# Materials in fusion energy systems

*and*

# a little on CFS

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*with inspiration from*

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*MIT Plasma Science and Fusion Center*

Commonwealth Fusion Systems

# Something about how I got here

I'm a nuclear materials scientists by training, not a fusion physicist, but making fusion energy real takes all kinds.

Maine, USA

BS, Engineering Physics, Cornell University

SM, Materials Science and Engineering, MIT

PhD, Nuclear Science and Engineering, MIT

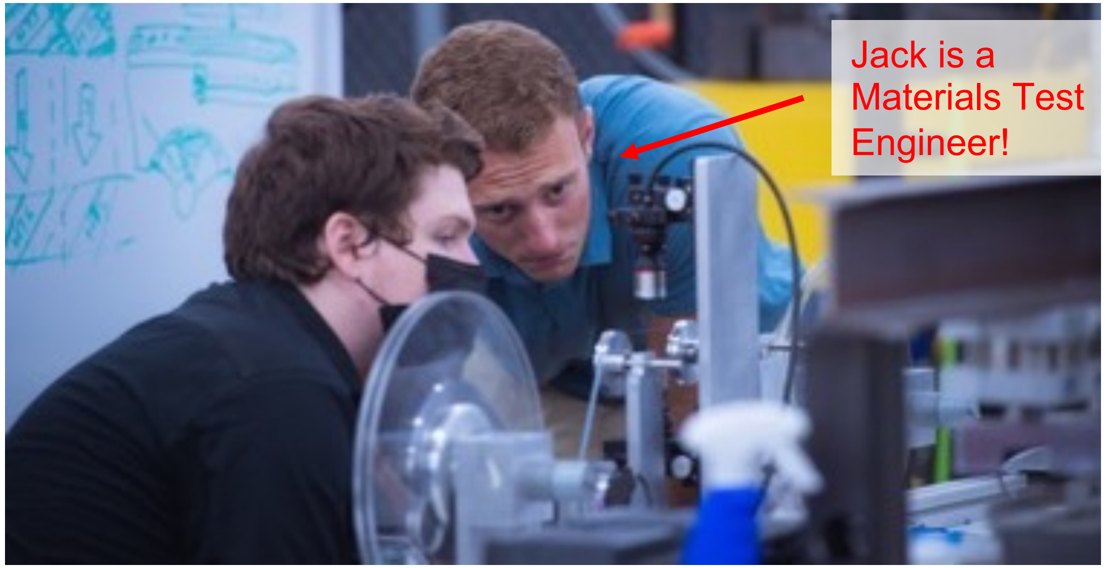
Visiting Researcher, Sandia National Laboratories

Materials Scientist, Idaho National Laboratory

Head of Materials, Commonwealth Fusion Systems

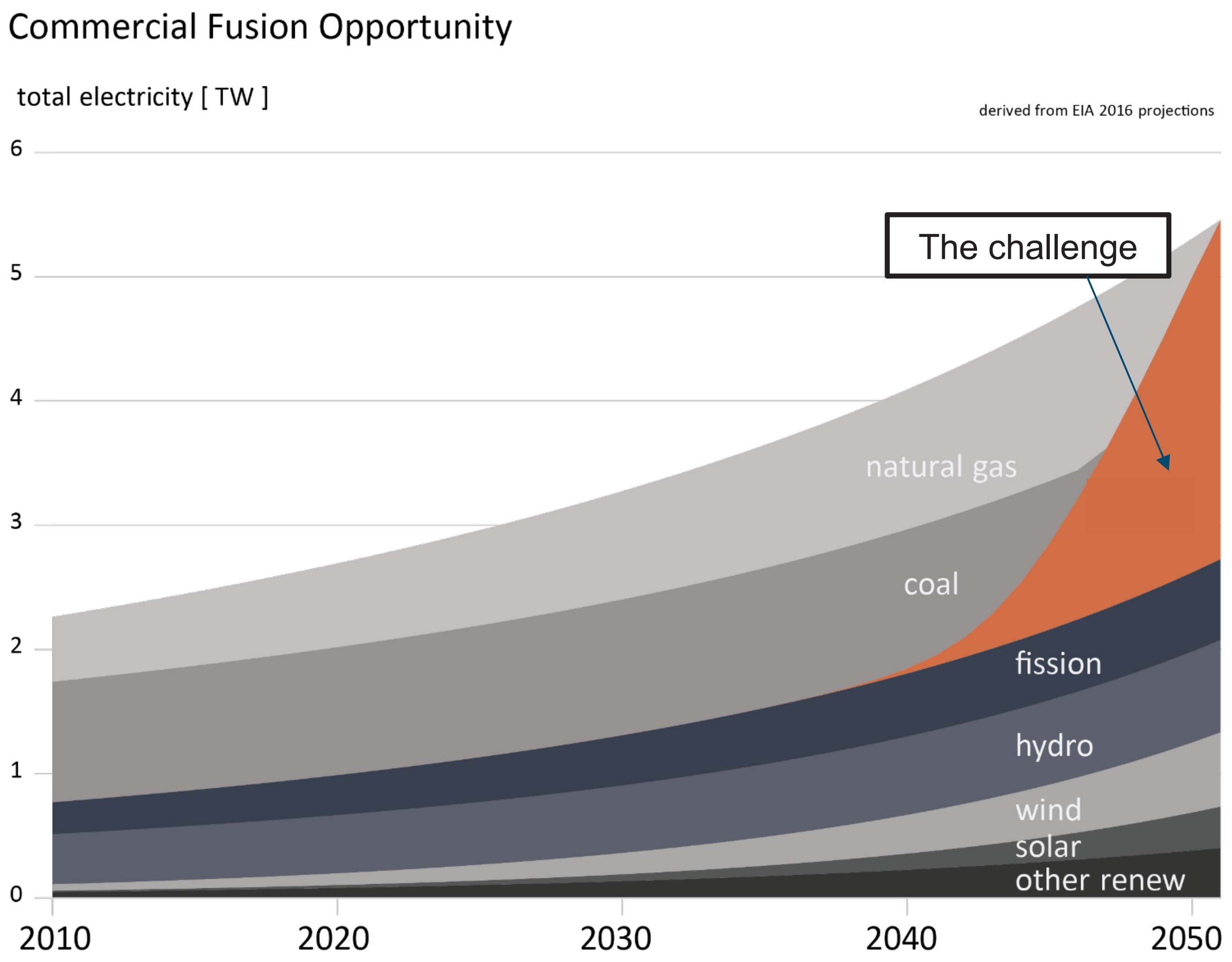
# CFS on a path to deliver commercial fusion energy

- CFS was founded in 2018, spun out of MIT
- Raised more than $2 billion from a diverse group of investors
- Built a high caliber, diverse team
- Now >500 employees




# The world needs a new clean energy technology

- Largest problem and opportunity facing humanity
- Largest industrial transformation in history
- Innovation at the generation source is highest leverage



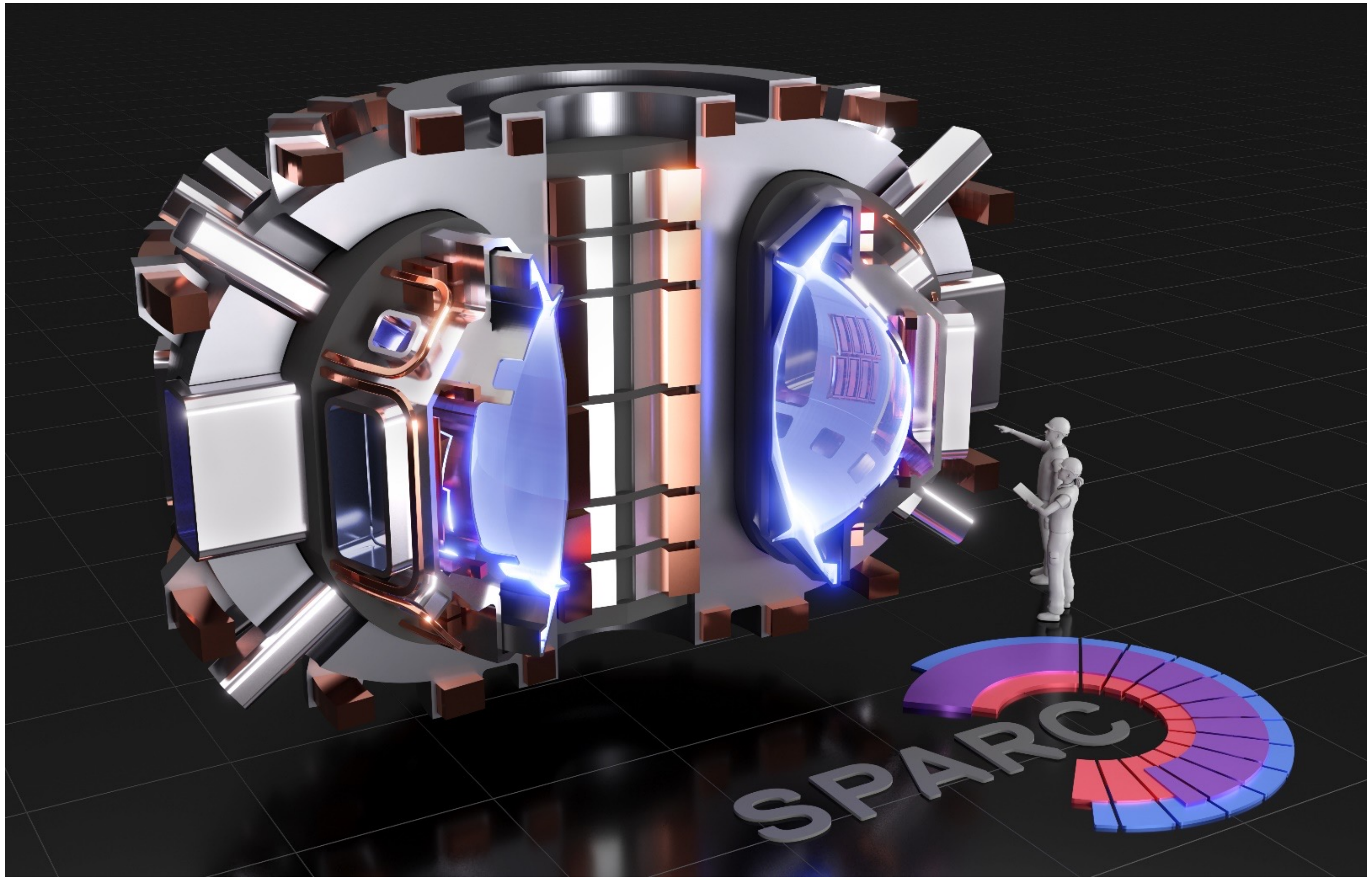
# CFS proprietary magnets unlock new fusion path

- CFS invented world's strongest High Temperature Superconductor (HTS) magnet
- Designed and built it in 3 years, demonstrated 20 Tesla
- Power plants can be >40x smaller, faster, and much lower cost

toroidal field model coil (TFMC) test in partnership with MIT

# SPARC will be the first commercially relevant fusion machine

- **Validated approach**
  peer reviewed publications
- **Demonstrated technology**
  world's strongest HTS magnets
- **Accelerated construction**
  we are building it now



Creely et al. J. Plasma Phys. 85 (2020)

# Construction of SPARC and magnet factory in Devens, MA

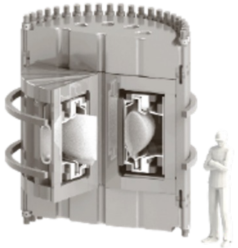

# Risk retirement in concrete steps

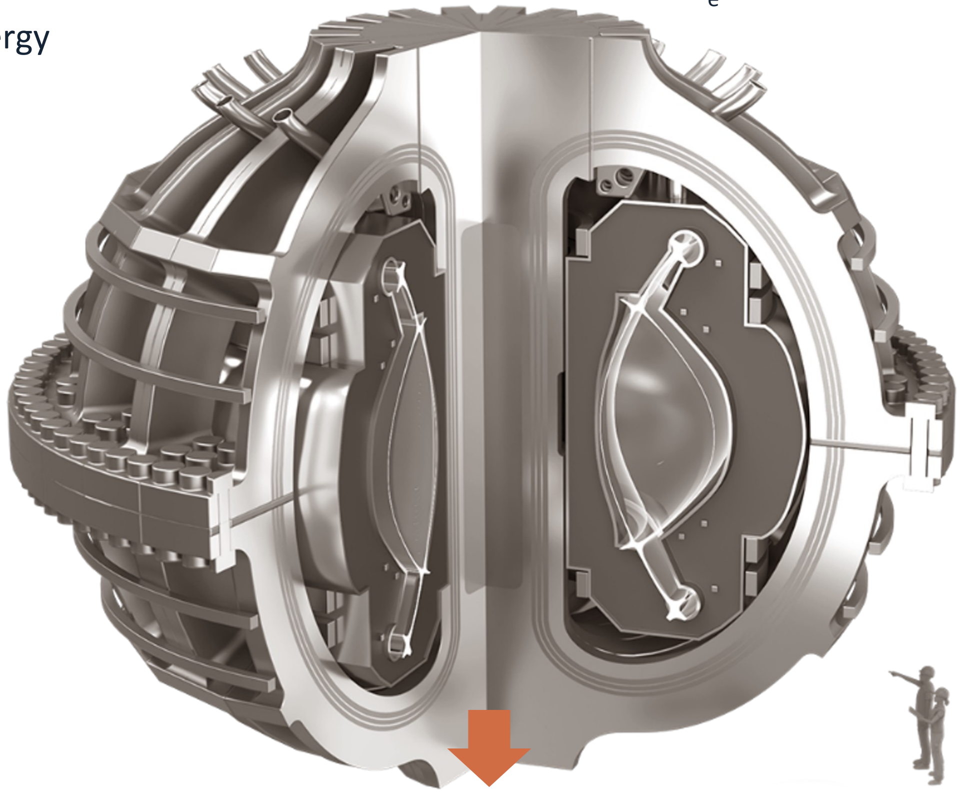
COMPLETED:
Alcator C-Mod
Record-setting
tokamak

COMPLETED:
Demonstrate groundbreaking
HTS magnets

CONSTRUCTION UNDERWAY
for 2025 LAUNCH:
SPARC Q>1
Achieve net fusion energy

EARLY 2030s:
ARC deployed
~400 $MW_e$





Commercially-relevant net fusion energy for the first time

Carbon-free commercial power on the grid

# The materials team at CFS

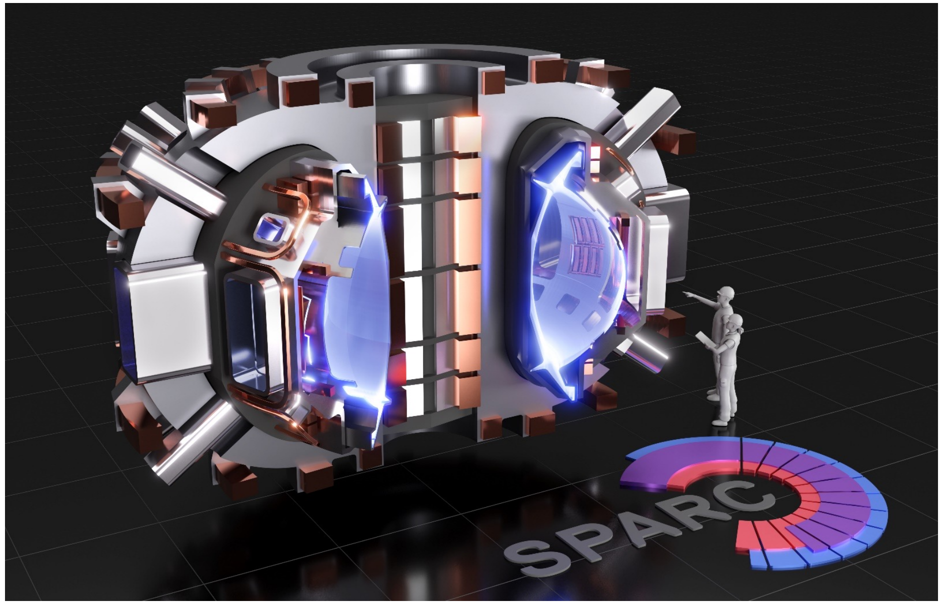
| MATERIALS RESEARCH | MATERIALS DEVELOPMENT | MATERIALS ENGINEERING |
|---|---|---|
| • How do materials perform and evolve in the operational conditions of a fusion power plant?<br>• Radiation effects, plasma sputtering and erosion, transmutation and activation, etc.<br>• We design programs, often with large national and international partners, to answer some of these questions as ARC is being designed | • For SPARC and ARC, how do we optimize material selections once we understand evolution/performance behaviors?<br>• Once selections are made, solutions need to be scaled up in manufacturing and production to meet current and future needs | • Support for design engineers in selecting materials for their systems<br>• Identification of relevant specification and testing standards, confirmation with vendors that products meet specification<br>• Support testing to confirm performance in relevant conditions<br>• Iterative failure analyses during development |

All this is done by actual humans!

*Lauren, Emily, Cody, Trevor, Deepthi, Dina, Drew, Jack, Taylor, and Polina*

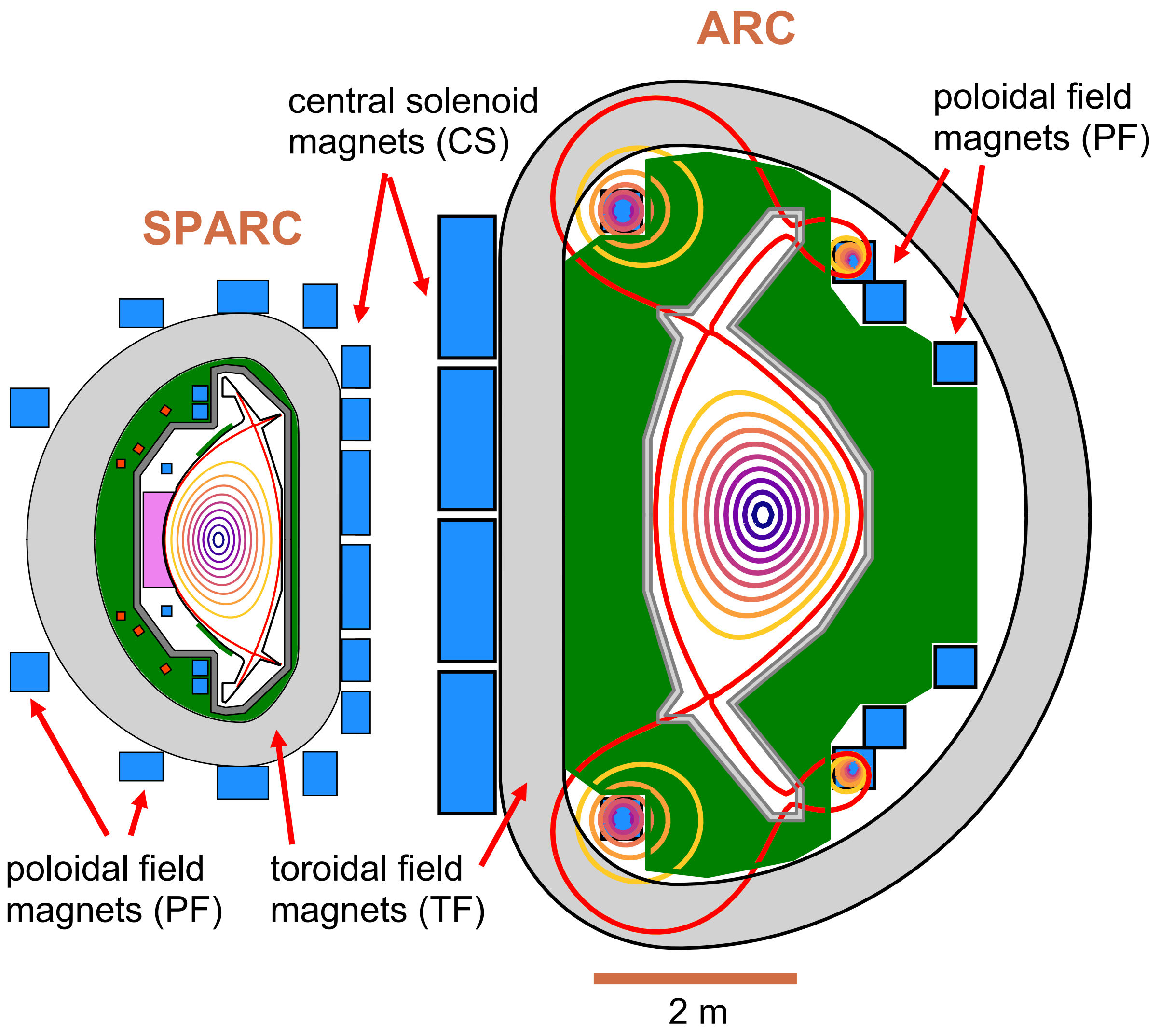
# SPARC validates key aspects of design for a commercially-relevant fusion power plant

- SPARC's mission is to achieve net energy (Q>1) by 2025 and will produce over 100 $MW_{th}$ of heat, but this heat will not be captured and used
- In order to build the smallest, fastest, and least expensive machine to do this, SPARC does not have all the features of a full power plant



# SPARC has been designed to de-risk ARC for the majority of subsystems

- 13 of the 17 major sub-systems in ARC are de-risked by successful SPARC operation
- Core tokamak is roughly 2x larger in ARC from SPARC
- Major technical gaps NOT closed by SPARC include:
  - Blanket systems with molten salt working fluid
  - **High, steady-state operation of materials under plasma and radiation exposure**
  - Balance of plant

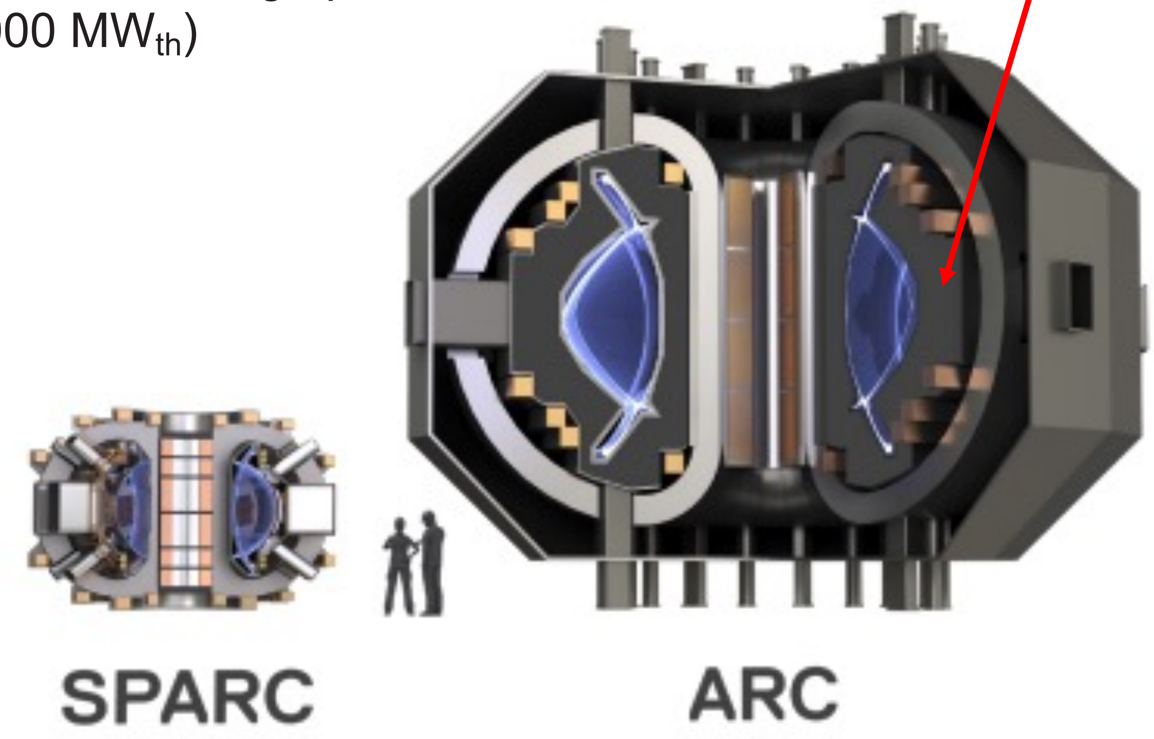


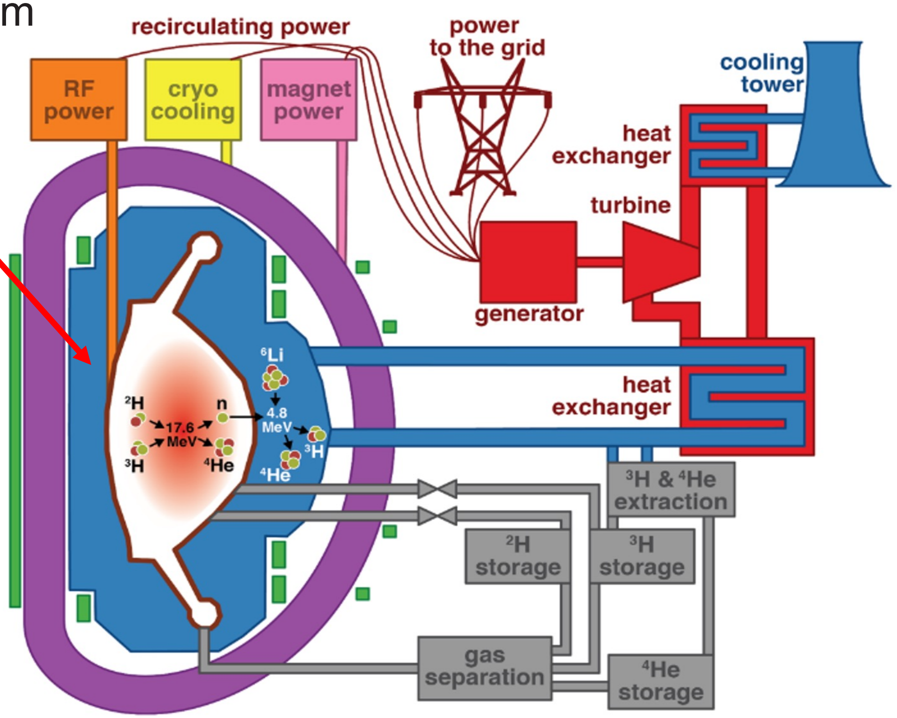
# A key technological difference between SPARC and ARC tokamaks is the blanket system to convert fusion power to heat

**Other key features:**

- Replaceable core internal components do not define plant lifetime
- Gaseous tritium reprocessing
- ~200-450 $MW_e$ design point ($500\text{-}1000\ MW_{th}$)

high temperature molten salt (FLiBe) liquid immersion blanket to capture heat and breed tritium



# The fusion environment combines extreme factors, placing stringent demands on materials selection

- Materials inside a fusion power plant will have to withstand combined extremes not realized in other applications:
  - High baseline operating temperatures
  - Neutron radiation damage
  - Neutron activation
  - Plasma exposure
  - Neutron transmutation + gas generation
  - High transient heat fluxes
  - Corrosion from liquid molten salts
  - High magnetic fields
  - Cryogenic operation (magnet structures)
- Traditional engineering materials most often fail under these combined extremes

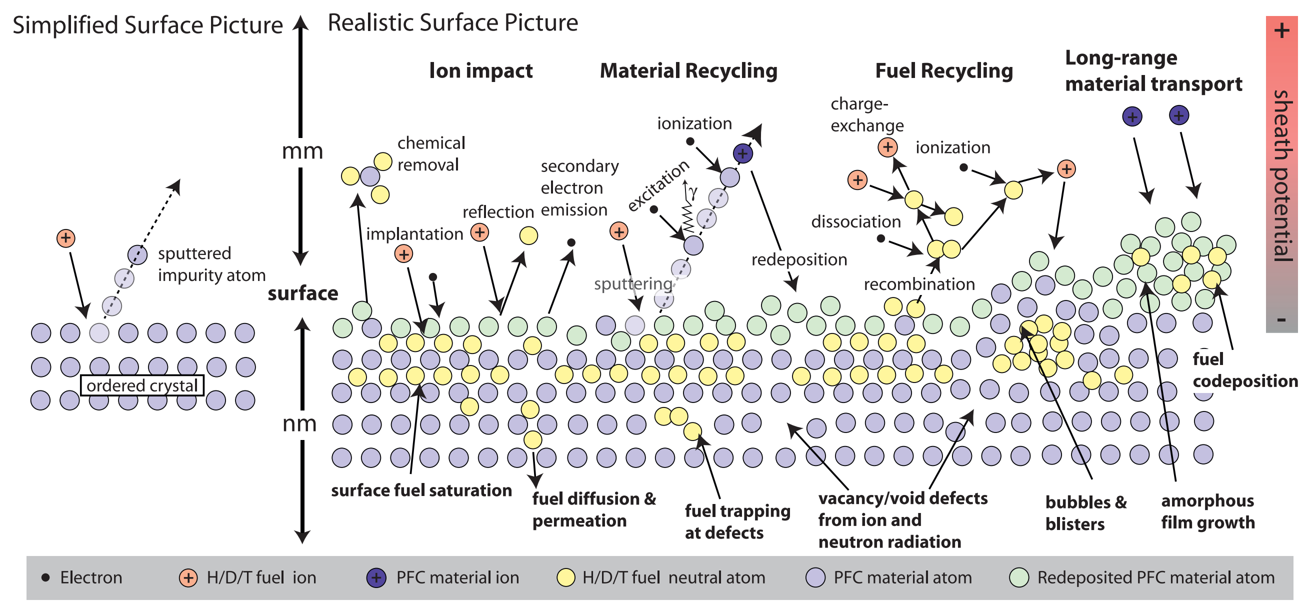
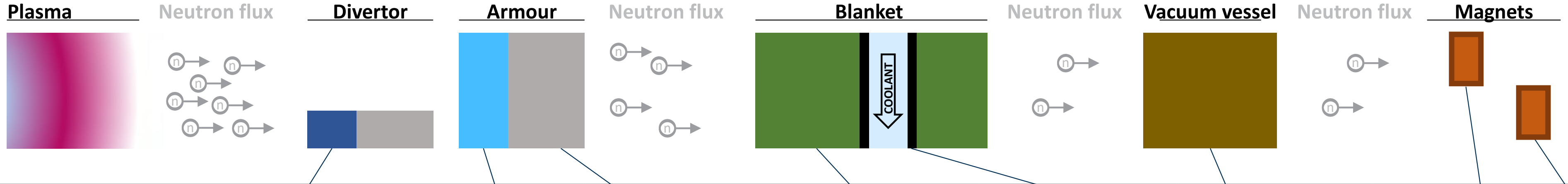



**Figure 1.** Schematic illustration of the complex, synergistic, and inherently multiscale surface interactions occurring at the material surface in a realistic magnetic fusion plasma environment. H, hydrogen; D, deuterium; T, tritium; PFC, plasma facing component; $\gamma$, gamma ray.

Wirth et al. MRS Bull. 36 (2011)

# Reference radial materials build for a DEMO-like fusion power plant

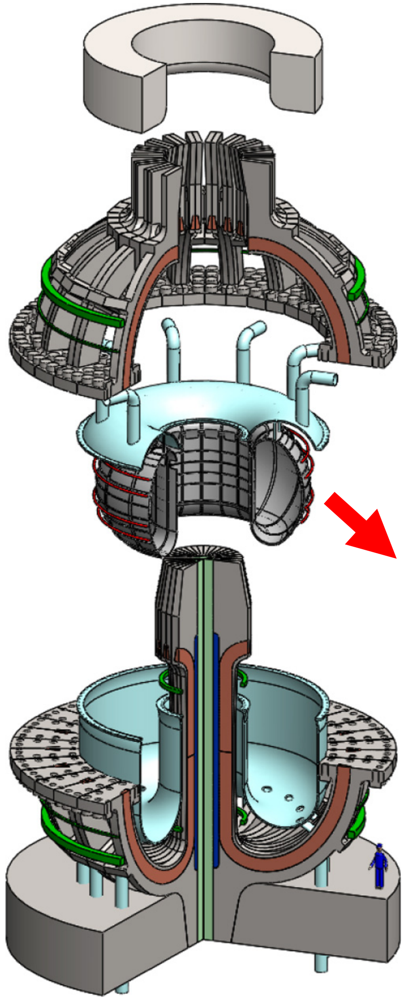



| Challenge | Divertor strike plate (detached divertors) | Armour surface | Armour substrate | Blanket breeder, multiplier and casing | Blanket cooling pipes | Vacuum vessel | Magnets |
|---|---|---|---|---|---|---|---|
| Neutron radiation | HIGH | VERY HIGH | HIGH | MEDIUM | MEDIUM | LOW | LOW |
| Temperature | VERY HIGH | YES | YES | MEDIUM | MEDIUM | NO | NO |
| Heat flux | HIGH | YES | YES | NO | NO | NO | NO |
| Magnetic stresses from coils | SOME | YES | YES | YES | YES | YES | YES |
| Corrosion | (IF ACTIVE COOLING) | NO | YES | YES | YES | (IF ACTIVE COOLING) | NO |
| Mechanical load | SOME | YES | YES | YES | YES | YES | YES |
| Helium generation | HIGH | HIGH | HIGH | MEDIUM | MEDIUM | LOW | NO |
| Cooling fluid pressure | NO | NO | YES | NO | YES | NO | NO |
| Plasma erosion | MEDIUM | YES | NO | NO | NO | NO | NO |
| Tritium absorption | YES | YES | LOW | YES | YES | LOW | NO |

UKAEA Fusion Materials Roadmap (2021)

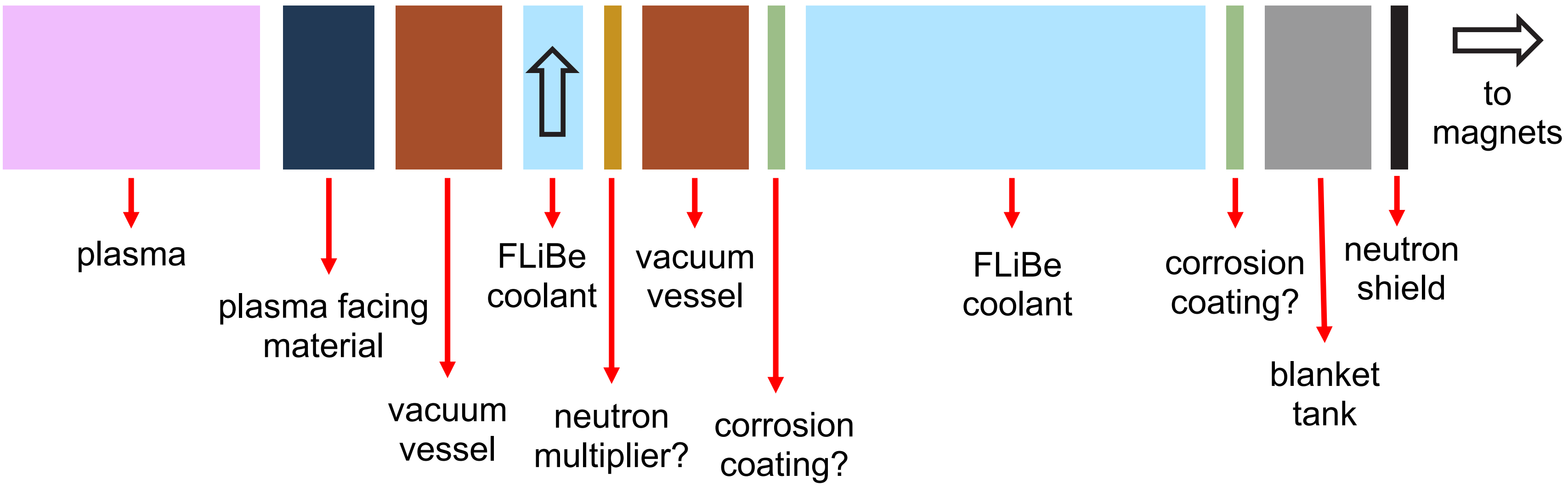
# Conceptual ARC outboard radial materials build

- Core internal components subject to harshest conditions designed to be replaceable and non-life-limiting
- From the fusion plasma outwards, the structural and functional material build is shown below
- Vacuum vessel must be conformal to the plasma and thermally and neutronically thin



Sorbom et al. Fus. Eng. Des. 100 (2015)

replaceable core internal components

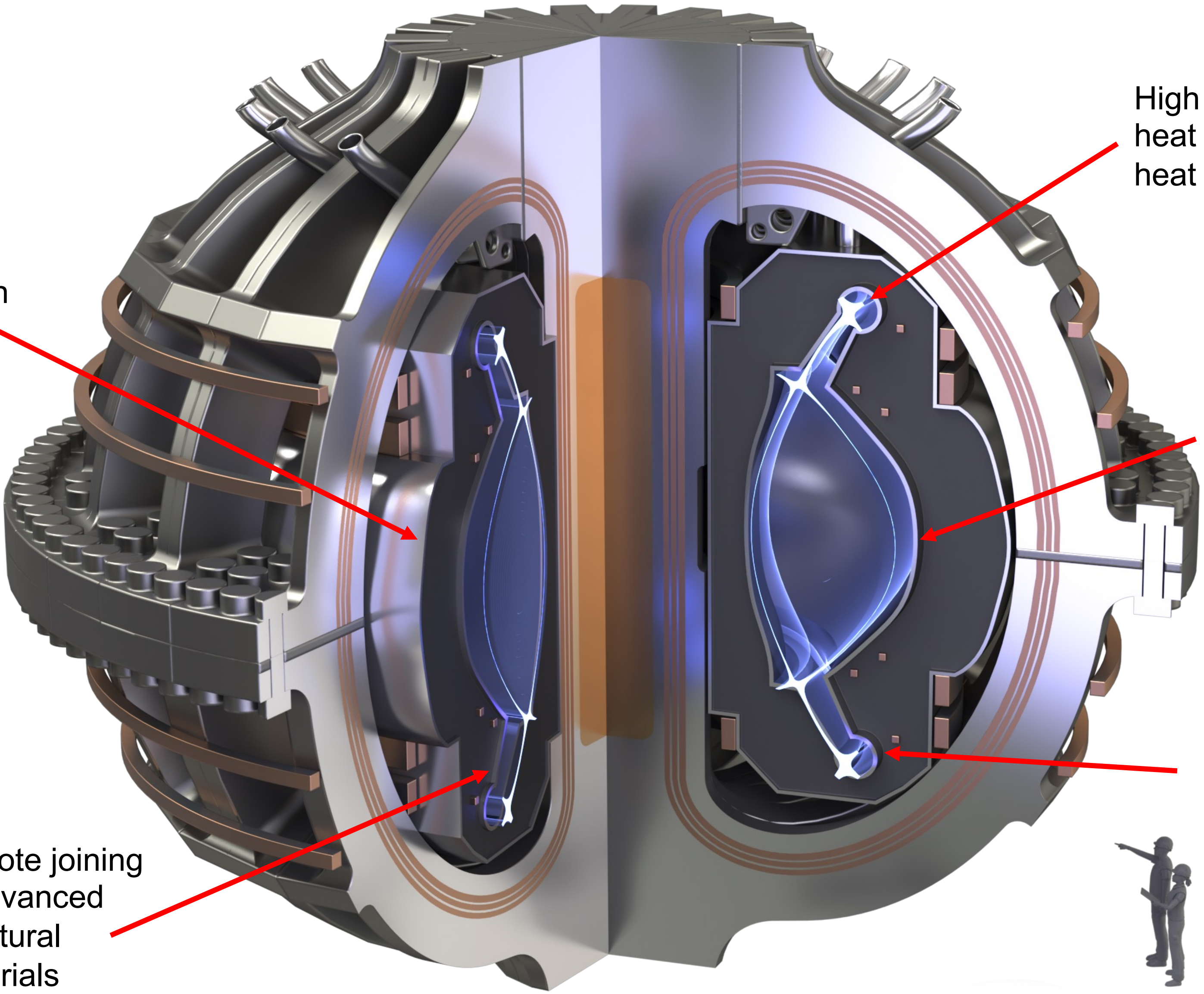


# ARC materials challenges

Corrosion mitigation and control from molten salt coolant

High particle and heat flux divertor heat exhaust

High temperature structural materials with high dose radiation effects



Monolithic joining of refractory plasma facing materials to structural materials

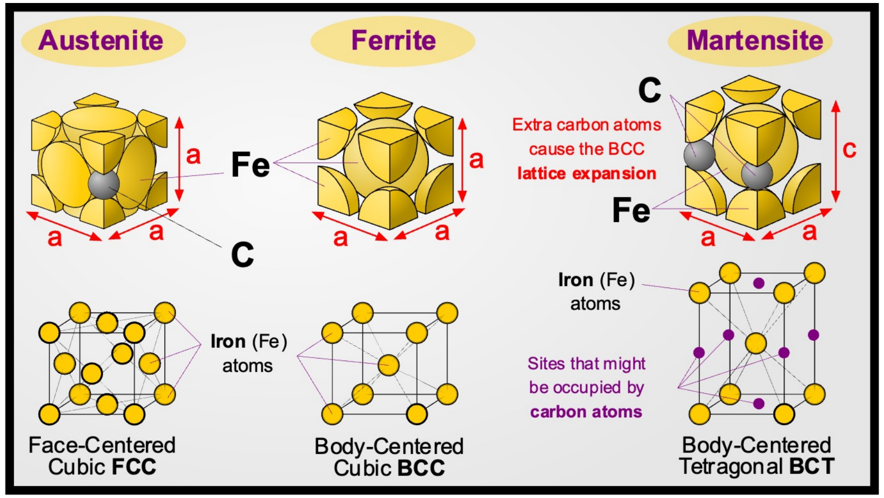
Remote joining of advanced structural materials

**Also:**

- No prototypic testing environments exist
- Structural loads from standard and disruptive E&M forces
- Integrated molten salt coolant channels near primary vacuum boundary
- Large-scale complex geometric topology

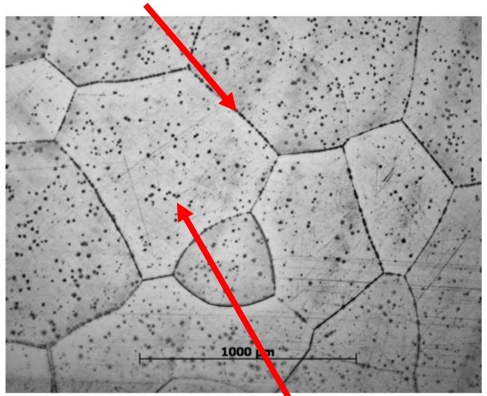
# How do you select a material anyway?

| Property | What it tells you |
|---|---|
| Modulus | Resistance to reversible deformation (elastic) |
| Strength | Resistance to irreversible deformation (plastic) |
| Fracture toughness | Resistance to crack propagation and “breaking” |
| Ductility | How much a material can deform |
| Thermal conductivity | How well heat is transported |
| Thermal expansion | How much expansion and contraction with temp. |
| Chemistry | Controls other properties as well as neutron interactions and activation |
| Manufacturability | Ok, can I get the material I think I need in the form I need it? |



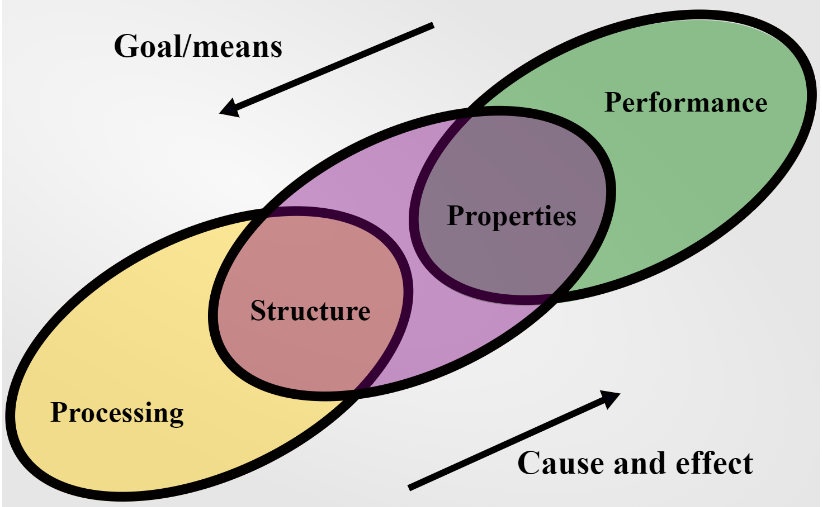

some crystal structures of steels

grain boundary




Fe-12Cr-2Si ferritic alloy grains, 50x, etched with Kalling's reagent

matrix precipitates




A version of the classic “materials science tetrahedron”

# Materials in fusion systems are continually dynamic

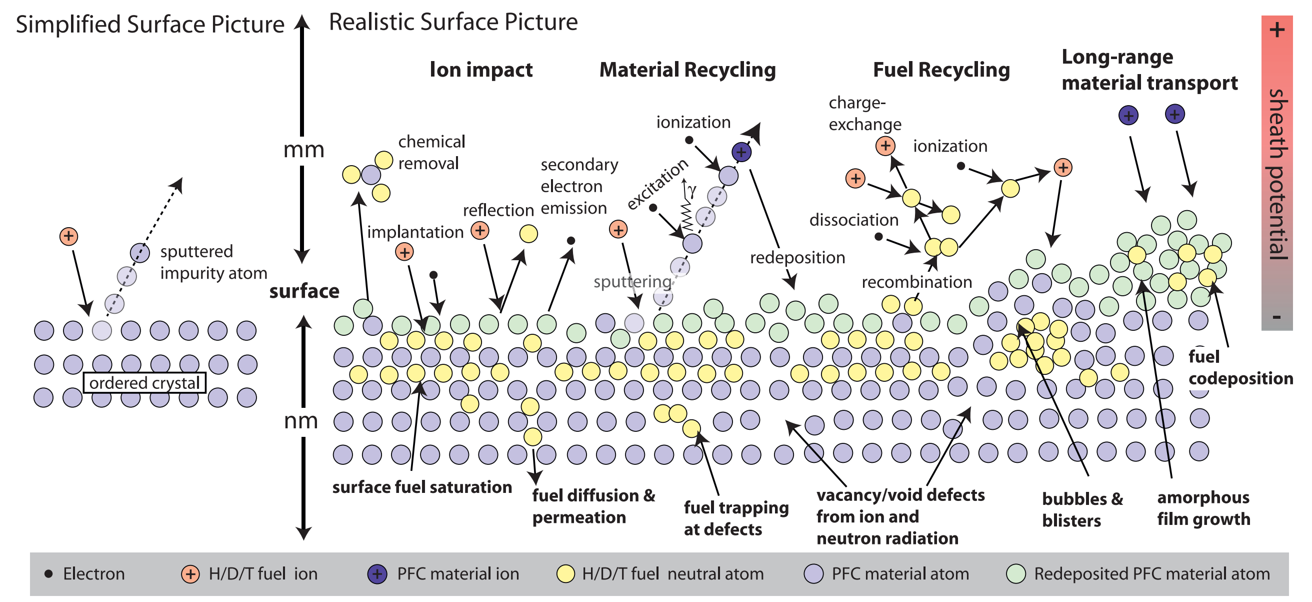



**Figure 1.** Schematic illustration of the complex, synergistic, and inherently multiscale surface interactions occurring at the material surface in a realistic magnetic fusion plasma environment. H, hydrogen; D, deuterium; T, tritium; PFC, plasma facing component; γ, gamma ray.

Wirth et al. MRS Bull. 36 (2011)

- The environments in fusion systems drive the evolution of properties and performance over time
- Microstructure will change as a function of
  - Radiation dose and dose rate
  - Radiation type
  - Plasma exposure
  - Temperature and temperature gradients
  - Mechanical stresses
  - Local chemistry / corrosion effects
  - Nuclear transmutation

**Selecting a material for your fusion system requires understanding how it will evolve and likely degrade over it's intended operational lifetime**

**This is extremely difficult!**

# Structural damage from neutrons drives long-term change in properties

DISPLACEMENT RATE

NUMBER DENSITY OF MATERIAL

DISPLACEMENT CROSS SECTION

$$R = \int_{E_{min}}^{E_{max}} N\phi(E)\sigma_D(E)dE$$

RADIATION FLUX

RADIATION ENERGY

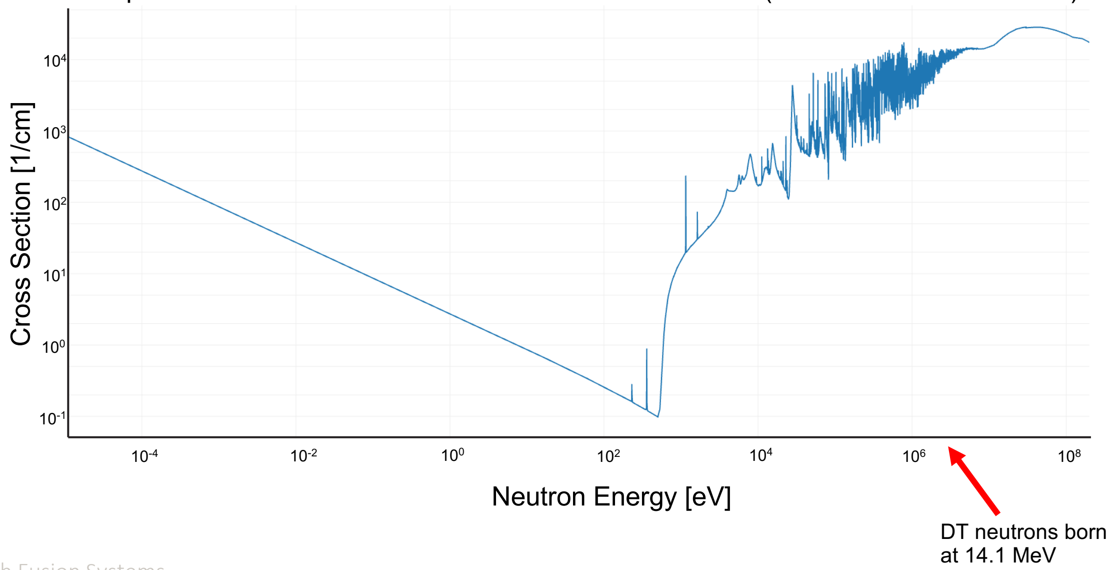
S.E. Ferry

**DPA = displacements per atom = R / N**

**For 1 dpa, every atom in the material has been displaced from its equilibrium position once**

- Under irradiation, atoms are knocked out of their equilibrium positions in the crystal lattice
- Most recombine immediately (picoseconds), but those that don't form defects that agglomerate and change structure and properties

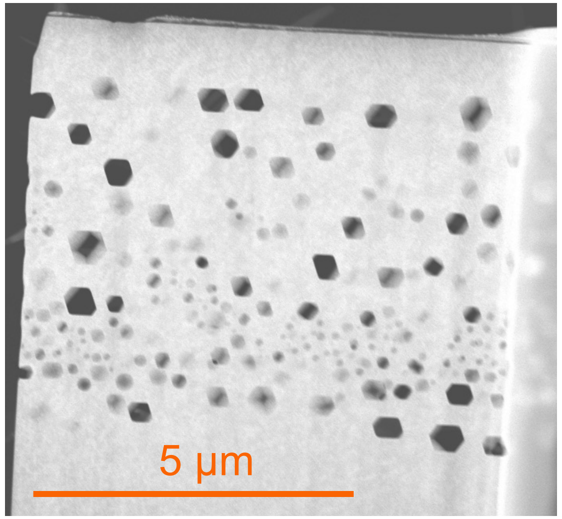
Displacement cross section for neutrons in Fe-17Cr-12Ni (model 316 stainless steel)



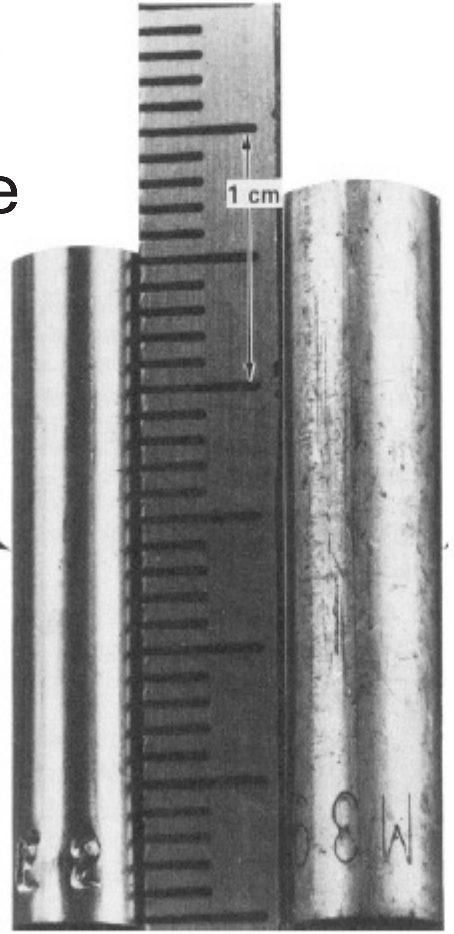
# Challenges in nuclear structural / vacuum vessel materials

- Required to retain strength, ductility, and toughness under high temperatures while undergoing atomic displacement damage
- Possible modes of damage evolution include precipitation, embrittlement, ballistic precipitate dissolution, and void/bubble growth
- Traditional high-temp, Ni-based structural materials struggle due to activation and He generation through nuclear reactions

Dennett et al. Acta Mater. 145 (2018)




pure Cu
90 dpa
400˚C
35 MeV Cu ions

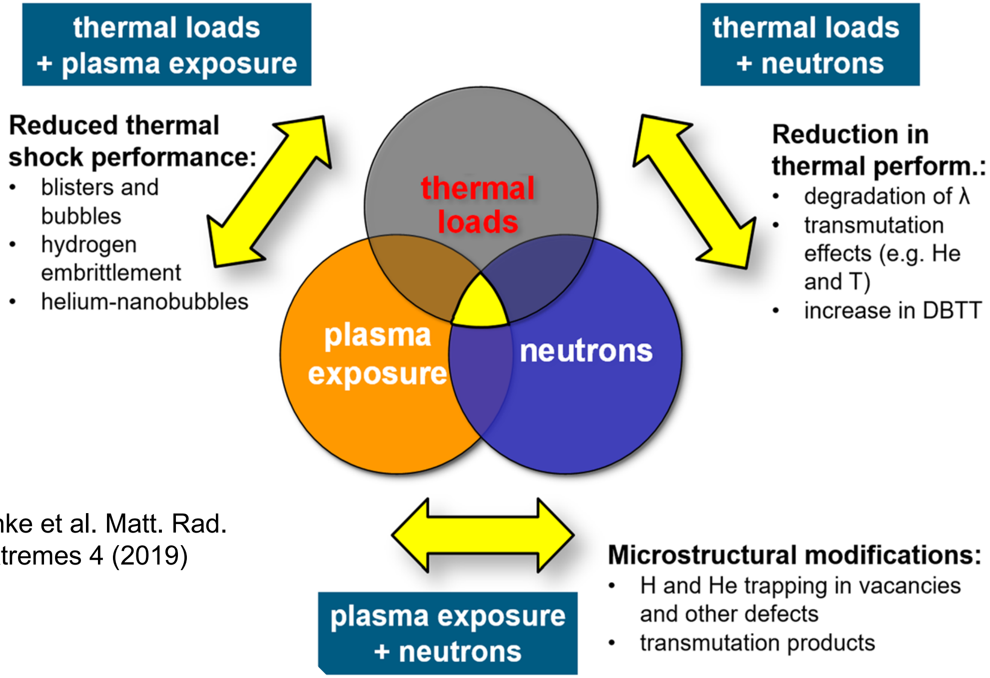



316 stainless steel
80 dpa
510˚C
thermal neutrons

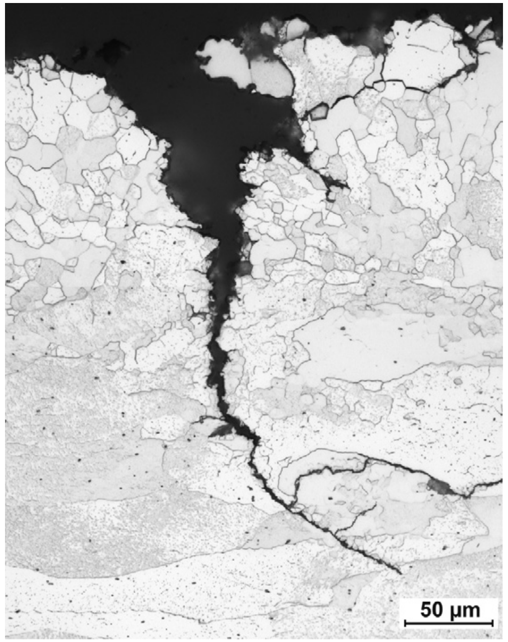
Mansur J. Nucl. Mater. 216 (1994)

# Challenges in plasma facing materials

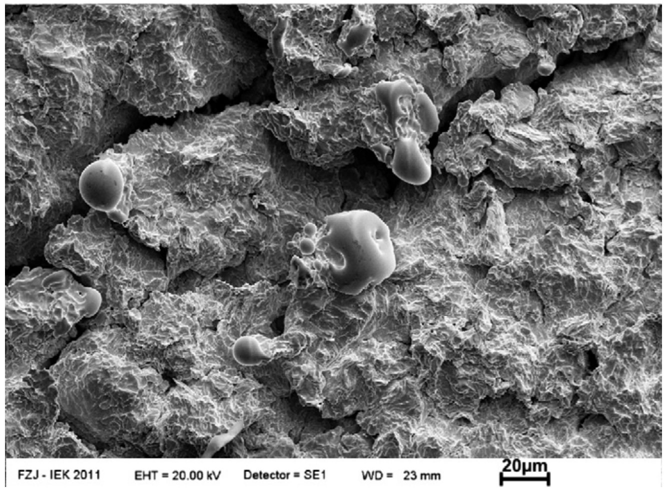
- Materials serving as the first interface to fusion plasma are exposed to high energy neutrons, lower energy ions (D, T, He), high heat fluxes, and complex mechanical loading
- Erosion and sputtering can inject impurities into the core plasma, degrading performance
- Traditional selections include low-Z materials (C, Be) or high-Z refractory materials (W, Mo)




Linke et al. Matt. Rad. Extremes 4 (2019)



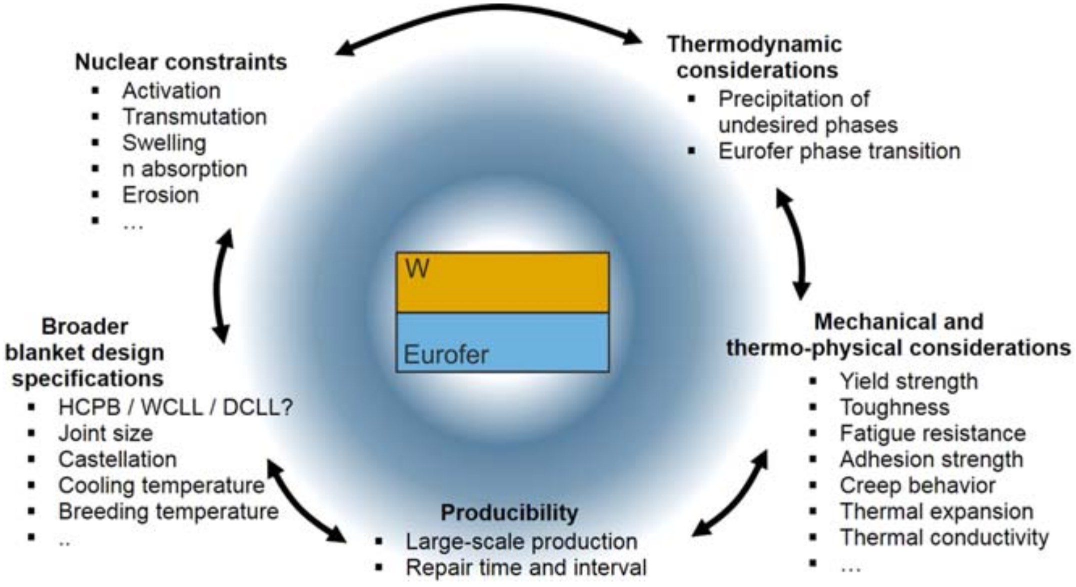

melted, cracked, and recrystallized W under high heat fluxes at 700˚C



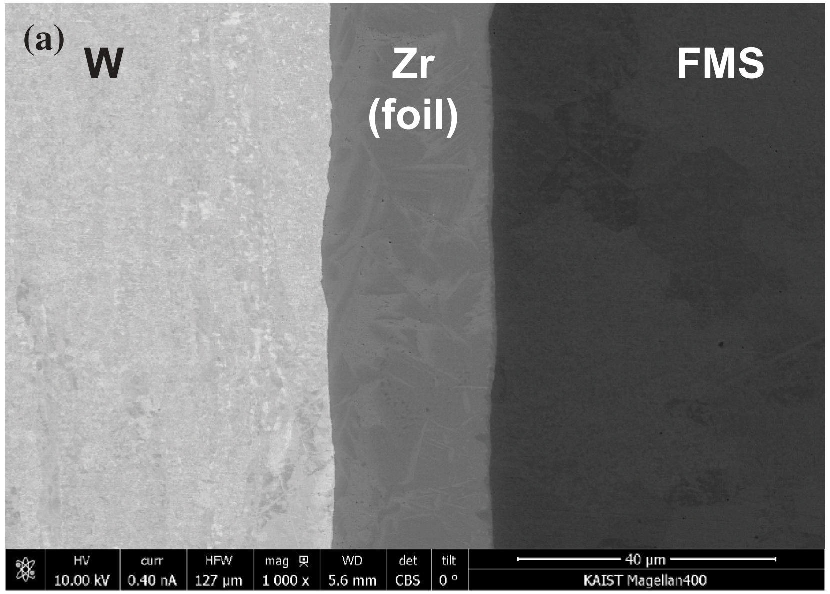

Loewenhoff et al. Fus. Eng. Des. 87 (2012)

# Joining structural and plasma facing materials

- For ARC, refractory plasma facing materials and structural vacuum vessel materials must be monolithically joined
- Dissimilar thermal expansion between refractories and most structural materials pose challenges for high-temp operation
- Mechanical integrity in coupled extreme environment must be maintained
- Community has explored functional grading, interlayers, and other concepts



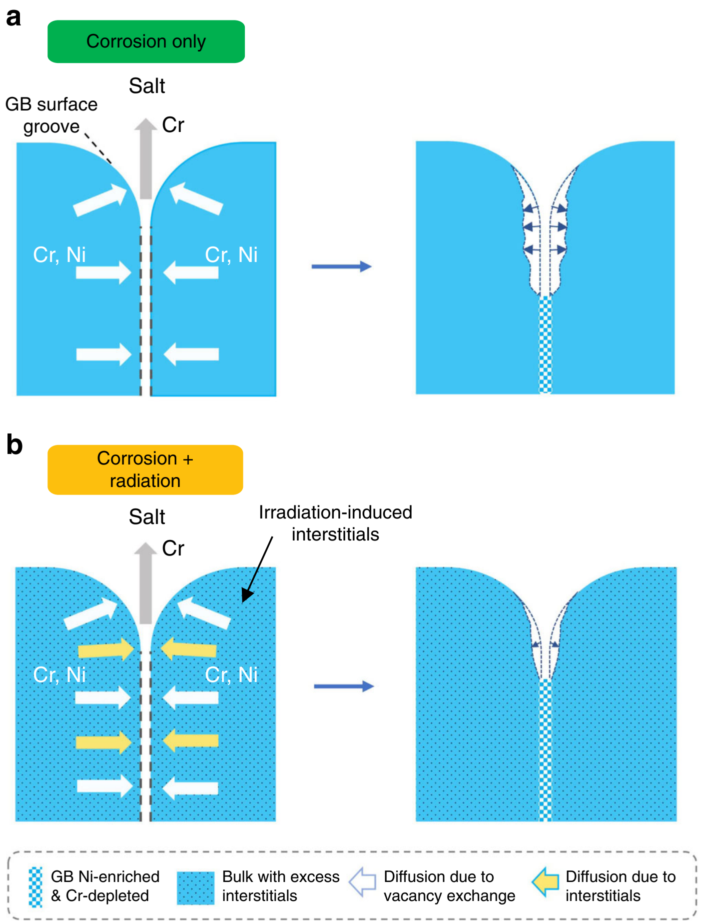

Heuer et al. Phys. Scr. T171 (2020)




Jung et al. Fus. Sci. Tech. 72 (2017)

# Challenges in molten salt corrosion

- In high temperature, fluorine-based molten salts, elements which passivate in aqueous environments do not provide protection
- Impure salts leach Cr from grain boundaries, providing crack initiation sites and destroying mechanical integrity
- Pure elemental coatings (W, Ni) perform well, but must be coated onto salt-facing components

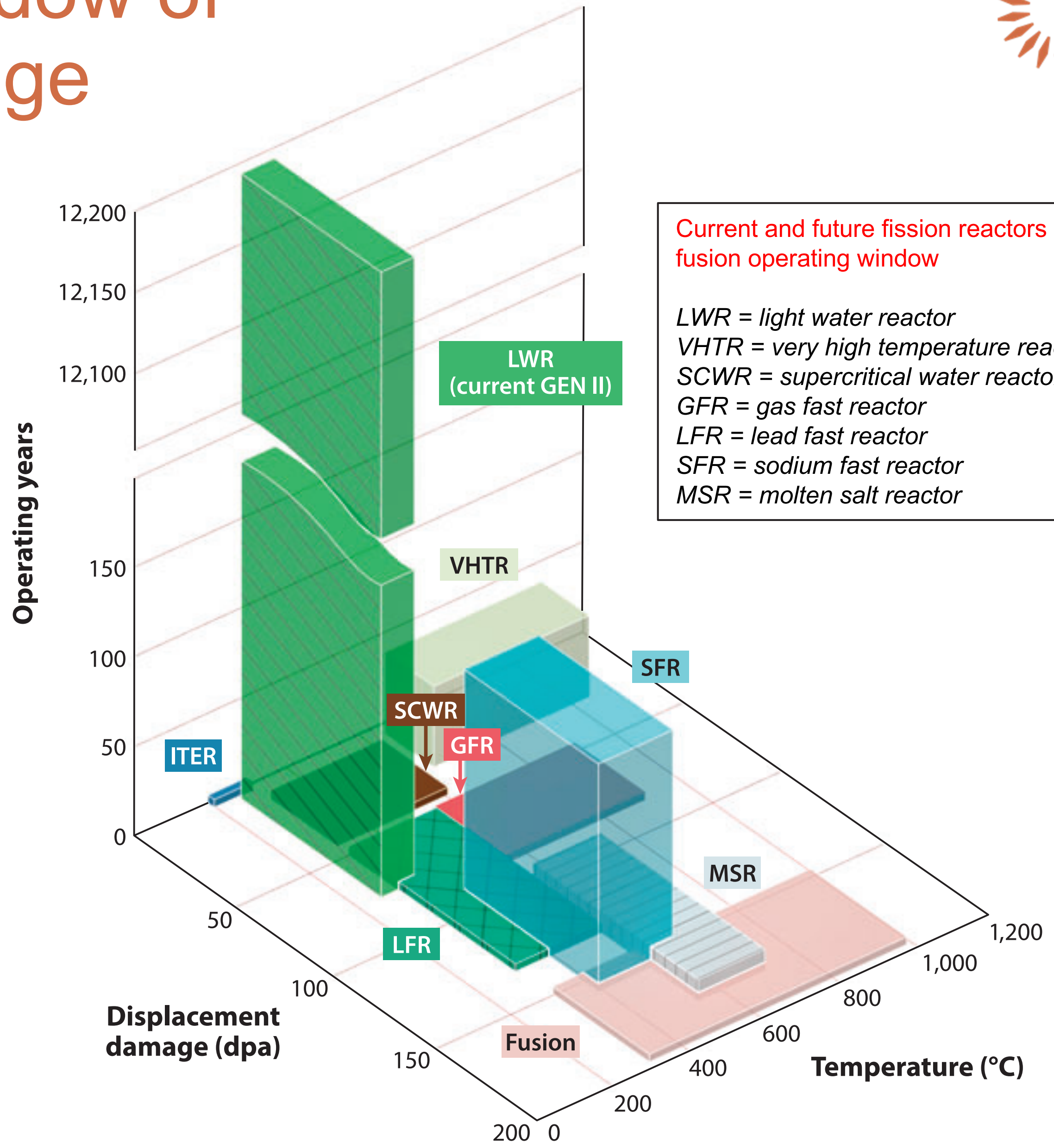



Zhou et al. Nat. Commun. 11 (2020)


Olson PhD Thesis, UW-Madison (2009)

# Humans only have a narrow window of experience with irradiation damage and temperature

- Long term damage accumulation depends sensitively on the temperature (material kinetics)
- Most operating experience worldwide comes from light water reactors, the world's commercial nuclear energy
- Operating conditions for fusion power plants will quickly take us outside the window of previous human experience




Current and future fission reactors + fusion operating window

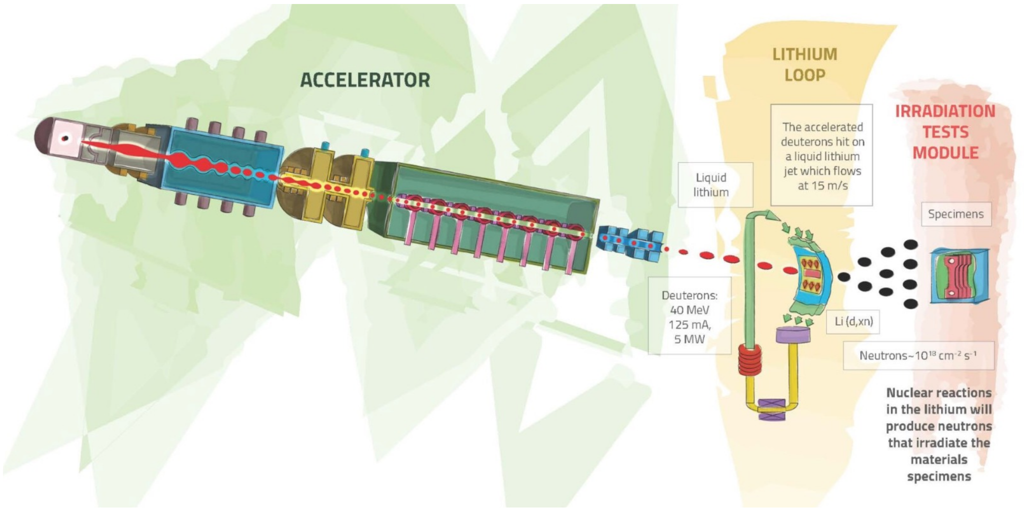
*LWR = light water reactor*
*VHTR = very high temperature reactor*
*SCWR = supercritical water reactor*
*GFR = gas fast reactor*
*LFR = lead fast reactor*
*SFR = sodium fast reactor*
*MSR = molten salt reactor*

Zinkle et al. Annu. Rev. Mater. Res. 44 (2014)

# Testing radiation performance in fusion relevant conditions is challenging

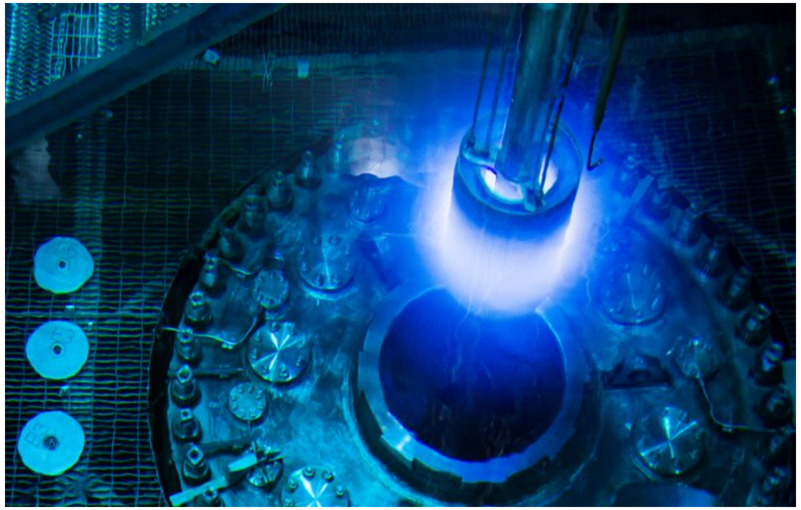
- All neutron testing is time consuming and costly due to the hazards and material handing challenges involved
- Using fusion-relevant neutron spectra for materials testing is currently not possible at scale in worldwide facilities

IFMIF-DONES
International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source



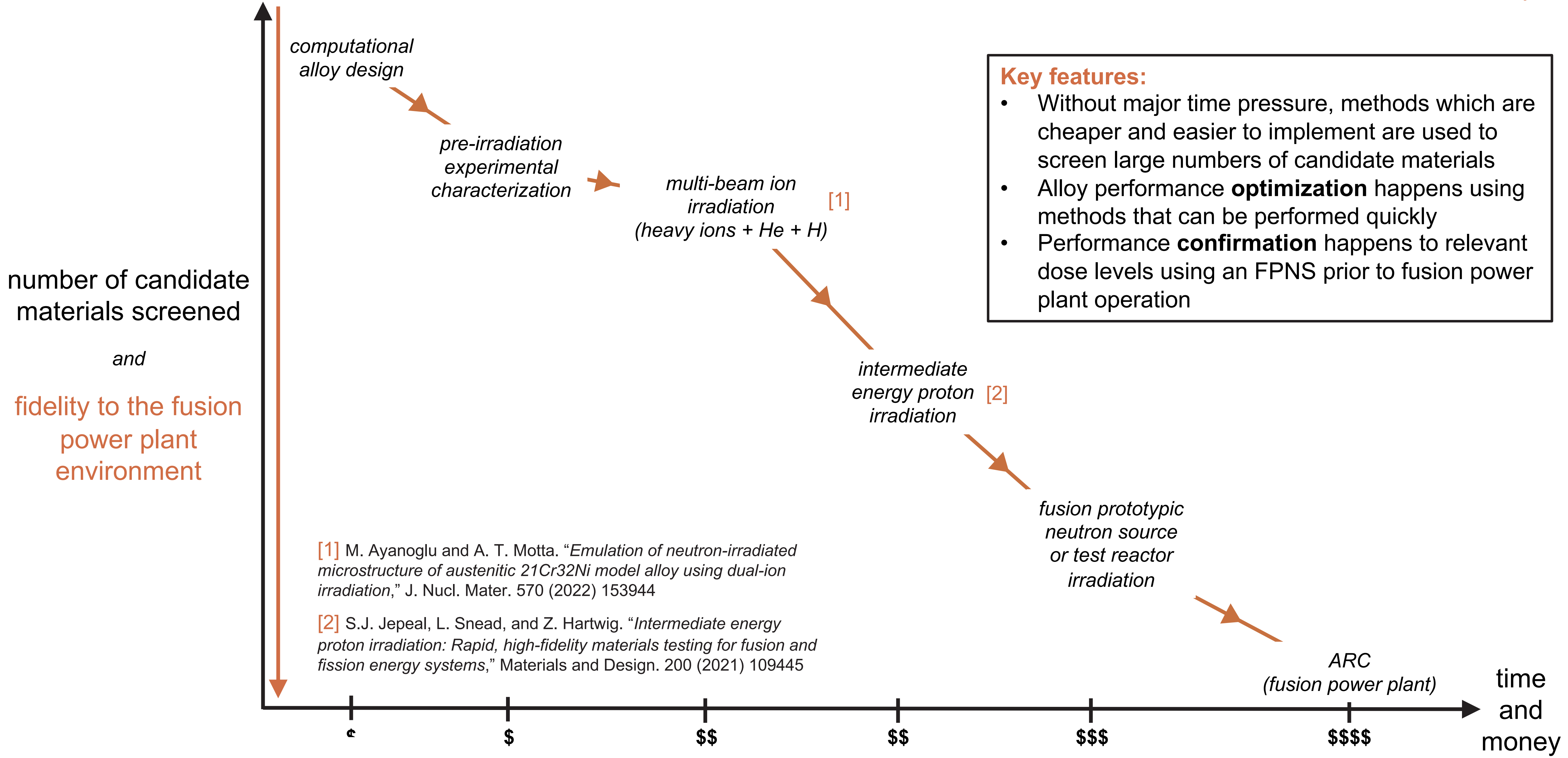

ifmif-dones.es

HFIR
High Flux Isotope Reactor – Oak Ridge National Lab



energy.gov

# Optimization funnel for fusion material radiation testing




**Key features:**

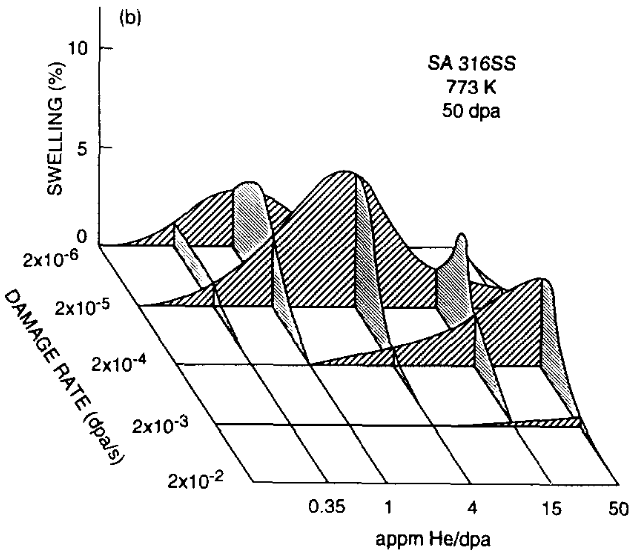
- Without major time pressure, methods which are cheaper and easier to implement are used to screen large numbers of candidate materials
- Alloy performance **optimization** happens using methods that can be performed quickly
- Performance **confirmation** happens to relevant dose levels using an FPNS prior to fusion power plant operation

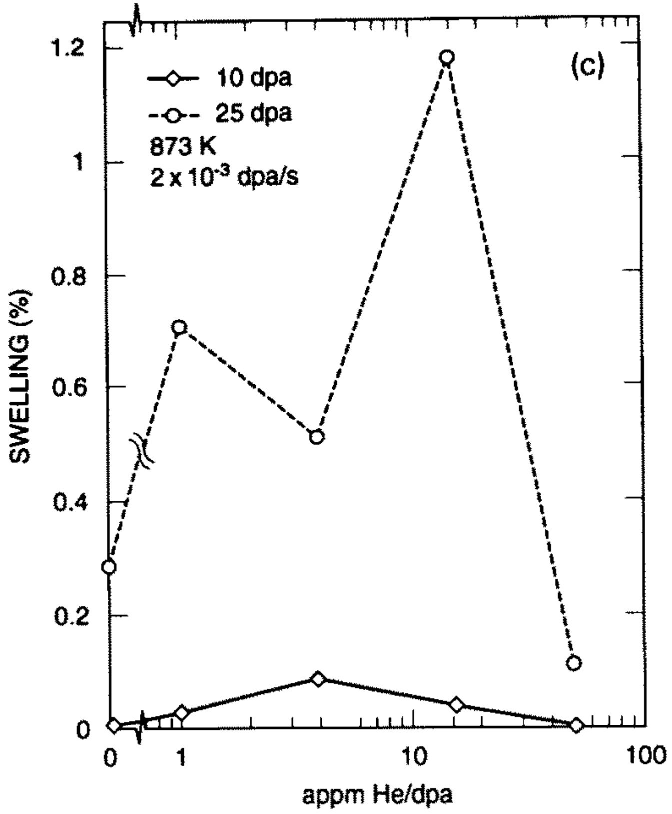

[1] M. Ayanoglu and A. T. Motta. "*Emulation of neutron-irradiated microstructure of austenitic 21Cr32Ni model alloy using dual-ion irradiation*," J. Nucl. Mater. 570 (2022) 153944

[2] S.J. Jepeal, L. Snead, and Z. Hartwig. "*Intermediate energy proton irradiation: Rapid, high-fidelity materials testing for fusion and fission energy systems*," Materials and Design. 200 (2021) 109445

# The ratio of insoluble gas generation to structural damage determines long-term defect evolution

- Insoluble gas generation, H and He, due to transmutations can stabilize nanoscale defect formation
- Overabundance of gas production can also suppress defect agglomeration as gas atoms can bind with isolated defects, reducing mobility
- Finding the right gas/dpa ratio for accelerated irradiation techniques is a major technical hurdle



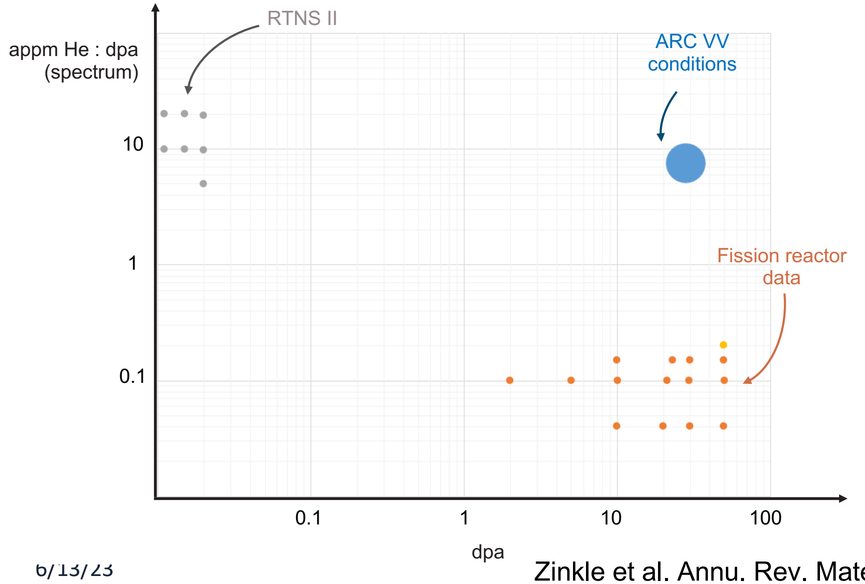

Katoh et al. J. Nucl. Mater. 210 (1994)

Dependence of void swelling in 316SS on dose rate and He/dpa ratio at 500-600˚C

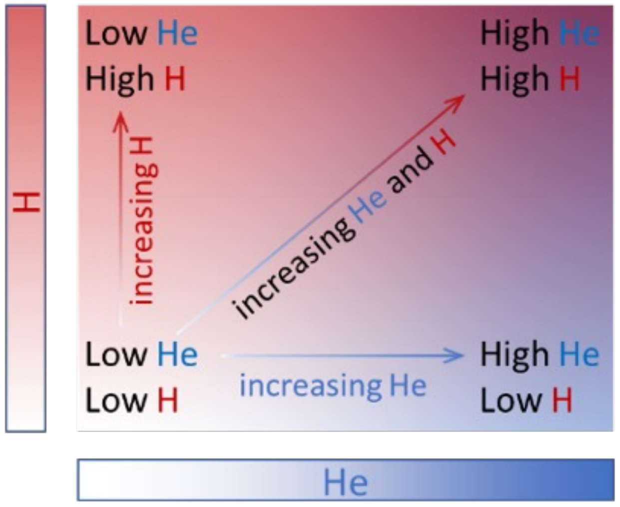
# Testing using triple beam ion irradiation can accelerate materials down selection and optimization

- Triple-beam ion irradiation program being carried out with MIT and U. Michigan
- Parameter space of H and He gas injection and damage via self ions will be mapped to best emulate historical reactor irradiations
- Identifying the "neutron-ion handshake" will enable screening irradiations of advanced structural alloys to be conducted rapidly to ARC-relevant conditions

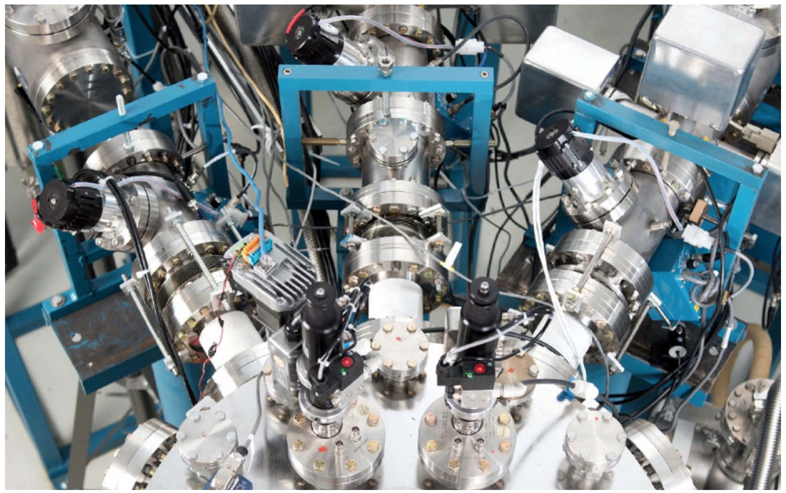
Current data available for structural steels do not meet projected ARC conditions




Zinkle et al. Annu. Rev. Mater. Sci. 44 (2014)




Triple Beam Irradiation Chamber at Michigan Ion Beam Lab

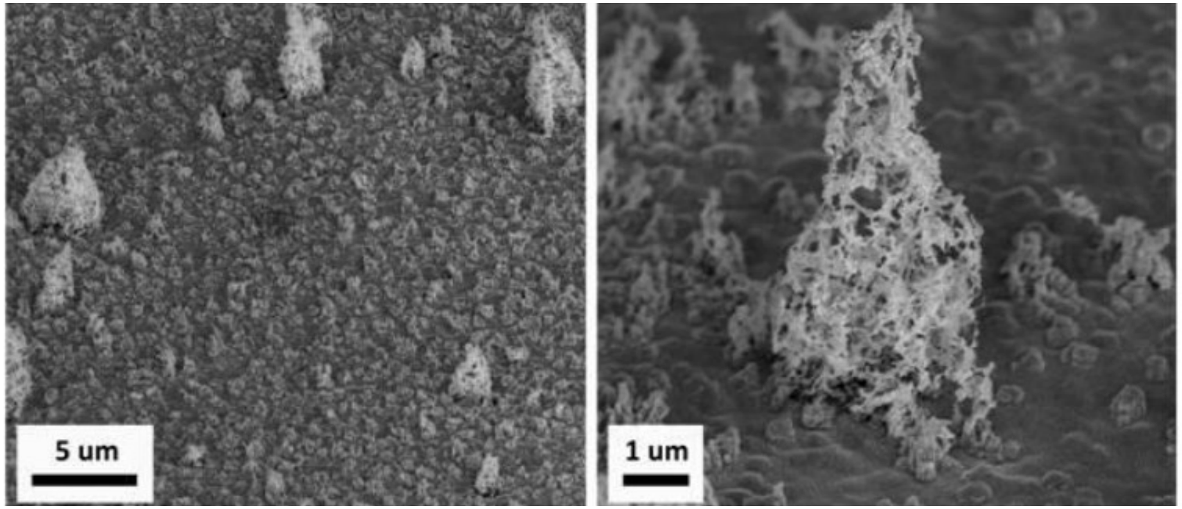


mibl.engineering.umich.edu

# What does that all mean for fusion power systems?

- Fusion technology development (materials, components, supply chains) is just as important as plasma physics to get a fusion power industry in time
  - *Sorry plasma physicists!*
- The challenges are real, but methods do exist to provide enough certainty to turn on first-of-a-kind systems
- We expect to observe new behaviors once fusion power systems operate
  - That's when the real interesting materials science happens.

Nano-tendril tungsten "fuzz" forming under low energy plasma exposure, just because its fun




Woller et al. Nuclear Fusion **57** (2017)

# CFS has ~90 open roles with more to come

- We're hiring!
- Check out cfs.energy/careers for more information
- Roles in R&D, manufacturing, control systems, plasma diagnostics, design engineering, and more
- Feel free to contact with any questions: cdennett@cfs.energy

CFS Careers

**MATERIALS**

Materials Engineer

SOMERVILLE, MA R&D – MATERIALS FULL-TIME HYBRID

APPLY

Materials Test Engineer

SOMERVILLE, MA R&D – MATERIALS FULL-TIME ON-SITE

APPLY

Roles in fusion materials!

Commonwealth
Fusion Systems