FES Toroidal Long Pulse: Tokamak Research

Progress toward closing tokamak science and technology gaps

FUSION POWER ASS0CIATES
45th Annual Meeting and Symposium
December 2-3, 2024
Grand Hyatt Washington, D.C.

Matthew Lanctot
Program Manager

U.S. research on tokamaks is organized under two new programs: Toroidal Long Pulse and Compact Toroidal Concepts

Office of Fusion Energy Sciences
Jean Paul Allain, Associate Director (IPA)

FES Budget, Planning, FESAC

Research
John Mandrekas, Director

- Theory & Simulation AI/ML — Michael Halfmoon
- High Energy Density Plasmas — Kramer Akli
- Toroidal Long Pulse — Matthew Lanctot
- General Plasma Science — Nirmol Podder
- Compact Toroidal Concepts — Josh King
- Quantum Information Science — (Vacant)
- Emergent Confinement Concepts — (Vacant)
- Inertial Fusion Energy (IFE) — Kramer Akli

Enabling Science and Partnerships
Jean Paul Allain, Director (Acting)

- Fusion Materials & Internal Components — John Echols
- Public-Private Partnerships — Colleen Nehl
- Closing the Fusion Cycle — Guin Shaw
- Private Facility Research — Josh King
- Enabling Fusion Technologies — (Vacant)
- Plasma Technology — (Vacant)
- Measurement Innovation — Curt Bolton
- Fusion Workforce Pathways — Guin Shaw

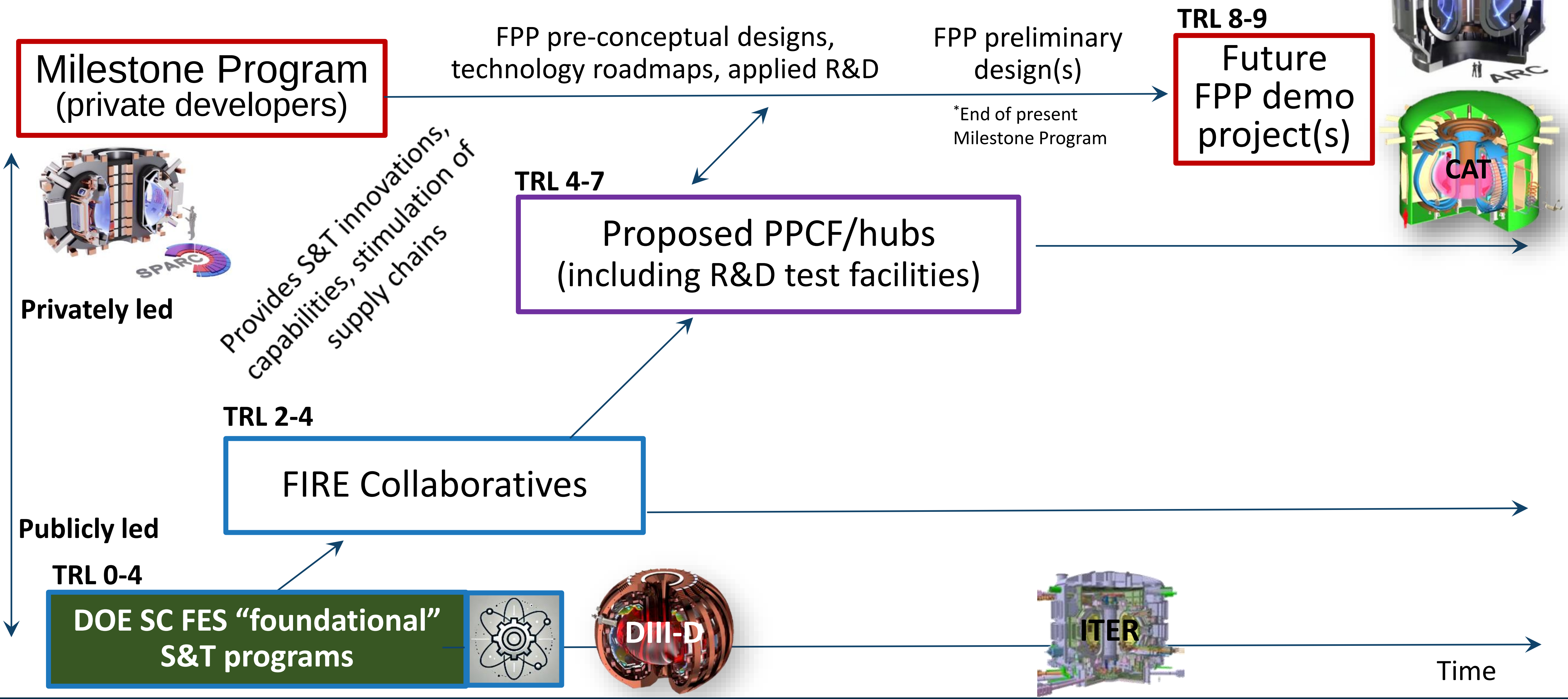
Facilities and Projects
Joseph J. May, Director

- MEC-U Project — Anthony Indelicato, Jeff Thomas
- ITER Project — Jeff Thomas, Anthony Indelicato
- Strategic Facilities — (Vacant)
- NSTX-U Recovery — Barry Sullivan, Kaitlyn Eng
- MPEX MIE — Barry Sullivan, Kaitlyn Eng
- ITER Organization Governance — Tom Vanek, Kaitlyn Eng

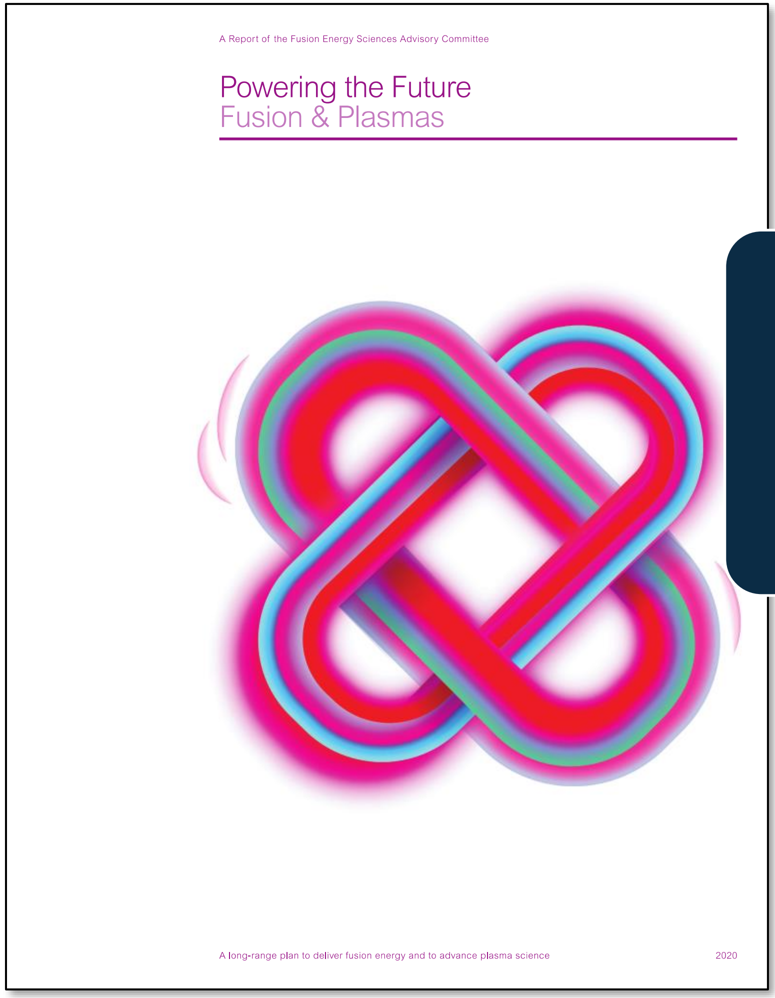
TLP Areas
- Tokamak & stellarator research
- DIII-D
- Small-scale domestic expts.
- Int'l collabs.
- ITER Research

CTC Areas
- Spherical Tokamaks
- High field tokamak

FES Research Division derisks new innovations and capabilities, supporting DOE tech and demo elements



TLP topics align with U.S. fusion strategy; US teams working with international partners to close out MFE gaps



2020 FESAC
Long-Range Plan (LRP)

"Fulfilling the [fusion] energy mission demands a shift in the balance of research toward FM&T (Fusion Materials and Technology)…" pg. 6 FESAC-LRP

Sustain a Burning Plasma

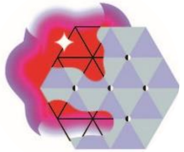
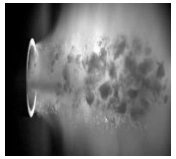
Engineer for Extreme Conditions

Harness Fusion Energy

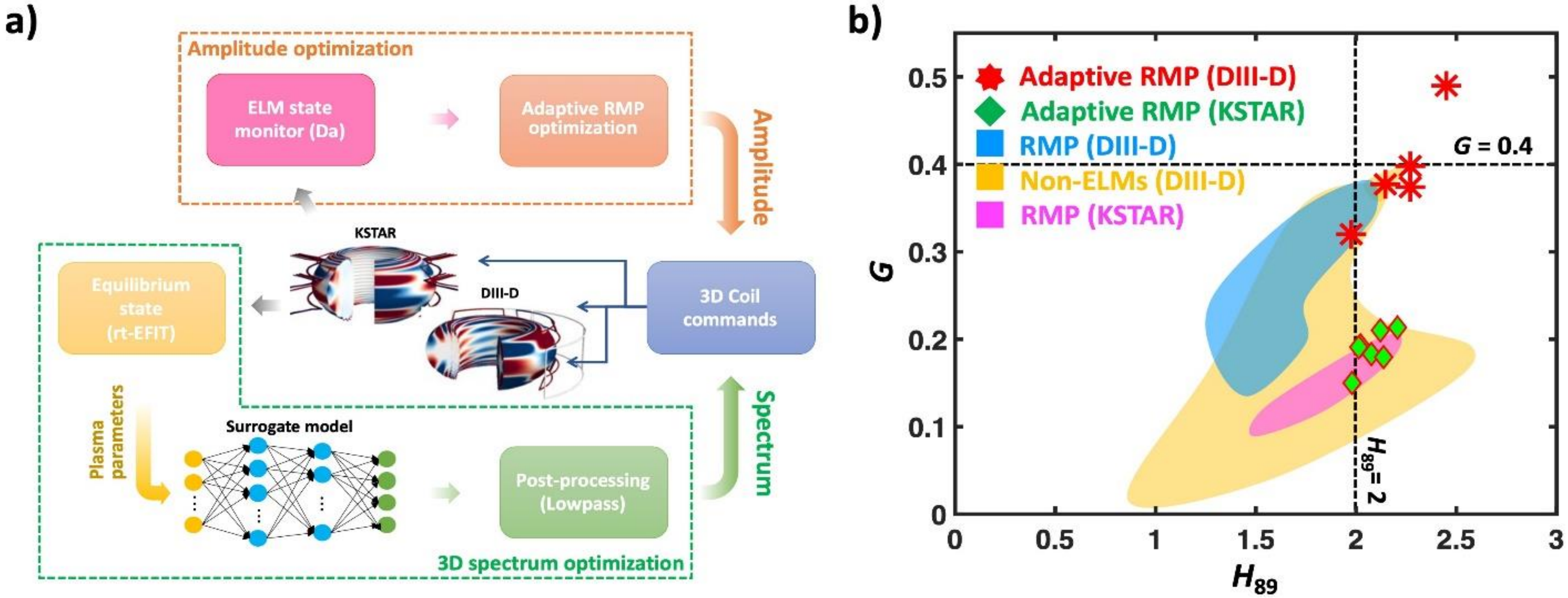
LRP Science Drivers

FPP

Tokamak Research Topical Divisions

Sustaining Burning Plasmas	Plasma Material Interactions	Exhaust Handling	Control of Damaging Transients	Technology, Engineering, & Operations
				

Sustaining Burning Plasma		
	Challenge	**Multi-parameter tokamak optimizations challenge classical control methods**
	Progress	Adaptive, AI-informed control strategies can sustain maximized plasma performance



$$G = \beta_N H_{98y2} / q_{95}^2$$

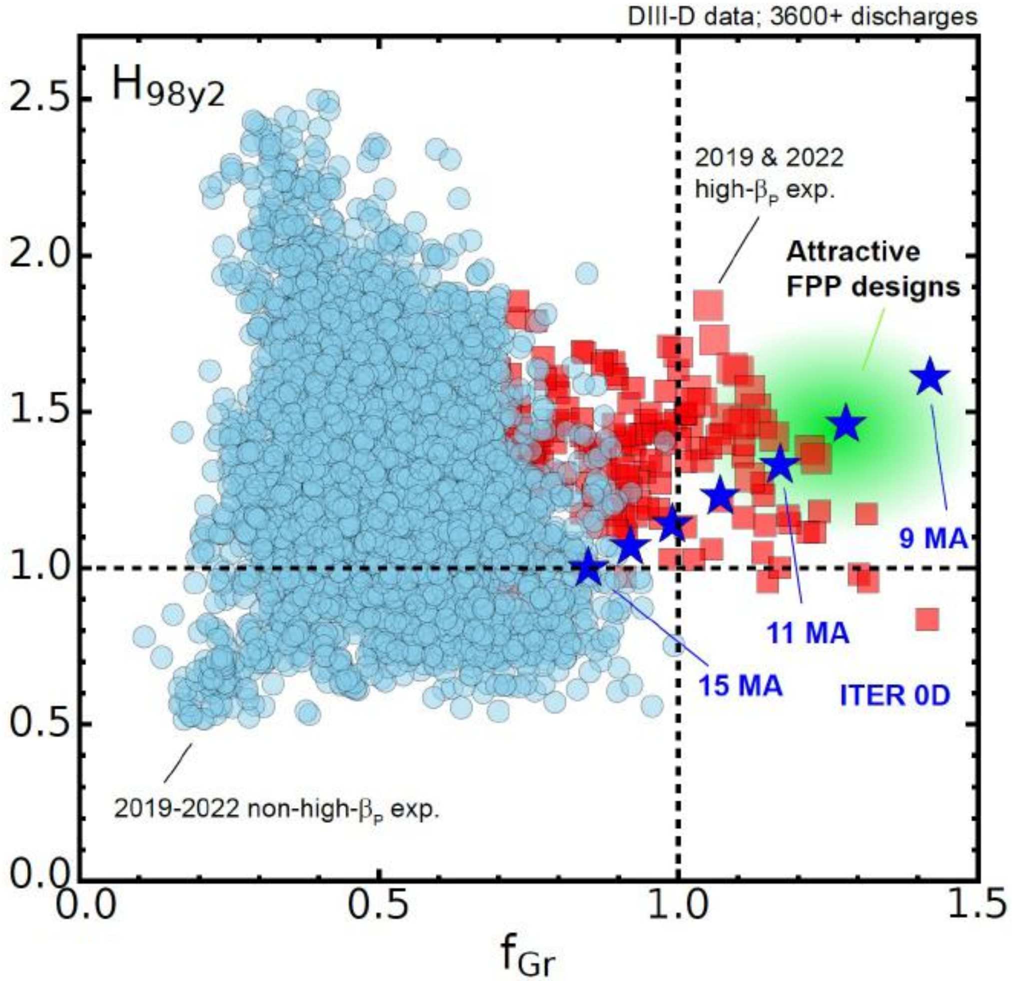
- Fully-automated, adaptive, ML controller minimizes applied 3D magnetic field while sustaining ELM suppression and maximizing plasma performance (G), best confinement/pressure w/o ELMs in DIII-D and KSTAR[1]
- Surrogate model derived from validated foundational simulations of plasma response (GPEC) moves beyond trial-and-error optimization methods and extrapolates to new facilities
- Results similar to 3D field optimizations that maintain edge 3D response for ELM control w/ small core response[2]

[1]Kim S.K. et al., *Nature Comms.* **16** (2024) 3990. SC Highlight
[2]S.M. Yang et al., *Nature Comm.* **15** (2024) 1275

Sustaining Burning Plasma

Challenge	**Fusion plant designs aim to increase efficiency by maximizing confinement & density**
Progress	Tokamak scenarios can operate above n_{GW} with high confinement and cool edge

- Scenario ("high β–poloidal") enabled by stabilization of turbulent transport by increased core density gradients (not rotation shear)
  - Recent experiments operate at high confinement above Greenwald density limit
- Operation with small ELMs and detached divertor reduces wall interactions and divertor heat flux
  - Variant of scenario used for 400-sec EAST H-mode
- Allows ITER Q=10 operation at lower plasma current, lowering risk of disruptions and increasing flexibility
- FPP using this scenario found at modest parameters
  - R = 4 m, R/a = 3.1, B_T = 7 T, Ip = 8.1 MA, q_{95} = 6.5, f_{Gr} = 1.3, $f_{Gr,ped}$ = 1.0, β_N = 3.6, H_{98y2} = 1.51, Q = 17.3 and 200 MWe

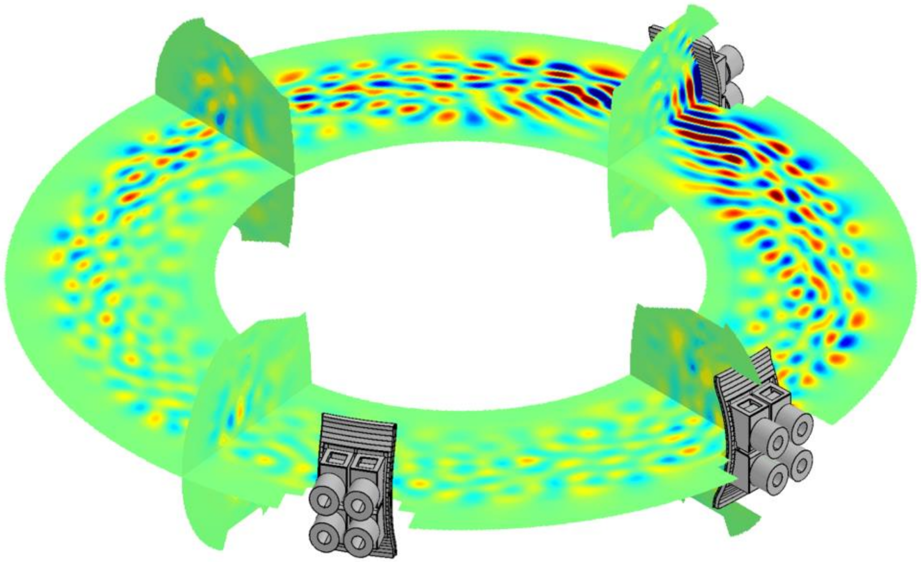


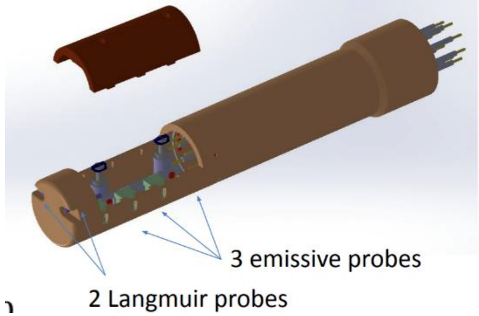
A.M. Garofalo, 2nd IAEA TM on Long-Pulse Operation of Fusion Devices, Oct 14-18, 2024, Vienna, Austria

Ding, S., et al., *Nature* 629, 555–560 (2024); SC Highlight

Plasma Material Interaction

Challenge	**Heating systems with in-vessel antenna can be a source of impurities.**
Progress	Measurements and PETRA-M modeling on WEST used to diagnose RF sheath potential.





Emissive Probe: PFSC

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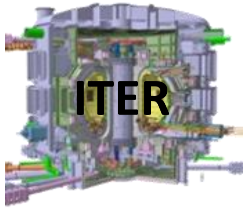
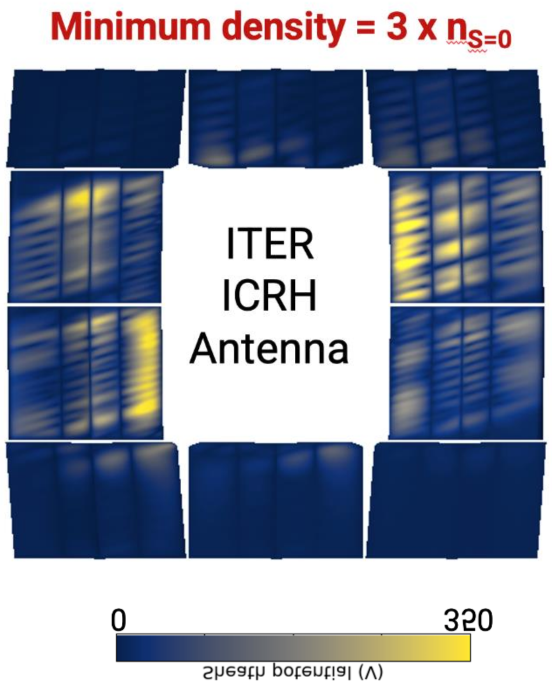
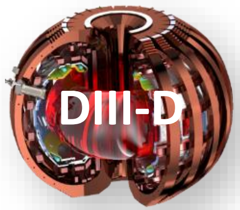
- PETRA-M prediction and reciprocating probe measurement consistent on RF induced sheath potential on WEST (≈200 eV)
- Similar level calculated for ITER using PETRA-M
- Analysis underway to determine conditions for minimizing RF sheath on ITER





Plasma Material Interaction

Challenge	Plasma-wall interactions and metal impurity influx limits long pulse operation
Progress	Real-time boron injection conditions wall and improves confinement, informing ITER.



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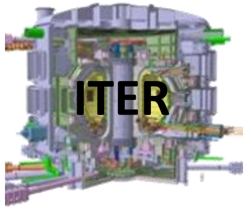
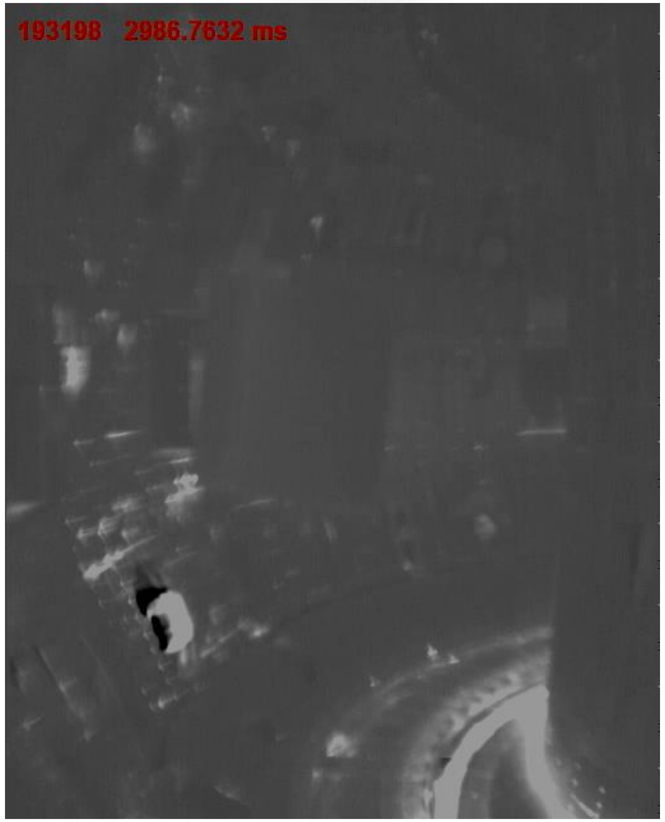
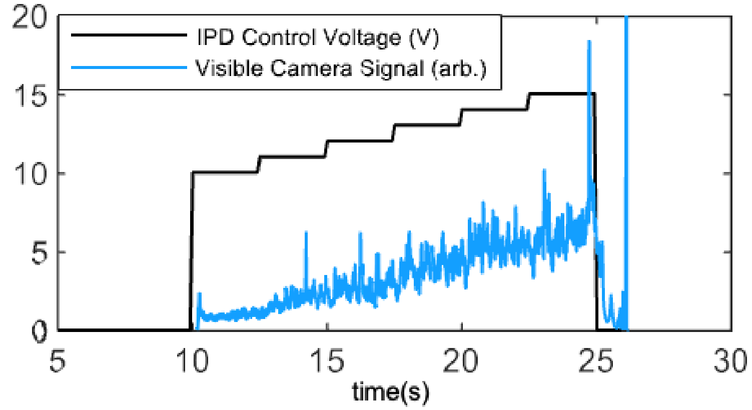
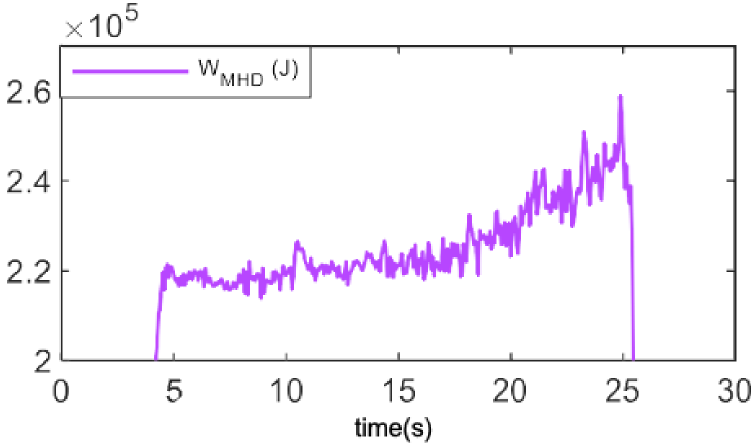








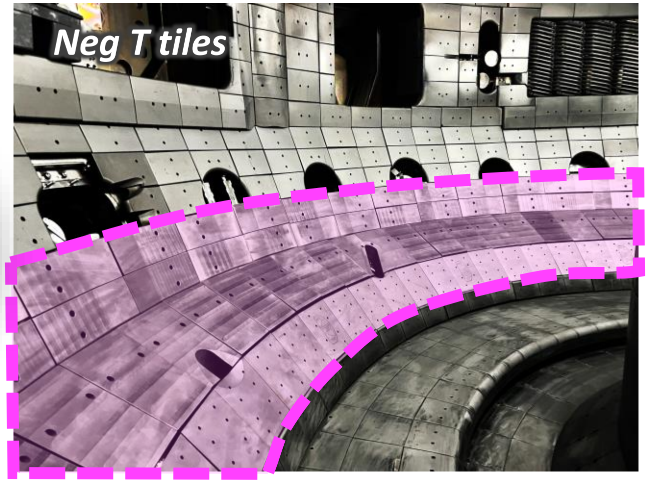
- Cumulative effect of boron injection on WEST similar to episodic (few times/year) application via glow discharge
- Single shot effect on confinement observed at higher injection rates
- Effect on W sputtering and transport under investigation
- Further optimization needed to avoid unacceptable levels of fuel dilution and to mature the technology
- Results inform feasibility study of real-time solid boron injection on ITER[2]

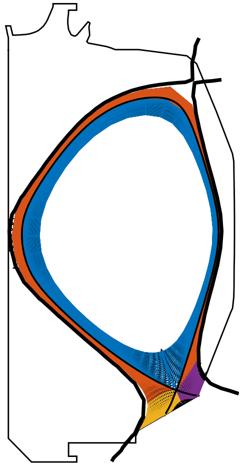
[1] G. Bodner et al., Plasma Phys. Control. Fusion 66 (2024) 045022
[2] J. Snipes, Nuclear Materials and Energy 41 (2024) 101809

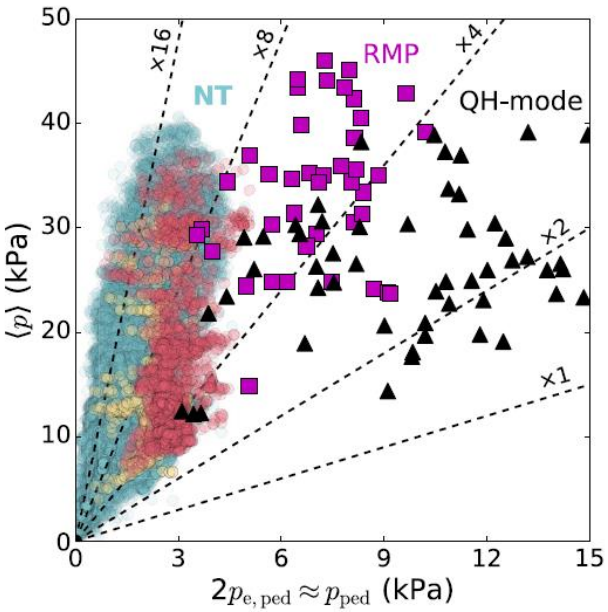
Exhaust Handling

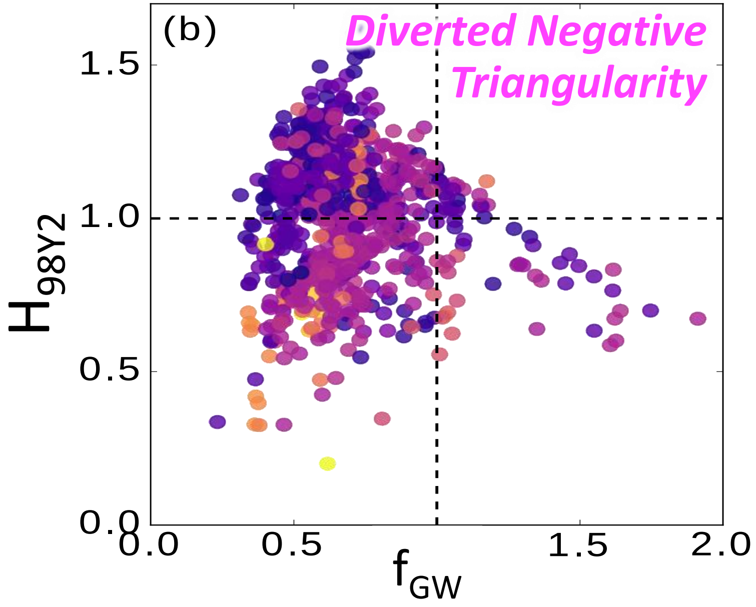
Challenge	**Tokamaks must achieve high core performance and manage heat/particle exhaust**
Progress	Negative triangularity (NT) shaped plasmas reach high performance out of the box

- NT divertor naturally allow heat flux distributed over a larger spatial region at larger major radius
- Four-week NT campaign in 2023 at DIII-D
  - δ~-0.5, Pinj=3-12 MW, q95=2.6 – 7
- Routine ELM-free operation with
  - H98≈1, β_T≈2.5 with f_{GW}≈1
  - f_{GW} up to ~2 with lower performance
- Volume average plasma pressure comparable to other ELM-free scenarios
- DIII-D expt's pursued together with EU (TCV, AUG), Japan partners

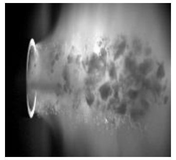






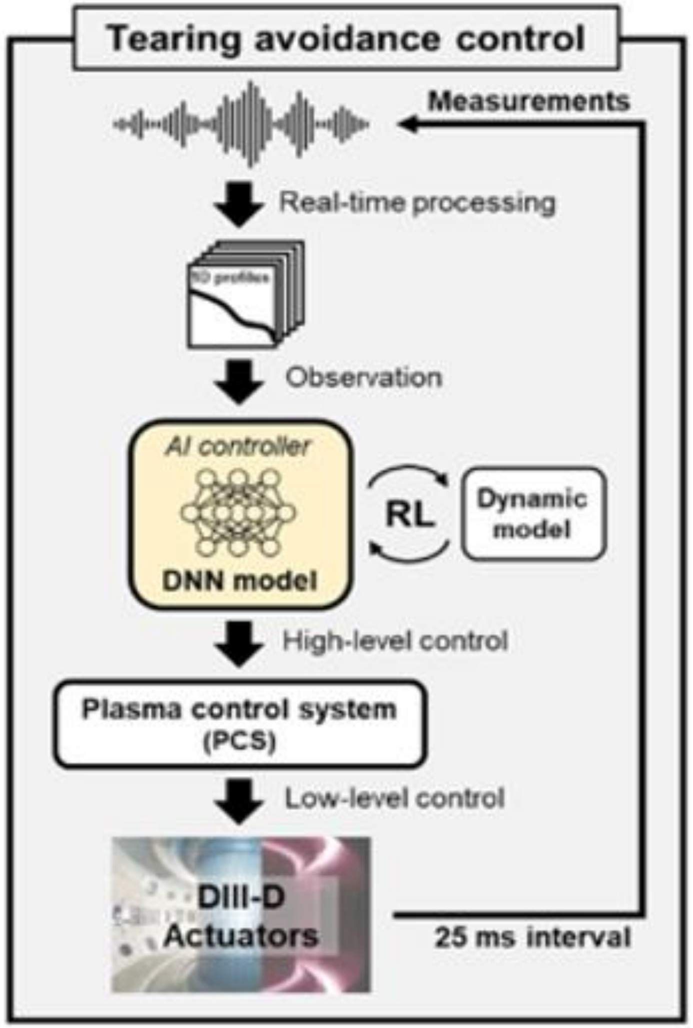


Nelson, A.O., et al, PRL 131, 195101 (2023)

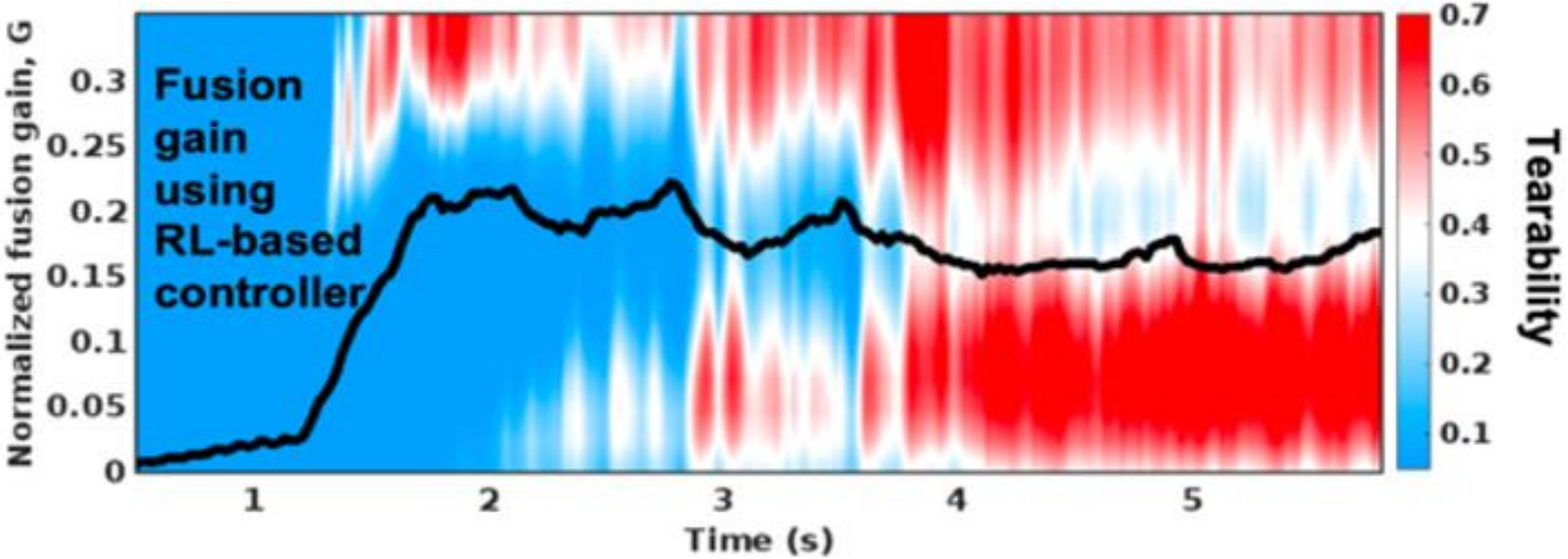


Control of Damaging Transients

Challenge	**Burning plasmas operate near limits, requiring multi-parameter optimization**
Progress	Autonomous control methods navigate around controllability limits

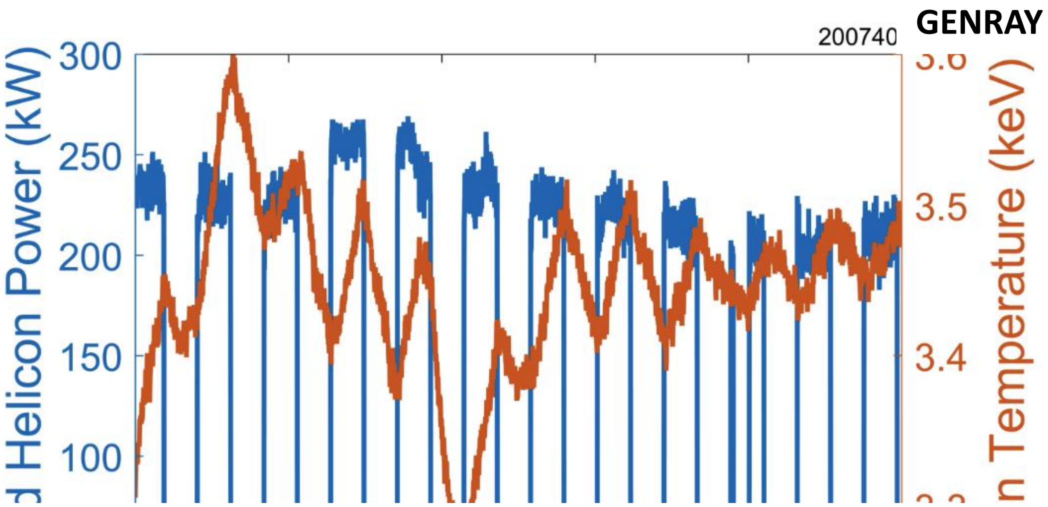


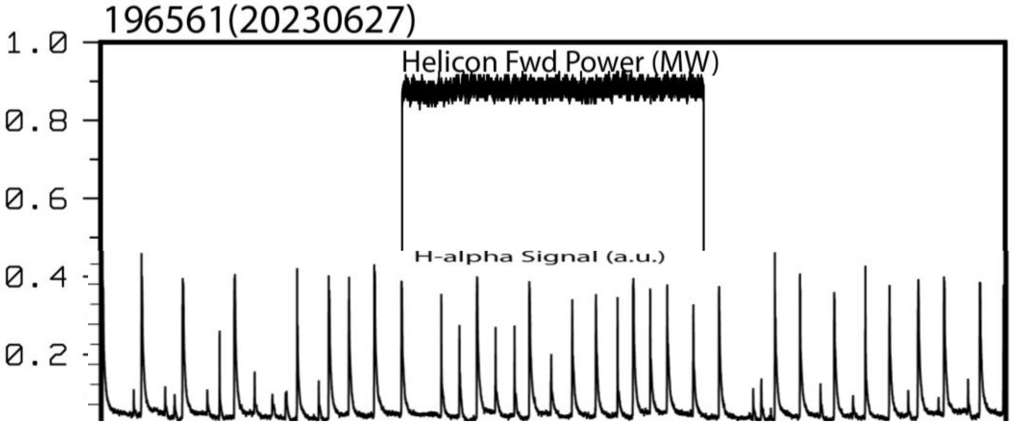
- **Large facility databases provide basis to predict proximity to tearing onset**
  - Reinforcement learning explores parameter space in real-time
- **Strategy maintains proximity to stability boundaries by evolving equilibrium, sustaining discharges for long durations**
- **AI enables facilities to safely pursue states considered too risky or unattainable, a game changer for accelerating facility exploitation**

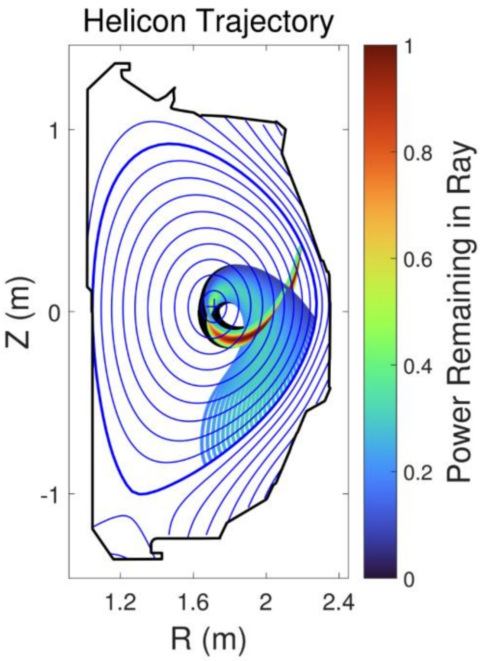


Seo, J., *et al.* *Nature* **626** (2024) 746–751.

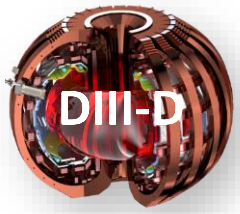
Challenge	Steady-state tokamak requires off-axis non-inductive current drive.
Progress	DIII-D Helicon power testing up to 500 kW confirms central electron heating.





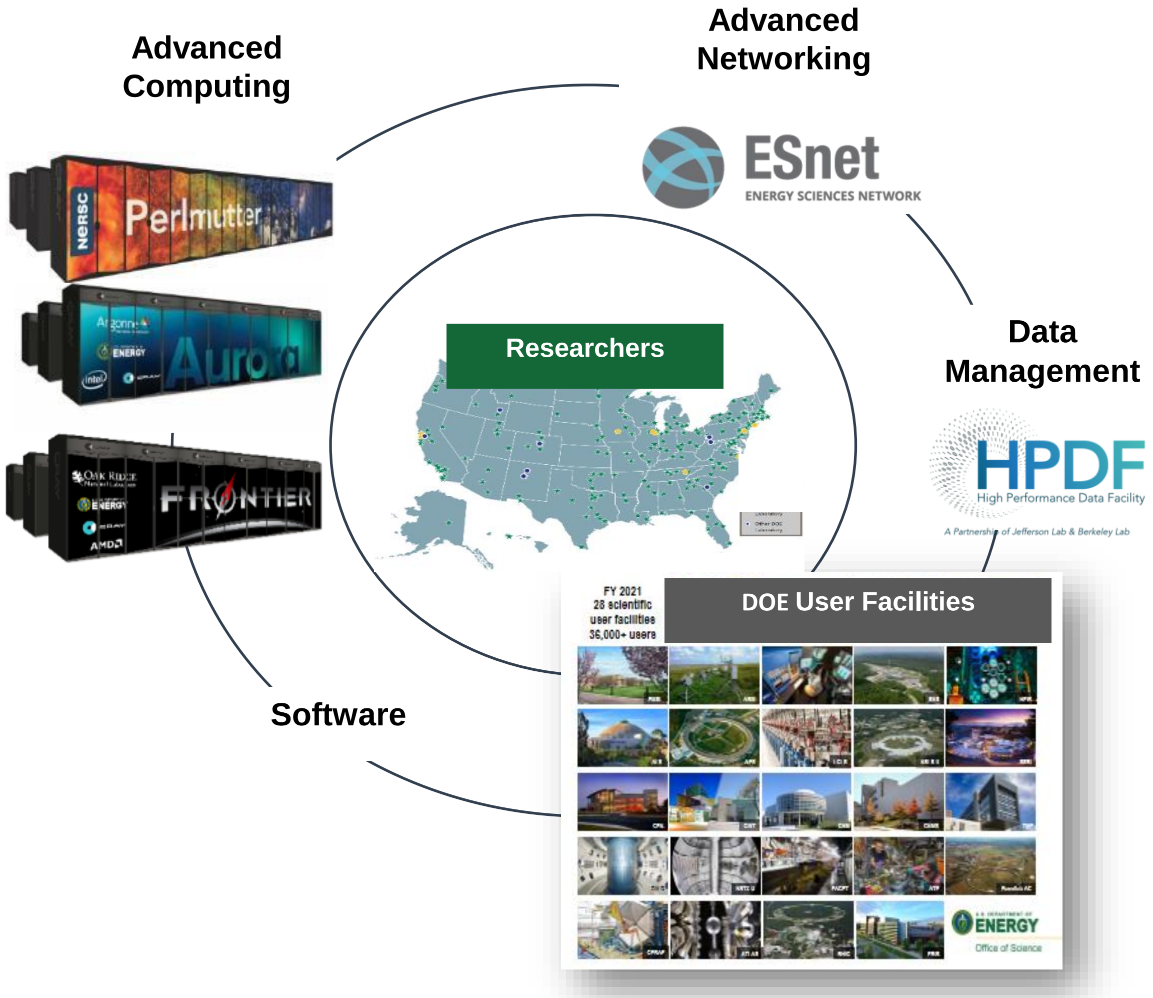


Helicon traveling wave antenna



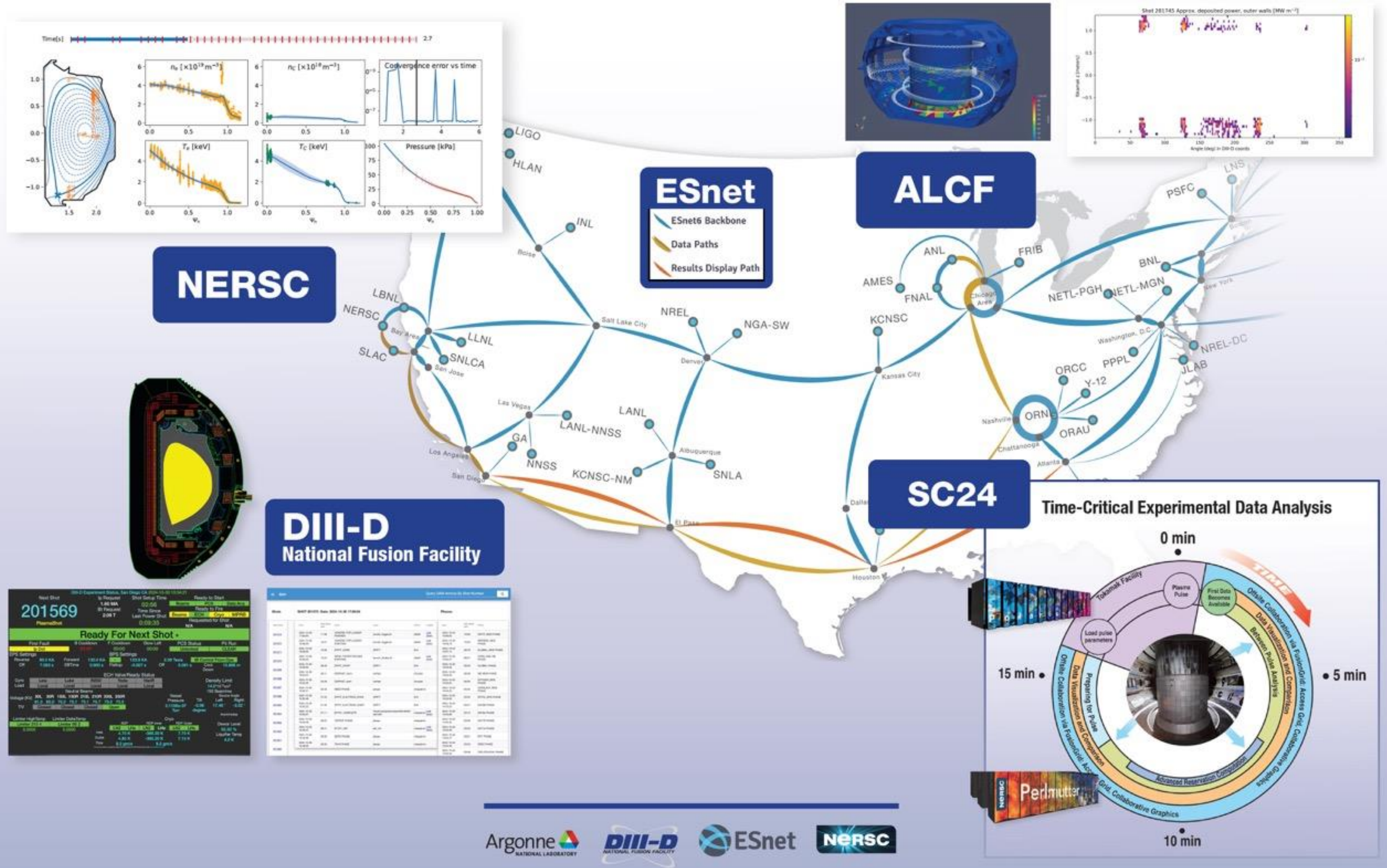
- **Over 500 kW Helicon coupled into H-mode DIII-D plasma**
  - Heating process resilient to ELMs
- **Central electron heating confirmed, consistent with modeling; MSE shows effect of current drive (preliminary)**
- **Part of program at DIII-D to study non-inductive current drive using helicon, top-launch ECCD, and lower hybrid**

Technology, Engineering, & Operations	Challenge	Tokamak exploitation enhanced by simulations executed in time-sensitive manner
	Progress	IRI program at DIII-D fully exploits DOE ecosystem, advancing digital twin technology



- Integrated Research Infrastructure (IRI) aims to link DOE's experimental and observational scientific user facilities, data assets, and advanced computing resources so that researchers can combine these tools in novel ways that radically accelerate discovery
  - New website: iri.science
- IRI launch in FY24-25 aimed at
  - Infrastructure at ASCR facilities
  - Program Governance
  - Coordinating IRI projects
  - Deploying IRI Testbed

IRI program at DIII-D exploits SC ecosystem, bringing advanced analysis into the control room and paving way for digital twin technology



- **DIII-D exp't in San Diego**
- **High fidelity plasma reconstructions at NERSC**
- **Ion Orbit trajectories computed at ALCF**
- **HPC Compute orchestrated using Globus data transfer**
  - Demo'd at SC24 during DIII-D plasma ops
- **Supports machine protection and rapid exploitation**
- **Method extensible to private sector facilities and ITER**

Summary

- TLP program is addressing major showstoppers for tokamak path to fusion energy with significant implications for future R&D in all sectors
- Additionally, several new initiatives are ramping up:
  - DIII-D plans to install tungsten wall in near term to support ITER and advance core-edge integration R&D
    - DIII-D, KSTAR, WEST Task Force on Long Pulse, W-compatible, Hybrid Scenario
  - EU-US Working Group on ELM-free Tokamak Operation (including NT scenario development) to establish the physics basis for these important operational scenarios
  - XICS, FIDA diagnostic contributions to JT-60SA – installation scheduled in 2025
- FES solicitation in FY25 will aim to support U.S. ecosystem for conventional tokamak research
  - TLP program will enable teams to work seamlessly across facilities and configurations (including stellarators) contributing to and benefitting from ITER and R&D in the private sector
  - New program will address key elements of FES Building Bridges Vision:
    - Building Workforce
    - Bridging S&T Gaps,and supporting
    - Advancing transformational science leading to technology transfer
  - Awards will be coordinated under a national program supporting the US Fusion Roadmap