OAK RIDGE National Laboratory

Solving the Hard Problems Faster: ORNL's Integrated Approach to Reach Fusion Energy

Cami Collins
on behalf of our ORNL Fusion team

Dec 20, 2023

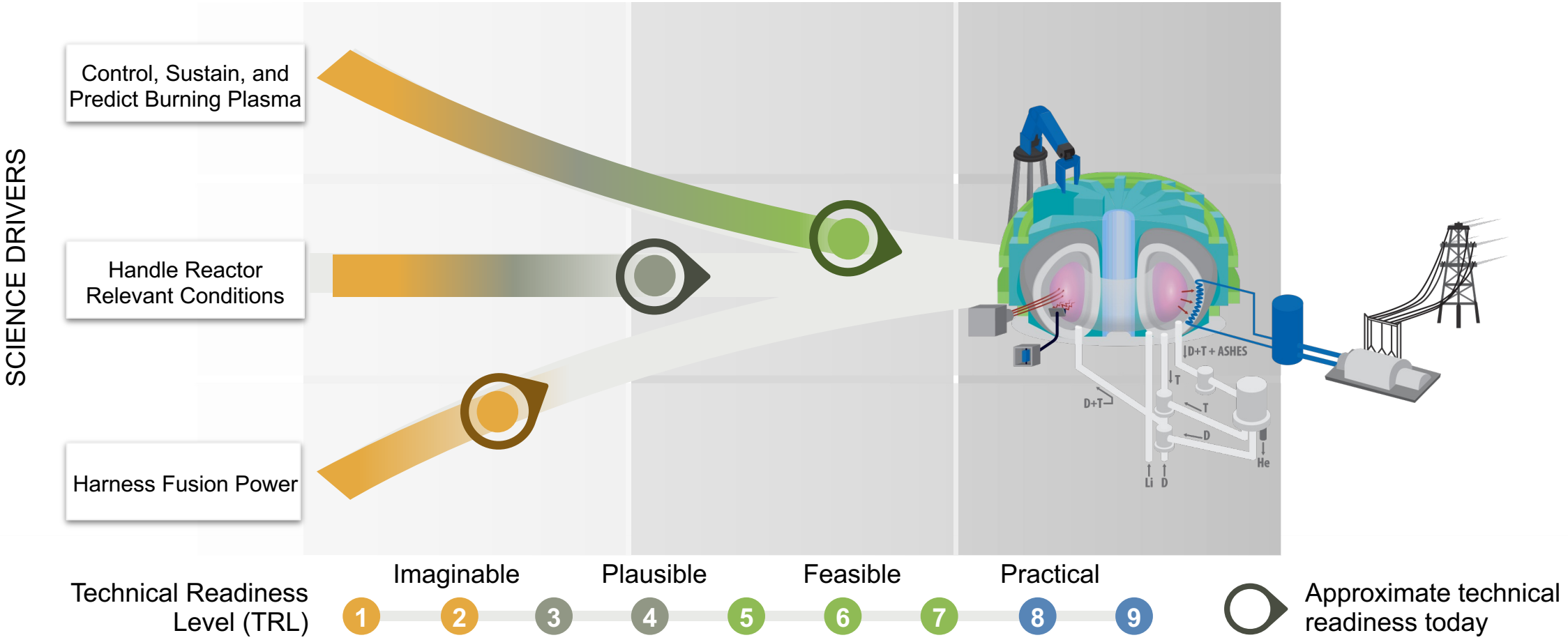
ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

Rapid progress is needed to reach a fusion pilot plant

NASEM '21

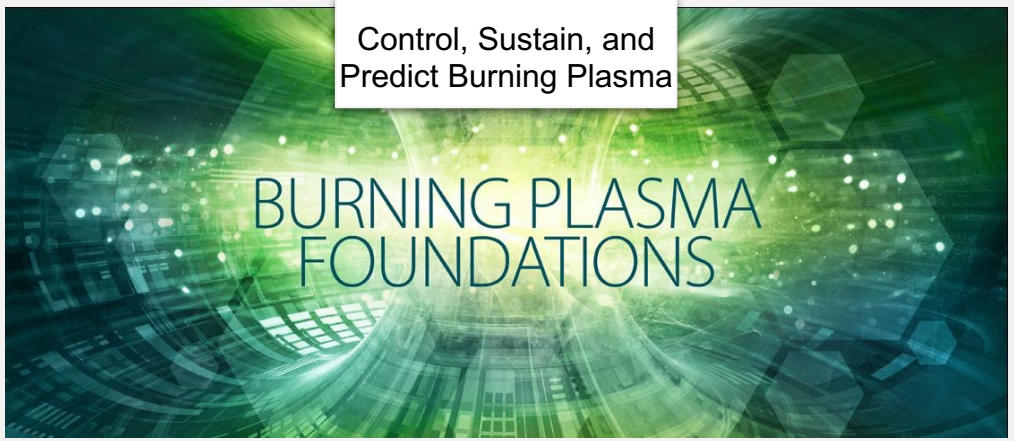
- **Phase 1**: ≳50 MWe peak electricity generation for ≥3 hours with Qe > 1, closed fuel cycle
- **Phase 2**: Demonstrate heat removal, material erosion, and tritium loss is managed for ~year
- **Phase 3**: Fully define lifetime, availability, and manufactured components of commercial plants



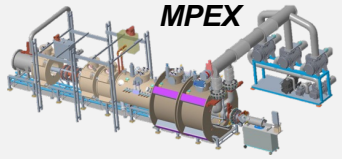
ORNL Program & Priorities are Driven by the CPP/FESAC LRP

ORNL FUSION ENERGY DIVISION

Control, Sustain, and Predict Burning Plasma



Handle Reactor Relevant Conditions



Plasma Material Interactions Science

Harness Fusion Power

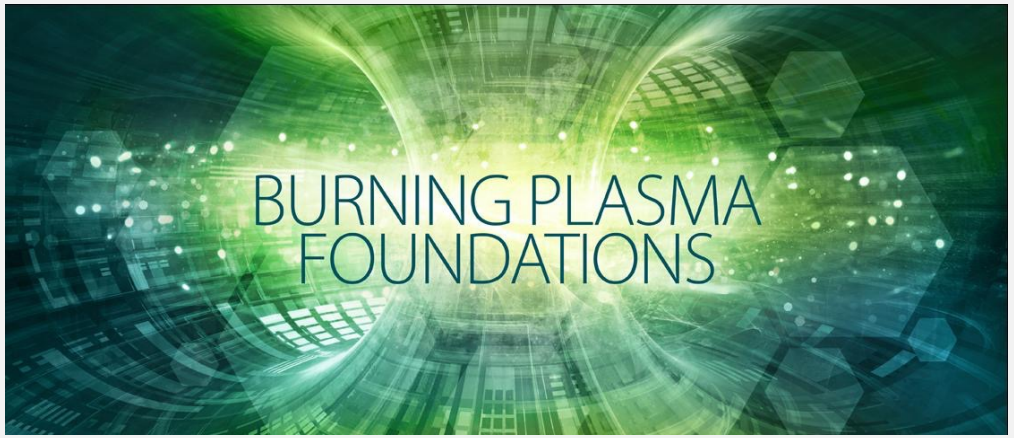
OUR MISSION

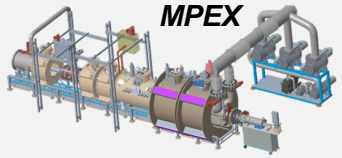
In partnership with public and private fusion efforts worldwide, establish the technical basis for integration of burning plasma physics, next-generation materials, and fusion nuclear technology critical to the design of a fusion pilot plant

ORNL is utilizing resources across the lab to advance fusion energy

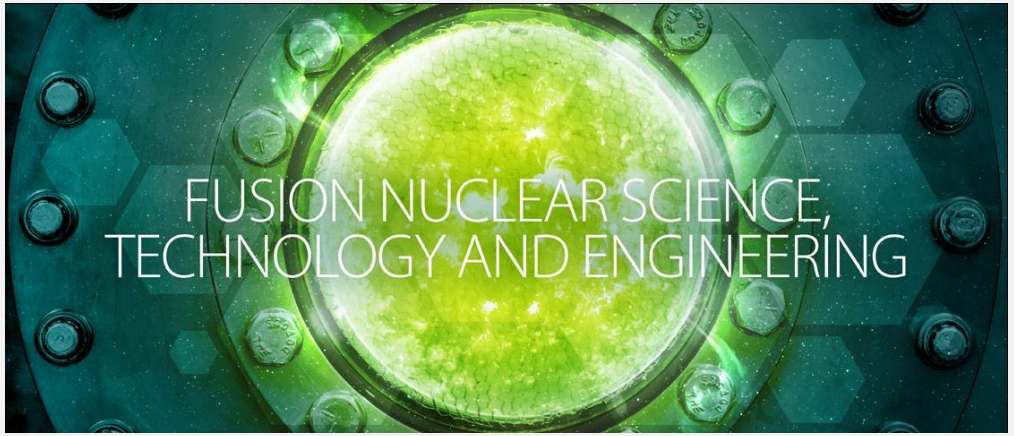
Phil Snyder
(interim) Division Director

ORNL FUSION ENERGY DIVISION





Plasma Material Interactions Science



Public & Private Partnerships

Integrated FPP R&D Program

Kathy McCarthy
US ITER Project Director

Mickey Wade
Fusion & Fission Associate Lab Director

OAK RIDGE National Laboratory

US iter

High Performance Computing

Materials Science

Advanced Manufacturing

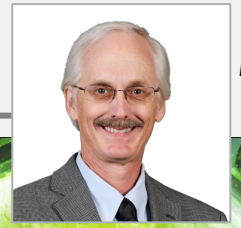
Fission

Fusion at ORNL is growing

Phil Snyder
(interim) Division Director

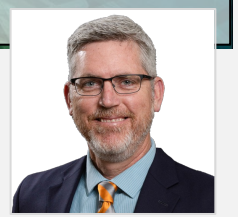
ORNL FUSION ENERGY DIVISION

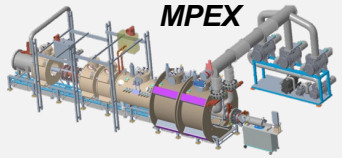
Cami Collins
(interim) Section Head



Larry Baylor
(interim) Section Head

BURNING PLASMA FOUNDATIONS

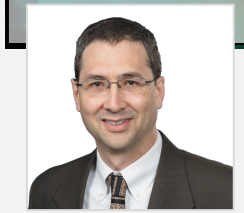
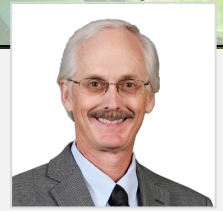
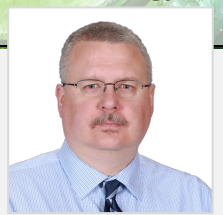
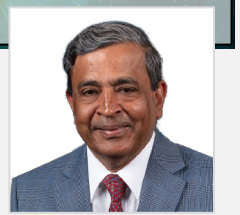
Advanced Tokamak Physics	Power Exhaust & Particle Control	Plasma Theory & Modeling	Diagnostics & Controls
			
Morgan Shafer	Zeke Unterberg	Gary Staebler	Ted Biewer



Plasma Material Interactions Science

Phil Ferguson
MPEX Project Director

FUSION NUCLEAR SCIENCE, TECHNOLOGY AND ENGINEERING

Fusion Engineering	Blanket & Fuel Cycle	Fusion Technology	Remote Systems
			
Arnold Lumsdaine	Larry Baylor	Robert Duckworth	Venu Varma

INFUSE

More than 100 staff in Fusion Energy Division, >30 new hires in 3 yrs

Chuck Greenfield
ITER R&D Lead

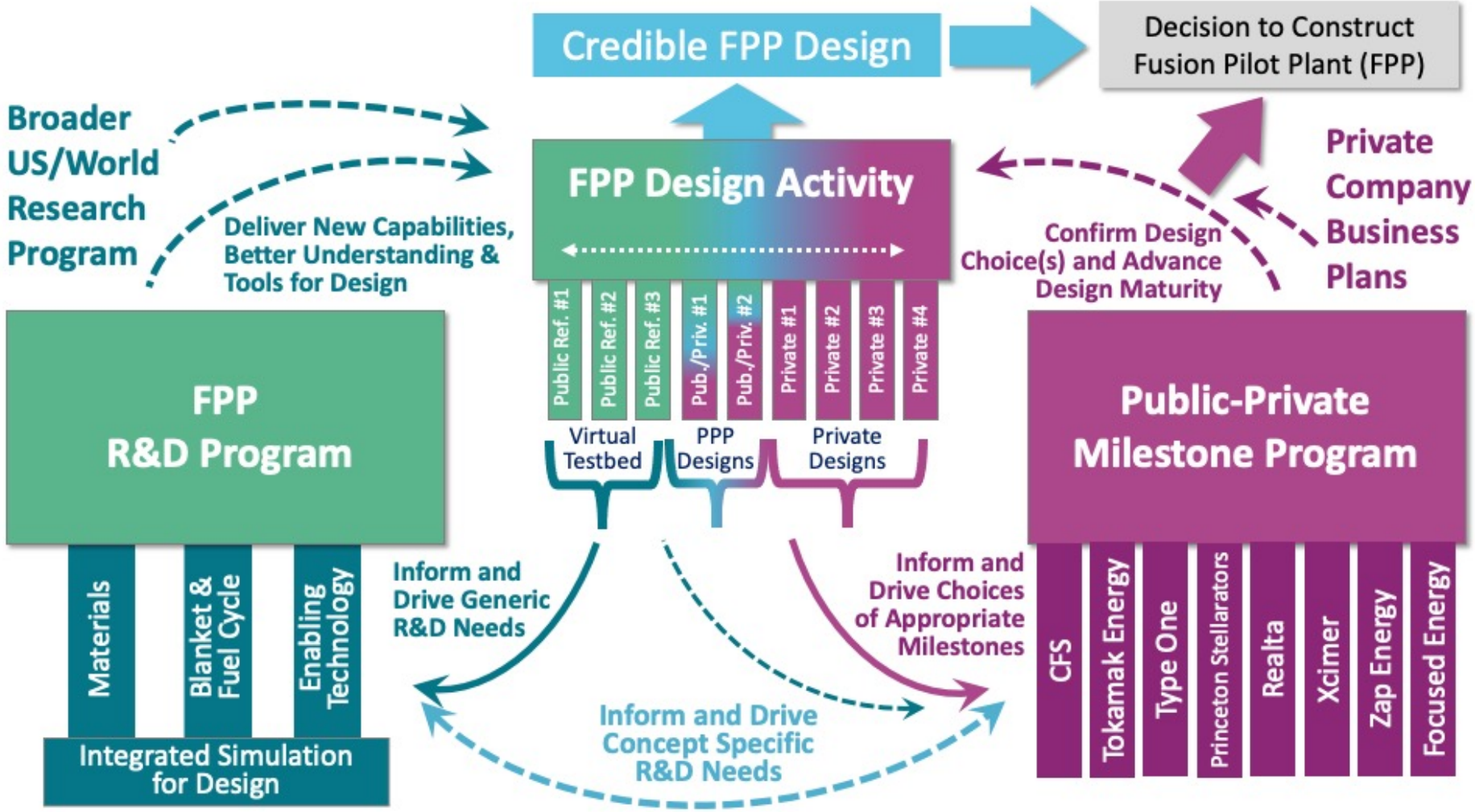
New!

Fusion Materials R&D Lead

Howard Wilson
FPP R&D Lead

More than 50 staff in FNSTE Section, >15 working on blankets

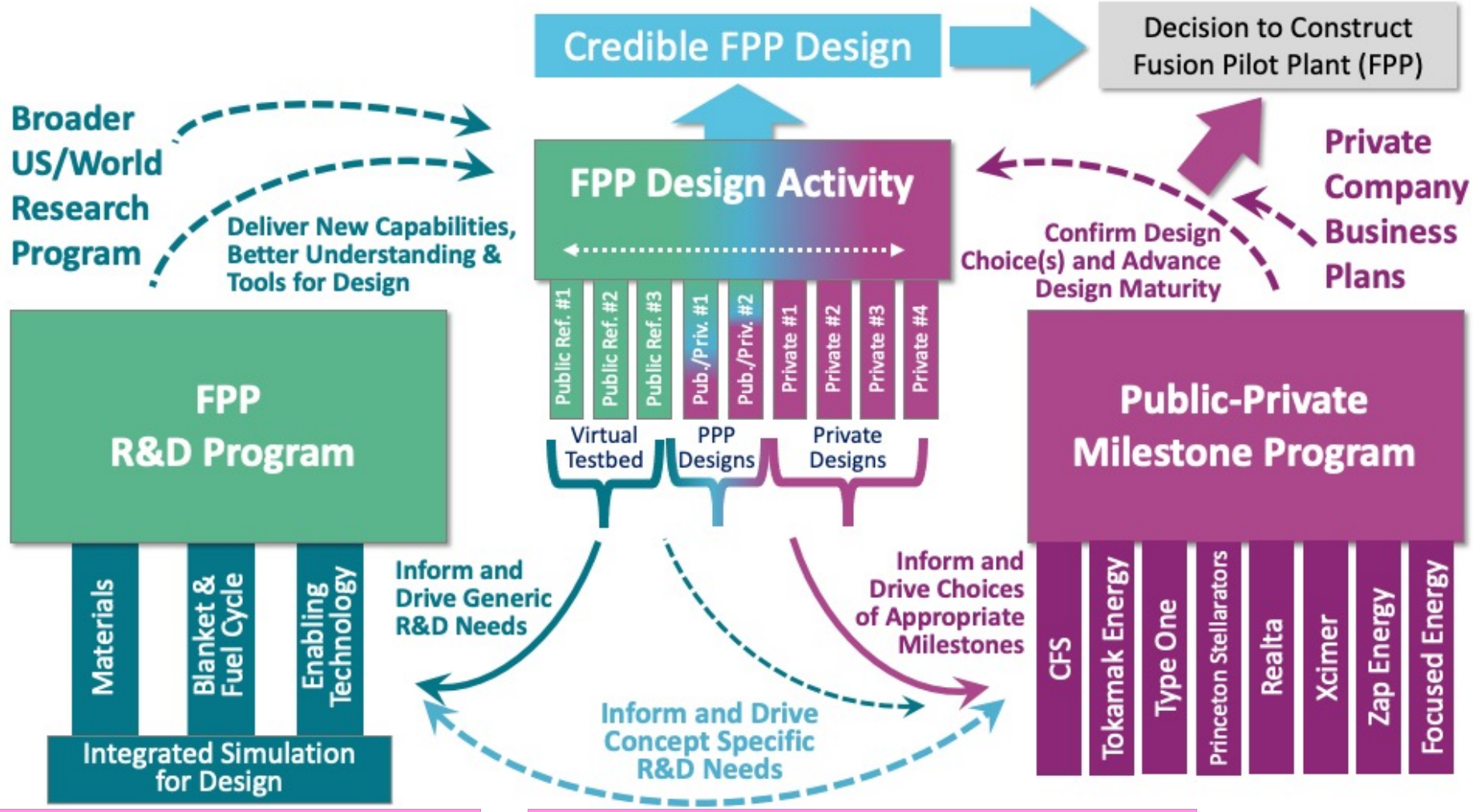
Our perspective on structuring the national program



APS-DPP-CPP PR-A: FPP design → **FPP Design Activity would utilize *all sectors*** to drive use-inspired research & technology innovation, facilities, & skills including universities and supply chain

[Mickey Wade, FPA 2022]

Our perspective on structuring the national program

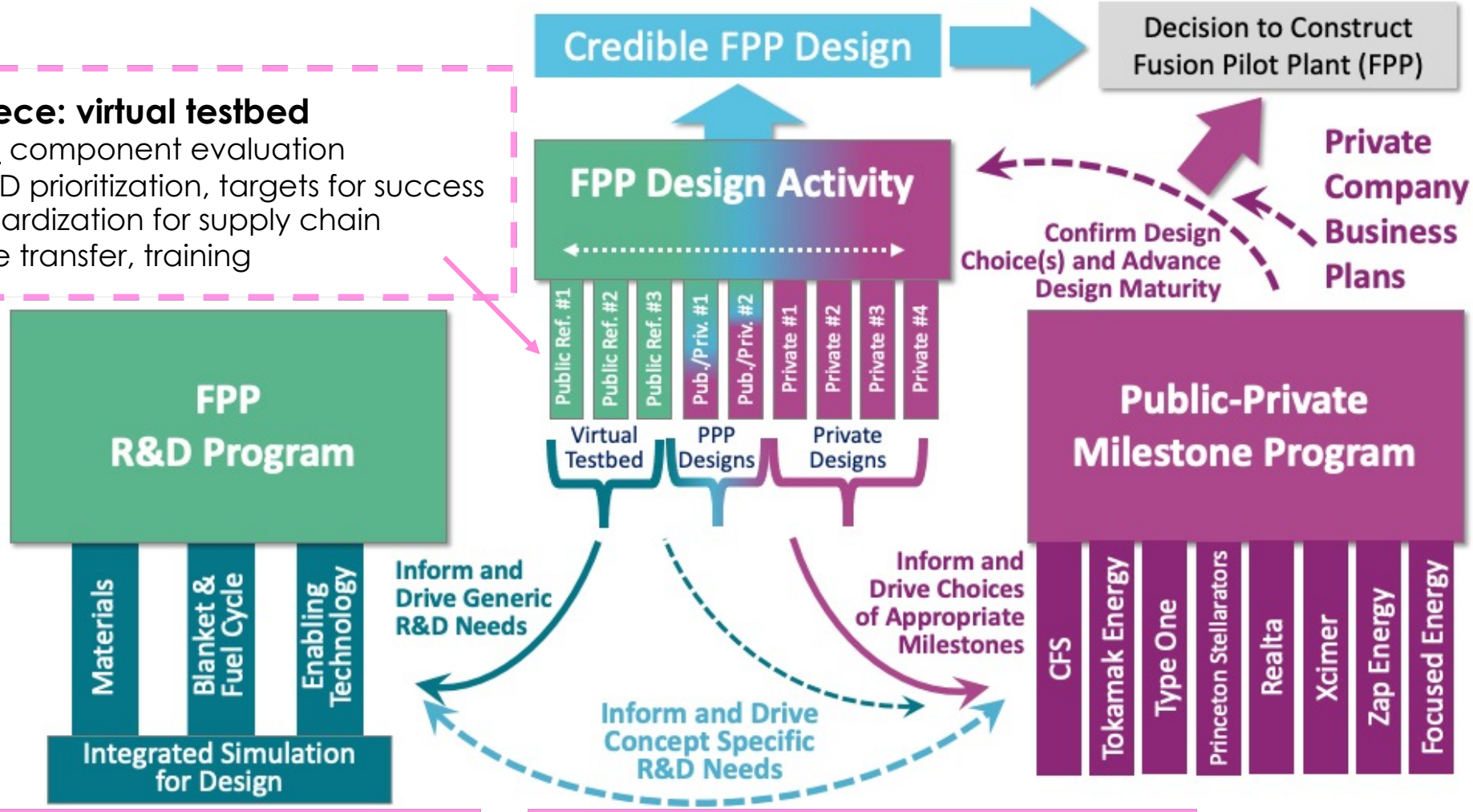


FIRE Centers, LRP Facilities
use-based R&D, metric-driven roadmap

New PPP Program/Consortium
translational research, tech transfer

Our perspective on structuring the national program

Missing piece: virtual testbed
- integrated component evaluation
- informs R&D prioritization, targets for success
- help standardization for supply chain
- knowledge transfer, training



FIRE Centers, LRP Facilities
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New PPP Program/Consortium
translational research, tech transfer

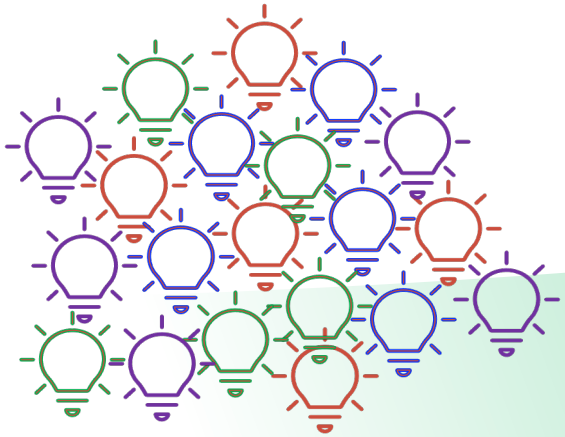
ORNL Seeks to Enable Private Industry at All Stages of Development

- Provide technical support on developing innovative ideas (INFUSE program)

- Provide expert advice and assistance in developing technology roadmaps and design (Milestone Program)

- Provide onsite or nearby siting opportunities for prototyping components and facilities, including FPP

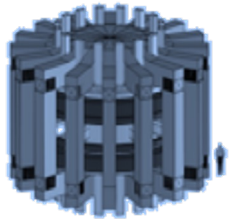
Innovate



Design

Build

Fusion Pilot Plant



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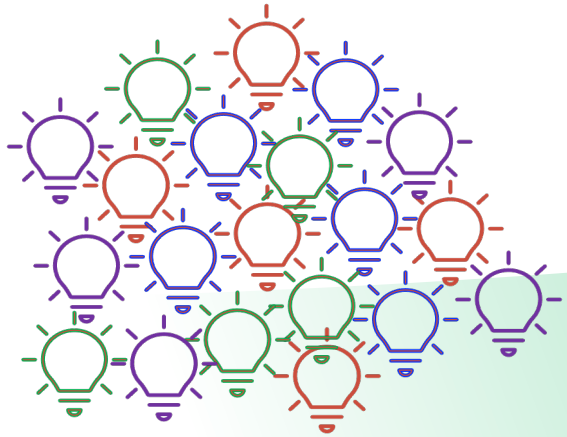

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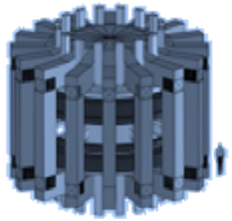
Fusion Pilot Plant



ORNL is a partner with 6 of 8 DOE milestone program companies

Commonwealth Fusion Systems
Tokamak Energy
Realta Fusion
Thea Energy
Xcimer Energy Corporation
Type One Energy

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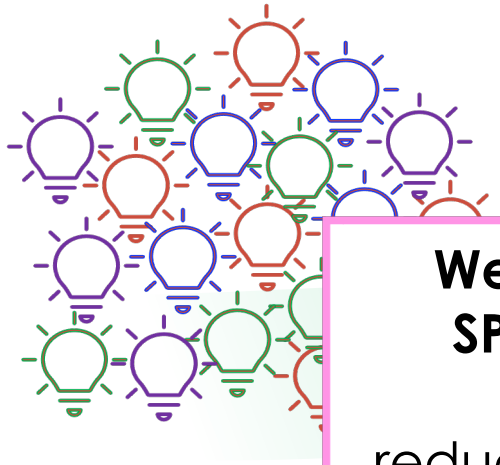
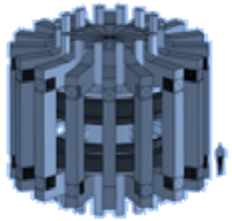




We are improving the SPP/CRADA process
hired specialists,
reduced turn-around time

ORNL is a partner with 6 of 8 DOE milestone program companies

Commonwealth Fusion Systems
Tokamak Energy
REALTA FUSION
THEA ENERGY
XCIMER ENERGY CORPORATION
TYPE ONE ENERGY

ORNL is starting the development of infrastructure to host Technology Test Facilities and a Future Fusion Pilot Plant

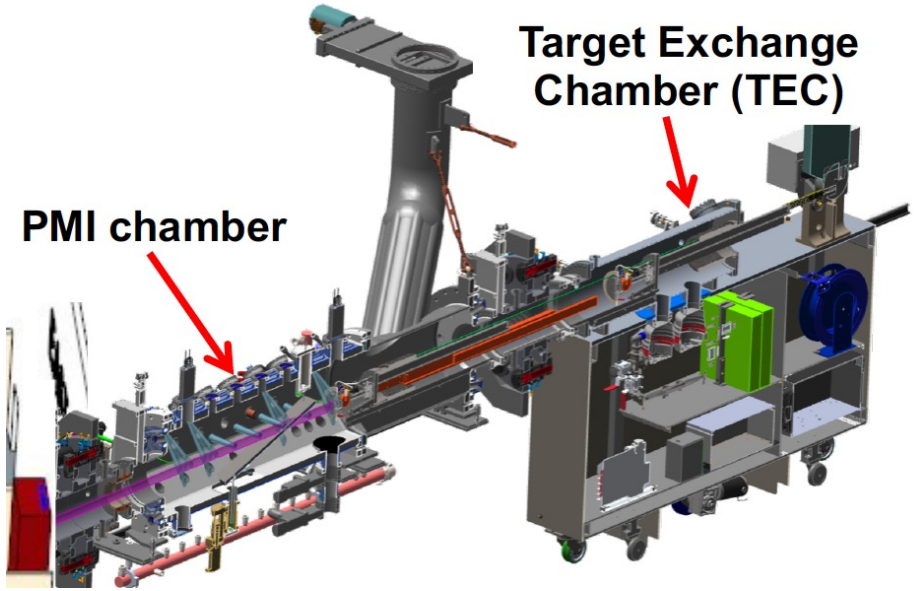
- Multiple siting options with access to required water and electricity needs
  - Working with lab facilities planning, local utility
- Comprehensive understanding for deployment
  - Broad range of technical capabilities
  - Strong regional partners including universities and utilities
  - Demonstrated capability to host major projects involving national teams
- Internal investment to accelerate readiness to construct LRP facilities

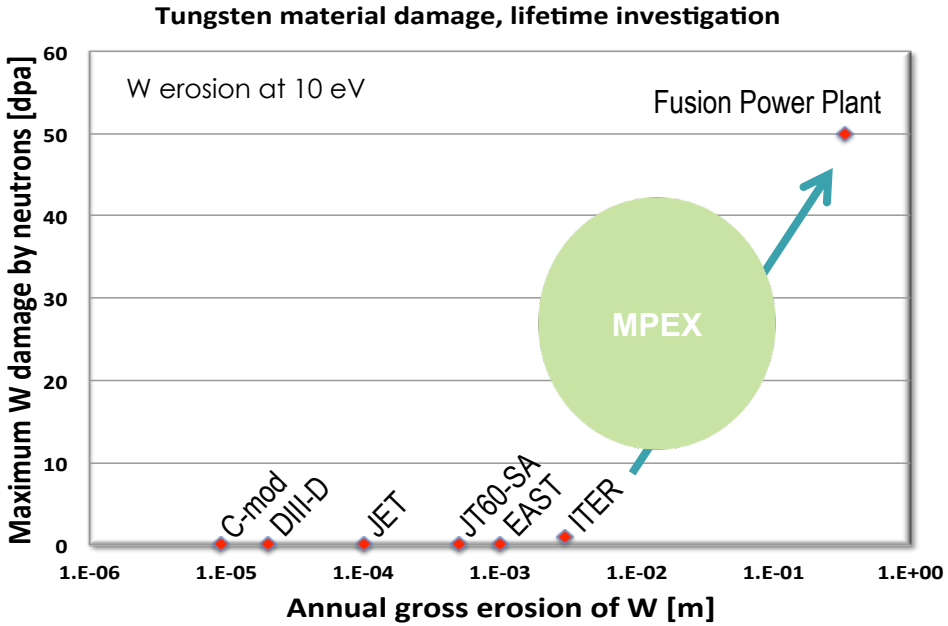
New Construction of Midscale+ Facilities	Constant	Modest Growth	Unconstrained
MPEX	Yes	Yes	Yes
FPNS	Yes, but highly delayed	Yes, but delayed	Yes
EXCITE	No	Yes, but highly delayed	Yes
Mid-Scale Stellarator	No	No	Yes
BCTF	No	No	Yes
HHF-Component	No	No	Yes

ORNL is starting the development of infrastructure to host Technology Test Facilities and a Future Fusion Pilot Plant

- **MPEX is on-time, on-budget**
  - Capable of lifetime exposures in 2 weeks
    - up to 10 MW/m^2 , can expose irradiated materials or liquid metals (small amounts)

Operations begin Q2FY28 (early completion Oct 2026)





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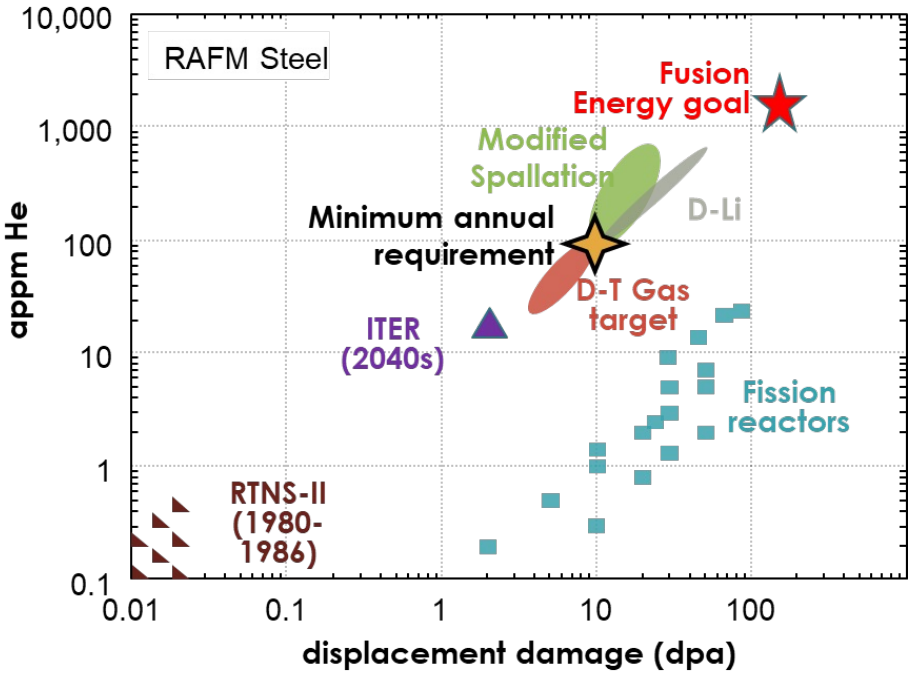
ORNL is starting the development of infrastructure to host Technology Test Facilities and a Future Fusion Pilot Plant

- **ORNL is leading the response to the May 2023 FPNS RFI**
  - Organizing community-led committees to compare concepts proposed in RFI
  - Evaluating performance (dpa/yr, transmutation levels, etc.), articulating risk/reward



ORNL is ready to help move the LRP/FES facilities list forward → ✅

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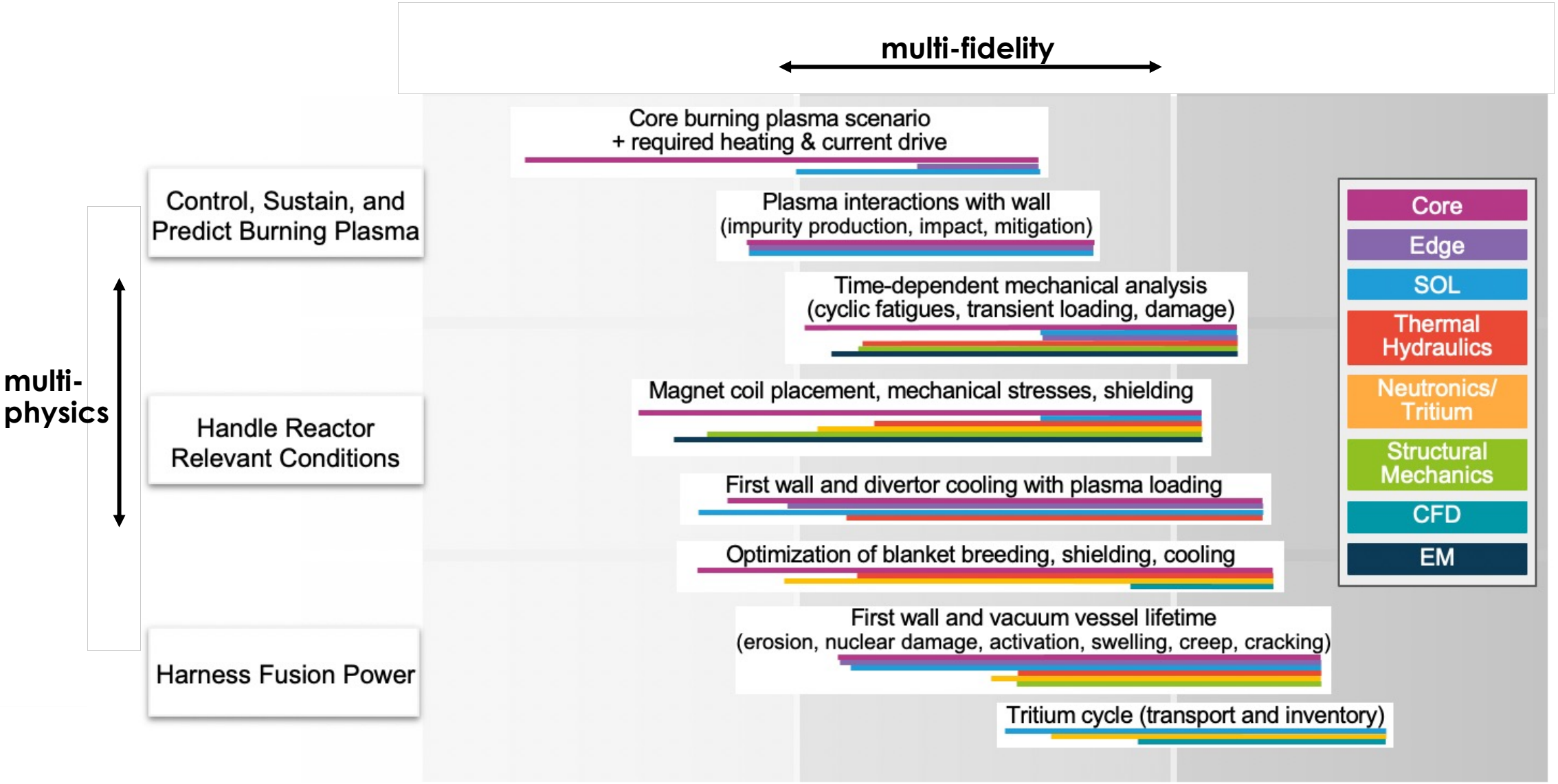
We approach challenge problems in an integrated way, with highly coordinated projects & funding sources



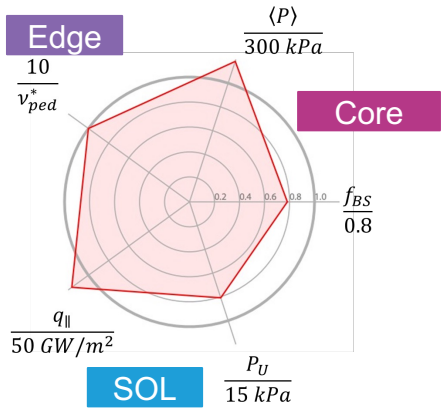
Ex: We're developing economical solutions for divertor/first wall

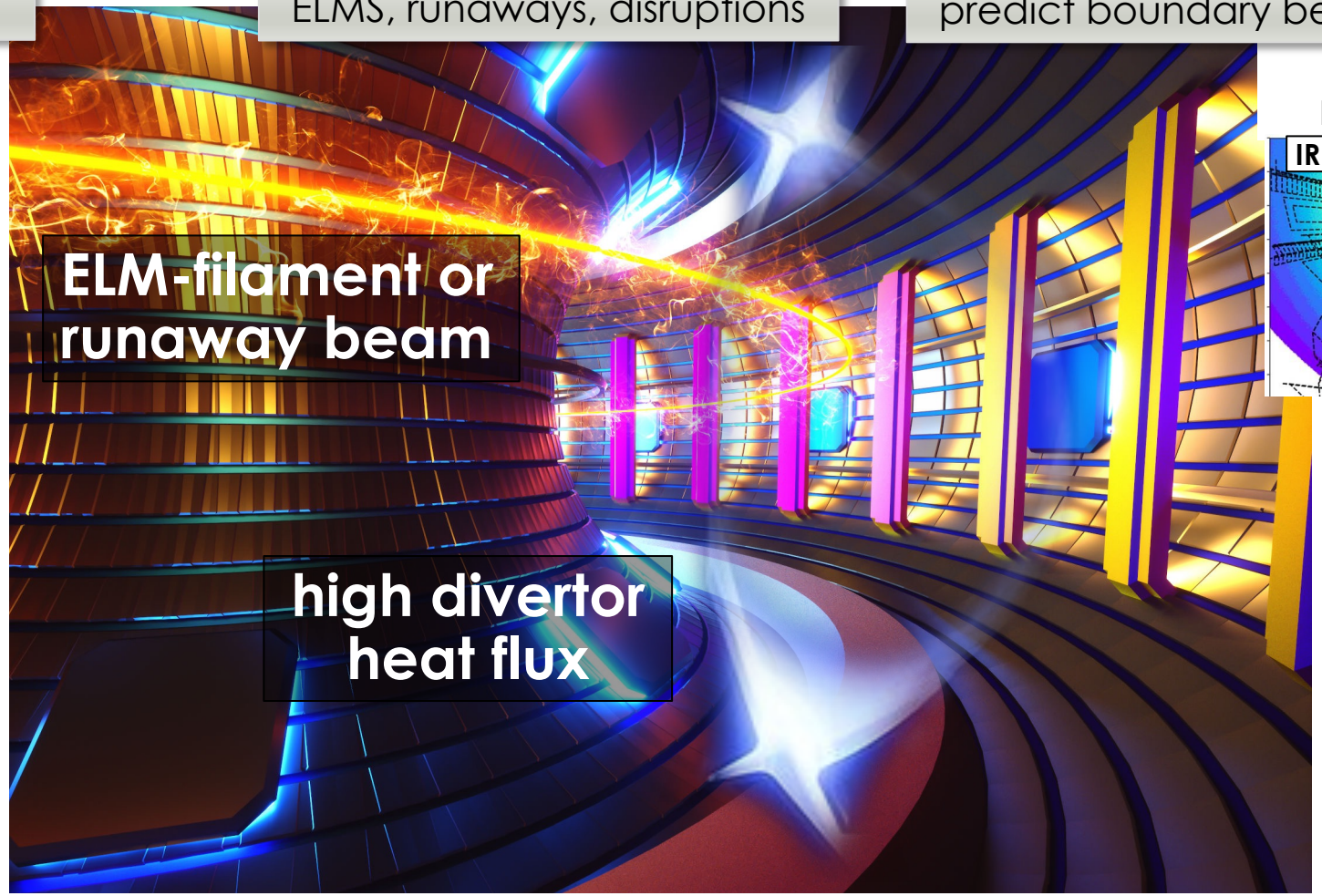
core | divertor | first wall | blanket/fuel | vessel/structural | magnets

Optimized Integrated Prediction

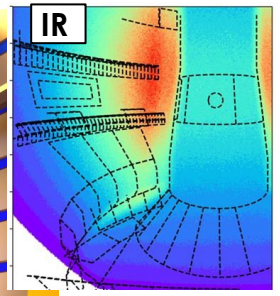
Mitigate or avoid ELMS, runaways, disruptions

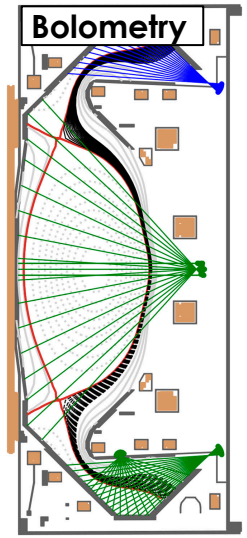
Validate across machines to predict boundary behavior





Novel Diagnostics





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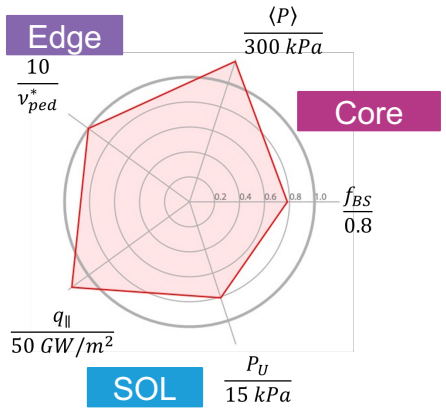
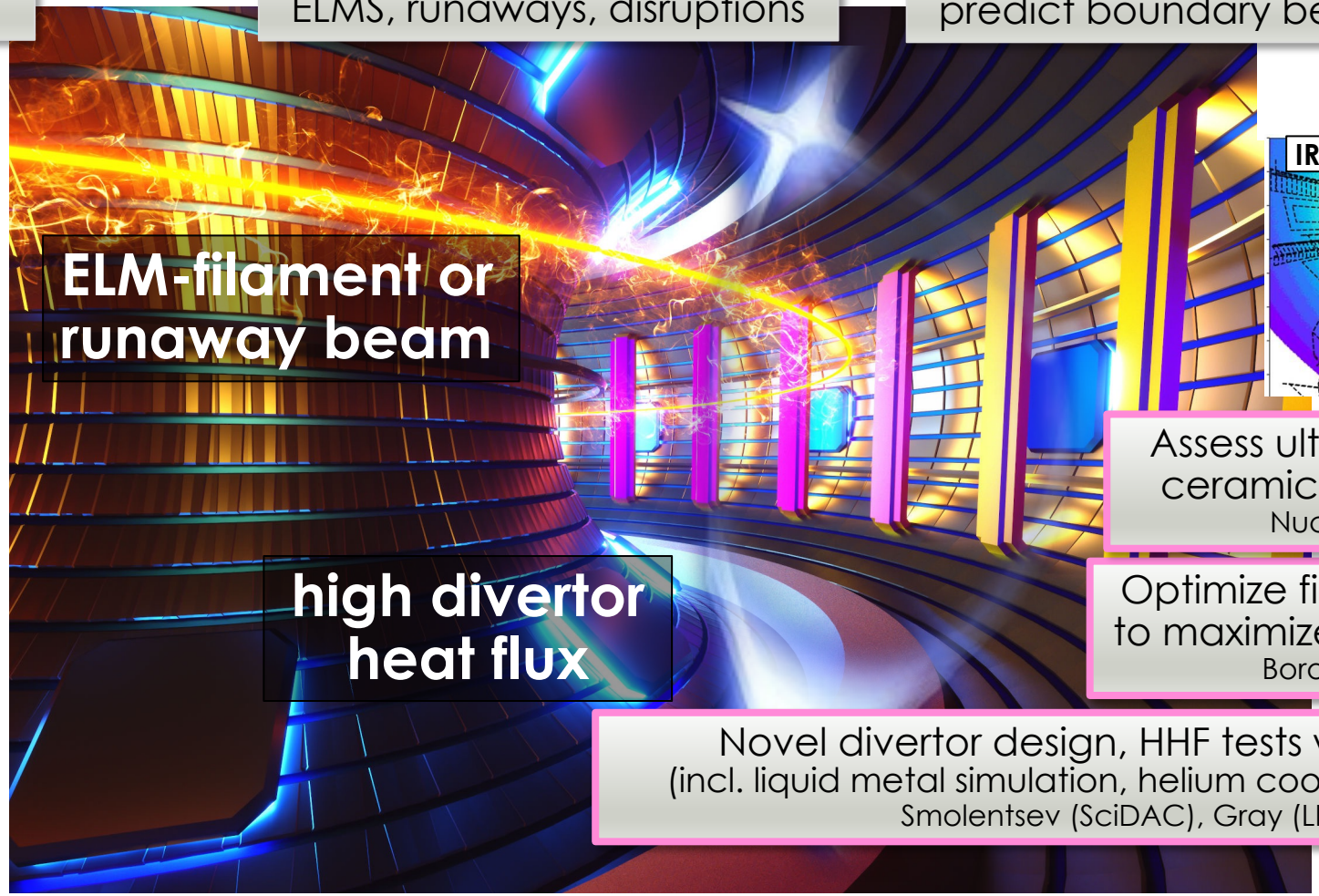


Mitigate or avoid ELMS, runaways, disruptions

Validate across machines to predict boundary behavior



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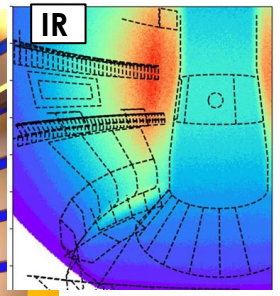

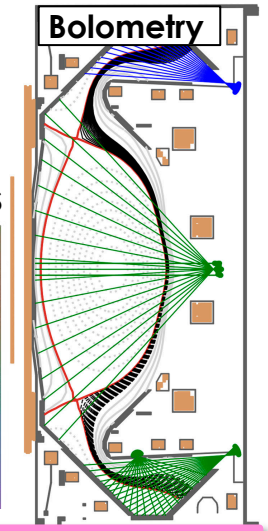

Assess ultra high temperature ceramics as limiter materials
Nuckols (FES postdoc)

Optimize first wall geometry to maximize tritium breeding
Borowiec (LDRD)

Novel divertor design, HHF tests w/ 800kW e-beam
(incl. liquid metal simulation, helium cooled component testing)
Smolentsev (SciDAC), Gray (LDRD), DIII-D

Ex: We're developing economical solutions for divertor/first wall

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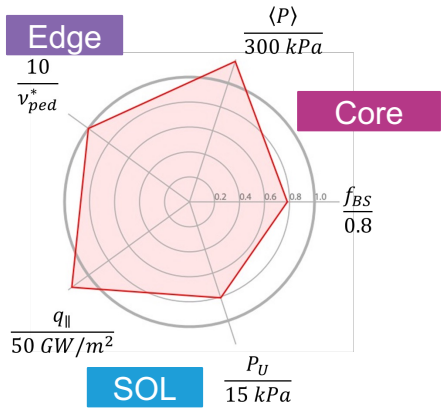

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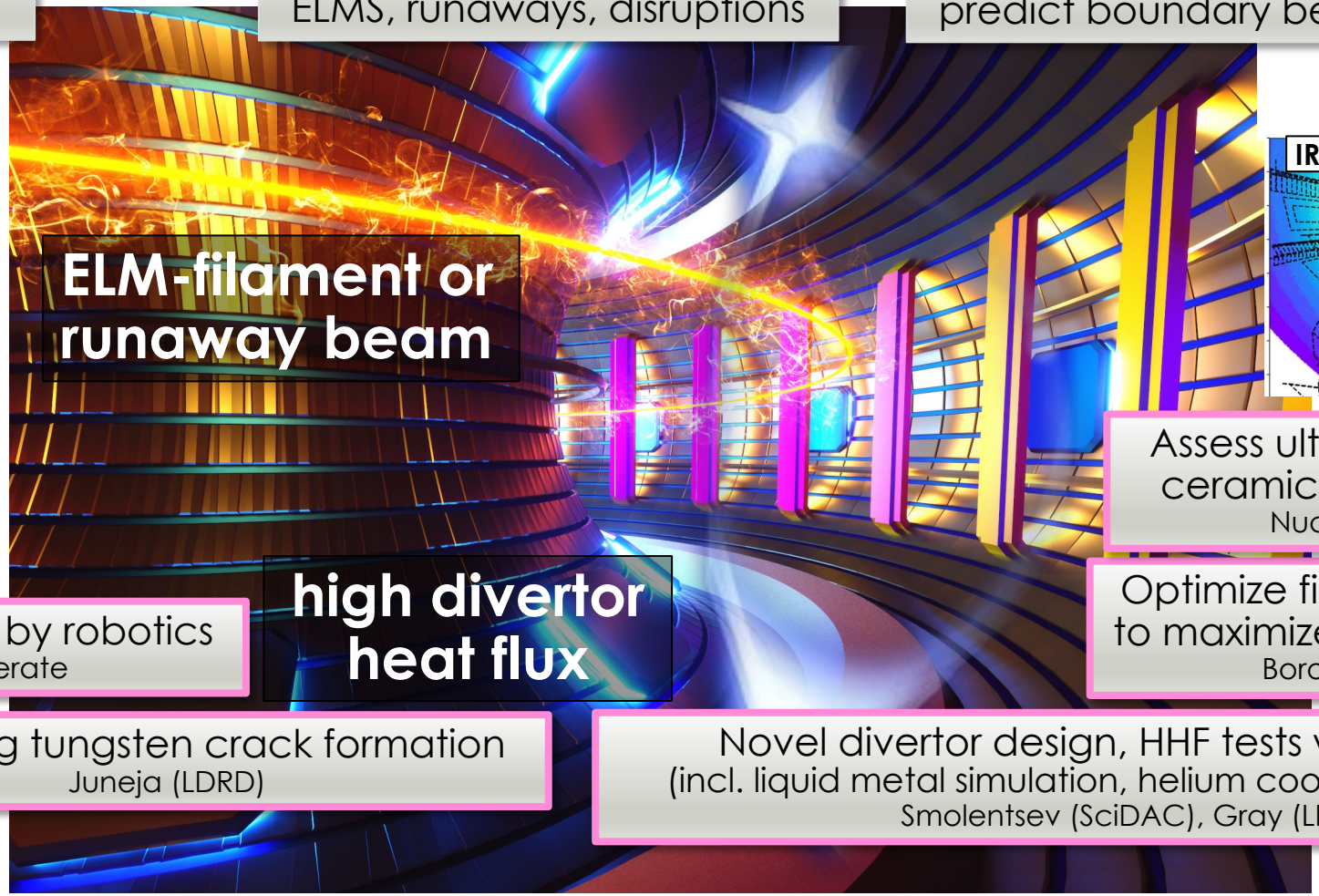

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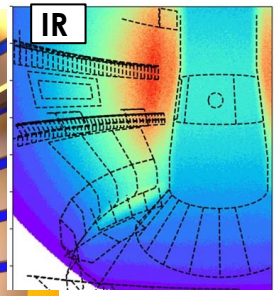
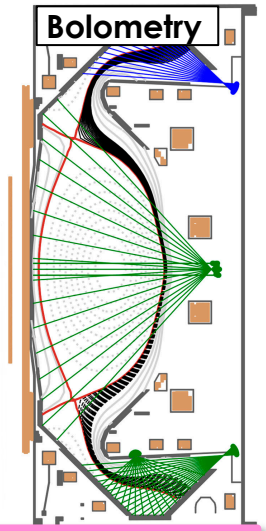




Assess ultra high temperature ceramics as limiter materials
Nuckols (FES postdoc)

Optimize first wall geometry to maximize tritium breeding
Borowiec (LDRD)

In-situ repair of armor by robotics
Varma, FES Accelerate

Predicting tungsten crack formation
Juneja (LDRD)

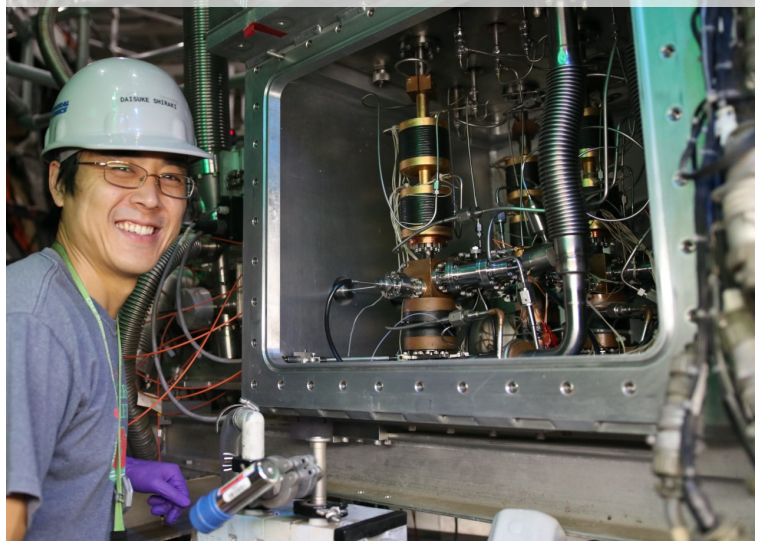
Novel divertor design, HHF tests w/ 800kW e-beam
(incl. liquid metal simulation, helium cooled component testing)
Smolentsev (SciDAC), Gray (LDRD), DIII-D

We develop techniques and technology for fueling sustained high performance burning plasmas

core | divertor | first wall | blanket/fuel | vessel/structural | magnets

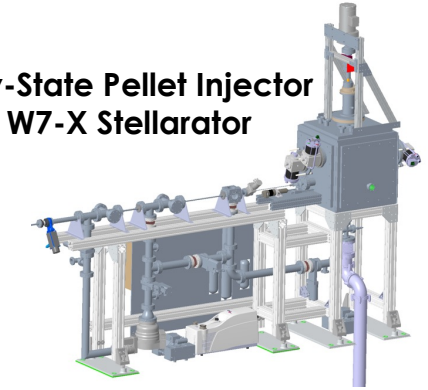
Impact of pellet fueling on plasma scenario ⟷ Requirements and development of steady-state fueling and pumping in a closed loop

Pellet Fueling Experiments on DIII-D Tokamak

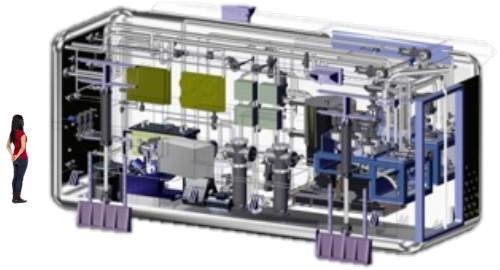


Delivering technology

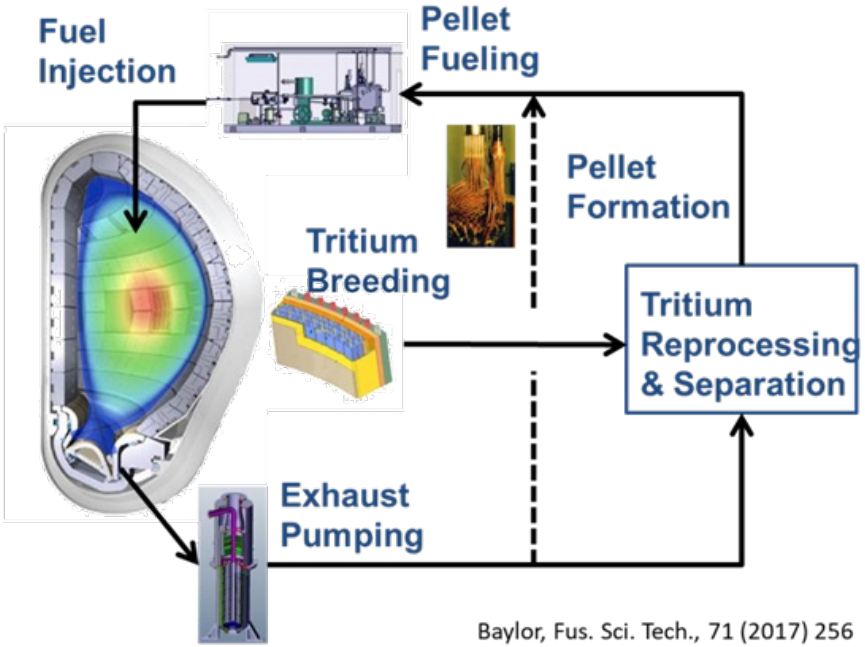
Steady-State Pellet Injector on W7-X Stellarator



ITER Pellet Injector



+ INFUSE (Tokamak Energy pellet injector)



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

+ **reactor-relevant diagnostics** like ITER DRGA for continuous monitoring & control

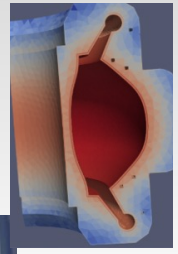
We're doing foundational R&D for blankets

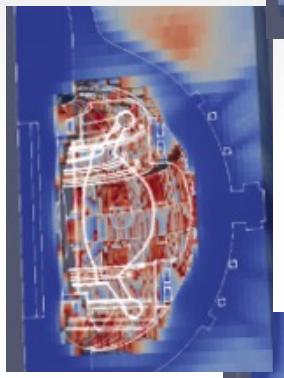
Analytical design evaluation/exploration ⟷ ***Experimental*** fusion breeders and coolants

base Blanket & Fuel Cycle (FES), Badalassi (ARPA-E), Smolentsev (SciDAC)

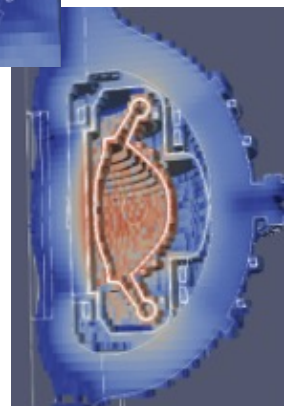
Neutronics

volumetric energy deposition





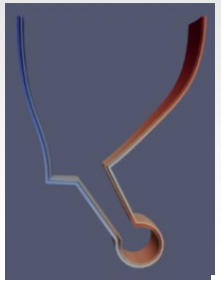
material activation, damage



shutdown dose rate

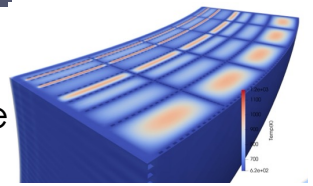
Thermo-mechanics

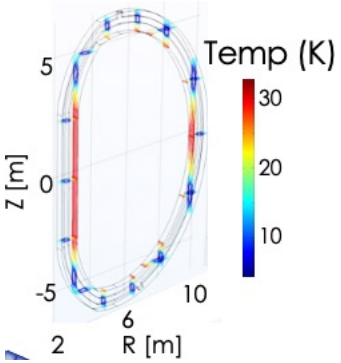
with irradiated property evolution



displacement

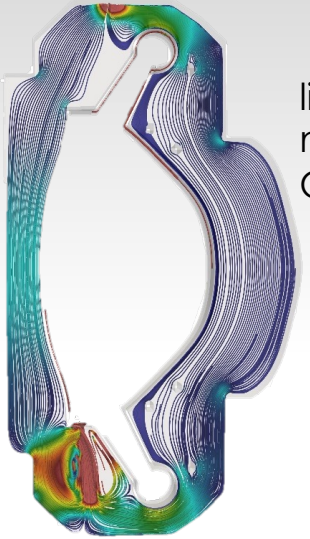
blanket temperature





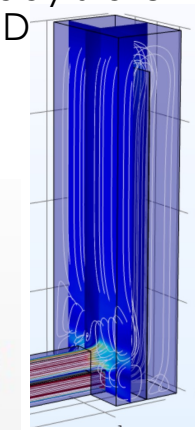
magnet heating

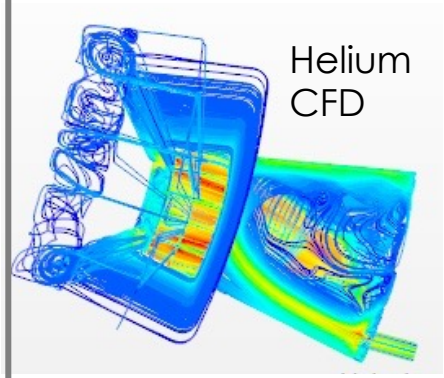
Thermal Hydraulics, MHD



liquid metal CFD

transient + steady state MHD

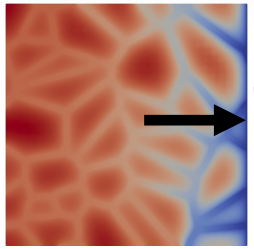




Helium CFD

Tritium Migration

Tritium in ceramic breeder grains

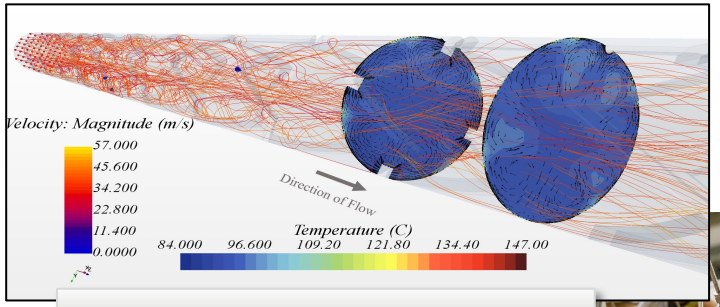


We're doing foundational R&D for blankets

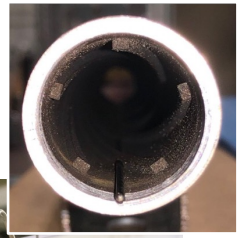
Analytical design evaluation/exploration ⟷ ***Experimental*** fusion breeders and coolants

Model + Manufacture + Test Components

Ribbed surface enhances heat transfer



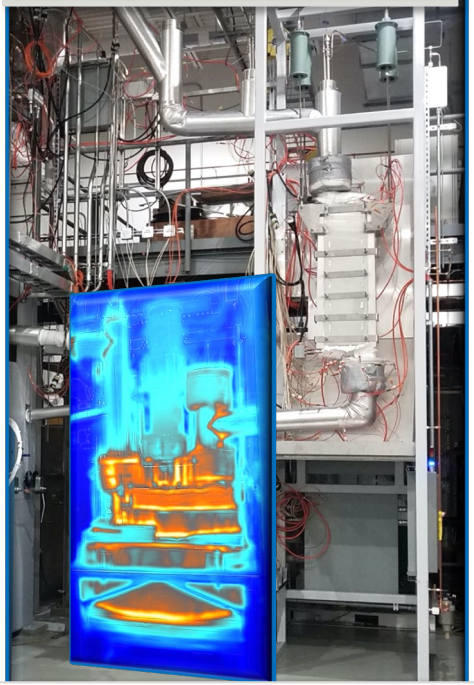
Advanced Manufacturing



Helium Cooling Test Bed

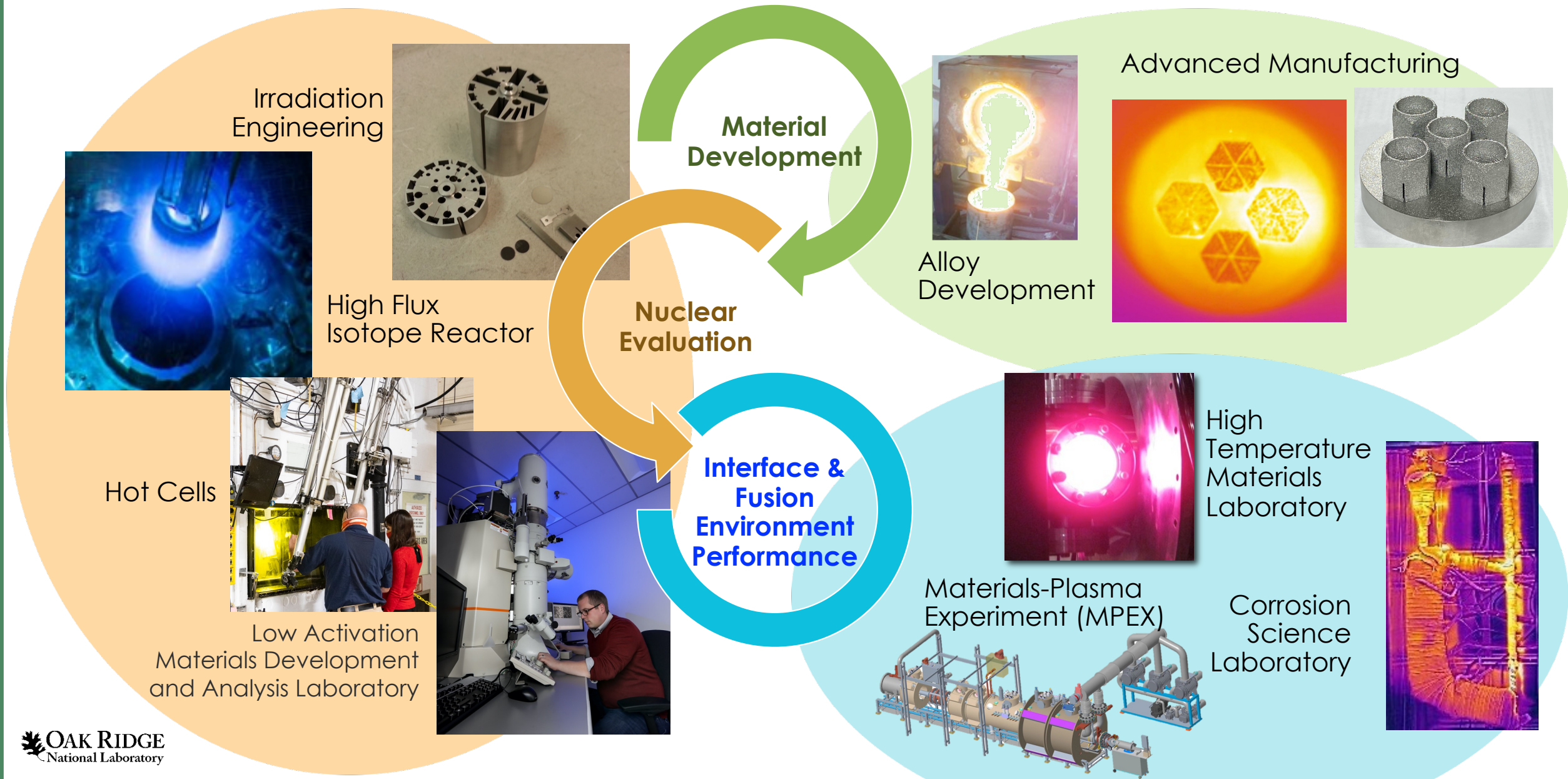
Materials Qualification

Molten Salt Testing



+ Testing PbLi Compatibility with Ferritic Steel in Thermal Convection and Corrosion Loop

The frontier: leverage facilities to take coupons → components, guided by integrated design/assessment



Why is simulation needed for fusion reactor design?

- Remarkable progress has led to construction of devices to demonstrate net energy gain, such as ITER and SPARC
  - But these devices are still far from FPP regime (extrapolation required)
  - In some cases there are no current experiments (need to simulate neutron damage)
- Simulations can save time and money
  - Catch issues with integration (de-risk with physics-based prediction and uncertainty)
  - Expedite innovative solutions (freedom to experiment in a virtual testbed)
- Simulations are needed for safety, economics/scalability
  - Many concepts will need evaluation of shielding, tritium management, materials activation and lifetimes *before you build*

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Fusion REactor Design and Assessment (FREDA) is a new SciDAC project that aims to utilize our best modeling tools to speed reliable fusion power plant design.

Oak Ridge National Laboratory | Lawrence Livermore National Laboratory | Sandia National Laboratories | General Atomics | UC San Diego

FREDA

+ contributions from many others, incl. Chuck Kessel, AToM teams

The ability to perform rapid *integrated* assessment and iteration before proceeding to detailed reactor design is a fundamental rate limiter

Traditional Fusion Reactor Design Studies

1. Systems code couples large set of simplified plasma + engineering relations to find target design point

2. Humans spend time drawing geometry/CAD

3. Feasibility is checked with complex high-fidelity simulations

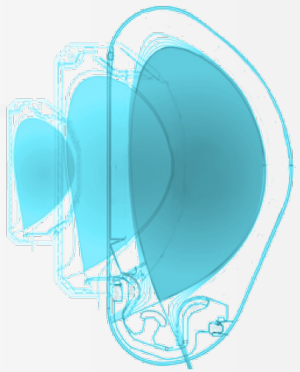
multi-physics

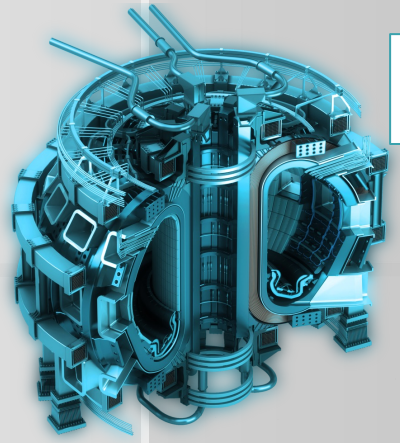
SCIENCE DRIVERS

Control, Sustain, and Predict Burning Plasma

Handle Reactor Relevant Conditions

Harness Fusion Power





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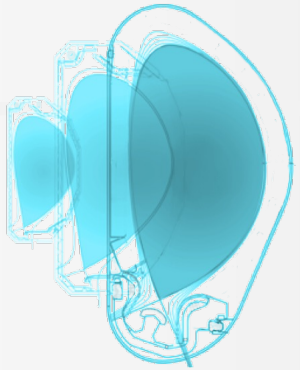
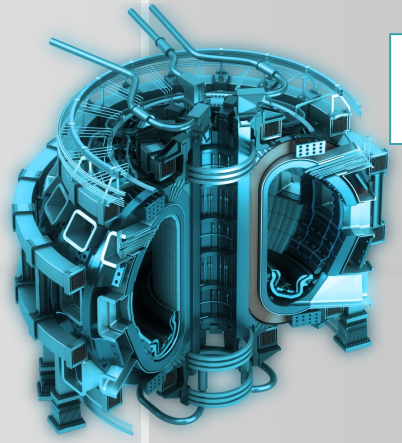
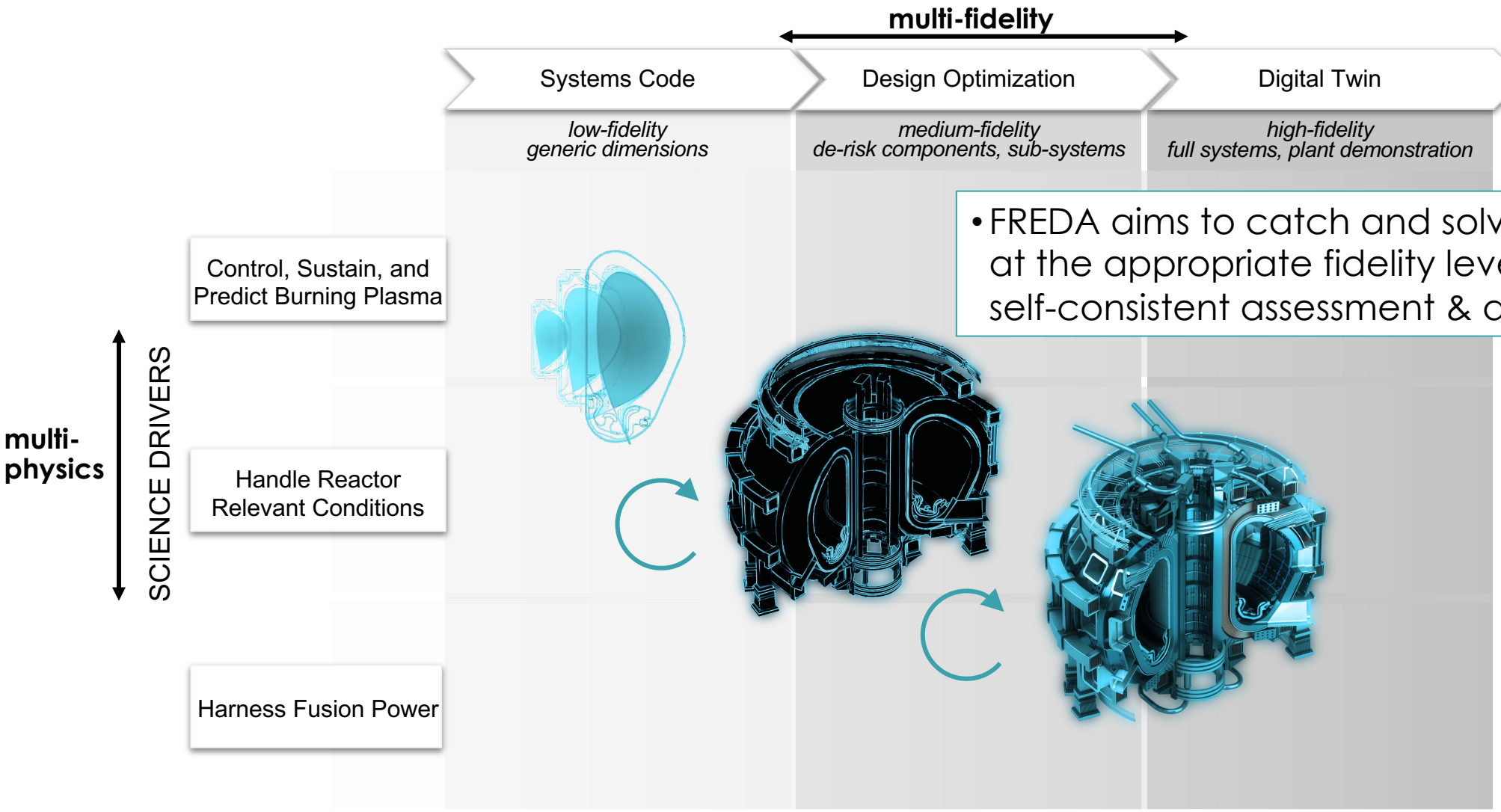




- Issue: **Empirical scaling misses connections** between plasma (e.g. actual profiles) and the machine design →design point not necessarily feasible or optimum

FREDA is a purpose-built framework for multi-fidelity assessment, uncertainty quantification, and iterative optimization with parametric design



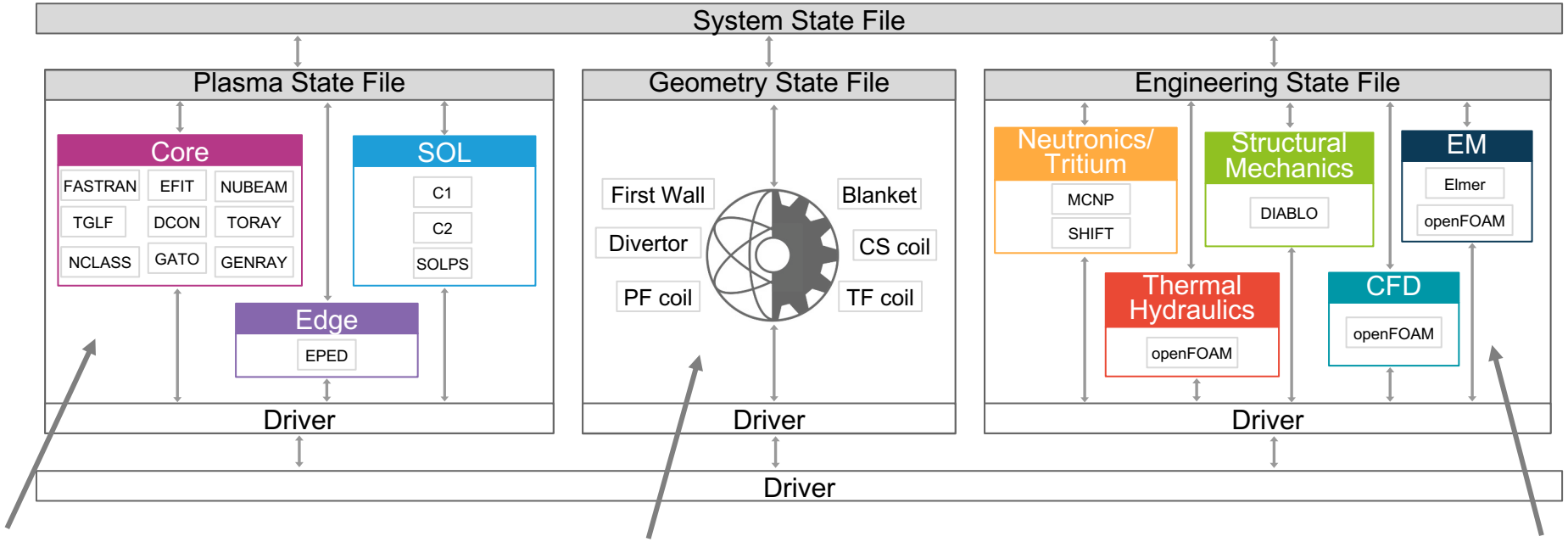
- FREDA aims to catch and solve 'show-stoppers' at the appropriate fidelity level using self-consistent assessment & design optimization

Will initially apply to tokamaks/STs, can expand to stellarators

Approach: flexible component-based framework & data structure

Framework & Workflow

Capable of integrating swappable modules with diverse CPU/GPU requirements



Fusion-Plasma

- Based on the open-source IPS (Integrated Plasma Simulator) developed in AToM SciDAC (over a decade)

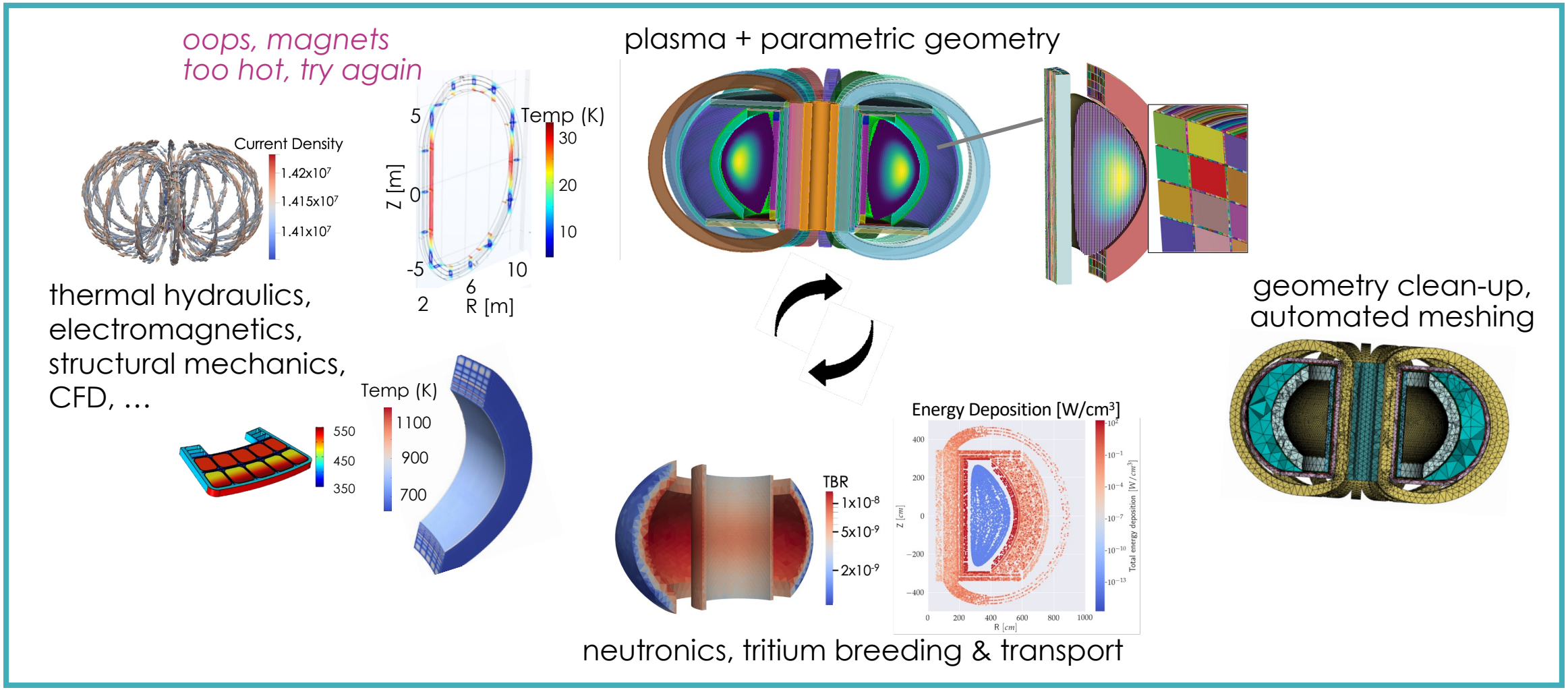
Parametric Geometry

- CAD is drawn by codes (or AI), not people

Fusion-Engineering

- Includes multiphysics simulation tools based on Fusion Energy Reactor Models Integrator (FERMI) (developed in past 3 years)

FREDA will help us see how each of the physics/engineering components and uncertainties impacts the full system



→ use it to optimize on different things (aspect ratio, TBR, materials limits/component lifetime, …)

Summary

- Integrated plasma and engineering simulation and testing is needed to develop deep expertise & speed credible, commercially viable fusion reactor designs
- ORNL is ready to start the milestone program, new centers & facility construction
  - We're actively supporting roadmapping process
    - blanket & fuel cycle, materials
    - need similar activity in simulation, focused on integrated design and virtual testbed
  - We're ready to help advance new facility requirements/design