Advances in Fusion and Preparing for ITER

Mar 7, 2024

Fermilab, Batavia IL

Presented by:
Raffi Nazikian
General Atomics

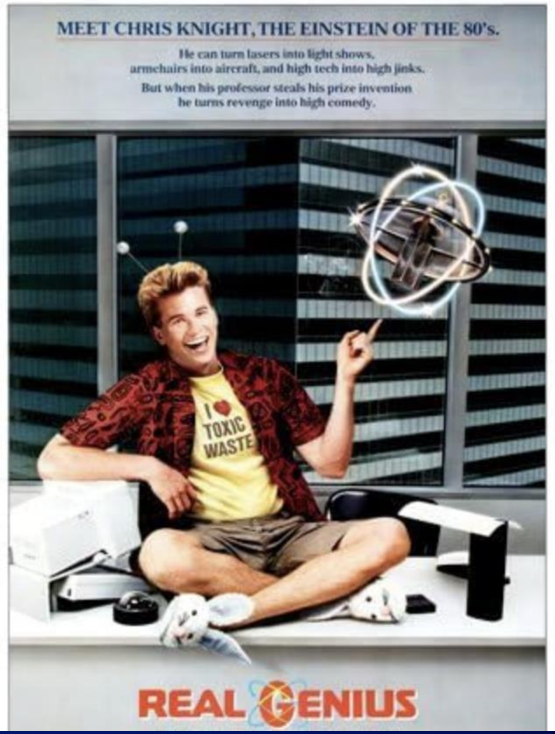
GENERAL ATOMICS

General Atomics Advanced Technologies

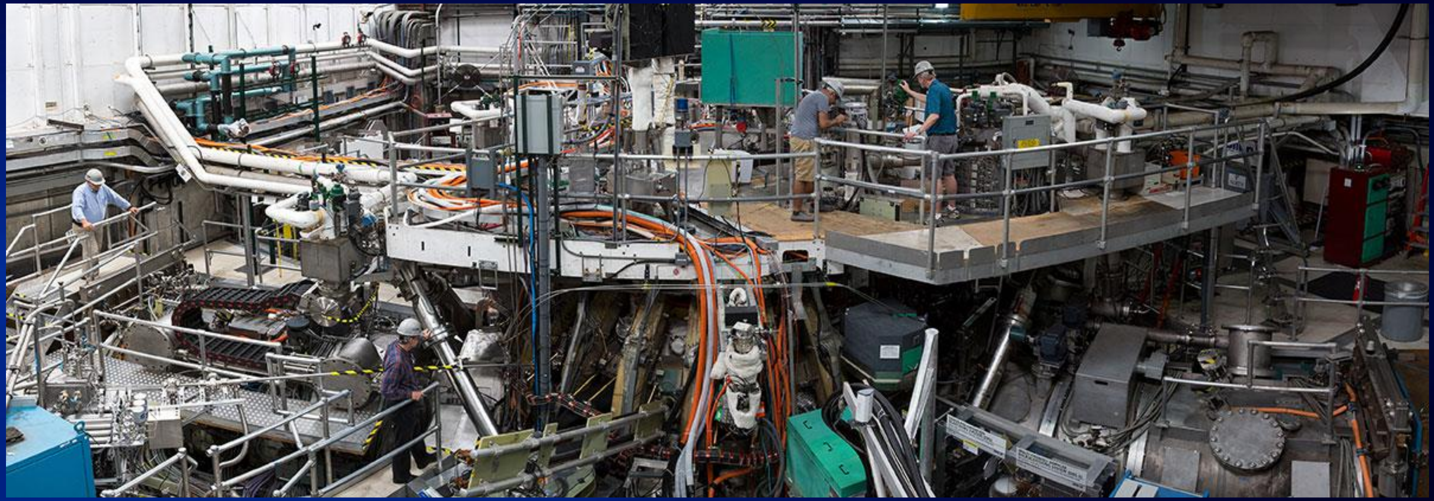
15,000 employees, multiple divisions

General Atomics Campus in San Diego

General Atomics Campus in San Diego



DIII-D National Fusion Facility Operated by GA for the DOE: The Leading Magnetic Confinement Experiment in the USA



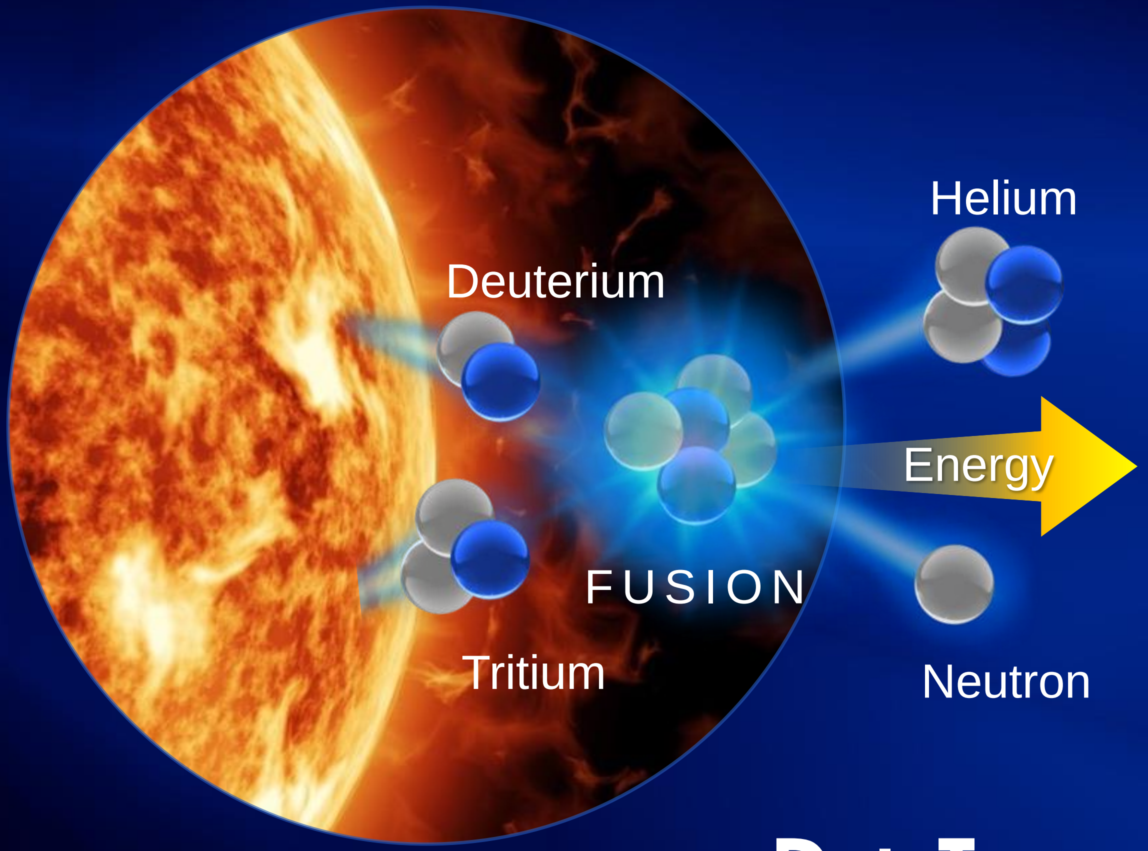
• DIII-D is the leading DOE-SC fusion facility in the US, based in San Diego
- operating since 1986
- 830 researchers worldwide
- 137 participating institutions

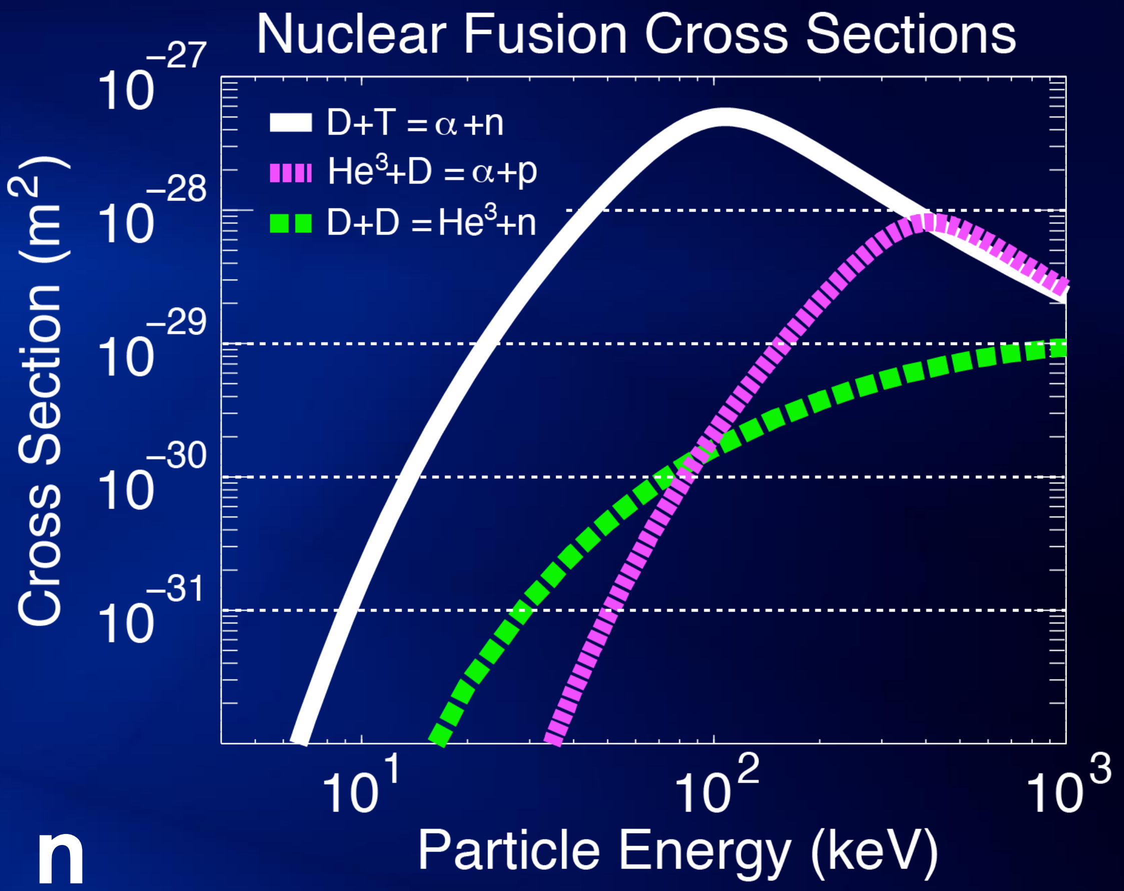
• Major contributor to the ITER design and informs path to advanced reactor
- serves as the US ITER simulator

• Operational Characteristics:
- episodic data ~ 10 s pulses, ~25 pulses/day, ~20 min intervals
~ 45 GB/pulse, ~600 TB total accumulated data

FUSION: Nearly Limitless Potential and Practical Challenges

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





D + T → ⟨ + n

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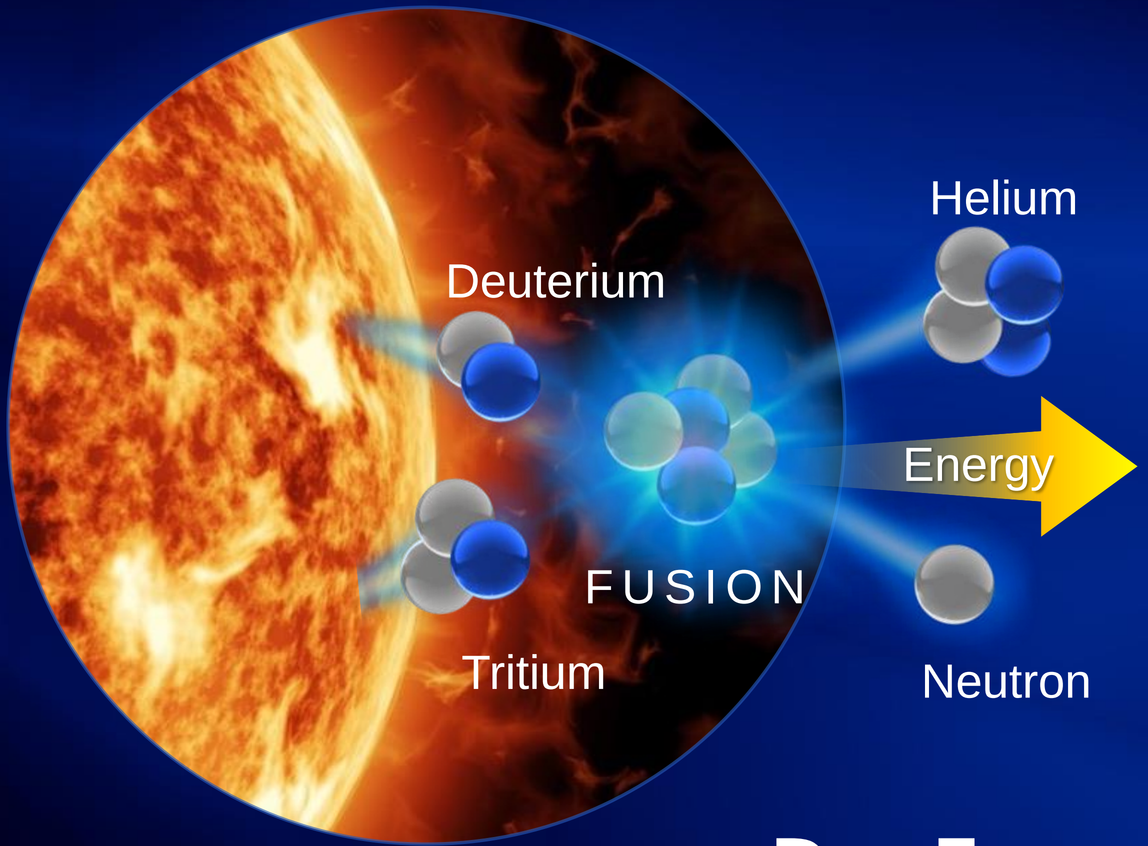

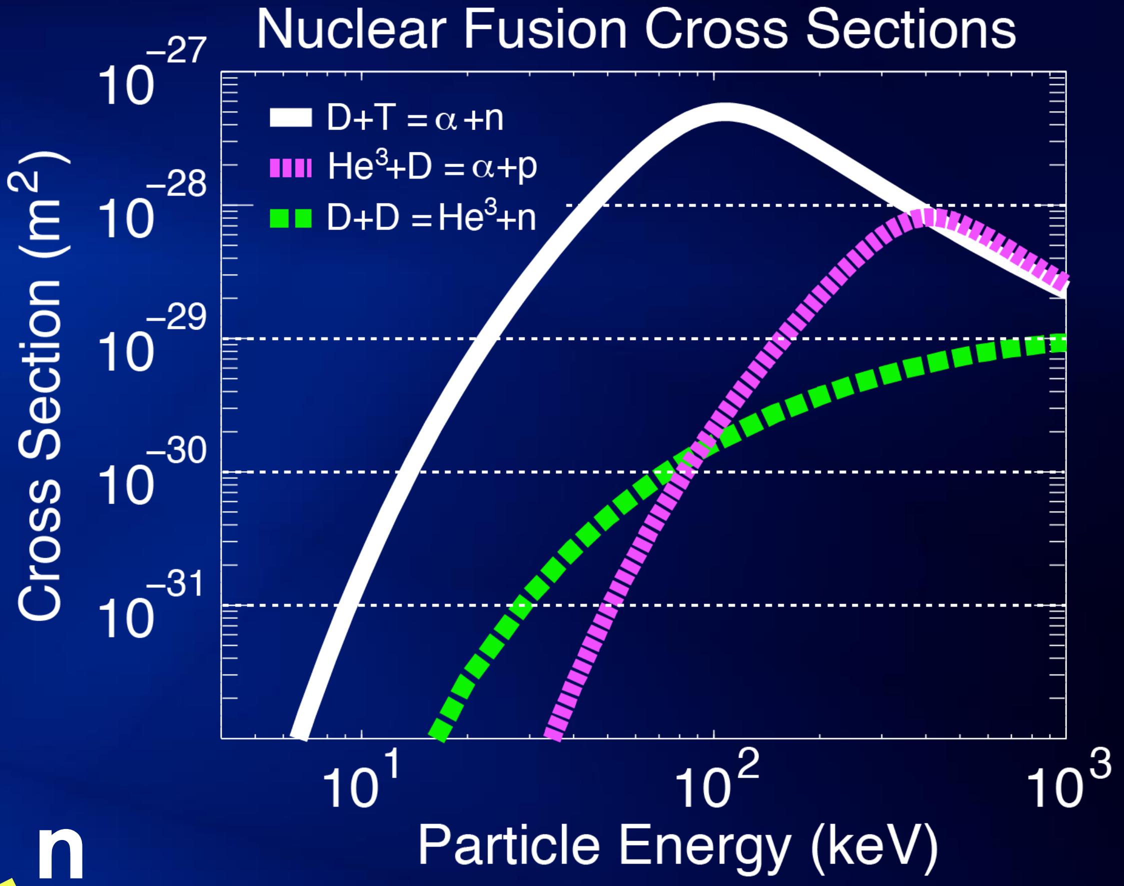

D + T → 〈 + n

Breeding T **^{6}Li + n → 〈 + T**

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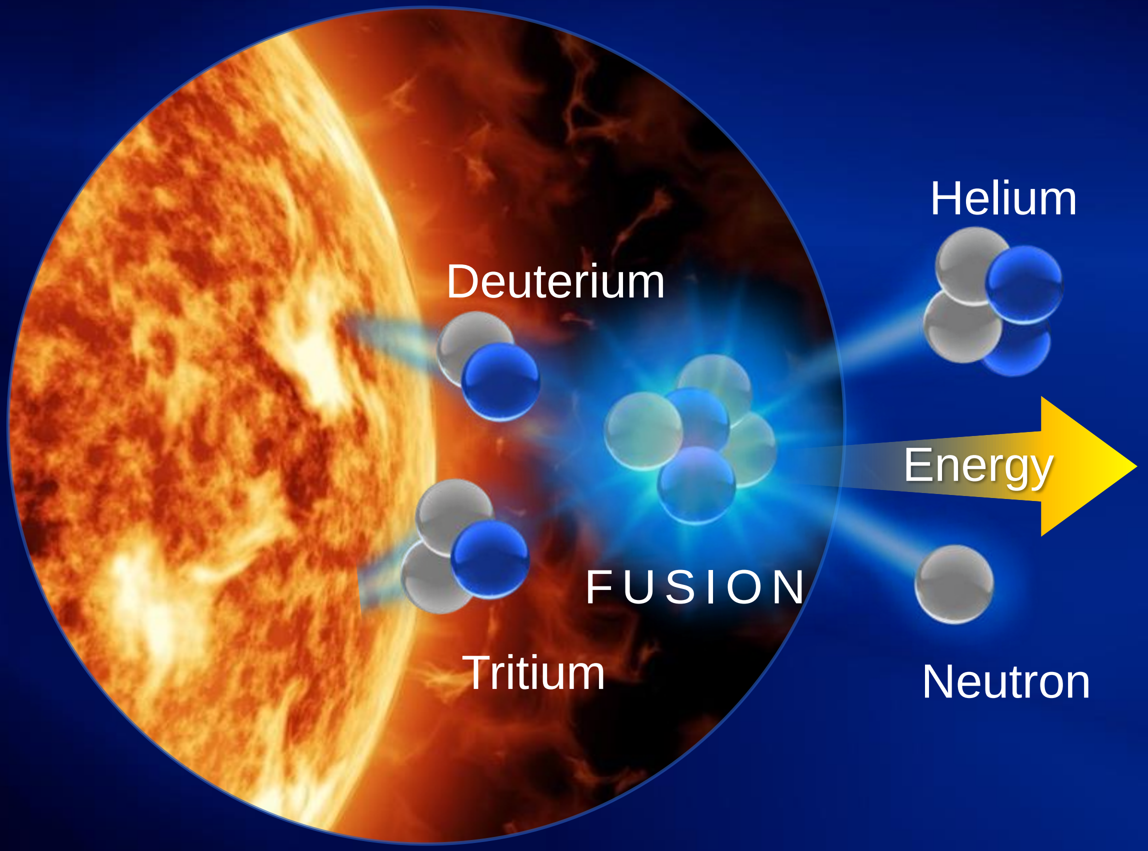

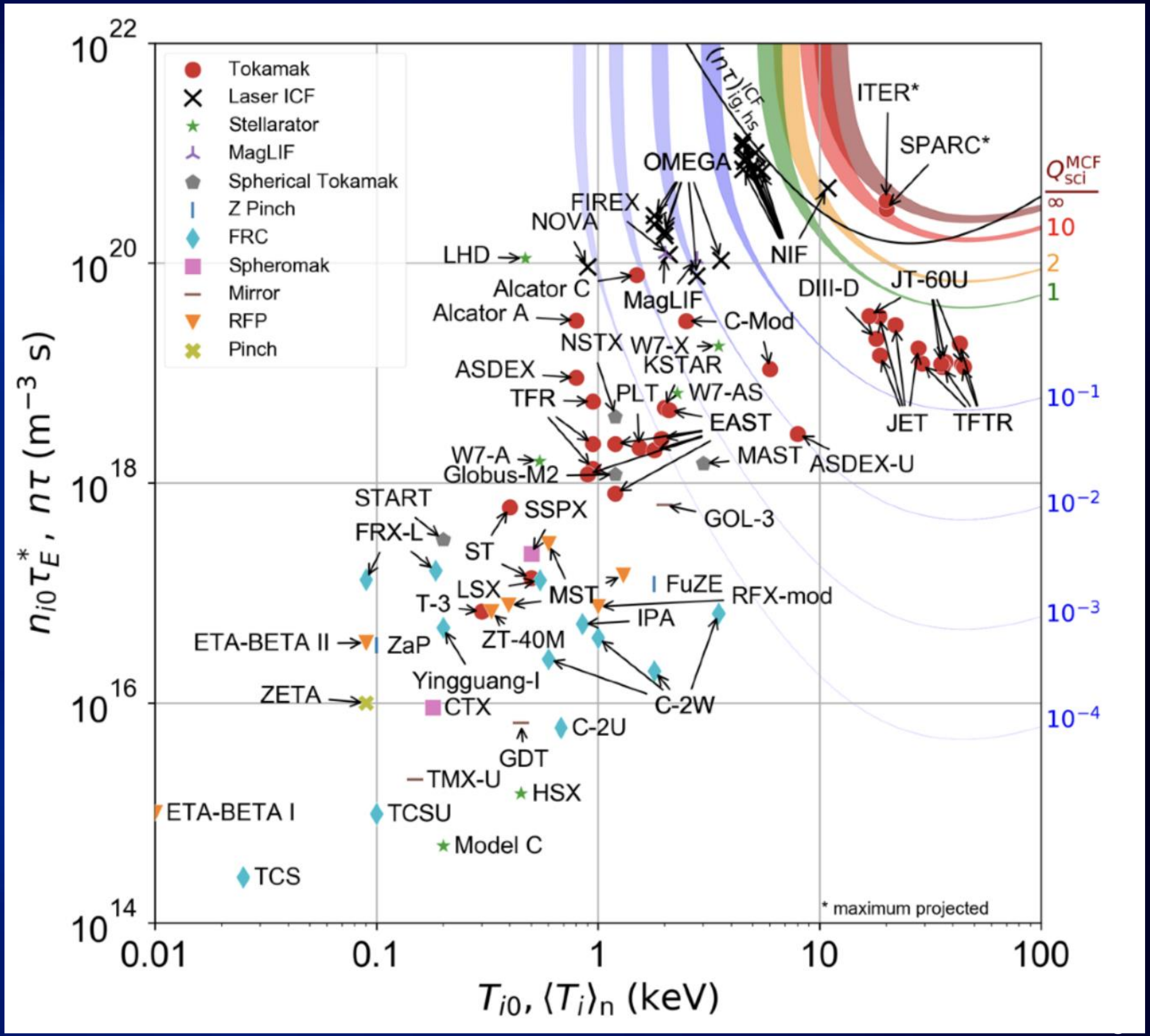

Lawson's criterion

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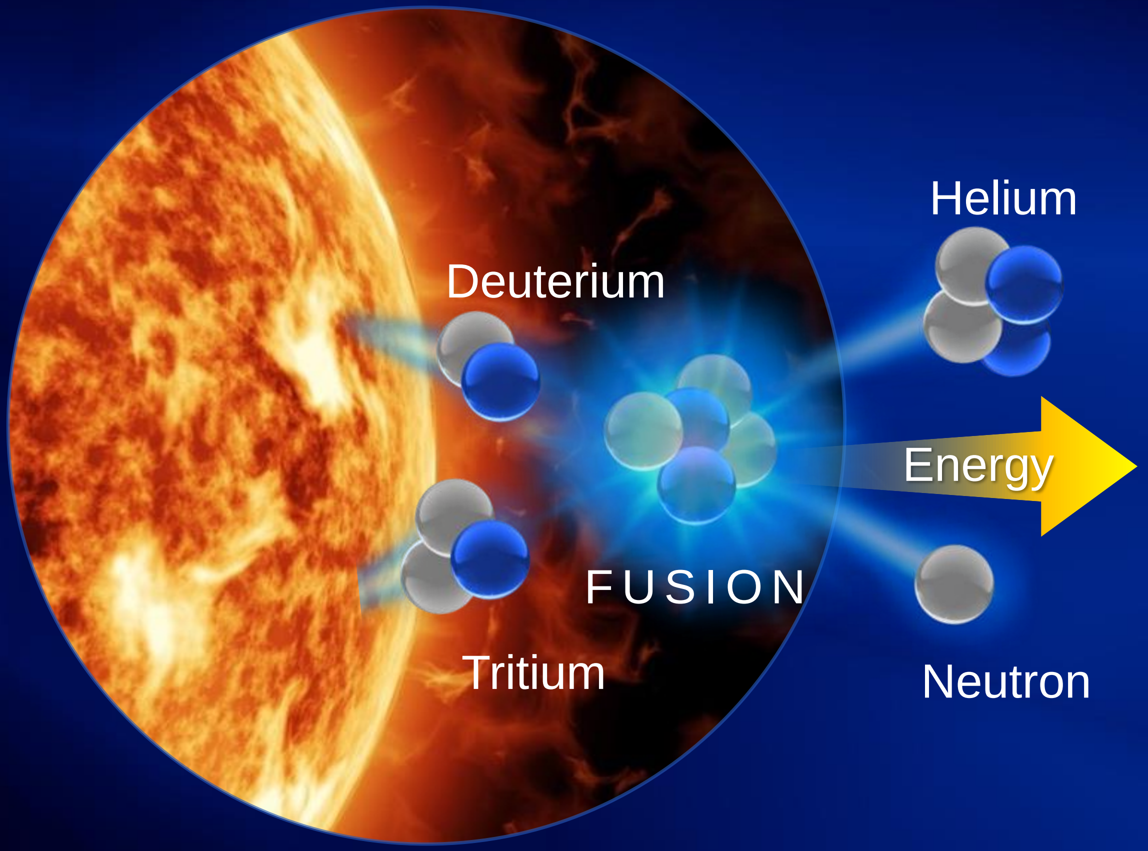
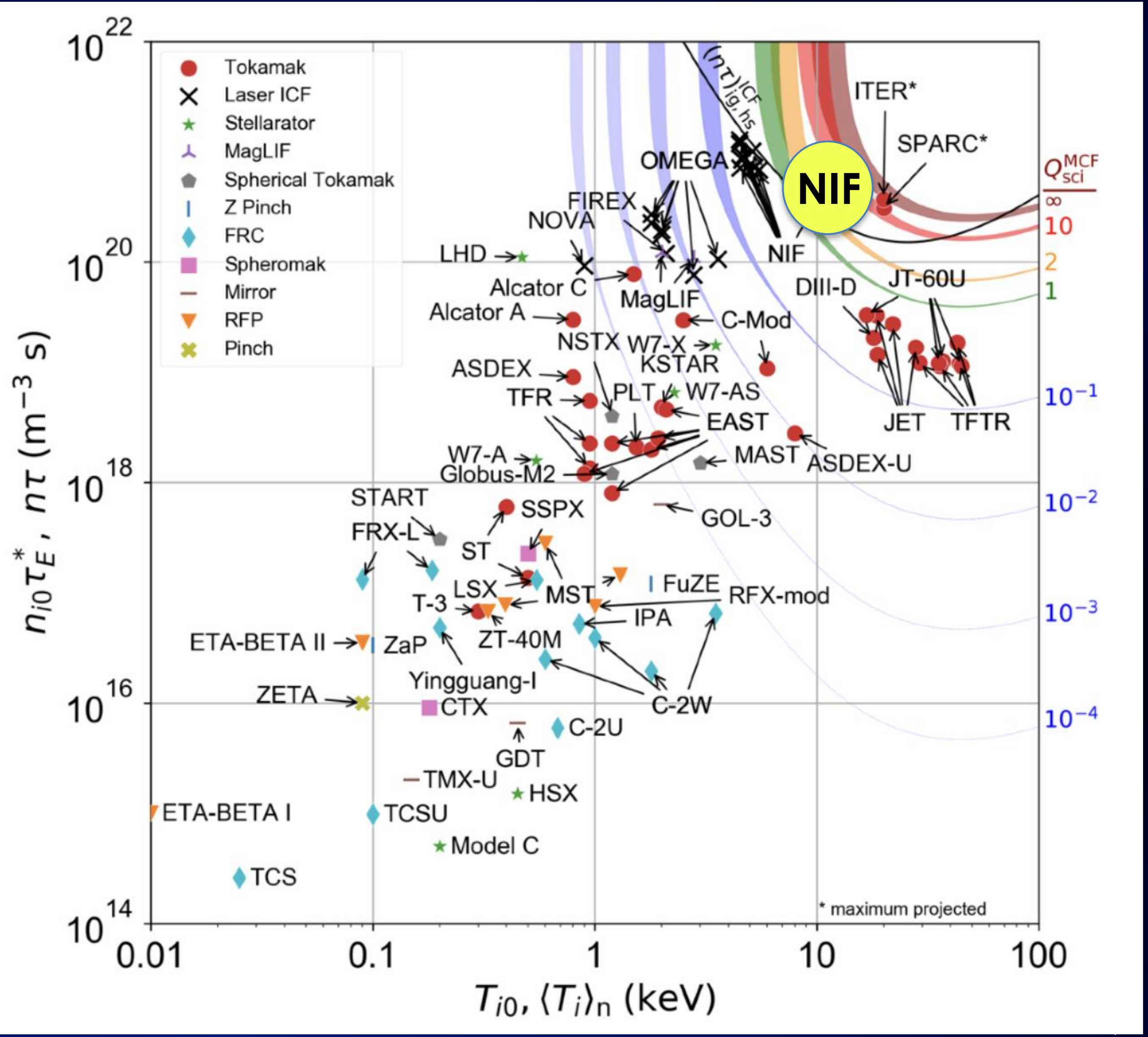
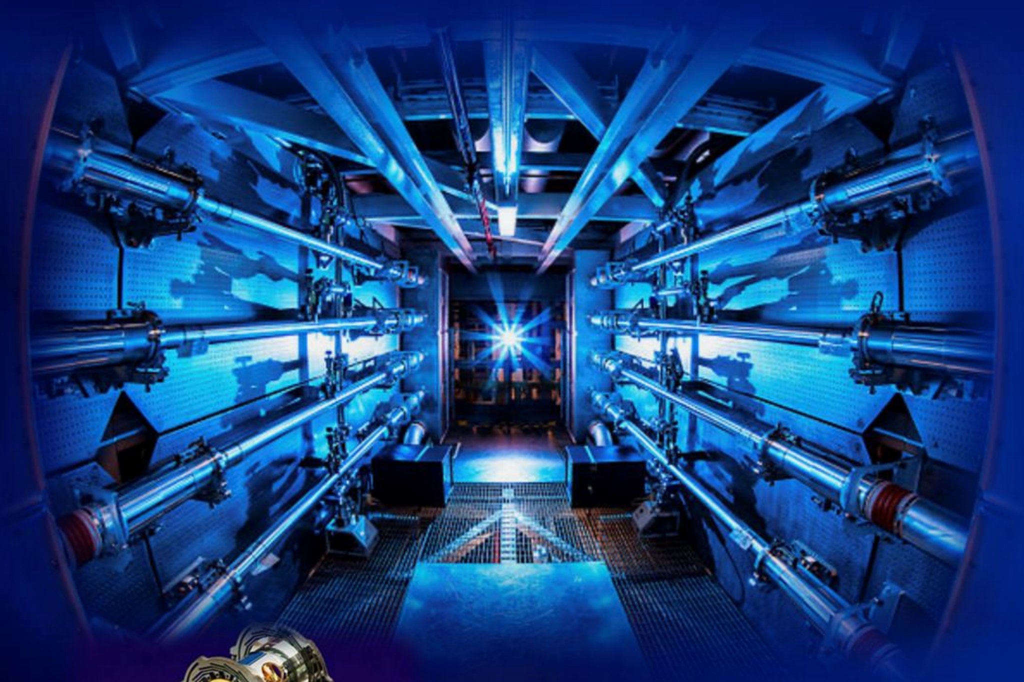




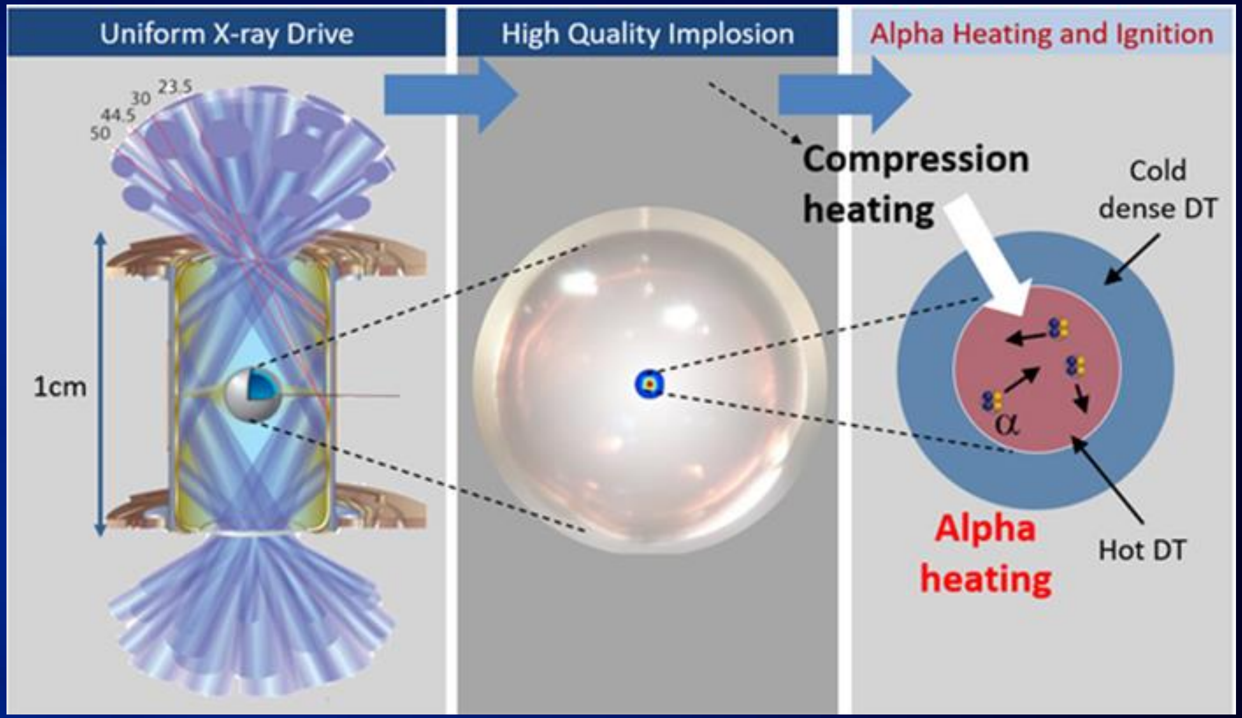
Lawson's criterion

National Ignition Facility Breakthrough in Fusion is Also a Triumph of Big Science and Persistence

Lawrence Livermore National Lab



Target fabrication: General Atomics



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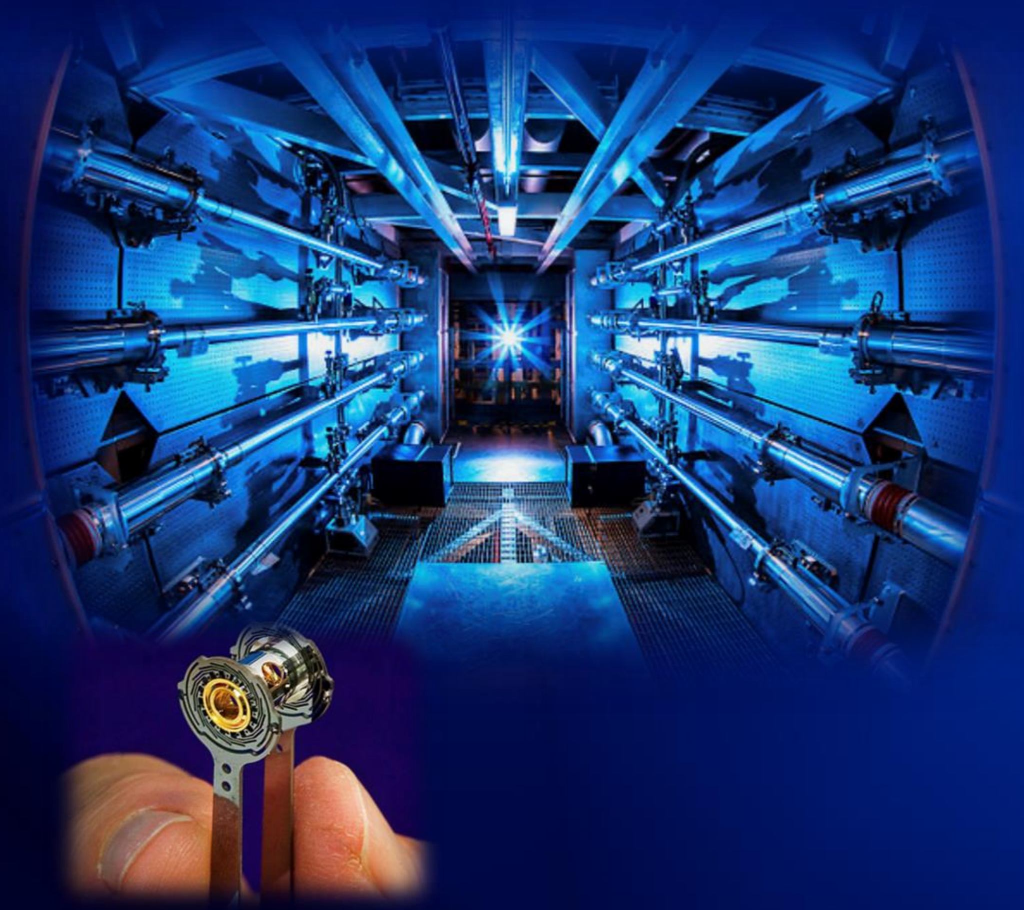
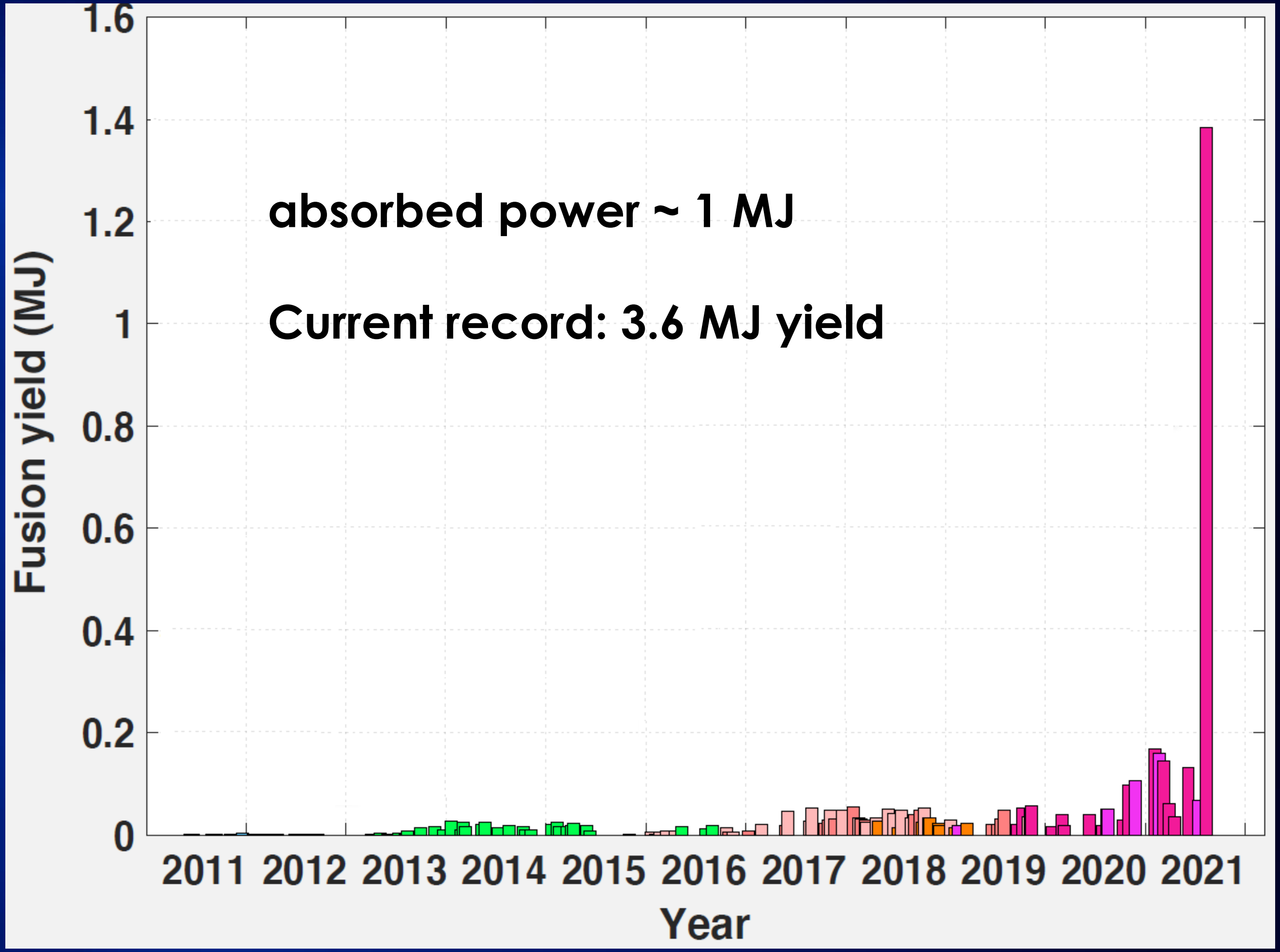


Target fabrication: General Atomics

Fusion Yield

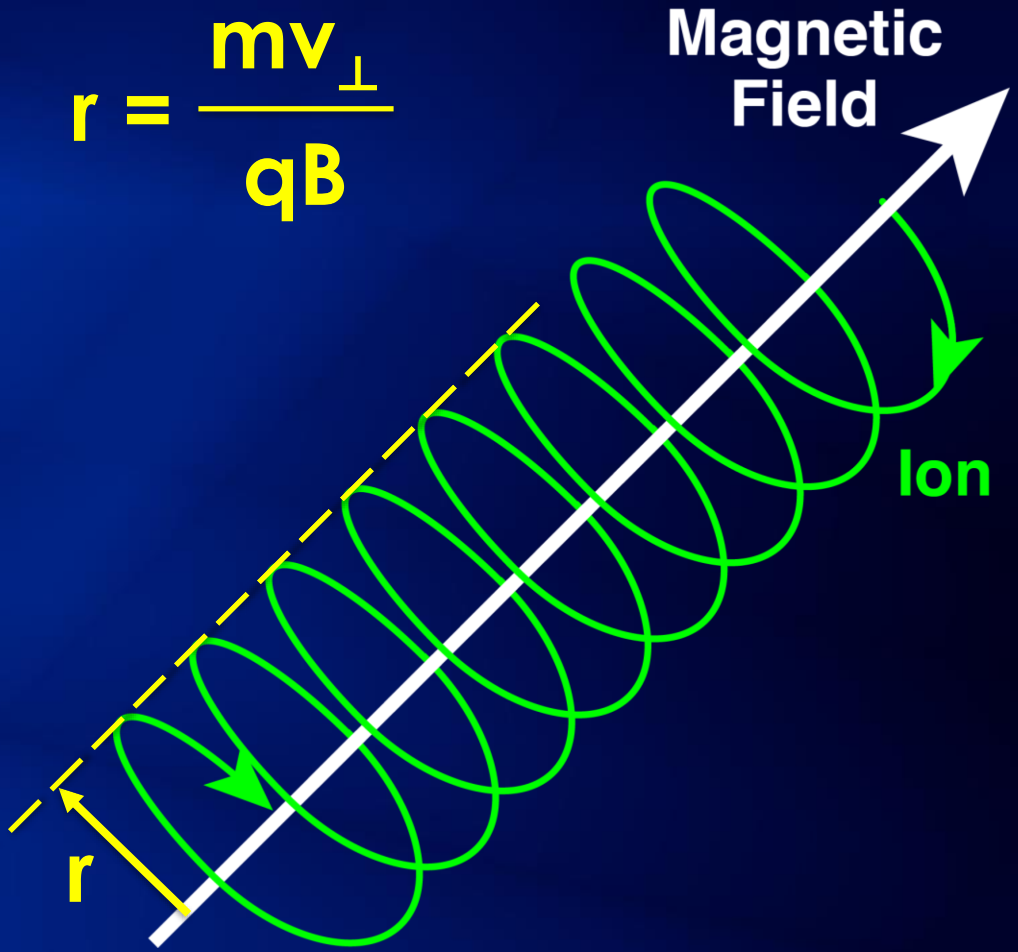


Magnetic Fusion: Charged Particles are Confined by Magnetic Fields

Particles Streaming Along
Magnetic Field Lines on the Sun

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

$$r = \frac{mv_\perp}{qB}$$



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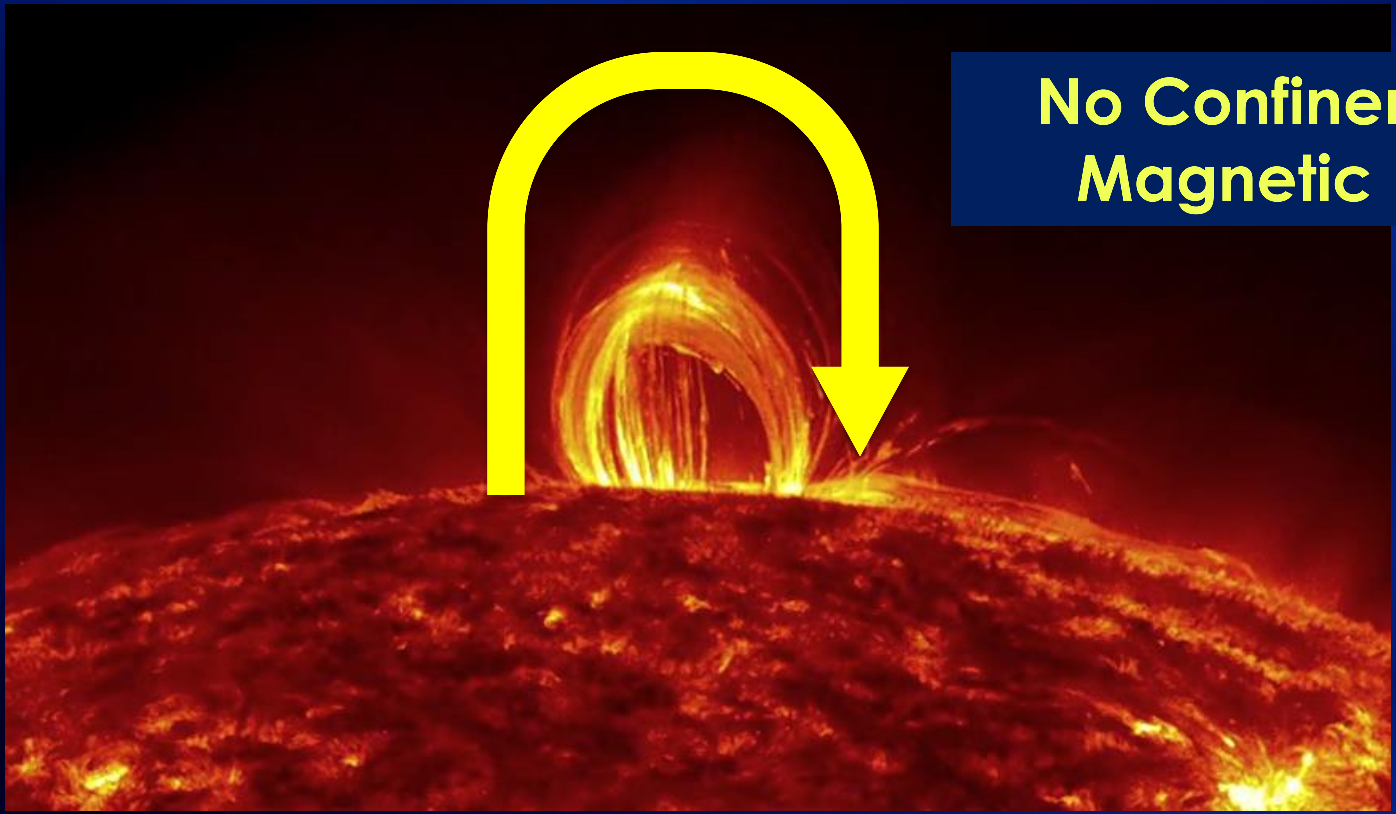
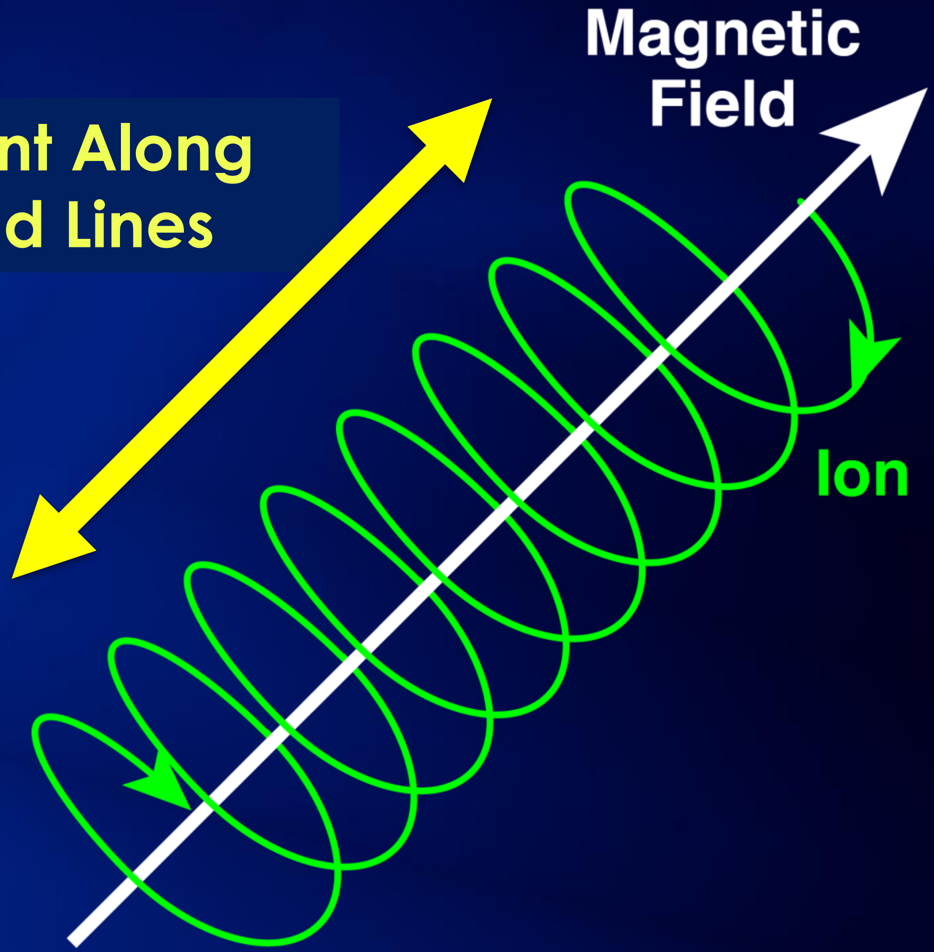


https://svs.gsfc.nasa.gov/11168

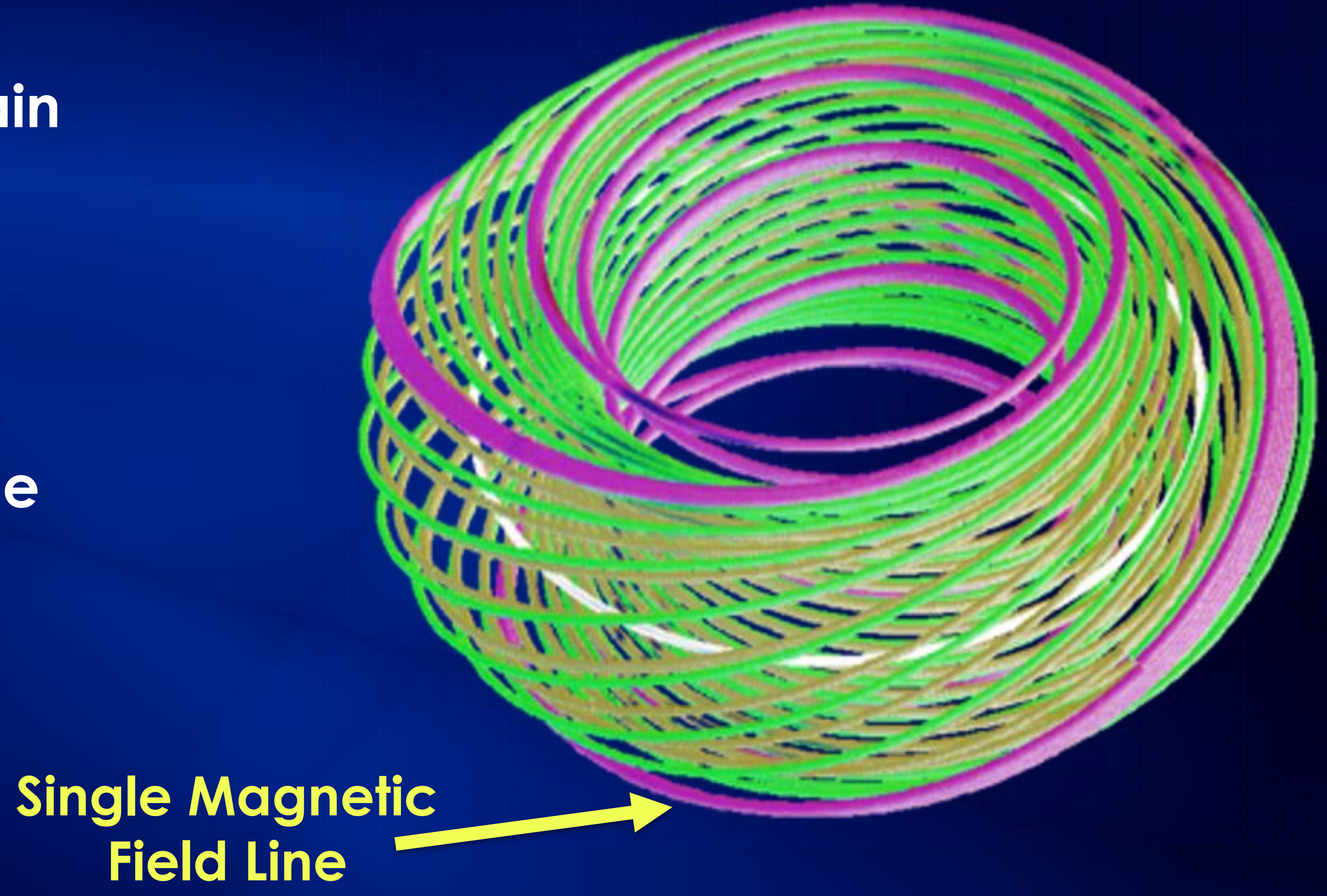
No Confinement Along
Magnetic Field Lines



Magnetic Bottle: Wrapping Magnetic Field Lines on Themselves

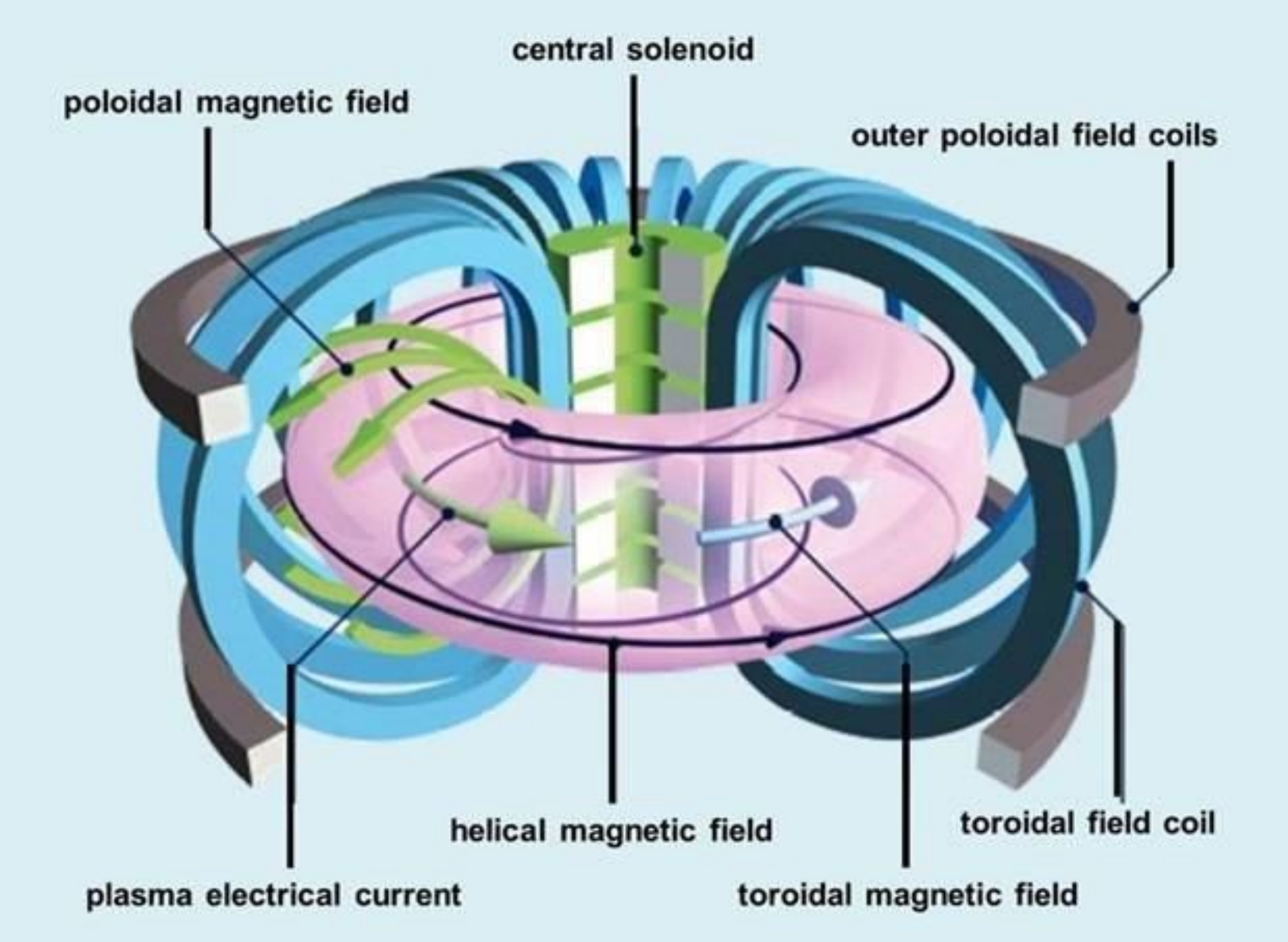
- Charged particles remain confined across the magnetic field

- Free streaming along the magnetic field is now a closed circuit



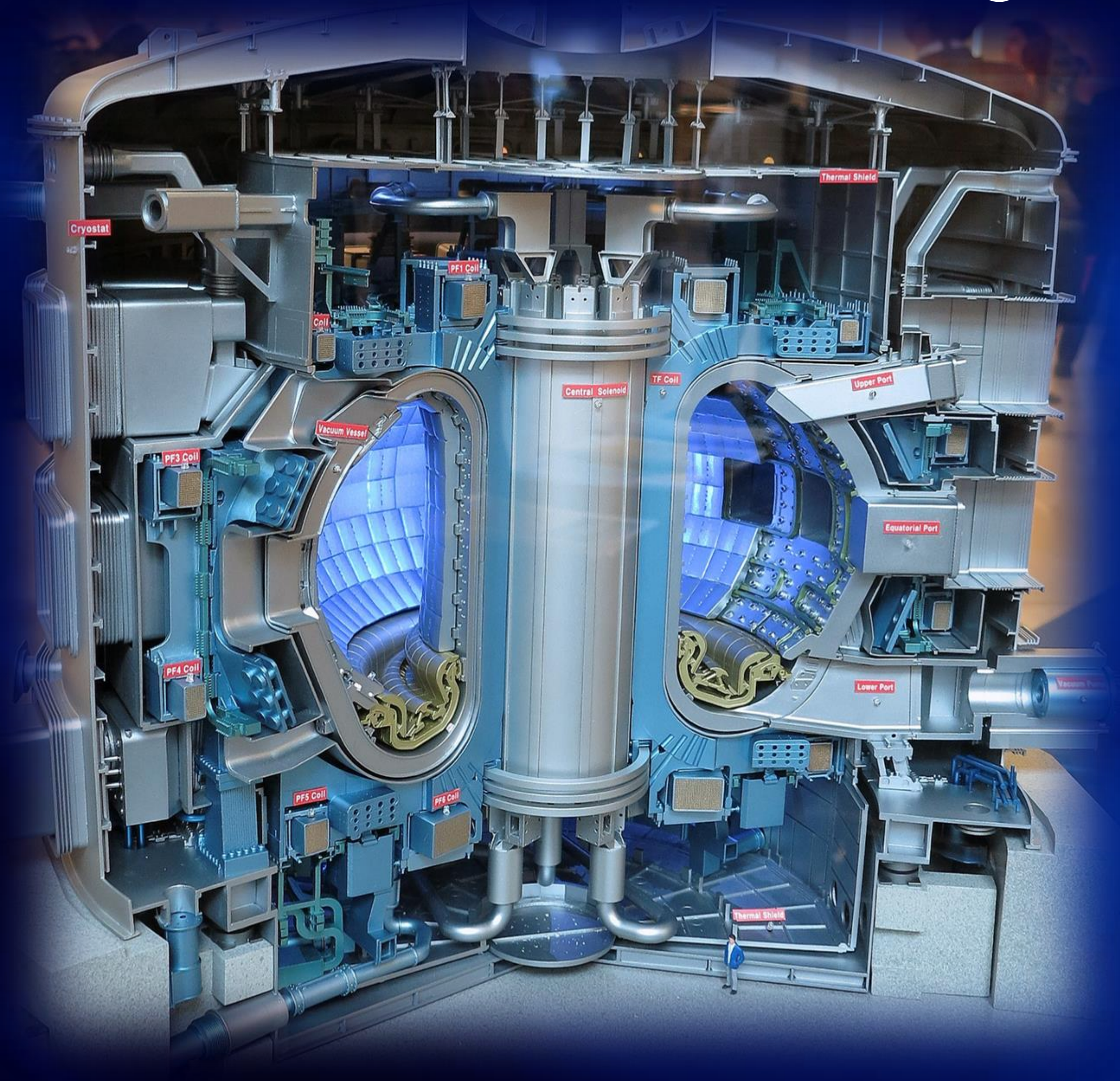
Tokamak: Planar Coils and Toroidal Plasma Current Lead to Simplest Closed Magnetic Surfaces

- External coils provide the primary magnetic field
- Plasma current prevents particle orbits from drifting out of confinement



https://www.energy.gov/science/doe-explainstokamaks

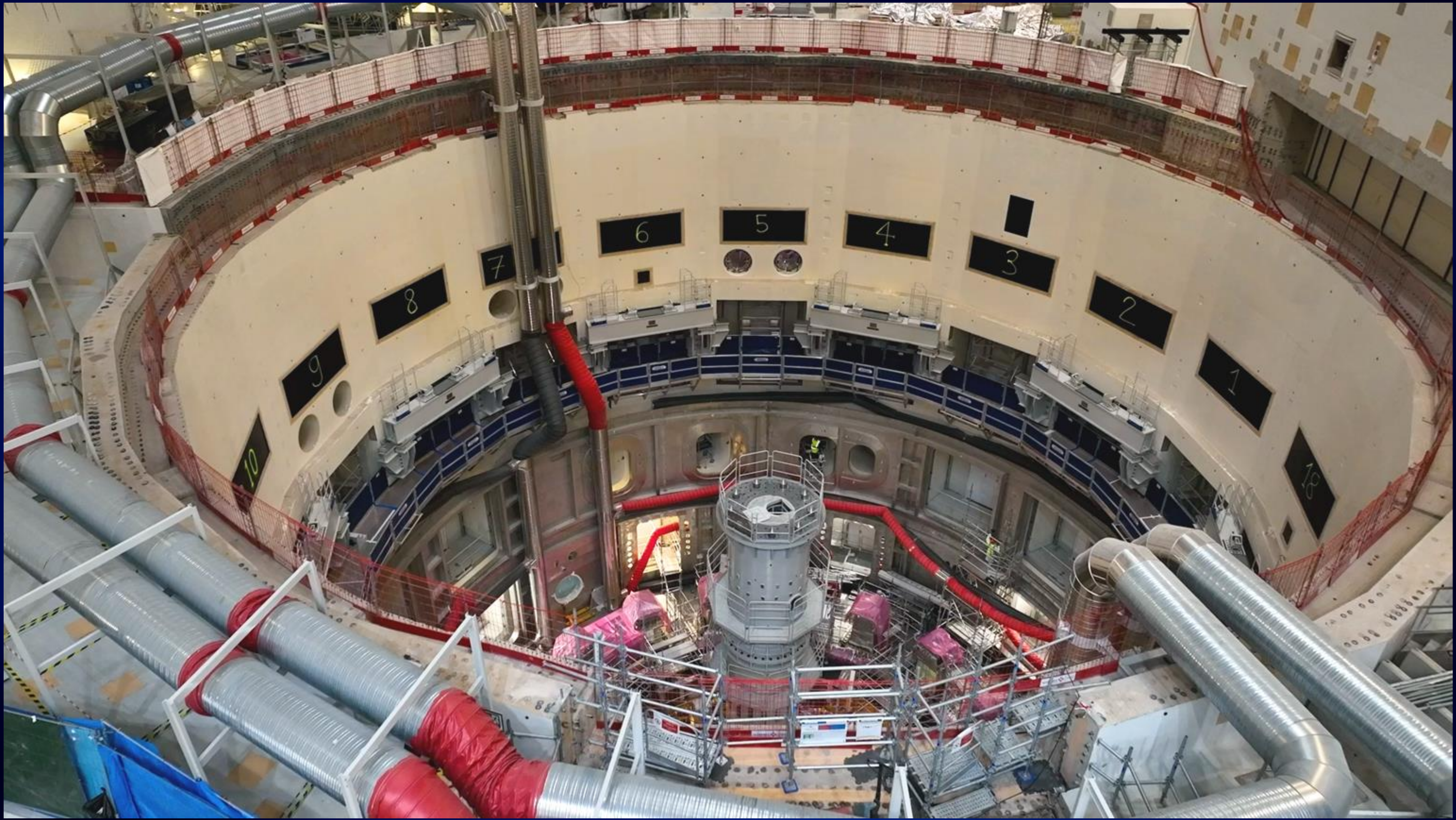
ITER is the First Magnetic Confinement Device Under Construction With the Goal of Producing Sustained Burning Plasmas

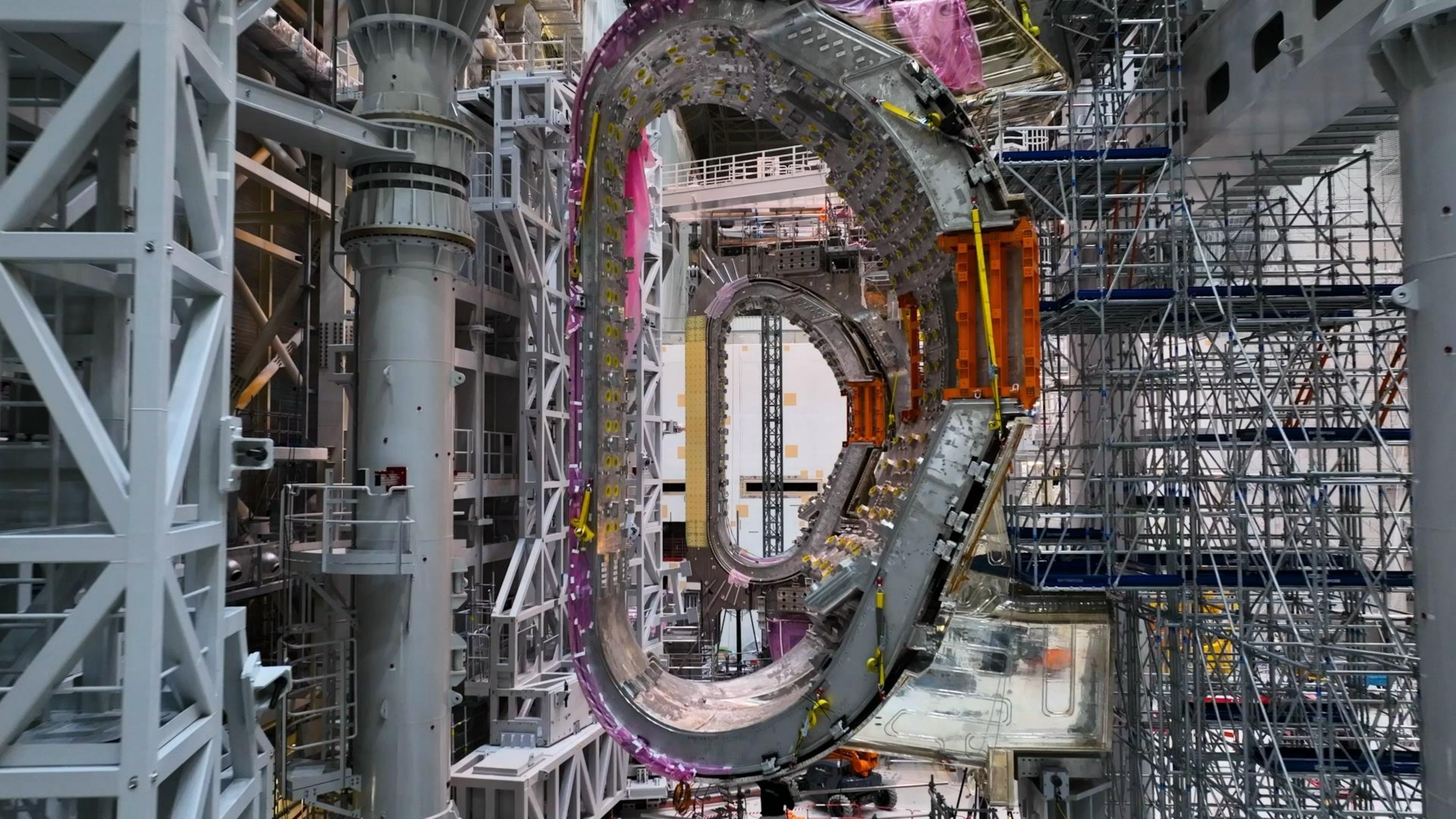


Goal:

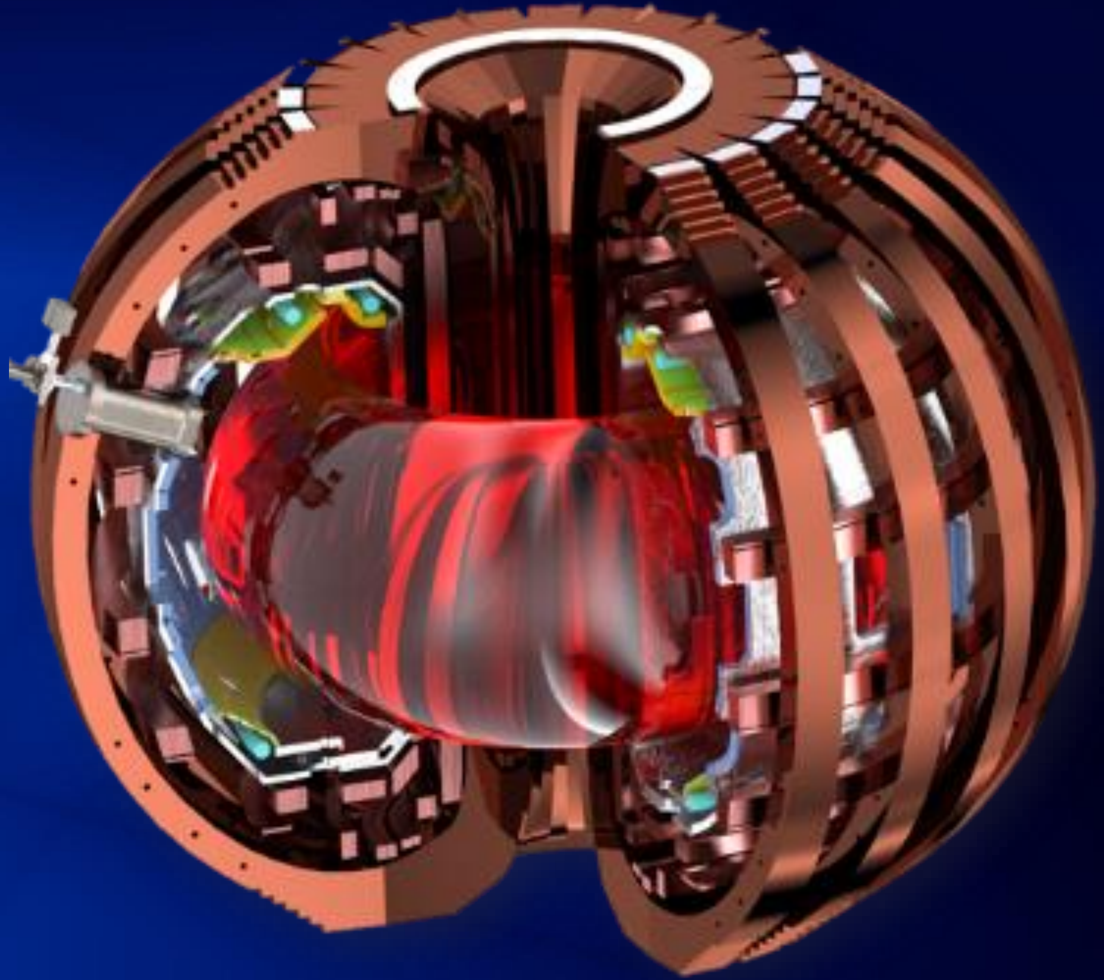
- **500 MW fusion power (10x input)**
- **400 sec → 3000 s**
- **Commence in the early 2030s**

ITER is Big



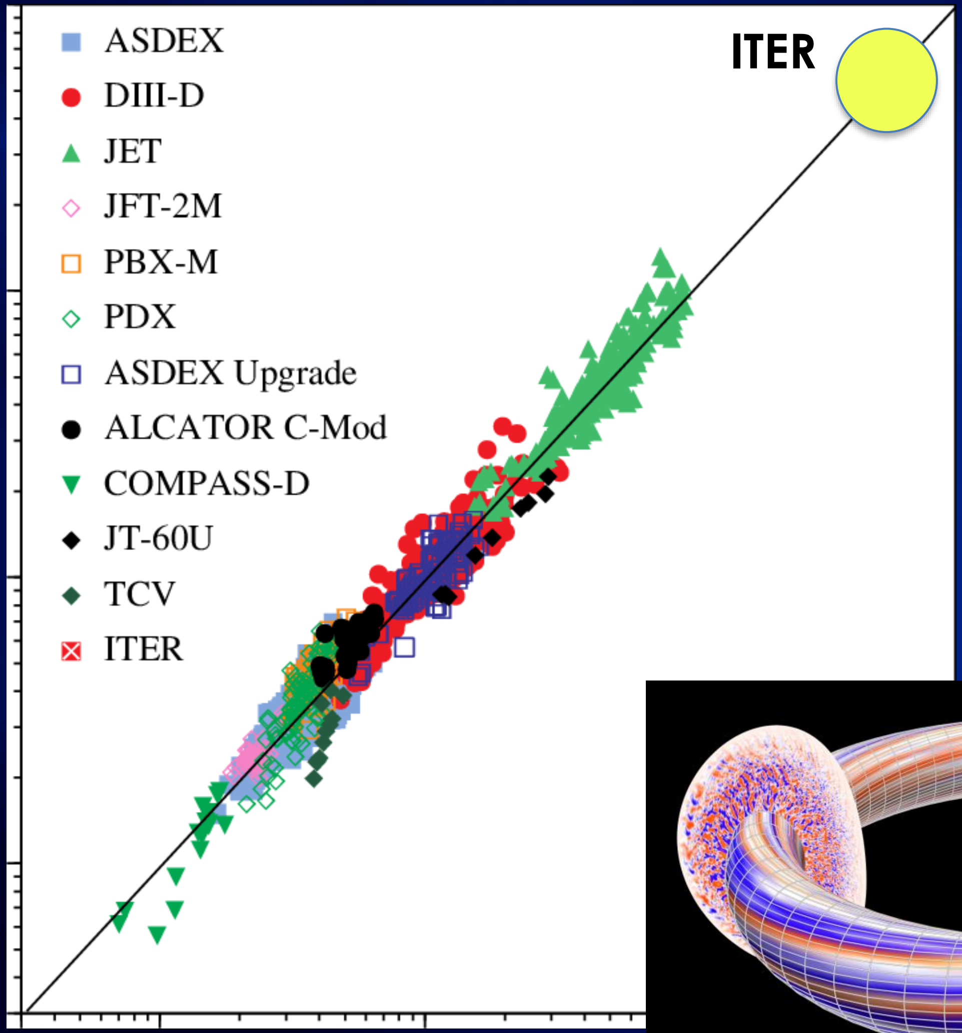


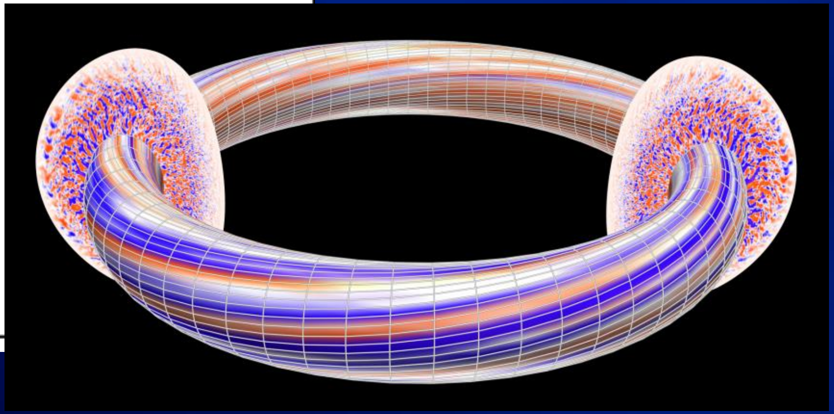
DIII-D Tokamak is the Largest Magnetic Confinement Fusion Research Facility in the US



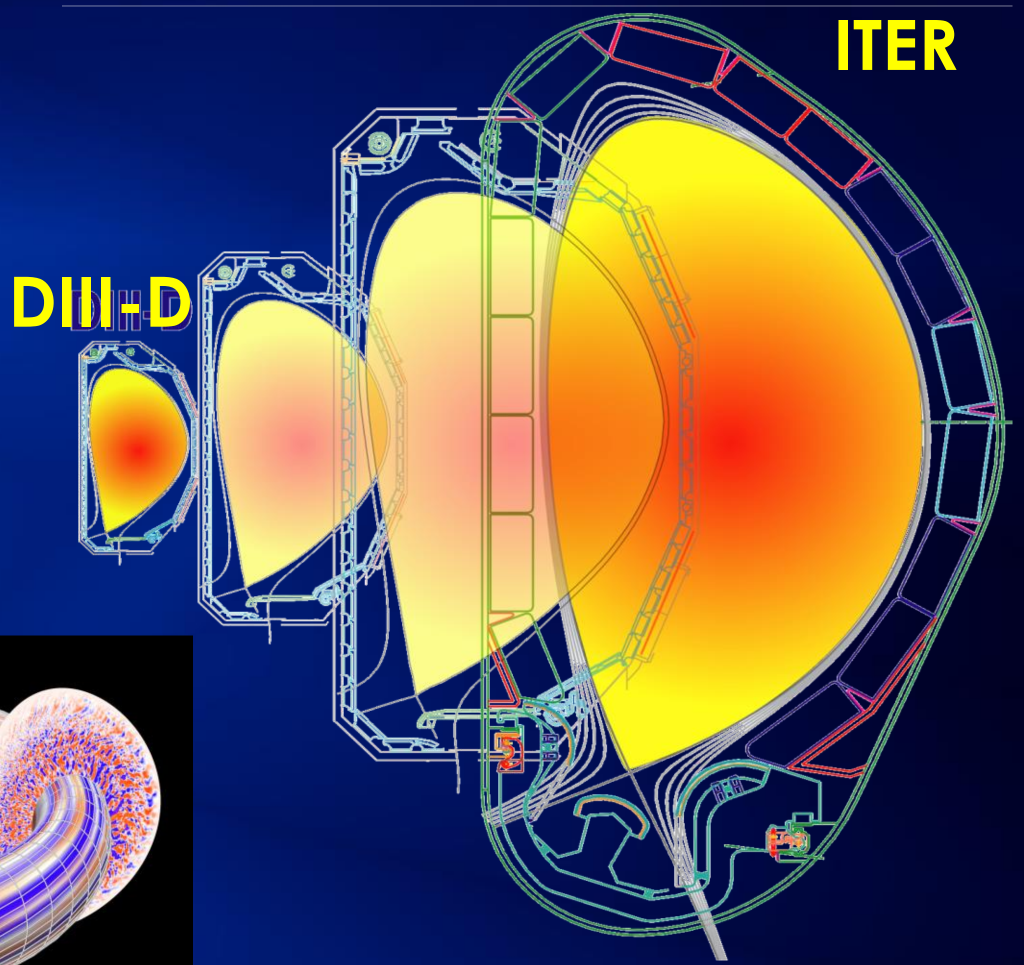
World-leading facility for support of ITER design and research planning

Advanced Simulations and Empirical Scaling Play a Vital Role in Bridging the Gap Between Present Experiments and ITER

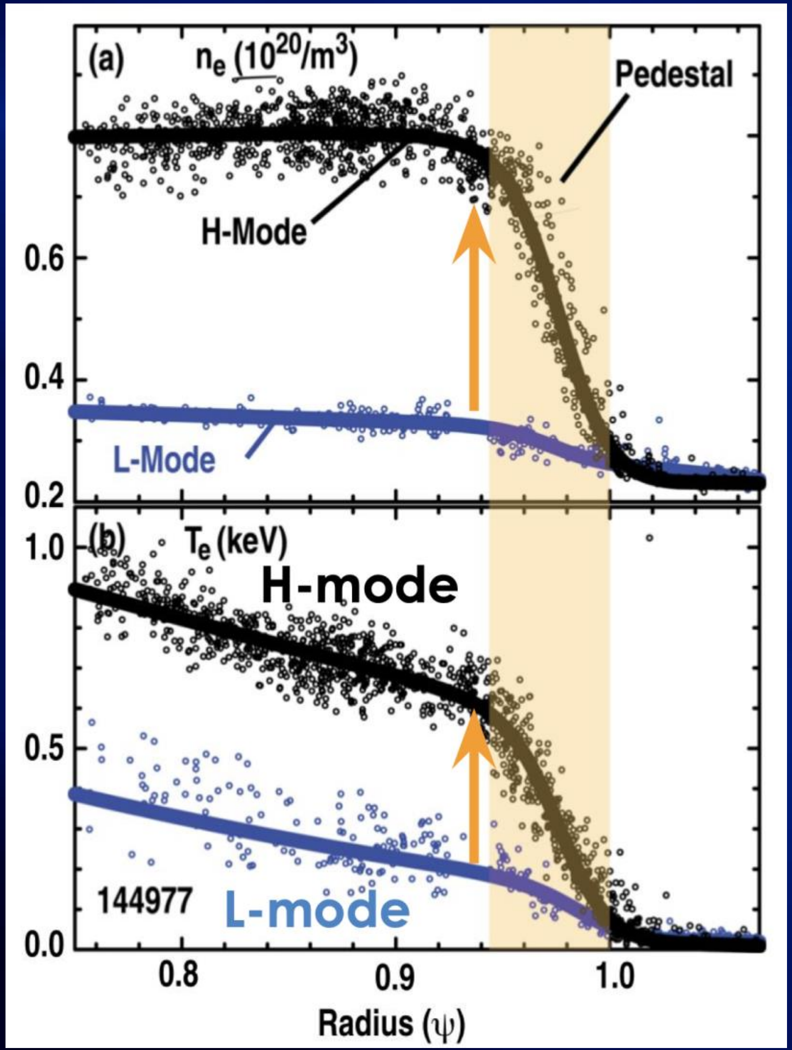




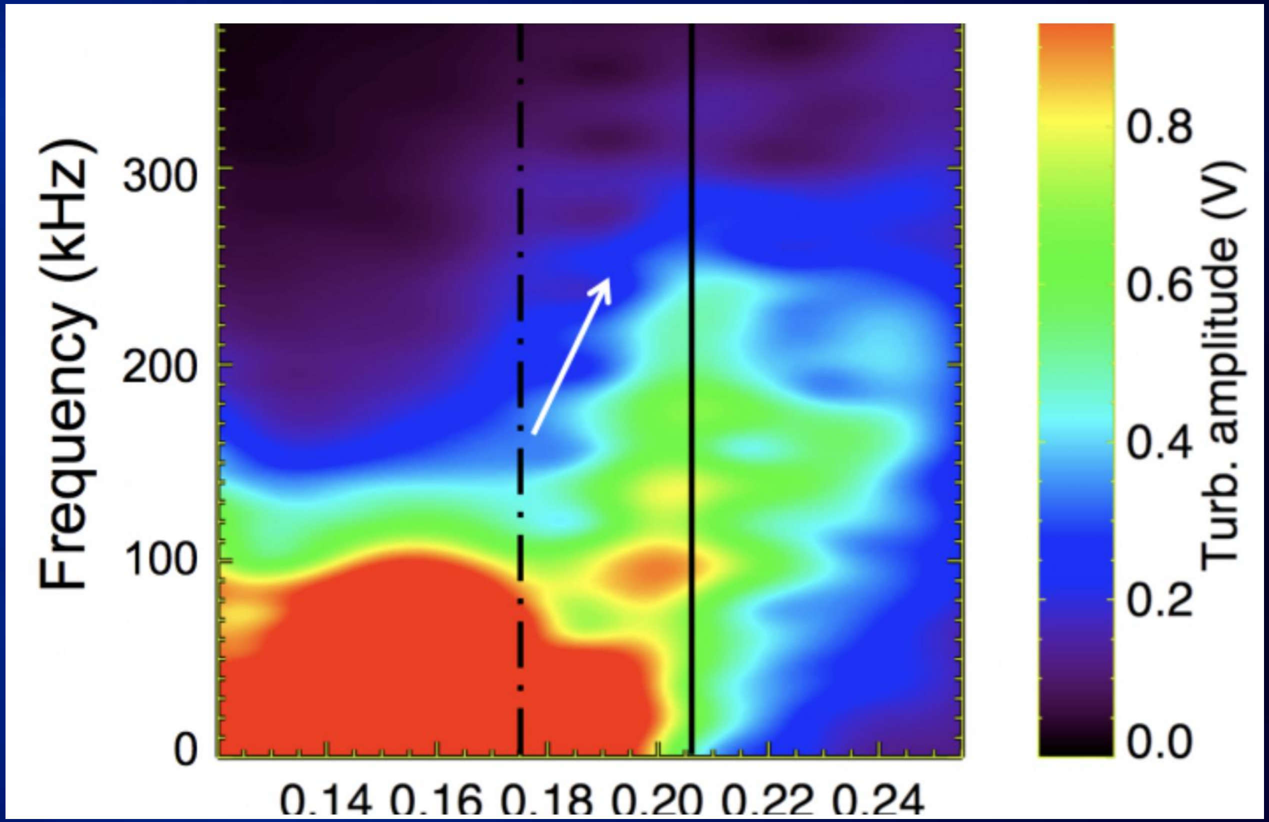
Gyrokinetic Simulation



Central to Tokamak Path to Fusion is the Spontaneous Formation of an Edge Transport Barrier

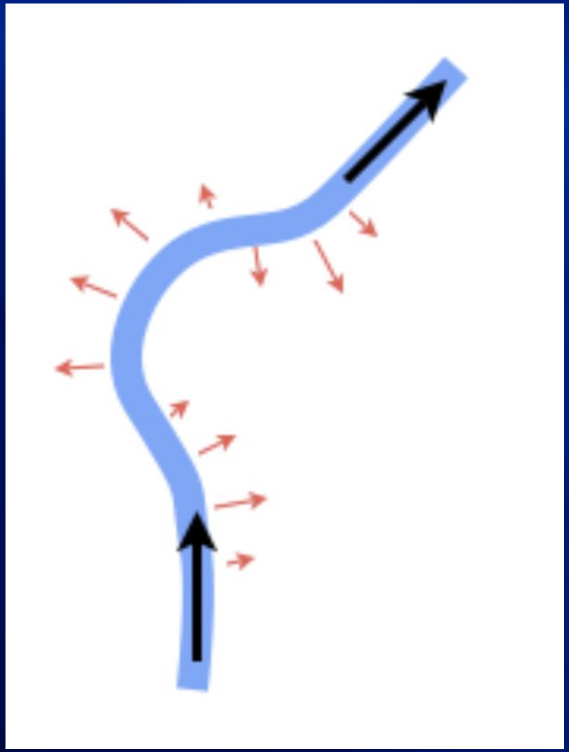


Gyrokinetic Simulation: SUMMIT

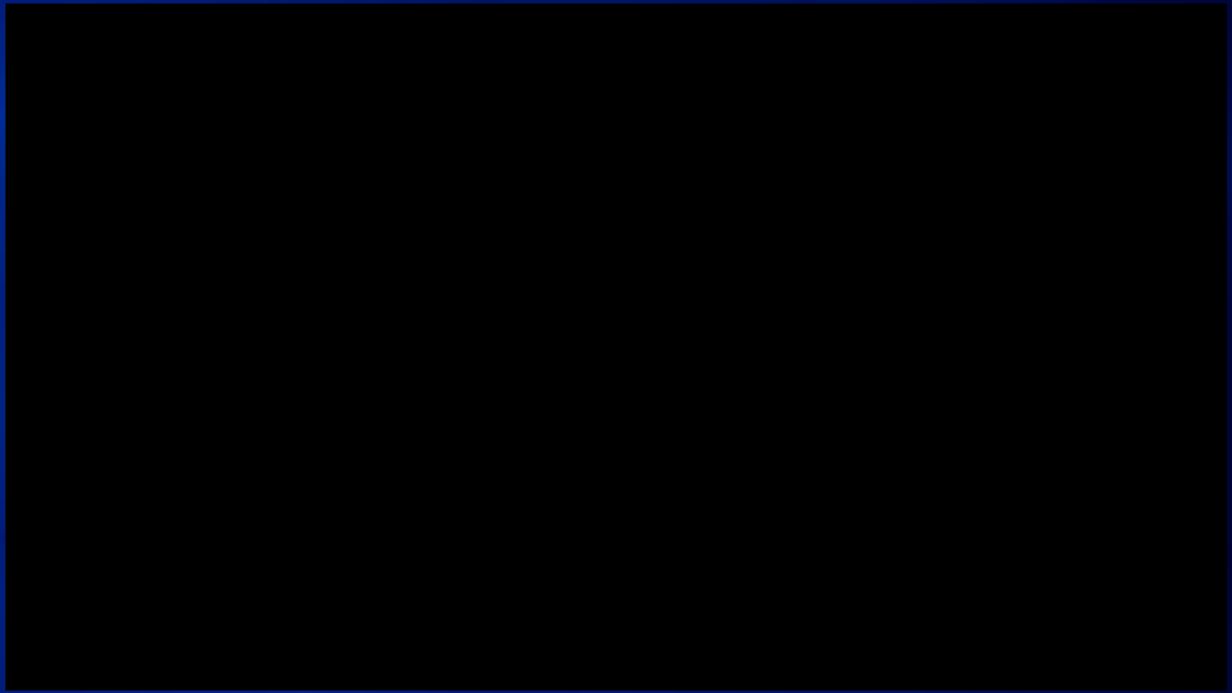


The Problem With Tokamaks: Disruptions

Firehose instability



C-MOD tokamak: Cambridge MA



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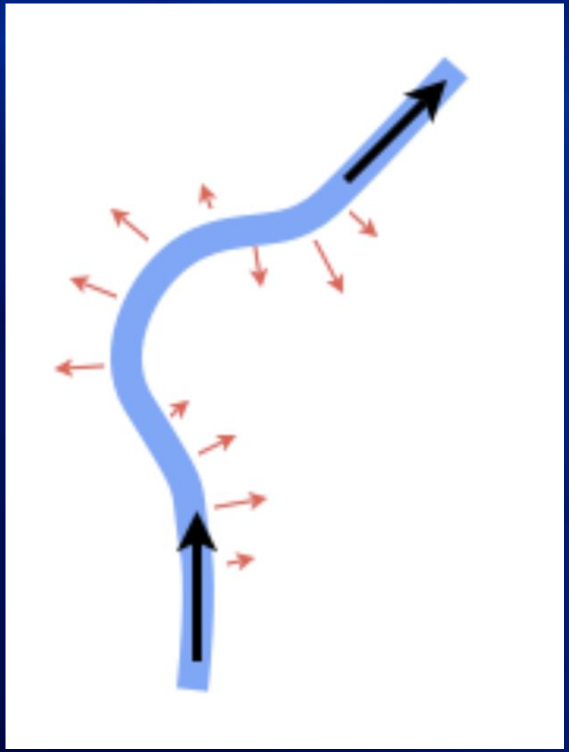
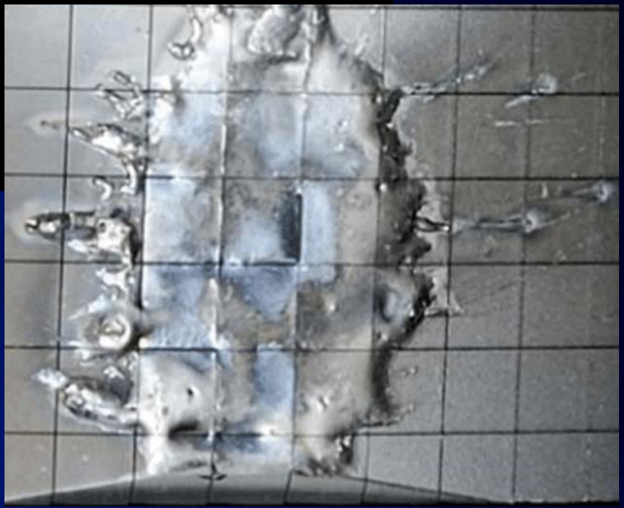


C-MOD tokamak: Cambridge MA

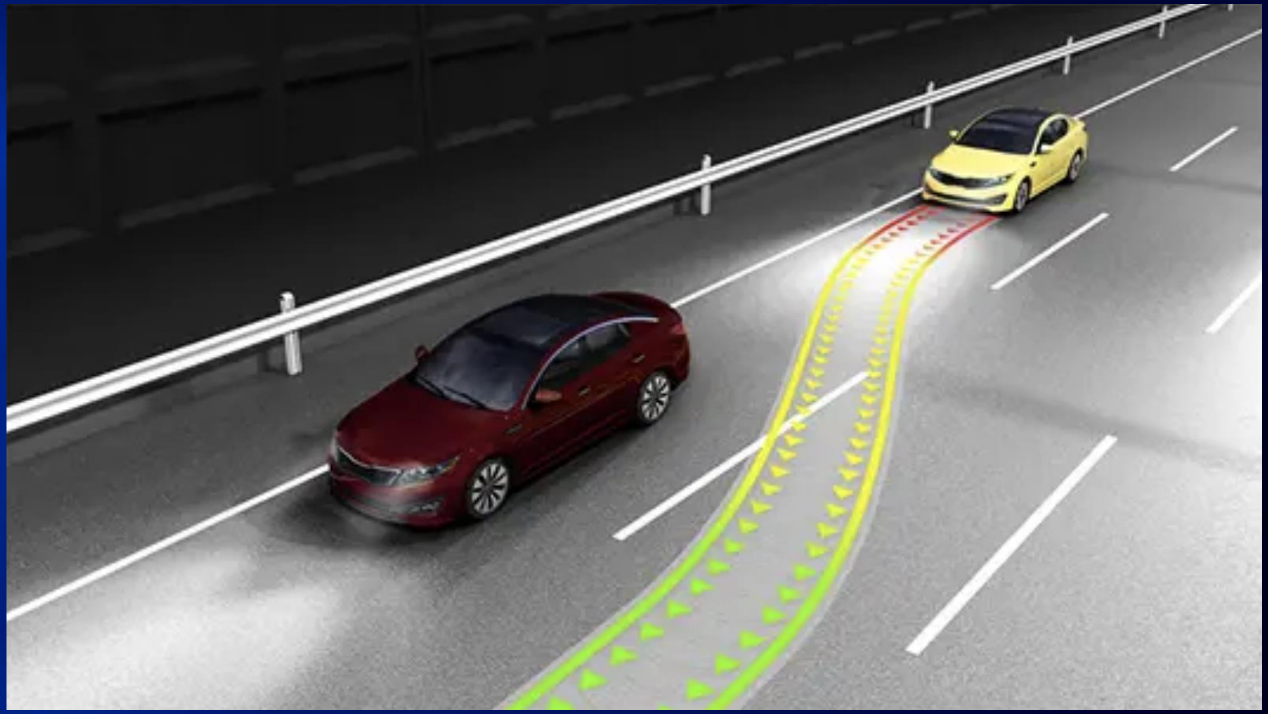
Tile melting: JET Culham, UK



Real-time Proximity Detection and Avoidance in Tokamaks Using AI/ML

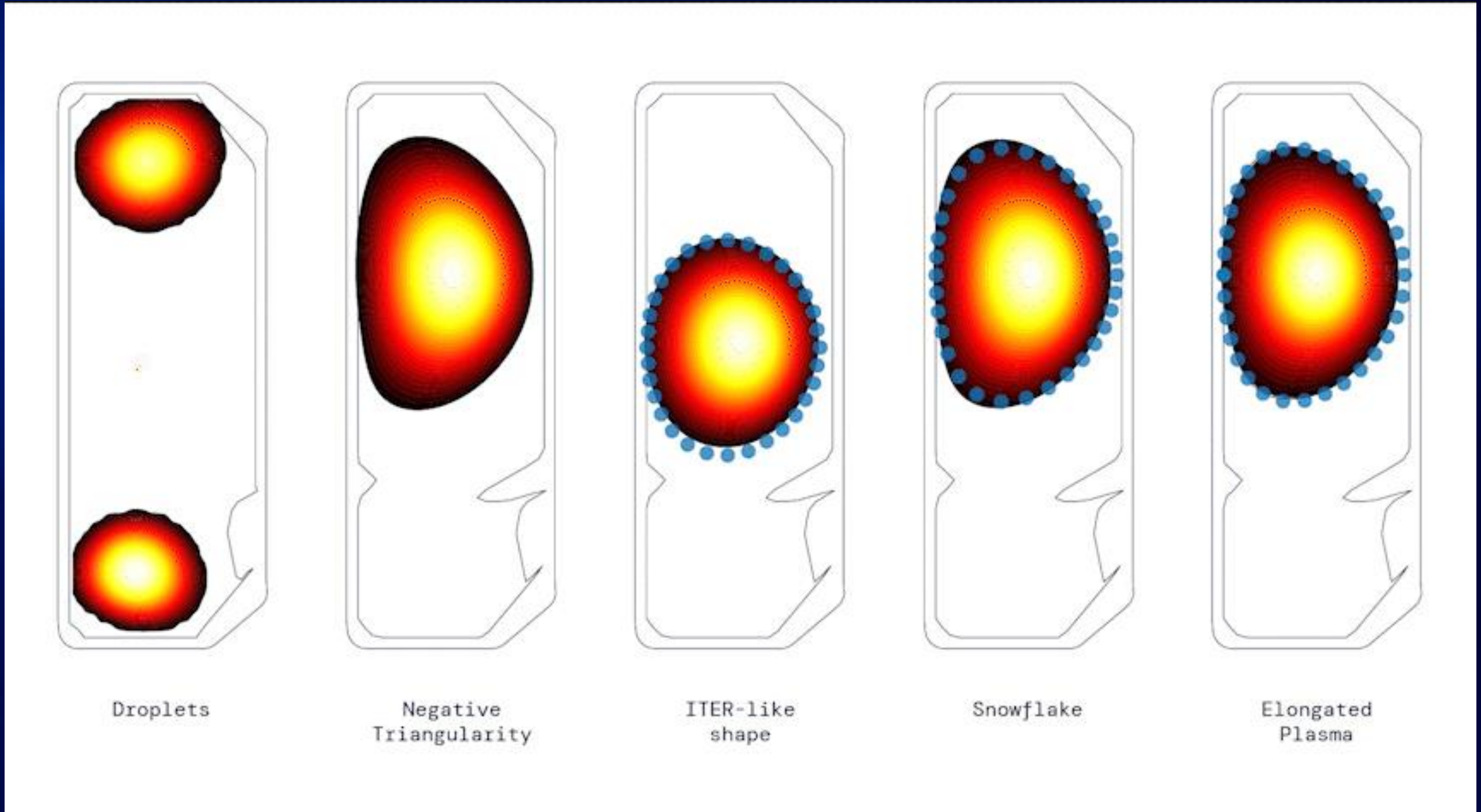
Disruption avoidance researchers DIII-D

Collision avoidance



Machine Learning for Tokamak Plasma Control is Rapidly Advancing

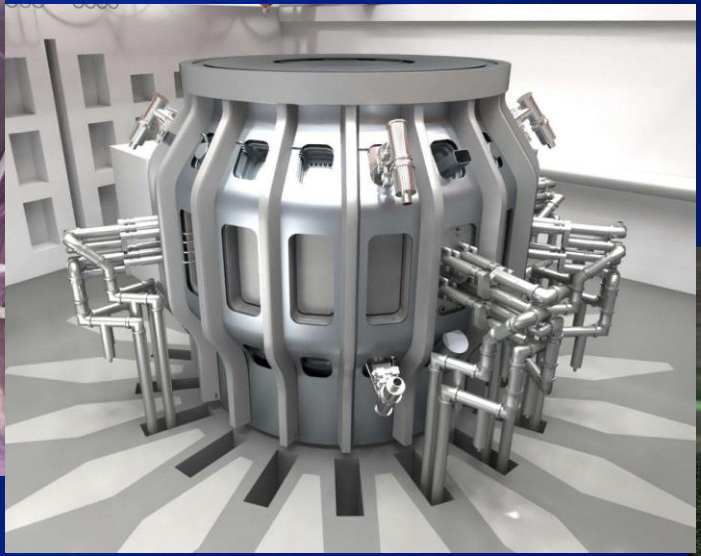
Reinforcement Learning at TCV: Jonas Degrave, et al., Nature 602, 414 (2022)



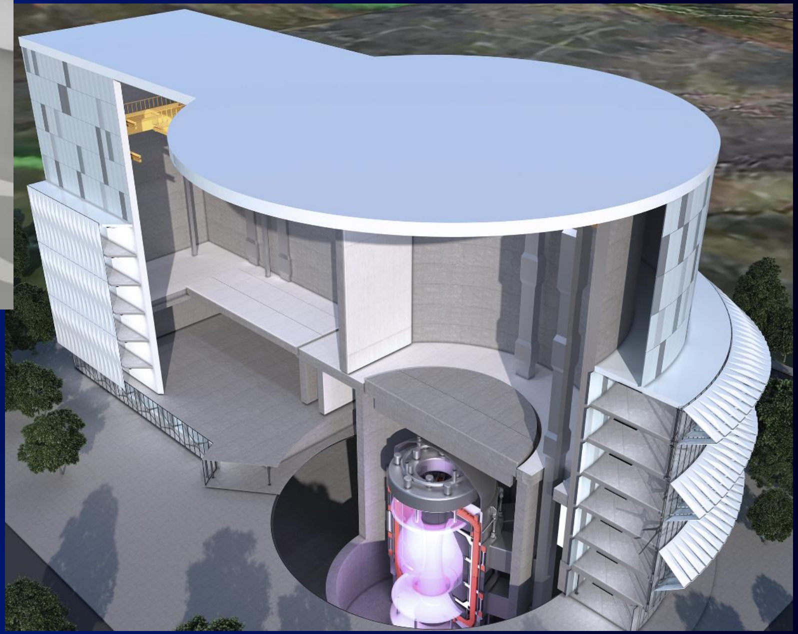
Disruption Avoidance Schemes are Central to Next Steps in Tokamak Reactor Development

ITER: Cadarache, France

SPARC: CFS, USA

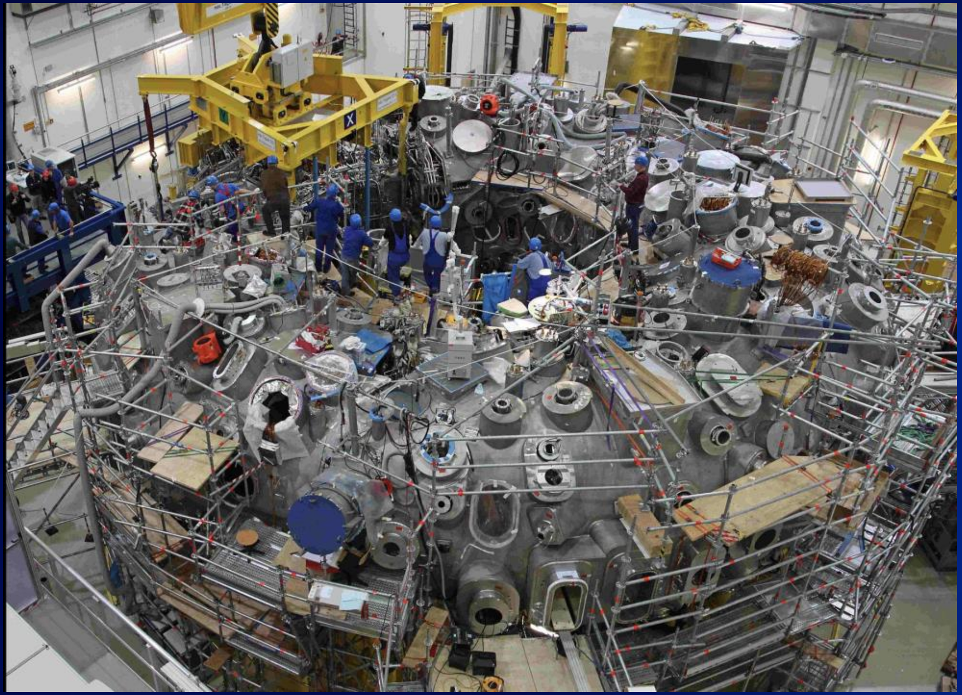


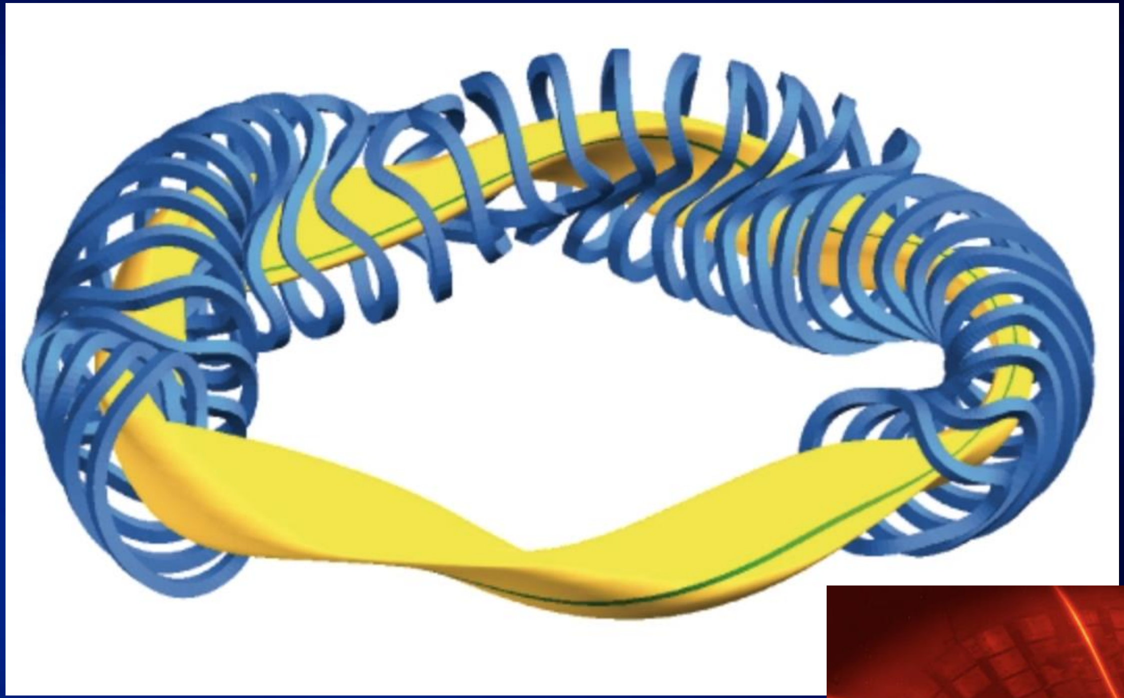
STEP: UKAEA

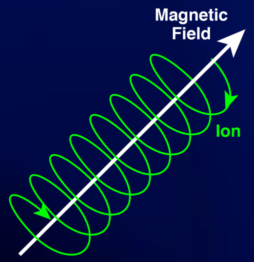


Alternative path: Stellarators and “Hidden Symmetries”

W7-X: Greifswald, Germany





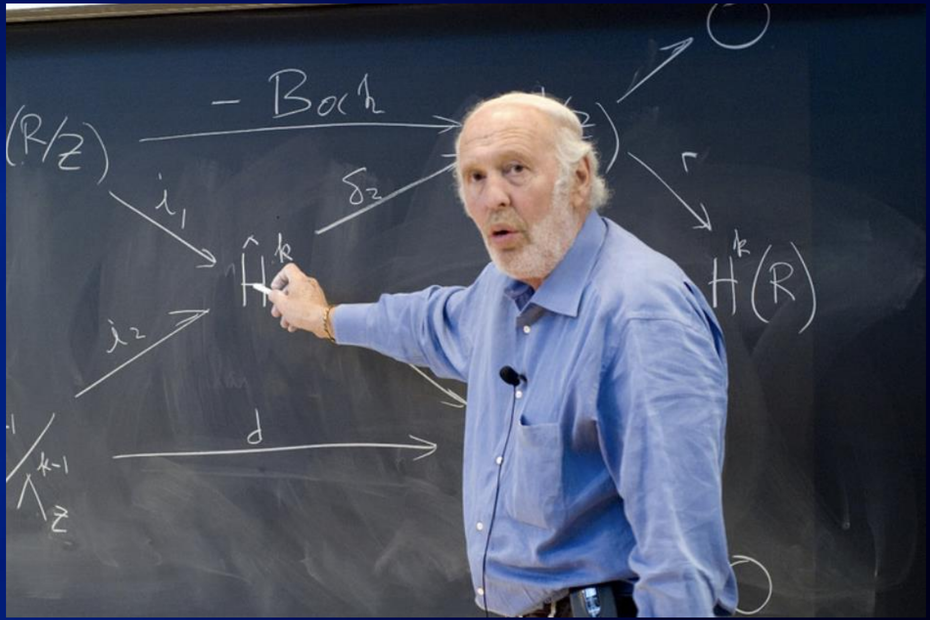


Searching for “quasi-constants” of motion

Hidden Symmetries Center Supported by Simons Foundation and the Flatiron Institute

Flatiron Institute New York NY

Jim Simons: Renaissance Technologies



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Flatiron Institute New York NY

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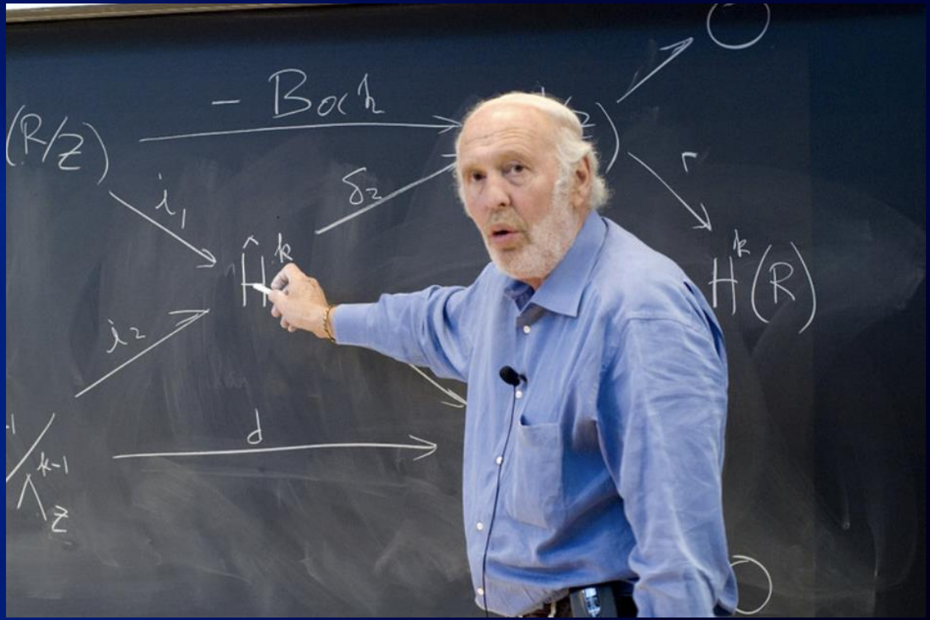
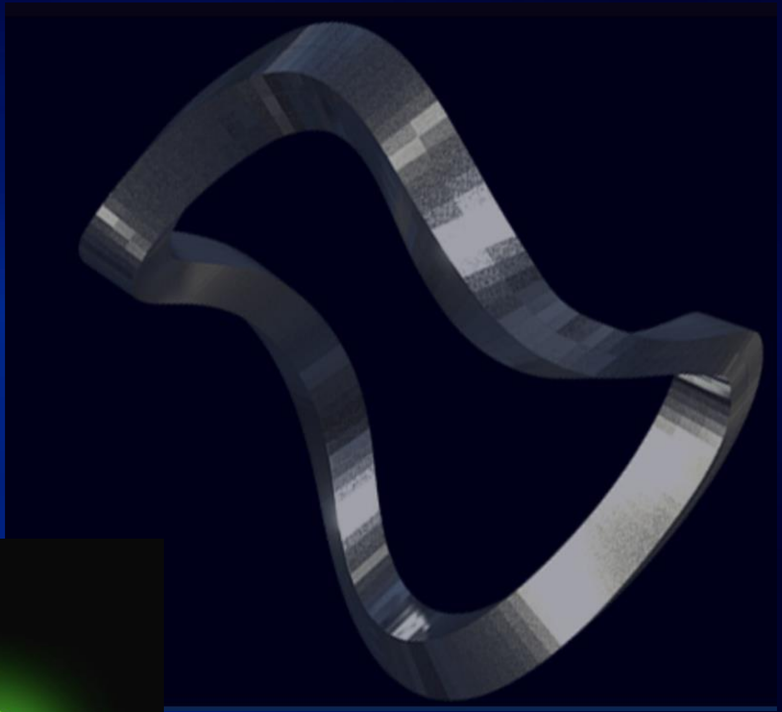
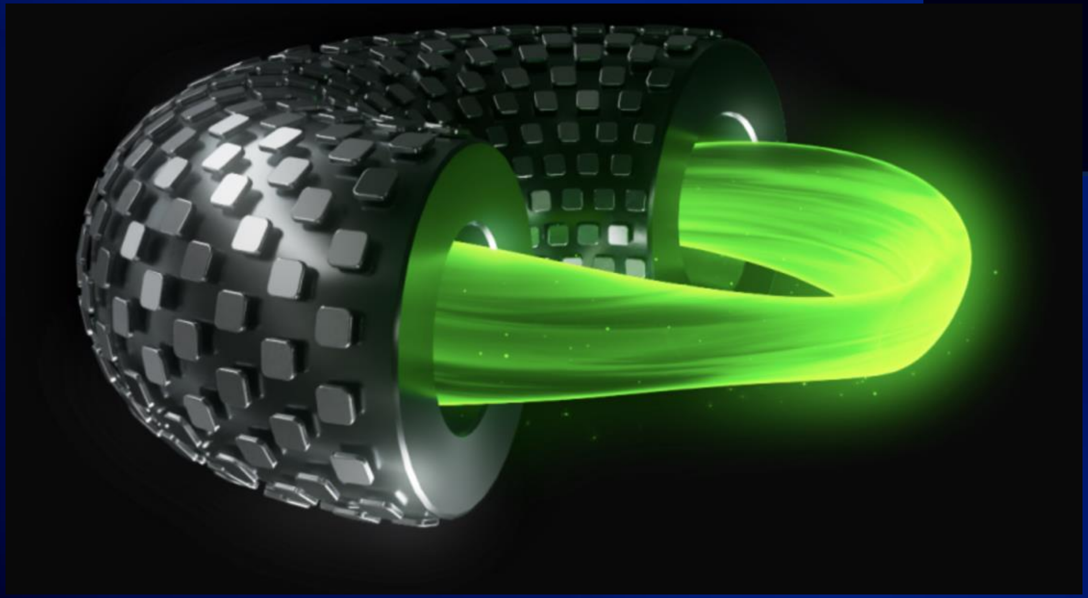


Industry interest in Stellarators is High

TYPE ONE ENERGY

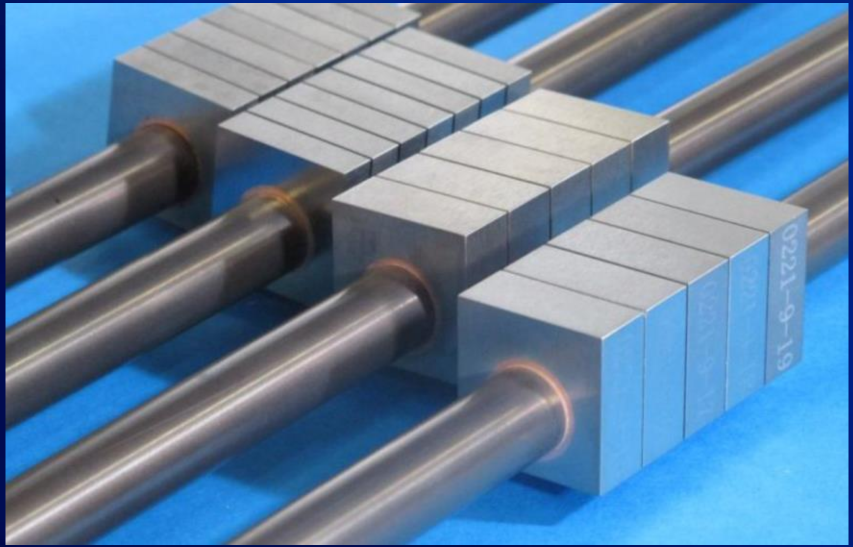


THEA ENERGY

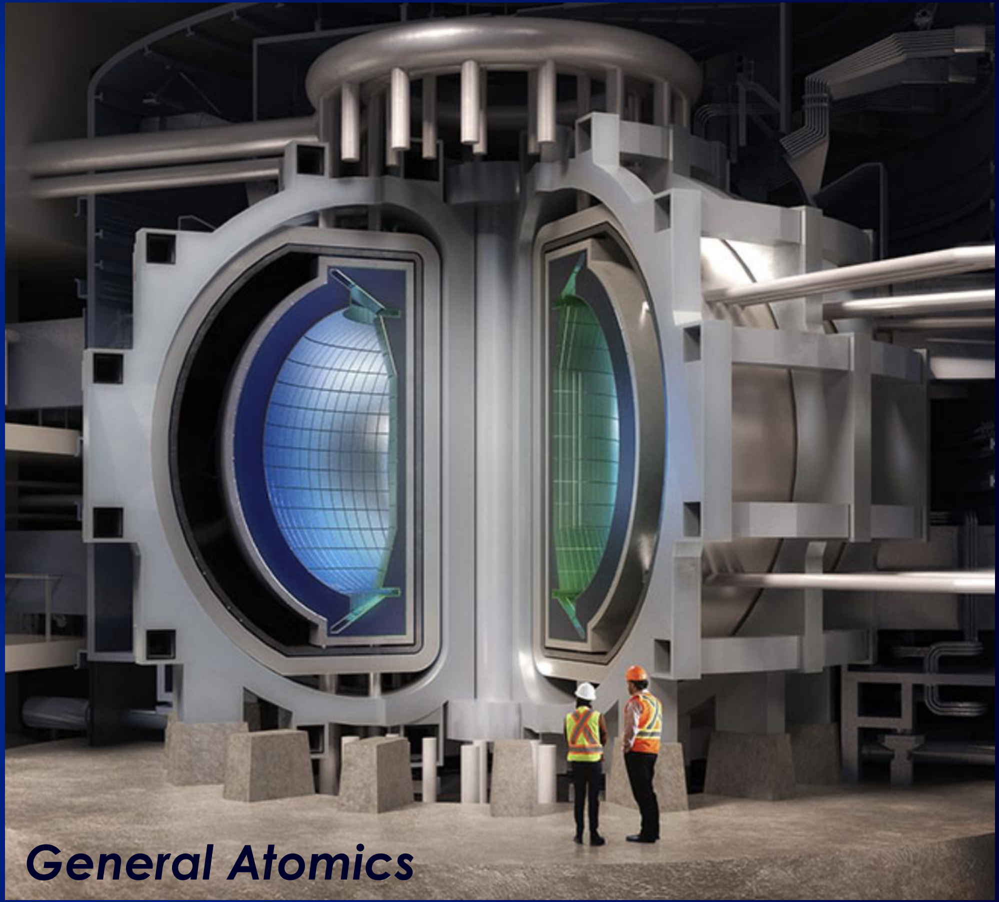


A Common Challenge for Fusion is Material Erosion and Impurity Influx Under Stationary Conditions

W mono-block & cooing channel ~10 MW/m^2

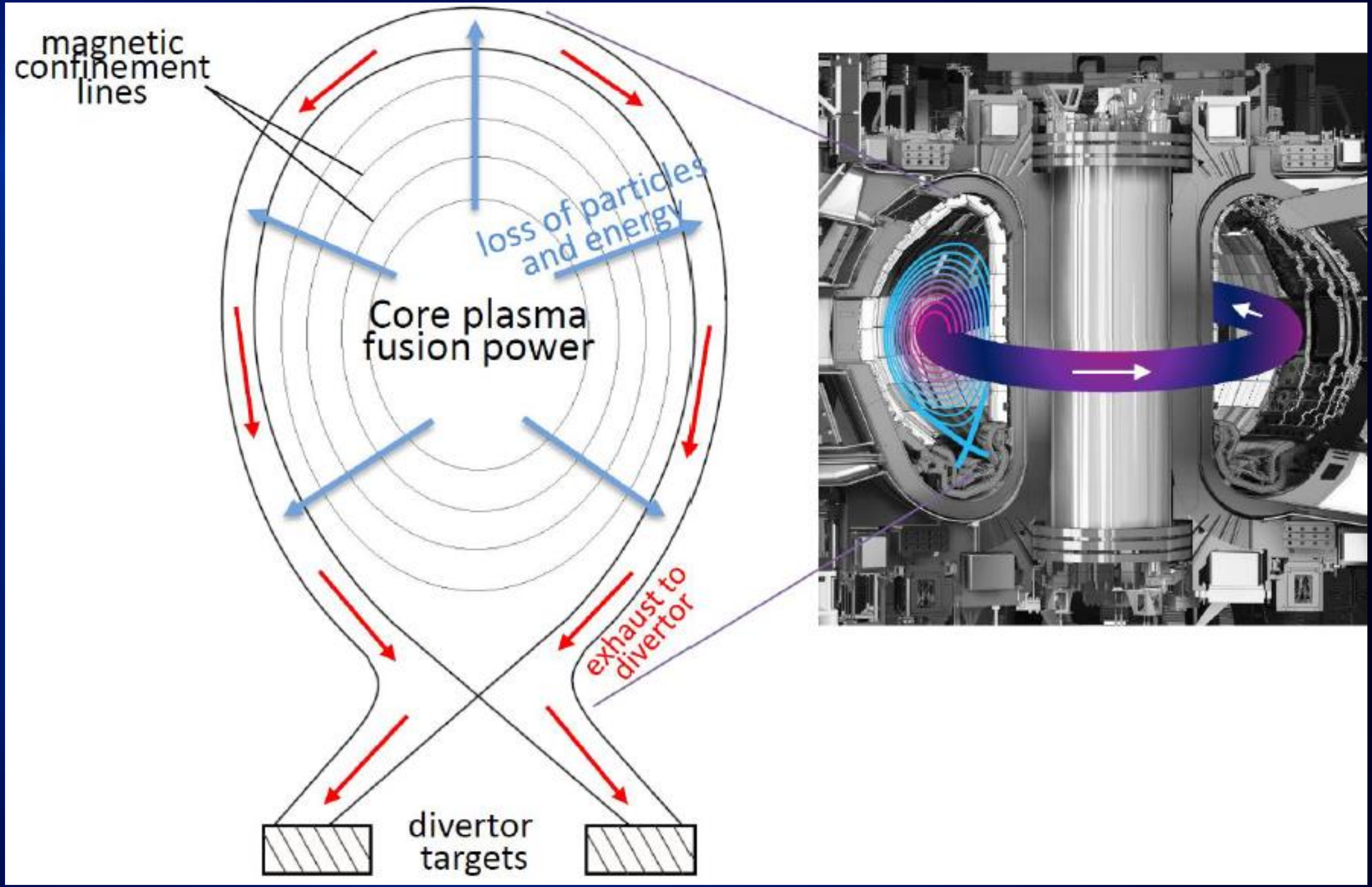


Fusion Pilot Plant (FPP) ~ 50-100 MW/m^2



"Divertor" Solutions Try To Minimize Heat Flux to Material Surfaces

TCV Tokamak: Lausanne, Switzerland



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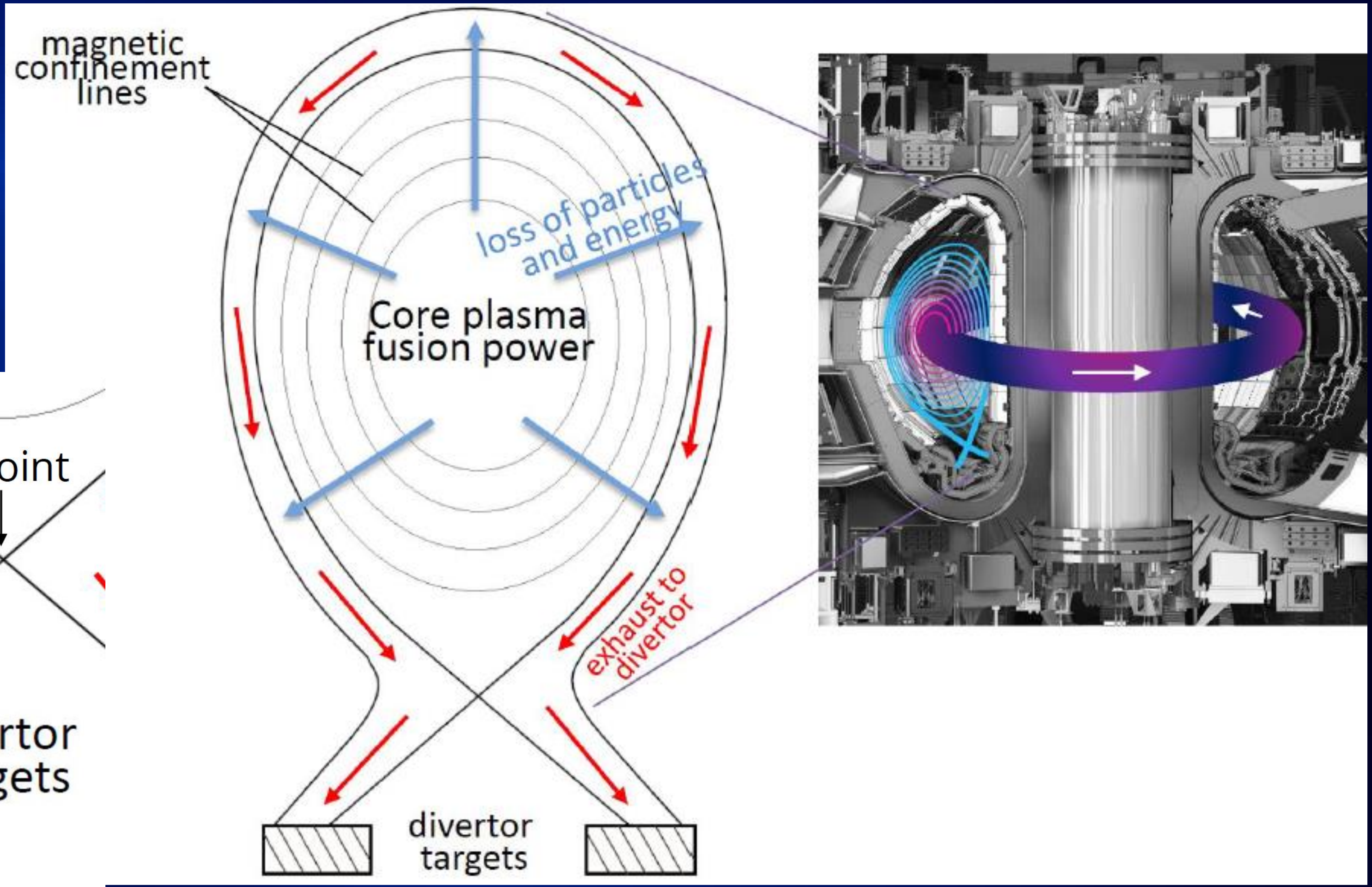
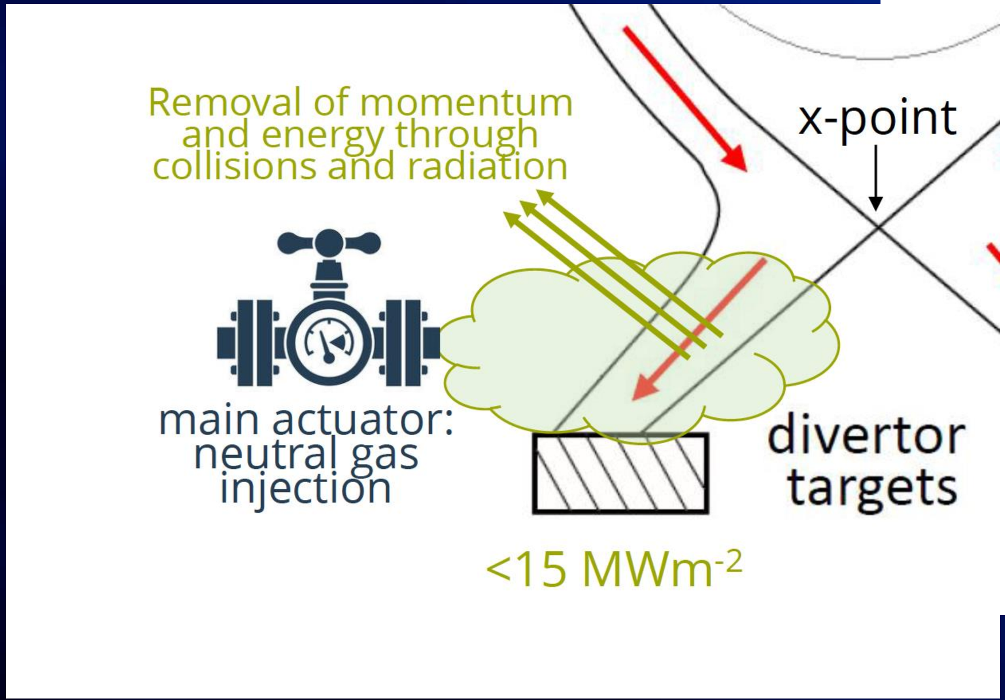
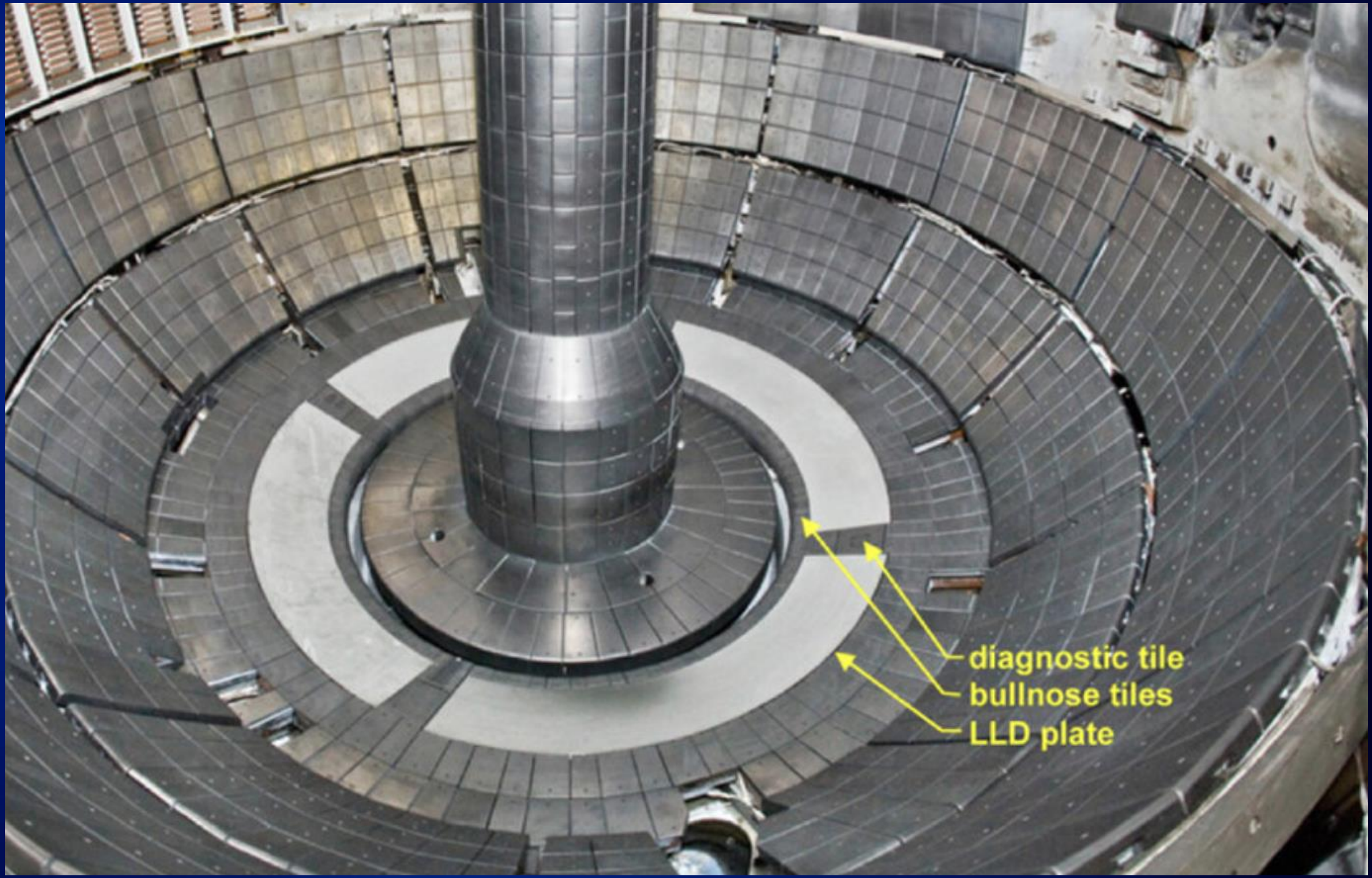




Liquid metals and vapors present an interesting alternative to solid material approaches

NSTX-U: Princeton Plasma Physics Laboratory



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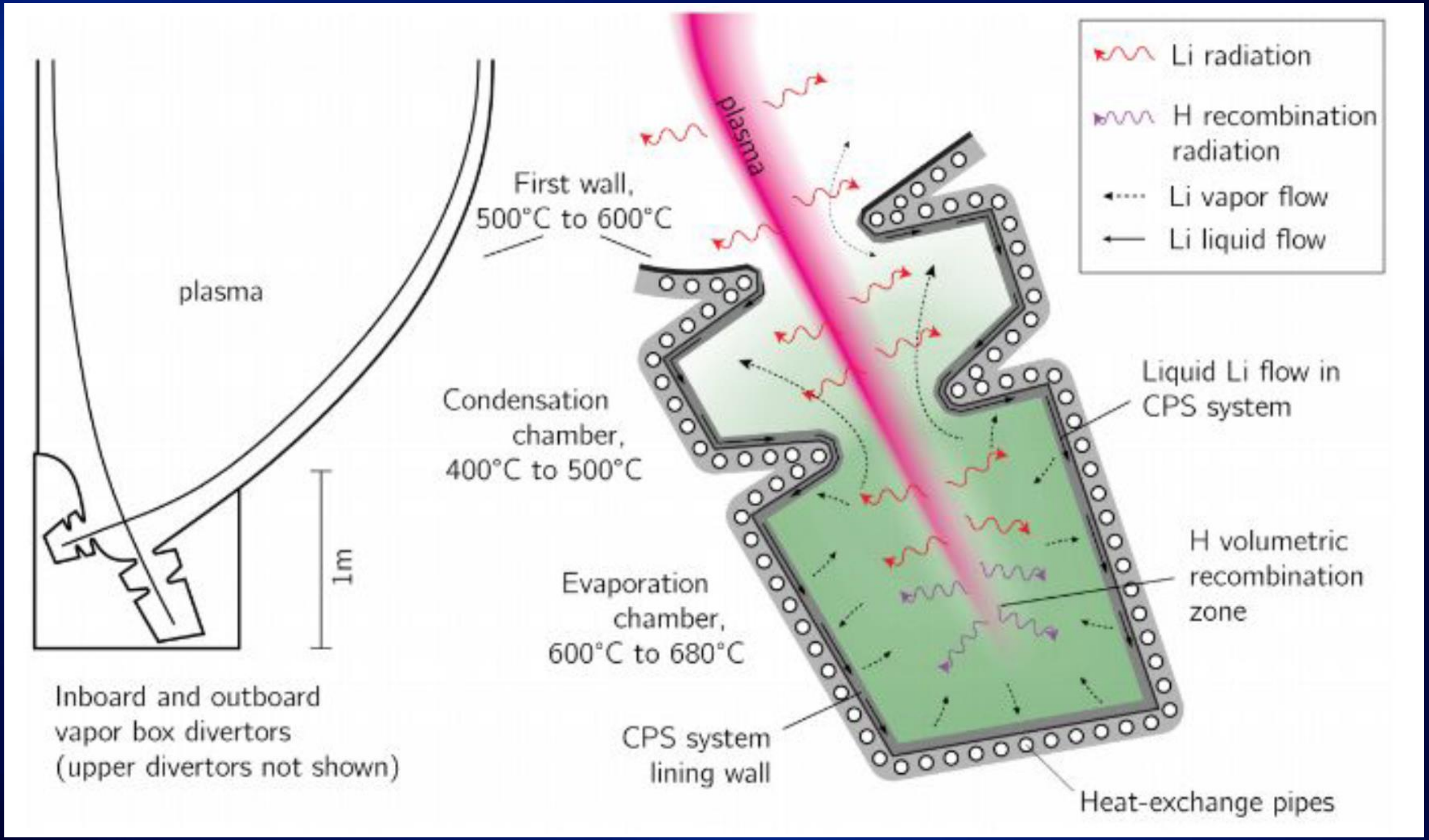
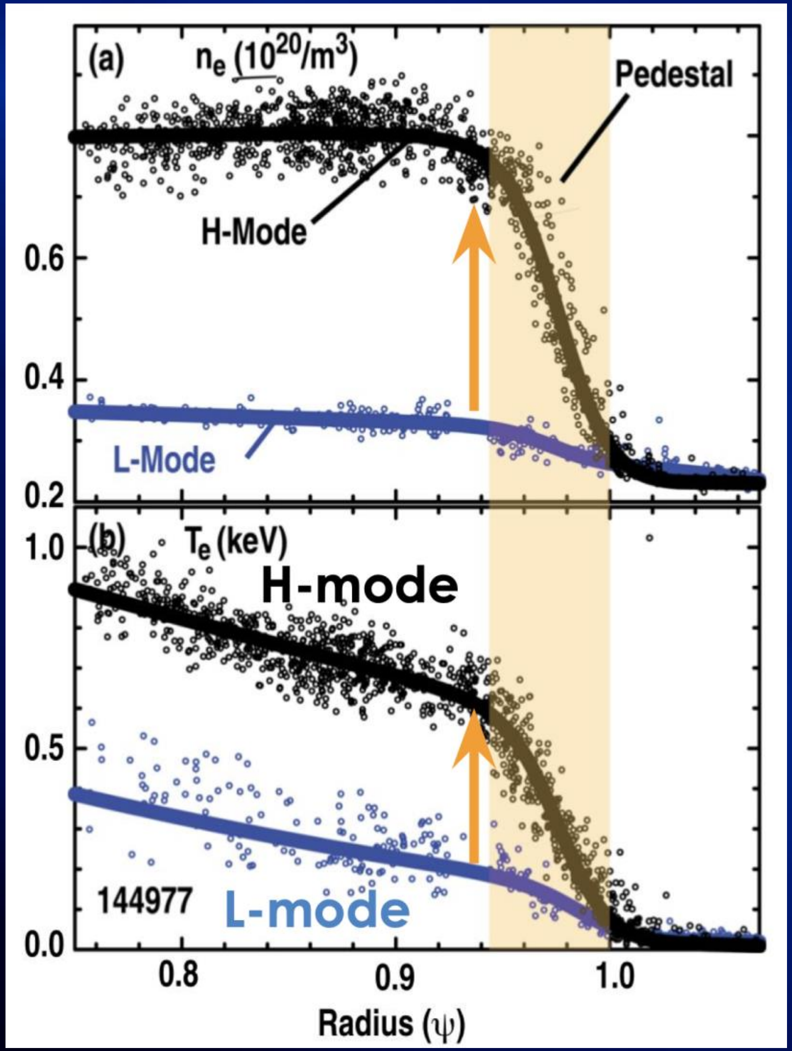
Princeton Plasma Physics Laboratory

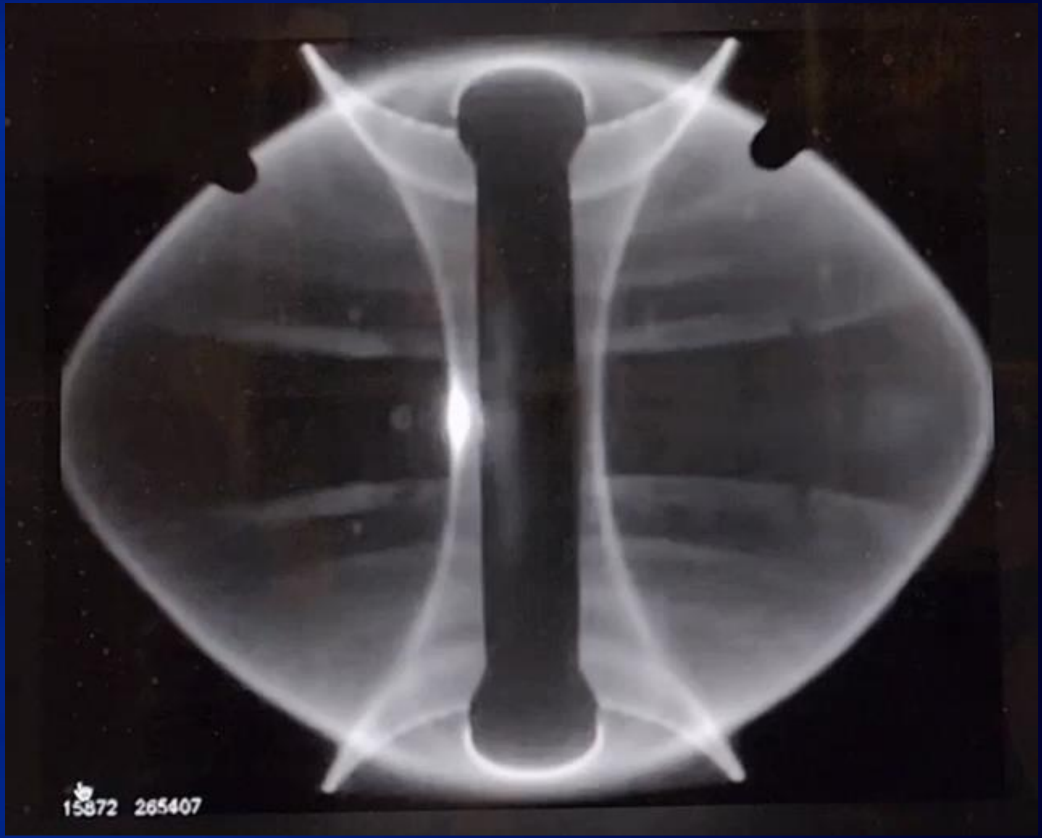


There are also transient heat flux challenges in nominally stationary plasma conditions, called ELMs

DIII-D H-mode vs L-mode: San Diego CA

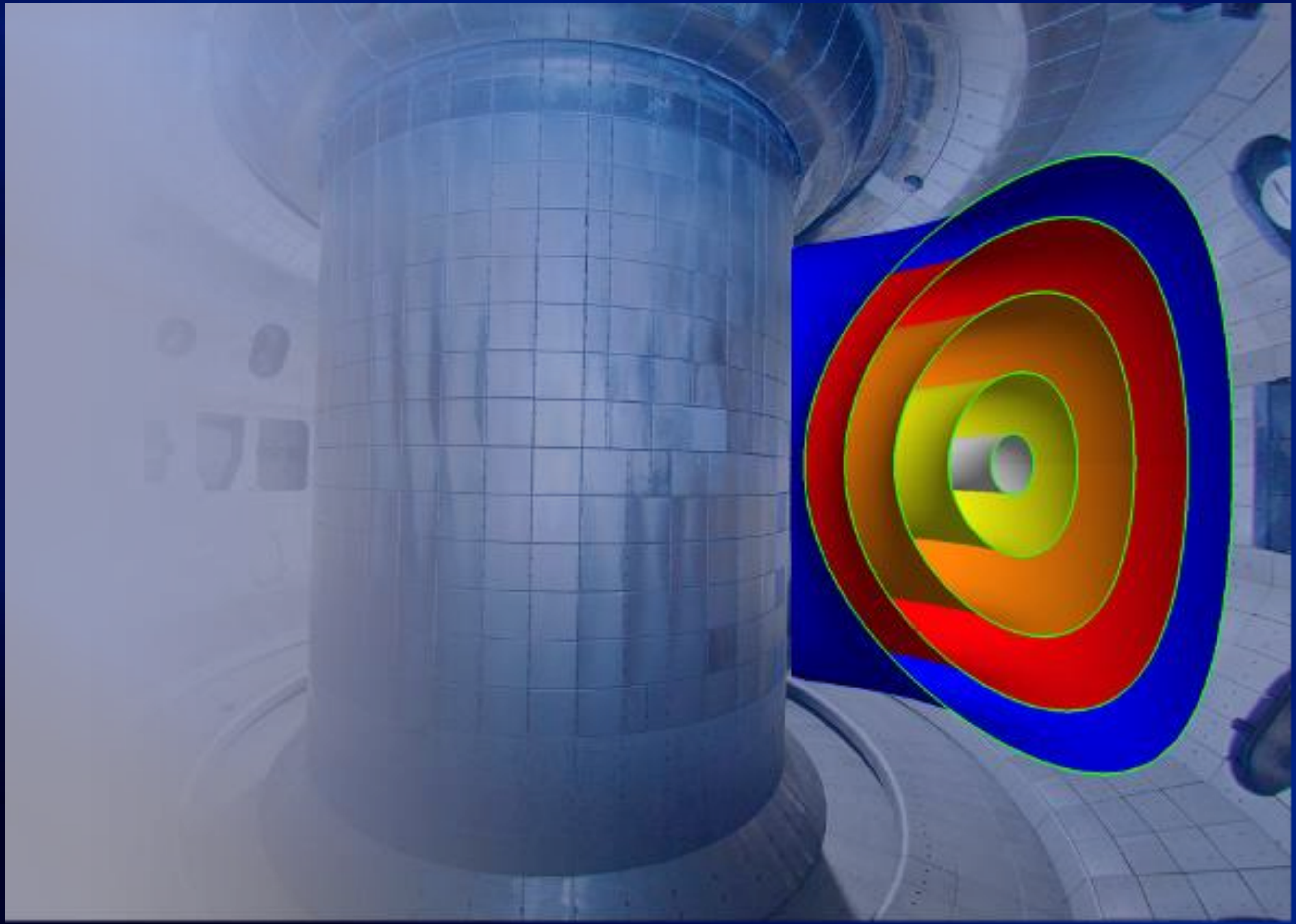


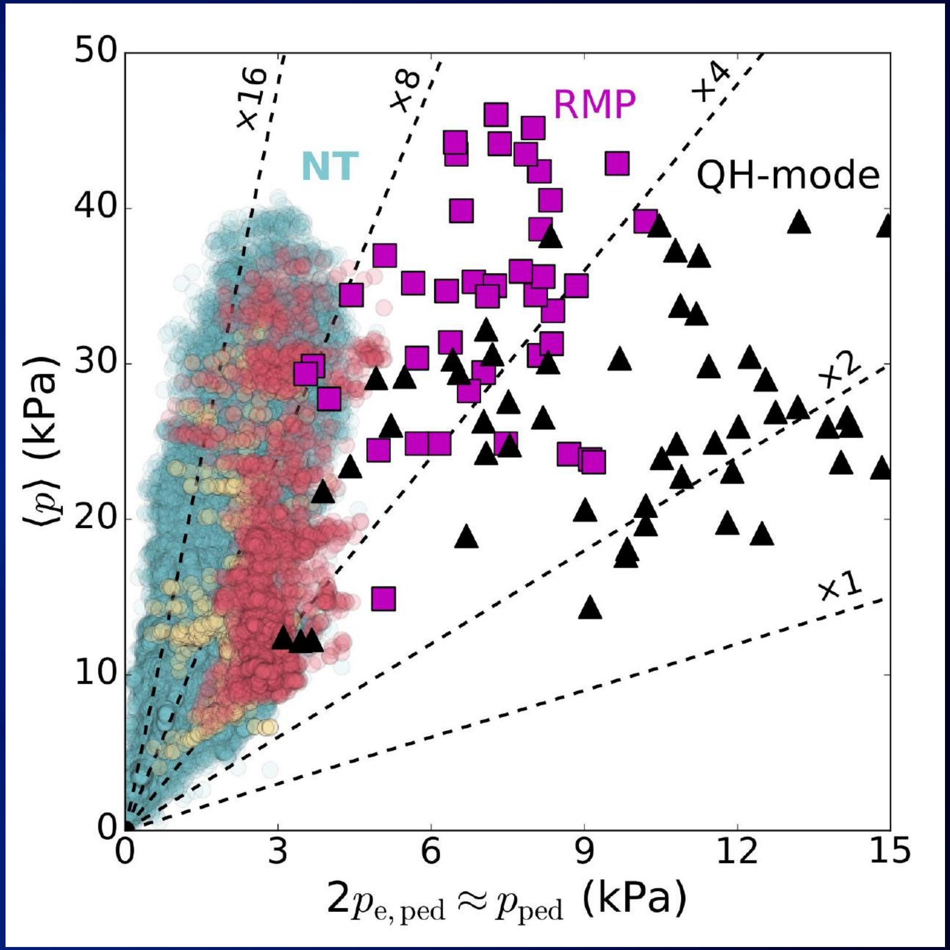
MAST: Culham UK



New breakthrough: How to keep high confinement with low edge pressure (ELM free) by changing plasma shape

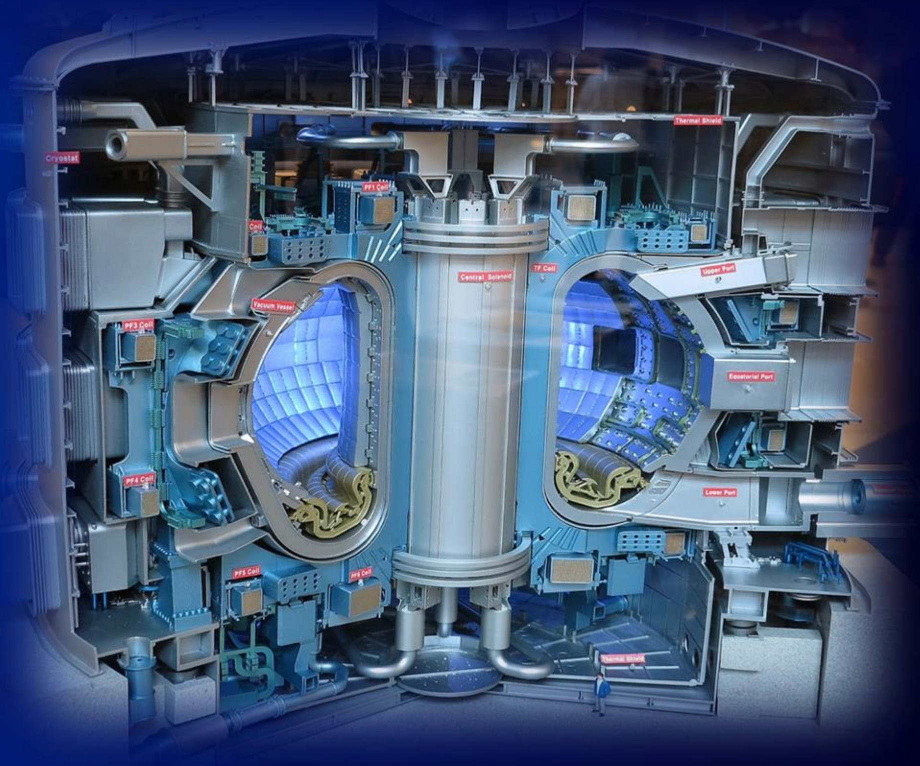
"Negative Triangularity" on the DIII-D tokamak





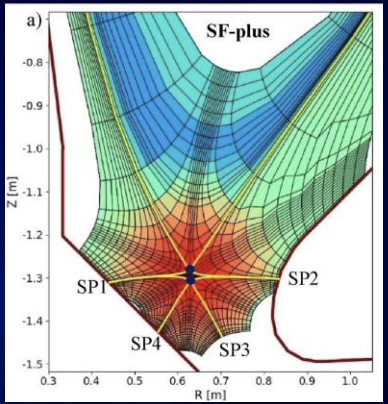
Preparing for ITER operation has many challenges
We can learn from you!

“How do we remain competitive from US soil?”

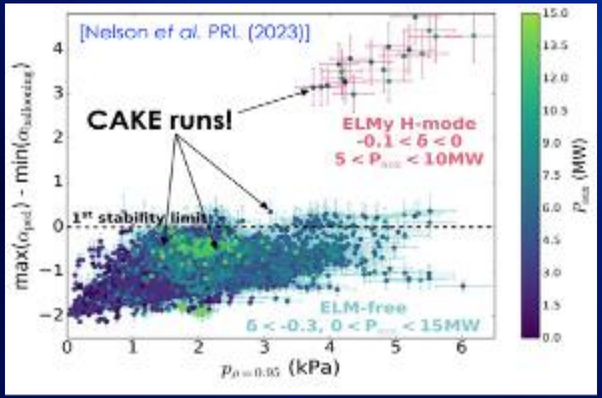


ITER (France)

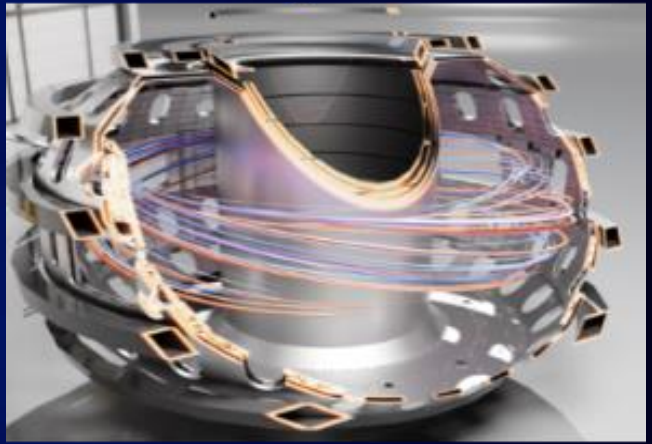
Must Partner With ASCR/NSF to Leverage National Supercomputing Resources and Networks to Build World-Leading Analysis Infrastructure



Rapid data assimilation & interpretation →



← AI/ML platform for exascale data



Predictive Digital Twin integrated into operations →

← Remote experimental participation capabilities

Physical Infrastructure also Required to Build Community, Create Critical Mass for US Leadership on ITER

Remote control room

Fusion Collaboration Center in San Diego

Seminar & meeting room

Computing center

Visualization lab

Hybrid work space

- 50,000 sq. ft., two levels, 100 offices, facilities

Thank you