Fusion's Tipping Point – How AI and Technology Breakthroughs Are Fueling a Global Race

Presented by:

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General Atomics

6th National Research Platform Workshop

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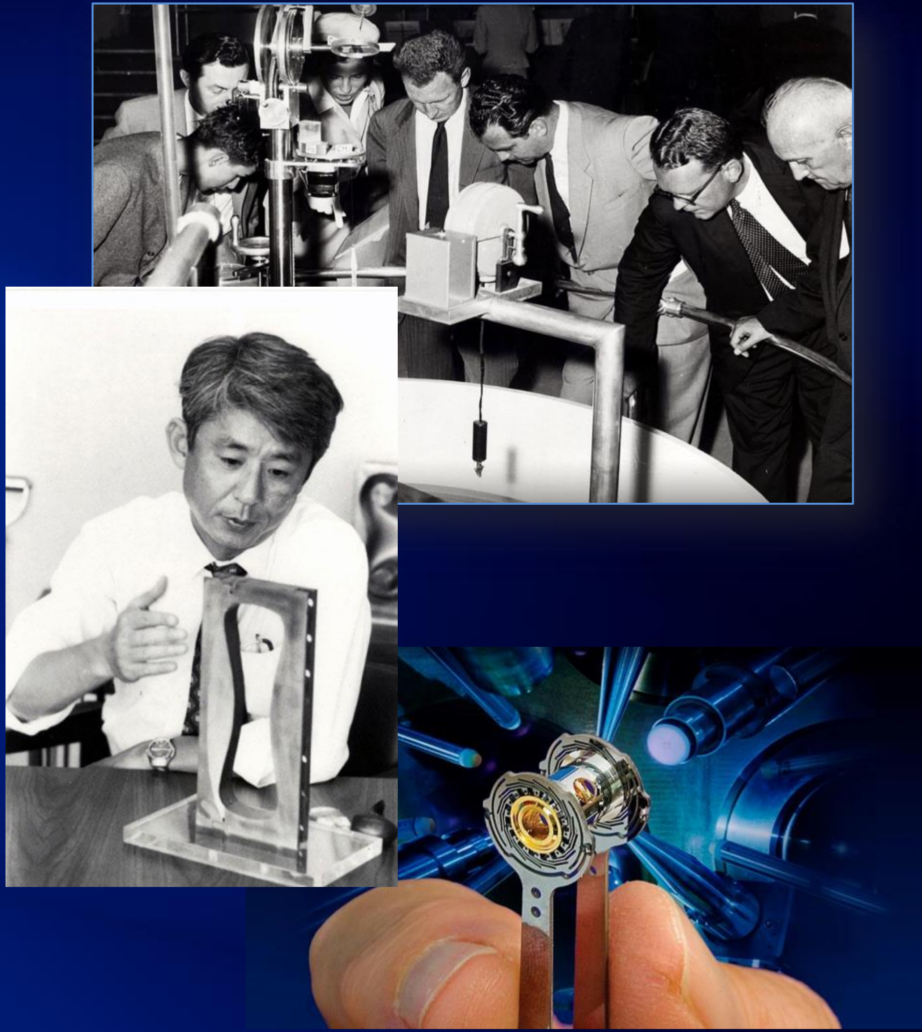
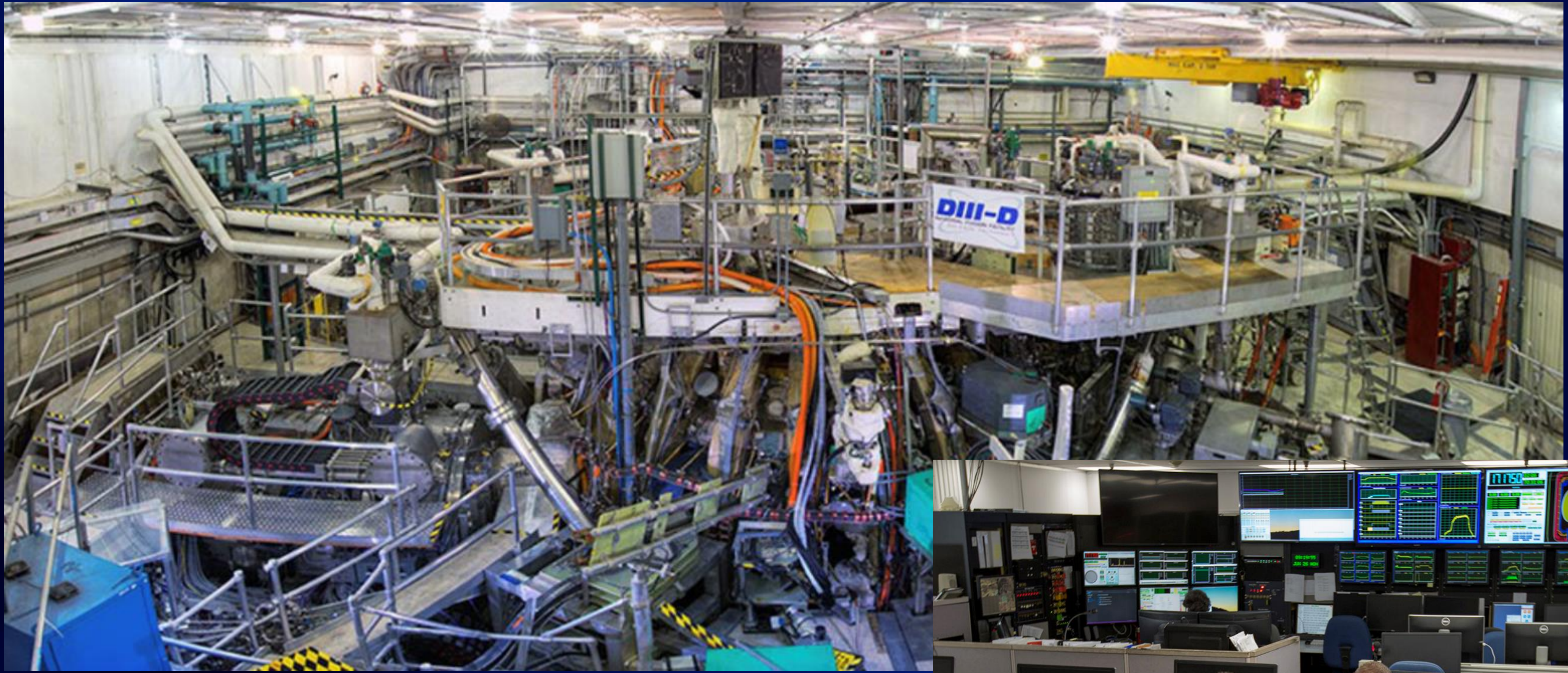
GENERAL ATOMICS

General Atomics is Across the Road From UCSD, Founded in 1955 After Eisenhower's Atoms for Peace Conference



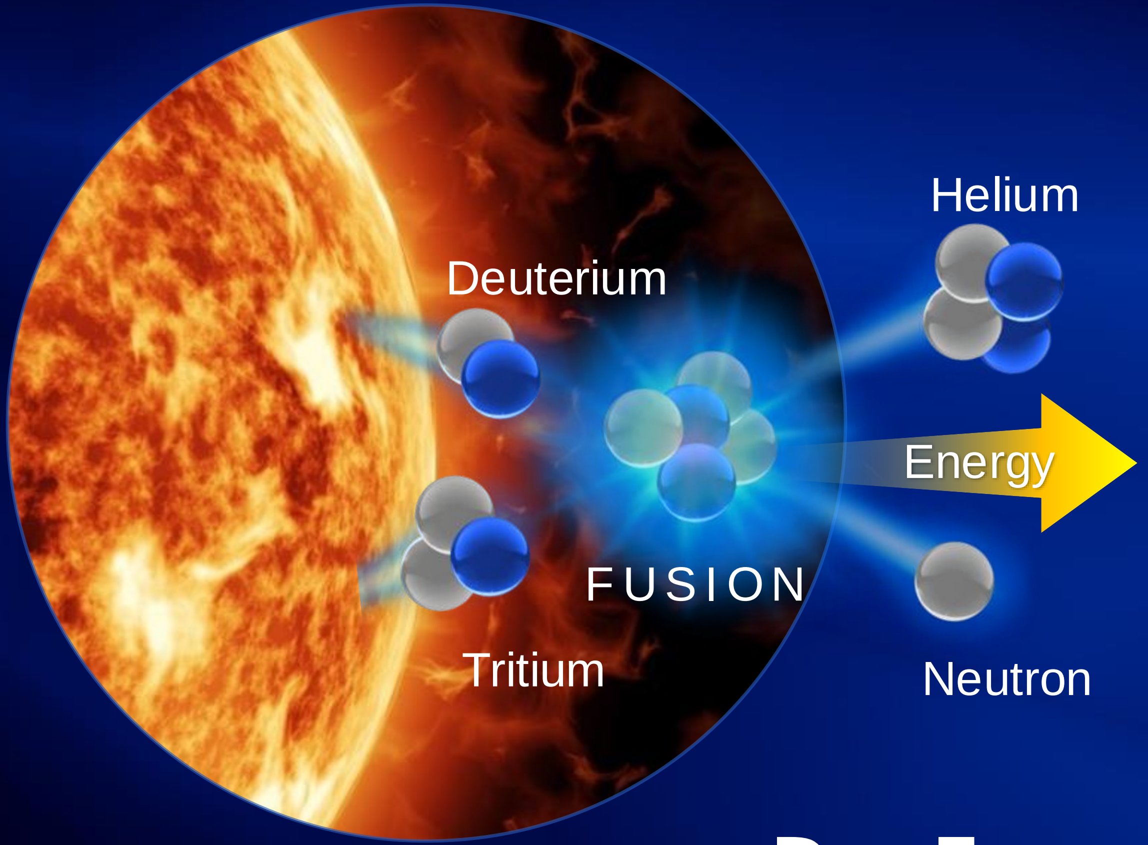
General Atomics Operates the DIII-D National Fusion Facility for the Department of Energy

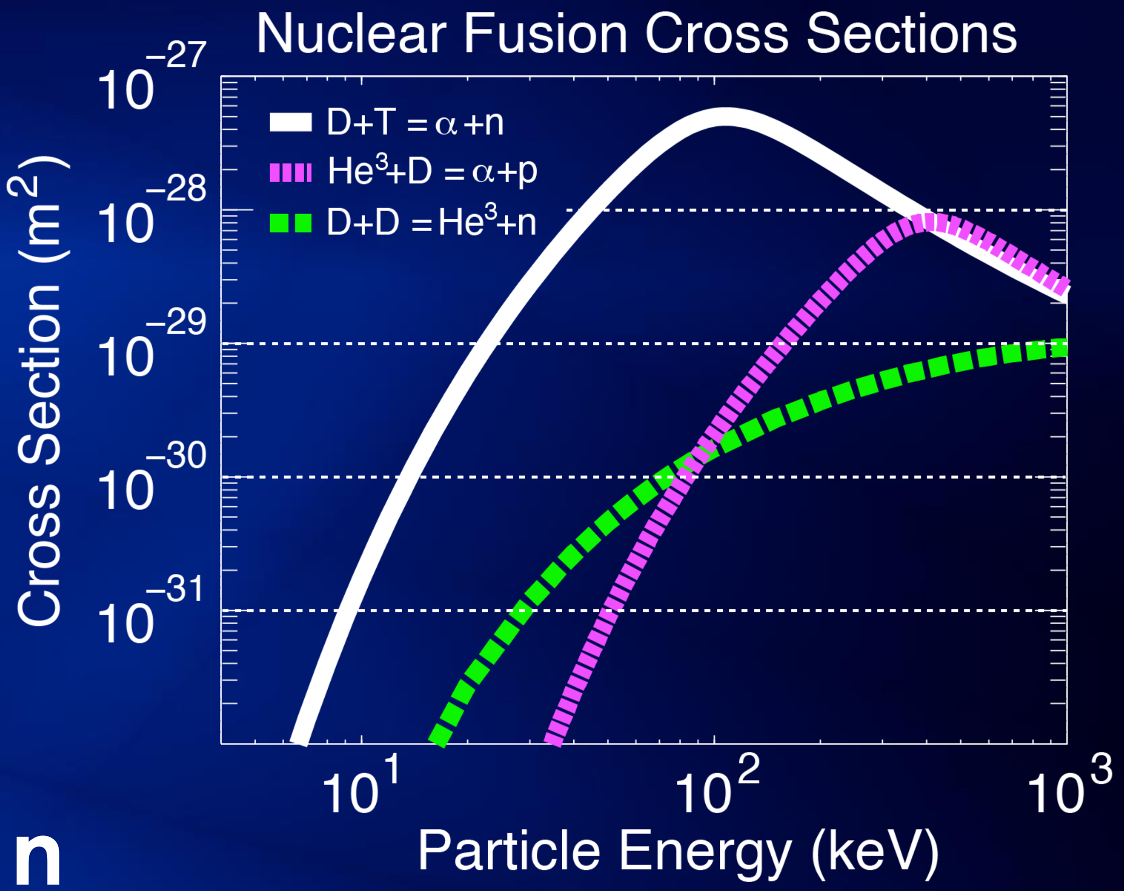
- DIII-D is the leading US fusion facility and key testbed for developing AI/ML solutions to fusion energy challenges due to its advanced diagnostic capabilities and operational flexibility



FUSION: Nearly Limitless Potential with Practical Challenges

- 400x energy gain per successful collision; most collisions are not successful





D + T → ⟨ + n

Requires ~100 M deg.

FUSION: Nearly Limitless Potential with Practical Challenges

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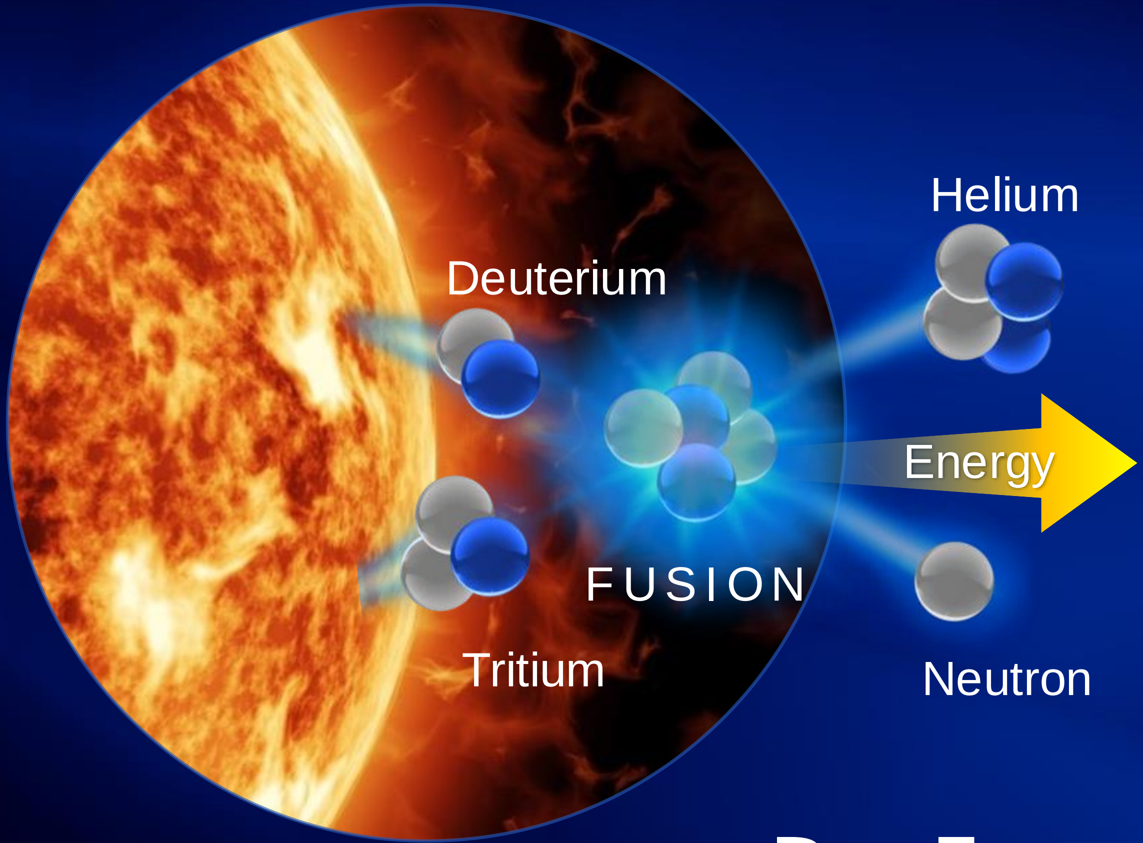

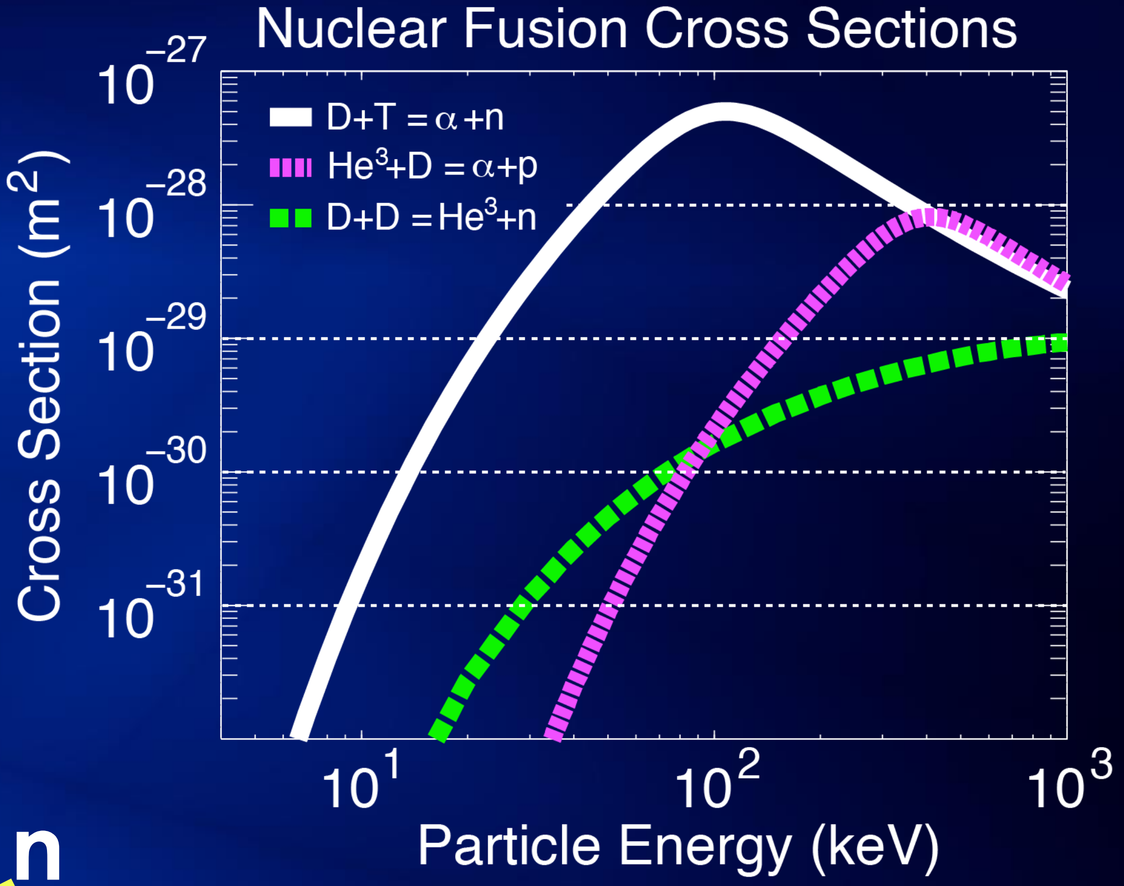

$$D + T \rightarrow \langle + n$$

$$^{6}Li + n \rightarrow \langle + T$$

Requires T breeding

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The Potential of Fusion: 1 gram of deuterium-tritium fuel equals the energy from about 2,400 gallons of oil

1 m^3 of sea water yields 30g deuterium fuel
→ Essentially inexhaustible source of energy

Challenges of fusion:

→ Attaining net energy gain

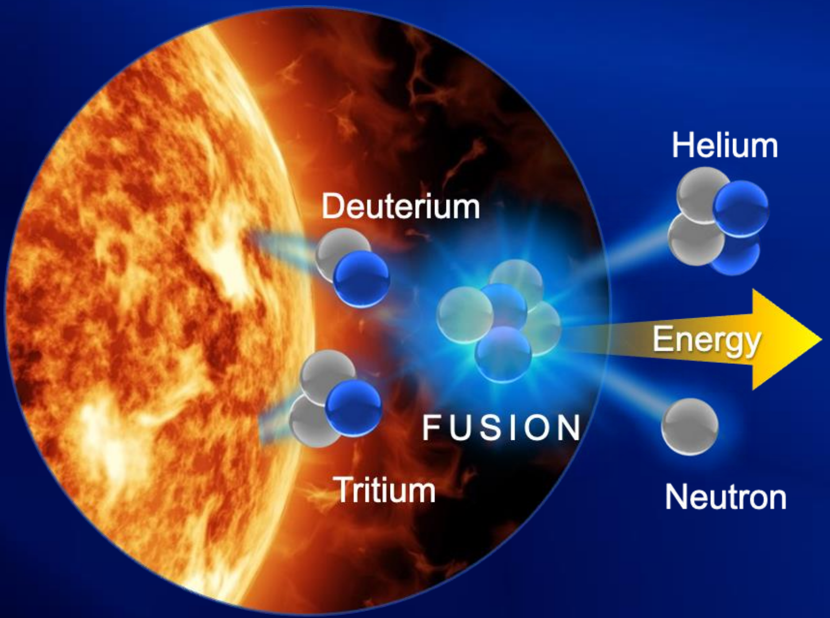
→ Achieving continuous operation

→ Avoiding instabilities that can damage facility

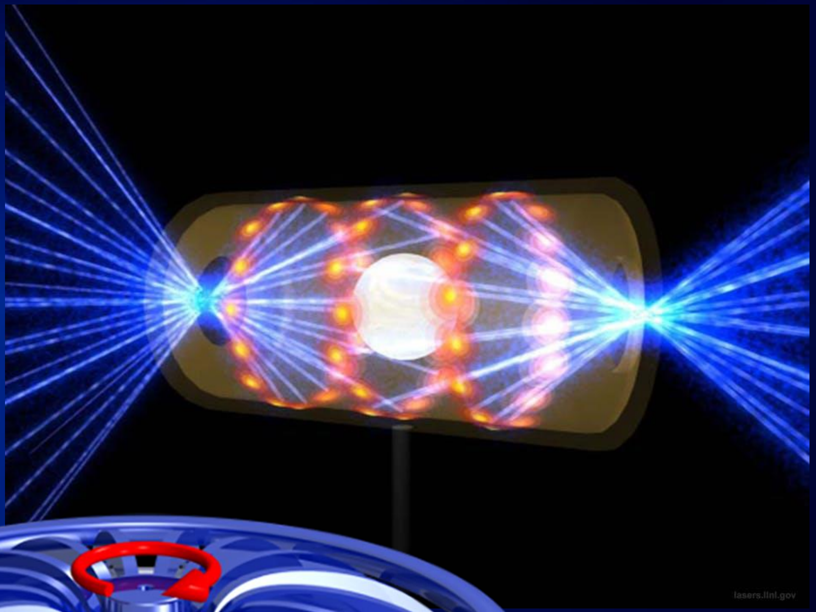
→ Reducing capital and operating cost

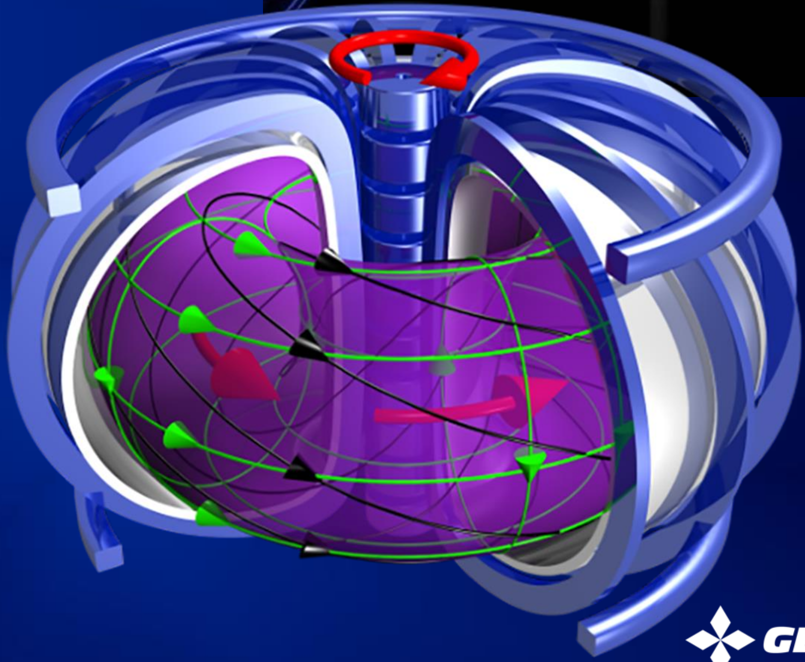
→ Managing complexity

Two Main Approaches to Fusion Energy



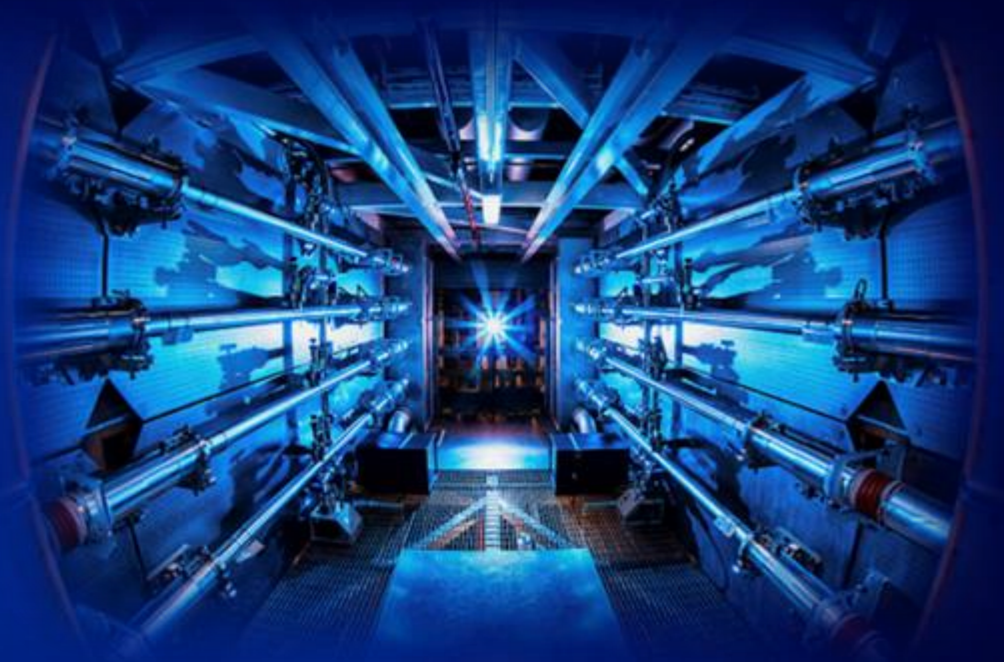
Inertial fusion





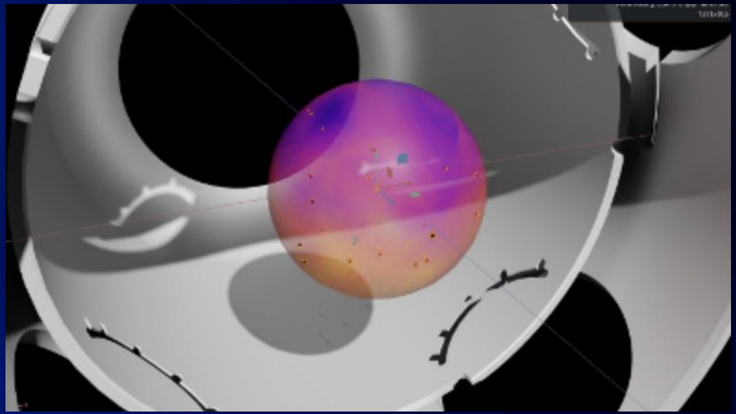
Magnetic fusion

In a Historic Announcement, National Ignition Facility (LLNL) Overcame The First Challenge – Attaining Net Energy

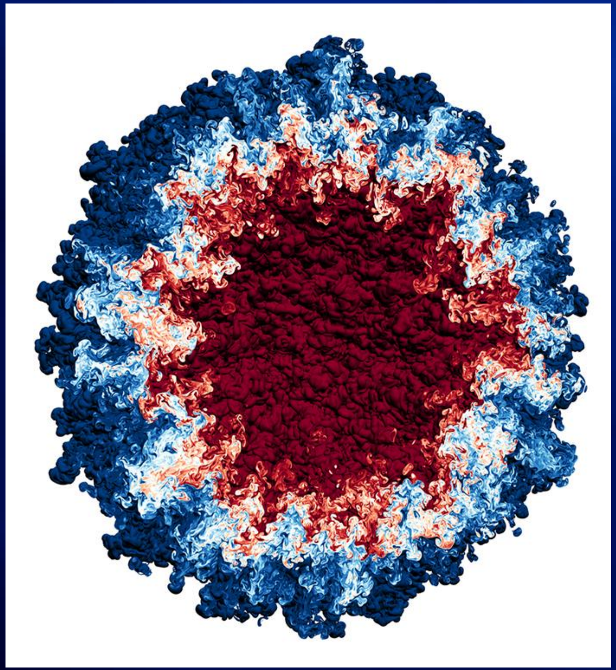


2 MJ input → 4 MJ output

Target produced at General Atomics →

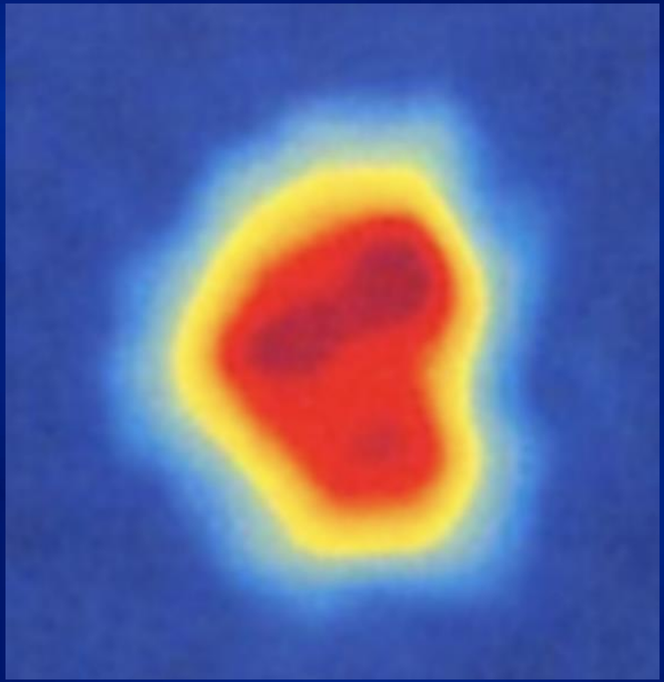


Tipping Point: Machine-Learning Methods Played A Key Role in Optimizing Fusion Yield Starting Circa 2019



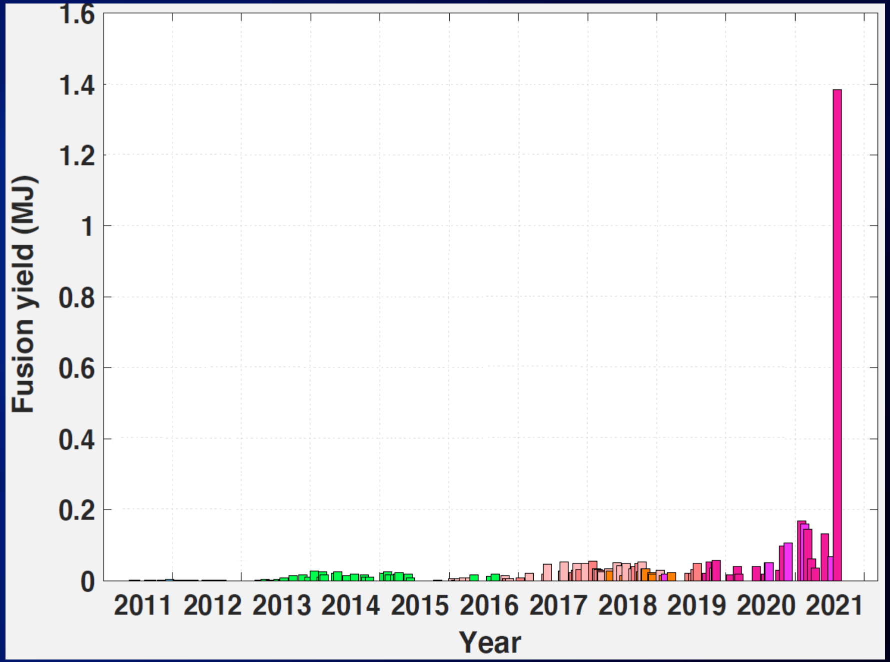
3D HYDRA simulation

+



X-ray imaging, …

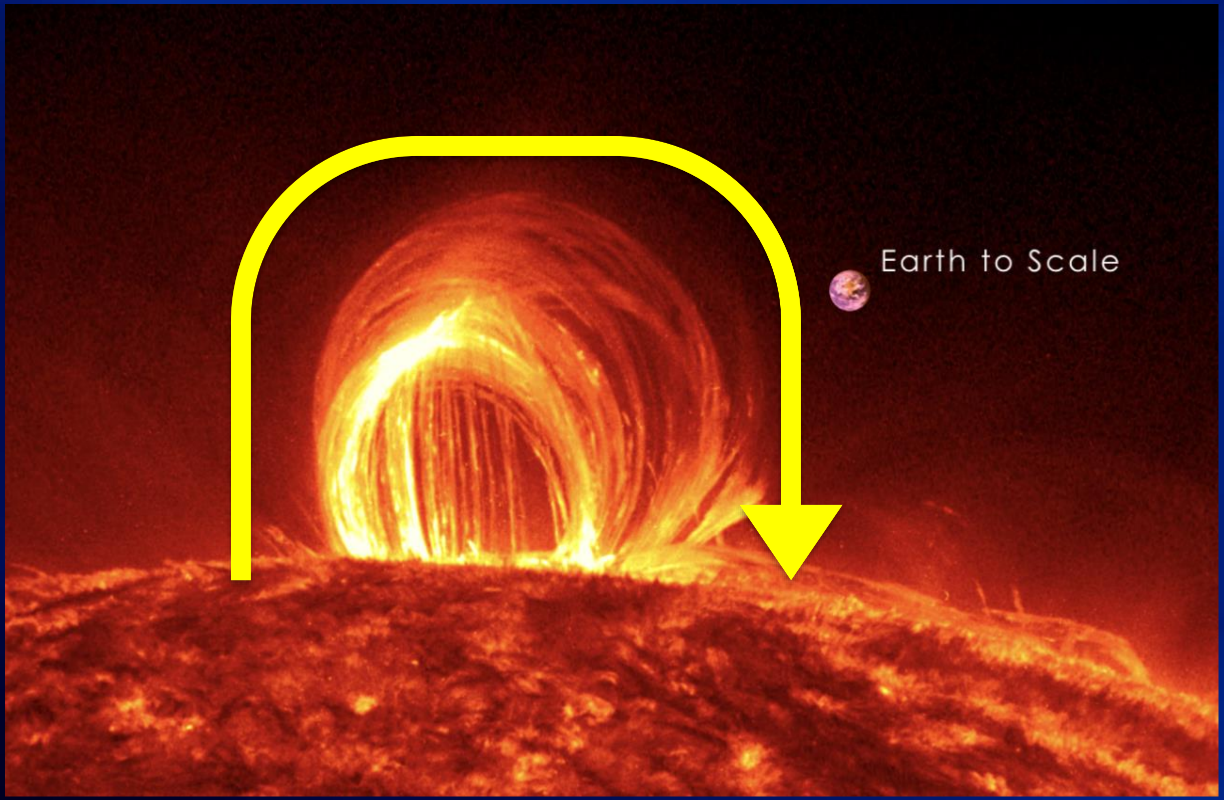
→



Net energy gain

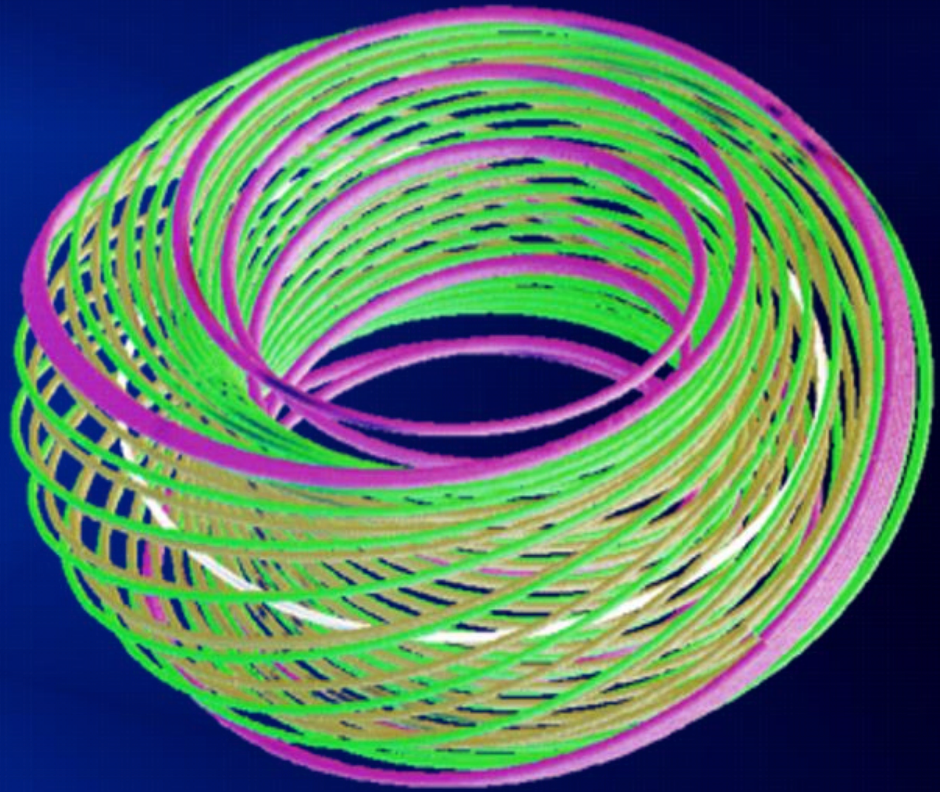
Magnetic Fusion Confines Charged Particles on Closed Magnetic Surfaces for Steady State Operation

Particles Streaming Along Magnetic Field Lines on the Sun



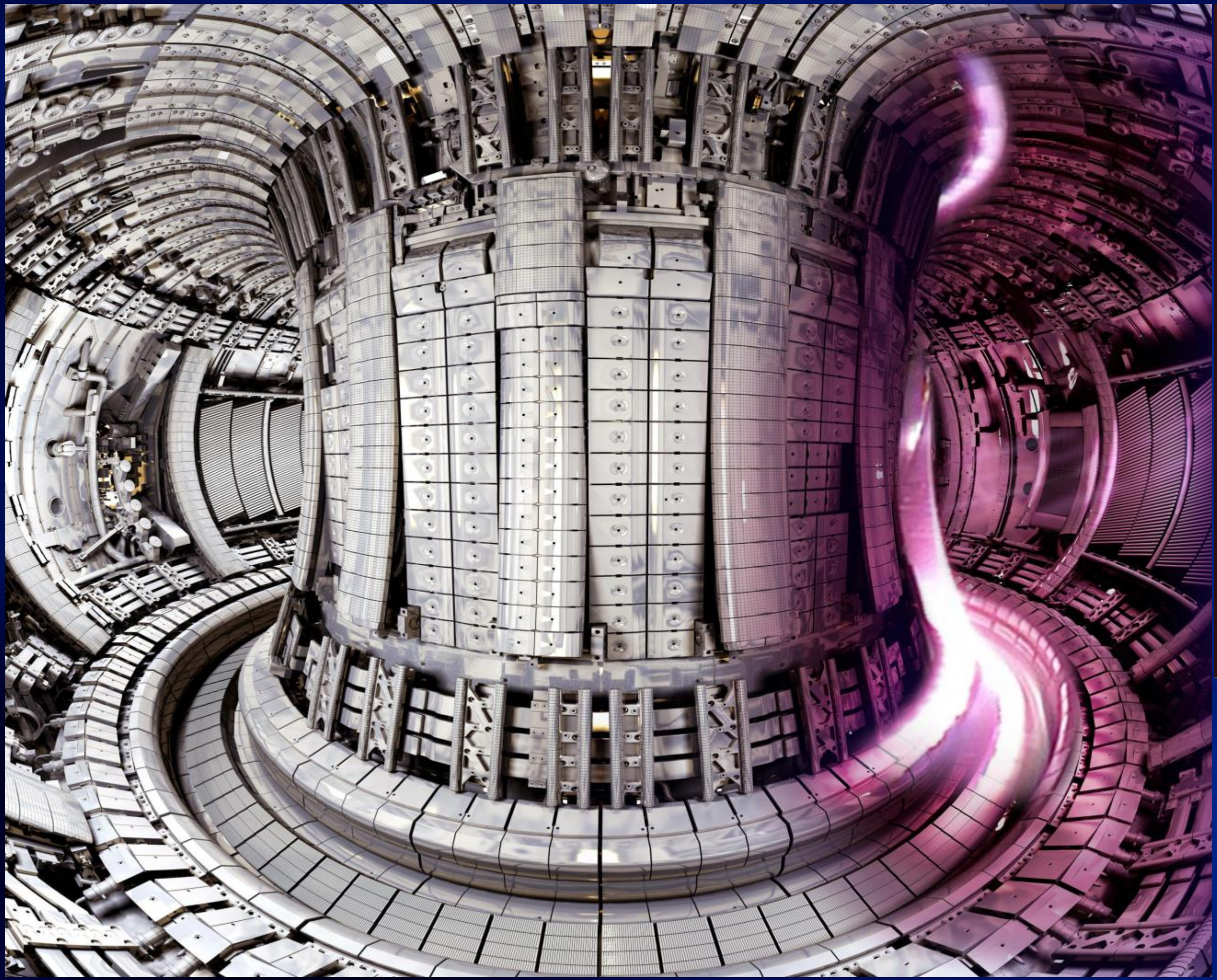
https://svs.gsfc.nasa.gov/11168

Closing the bottle prevents escape of particles on earth



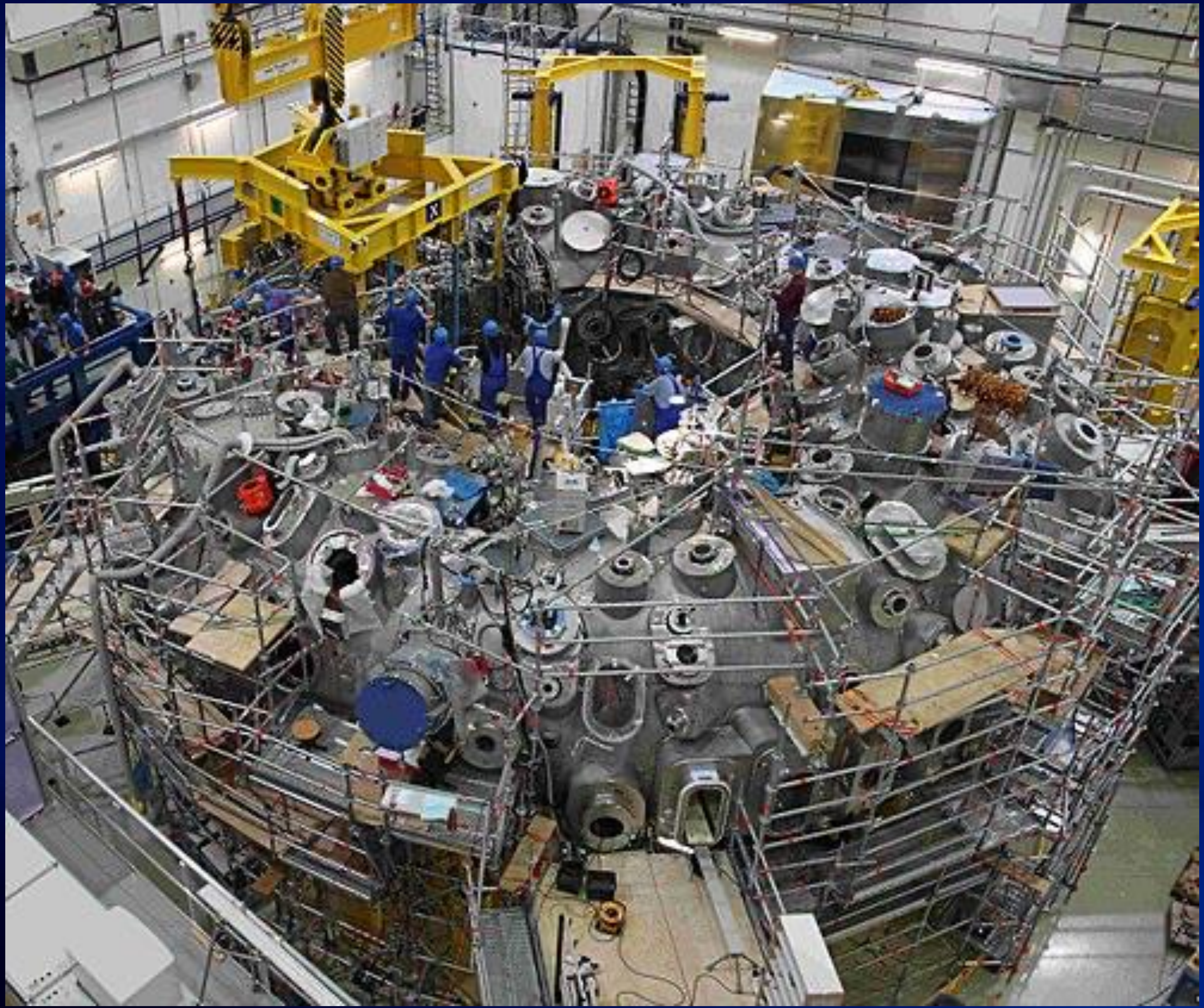
Tokamak

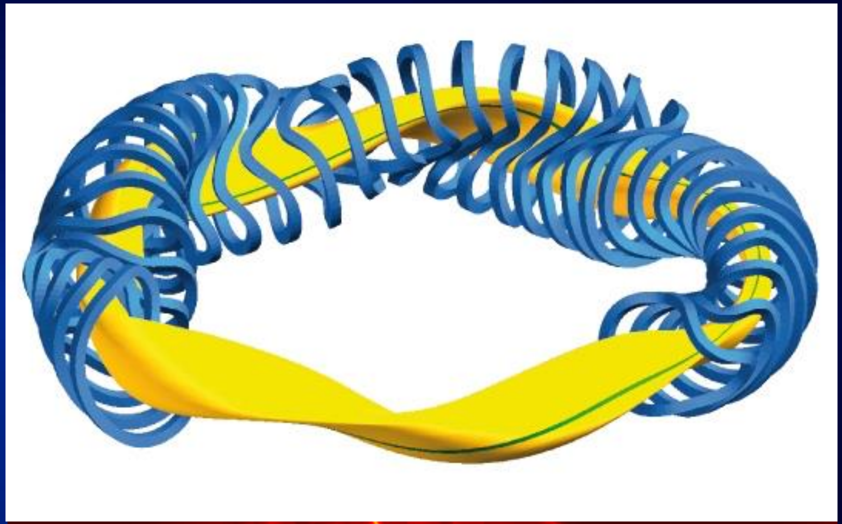
Joint European Torus in the UK Produced a World Record 59 MJ Fusion Energy

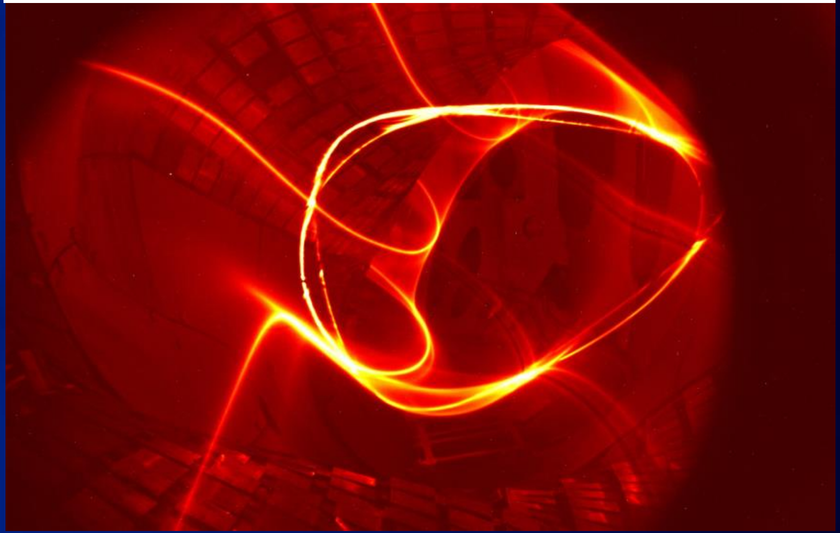


1. Input power ≈ 5x output power
2. Not steady state

Not to be Outdone, Wendelstein 7-X Demonstrated The Advantages of Twisty Magnetic Bottles for Sustainment







Search for "hidden symmetries" in 3D systems demands advanced AI/ML

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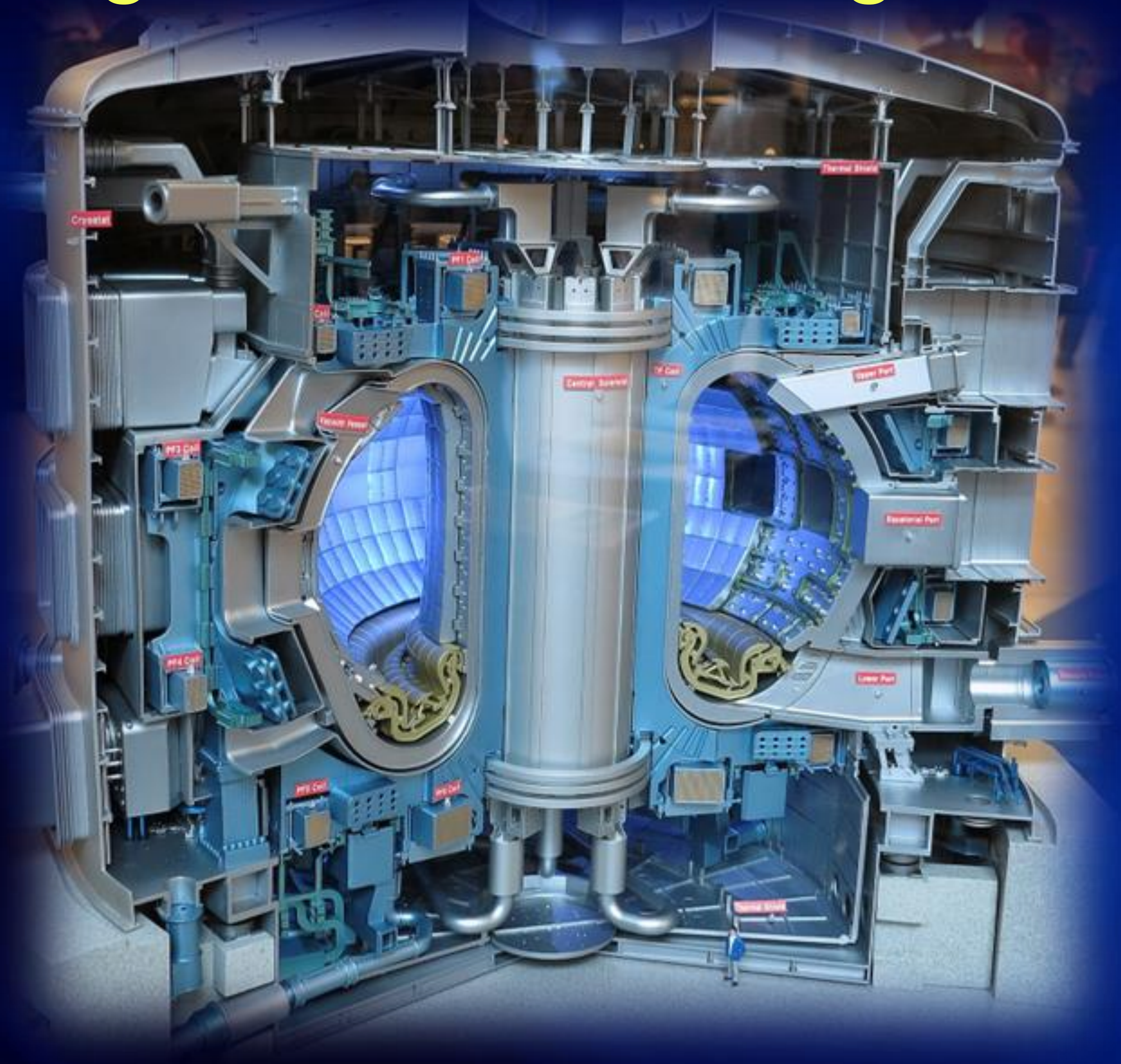
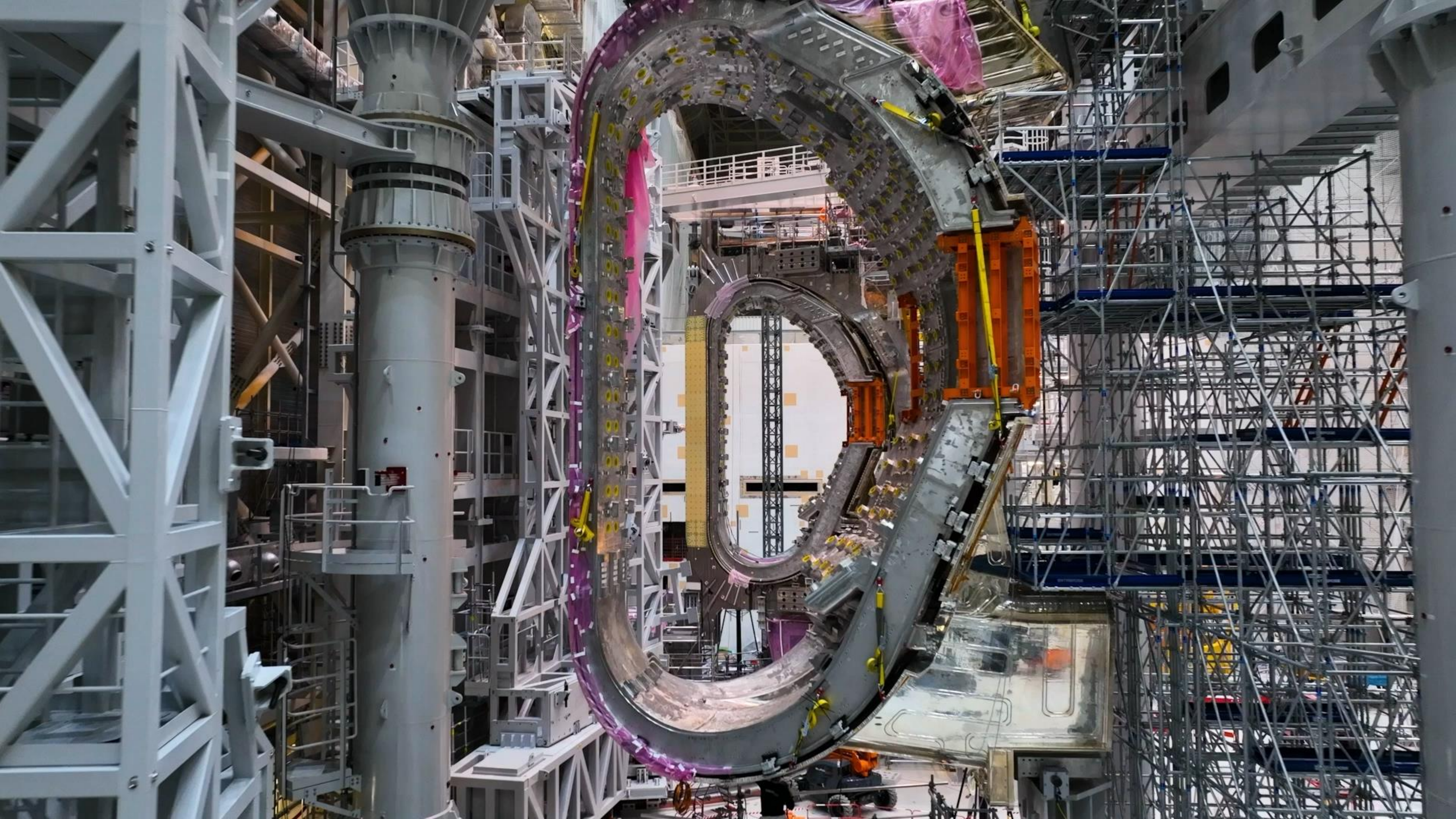
Knowledge From DIII-D and World Leading Facilities Integrated into ITER Design, Now Under Construction in France



Multinational project:
- 500 MW fusion power (10x input)
- 400 sec → 3000 s
- Commence in the 2030s

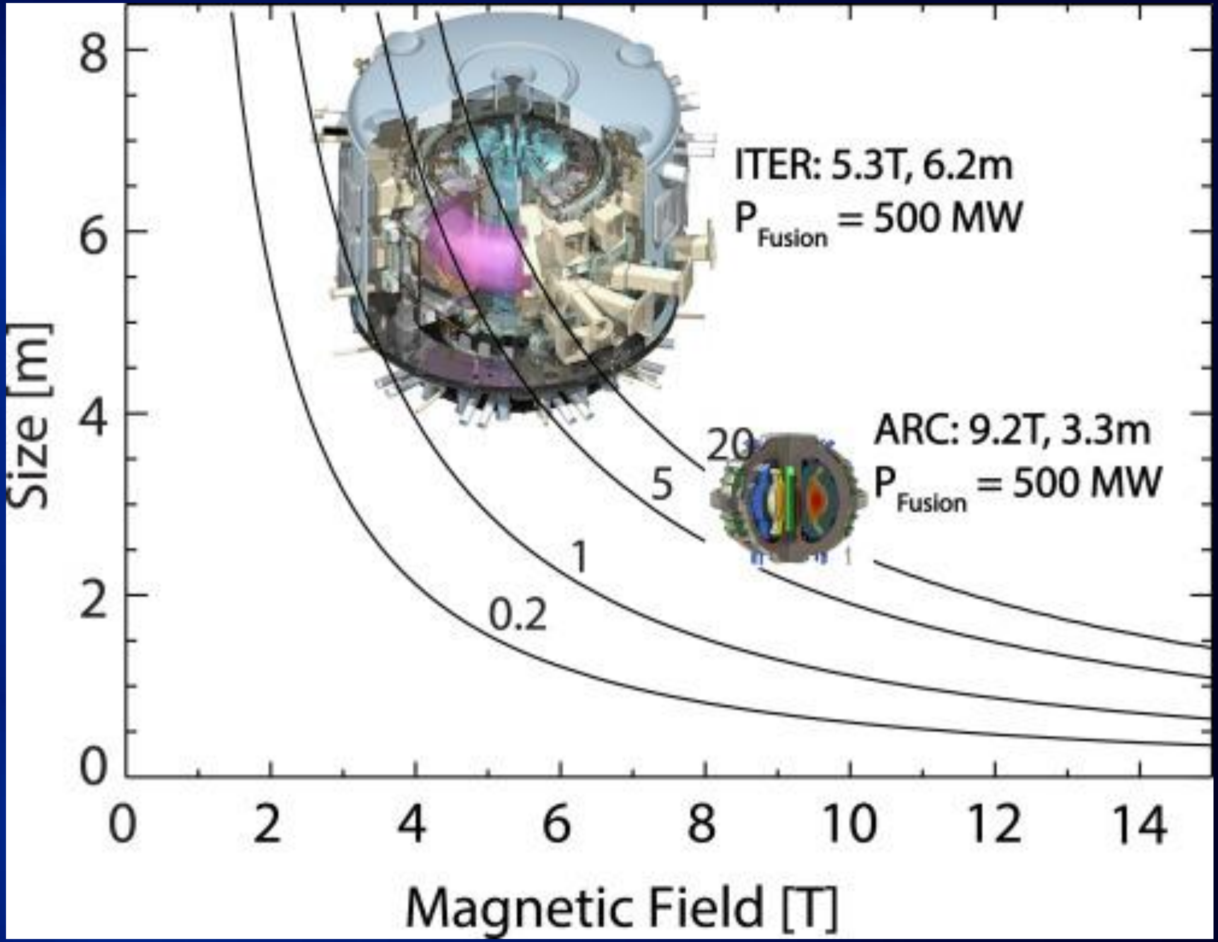
Challenge for Commercial fusion:
- Massive size, high capital cost ~ $20 B
- Instabilities that can damage the machine & limit operations



Tipping Point: High Temperature Superconductors Promise to Reduce size and Capital Cost up to 90%

- Cost ~ R^3

HTS magnet: Commonwealth Fusion Systems (MA)



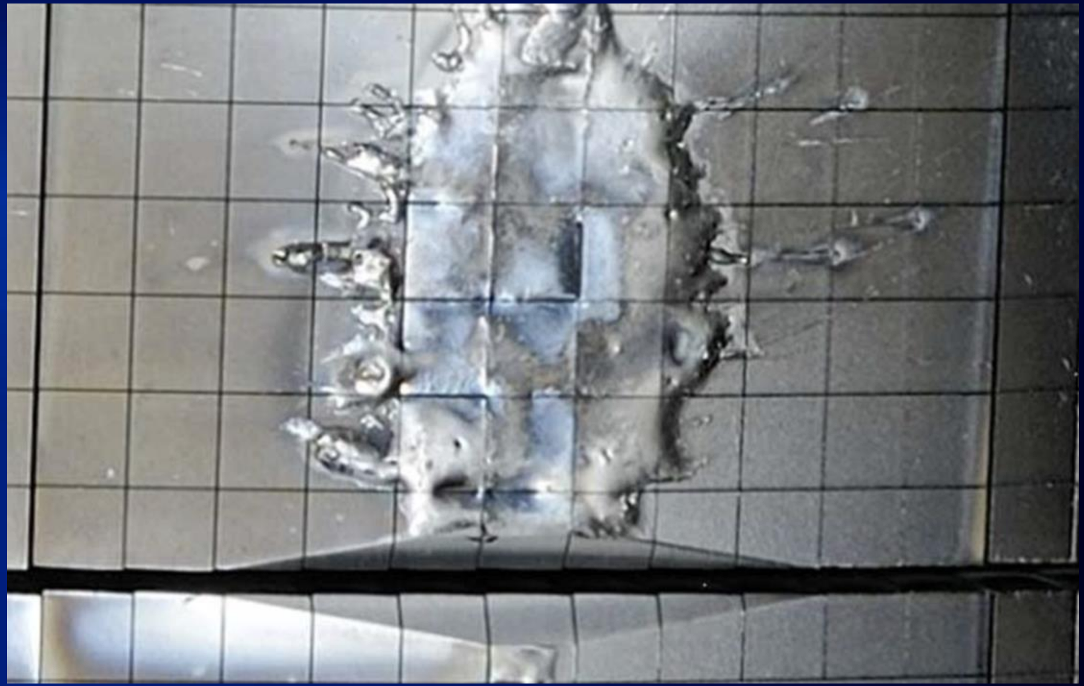
Tipping Point: Machine Learning Yields Impressive Results in Controlling Damaging Instabilities like Disruptions

TFTR

Actual Time

39.5ms Elapsed Time

Tile damage

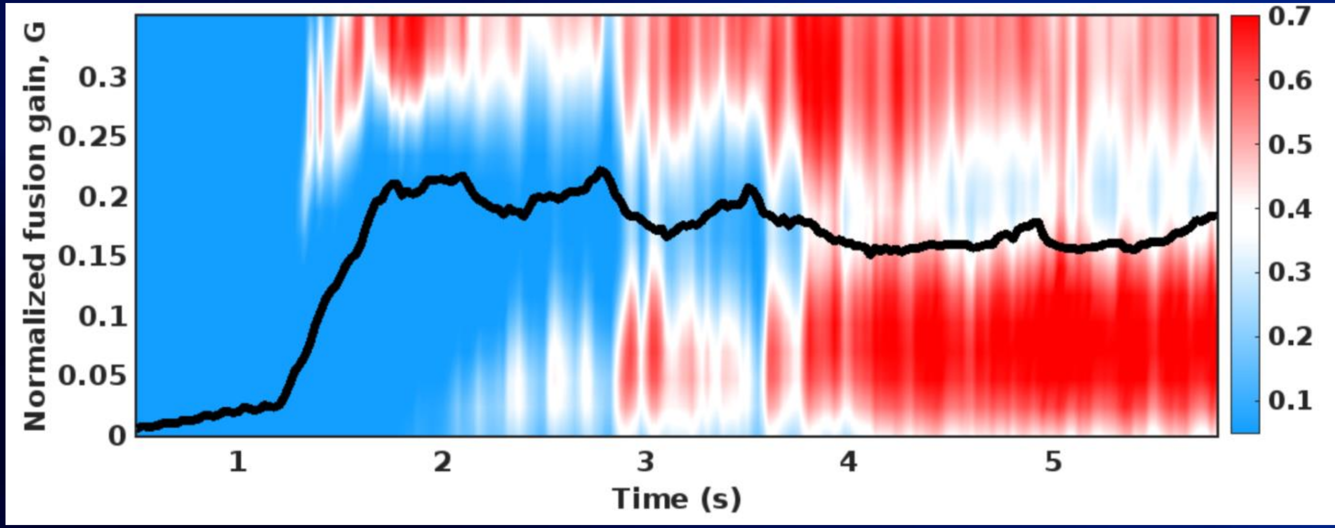


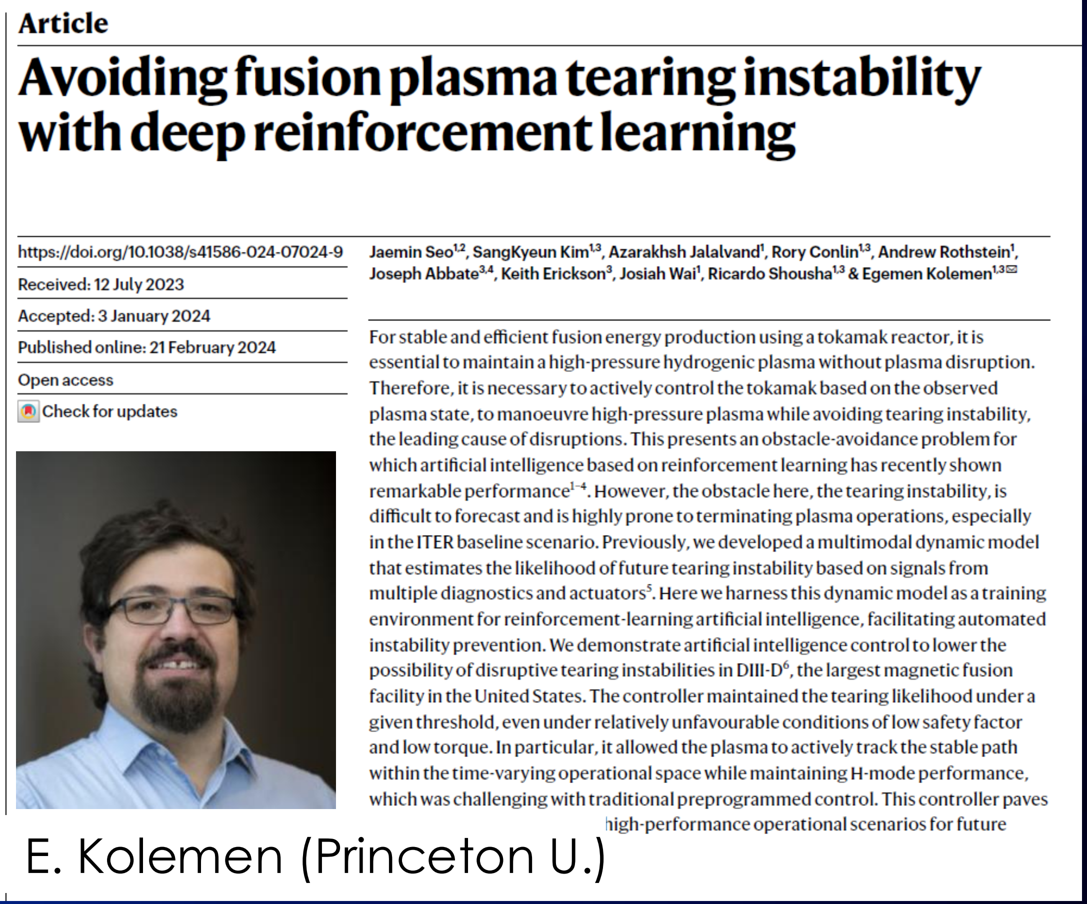
Disruptions present a danger to the facility despite decades of research

Recent ML Breakthrough on DIII-D Promises Disruption Free Operation of ITER and Commercial Reactors

- Train a deep Reinforcement Learning model to optimize Reward Function
→ Too high pressure is bad for stability
→ Too low pressure is bad for fusion power

- Result is optimized discharge trajectory for pressure and stability





Article

Avoiding fusion plasma tearing instability with deep reinforcement learning

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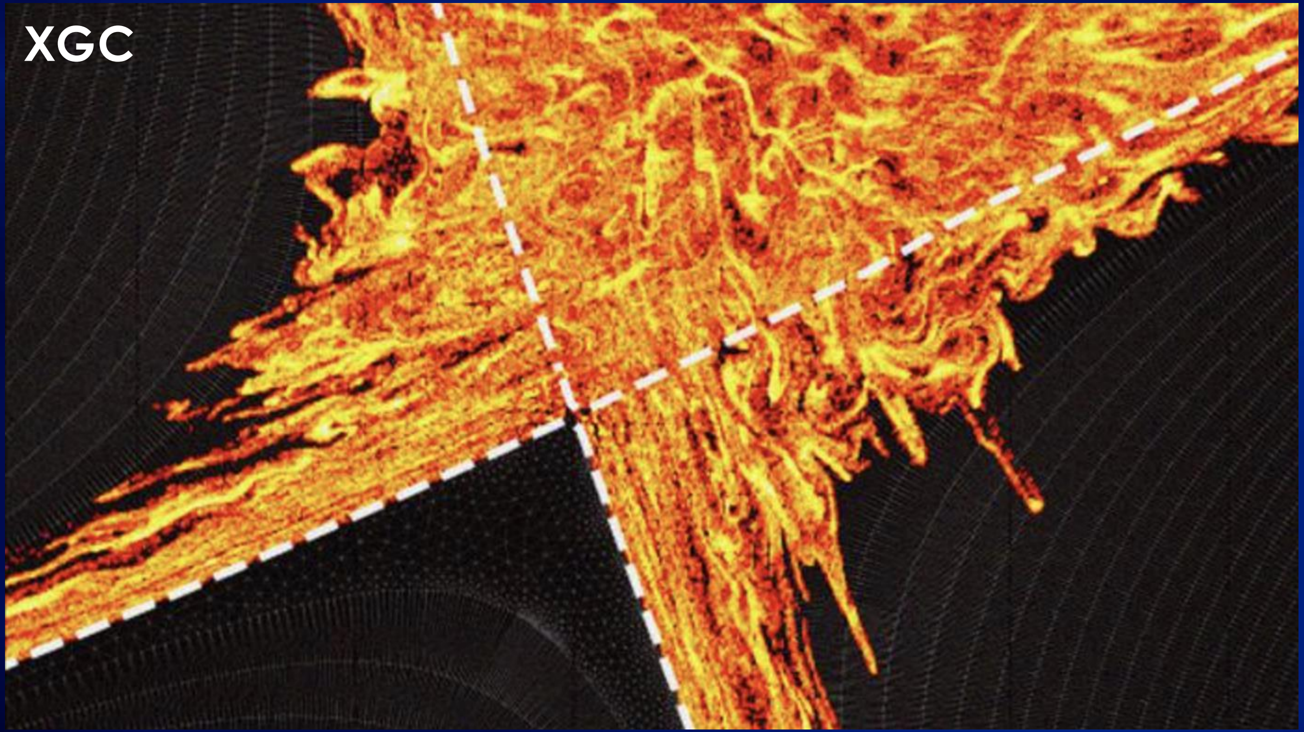
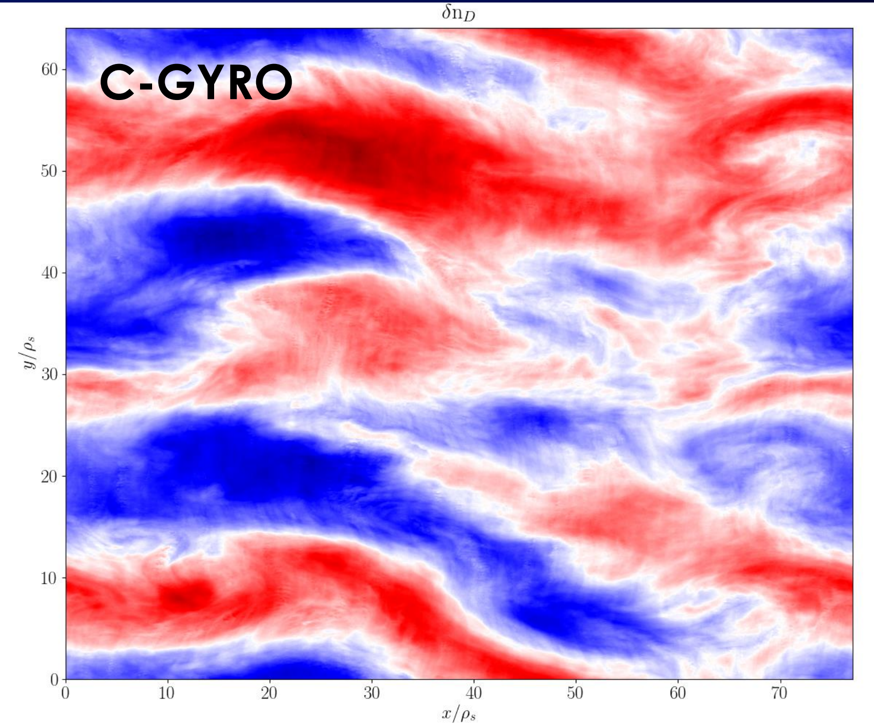
For stable and efficient fusion energy production using a tokamak reactor, it is essential to maintain a high-pressure hydrogenic plasma without plasma disruption. Therefore, it is necessary to actively control the tokamak based on the observed plasma state, to manoeuvre high-pressure plasma while avoiding tearing instability, the leading cause of disruptions. This presents an obstacle-avoidance problem for which artificial intelligence based on reinforcement learning has recently shown remarkable performance[1–4]. However, the obstacle here, the tearing instability, is difficult to forecast and is highly prone to terminating plasma operations, especially in the ITER baseline scenario. Previously, we developed a multimodal dynamic model that estimates the likelihood of future tearing instability based on signals from multiple diagnostics and actuators[5]. Here we harness this dynamic model as a training environment for reinforcement-learning artificial intelligence, facilitating automated instability prevention. We demonstrate artificial intelligence control to lower the possibility of disruptive tearing instabilities in DIII-D[6], the largest magnetic fusion facility in the United States. The controller maintained the tearing likelihood under a given threshold, even under relatively unfavourable conditions of low safety factor and low torque. In particular, it allowed the plasma to actively track the stable path within the time-varying operational space while maintaining H-mode performance, which was challenging with traditional preprogrammed control. This controller paves high-performance operational scenarios for future

E. Kolemen (Princeton U.)

Seo, J., *et al.* *Nature* **626**, 746–751 (2024).
https://doi.org/10.1038/s41586-024-07024-9

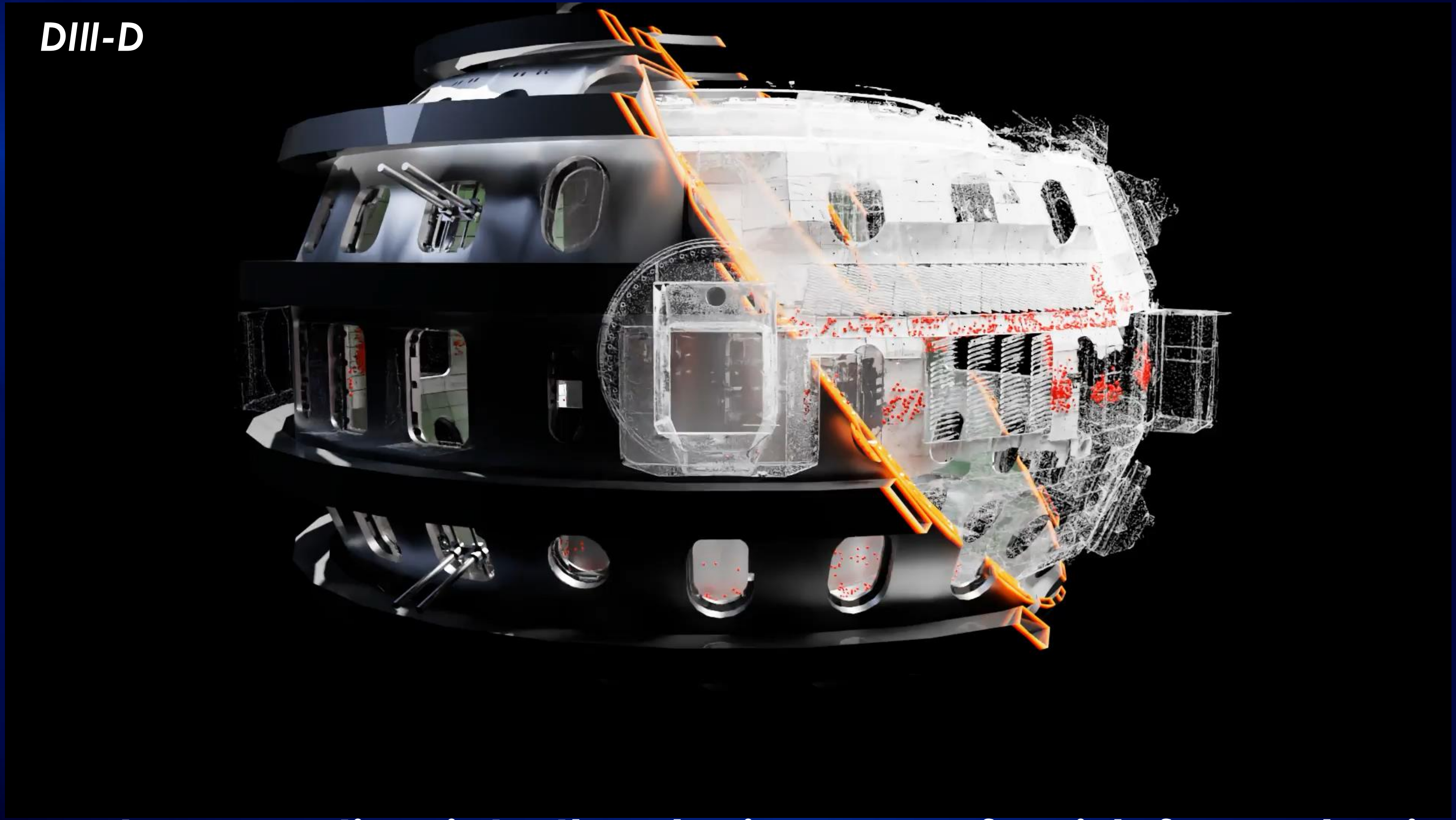
Discharge Trajectory Control Will Improve With a Surrogate Model for Transport, Based on Gyrokinetic Simulation





High fidelity simulations exist, but surrogate models needed to explore and optimize multi-dimensional operational space

Integration of AI Models in Digital Twin for Virtual Operation and Design Can Server as the Next Tipping Point for Fusion



General Atomics & NVIDIA

Integrate operation into the design: Transfer risk from physical to virtual domains

The Race is On: Private Investment in Fusion Rose From $500M in 2020 to $7B+ in 2025

Tokamak Energy

XCIMER ENERGY CORPORATION

HB11 ENERGY

nT-tao Compact Fusion Power

Helical Fusion

general fusion

MIFTI

GAUSS FUSION

HELION

FOCUSED

REALTA FUSION

First Light

THEA ENERGY

fuse

Tokamak Energy

Marvel Fusion

AVALANCHE

RENAISSANCE FUSION

STELLARIS

LPP FUSION

NOVATRON

ELECTRIC FUSION SYSTEMS

LONGVIEW FUSION ENERGY SYSTEMS

OPENSTAR TECHNOLOGIES LTD

KYOTO FUSIO

acceleron

LaserFusionX

HORNE TECHNOLOGIES

HelicitySpace

BLUE LASER FUSION

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The Fusion Industry Requires A Growing Highly Skilled Workforce and California is a Hub for Fusion Energy

- **Multi-disciplinary workforce needed, including**

→ Data science, AI/ML, and HPC

→ Digital engineering and simulation

- **Monday's fusion workshop identified exciting opportunities for:**

→ Near term contribution of fusion modules to NRP for use in existing courses

→ Internship opportunities at national labs and industry (Charles Lively LBNL)

→ Long term fusion course development in engineering and sciences

Thank you