AI/ML in Fusion Energy

Tyler Ellis, Ph.D.

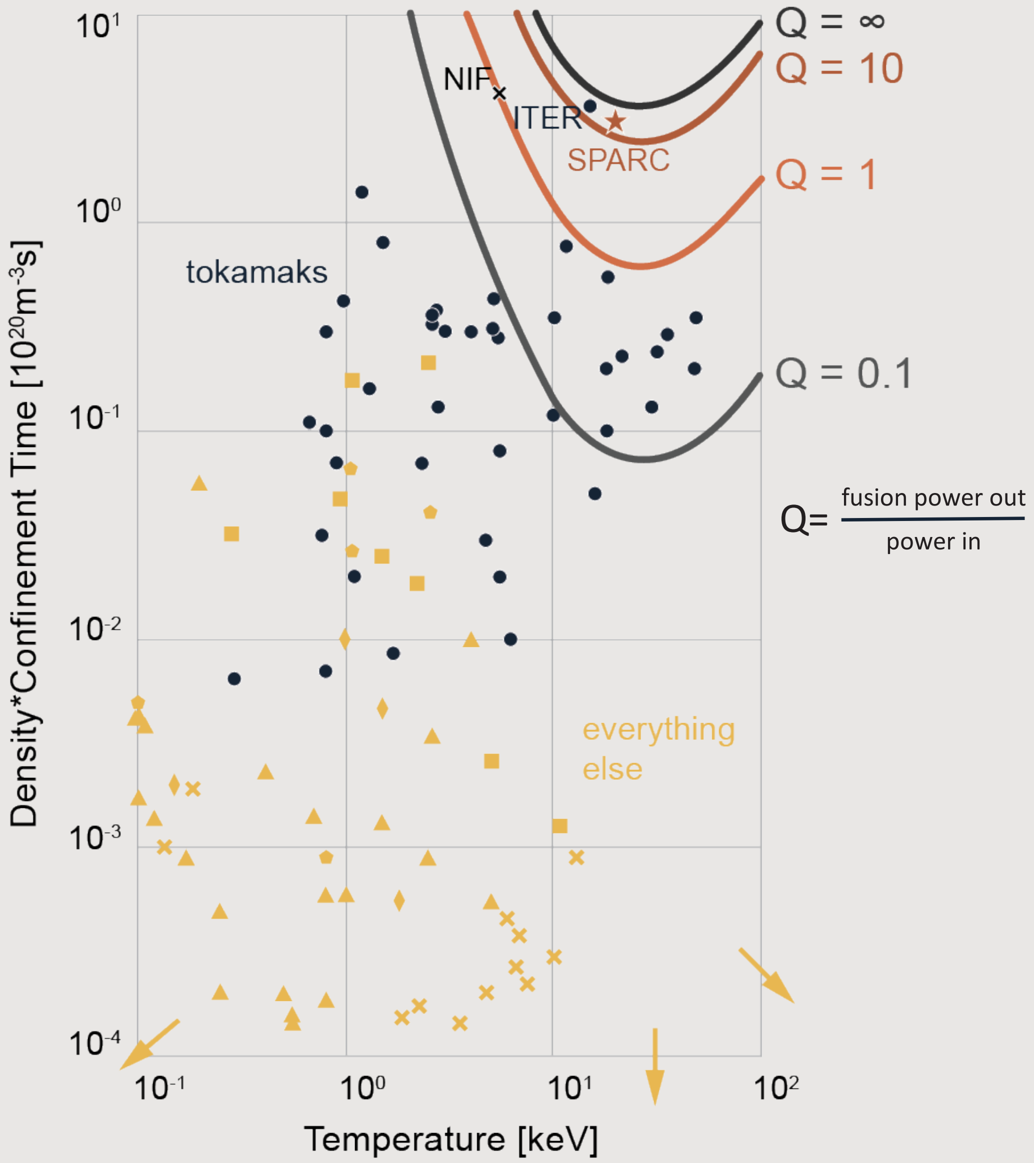
Commonwealth Fusion Systems

CFS on a path to deliver commercial fusion energy

- CFS founded in 2018, spun out of MIT
- Raised more than $2 billion
- Built a high caliber, diverse team
- Over 900 employees

On the verge of commercially relevant fusion power

- On the cusp of a key milestone of net energy gain, more energy out than in (Q>1)
- Machines called "tokamaks" are closest
- >150 tokamaks have been built worldwide
- Magnets hold and insulate the plasma and very high magnetic fields make tokamaks smaller



SPARC, first commercially relevant fusion machine

Validated approach


J. Plasma Phys. (2020), *vol.* 86, 865860502

1
Published by Cambridge University Press

doi:10.1017/S0022377820001257

Overview of the SPARC tokamak

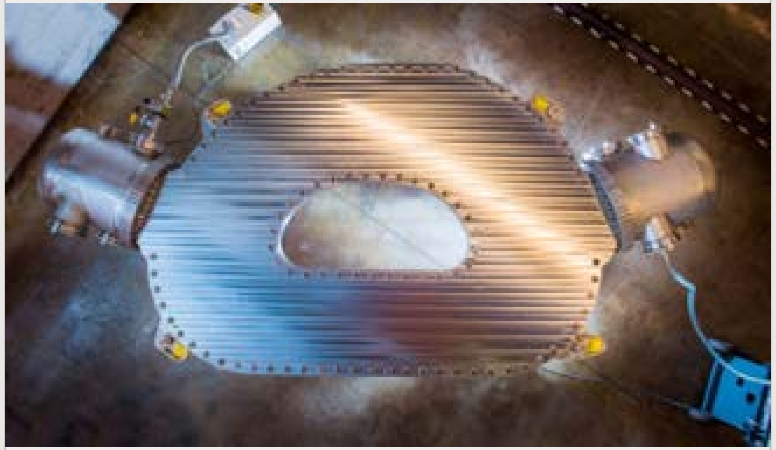
A. J. Creely[1,†], M. J. Greenwald[2], S. B. Ballinger[2], D. Brunner[1], J. Canik[3], J. Doody[2], T. Fülöp[4], D. T. Garnier[2], R. Granetz[2], T. K. Gray[3], C. Holland[5], N. T. Howard[2], J. W. Hughes[2], J. H. Irby[2], V. A. Izzo[6], G. J. Kramer[7], A. Q. Kuang[2], B. LaBombard[2], Y. Lin[2], B. Lipschultz[8], N. C. Logan[7], J. D. Lore[3], E. S. Marmar[2], K. Montes[2], R. T. Mumgaard[1], C. Paz-Soldan[9], C. Rea[2], M. L. Reinke[3], P. Rodriguez-Fernandez[2], K. Särkimäki[4], F. Sciortino[2], S. D. Scott[1], A. Snicker[10], P. B. Snyder[9], B. N. Sorbom[1], R. Sweeney[11], R. A. Tinguely[2], E. A. Tolman[2], M. Umansky[12], O. Vallhagen[4], J. Varje[10], D. G. Whyte[2], J. C. Wright[2], S. J. Wukitch[2], J. Zhu[2] and the SPARC Team[1,2]

[1]Commonwealth Fusion Systems, Cambridge, MA, USA

[2]Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA, USA

Peer reviewed publications

Demonstrated technology



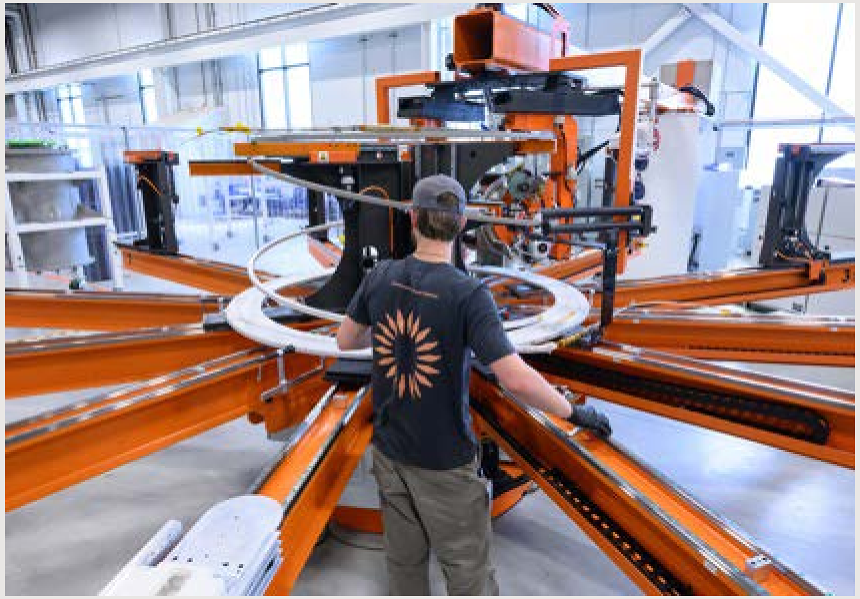
Built world's strongest superconducting magnets

Accelerated construction

We are building it now

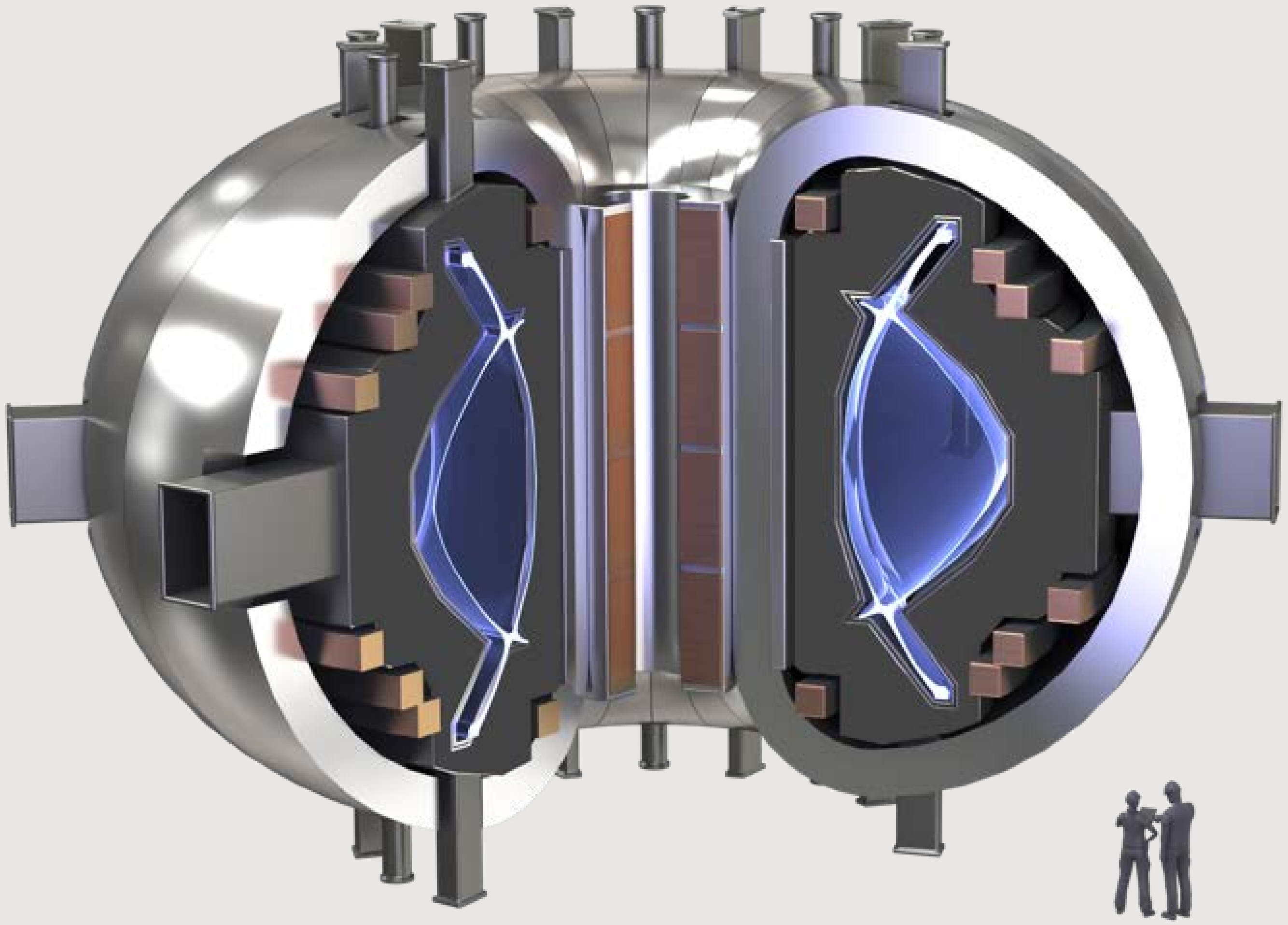
Construction of SPARC Facility in Devens, Massachusetts

CFS magnet factory in Devens, Massachusetts



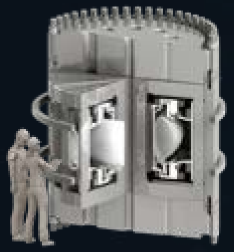
ARC, world's first commercial fusion power plant

- Validation from SPARC platform that de-risks:
  - Economics
    using SPARC costs and supply chain
  - Performance
    using SPARC operations to optimize
  - Technology
    using SPARC and innovative R&D pathways in parallel
- Preparing to construct ARC, site search underway



Risk retirement in concrete steps

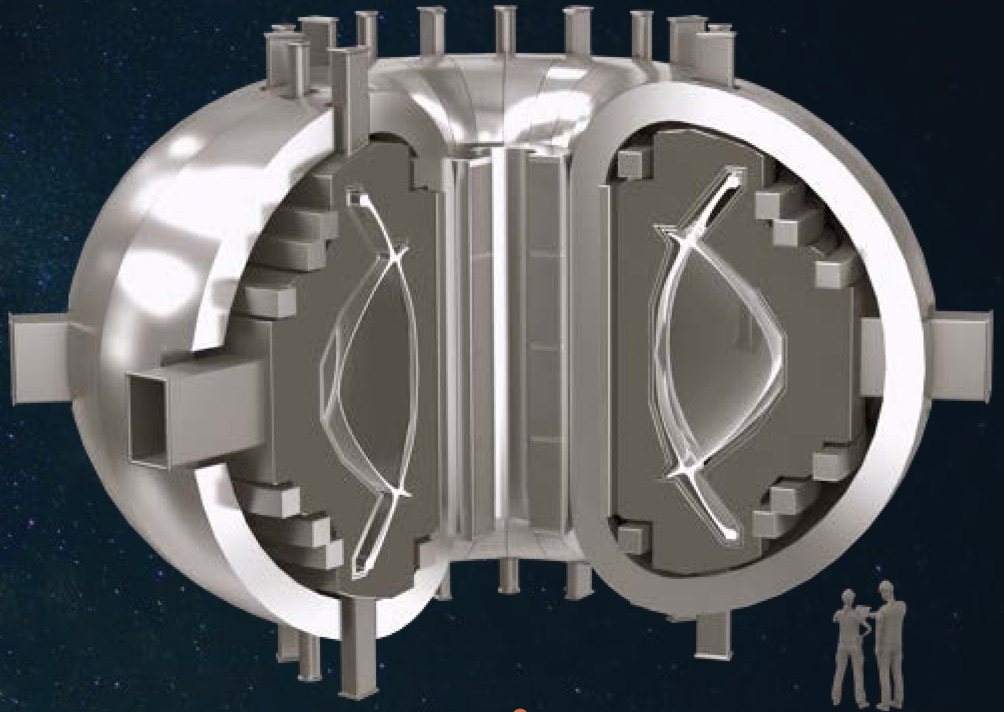
R&D — Commercial demo — Commercial powerplant



Physics
COMPLETED

Magnet tech
COMPLETED

SPARC
UNDER CONSTRUCTION



ARC
EARLY 2030s

U.S. Regulatory Treatment for Fusion

- The optimal approach to regulate fusion was discussed over two years through 10 NRC-led public meetings with wide stakeholder input.
- In March 2023, the NRC Commission unanimously voted in favor of regulating fusion energy facilities under a byproduct materials approach (10 CFR 30).
- The ADVANCE Act, signed into law July 9, 2024, codified this regulatory treatment for fusion into the Atomic Energy Act.

NRC Commissioner meeting on fusion regulations

AI/ML in Fusion

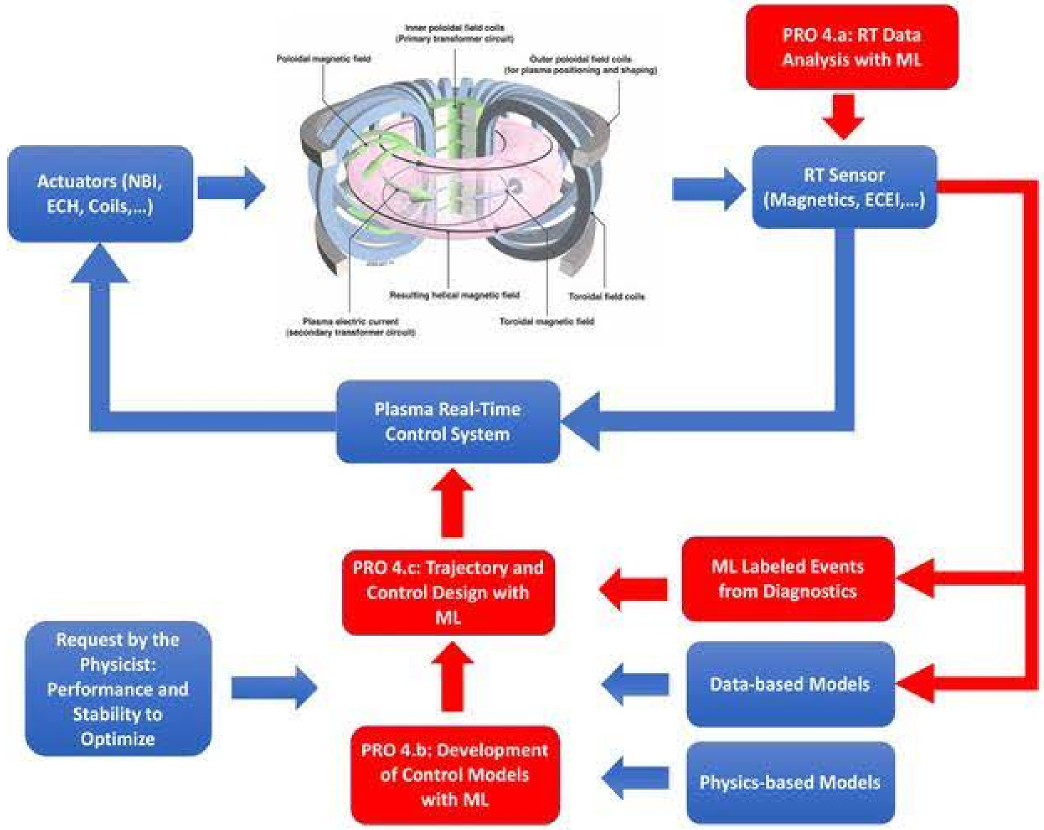
- AI/ML has been applied to fusion in three major ways:

1. AI/ML can better compare datasets across different existing fusion machines since they have taken data in different ways. This would provide more data that could further improve operational models.
2. AI/ML can develop enhanced plasma control models that enhance uptime operations. For example, the development of ML algorithms that actively monitor for disruptions.
3. AI/ML can help the discovery of surrogate/reduced models in several areas like prediction of turbulent transport.

- Basically, AI/ML can be a means to speed up the pathway of fusion commercialization and enhance uptime operations but it’s not likely to enable breakthroughs in the final design of mature fusion machine concepts.

Summary of main AI/ML applications for fusion

Data drives fusion experiments' design, simulation, analysis, control and optimization



Machine Learning has a key role in:

- advancing science discovery;
- accelerating simulations via surrogates;
- predictive modeling;
- trajectory planning and control;
- database and data analysis;
- ...

Adapted from D. Humphreys et al. "Advancing Fusion With Machine Learning" DOE Workshop (2020)

14 C. Rea | Bicocca AI | 1/8/24

Credit: Cristina Rea, MIT PSFC

Active fusion research initiatives in AI/ML at MIT PSFC

- MIT Plasma Science and Fusion Center is a Collaborating Centre on AI in Fusion and Plasma Science for IAEA and has research groups studying:
  - Training of sequence-to-sequence models that predict the onset of disruptions [1,2]
  - Addressing plasma dynamical uncertainty by training control policies on parallel physics simulators [3]
  - ML models to accelerate plasma simulations to both aid in the discovery of new physics/optimized designs as well as allow more accurate models to potentially be used inside control systems [4,5]

[1] Keith, Zander, et al. "Risk-Aware Framework Development for Disruption Prediction: Alcator C-Mod and DIII-D Survival Analysis." Journal of Fusion Energy 43.1 (2024): 21.
[2] Zhu, J. X., et al. "Integrated deep learning framework for unstable event identification and disruption prediction of tokamak plasmas." Nuclear Fusion 63.4 (2023): 046009.
[3] Wang, Allen M., et al. "Active Disruption Avoidance and Trajectory Design for Tokamak Ramp-downs with Neural Differential Equations and Reinforcement Learning." arXiv preprint arXiv:2402.09387 (2024).
[4] Rodriguez-Fernandez, P., et al. "Enhancing predictive capabilities in fusion burning plasmas through surrogate-based optimization in core transport solvers." Nucl. Fusion 64 076034. (2024).
[5] Rodriguez-Fernandez, P., et al. "Core performance predictions in projected SPARC first-campaign plasmas with nonlinear CGYRO." Physics of Plasmas. 31 062501 (2024).

Commonwealth
Fusion Systems