result of these engagements.	Companies own inventions they make during the collaboration and have an option to negotiate an exclusive license in a specific field of use to inventions made by ORNL.
Protection of Generated Information	Information generated is publicly available.	Companies paying for services with corporate funds can treat all generated data as their proprietary information.	Commercially valuable information generated under a CRADA may be protected for up to 5 years, depending on funding source.

Addressing Power Handling Challenges Can Involve New Materials

Achievement

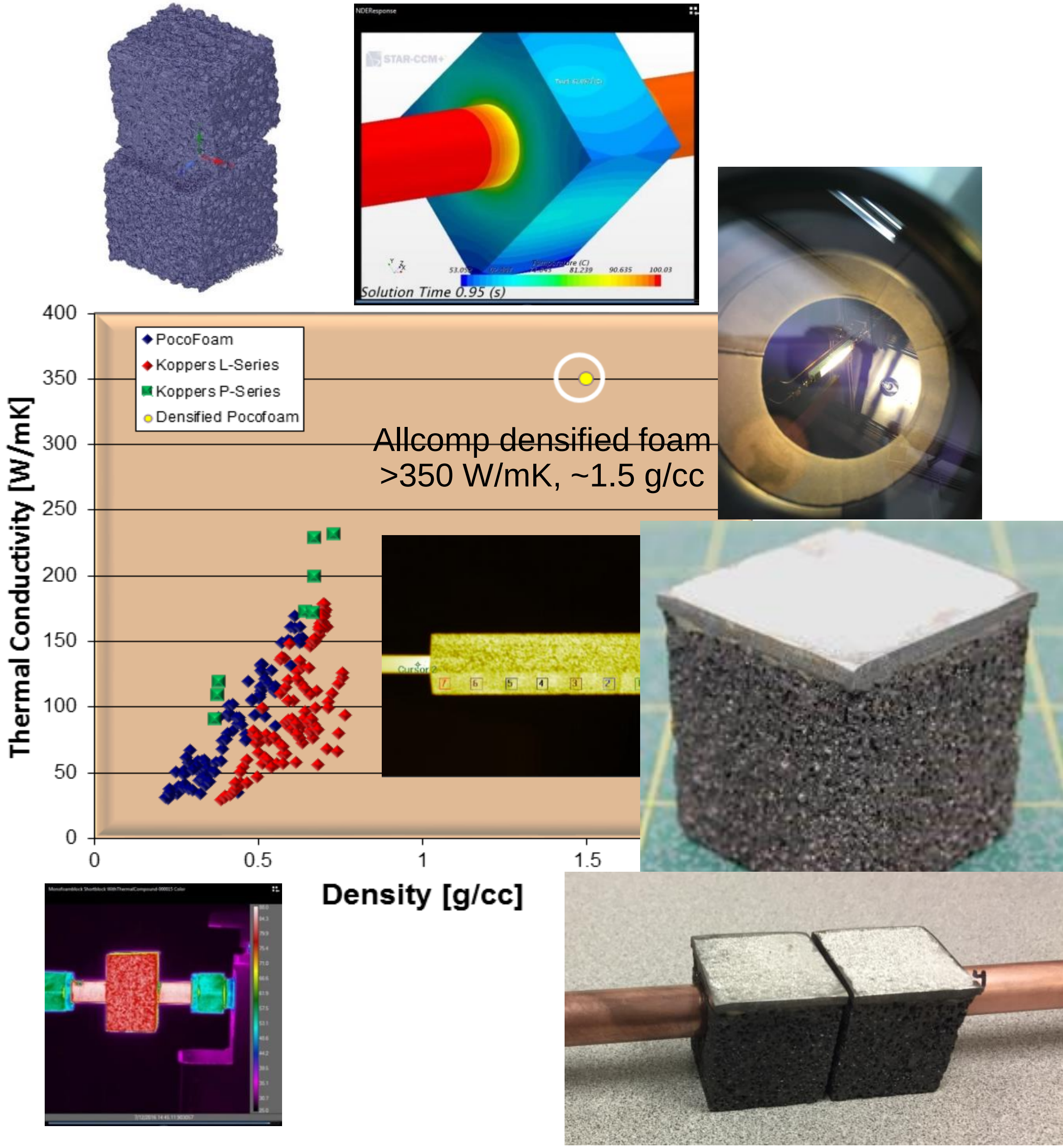
- Demonstrated that a <u>*nearly isotropic high-conductivity, low-Z plasma facing material*</u> is possible by combining pyrolytic graphitic ligaments with an isotropic-engineered microstructure

Significance and Impact

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

Research Details

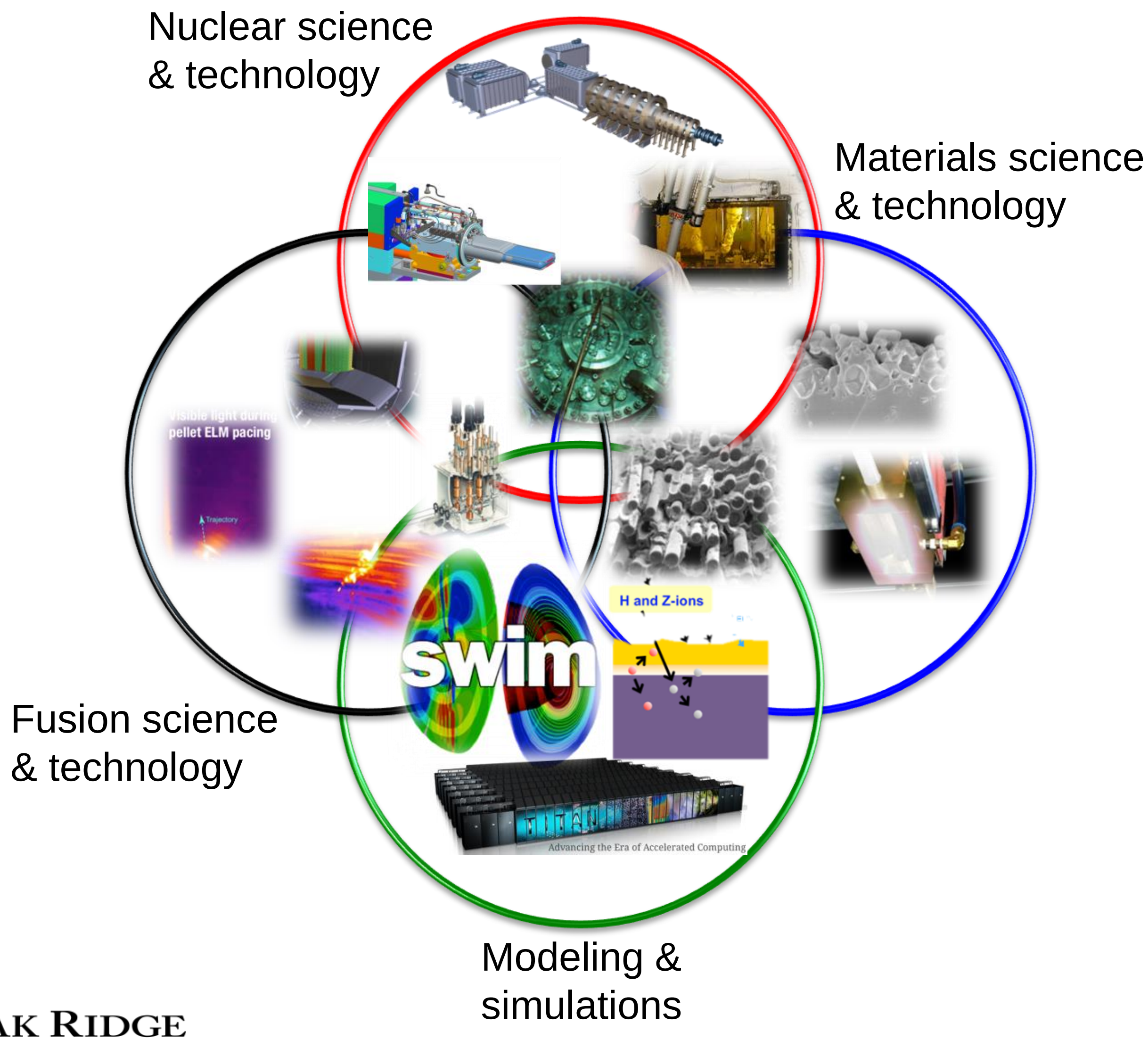
- Densified graphitic foam and mock-ups produced
- Thermal properties measured, <u>*k=265 W/mK to date*</u>, expect 350 W/mK
- <u>*Robust braze joint*</u> obtained on CuCrZr tubes
- Hot water IR thermography showed that using no braze joint actually delivers best thermal performance
- W-coated monoblocks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



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

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