Beyond the Headlines: A Path to Practical Fusion Power

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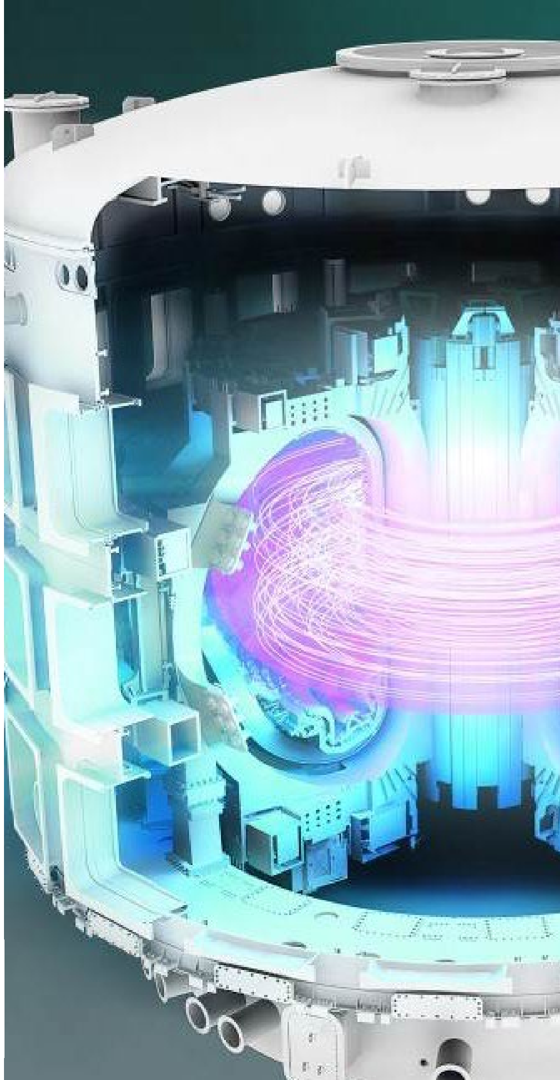
US iter

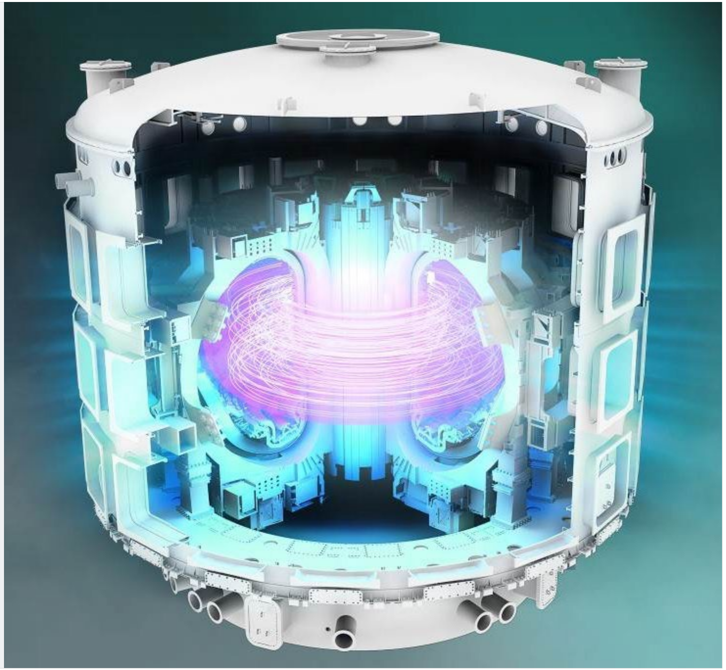
U.S. DEPARTMENT OF ENERGY | Office of Science
OAK RIDGE National Laboratory
PPPL PRINCETON PLASMA PHYSICS LABORATORY
Savannah River National Laboratory



Outline

- Fusion Basics
- Understanding Fusion News
- Challenges for Fusion (and pressure vessel equipment)
  - Fusion environment
  - High precision components
  - 3 main technical challenges
- Current Public and Private Activities in Fusion

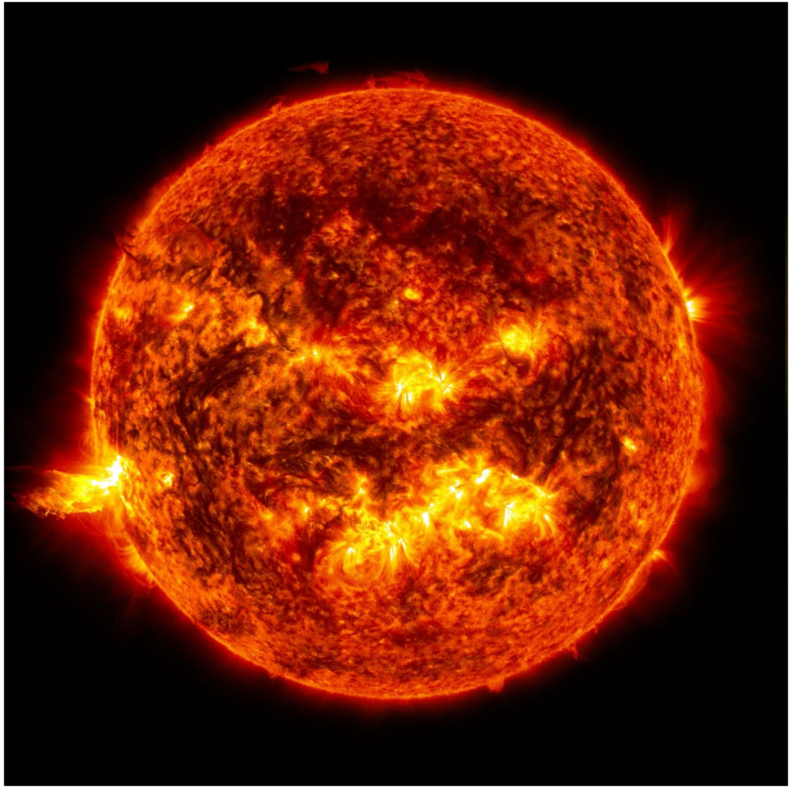
Fusion Basics



The Sun is an impressive fusion reactor

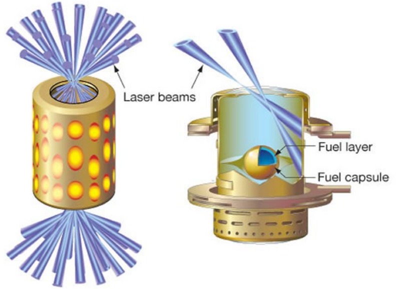
- **Fusion** is the process that powers the Sun and the stars, releasing energy that makes life on Earth possible.

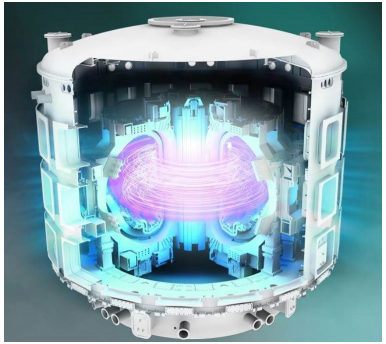
- By confining hot plasma created by heating hydrogen atoms, it is possible to create an artificial star to produce abundant energy that can be converted into electricity.

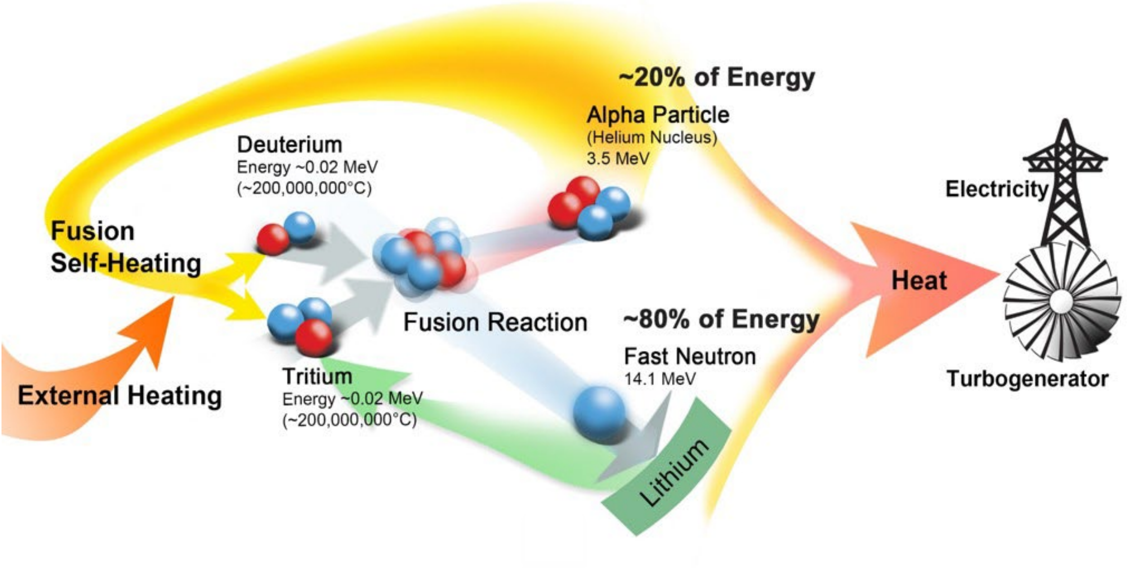


Credit: NASA

Deuterium-Tritium (DT) fusion reaction & energy flow







Goal: Deliver abundant, carbon-free, safe carbon-free baseload power at large scale

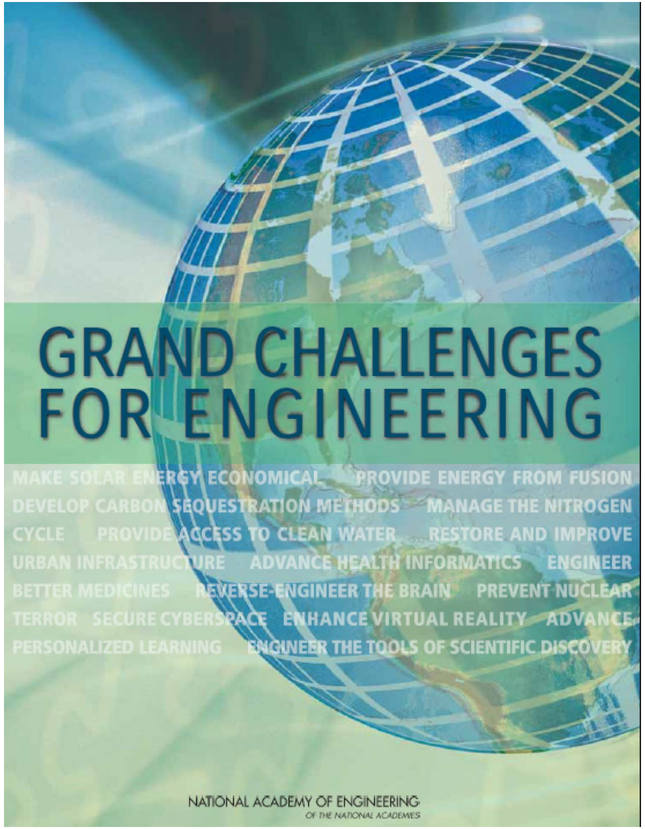
Fuel fuel is plentiful worldwide

IAEA

"**Fusion fuel is plentiful and easily accessible**: deuterium can be extracted inexpensively from seawater, and tritium can potentially be produced from the reaction of fusion generated neutrons with naturally abundant lithium. **These fuel supplies would last for millions of years**. Future fusion reactors are also intrinsically safe and are not expected to produce high activity or long-lived nuclear waste. Furthermore, as the fusion process is difficult to start and maintain, there is no risk of a runaway reaction and meltdown; fusion can only occur under strict operational conditions, outside of which (in the case of an accident or system failure, for example), the plasma will naturally terminate, lose its energy very quickly and extinguish before any sustained damage is done to the reactor."

Matteo Barbarino, IAEA Department of Nuclear Sciences and Applications August 2023
https://www.iaea.org/newscenter/news/what-is-nuclear-fusion

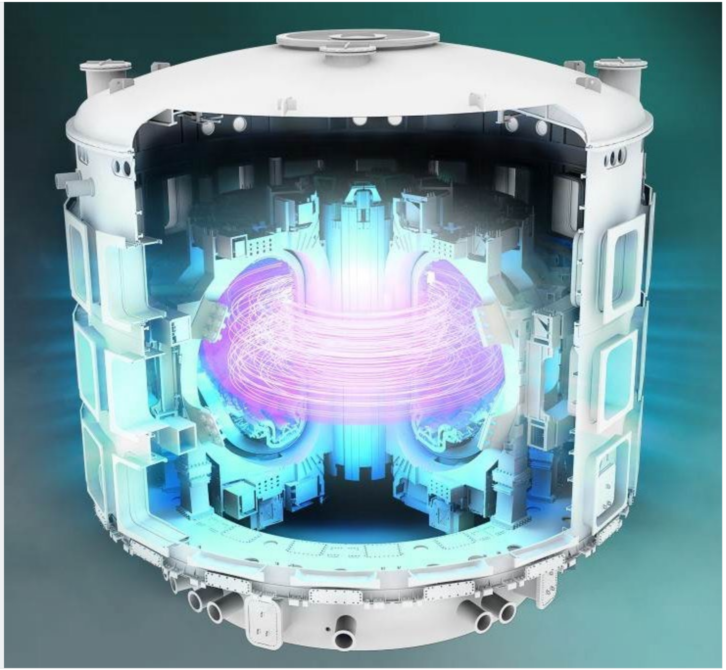
National Academy identified fusion as a 21st century grand challenge for engineering



Deliver Energy from Fusion

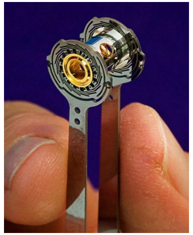
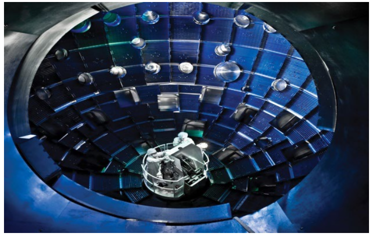
"Human-engineered fusion has already been demonstrated on a small scale. The challenges facing the engineering community are to find ways to scale up the fusion process to commercial proportions, in an efficient, economical, and environmentally benign way."

Understanding Fusion News

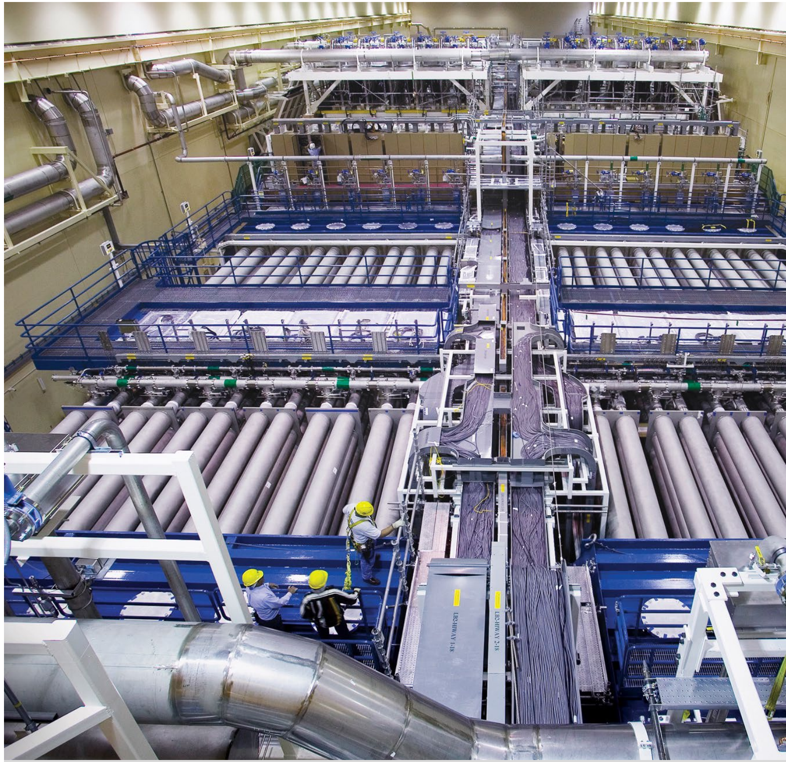


NIF is an inertial confinement approach to fusion
Ignition demonstrated first time in 2022 and again in 2023

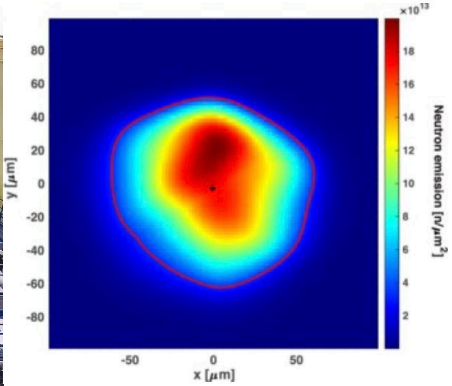
- National Ignition Facility (NIF), Lawrence Livermore National Lab
- Approach: Inertial confinement, laser-driven, DT fuel capsule

NIF Target (l) and target chamber. Credit: LLNL



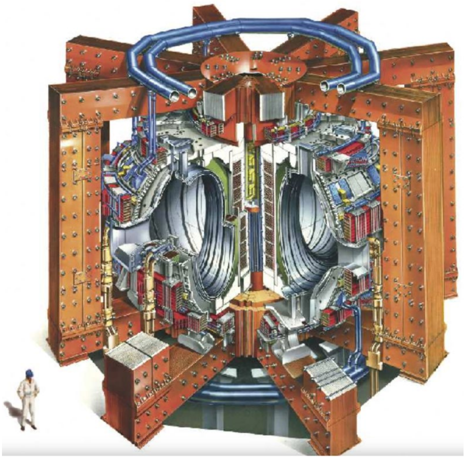
National Ignition Facility Laser Bay at Lawrence Livermore National Laboratory. Credit: LLNL

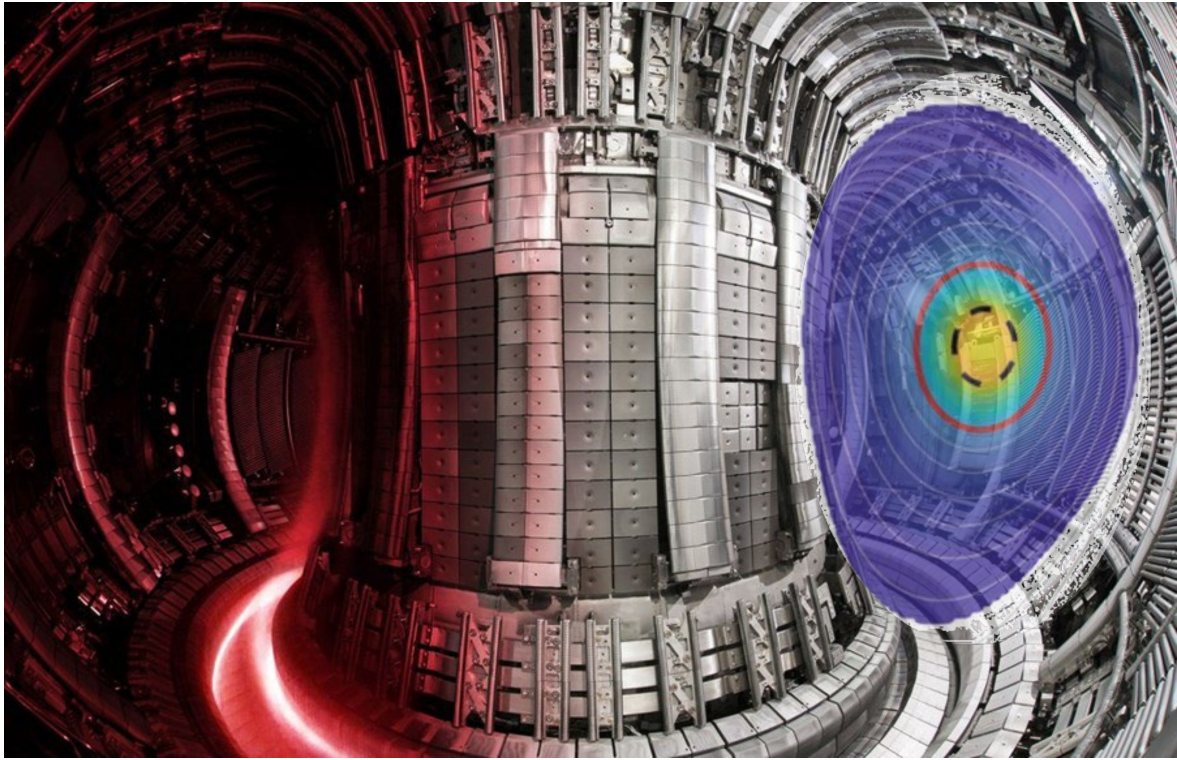


D. N. Fittinghoff, N. Birge, and V. Geppert-Kleinrath, “Neutron imaging of inertial confinement fusion implosions,” Rev. Sci. Instrum. 94, 021101 (2023)

New fusion energy record achieved at JET tokamak (UK) in 2023

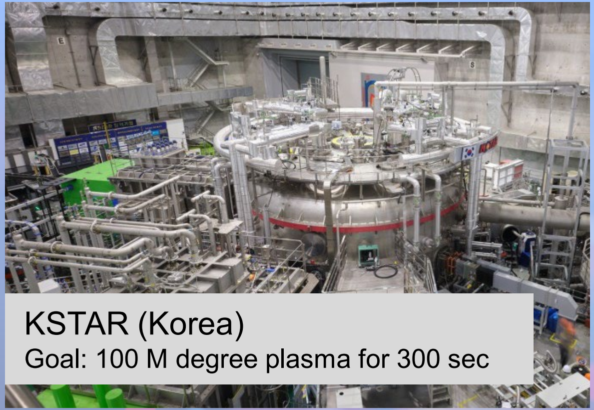
- 69 megajoules of sustained fusion energy for ~6 seconds (Oct. 3, 2023)
- Approach: Tokamak, magnetic confinement, Deuterium-Tritium (DT) fuel



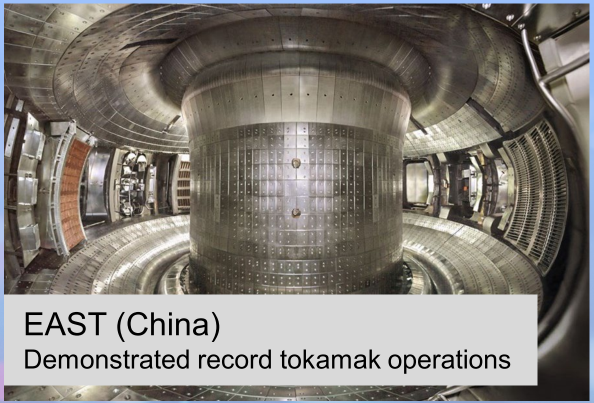


Fusion machines around the world are producing new results and records

JT60-SA (Japan)
Now world's largest operating tokamak



KSTAR (Korea)
Goal: 100 M degree plasma for 300 sec



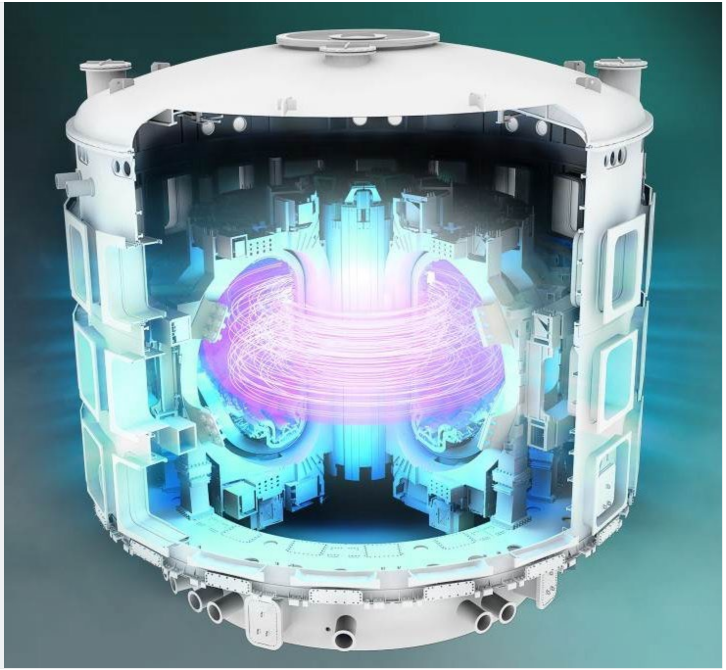
EAST (China)
Demonstrated record tokamak operations

Wendelstein 7-X (Germany)
Stellarator achieved record energy turnover

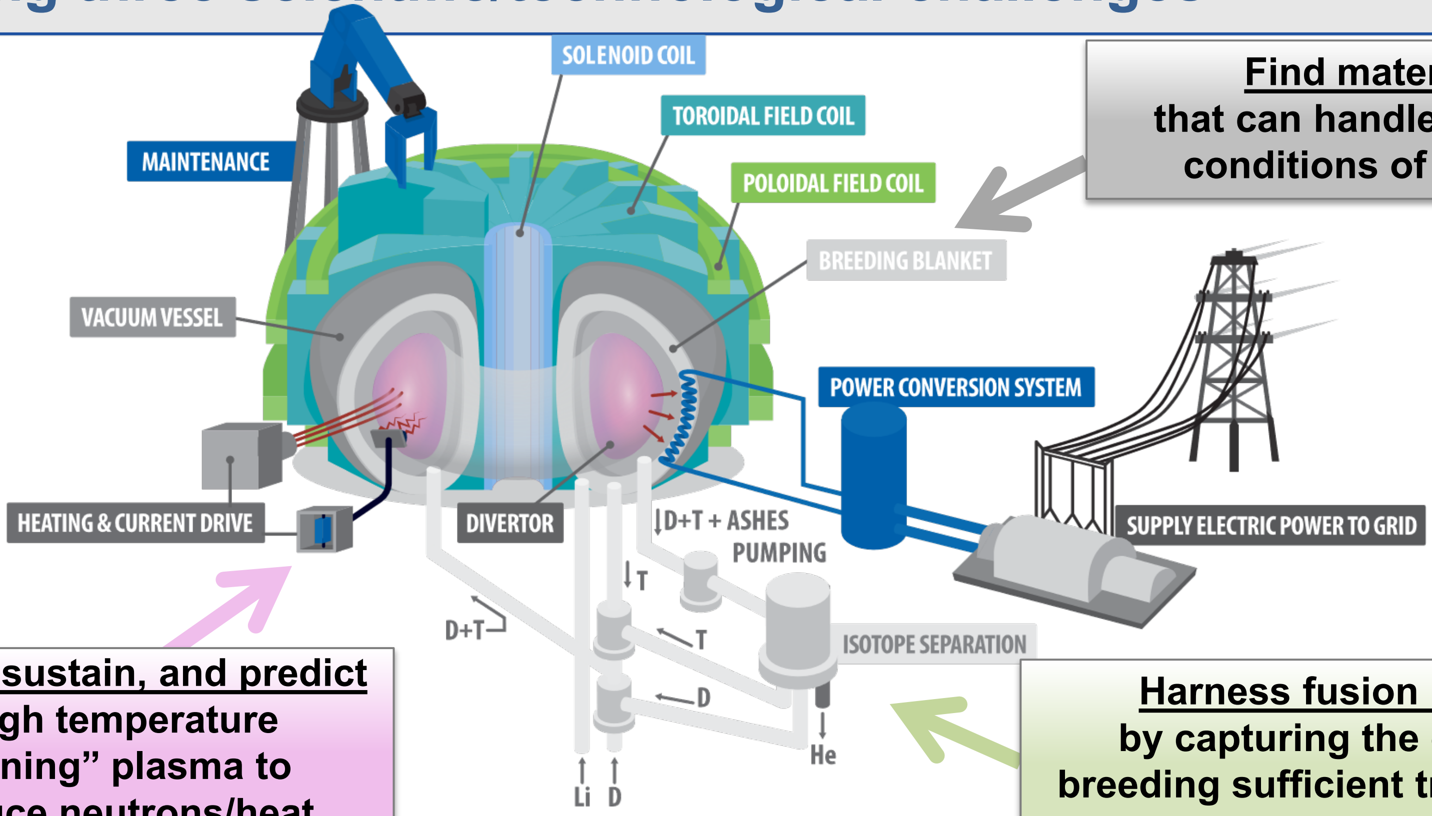
ITER (France)

Now under assembly with international partners:
EU (host), China, India, Japan, Korea, Russia and the US

Challenges for Fusion



Generating electricity from fusion energy requires meeting three scientific/technological challenges



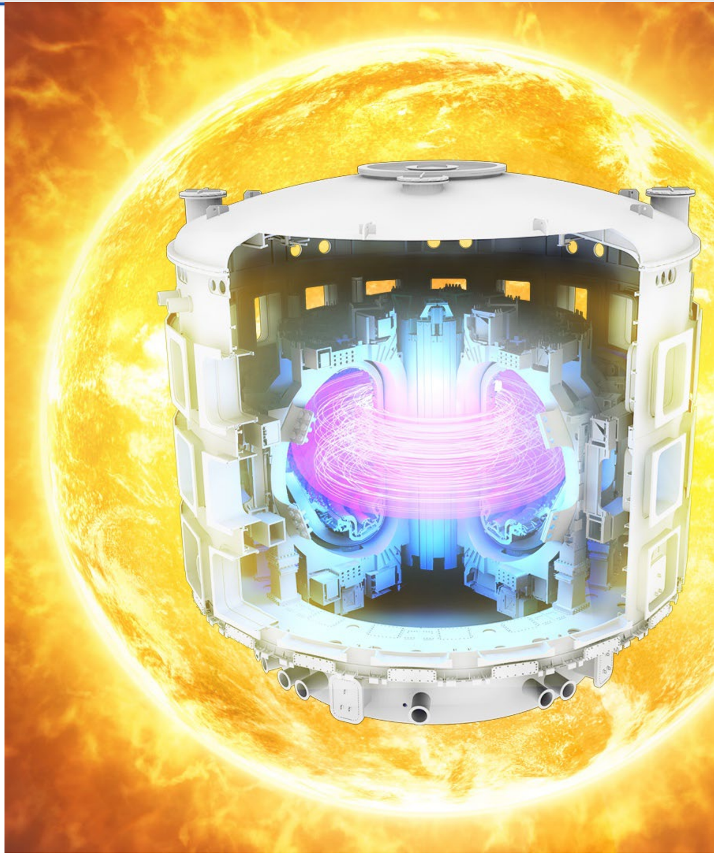
Find materials that can handle extreme conditions of reactor

Control, sustain, and predict a high temperature “burning” plasma to produce neutrons/heat

Harness fusion power by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

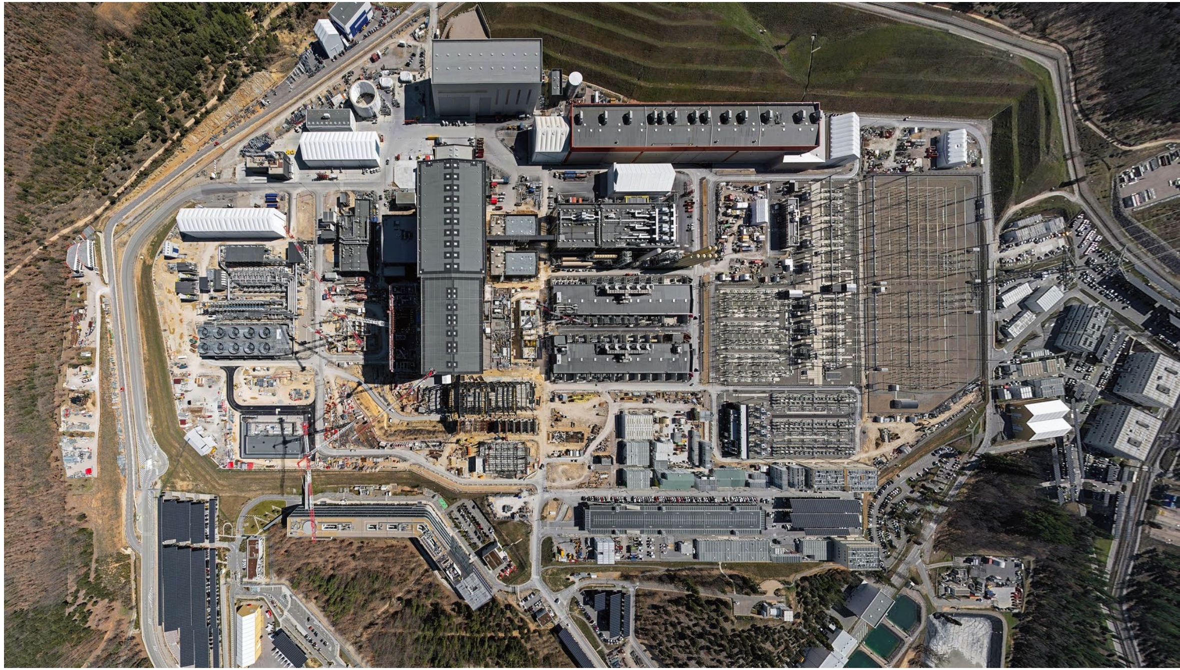
ITER will deliver a unique fusion experience

- **Fusion gain** up to a Q of 10 (10x power out)
- **Fusion power** up to 500 MW
- **Duration** of 400 seconds at high power or 3,000 seconds at lower power
- **DT fuel cycle** with testing of closed-cycle fuel production
- **Industrial-scale** fusion systems integration and operations
- **Licensing** to demonstrate safety features for a licensed fusion power plant

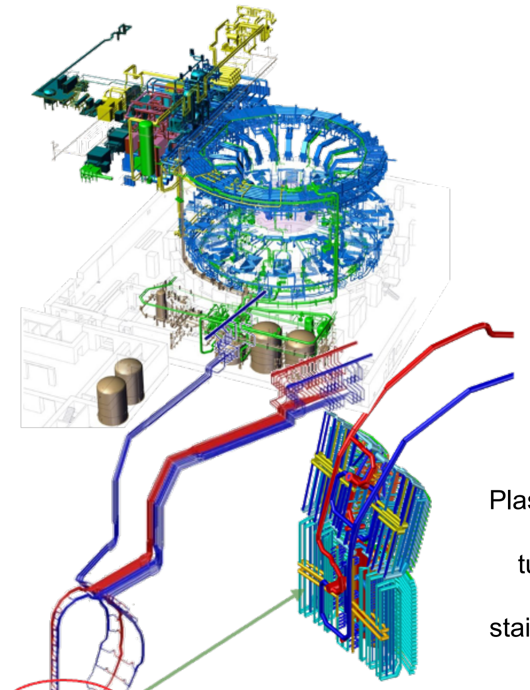


ITER will provide exceptional resources as an R&D facility

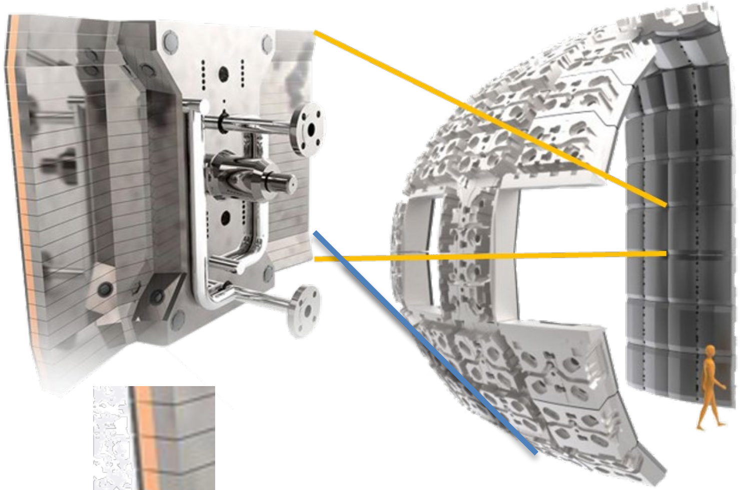
- Flexible operations to address different plasma scenarios and fusion configurations
- Long durations to aid operational studies
- Extensive diagnostics to measure performance
- Expertise to support industrial R&D needs

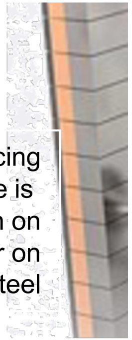


Components for 1000 MW tokamak heat removal water cooling system provided by US ITER



S. Kim, et al., *Draining and Drying Process Development of the Tokamak Cooling Water System of ITER, Fusion Engineering Design* 109-111 (2016) 272-277.



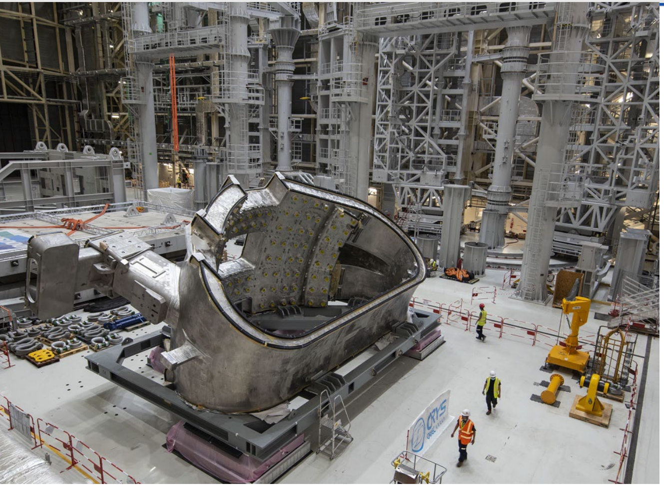


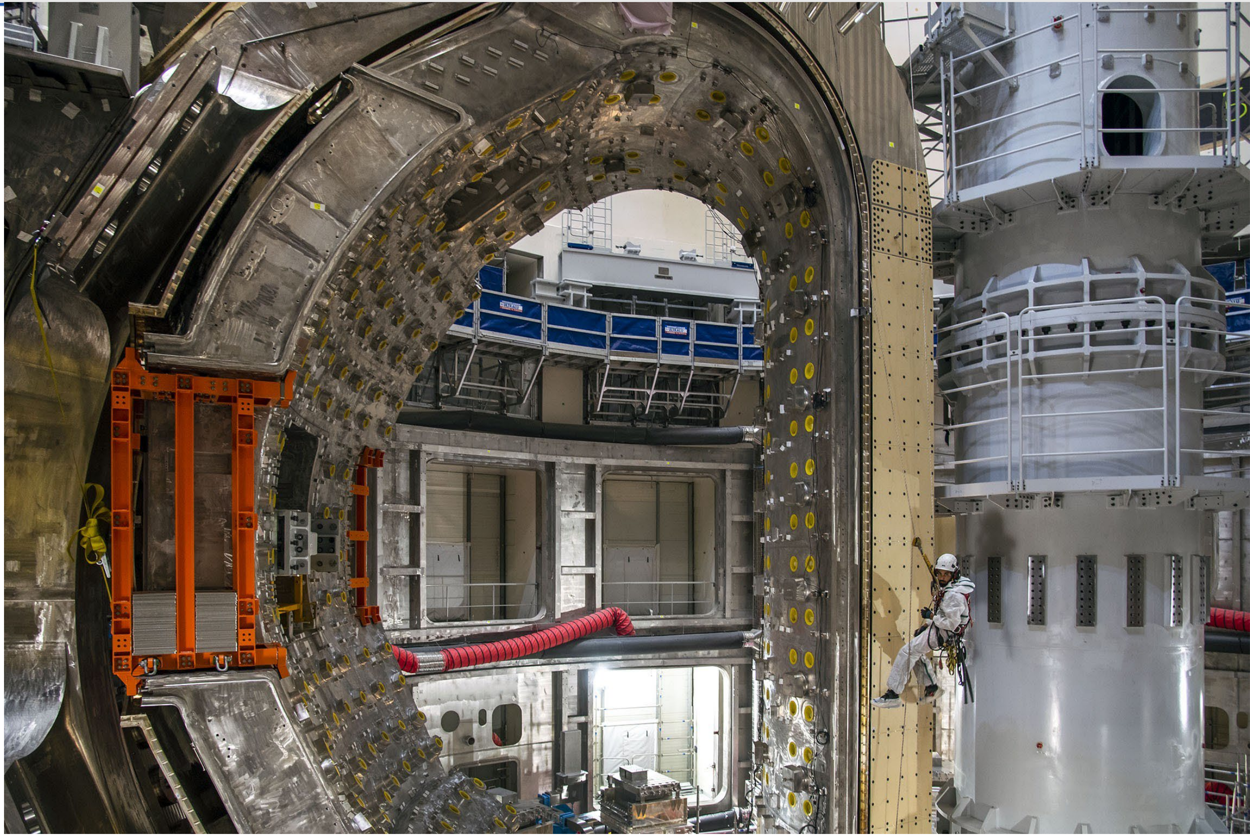
Plasma facing surface is tungsten on copper on stainless steel

Condenser core

Tank for pressurized nitrogen drying system

ITER vacuum vessel sectors

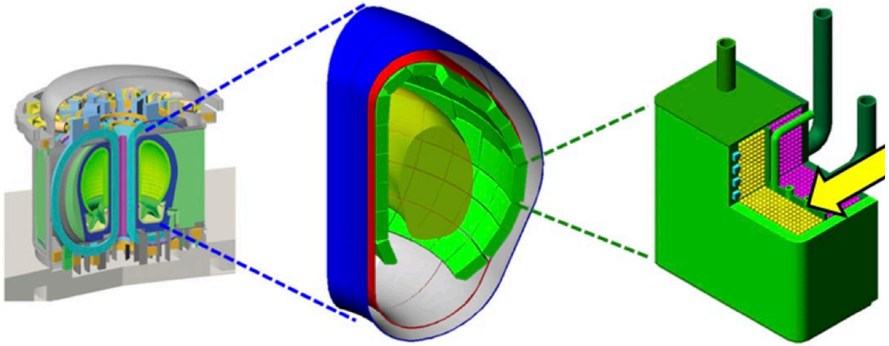




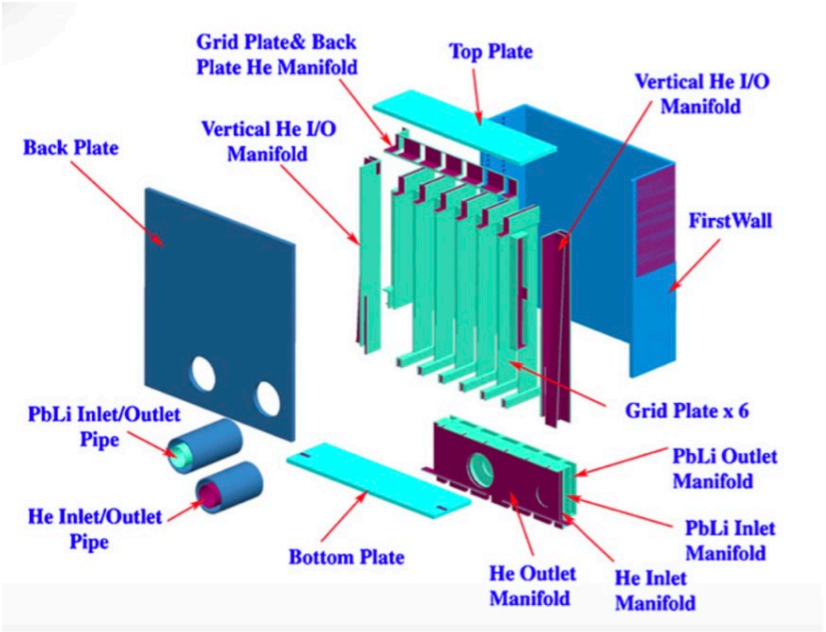
Vacuum vessel vectors in the ITER assembly hall and tokamak pit.

ITER cryogenics plant

Disciplines involved in blanket design

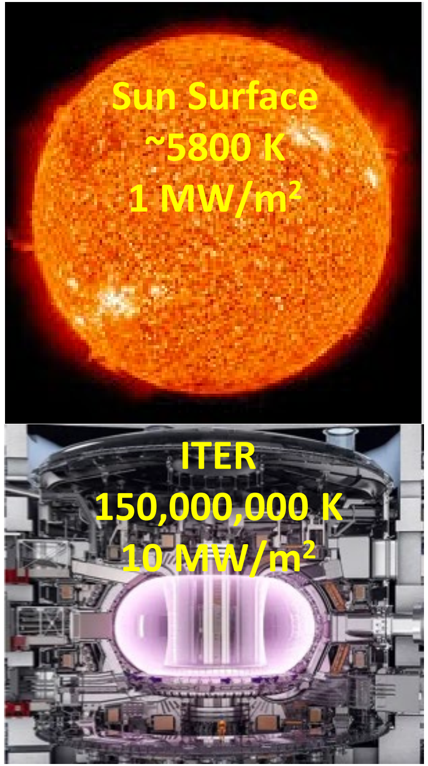


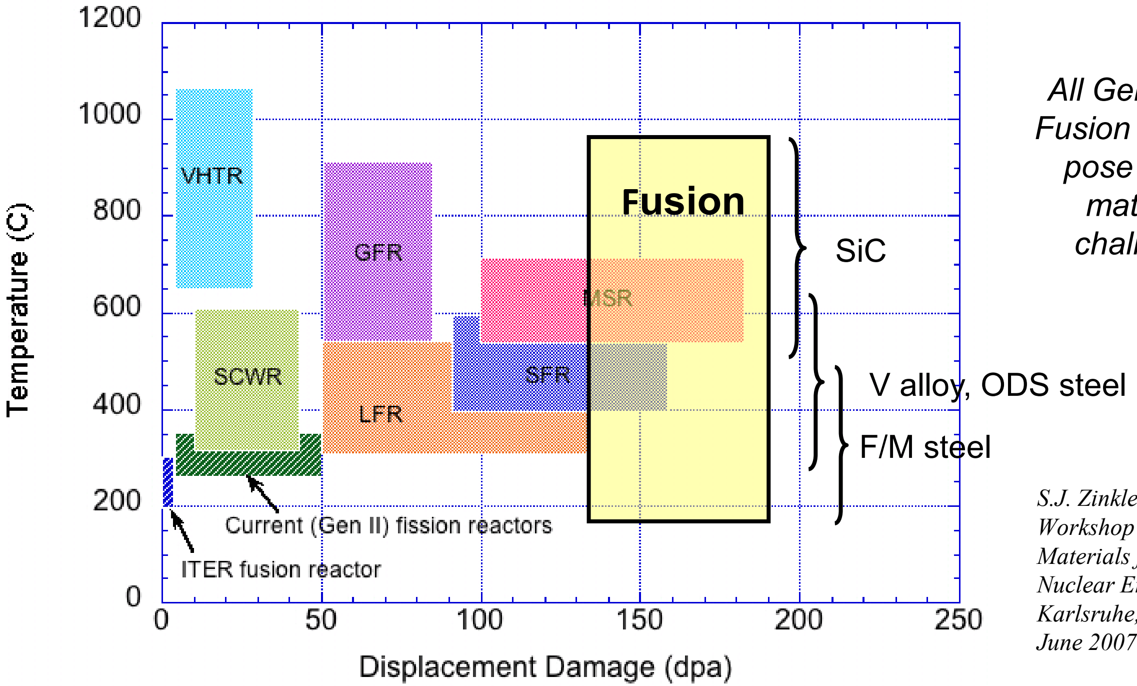
- Thermo-mechanics
- Computational fluid dynamics
- Thermal hydraulics
- Edge plasma physics
- Tritium migration
- Liquid metal MHD
- Materials and manufacturing
- Transients
- Nuclear analysis
- Fusion design codes



C. E. Kessel ORNL 2020

Fusion structural materials will face the most extreme environments imaginable

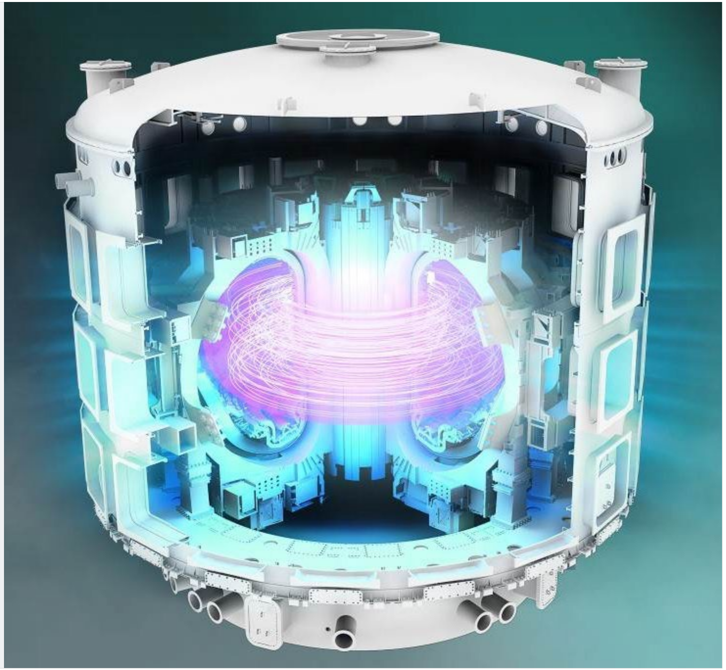




All Gen IV and Fusion concepts pose severe materials challenges

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

Current Activities in Fusion



Public and private activities are underway, including licensing development

U.S. DEPARTMENT OF ENERGY

THE WHITE HOUSE
WASHINGTON

The National Academies of SCIENCES ENGINEERING MEDICINE

INFUSE Program
Innovation Network for Fusion Energy

Bold Decadal Vision
Milestone-based Fusion Development Program

University Fusion Association

Oak Ridge National Laboratory

PPPL Princeton Plasma Physics Laboratory

INL Idaho National Laboratory

Sandia National Laboratories

U.S.NRC

Berkeley Lab

Los Alamos National Laboratory

Savannah River National Laboratory®

Fusion Industry Association

Private fusion interest has accelerated

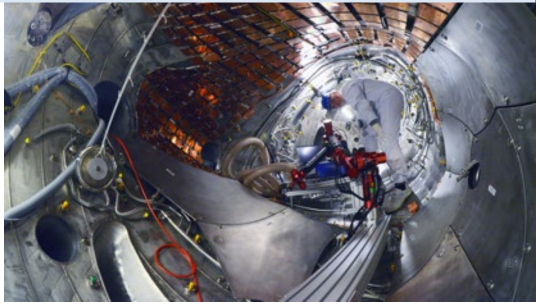
- >$6B in global private investment to date
- >20 companies in US alone
- Variety of fusion concepts
- Some energy-focused; some technology-focused

Fusion Industry Association

Commonwealth Fusion Systems · General Fusion · Zap Energy · Helion · TAE · Type One Energy · Focused Energy · Tokamak Energy · Fuse · Renaissance Fusion · Nearstar Fusion · Proxima Fusion · Horne Technologies · NK · HB11 Energy · Gauss Fusion · EX-Fusion · nT-tao Compact Fusion Power · Thea Energy · LPP Fusion · Realta Fusion · Princeton Satellite Systems · First Light · Avalanche · Helical Fusion · Stellarex · SHINE · MIFTI · Novatron · LaserFusionX · Kyoto Fusioneering · Xcimer Energy Corporation · Marvel Fusion · Helicity Space · Blue Laser Fusion · Electric Fusion Systems · Longview Fusion

Diverse fusion approaches continue to be developed in public and private sectors

Stellarator



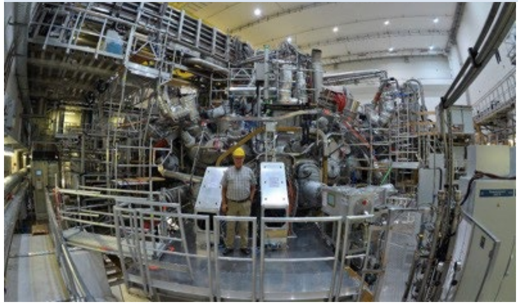
Wendelstein 7-x | IPP Max Planck

Compact Spherical Tokamak

NSTX-U | PPPL

MAST | CCFE

Magneto-inertial Configurations



LANL | PLX

High-field Tokamak

SPARC | MIT/Commonwealth Fusion

ST40 | Tokamak Energy

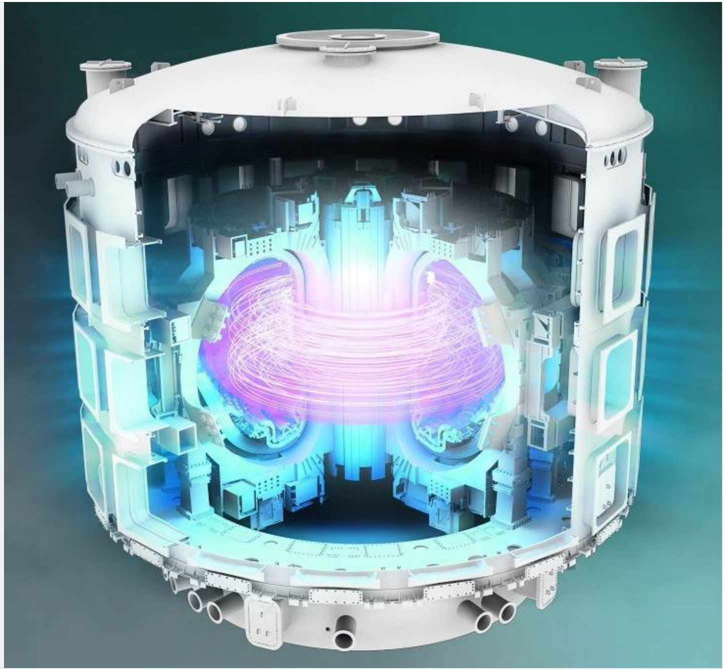
Reverse-Field

Norman | TAE Technologies

Magnetized Target

Plasma Injector | General Fusion

Summary



Other areas must also be addressed before fusion electricity can be a reality

- Supply chain development
- Workforce development
- Development of social license
- Economic viability
- Safety and regulatory certainty
- Utility integration into market