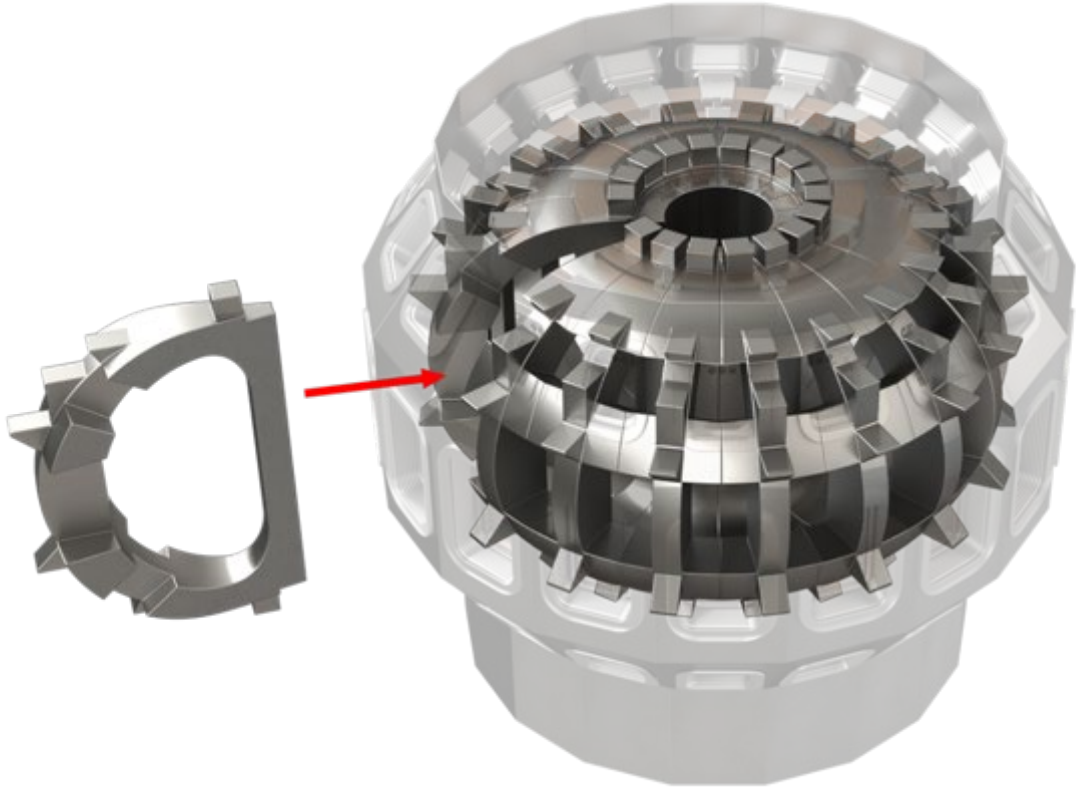
The path to commercial fusion energy

Commonwealth Fusion Systems

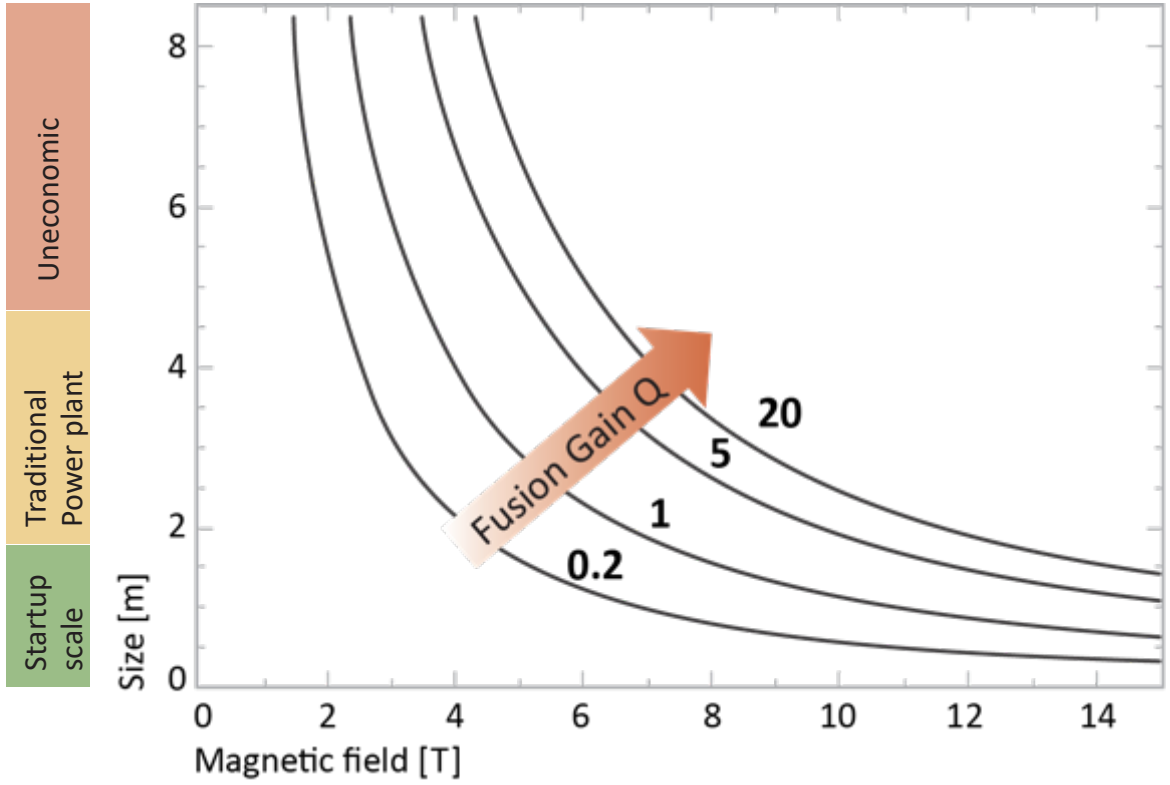
Tokamaks are magnetic bottles

- Magnets hold and insulate the plasma
- Tokamak performance scales with magnetic field to the 4th power



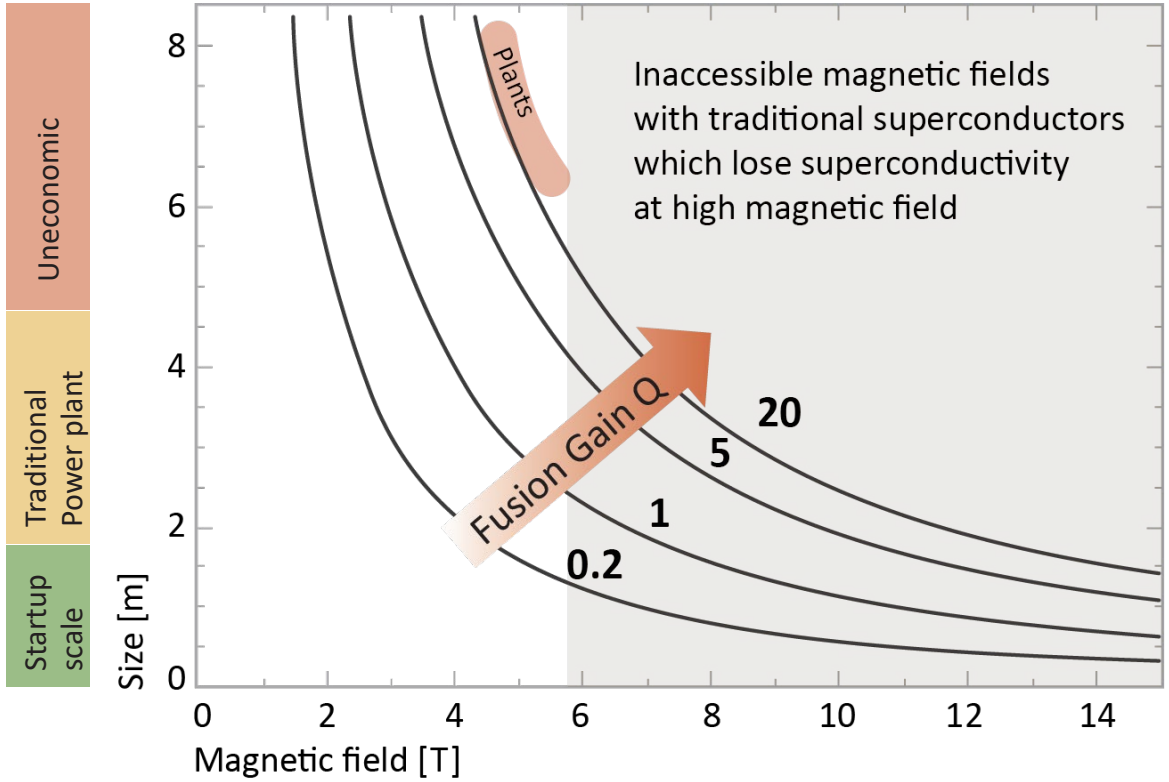
Tokamaks trade size and field

- 60 years of research across the world has assembled the data we need to design tokamaks
- This is the type of data that can underpin an entirely new industry



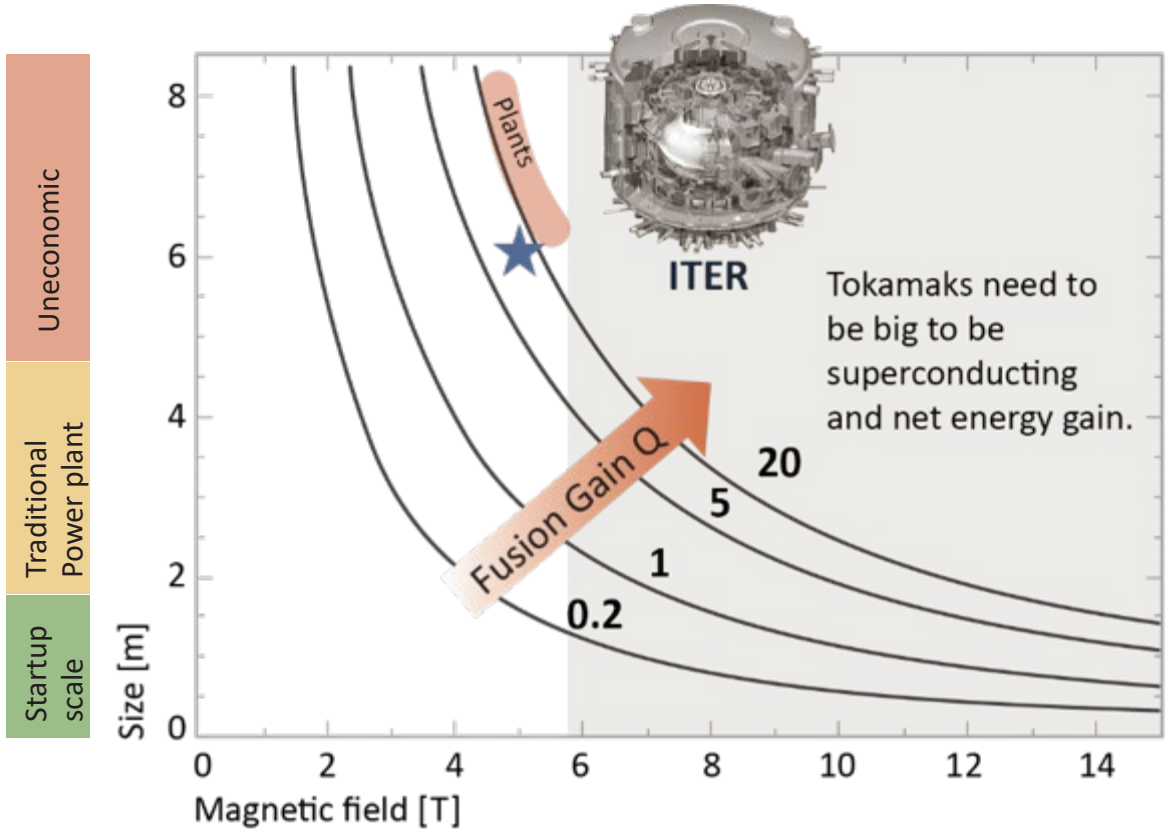
However, technical limits, not science have limited options

- The magnet technology precluded operating fusion-relevant machines at high magnetic field



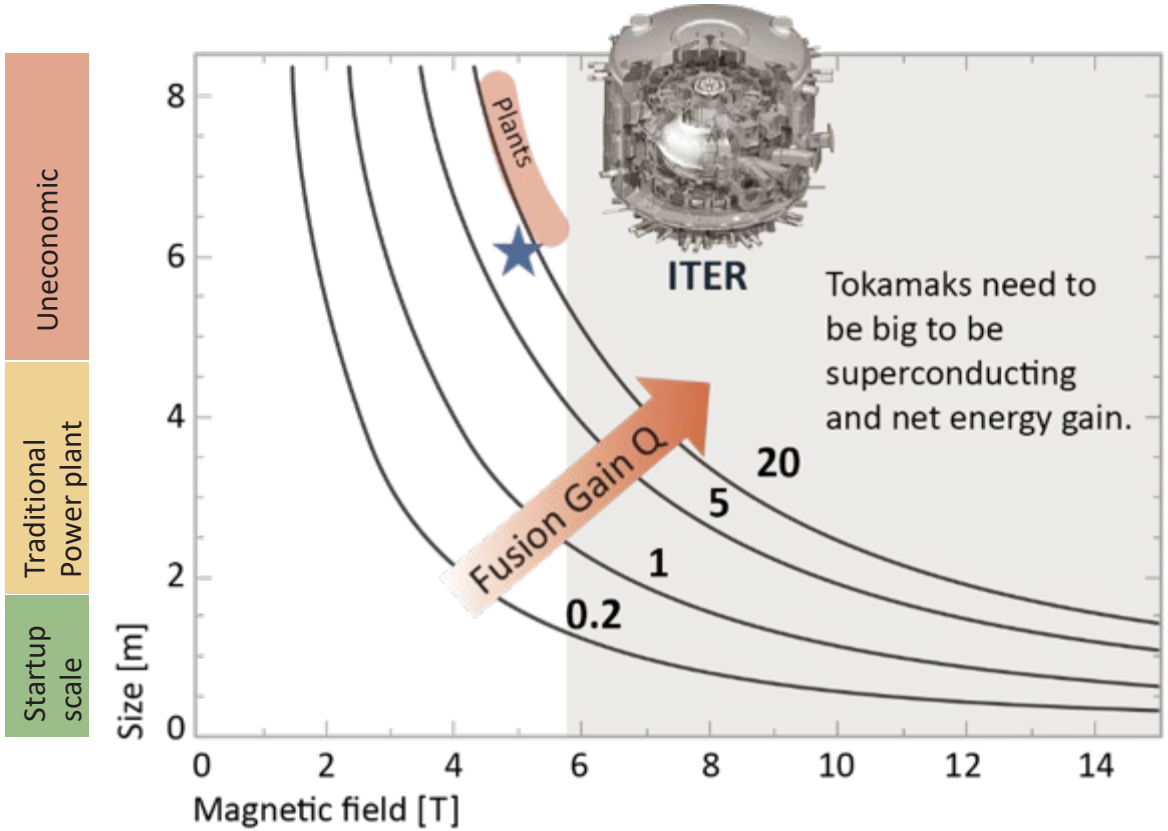
Magnet technology limited tokamak progress for decades

- ITER is the smallest machine that would “burn” given known plasma physics and ‘90s magnet technology



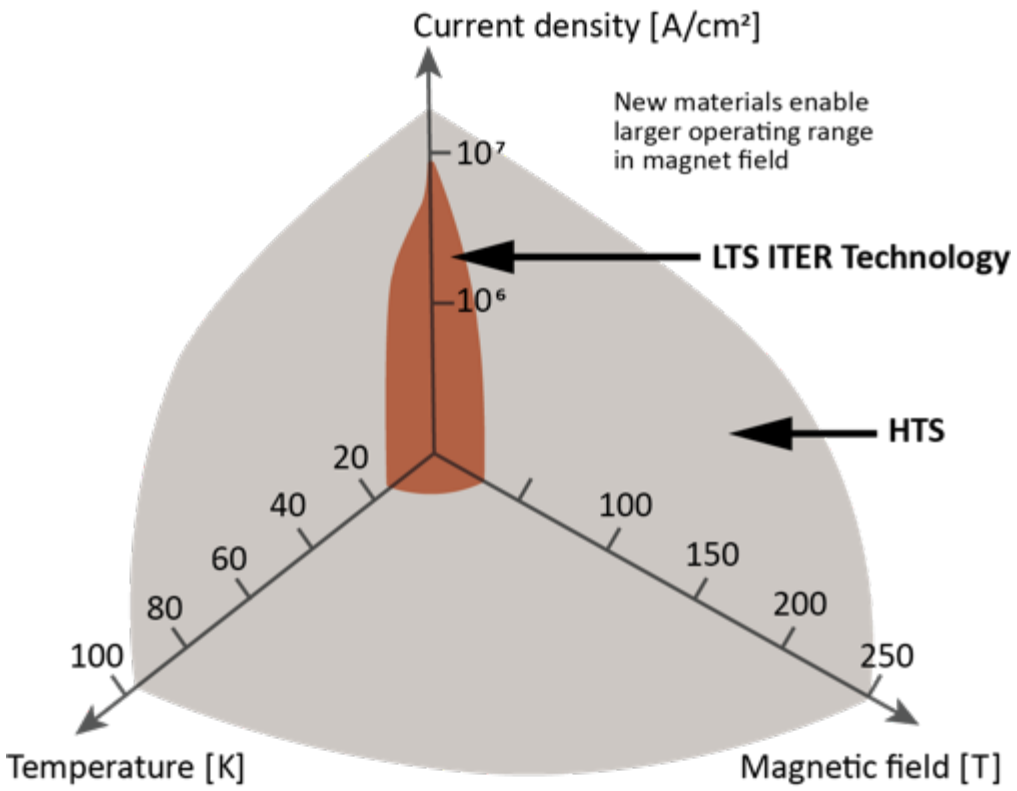
Magnet technology limited tokamak progress for decades

- But it was known that higher fields could unlock smaller and more economical machines
- We have done the experiments



CFS has invented HTS magnets for higher field

- High-Temperature Superconductor (HTS) materials expanded possibilities
- New material enables re-optimization of magnet design
- CFS developed a new generation of superconducting magnets
- Doubling the magnetic field in fusion machines



HTS material

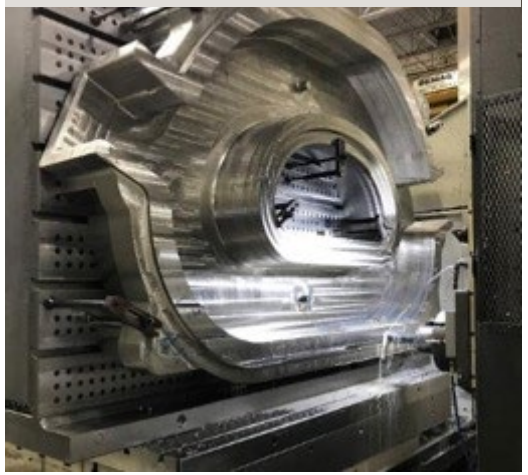
CFS magnets

CFS built a revolutionary full-scale magnet

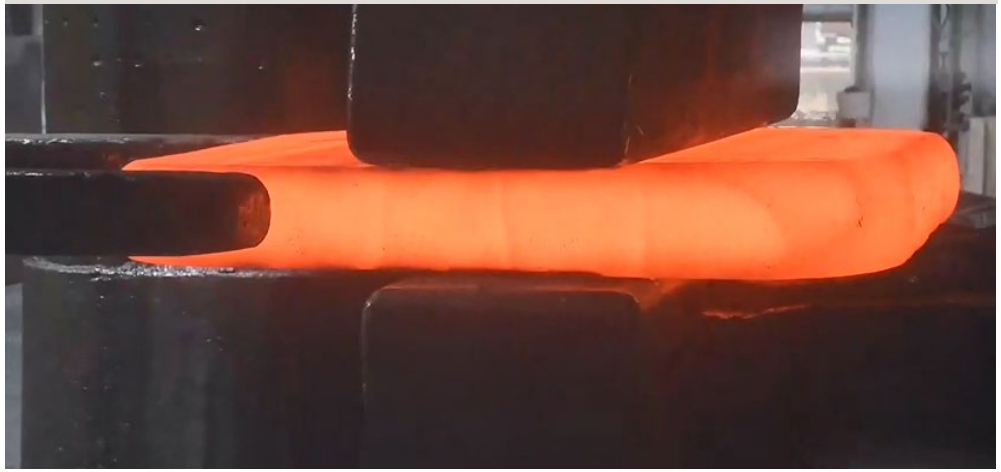
- Novel construction
- Optimized with proprietary software
- Superconducting quench for HTS now understood and tamed
- Robust and easy to manufacture

This is the future for all superconducting magnets

Machining the structural case



Forging the TFMC case



Stacking the layers

Torquing the final bolts in assembly

New magnet test facility at MIT

World's strongest HTS magnet demonstrated

The Boston Globe

Cambridge startup takes big step toward clean fusion power

By Hiawatha Bray Globe Staff, Updated September 8, 2021, 1:50 p.m.

A team of engineers and scientists from CFS and MIT's PSFC lower the superconducting magnet into the test stand in which the magnet was cooled and powered to produce a magnetic field of 20 tesla. COMMONWEALTH FUSION SYSTEMS

The scientists from MIT and Commonwealth Fusion Systems said they may have a device ready for everyday use in the early 2030s.

"This was designed to be commercial," said MIT Vice President Maria Zuber, a prominent physicist. "This was not designed to be a science experiment."

CNBC

Fusion gets closer with successful test of new kind of magnet at MIT start-up backed by Bill Gates

ars TECHNICA BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTUR

IT'S ALIVE —

Fusion startup builds 10-foot-high, 20-tesla superconducting magnet

Calculations indicate the magnet should allow fusion to break even, energy-wise.

"Because we've been able to go to very high magnetic field, we've relieved a lot of the constraints that push all those other aspects up against some really tough technical challenges," Mumgaard said. "We really pushed hard on the magnet side so that we could get some relief on these other types of issues."

U.S.News & WORLD REPORT **Los Angeles Times**

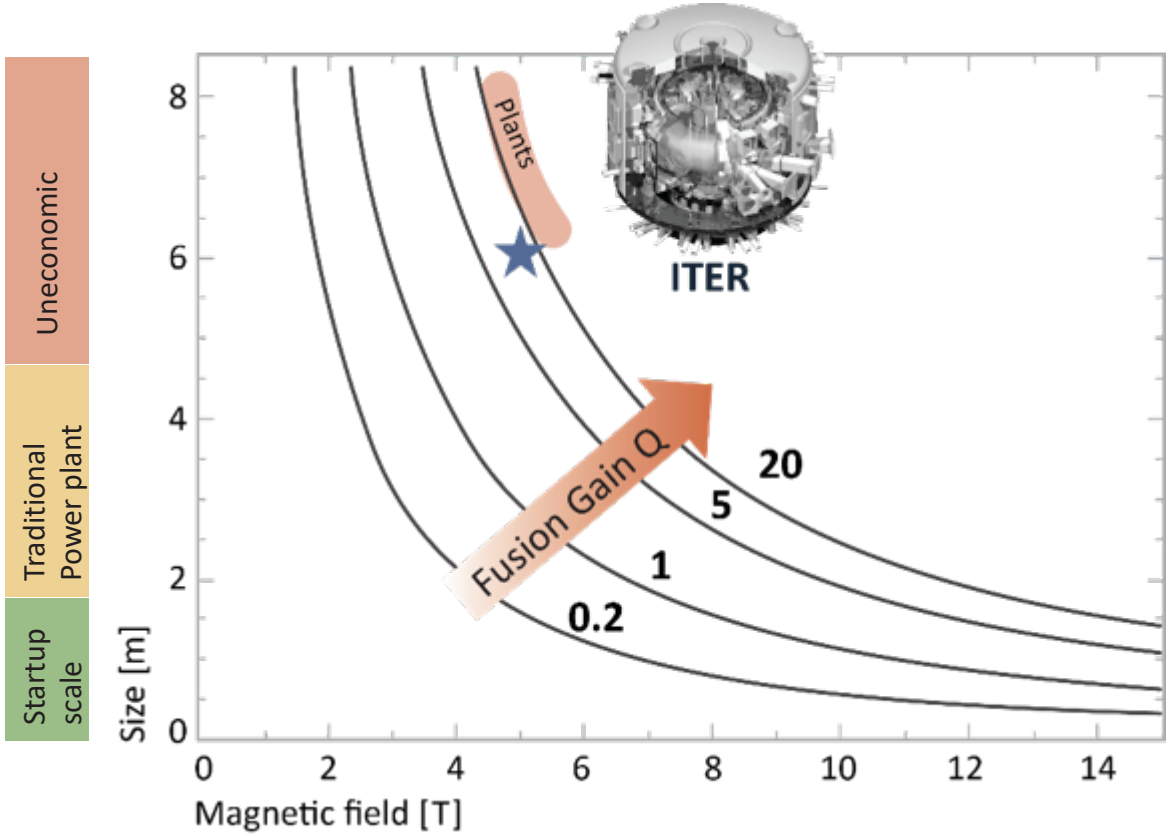
Magnet milestones move dream of nuclear fusion closer

AP

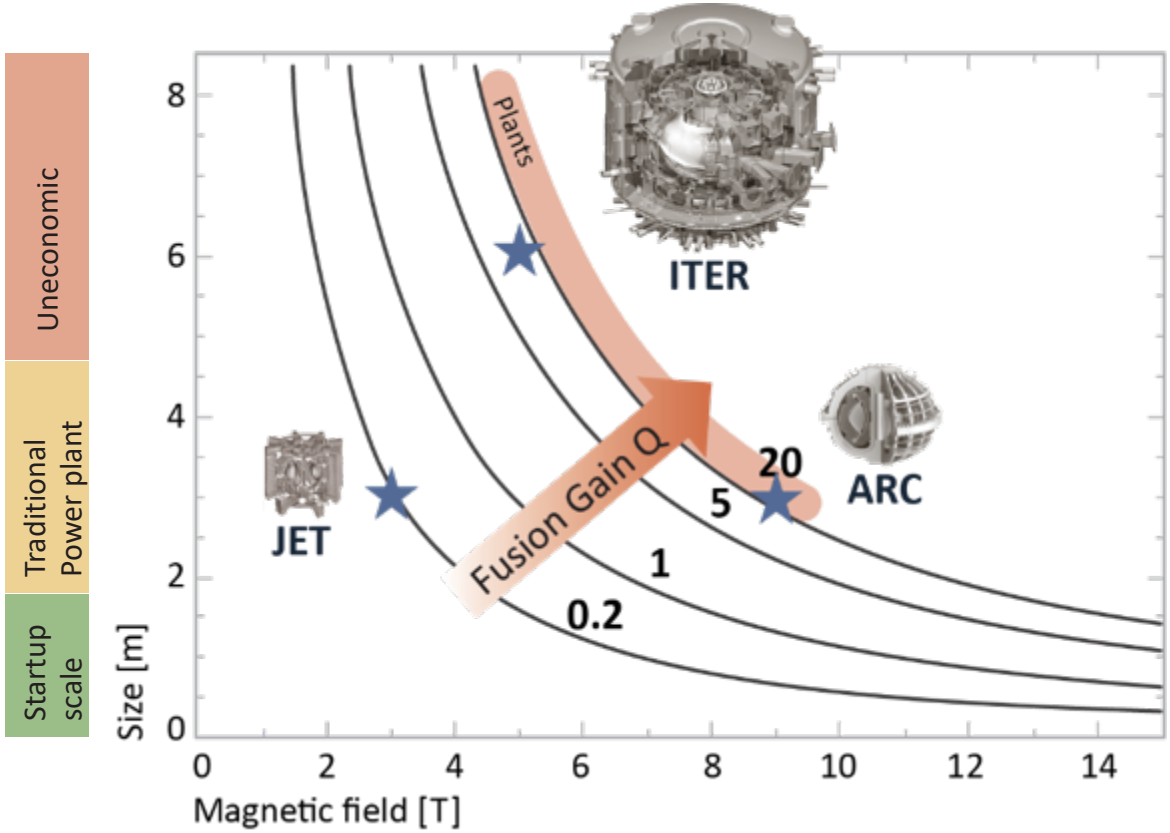
The high temperature superconducting magnet demonstrated on Sunday will be used in CFS and MIT's test fusion device, called SPARC, which is already under construction in Devens, Mass., and is and on track to demonstrate net energy from fusion by 2025, the teams said.

Magnet technology opens the space

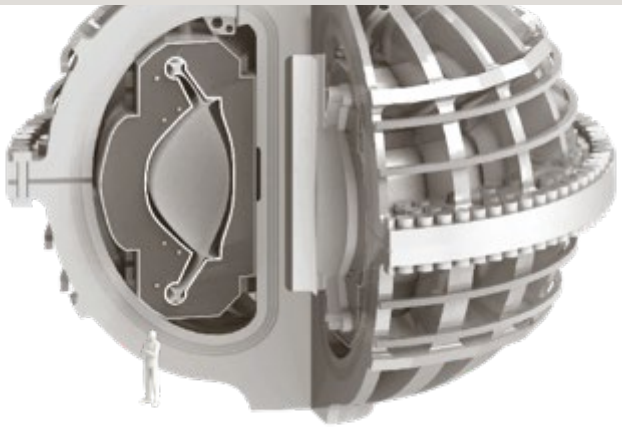
- Strong magnets are the key technology to fusion
- CFS invented the world's strongest High-Temperature Superconductor (HTS) magnets
- Higher magnetic field in much smaller form - designed and built in 3 years
- Power plants can be >50x smaller, faster, and much lower cost



New magnets reoptimize power plants

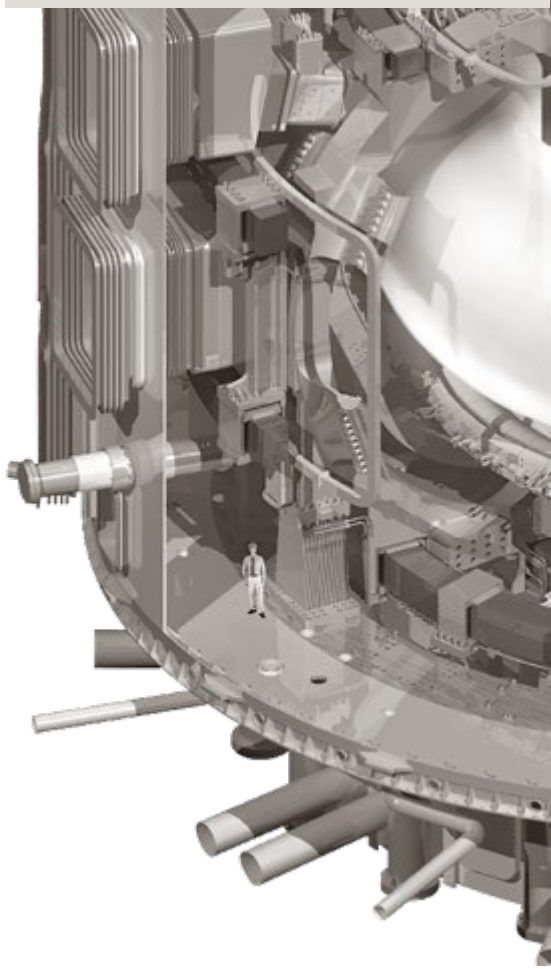


ARC – fusion power plant using known physics + new magnets

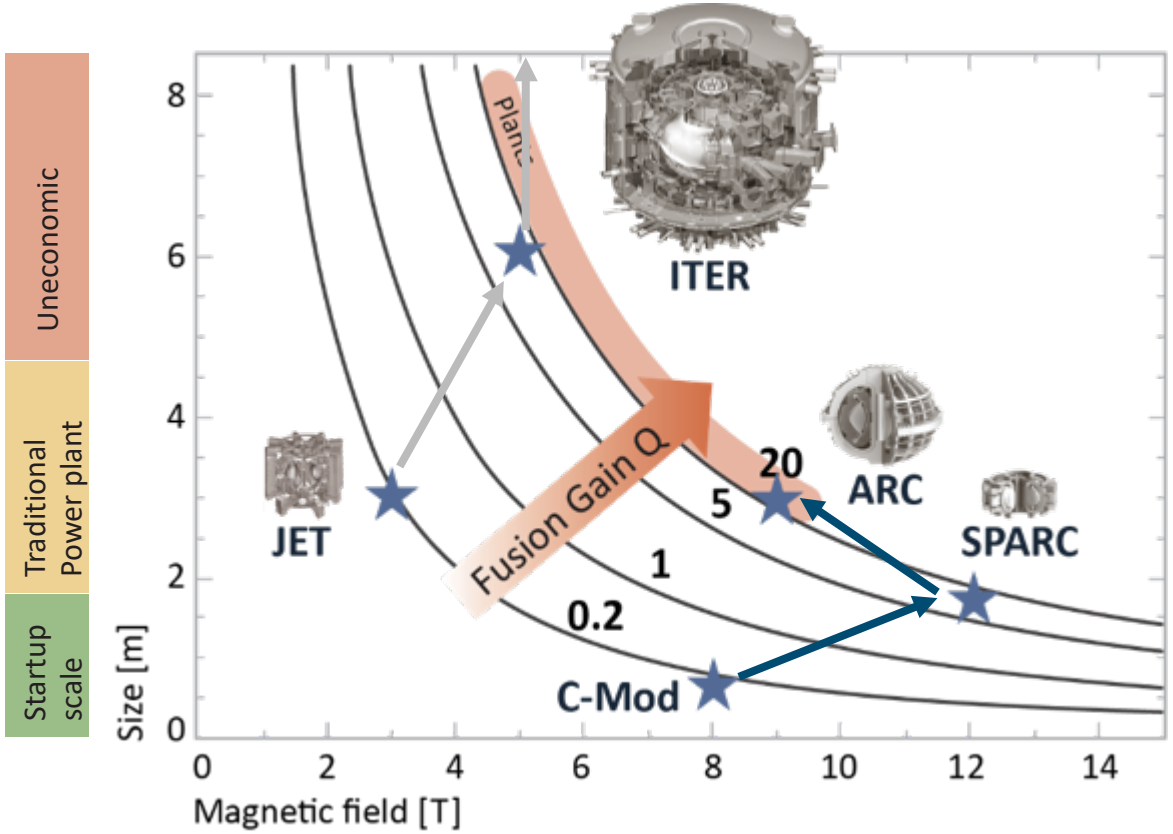


	ARC	ITER
R [m]	3.2	6.2
Magnet	HTS	LTS
B [T]	9.2	5.3
P_{fusion} [MW]	500	500
Q	10	10
$P_{electric}$ [MW]	**200**	**0**

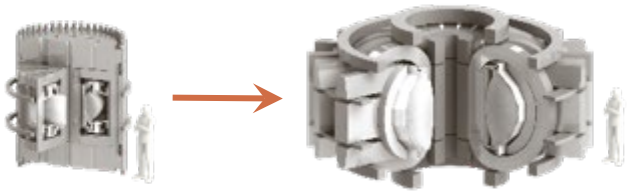
ITER – to scale



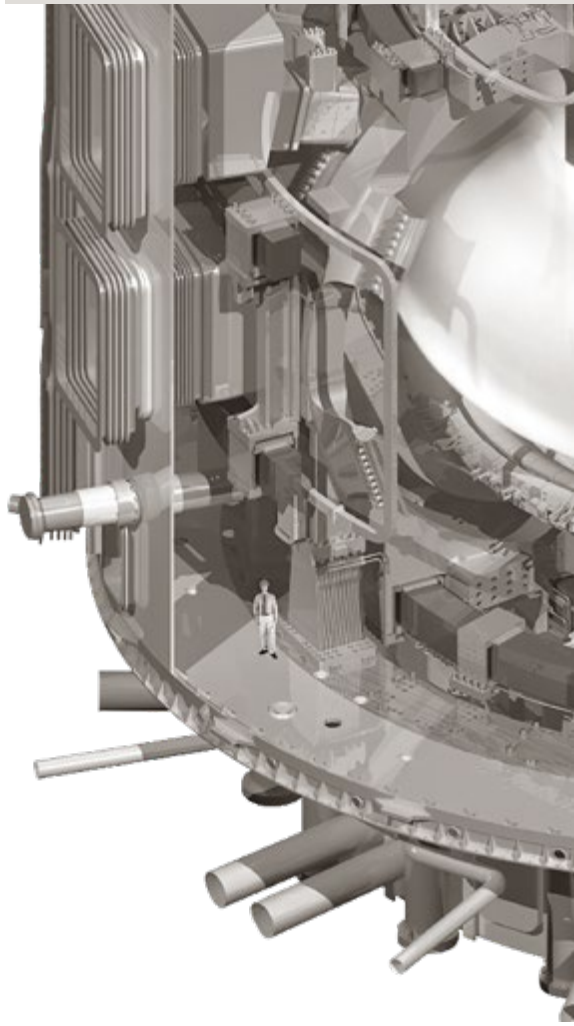
Opening a new development pathway



C-Mod and SPARC



ITER – to scale



Risk retirement in concrete steps

COMPLETED:
Alcator C-Mod
Record-setting tokamak

COMPLETED:
Demonstrate groundbreaking HTS magnets
(A/A2 rounds, $250m)

Early revenue from magnet platform

CONSTRUCTION UNDERWAY for 2025 LAUNCH:
SPARC Q>1
Achieve net fusion energy
(B round, $1.8B)

Commercially-relevant net fusion energy for the first time

EARLY 2030s:
ARC deployed
~400 MW

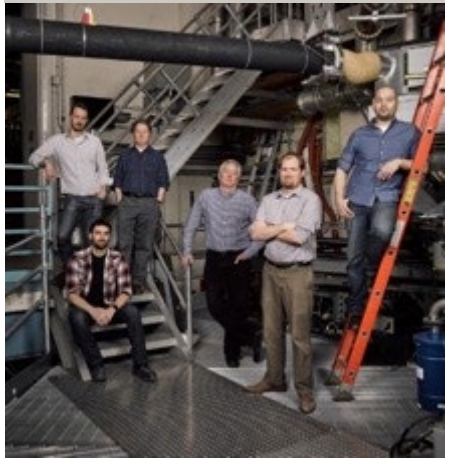
Carbon-free commercial power on the grid

CFS is a company that executes

- CFS Founded in 2018, spun out of MIT
- Based on DOE research with exclusive licenses and a partnership to advance fusion
- Built a high caliber, diverse team from SpaceX, Tesla, Boeing Company, TerraPower, Blue Origin, GE, Google, Amazon, Virgin Galactic, other tough tech leaders
- Now >375 people in 5 facilities
- Delivering projects on time and on budget

Execution - Self-critique - Integrity - Impact

CFS Co-founders



Strong partners

Massachusetts Institute of Technology

PSFC

Plasma Science and Fusion Center
Massachusetts Insitute of Technology

A diverse and talented team

SPARC physics basis has been peer reviewed and published

- Published in the Journal of Plasma Physics in a special 2020 issue
- Builds extensively on the decades of government funded fusion research
- 7 of the top 10 read articles in JPP in 2021

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]

Projections of H-mode access and edge pedestal in the SPARC tokamak

J. W. Hughes[1,†], N. T. Howard[1], P. Rodriguez-Fernandez[1], A. J. Creely[2], A. Q. Kuang[1], P. B. Snyder[3], T. M. Wilks[1], R. Sweeney[1] and M. Greenwald[1]

Divertor heat flux challenge and mitigation in SPARC

A. Q. Kuang[1,†], S. Ballinger[1], D. Brunner[2], J. Canik[3], A. J. Creely[2], T. Gray[3], M. Greenwald[1], J. W. Hughes[1], J. Irby[1], B. LaBombard[1], B. Lipschultz[4], J. D. Lore[3], M. L. Reinke[3], J. L. Terry[1], M. Umansky[5], D. G. Whyte[1], S. Wukitch[1] and the SPARC Team

Predictions of core plasma performance for the SPARC tokamak

P. Rodriguez-Fernandez[1,†], N. T. Howard[1], M. J. Greenwald[1], A. J. Creely[2], J. W. Hughes[1], J. C. Wright[1], C. Holland[3], Y. Lin[1], F. Sciortino[1] and the SPARC team

[1]MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
[2]Commonwealth Fusion Systems, Cambridge, MA 02139, USA
[3]Center for Energy Research, University of California San Diego, San Diego, CA 92093, USA

(Received 11 May 2020; revised 14 August 2020; accepted 17 August 2020)

Physics basis for the ICRF system of the SPARC tokamak

Y. Lin[1,†], J. C. Wright[1] and S. J. Wukitch[1]

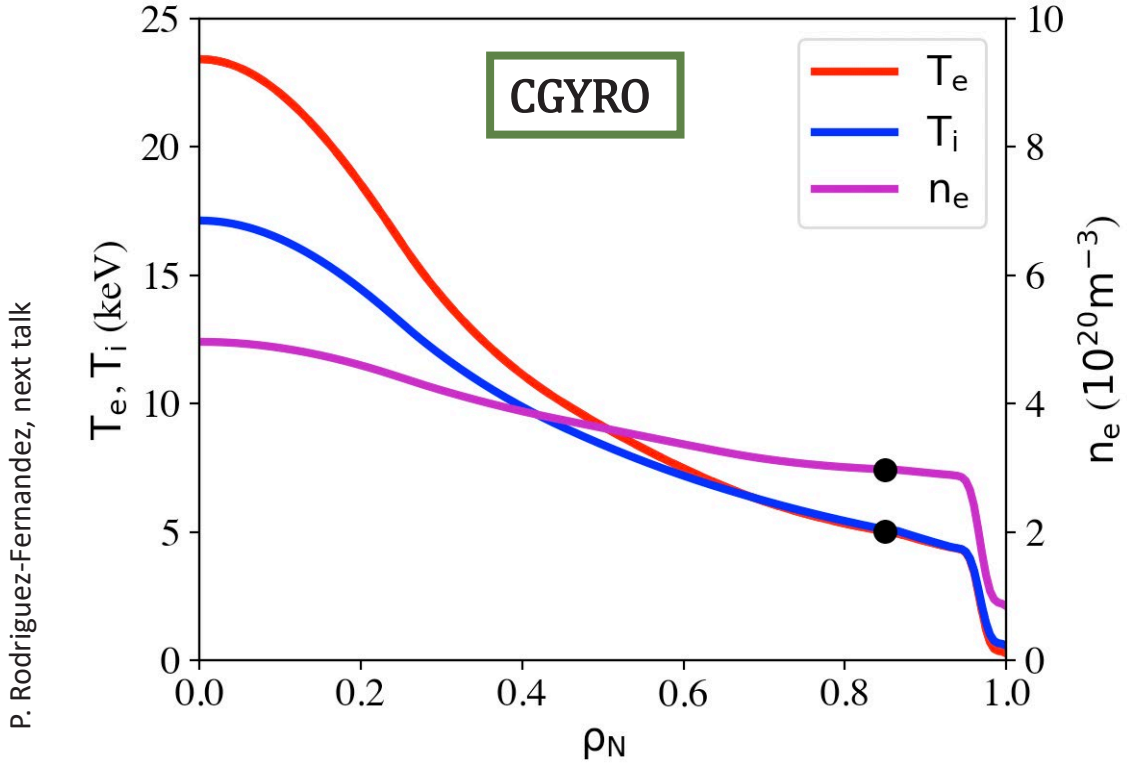
MHD stability and disruptions in the SPARC tokamak

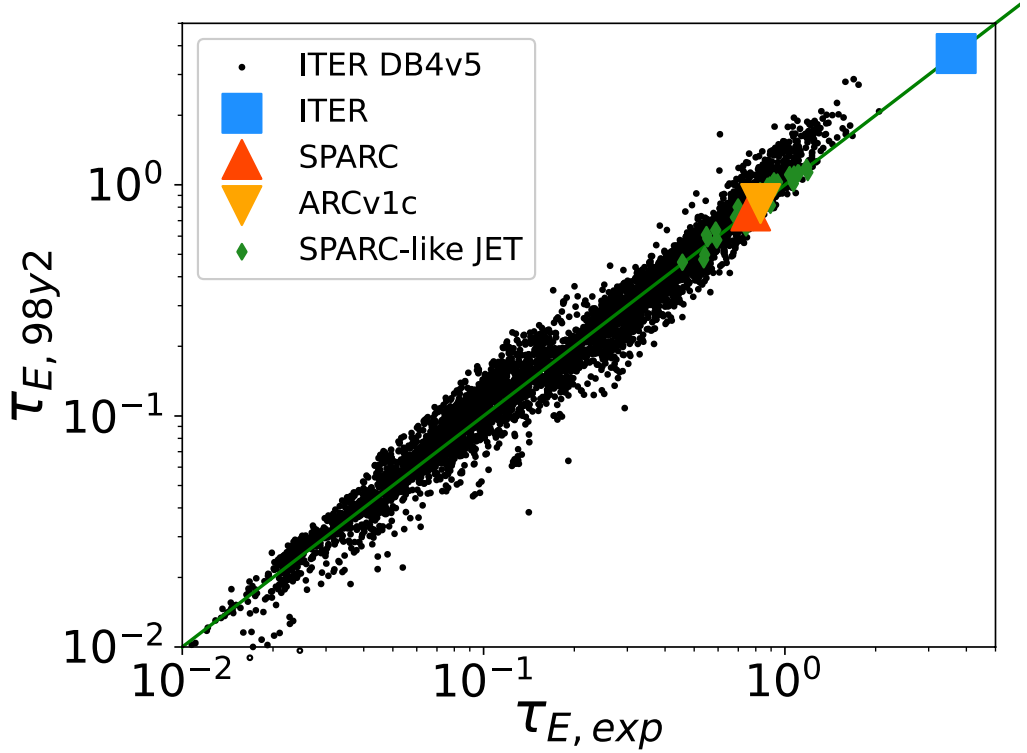
R. Sweeney[1,†], A. J. Creely[2], J. Doody[1], T. Fülöp[3], D. T. Garnier[1], R. Granetz[1], M. Greenwald[1], L. Hesslow[3], J. Irby[1], V. A. Izzo[4], R. J. La Haye[5], N. C. Logan[6], K. Montes[1], C. Paz-Soldan[5], C. Rea[1], R. A. Tinguely[1], O. Vallhagen[3] and J. Zhu[1]

Fast-ion physics in SPARC

S. D. Scott[1,†], G. J. Kramer[2], E. A. Tolman[3], A. Snicker[4], J. Varje[4], K. Särkimäki[5], J. C. Wright[3] and P. Rodriguez-Fernandez[3]

Confinement: SPARC will operate at absolute densities, temperatures, and confinement times equivalent to ARC

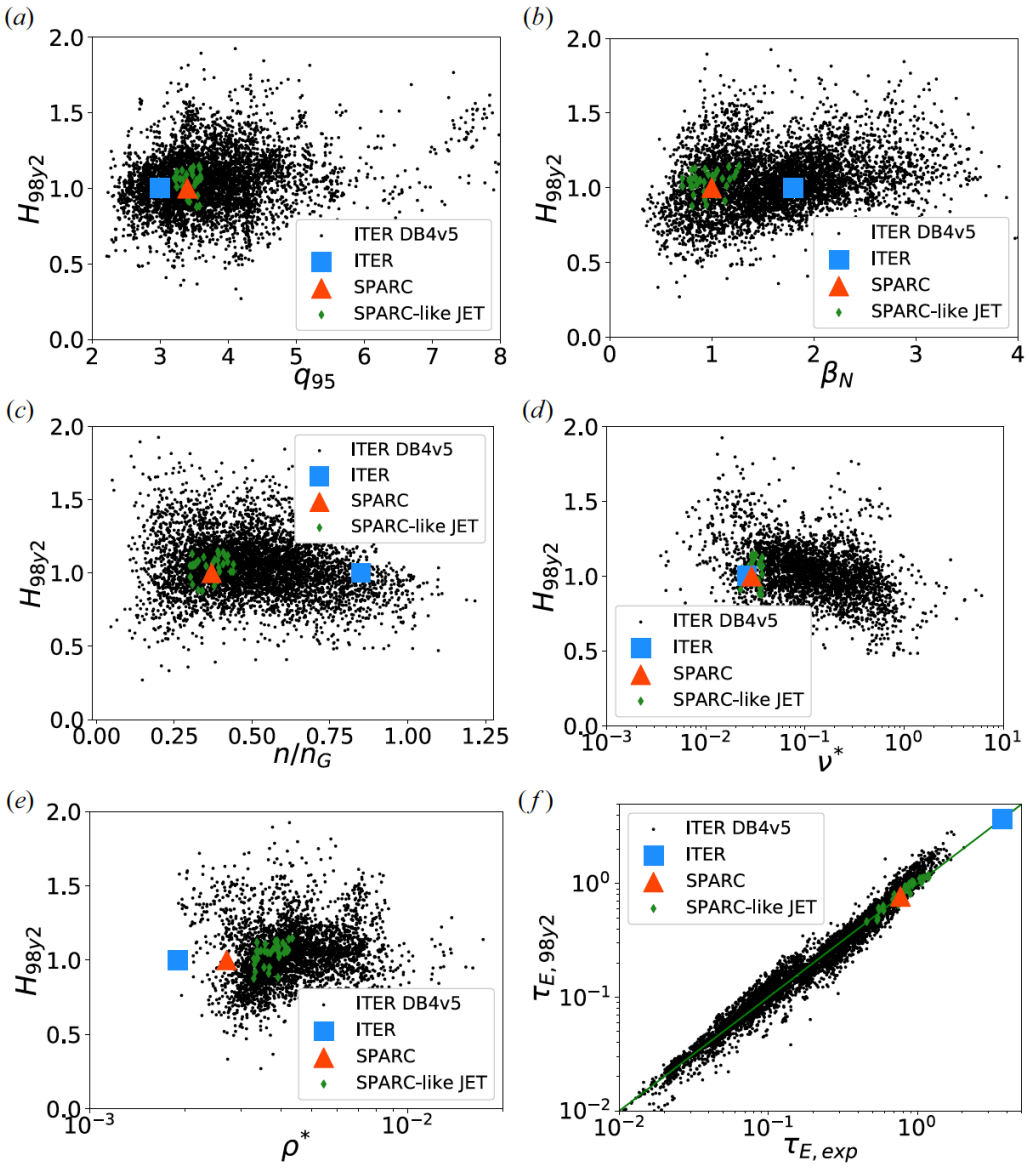




- Initial ARC design will proceed using same confinement scalings as SPARC [2]
- SPARC data will both reduce uncertainties in empirical confinement scalings and validate first-principles simulations, such as those performed in CGYRO by P. Rodriguez-Fernandez [3, next talk]
- This data, and exploration of alternative confinement regimes, will allow for interpolation of ARC operation, as opposed to extrapolation far from demonstrated space

Performance is based on extensive tokamak database

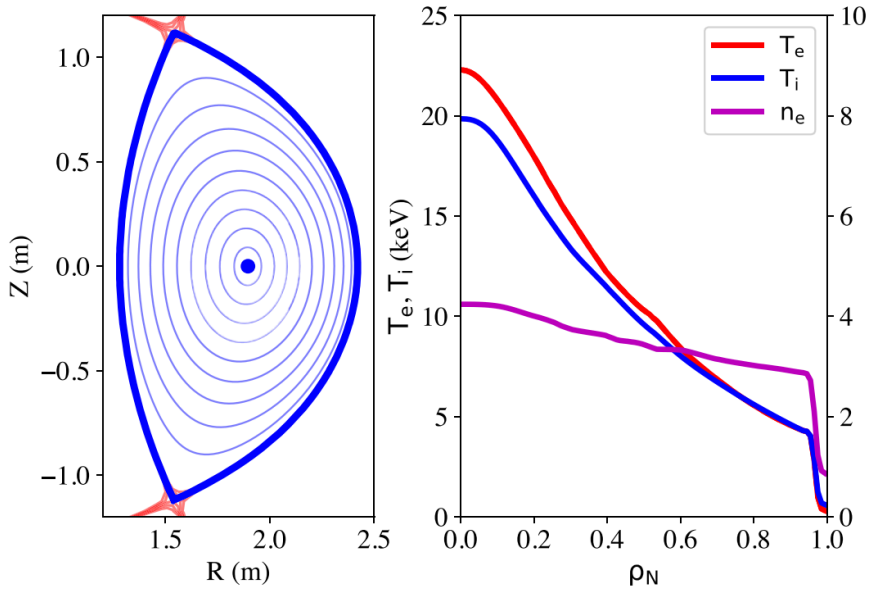
- International tokamak database was assembled to predict energy confinement time extrapolation to ITER
- Similar to finding power law correlations for turbulent fluids
- Methods done based on both dimensional and dimensionless parameters
- SPARC energy confinement time is interpolation in database
- **Discharges on JET tokamak are identity match in dimensionless parameters**
- Have very strong confidence in predicting performance

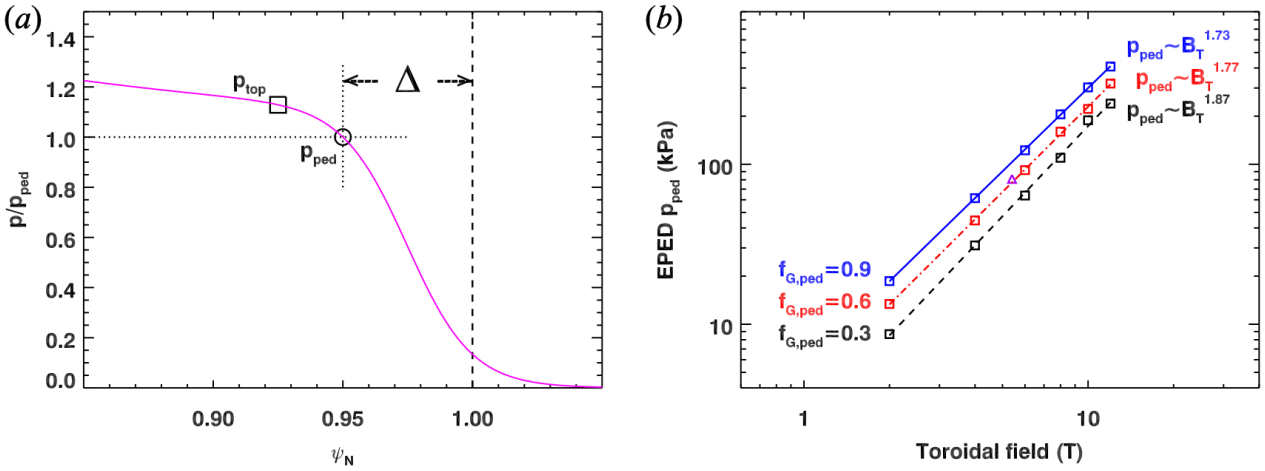


Creely, A., Greenwald, M., Ballinger, S., Brunner, D., Canik, J., Doody, J., . . . Zhu, J. (2020). Overview of the SPARC tokamak. *Journal of Plasma Physics, 86*(5), 865860502. doi:10.1017/S0022377820001257

SPARC is first tokamak built integrated physics modeling to predict performance

- Same engineering inputs as empirical scaling (size, magnetic field, shaping, etc.)
- Uses suite of validated physics codes to predict plasma profiles and turbulent transport
- Integrated physics results in $Q_{physics}$ that's remarkably close to empirical prediction: ~8 and ~11, respectively





Hughes, J., Howard, N., Rodriguez-Fernandez, P., Creely, A., Kuang, A., Snyder, P., . . . Greenwald, M. (2020). Projections of H-mode access and edge pedestal in the SPARC tokamak. Journal of Plasma Physics, 86(5), 865860504. doi:10.1017/S0022377820001300

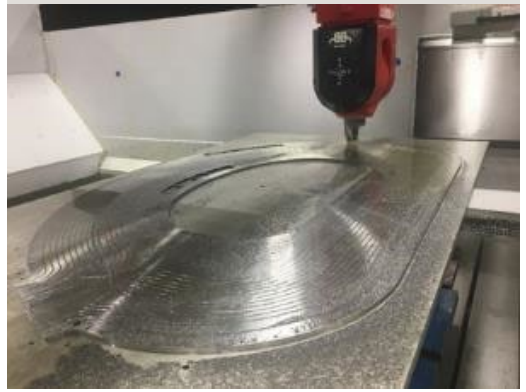
Rodriguez-Fernandez, P., Howard, N., Greenwald, M., Creely, A., Hughes, J., Wright, J., . . . Sciortino, F. (2020). Predictions of core plasma performance for the SPARC tokamak. Journal of Plasma Physics, 86(5), 865860503. doi:10.1017/S0022377820001075

Ramping procurements for the machine

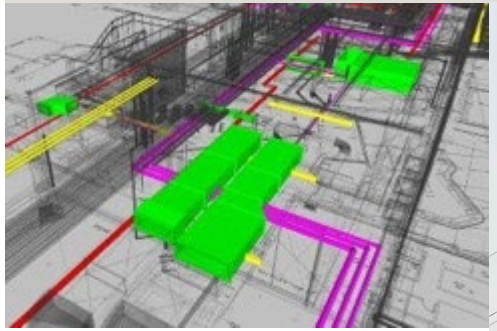
- Ramping purchase orders for long lead items
- Material orders at foundries
- Locking equipment specs and layouts
- Onboarding vendors and partners

Preparing materials

Production ready



Detailed SPARC facility layout



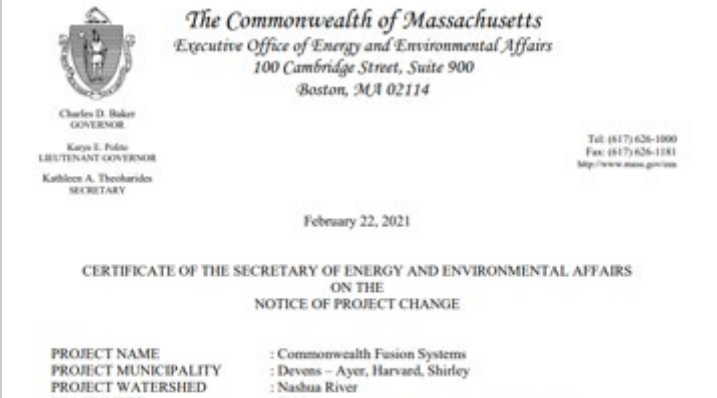
Progression in parallel with engineering

SPARC site found and license pathway clear

- Site selected after national search
- NRC agreed this is not in their jurisdiction
- State license similar to a cancer treatment center

The path is clear to build the first net energy fusion machine

Environmental clearance



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Charles D. Baker
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February 22, 2021

CERTIFICATE OF THE SECRETARY OF ENERGY AND ENVIRONMENTAL AFFAIRS
ON THE
NOTICE OF PROJECT CHANGE

PROJECT NAME : Commonwealth Fusion Systems
PROJECT MUNICIPALITY : Devens – Ayer, Harvard, Shirley
PROJECT WATERSHED : Nashua River

Construction parties on boarded

DEVENS
nationalgrid
HDR
BOND
KSP King Street Properties

SPARC building

Site purchased and construction accelerating

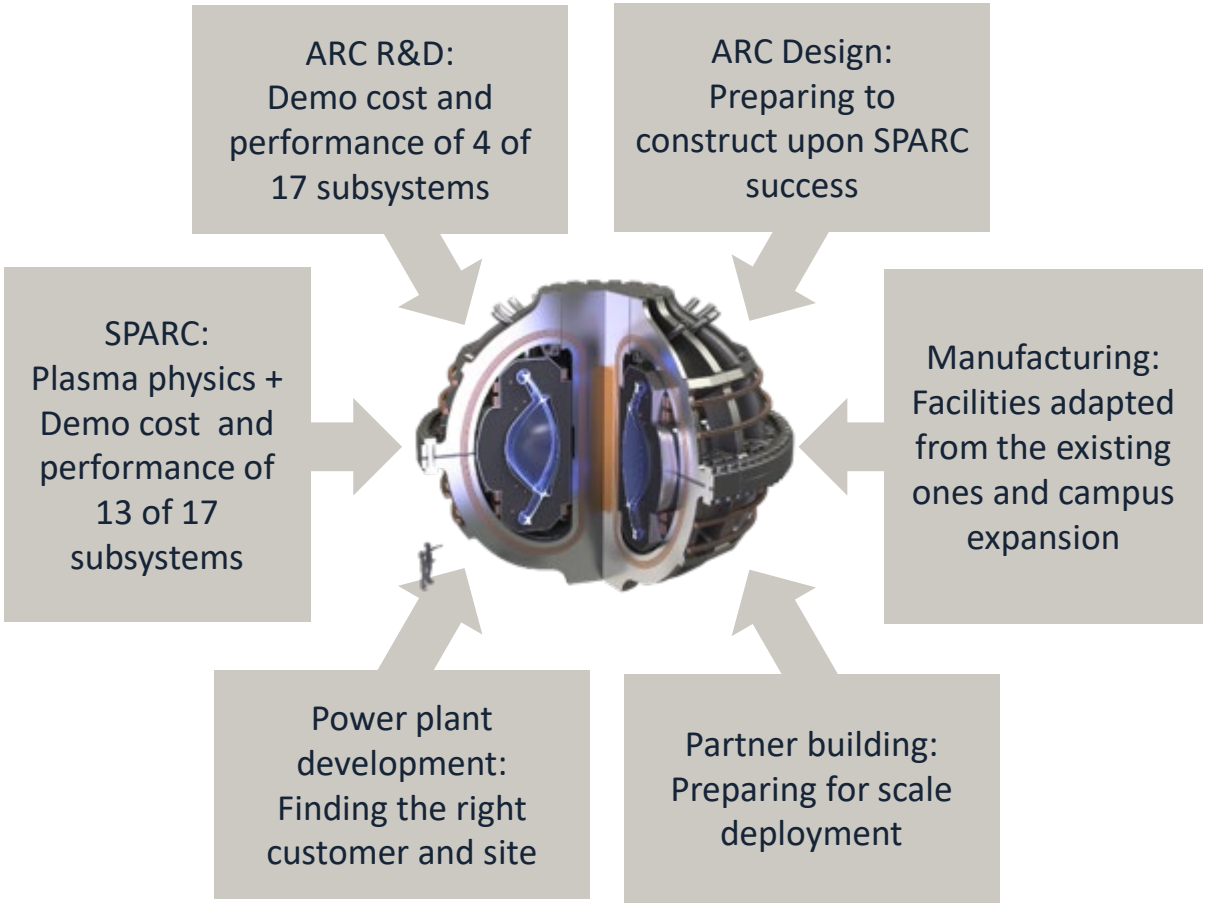
- Environmental review complete
- Community engaged and excited
- 47-acre site purchased
- Readying for move into HQ and magnet factory

Devens, Massachusetts construction progress

CFS magnet manufacturing, HQ and SPARC

Positioning to move to ARC ASAP after SPARC

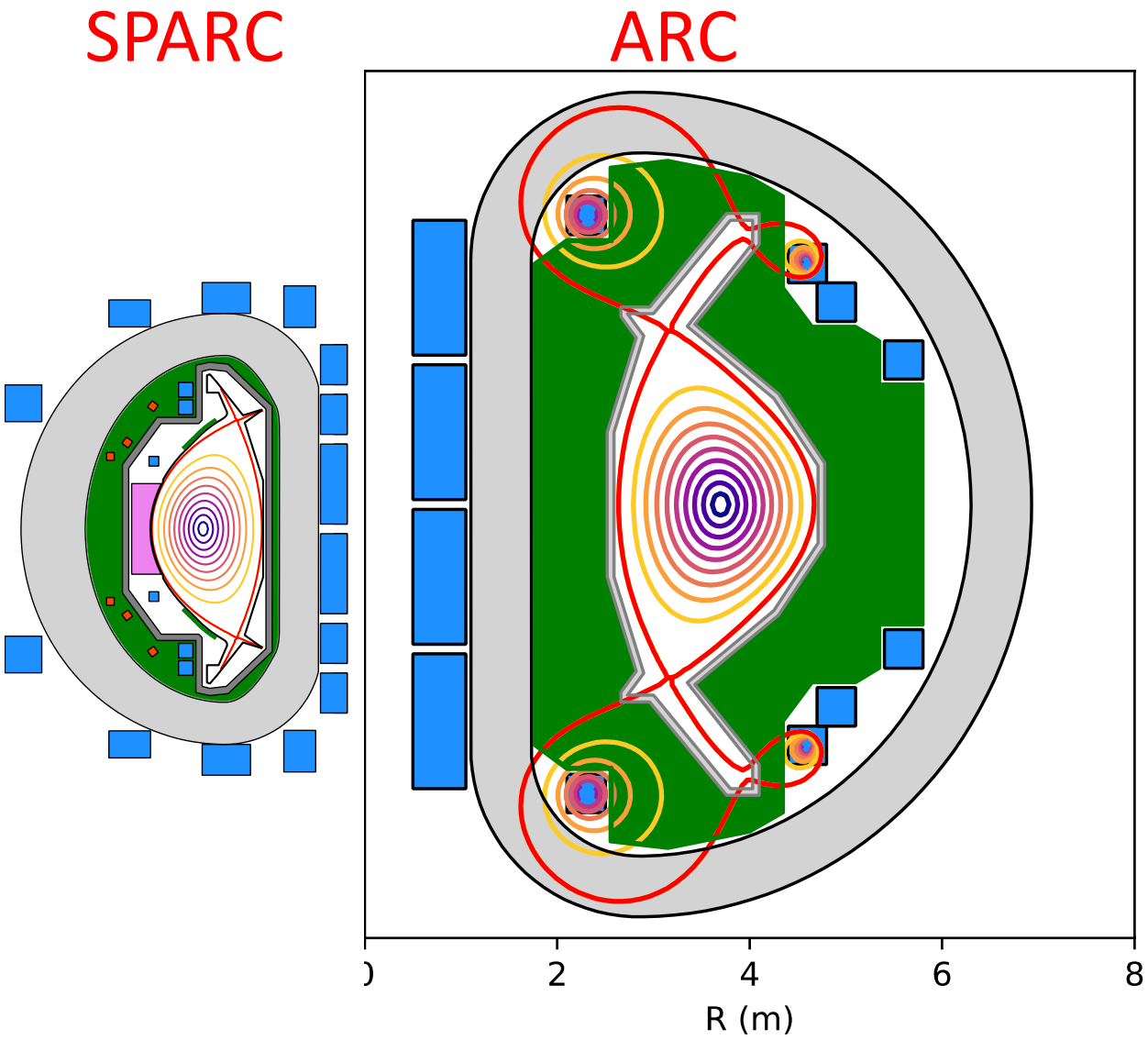
- Economics de-risked using our receipts from SPARC
- Performance de-risked using SPARC to optimize it
- Technologies de-risked using SPARC and other R&D
- Business development to find beachhead
- We'll have assembled the partners and found the first customer
- Manufacturing using our facilities



Set up to move to ARC construction immediately after SPARC demonstrated

ARC-specific design and R&D starting in earnest

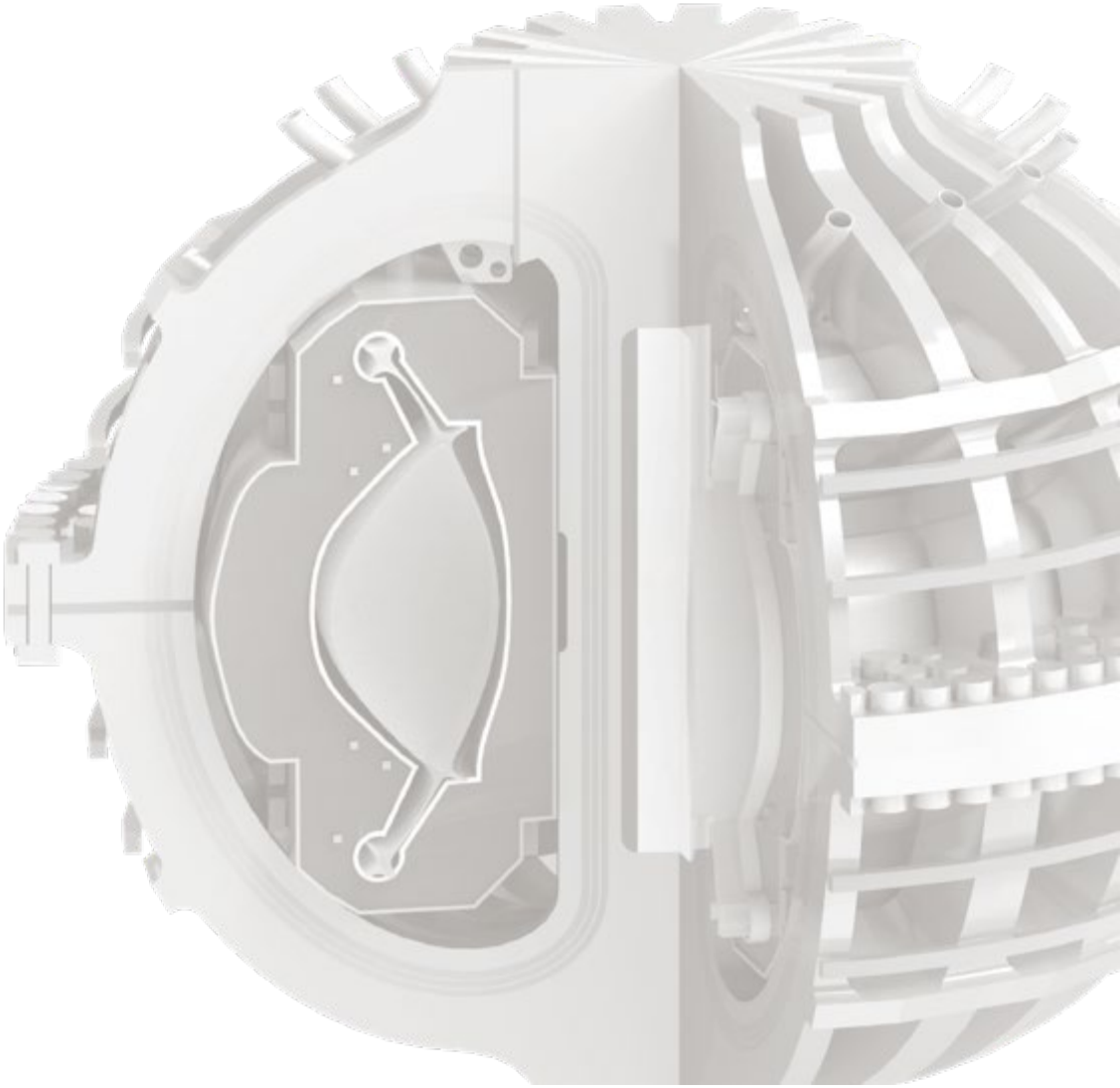
- ARC is ~2x linear scale-up of SPARC
- ARC still pre-conceptual design
- ARC R&D programs starting, focusing on technology needed to make fusion energy:
  - Molten salt blanket
  - Materials and manufacturing
  - Maintenance
  - Magnets
  - Tritium
  - Diagnostics
  - Power cycle



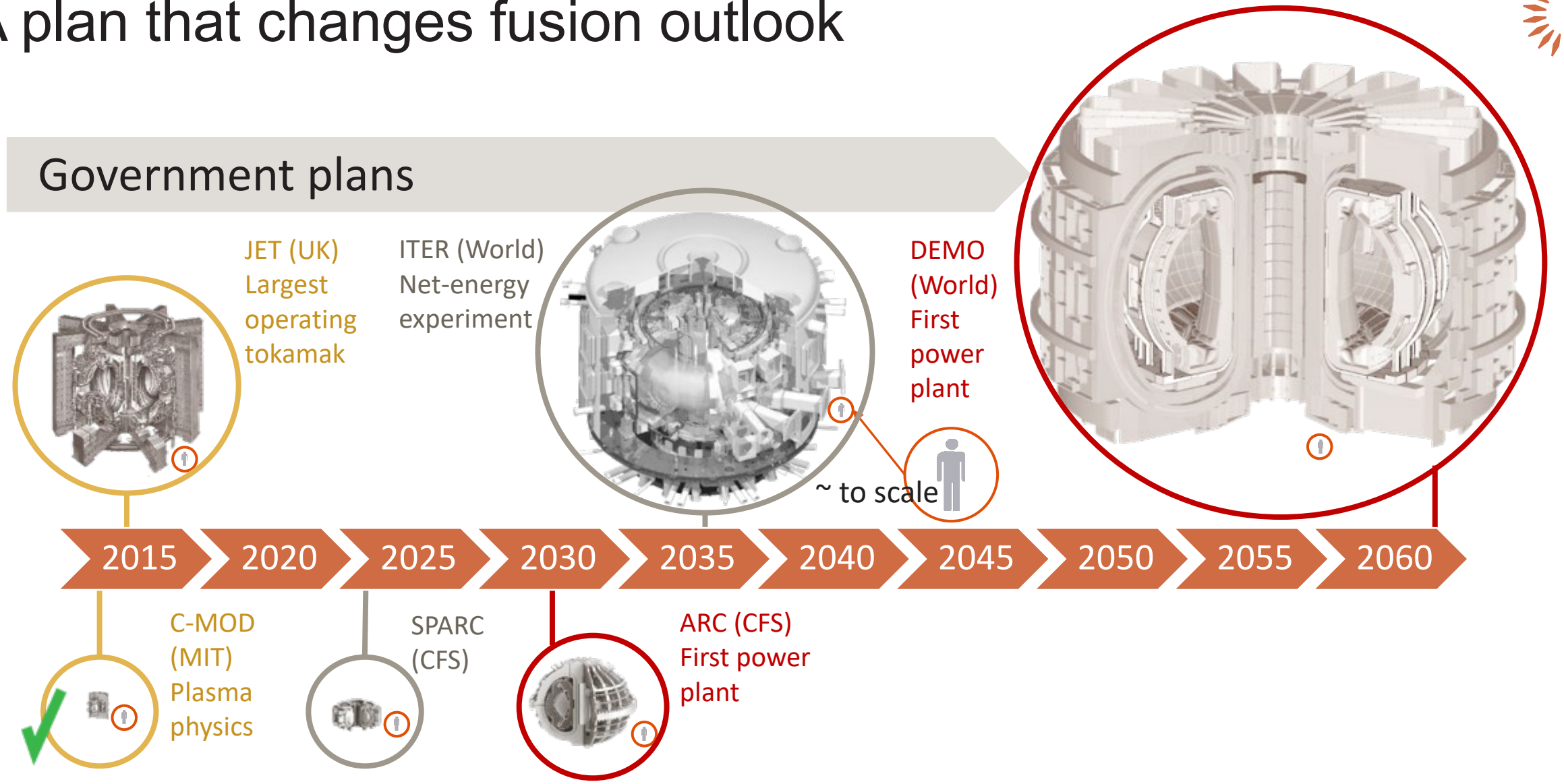
ARC site selection underway

- Developing selection criteria for ARC 1 / ARC Block A
- Engaging potential ARC customers to inform criteria and down select target markets
- Lobbying governments to support commercial fusion

Identifying ARC siting criteria and initial target markets



A plan that changes fusion outlook



Commonwealth Fusion Systems