Challenges in Fusion Energy Development and Technology Opportunities

Presented at

DIII-D Industry Day

General Atomics - G34

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Plasma Performance Continues to be Recognized as the Biggest Challenge Facing Fusion Energy Development

- **Near term (5-10 yrs)**
  - Fusion performance
  - Funding
- **Post-demonstration**
  - Fuel cycle
  - Materials
  - Plant lifecycle

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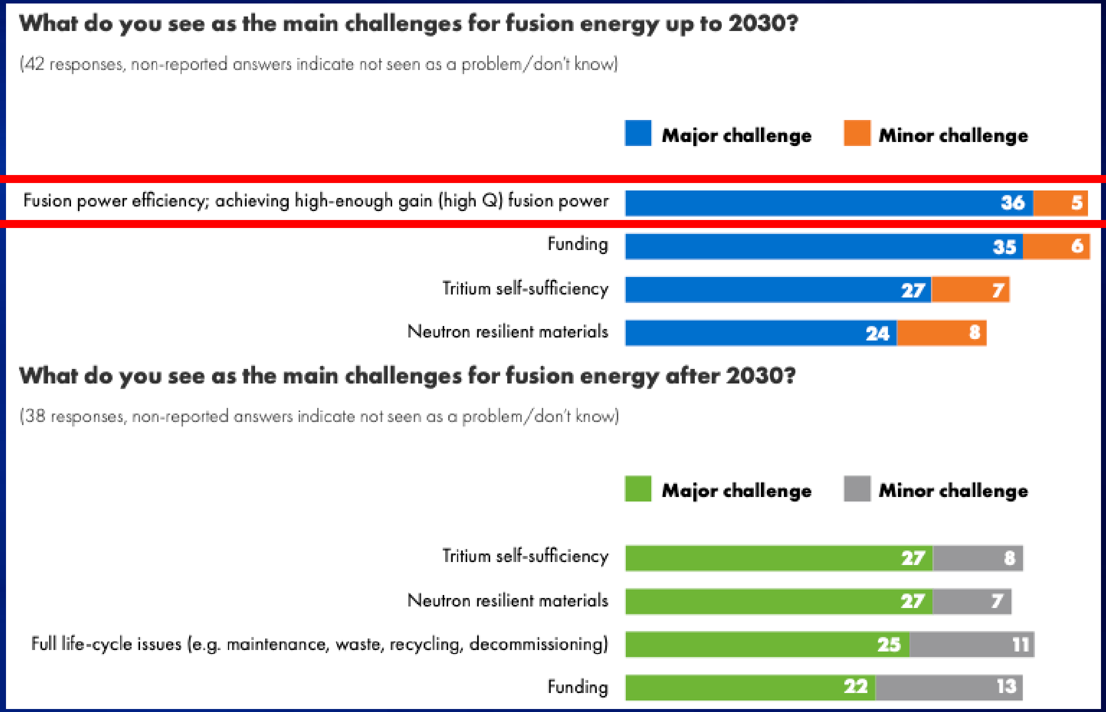

Conclusion from Mike Bell's excellent seminar on TFTR in 2014*

- Confinement was the outstanding issue ***and remains so***

*available at fire.pppl.gov/TFTR.html

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Where Capital is Being Deployed *Now* Reinforces the Challenge on Demonstrating Sufficient Plasma Confinement

Intent is voiced, but priority is funded

- **Commonwealth Fusion Systems**
  - **SPARC** → ARC
- **Helion Energy**
  - **Polaris** → Orion
- **Tokamak Energy**
  - **ST80** → FPP
- **Type One Energy**
  - **Infinity One** → Infinity Two
- **Thea Energy**
  - **Eos** → Helios
- **Realta Fusion**
  - **Anvil** → Hammir


Loading TRISO-X fuel pebble in ATR for X-Energy, Nov 2025

***Opportunity**: Leveraging flexibility of DIII-D (like ATR) as a platform to de-risk design and operation over next 5-10 years*

Representative selection of magnetic fusion companies
Devices in green indicate physics validation devices

2025 Roadmap Articulates Broader Portfolio of Challenges Beyond Plasma Confinement & Performance

Core Challenge Areas

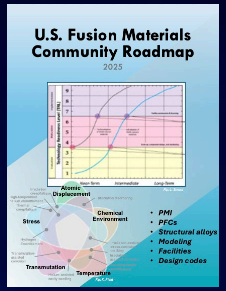
	Structural Materials Science & Technology	Survive extreme low and high temperatures, high stress and neutron damage.
	Plasma-Facing Components and Plasma-Materials Interactions	Designing and testing materials and systems that can endure fusion's extreme heat flux, neutrons, and plasma interactions to ensure durable, maintainable reactor components.
	Advancing Confinement Approaches	Understanding and controlling burning plasmas to achieve stable, high-performance confinement and sustained fusion energy.
	Fuel Cycle and Tritium Processing	Developing closed-loop systems to produce, manage, and recycle fusion fuel safely and efficiently.
	Blanket Science & Technology	Advancing and testing blanket systems to ensure efficient heat extraction, tritium breeding, and long-term reliability.
	Fusion Plant Engineering & System Integration	Designing and integrating the full fusion power plant—power conversion and controls to maintenance, robotics, and digital modeling.

- **Build the enabling infrastructure**
  - Leverage the existing *now*
  - Mindset of "and" not "or"
- **Accelerate digital integration**
  - Digital twins of existing assets to inform design of next generation
- **Leverage FIRE Collabs and public-private partnerships**
  - Going *far* means going *together*

Opportunities are in creative use of existing facilities now while building future capabilities

Specific Technology Categories

Structural Materials – From Steels to Advanced Composites



Challenges

- Fusion-spectrum irradiation and transmutation uncertainty
- Harsh coolant/breeder interactions Tight & conflicting design windows
- Immature routes for manufacturing, joining & inspection
- Incomplete codes and databases for licensing approval
- Insufficient test infrastructure to close gaps on aggressive timelines

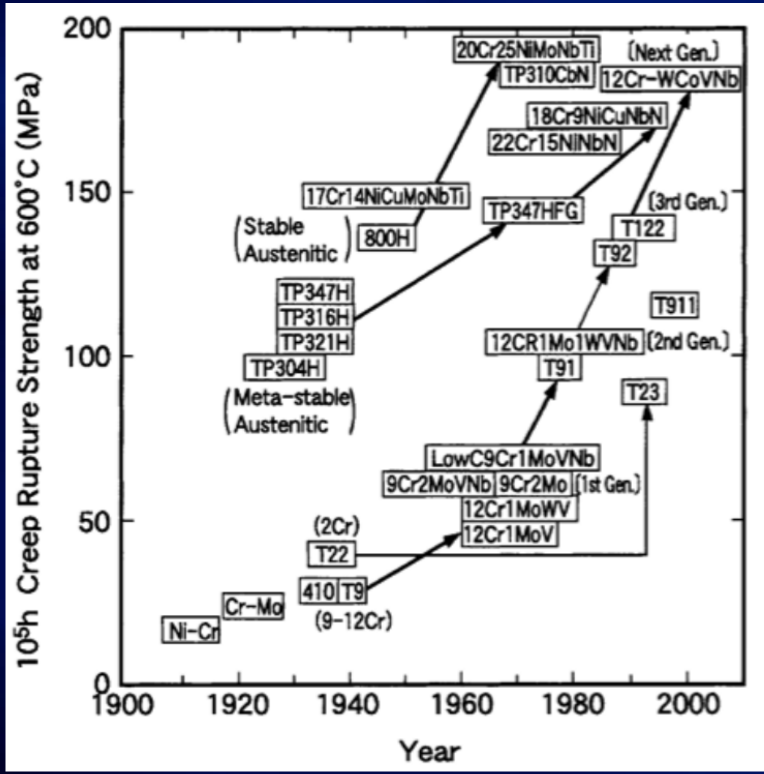
Opportunities

- Deep-blanket-relevant irradiation at national fission user facilities
- Functionally graded and tailored material composition
- Bonding, additive manufacturing, inspection as core fusion tech
- Coordinated irradiation, high-heat-flux, and corrosion databases

Turn radiation limits into design rules

Low-Activation Structural Materials for Fusion
Fe-Steels, V-Alloys & SiCf/SiC Back in U.S. Focus

Ferritic martensitic steel

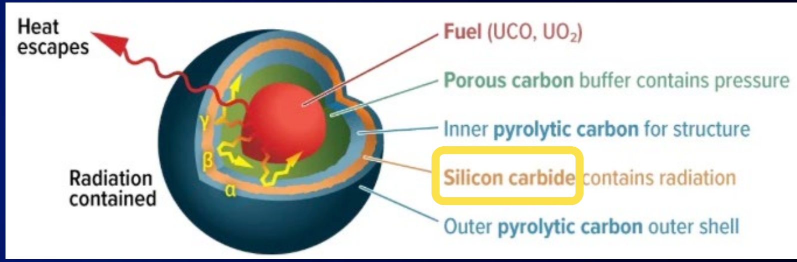


Improvement through optimization of thermo-mechanical processing and microstructural precipitates

Vanadium Alloys

Dedicated program produced qualification data on tensile strength, thermal creep, and demonstration of multiple welding techniques

Silicon Carbide (SiCf/SiC)



Maturing technology with a defined set of metrics around irradiation data, hermeticity, joining, and probabilistic design methods to reach TRL 6/7

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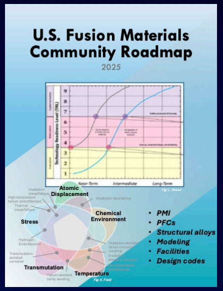
Plasma Facing Materials – The First Line of Defense



Challenges

- Extreme, coupled loads;
  Heat fluxes, 14 MeV neutrons, plasma bombardment
- Controlling surface evolution and tritium behavior with re-dep, co-dep, changes in surface chemistry
- Recovering from off-normal events without coolant ingress
- Closing the integration gap with sufficient safety basis & margin

Opportunities

- PFMs not material but co-designed material-interlayer resisting sputtering, thermal shock
- Tritium control into an engineered surface-interface-coolant technology system
- Self-healing & shielding concepts
- ↑ HHF testing facility incl. above ↑

Turn the plasma-facing wall from a survival challenge to a designed system

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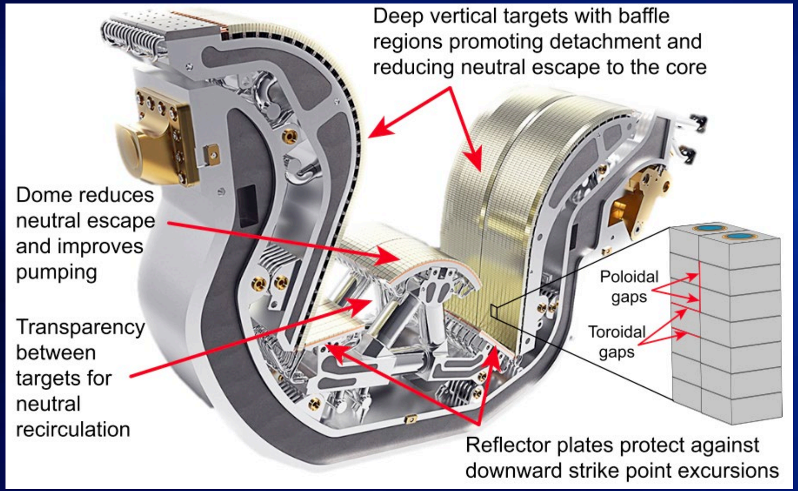
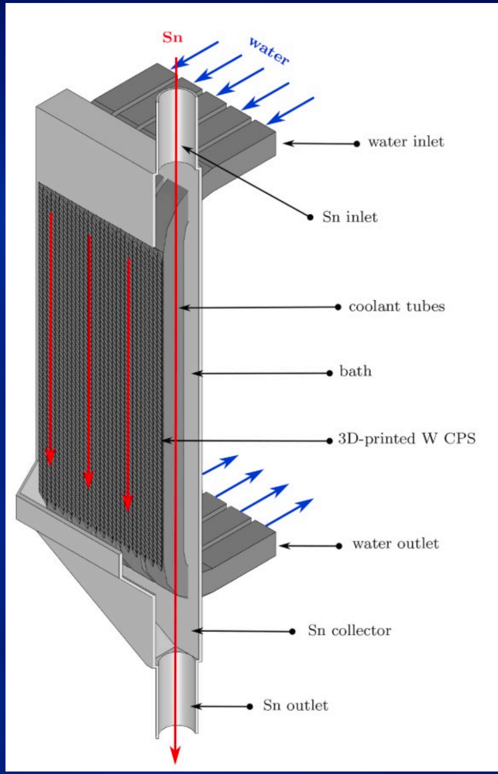
Power-plant Levels of Neutron Damage and Heat Flux Demand Innovations over State of the Art

State of the Art



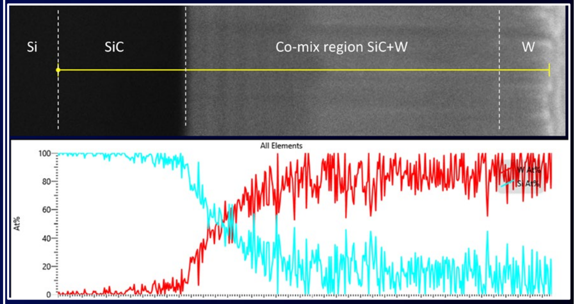
Water-cooled W-monobloc ITER Divertor is highest TRL high-heat-flux component for fusion ever manufactured

Self-healing Liquid Metal Surface



Capillary porous system maintains liquid tin surface on tungsten substrate with continuous material replenishment

Fiber-based and Functional Graded Surfaces



Retain favorable W properties (high T_{melt}) while mitigating shortcomings (brittle) with fibers and functional grading

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Continuous Tritium Processing and Approaches to Low Inventory Operation Remain to be Developed

Challenges

- Far from demonstrating tritium self-sufficiency in closed fusion system
- Core units in fuel cycle not ready for continuous operation
- Lack of integrated, tritium-capable test infrastructure at scale
- No shared, architecture-agnostic design and data framework

Opportunities

- Emerging international facilities focusing on sub-scale closed loop
- Direct internal recycling concept for inner loop, smaller T plant
- Increased scale and breadth of H&D testing of materials & systems
- Tools for co-design of holistic blanket/tritium system

Turn the plasma-facing wall from a survival challenge to a designed system

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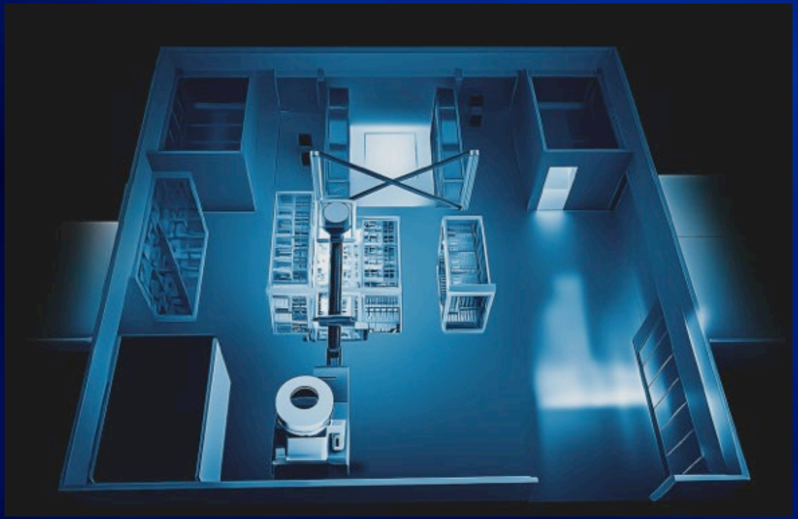
Far Outer Fuel Cycle Technology is Mature
The Opportunity is the Inner Cycles & Systems Optimization

UNITY-2 Facility

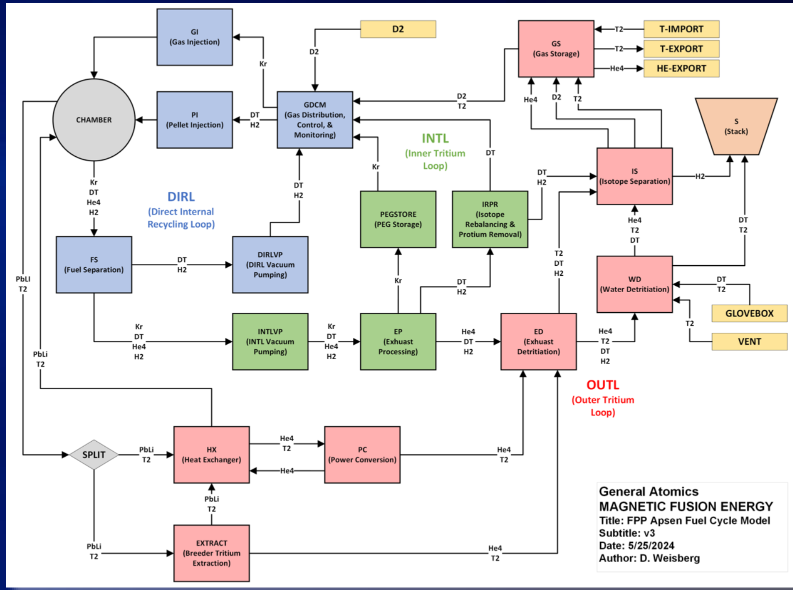


Opportunity to validate closed-loop fuel handling at realistic scales for safe, self-sufficient fusion power plants

Hydrogen Permeators & Barriers

Enables safer, more efficient fuel handling and is essential for achieving reliable, closed-loop fusion fuel cycles

Multi-loop Process Flow



Opportunity to optimize the entire fuel cycle virtually, shortening development cycles and reducing risk and cost

Blankets are the Energy Engine and Fuel Factory Yet No Functioning Blanket Has Ever Been Made

Challenges

- Single-effect tests lack well-known synergistic physical effects
- Materials, chemistry, MHD behavior are not yet understood or qualified
- Design tools and data are insufficient to de-risk & down-select
- The U.S. lacks integrated testbeds to replicate relevant blanket environmental conditions

Opportunities

- Exploit international blanket testbeds now
- Stand up a staged suite of blanket & fuel-cycle facilities
- Create an open blanket property and data ecosystem through FIRE Collaboratives

Blankets are fusion's biggest gap and therefore the biggest opportunity for innovation

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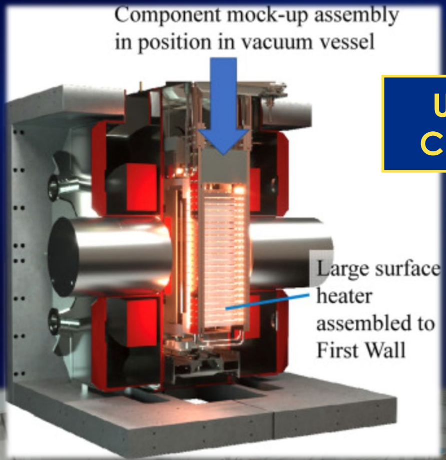
Collaborating Across Borders and Platforms with FIRE + Facilities as a Unified Innovation Engine

Collaborate on Int'l Facilities



UKAEA-CHIMERA

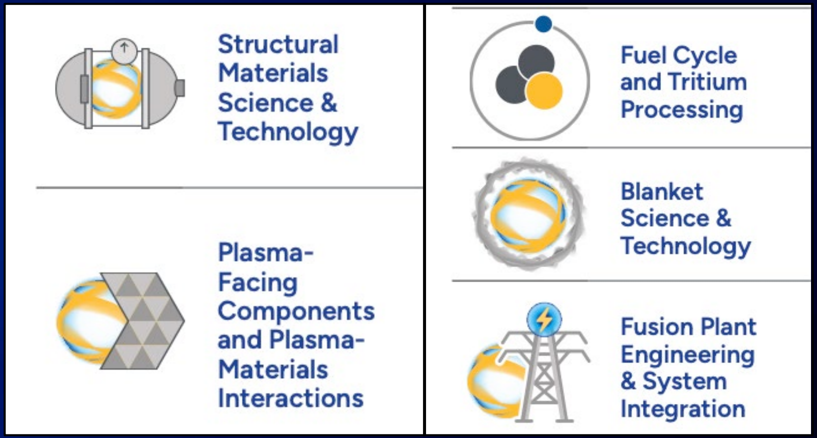
Kyoto Fusioneering-UNITY-1

Attack low-TRL gaps in first wall, materials compatibility, and sub-scale plant tech while domestic infrastructure spins up

Build Upon Domestic Facilities

Grow from from single-effect tests to *eventual* integrated nuclear-grade blanket–fuel-cycle testing facility

Leverage FIRE Collaboratives with Blanket Focus



FEDER
Fusion Energy Data Ecosystem & Repository

Accelerate blanket technical readiness with data-informed design evolution and concept-tailored solutions

Diagnostics and H&CD Systems are Closely Linked
Eyes & Ears + Hands & Feet of the Plant

Challenges

- Achieving efficient, reliable microwave and RF heating & current drive at FPP field & scale
- High efficiency, high voltage NBI
- Delivering a minimal, radiation-hard diagnostics for control-grade measurements
- Developing plant-wide sensing and metrology for operation & maintenance

Opportunities

- Leverage existing and developing domestic dedicated driver test stands for H&CD systems
- Leverage experience from nuclear-qualified ITER diagnostics for the next order of magnitude fluence
- Tie sensing & actuators directly into AI-driven control and digital twins

Efficient actuators, better sensors, robust control - trio that turns plasma into power

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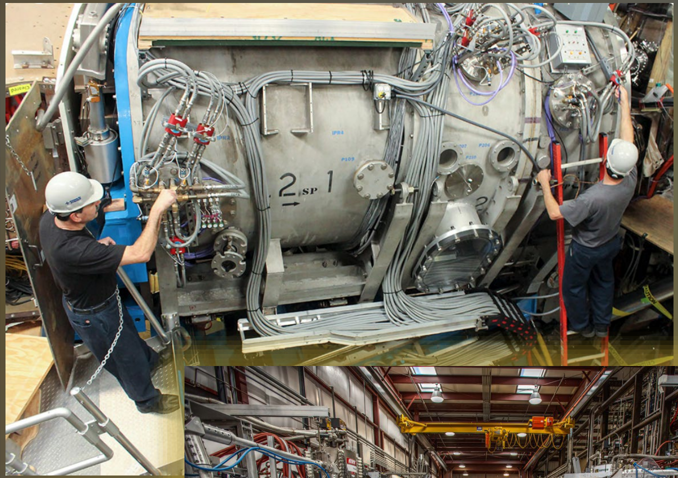
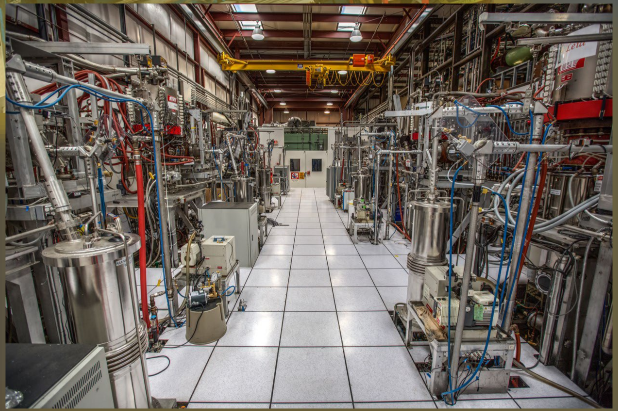
From Proven Actuators to Smart Sensing: Leveraging Today's Systems and Tomorrow's Digital Intelligence for Integrated Fusion Control

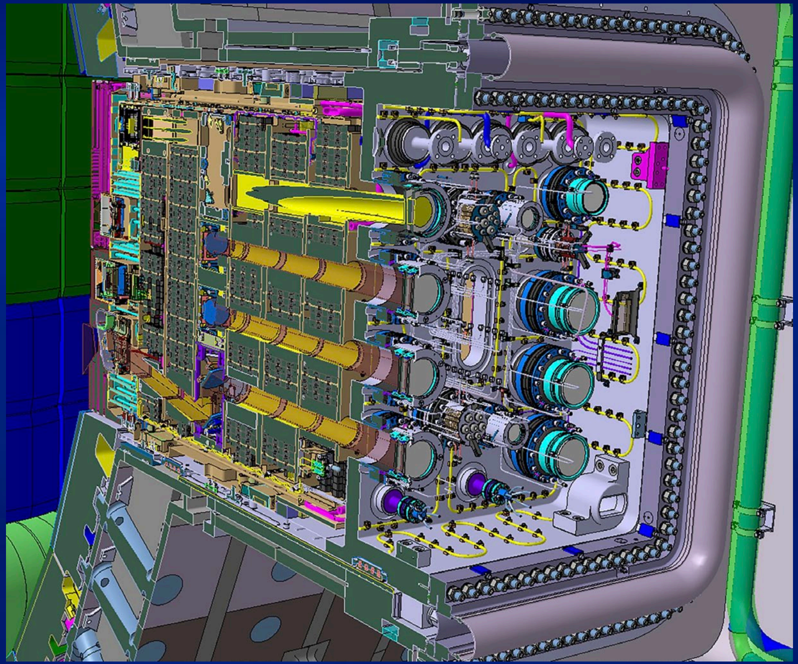
Leverage Existing Capabilities





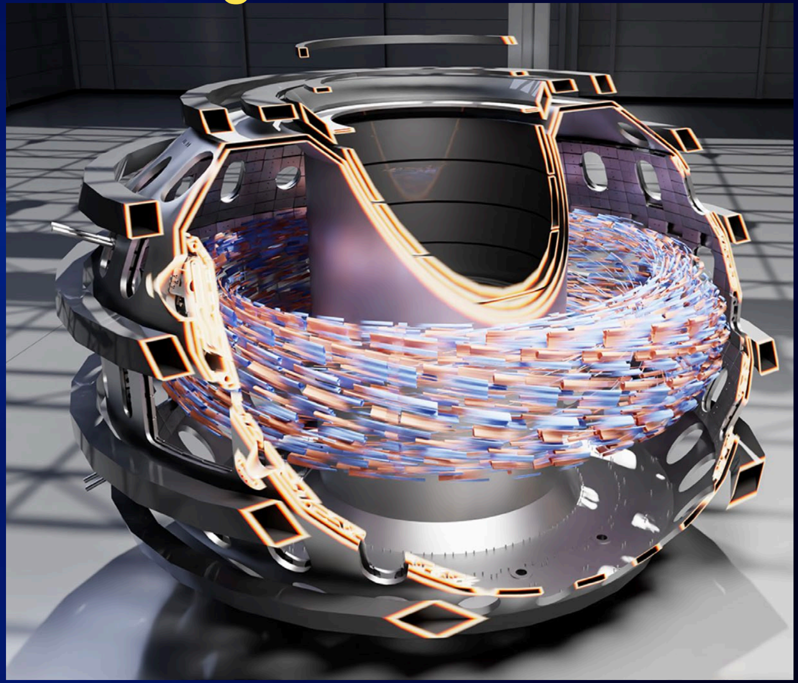
Real-world testbed to prove, refine, and de-risk advanced heating and current-drive systems before deployment

Knowledge Gained from ITER



Crucial head start to define radiation-hard diagnostic requirements and design systems that will robustly perform

Build Foundation for Digital Acceleration



Nerve center that continuously links diagnostics and heating actuators to keep the fusion plasma stable, efficient, and under precise control

Summary & Perspective

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Unleash your inner entrepreneur. Search for challenge and exploit it as an opportunity.

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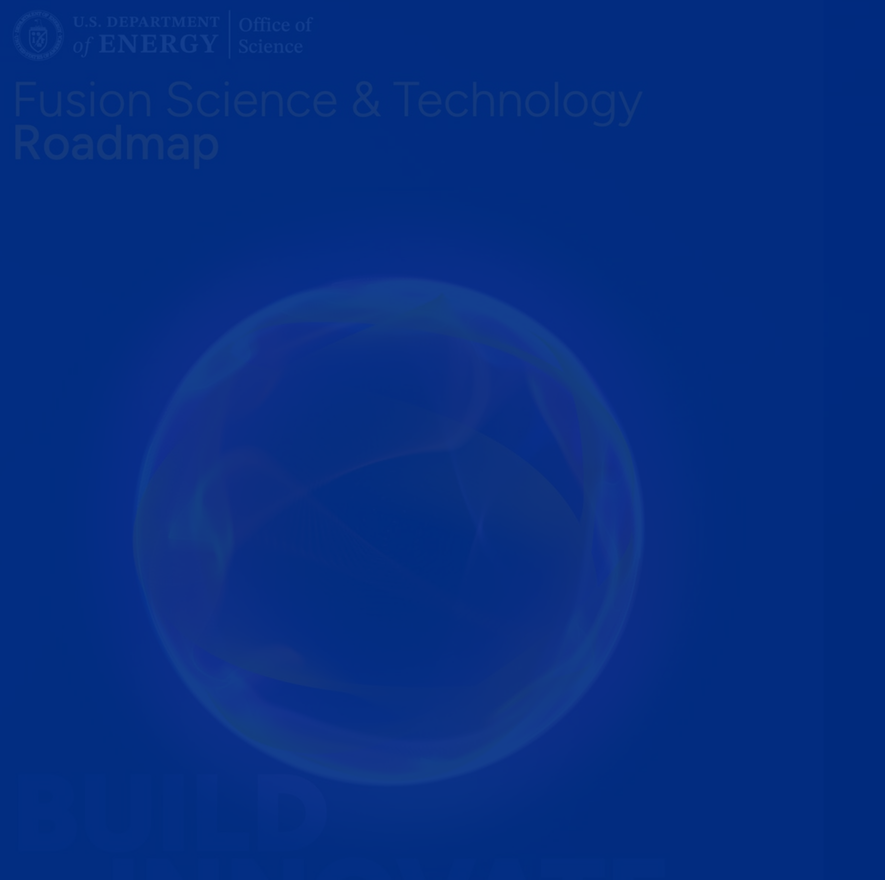

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Questions?

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