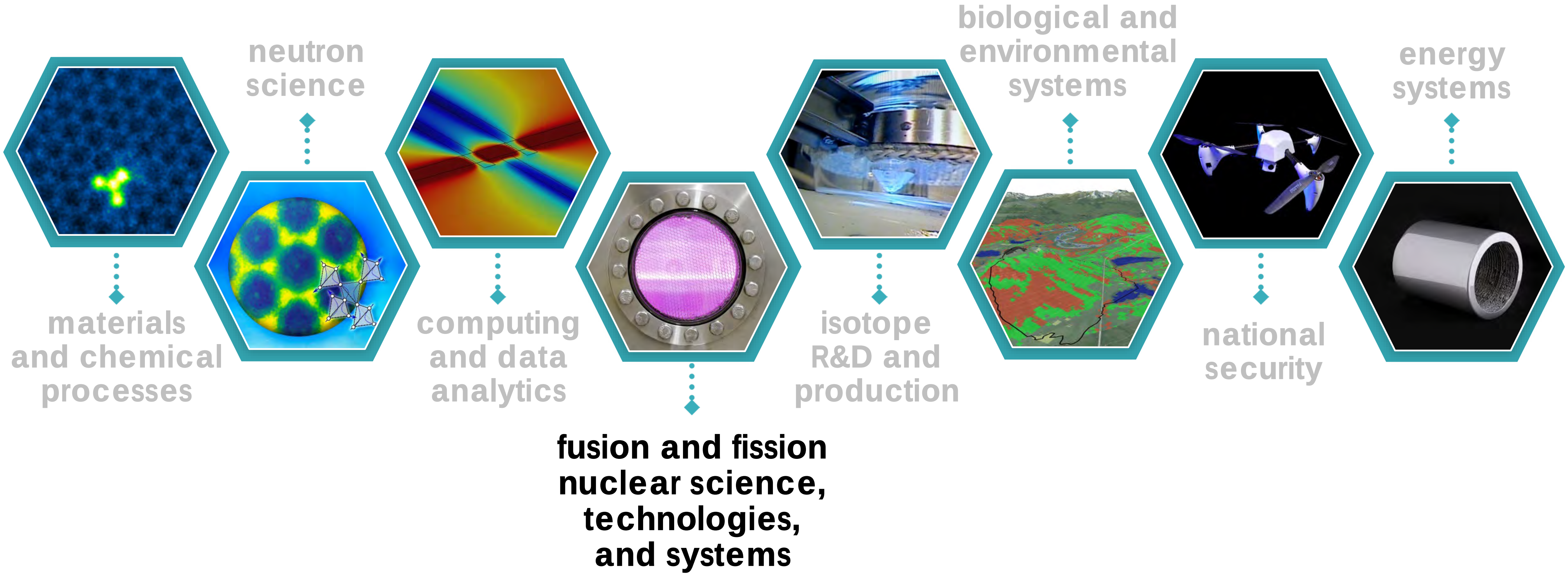
ORNL Activities to Support Commercial Fusion

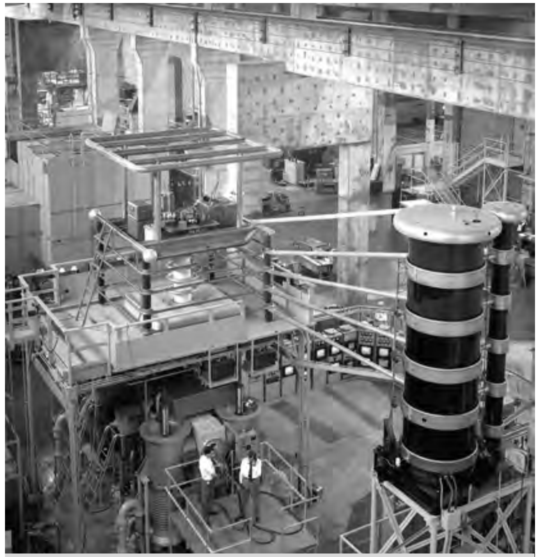
Kathy McCarthy

US ITER Project Director

ORNL is the nation's largest multi-program science and technology laboratory

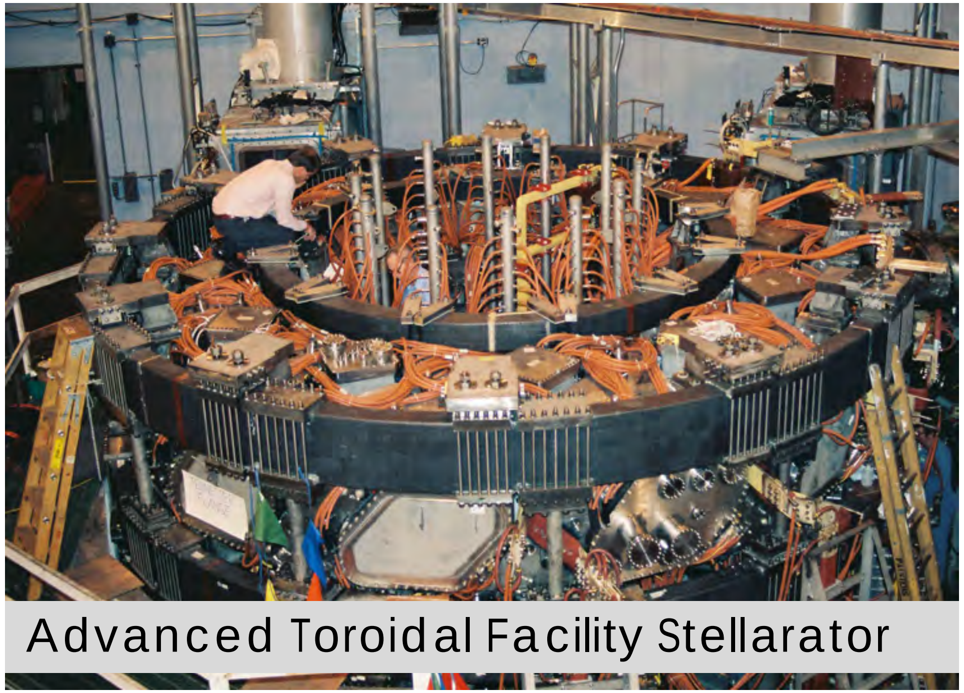


ORNL has over 60 years of experience in fusion



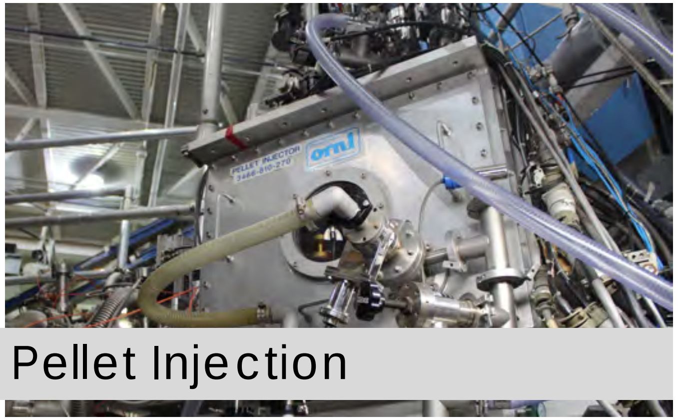
Advanced Current Experiment

Large Coil Test Facility



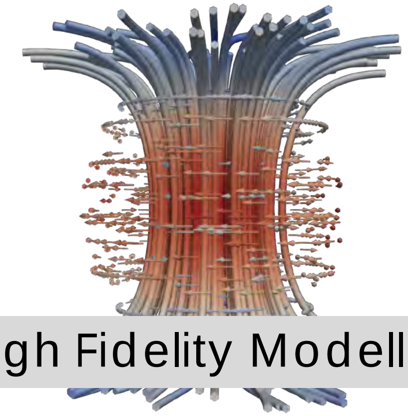
Advanced Toroidal Facility Stellarator

ORMAK Tokamak



Pellet Injection

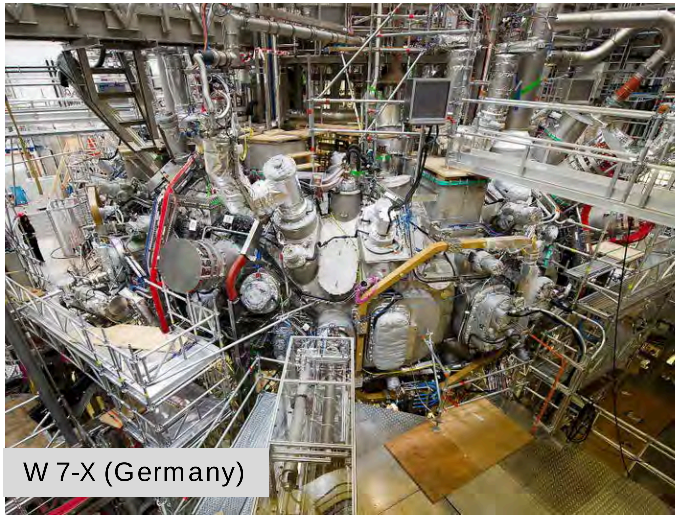
Proto-MPEX



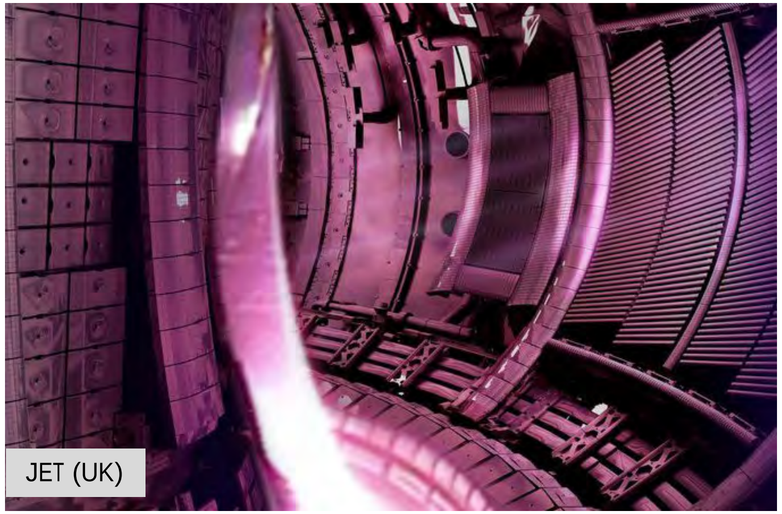
High Fidelity Modelling

ORNL contributes fusion expertise around the globe

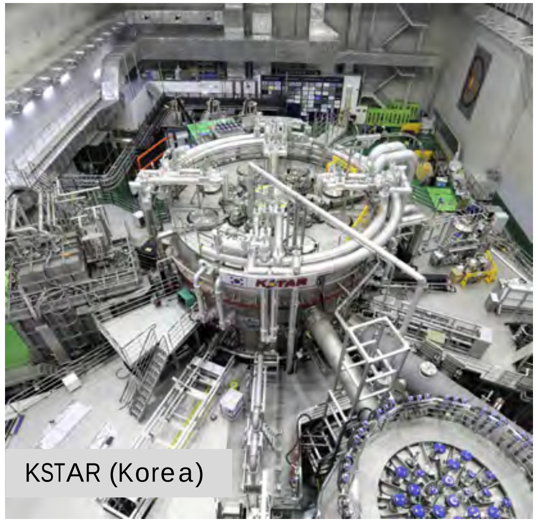
DIII-D (US)



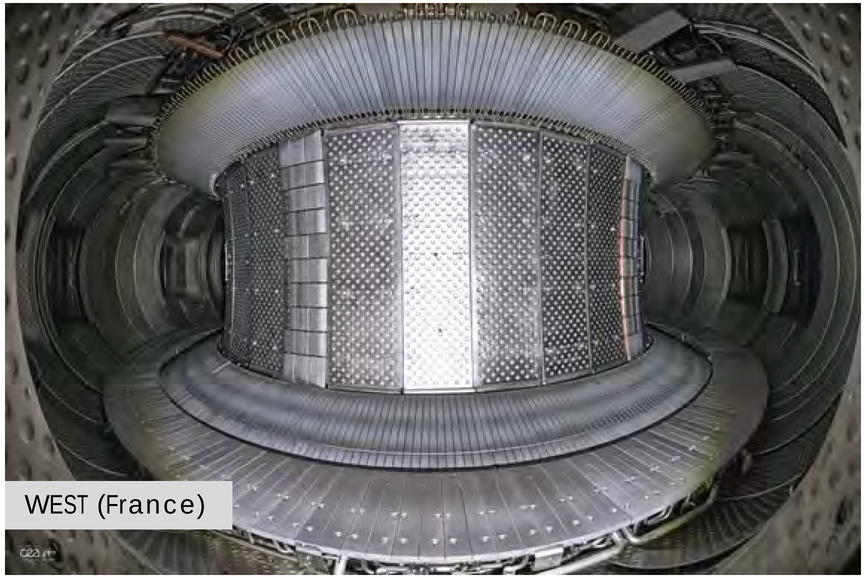
W 7-X (Germany)



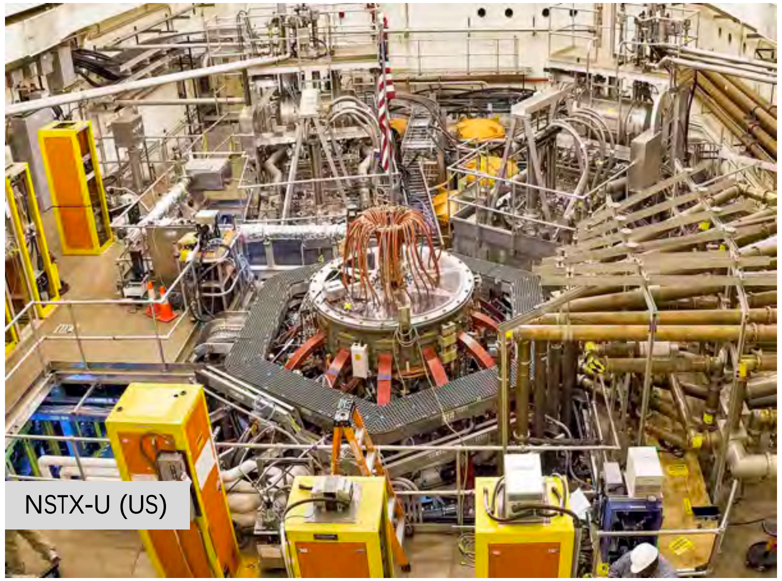
JET (UK)



KSTAR (Korea)



WEST (France)



NSTX-U (US)

ITER (global collaboration sited in France)

Diverse fusion approaches are underway in public and private sectors

Stellarator

Wendelstein 7-x | IPP Max Planck

Compact Spherical Tokamak

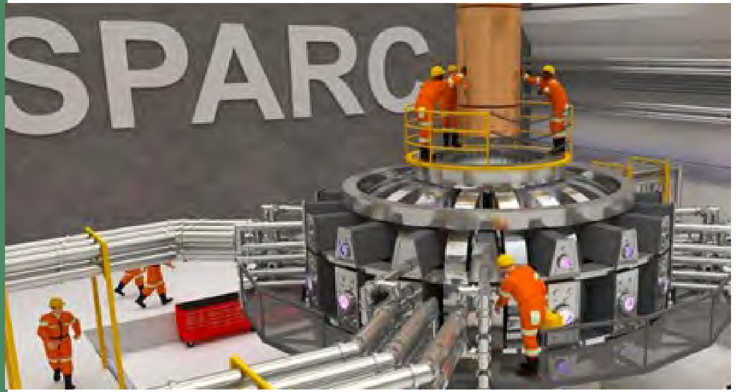
NSTX-U | PPPL

MAST | CCFE

Magneto-inertial Configurations

LANL | PLX

High-field Tokamak



SPARC | MIT/Commonwealth Fusion

ST40 | Tokamak Energy

Reverse-Field

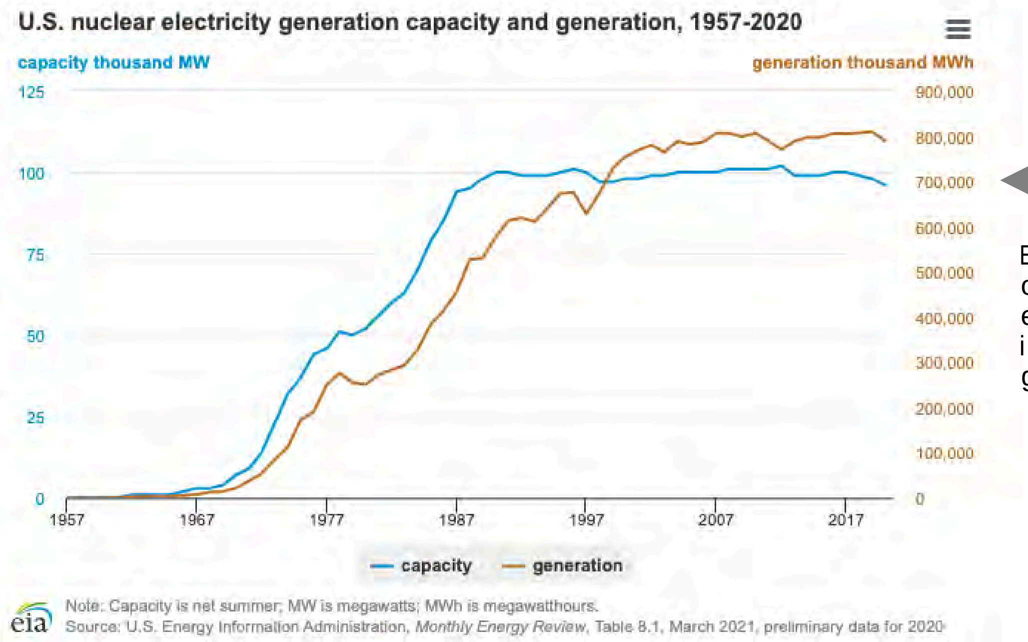
Norman | TAE Technologies

Magnetized Target

Plasma Injector | General Fusion

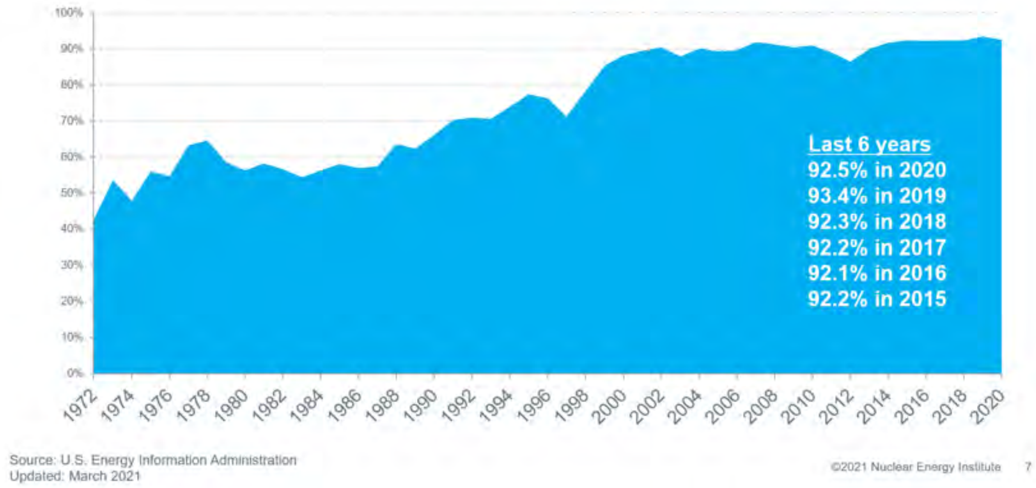
Fission reactor history offers lessons for fusion energy development

- The first nuclear plant to provide electrical energy to the US power grid was in 1957
- Deployment increased rapidly for the next 20 years; then from 1979 through 1988, 67 planned builds were canceled (post Three Mile Island)
- Fission plants now operate on average >90% of the time (including refueling outages and maintenance); fusion should aspire for the same
  - The typical refueling outage duration for U.S. nuclear plants is 35 days and takes place every 18-24 months
  - Inspections and maintenance are performed at the same time as refueling
- Sufficient Technology Readiness Levels of core systems is crucial for widespread adoption of a new energy source



Enhanced outage efficiencies impact MWh generation

Nuclear power plant capacity 1972-2020



OAK RIDGE National Laboratory

Kathy McCarthy

Fusion is different from fission

- No risk of runaway reactions
- Limited long-lived waste compared to fission products; waste is produced primarily by activation of structural materials
- Proliferation risk is considered lower
- Broadly available fuel supports global energy equity
  - Lithium is required to breed tritium for deuterium-tritium (DT) fuel
  - Other fuel cycles are under development (each with pros and cons)
- DT fusion produces 14 MeV neutrons compared to 2 MeV neutrons in fission (tritium is an alpha emitter and must be managed)
- The source term and energy to mobilize the source term vary greatly in the fusion designs under consideration

Comparison of fusion systems with advanced fission

Fusion

- Demonstration: Experiments focused on plasma physics
- Fuels: TBD (DT, other hydrogen species); complete fuel cycle not yet demonstrated
- Pilot Plant Designs: in development with a wide variety of options under consideration
- Operating experience: experiments (including with D-T fuels)
- Regulation: in development, with several studies done to inform regulation

Advanced Fission Reactors

- Demonstration: technology for most advanced fission reactors under serious consideration have been demonstrated in some form at some scale
- Fuels: multiple qualified fuels, others tested
- (Pilot Plant) Designs: varying maturity depending on the specific technology to be used (water, sodium and gas-cooled demonstrated commercially)
- Operating Experience: varies, but most technologies operated in some form at some scale
- Regulation: depends on country, but most experience is with LWRs

As a national laboratory, ORNL has critical role to play in resolving technical challenges and reducing risk for a range of future fusion energy approaches

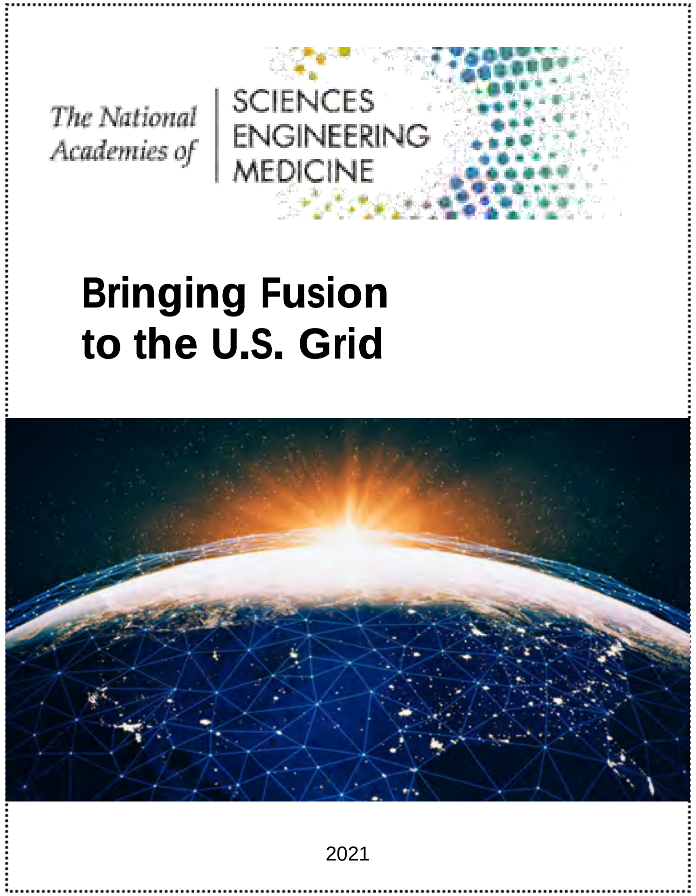
Our contributions include:

- Sustained R&D to resolve technical challenges and advance technical readiness of diverse fusion systems
- Integration across technologies for fusion systems
- Long-range planning for efficient, safe and reliable delivery of fusion energy from source to consumer

Our expertise and contributions are important for connecting:

- Public R&D program
- Fusion Pilot Plant (FPP) design activity (in development)
- Public-Private Milestone program (in development)
- Energy policy for long-term impact

2021 National Academies report outlines essential fusion technology performance needs for a pilot plant



Technology must demonstrate:

- Safety
- Economic viability
- Cost certainty
- Regulatory certainty
- Reliability and availability

Note: A fusion pilot plant will need to operate through at least one environmental cycle to demonstrate reliability, availability and maintenance

ORNL's fusion focus today: Science, technology + integration to prepare for a fusion pilot plant

We are developing and advancing the:

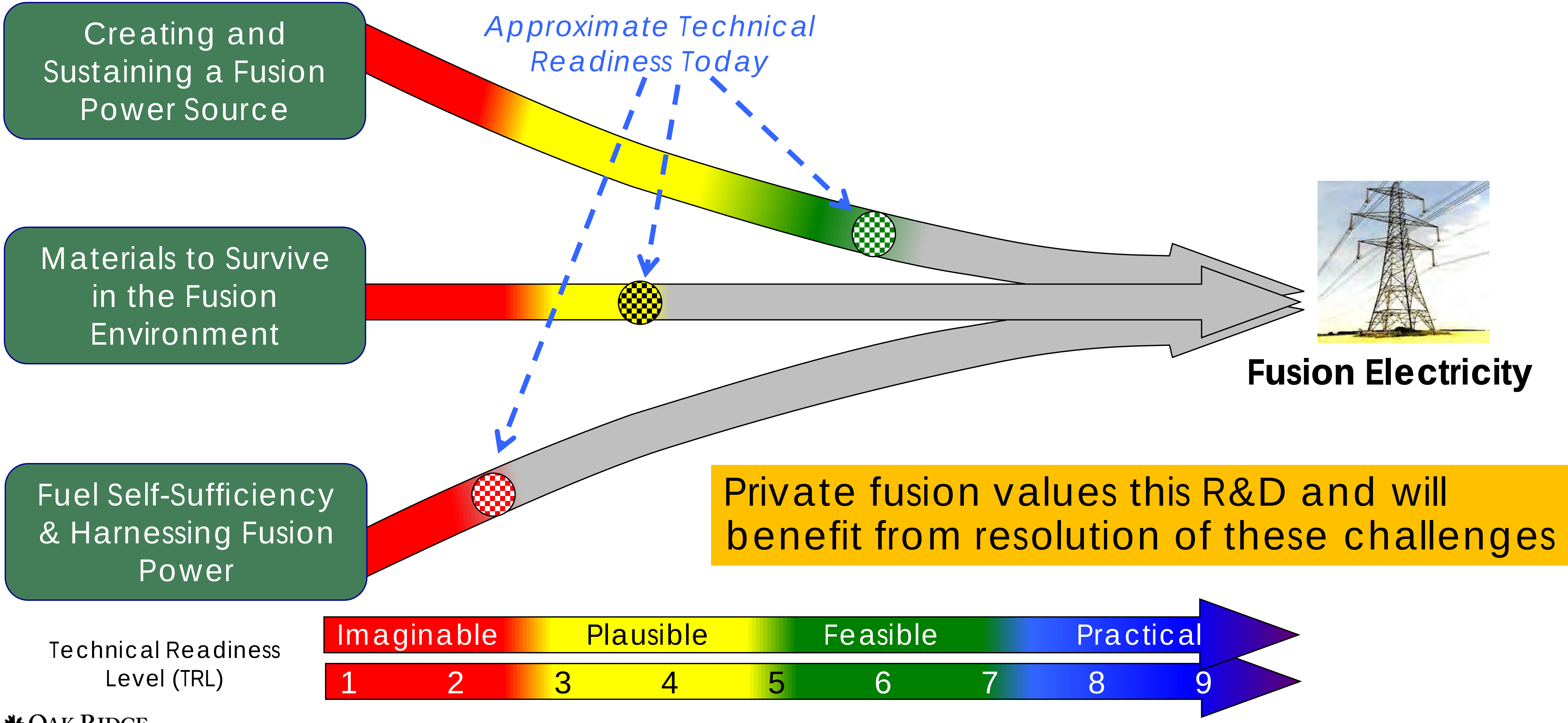
- Physics basis for a self-sustaining plasma and prepare to capture essential knowledge from ITER and other fusion devices
- Materials that function in the extreme fusion environment
- Fusion fuel cycle, including a fusion blanket that delivers fuel self-sufficiency, efficient heat removal, and neutron shielding
- Integration of advanced manufacturing, AI, and modeling for fusion technologies and systems

All of these efforts support resolution of the major technical challenges facing practical, economical fusion

National laboratories support essential input for NRC decisions

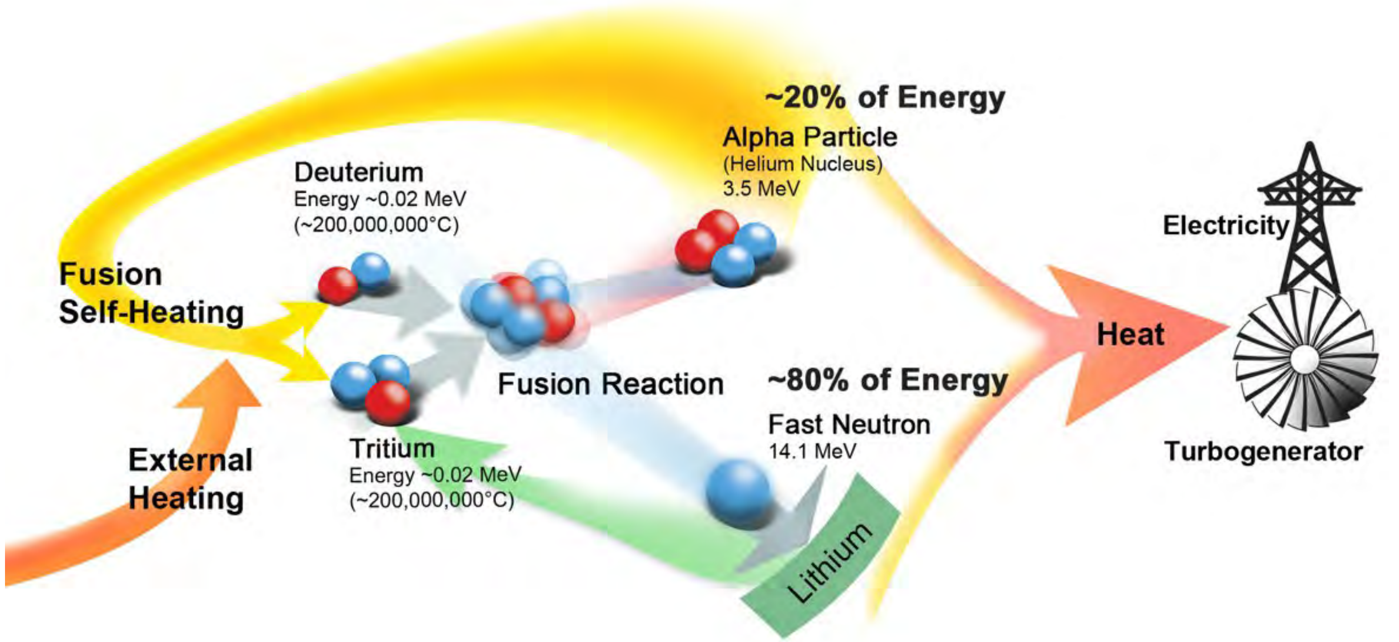
- Lessons Learned from the Light Water Reactor Sustainability (LWRS) Program
- Materials and fuels development and qualification
- Efficiencies for operations and maintenance
- Design development and evolution
- Expert input for licensing support

ORNL is contributing to the 3 prime technical challenges that must be resolved to realize practical fusion energy

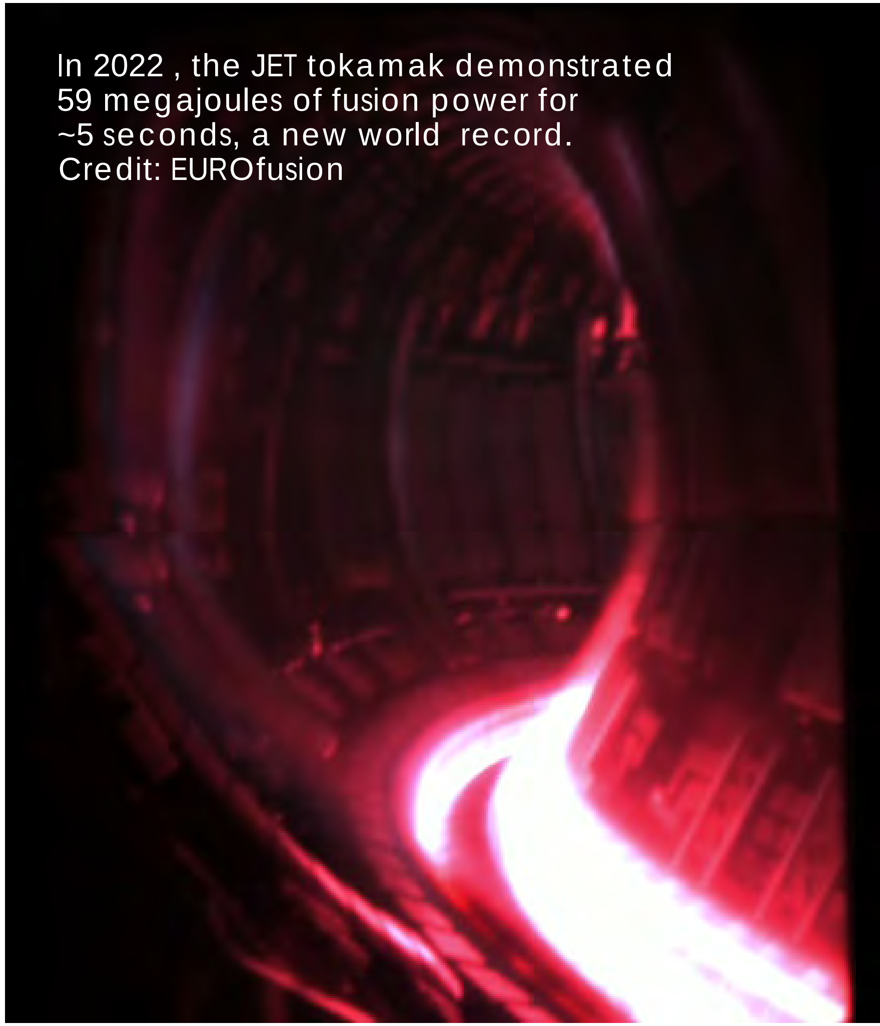


Challenge 1: Sustained fusion power source

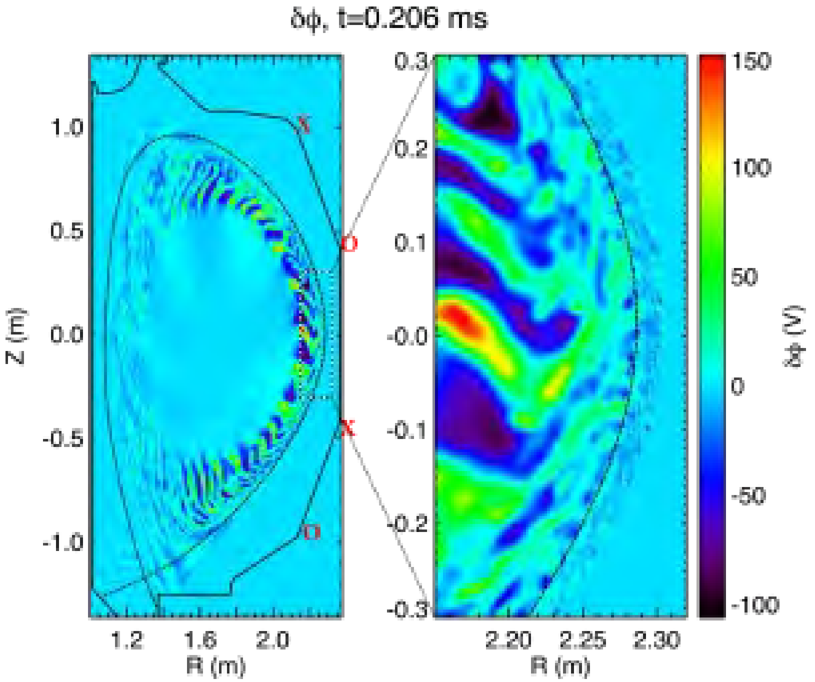
To deliver efficient, economical fusion power, fusion reactions must be self-sustaining, where plasma heating is dominated by the fusion reaction itself--not by external heating.



Deuterium-Tritium (DT) fusion reaction is "easiest" to achieve and the most studied and typically planned.

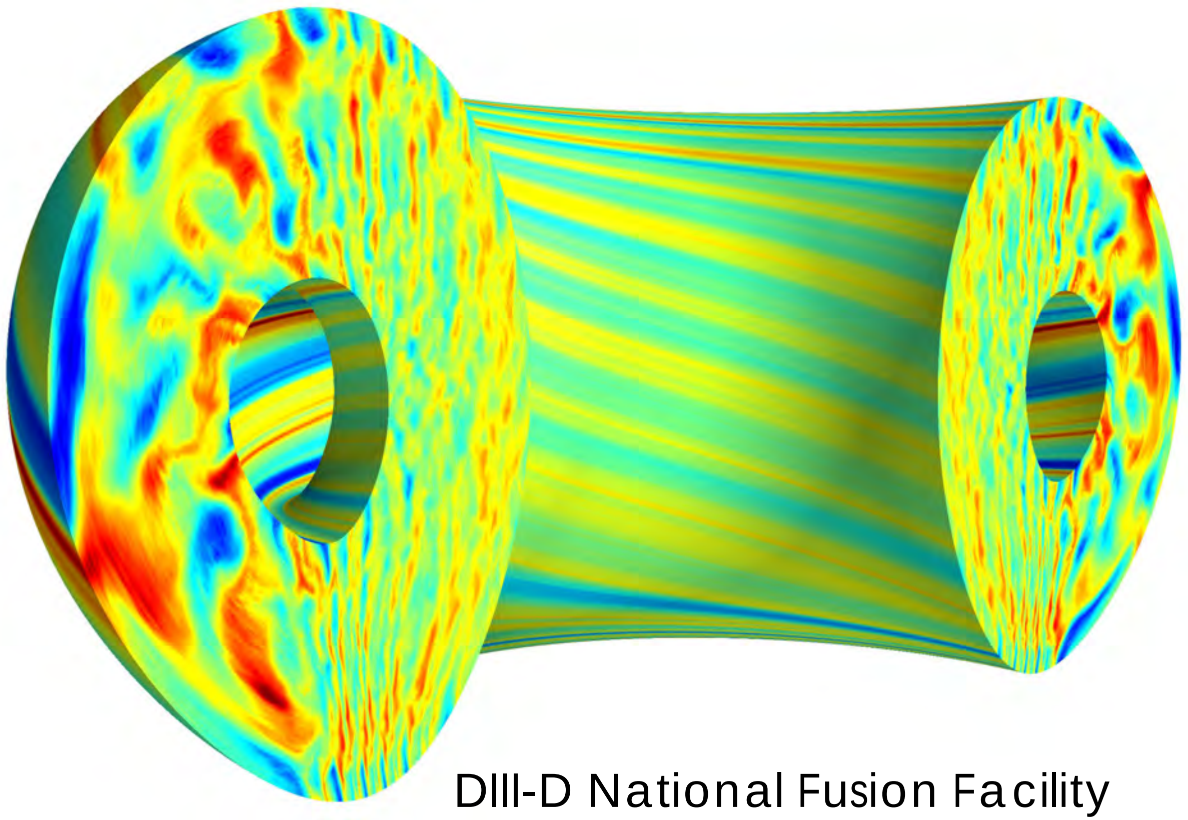


National laboratory resources, such as supercomputing at ORNL, enable modeling and simulation to advance understanding of fusion plasmas



Princeton Plasma Physics Laboratory

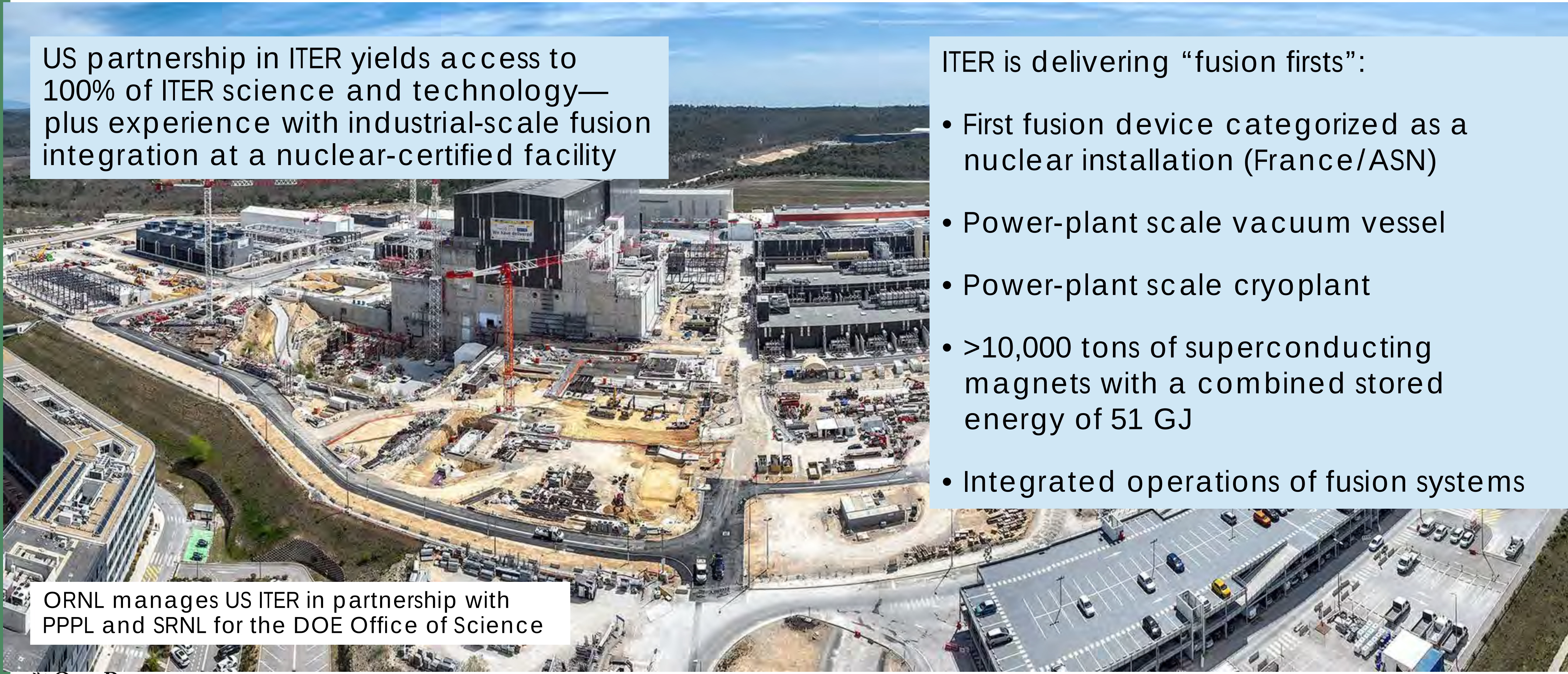
Plasma turbulence in the DIII-D tokamak was simulated on ORNL's Summit supercomputer utilizing a new particle-resampling technique. Related publication: C. S. Chang et al., Journal of Computational Physics 409 (May 15, 2020).



DIII-D National Fusion Facility

A visualization of deuterium-tritium density fluctuations in a tokamak driven by turbulence.
Image Credit: Emily Belli, General Atomics
Related Publication: Emily A. Belli and Jeff Candy, Physics of Plasmas 28, no. 6 (2021)

ITER is designed to demonstrate self-heated 500 MW "burning plasma" performance at full power



US partnership in ITER yields access to 100% of ITER science and technology—plus experience with industrial-scale fusion integration at a nuclear-certified facility

ITER is delivering "fusion firsts":

- First fusion device categorized as a nuclear installation (France/ASN)
- Power-plant scale vacuum vessel
- Power-plant scale cryoplant
- >10,000 tons of superconducting magnets with a combined stored energy of 51 GJ
- Integrated operations of fusion systems

ORNL manages US ITER in partnership with PPPL and SRNL for the DOE Office of Science

ITER know-how and R&D benefits US fusion industry in multiple areas

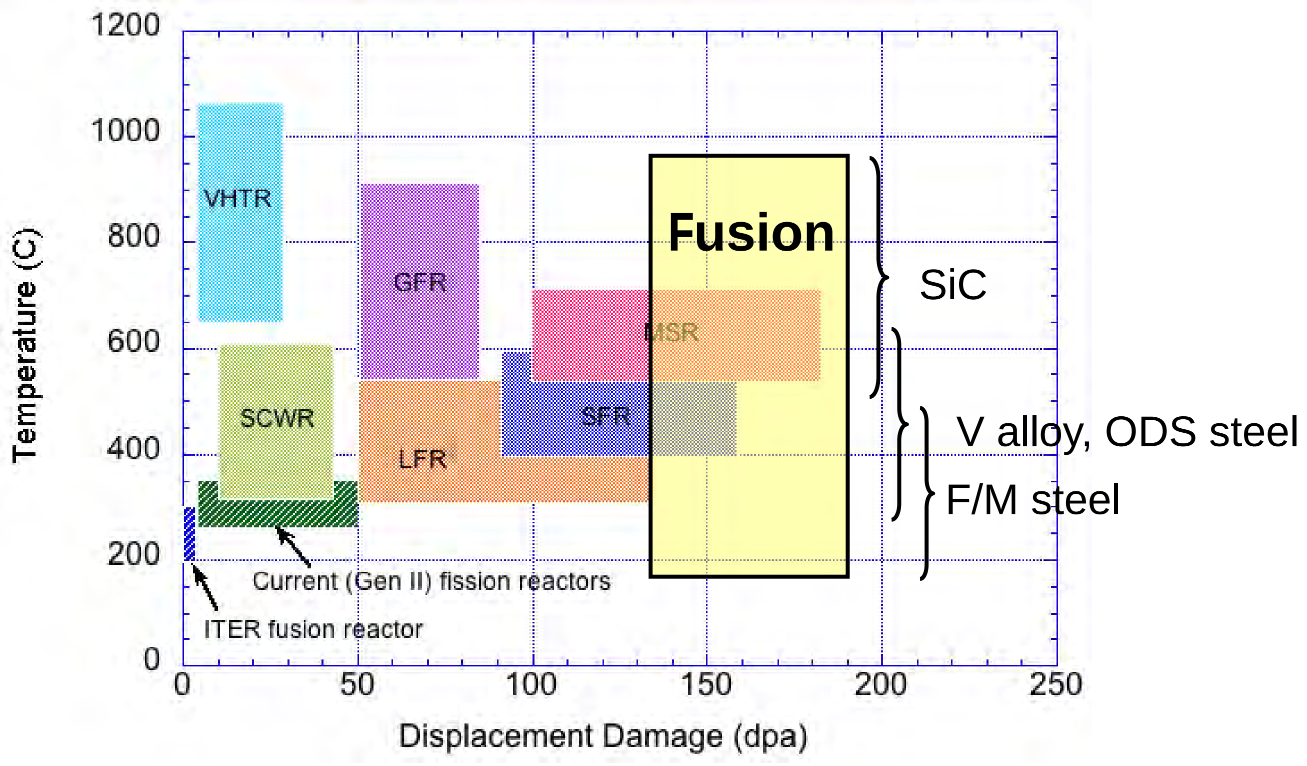
- Tools and strategies for plasma control and performance
- Superconducting magnet technologies
- Radiation transport analysis
- High-powered plasma heating
- DT fuel cycle technologies
- Continuous plasma fueling
- Fusion materials
- Fusion power and particle handling
- Burning plasma science and diagnostics

ITER tokamak pit (October 2022). Credit: ITER Organization

DOE is establishing a process to facilitate industry access to ITER information of interest

Challenge 2: Fusion materials

- Fusion environment is much more extreme than that of today's fission reactors:
- Plasma material interactions in a fusion reactor will impact the lifetime of materials
- New materials must be developed to support sustained fusion power operation
- Remote handling for component installation and maintenance is necessary



Credit: S.J. Zinkle ,OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007

ORNL is home to the largest DOE Office of Science fusion materials program

Lab resources support materials development, nuclear evaluation and evaluation of fusion performance

Pure tungsten (W) plasma-facing component coupled with mesh structure

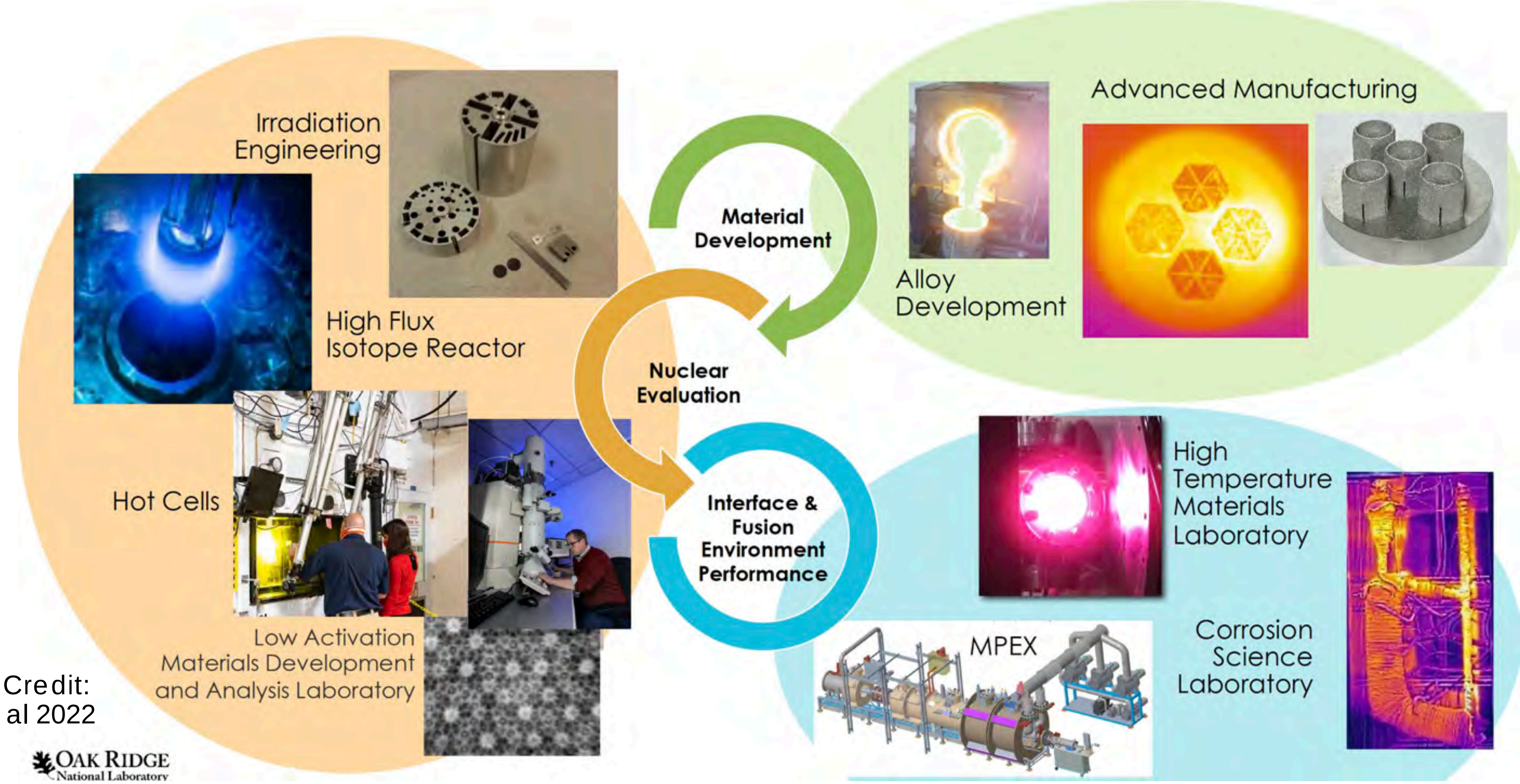
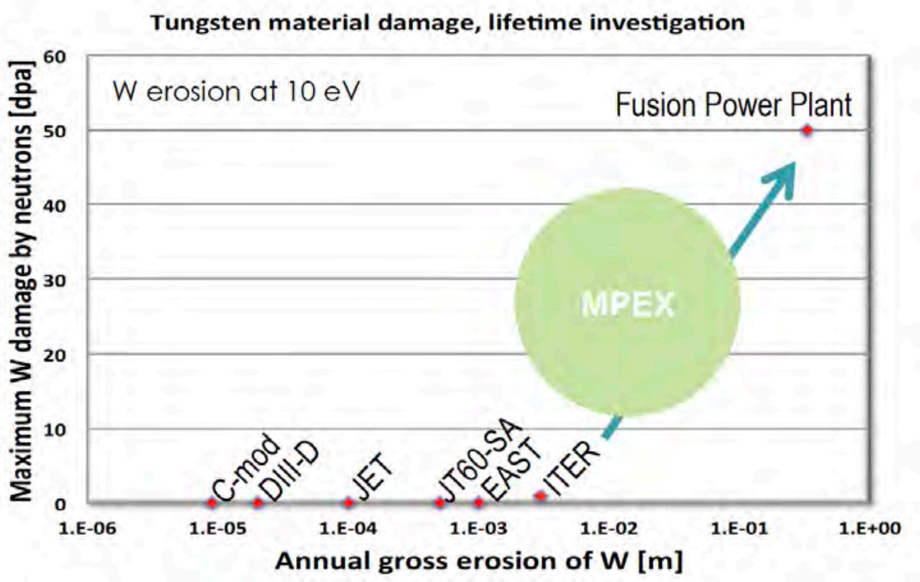


Diagram Credit: Collins et al 2022

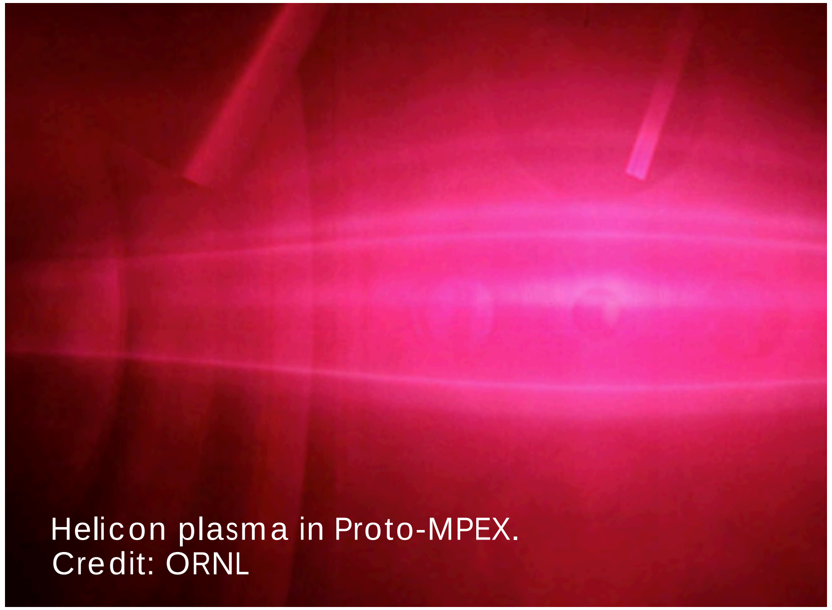
New test facilities will be important for fusion industry

Materials Plasma Exposure eXperiment (MPEX)
(under construction at ORNL; operations to begin in FY28)

MPEX will be a platform to test fusion materials relevant for a fusion pilot plant, enabling life-time exposures in just 2 weeks



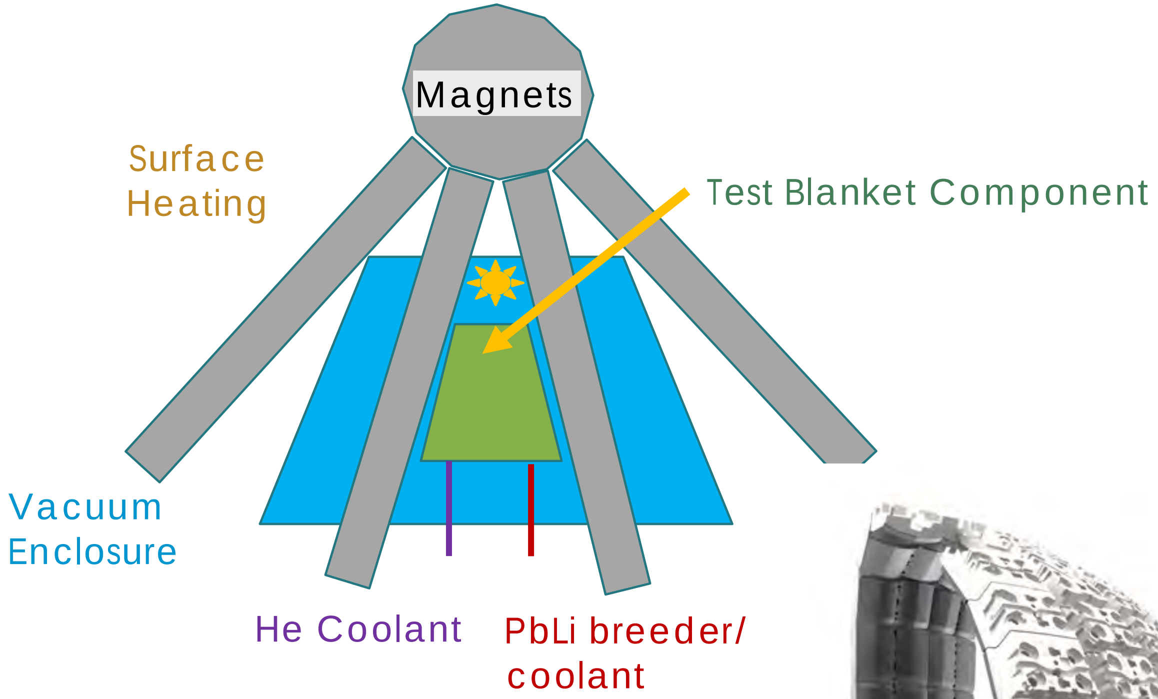
Tungsten has the highest melting point of any pure metal and is a prime candidate for plasma-facing components for fusion energy.



Helicon plasma in Proto-MPEX.
Credit: ORNL

Challenge 3: Closing the fusion fuel cycle

- Fusion fuels for a pilot plant may be deuterium-tritium (DT) or other fuels
- DT will require the production of tritium, ideally within a fusion reactor
- Extraction of fusion power regardless of fuel must be highly efficient for an economical system
- Management issues to address include tritium inventory, helium ash removal, and neutron-activated structures



Schematic of a blanket component test facility

ITER will have test blanket modules installed

ORNL is home to the national fusion blanket and fuel cycle program

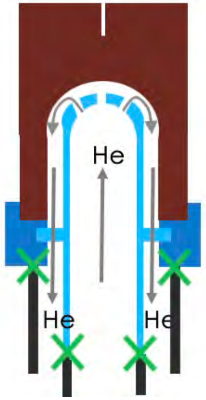
Program Goal: Develop the basis, design, construct, and operate a Blanket Component Test Facility (BCTF) for fusion systems

Key R&D: Testing helium cooling strategies for blankets

Additive manufacturing of ribbed piping for improved heat transfer

Helium flow loop test stand. Helium provides advantages over water-based cooling

Key R&D: Testing helium cooled plasma facing components under heat loads



Additive Manufacturing

+

High heat flux source

Industry partners value ORNL expertise, especially in enabling technologies that make fusion systems viable

INFUSE

ORNL leads the INFUSE Innovation Network for Fusion Industry (65 awards, 19 companies to date)

ORNL supports 22 INFUSE projects for 7 companies

Commonwealth Fusion Systems

Energy Driven Technologies

generalfusion®

Princeton Fusion Systems
Clean, Compact Fusion

tae TECHNOLOGIES

tokamak energy

TYPE ONE ENERGY

ORNL expertise enables aggressive attempts by private fusion to advance the technical maturity of their concepts and demonstrate component performance

Interest is high in receiving support for enabling fusion technology areas

To move from physics models to practical systems, fusion industry must develop a wide range of design and engineering solutions that can result in integrated systems.

The integrative engineering expertise of DOE national laboratories is essential for these areas, such as:

- Magnets
- Plasma performance management
- Heating systems
- Plasma facing components
- Shielding
- Remote handling
- Tritium processing and management

Additional areas of industry need

- Diagnostics: Diagnostic technologies deliver documentation of fusion performance and insight on plasma conditions. To test, calibrate and demonstrate the performance of novel fusion systems, private industry is partnering with the deep diagnostic expertise of national laboratories and universities.

- Modeling and simulation: Mod-sim using codes established by national laboratories is of great interest to fusion industry to predict the performance, reliability and economics of fusion reactor concepts. In addition, national laboratories offer access to exceptional high performance computing resources.

- Fusion materials: New materials must be developed and tested to deliver for novel fusion systems. Of great interest now for private fusion is the testing and performance documentation of materials such as high temperature superconductors.

Test stands and other facilities are also needed by fusion industry

- In addition, fusion industry is interested in access to experimental test stands and tools, whether at current fusion devices or other DOE user facilities
- Needs include materials irradiation, remote handling, and materials analysis
- We expect demands for test stands and user facilities to grow as fusion industry concepts mature and engineering designs under testing

Summary: ORNL is committed to delivering expertise to benefit private fusion

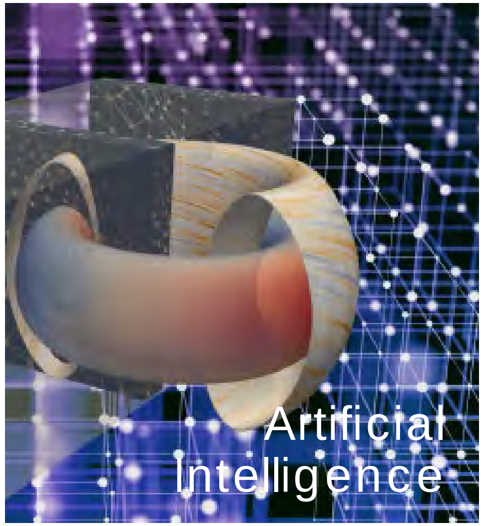
- ORNL brings decades of expertise in fusion science and technology, including a variety of confinement approaches, and offers important resources for fusion industry and NRC needs; our partnerships with other national laboratories are key
- ORNL's support of commercial fission energy brings important knowledge and lessons learned that benefit fusion energy development
- ORNL is addressing the 3 major technical challenges that must be resolved for practical fusion energy.
- ORNL is working effectively with fusion industry and is providing key contributions to enabling technologies
- As a national laboratory, ORNL delivers sustained and long-term contributions to the development of fusion as an energy source

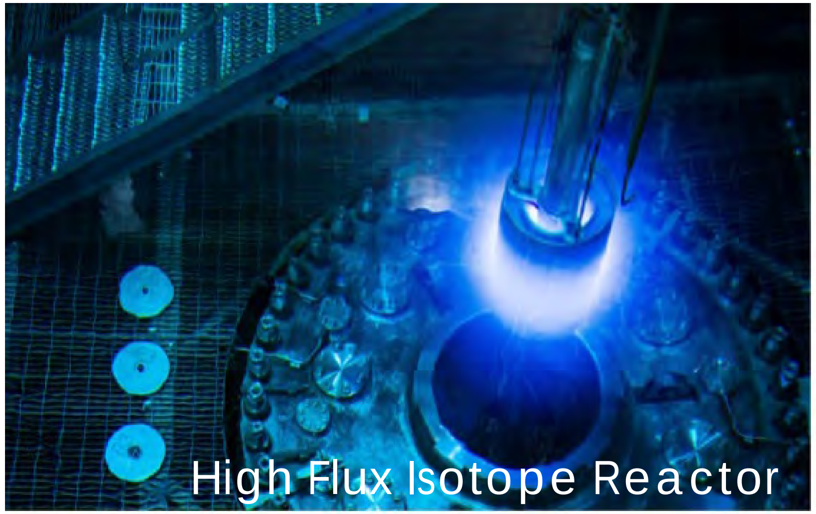
Oak Ridge National Laboratory

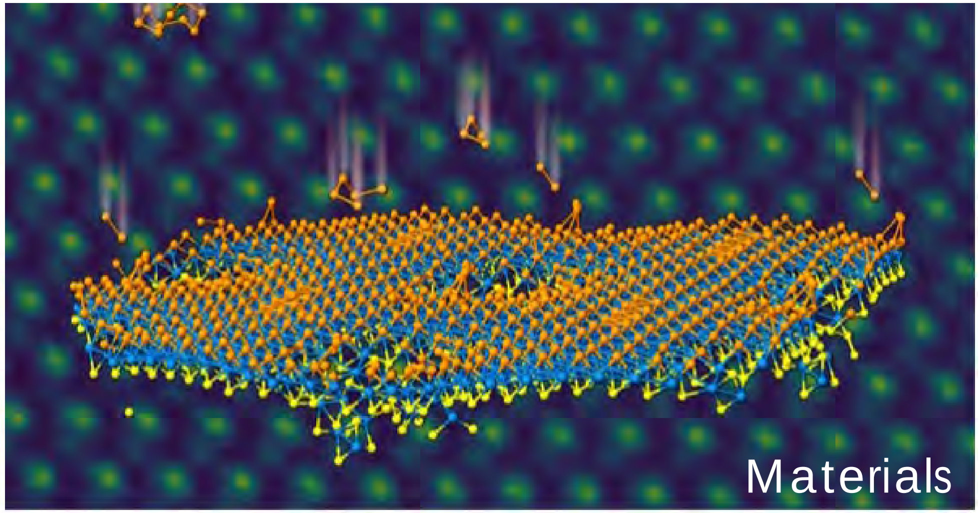
Thank you

BACK-UP

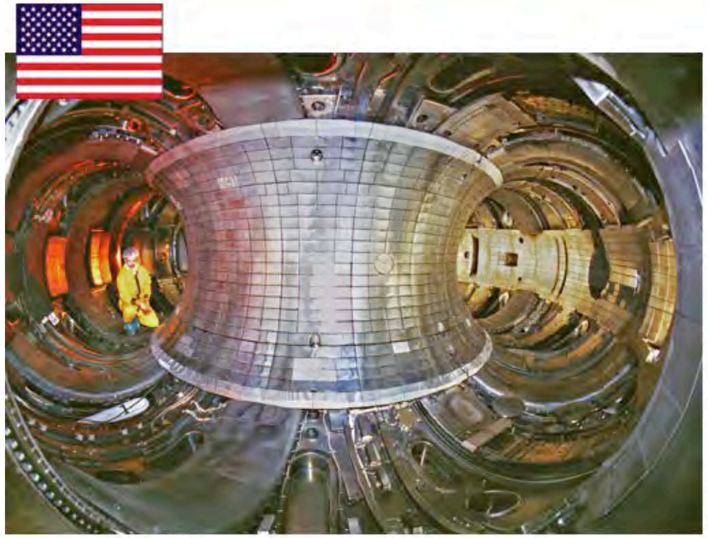
Unique ORNL facilities and capabilities support fusion energy development



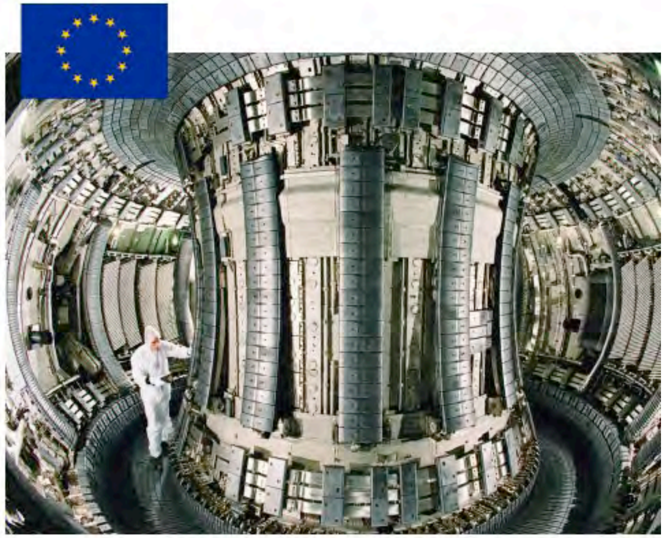




Fusion power has been demonstrated, mainly in tokamaks

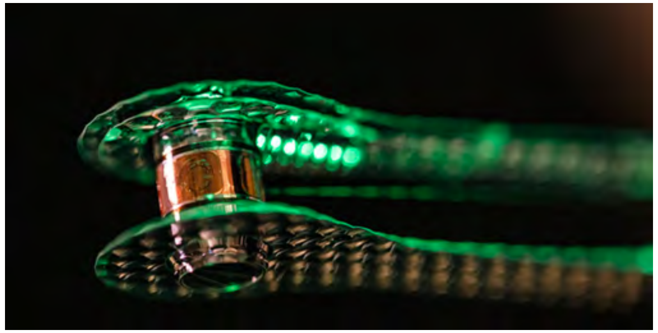


Tokamak FusionTest Reactor (TFTR)
10 MW fusion power (1994)



Joint European Torus (JET)
16 MW fusion power (1997)

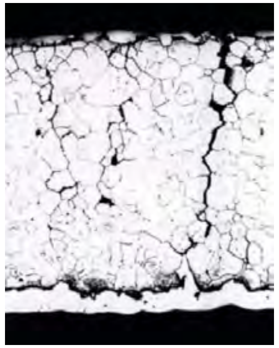
New fusion record!
JET produced 59 megajoules of energy over 5 seconds in February 2022



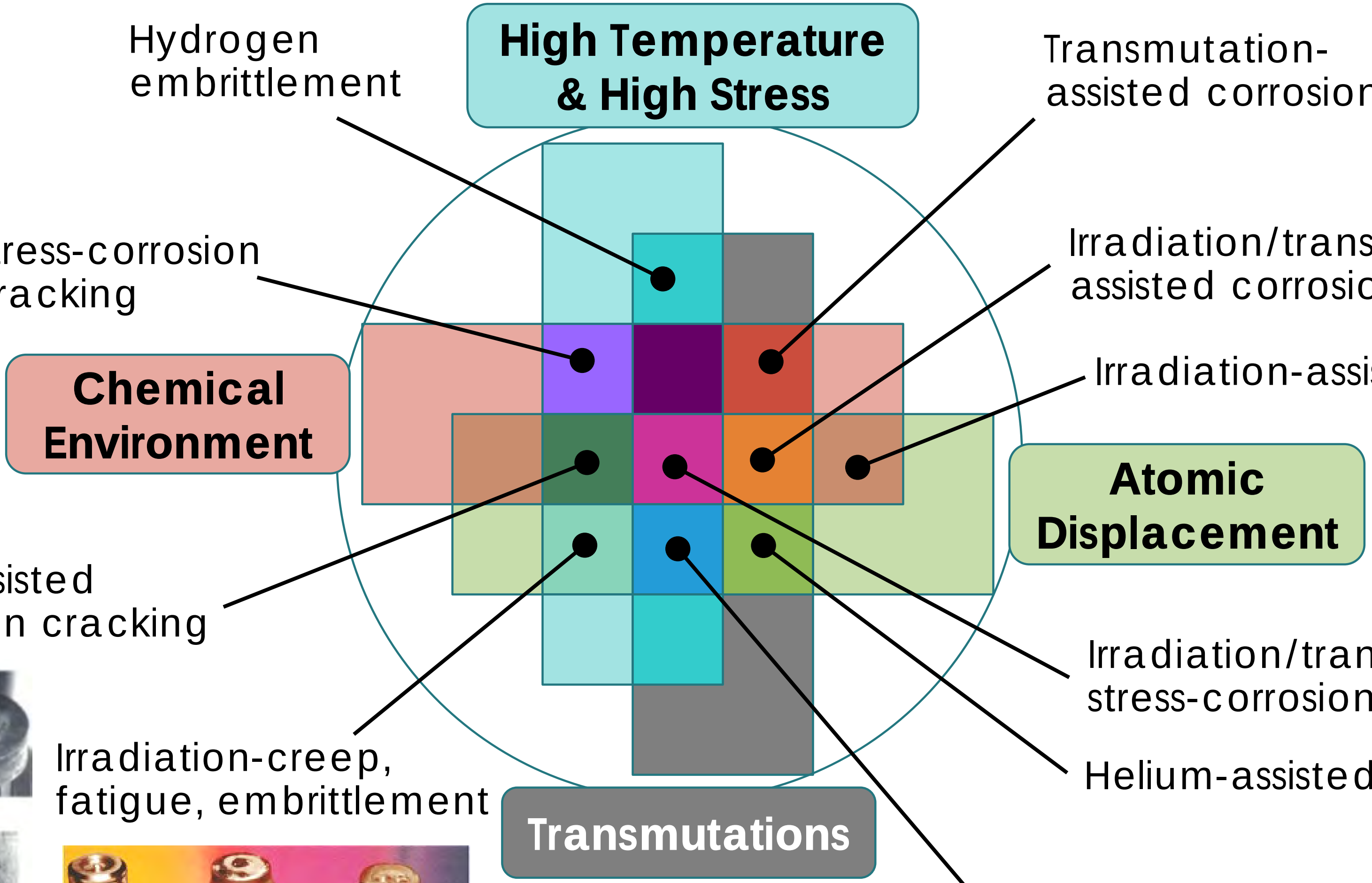
National Ignition Facility (NIF)

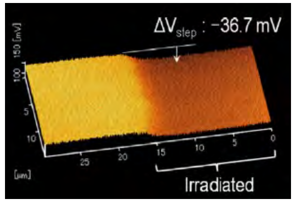
NIF yielded 1.1 megajoules in 2021, a 25-fold increase in energy yield since the prior record in 2018

Fusion environments are highly challenging for materials

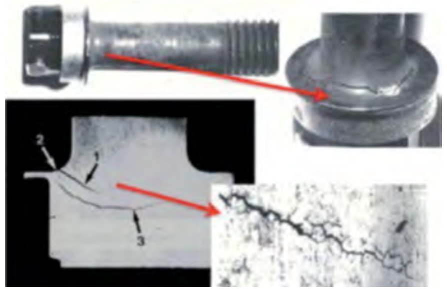


Cottant et al., 2008

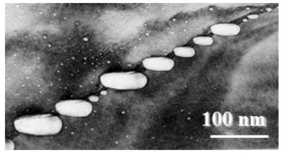




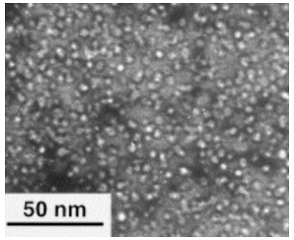
Kondo et al., 2016



Allen et al., 2010



Braski et al., 1979



Chernov et al., 2003

Diagram Credit:
Collins et all 2022

Example of an INFUSE Project with ORNL

Commonwealth Fusion Systems

Project: Divertor component material testing

Need: Testing of materials under relevant heat flux conditions, a necessary step for developing a robust and reliable power exhaust system for SPARC compact fusion system

Results: Informed selection of SPARC plasma facing material

INFUSE

Example of an INFUSE Project with ORNL

tokamak energy

Project: Design of a pellet injector for the ST40 compact spherical tokamak

Need: Design and modelling of a pellet system for fueling ST plasmas to demonstrate high density operation and to eventually be used in future devices to inject DT pellets

Results: 3D CAD model of the pellet injection system and component definition for the injection line, gas handling, and a pellet mass and speed diagnostic

INFUSE

Example of an INFUSE Project with ORNL

tae TECHNOLOGIES

Project: Measurement of magnetic field using doppler-free saturation spectroscopy

Need: Measurement of internal magnetic field profile is important to verify the presence of the field reverse configuration and to estimate/simulate the orbit of confined fast ions

Results: in progress (initiated in 2020)

INFUSE

Example of an INFUSE Project with ORNL

generalfusion®

Project: Magnetohydrodynamic (MHD) simulation of General Fusion devices

Need: Large scale calculations of kinetic electron orbits in fusion plasmas. These tools will enable a powerful approach to efficient modelling of General Fusion's Magnetized Target Fusion (MTF) devices

Results: in progress (initiated in 2022)

INFUSE