Commonwealth Fusion Systems MIT PSFC

# SPARC, ARC and the high-field path to burning plasmas and commercial fusion energy

Dennis Whyte

Director, MIT Plasma Science & Fusion Center

Representing my colleagues at Commonwealth Fusion Systems, MIT-PFSC and our many collaborators

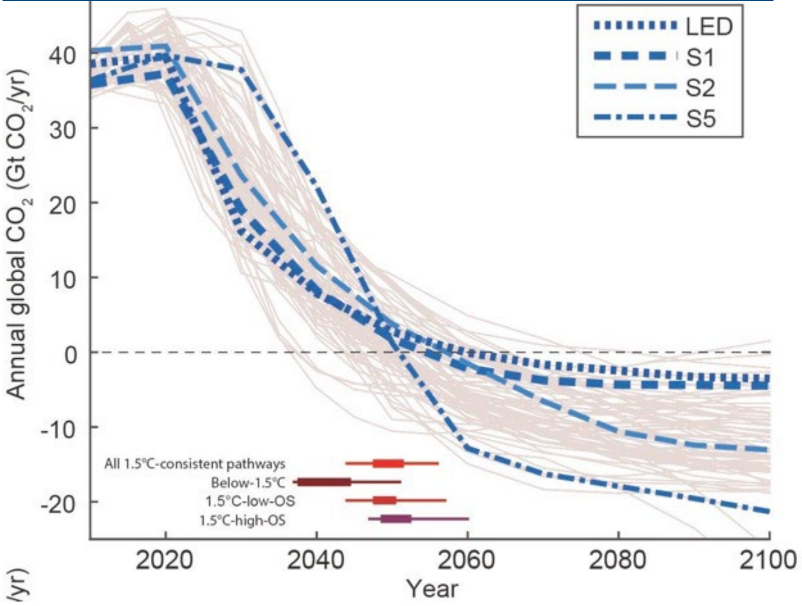
# Outline

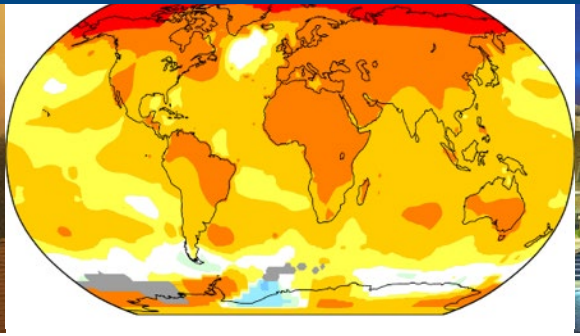
- The high field burning plasma plan & the energy transition
- SPARC and its mission
- The public-private ecosystem
- ARC as a Fusion Pilot Plant platform

# Decarbonization is the largest trend this century

- The verdict is unanimous, we need to decarbonize to net-zero by 2050.
- Climate sets the timeline, not technology.
- The World is going to do what it takes.
- Climate / Sustainability / Energy Transition require a massive shift in how we generate and consume energy
- Decarbonization will transform ~5-6% of global GDP

What MUST be done




| Risk | Science | Finance | Society |
| --- | --- | --- | --- |
|  |  |  |  |

# Burning Plasmas are a necessary but insufficient part of delivering fusion energy to meet decarbonization goals

- Net energy gain commensurate with commercialization → physics tells us we must obtain burning plasma self-heating regime
  - $Q_p$ > 10- for D-T power plant, burning plasma regime $Q_p > 5$

- Yet the urgency for decarbonization has completely modified the context and drive for obtaining burning plasma, which must have
  - Timeline commensurate with commercialization
  - Approach with obvious and relatively small extrapolation to commercial entity in terms of confinement scheme
  - Altered risk assumptions: will accept/require parallel development paths

- If these are met, more resources will arrive to support BP mission (not a zero sum game)
- This reality has fundamentally changed the BP strategy. A single collective BP experiment that does not meet these criteria is insufficient

# Commercial fusion risk retirement in concrete steps

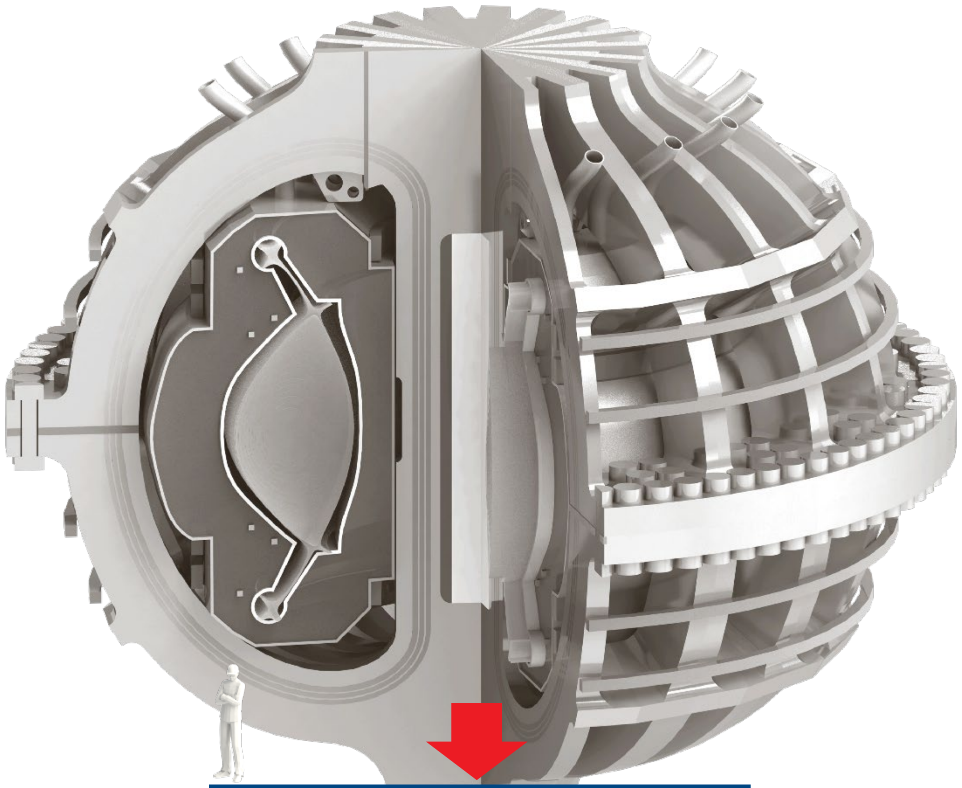
COMPLETED:
Alcator C-Mod

COMPLETED
TFMC demonstrated
September 5, 2021

CONSTRUCTION
PLANNING UNDERWAY
for 2025 LAUNCH
SPARC achieves net energy

Net energy

Early 2030s
ARC fusion power on the grid



Carbon-free scalable commercial power

# Commercial fusion risk retirement in concrete steps

**COMPLETED:**
Alcator C-Mod

**COMPLETED**
TFMC demonstrated
September 5, 2021

**FUNDED at 1.8 B$**
December 1, 2021

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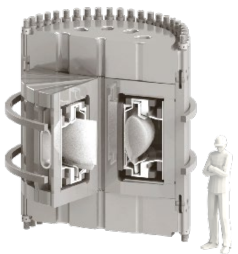
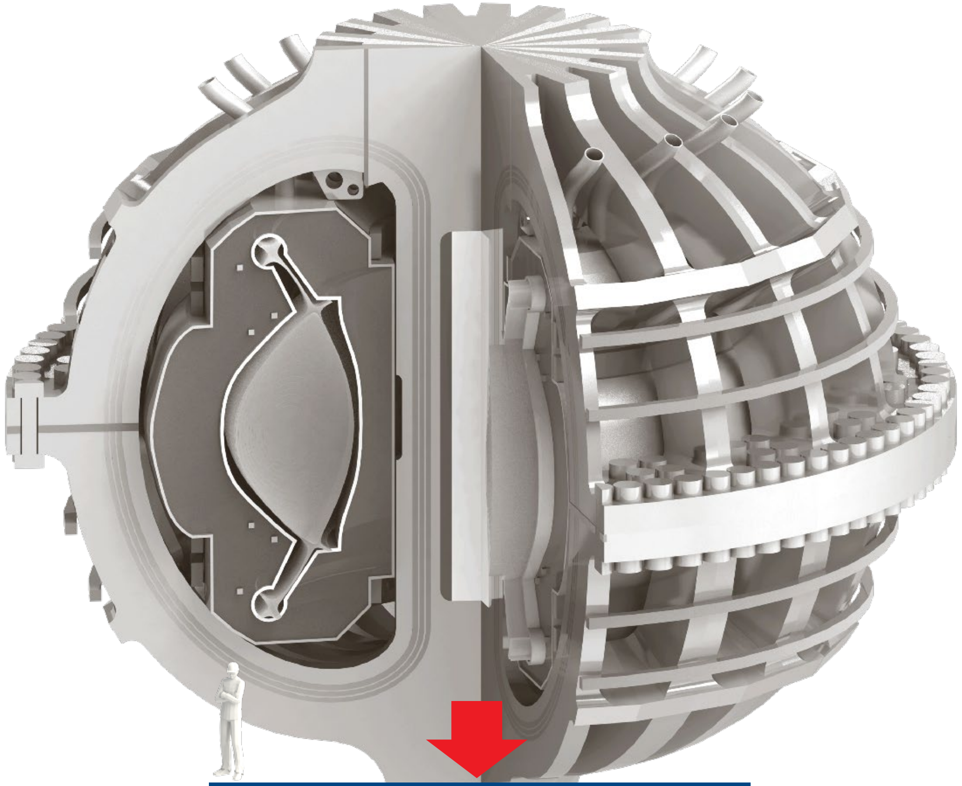
SPARC achieves net energy

**Early 2030s**
ARC fusion power on the grid



Net energy



Carbon-free scalable commercial power


WSJ NEWS EXCLUSIVE

**Nuclear-Fusion Startup Lands $1.8 Billion as Investors Chase Star Power**

No one has been able to generate net energy by combining atoms, yet Commonwealth Fusion Systems has attracted Bill Gates and George Soros

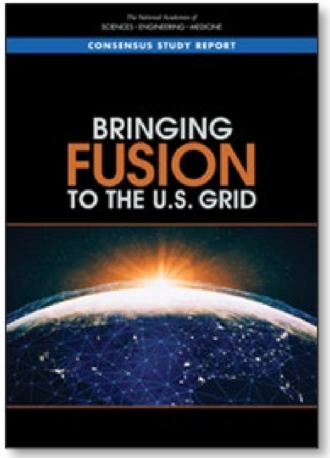
# SPARC ~ Nov 15 2021

# Fundamentally aligned with NAS Report, FESAC LRP and US BPO

"Phase 1a: Production of net fusion plasma energy gain"

"Phase 1b: Capture and conversion into electricity"

"Phase 2,3: Production of fusion power for one/ many environmental cycles "



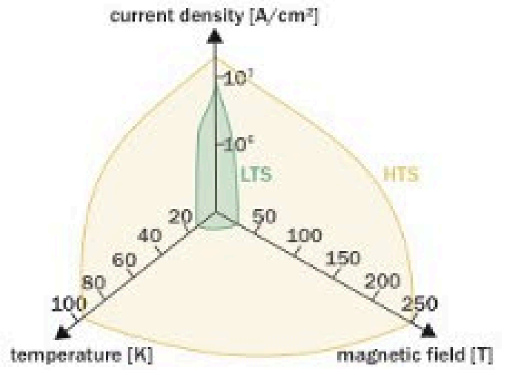

[1] National Academies of Sciences, Engineering, and Medicine 2021. Bringing Fusion to the U.S. Grid. Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

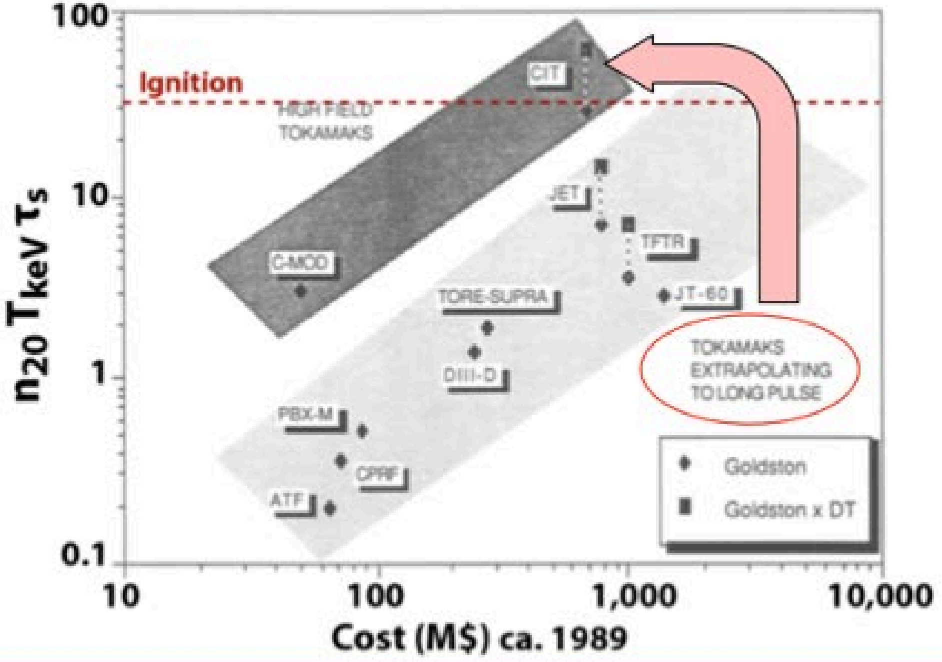
# The Case for High Field (APS 2017)

| Issue | Scaling | |
|---|---|---|
| Power density | $B^4$ | 😀 |
| Confinement (generic) | $R^2 B^2$ | 😀 |
| Confinement (tokamak) | $R^{2.7} B^{3.5}$ ($H_{98}$)<br>$R^{3.1} B^{2.1}$ (Petty) | 😀 |
| Confinement (stellarator) | $R^{2.8} B^{2.1}$ | 😀 |
| Gain | $R^{2\text{-}3.1}$ $B^{4\text{-}5.5}$ | 😀 |
| Stable pedestal | $\sim \beta_N B^2$ | 😀 |

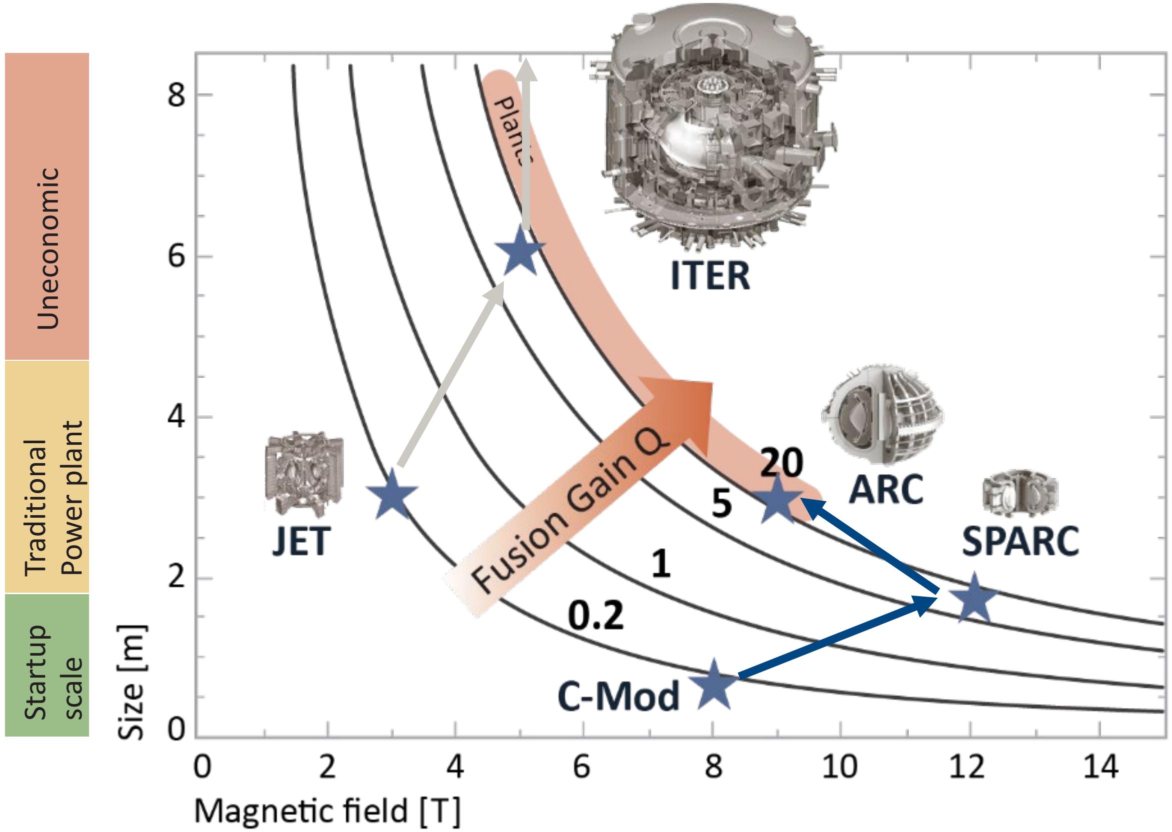
| Issue | Scaling | |
|---|---|---|
| Density (tokamak) | $R^{-1} B^1$ | 😀 |
| Density (stellarator) | $\beta B^{2.5}$ (burning) | 😀 |
| Heat exhaust: min. $f_Z$ | $R^{1.3} B^{0.9}$ | 😀 |
| Heat exhaust: $q_{//}$ | $B^{-1}$ (burning) | 🤔 |
| Runaway e- amp. | $\exp(R^{0.28} / B^{0.3})$ | 😀 |
| Synchrotron: runaways | $B^2$ | 😀 |
| Synchrotron:thermal | $\sim B^{1.5}$ | 😀 |
| TAE | $n \sim B$, $v_A \sim B$ | 🤔 |

WORK IN PROGRESS

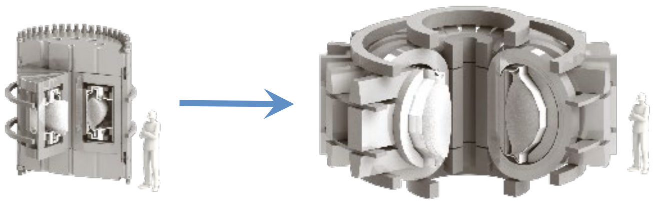


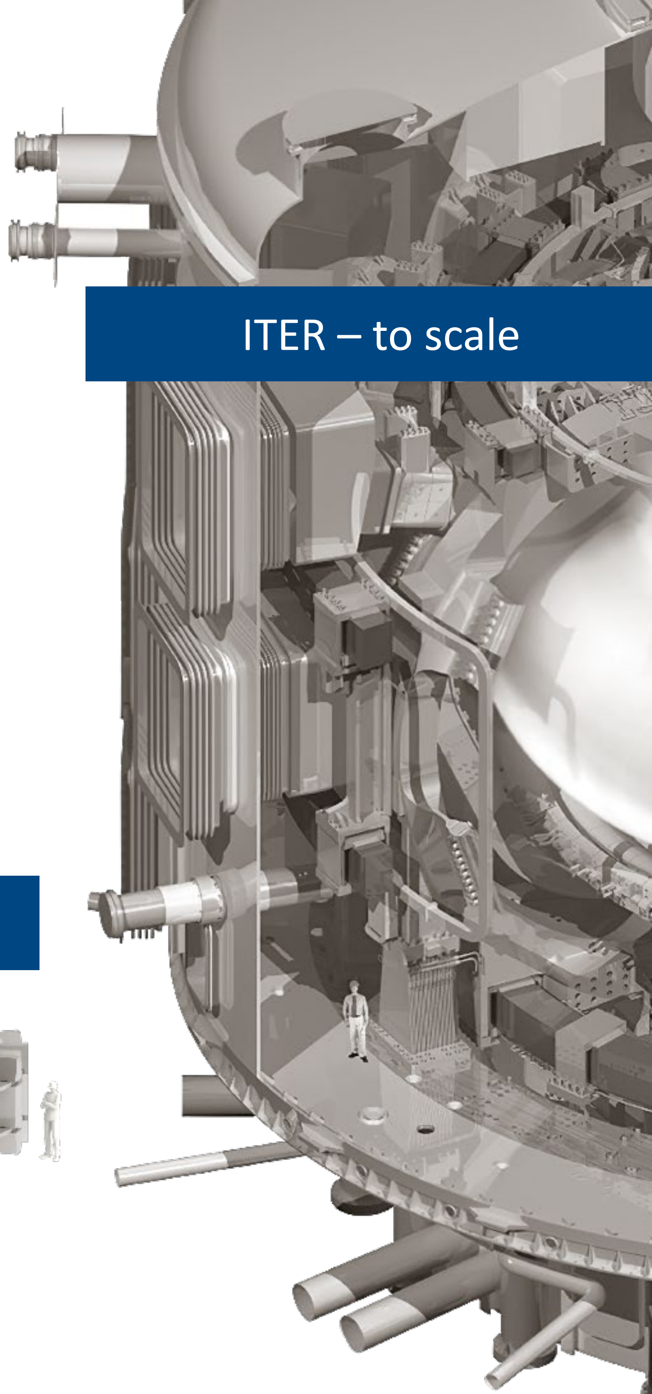



# High-field magnets open new pathway
# We have been executing this plan for 3 years.




C-Mod and SPARC





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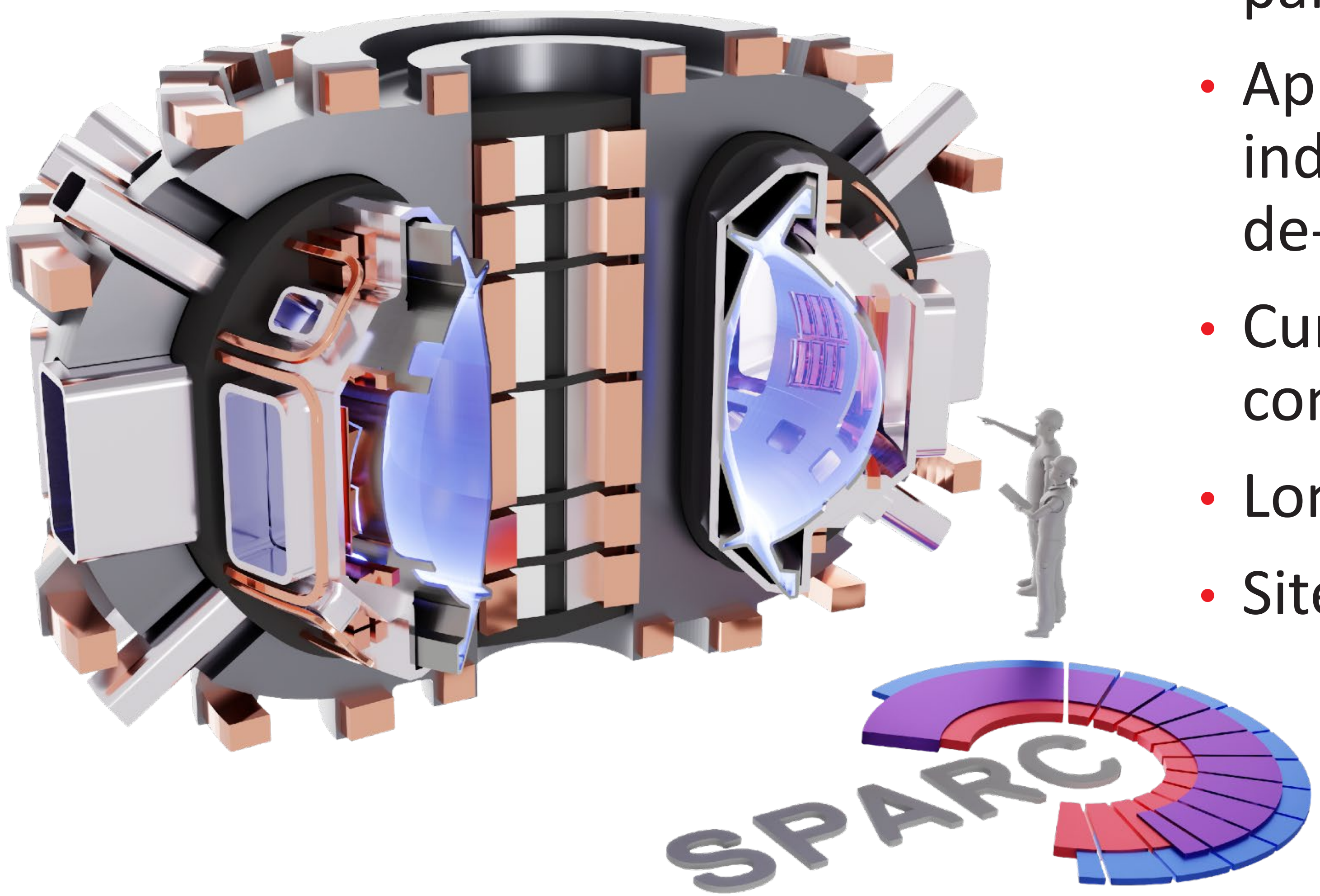
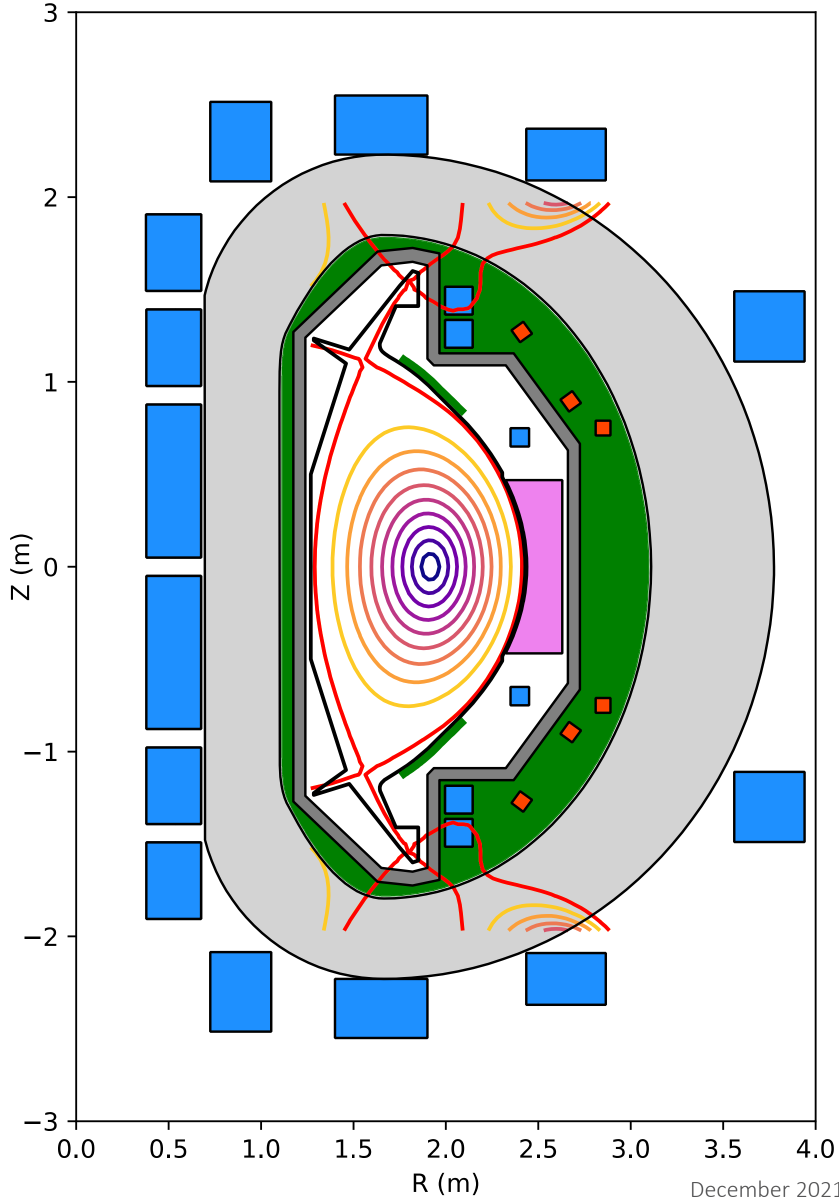
# SPARC was designed and construction started at risk for speed




- Magnet development run in parallel
- Applied agile practices from industries like space – systematic de-risking
- Currently at >30% design completion
- Long-lead procurement begun
- Site, licensing settled, build started

# SPARC design and operations are pushed by the need to inform ARC

- Get early DT results in L-mode
- H-mode confinement data at high field, including power threshold
- Burning plasma physics including alpha interactions
    - P. Rodriguez-Fernandez et al APS 2021.
- Disruptivity at ARC relevant parameters
    - R. Sweeney et al APS 2021
- Passive runaway electron mitigation
    - D. Garnier et al APS 2021.
- Gas fueling efficiency at high opacity
- Diagnostics and control for burning plasmas
- Heat removal via an X-point target divertor configuration (see right)

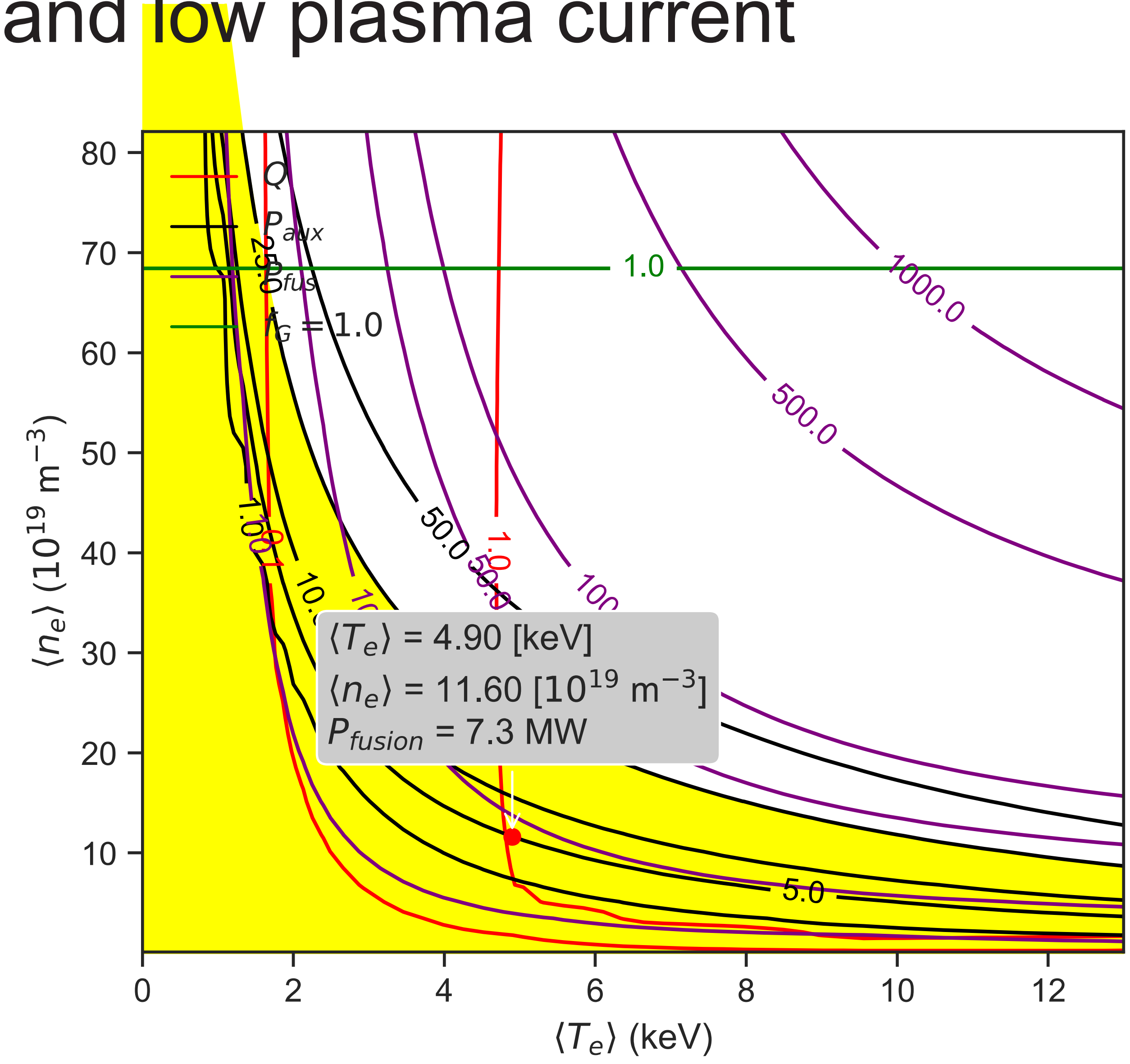


# Q > 1 is achievable on SPARC in L-mode at low power and low plasma current

- SPARC is designed to achieve Q=11 in standard H-mode, but it can also achieve Q>1 in a much simpler L-mode plasma
  - L-mode (no ELMs)
  - Lower elongation (easier vertical control)
  - Lower plasma current (less disruptive)
  - Low power (reduced neutron activation)
- Same assumptions as in [Creely JPP] including a 50-50 DT mix
- Q>1 plasmas can be achieved rapidly and without much neutron activation, such that in-vessel maintenance is possible

| SPARC Q>1 L-mode Plasma | | |
|---|---|---|
| $B_0$ | 12.2 | T |
| $I_p$ | 7.0 | MA |
| $q^*$ | 3.3 | |
| $\kappa_a$ | 1.6 | ($\kappa_{sep}$ = 1.8) |
| $\langle T_e \rangle$ | 4.9 | keV |
| $\langle n_e \rangle$ | 1.2 | $10^{20}m^{-3}$ |
| $f_g$ | 0.2 | |
| $H_{89}$ | 1.0 | |
| $P_{ohmic}$ | 2.2 | MW |
| $P_{rf,coupled,operating}$ | 4.9 | MW |
| $P_{fus}$ | 7.3 | MW |
| Q | 1.0 | |

# Q > 1 is achievable on SPARC in L-mode at low power and low plasma current

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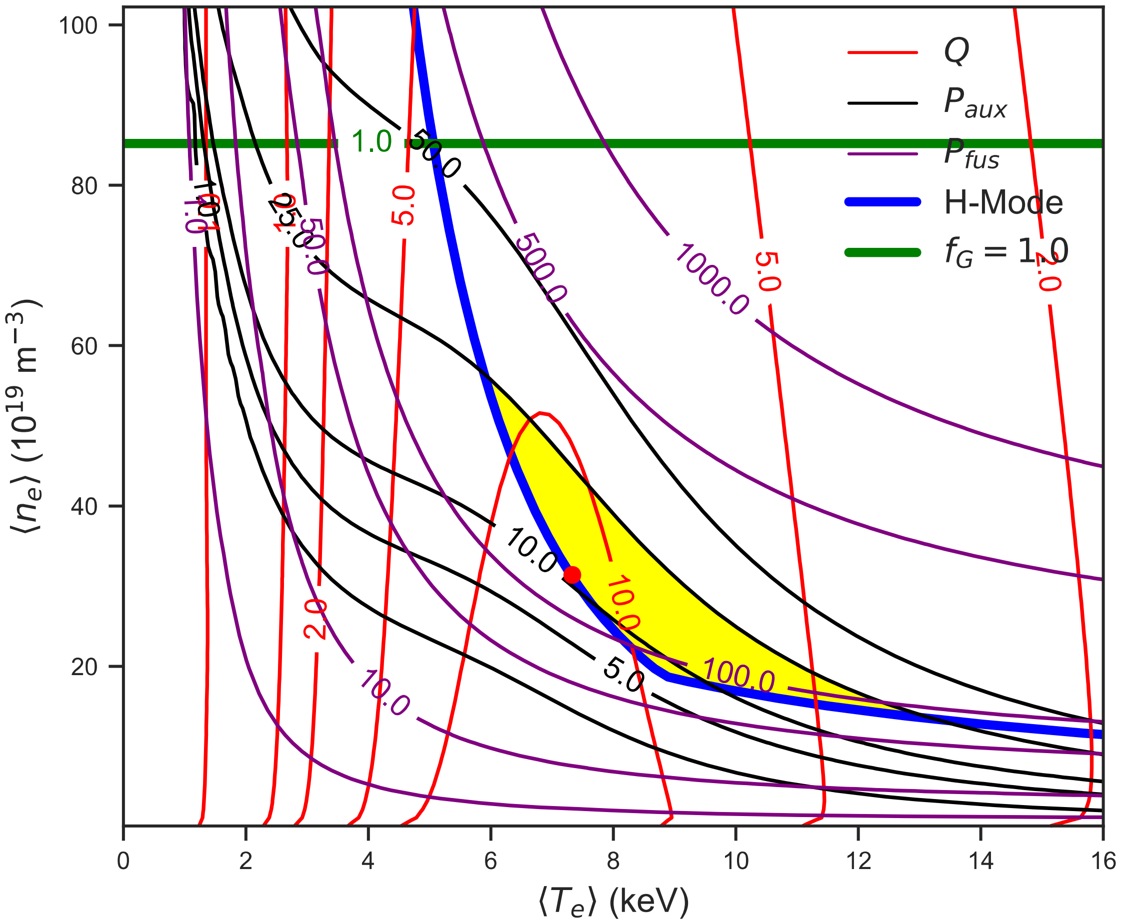
| Q | 1.0 | |

# SPARC H-mode window will explore a range of burning plasma regimes directly relevant to ARC

- In the second and third campaigns, SPARC will ramp to high performance relevant to ARC

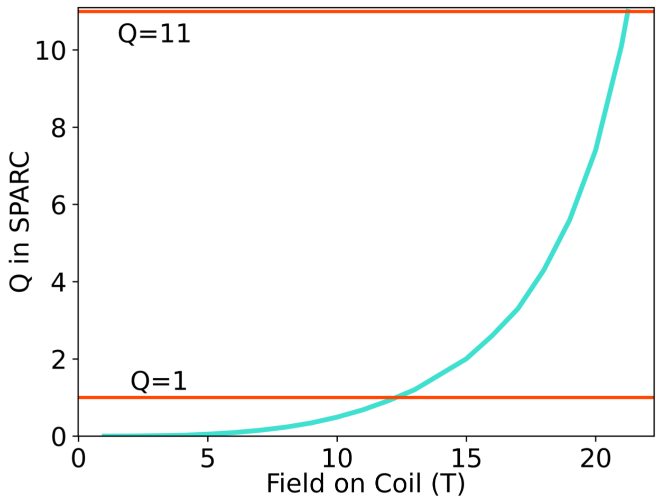



| $B_0$ | **12.2** | **T** |
|---|---|---|
| $I_p$ | 8.7 | MA |
| $q^*$ | 3.05 | ($q_{95}$ = 3.4) |
| $\kappa_a$ | 1.75 | ($\kappa_{sep}$ = 2.0) |
| <$T_e$> | 6 - 13 | keV |
| <$n_e$> | 1.4 – 5.5 | $10^{20}$m$^{-3}$ |
| $f_g$ | 0.17 – 0.65 | |
| $\beta_N$ | 0.8 – 1.5 | m·T/MA |
| $P_{sep}B_0/R_0n_{e,20}^2$ | 9 - 126 | MW·T·m$^5$ |
| $P_{fus}$ | 80 – 150 * | MW |
| Q | 3.4 - 11.0 | |

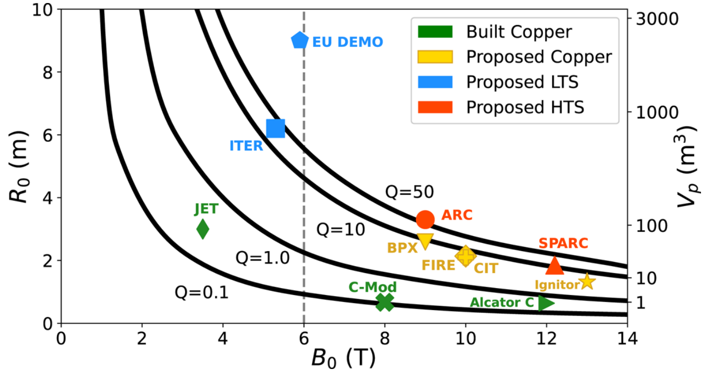
* Fusion power limited by magnet heating

# SPARC is an ITER equivalent burning plasma machine

- Design validated using the ITER tools
- Q=11 @ H=1; long-legged divertor
- JPP peer-reviewed physics papers




Same physics as ITER, FIRE, BPX, CIT….




2020's most downloaded plasma physics paper


commercial re-use or in order to create a derivative work.
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
[3]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[4]Chalmers University of Technology, Göteborg, Sweden
[5]University of California – San Diego, San Diego, CA, USA
[6]Fiat Lux, San Diego, CA, USA
[7]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[8]York Plasma Institute, University of York, Heslington, York, UK
[9]General Atomics, San Diego, CA, USA
[10]Aalto University, Espoo, Finland
[11]ORISE, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[12]Lawrence Livermore National Laboratory, Livermore, CA, USA

(Received 18 May 2020; revised 9 September 2020; accepted 10 September 2020)

The SPARC tokamak is a critical next step towards commercial fusion energy. SPARC is designed as a high-field ($B_0 = 12.2$ T), compact ($R_0 = 1.85$ m, $a = 0.57$ m), superconducting, D-T tokamak with the goal of producing fusion gain $Q > 2$ from a magnetically confined fusion plasma for the first time. Currently under design, SPARC will continue the high-field path of the Alcator series of tokamaks, utilizing new magnets based on rare earth barium copper oxide high-temperature superconductors to achieve high performance in a compact device. The goal of $Q > 2$ is achievable with conservative physics assumptions ($H_{98,y2} = 0.7$) and, with the nominal assumption of $H_{98,y2} = 1$, SPARC is projected to attain $Q \approx 11$ and $P_{fusion} \approx 140$ MW. SPARC will therefore constitute a unique platform for burning plasma physics research with high density ($\langle n_e \rangle \approx 3 \times 10^{20}$ m$^{-3}$), high temperature ($\langle T_e \rangle \approx 7$ keV) and high power density

† Email address for correspondence: alex@cfs.energy



**SPARC will give the burning plasma data the world needs – but in a commercially relevant platform and context**

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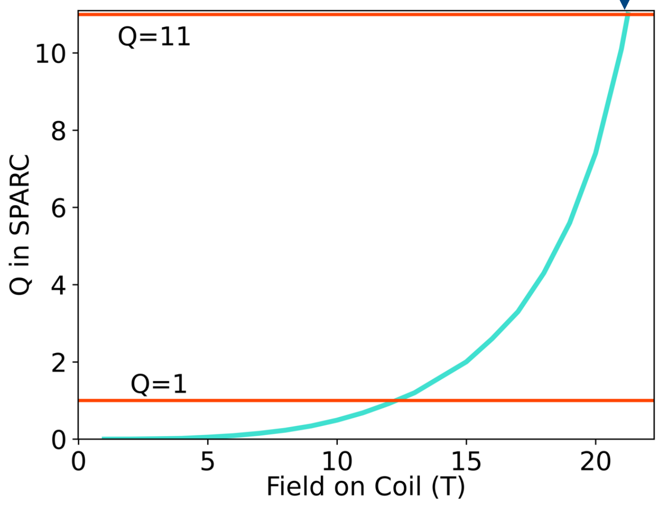
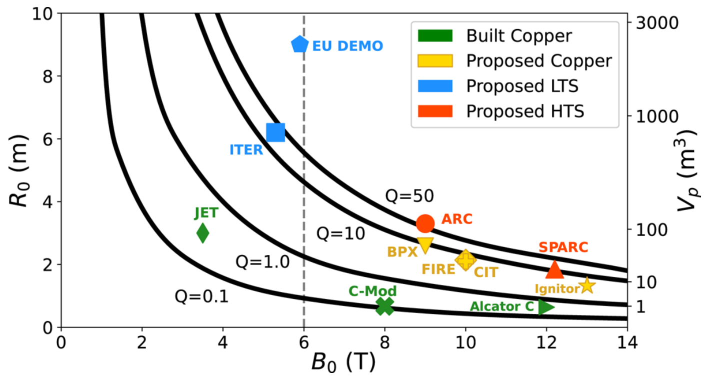
$B_{coil}$ > 20 T ?




"Reading these papers gives me the sense that **they're going to have the controlled thermonuclear fusion plasma** that we all dream about," said Cary Forest, a physicist at the University of Wisconsin — *The New York Times*

Same physics as ITER, FIRE, BPX, CIT….

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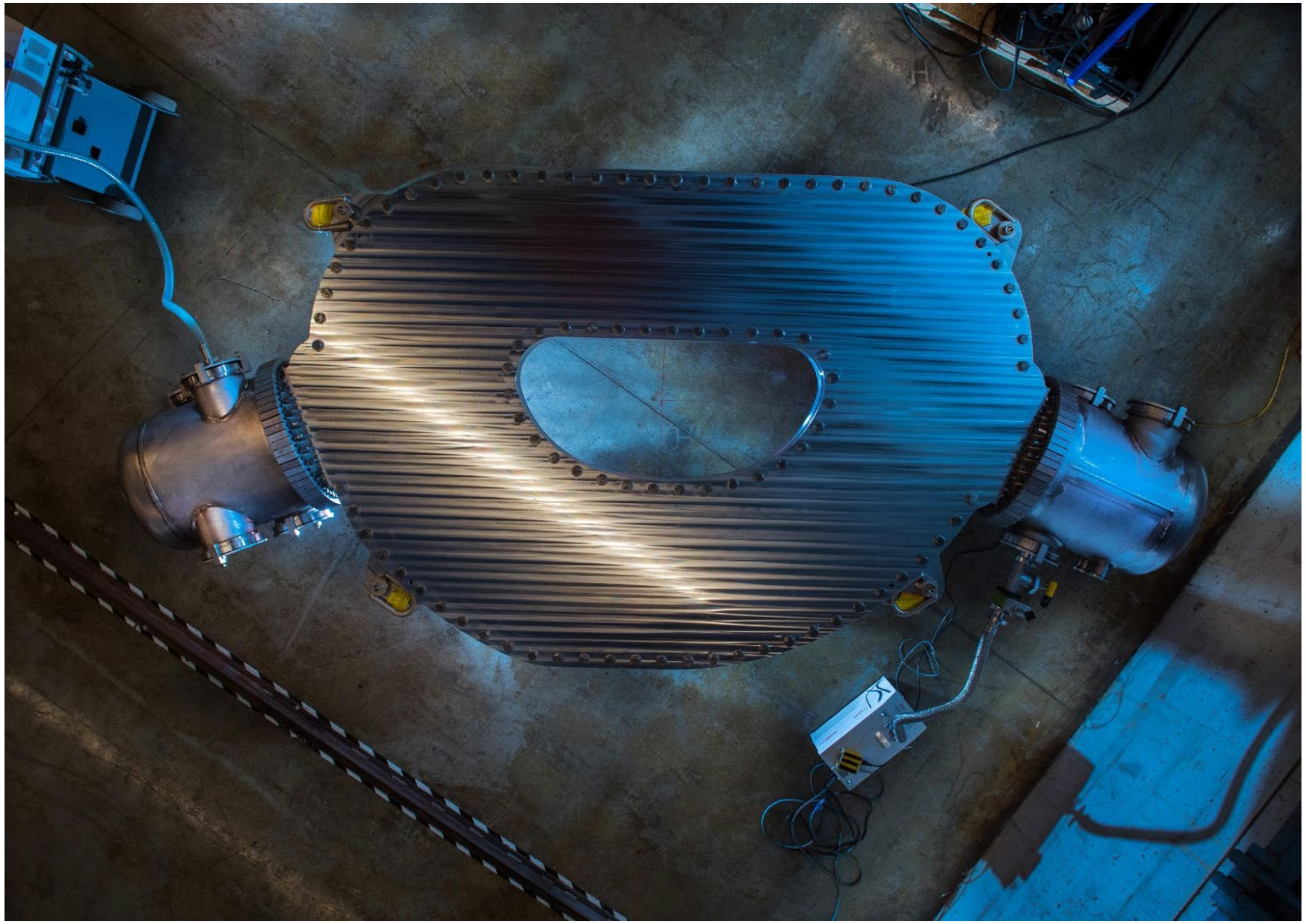
# Developing the HTS was part of an integrated strategy that itself informed our magnet development

- Must be based on robust science and engineering
- Must be eventually manufacturable at scale and economically
- Don't leave innovations on the table, yet know when knowledge was good enough → parallel developments
- Build-test-understand cycle as fast as possible

# We quickly constructed a large integrated coil test stand in the Alcator C-Mod power room

# We have built and tested the non-insulated high-field magnet



- Fully representative of SPARC coil operation
- 20T on coil, well beyond what LTS can do
- Largest HTS magnet in the world by a factor of 100x
    - Stored energy: 110 MJ
    - Mass: 9265 kg
    - HTS tape in coil: 267 km
    - Size: ~ 2 meters tall
- Modular: Each of 16 pancake is world's largest HTS magnet
- **Successfully tested: September 5, 2021**

# While developomg scalable magnet manufacturing

- Magnets produced with proprietary techniques
- Magnet is composed of 16 layers to aid in low cost manufacturing and modularity
- Process built for scale and speed

Assembly machines

Test stand

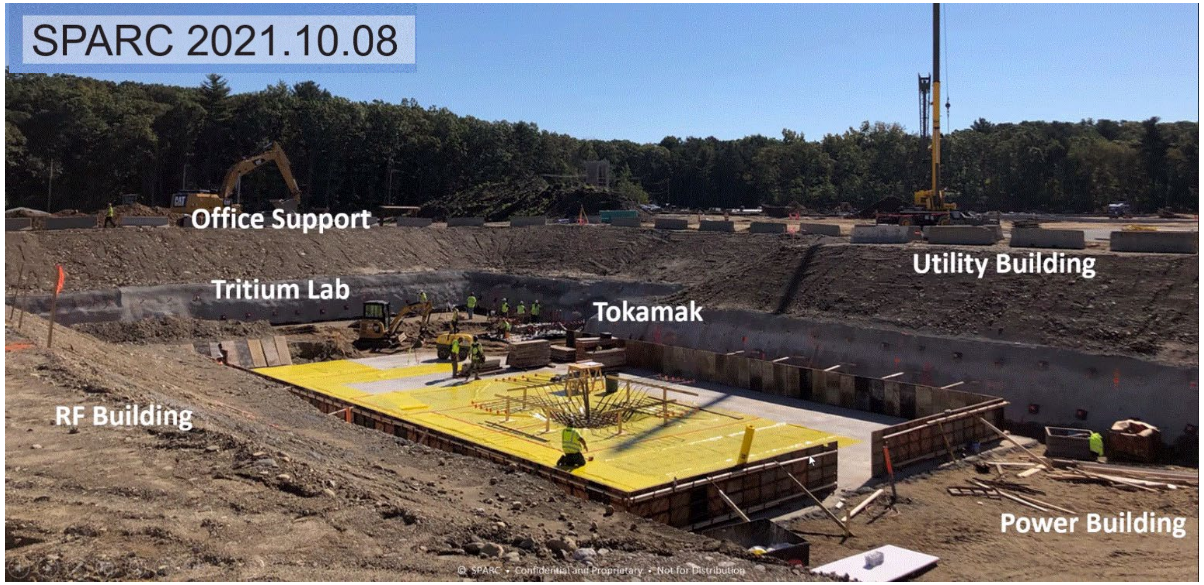

Manufacturing line

Curing oven

# SPARC construction underway

Commonwealth Fusion Systems

- Host magnet manufacturing for both SPARC and ARC
- Will be an entire CFS campus eventually housing >1000 people + MIT scientists and students + collaborators
- NRC concurs this will be dealt with by state of MA, an agreement state
  - State agreed to license similar to a cancer treatment center

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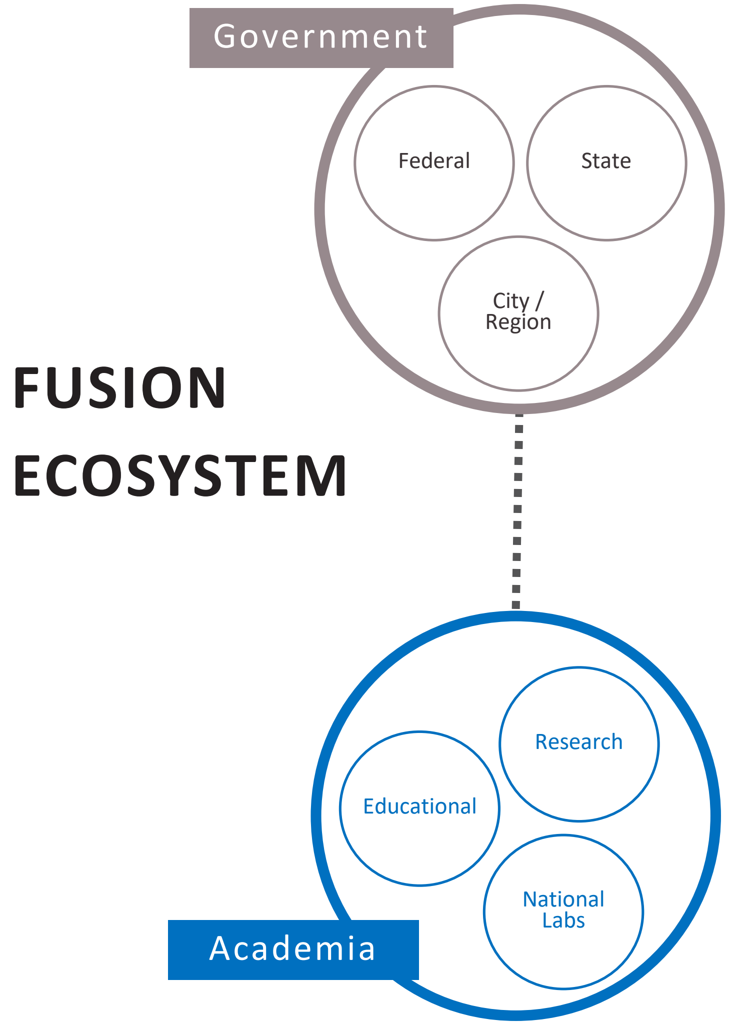
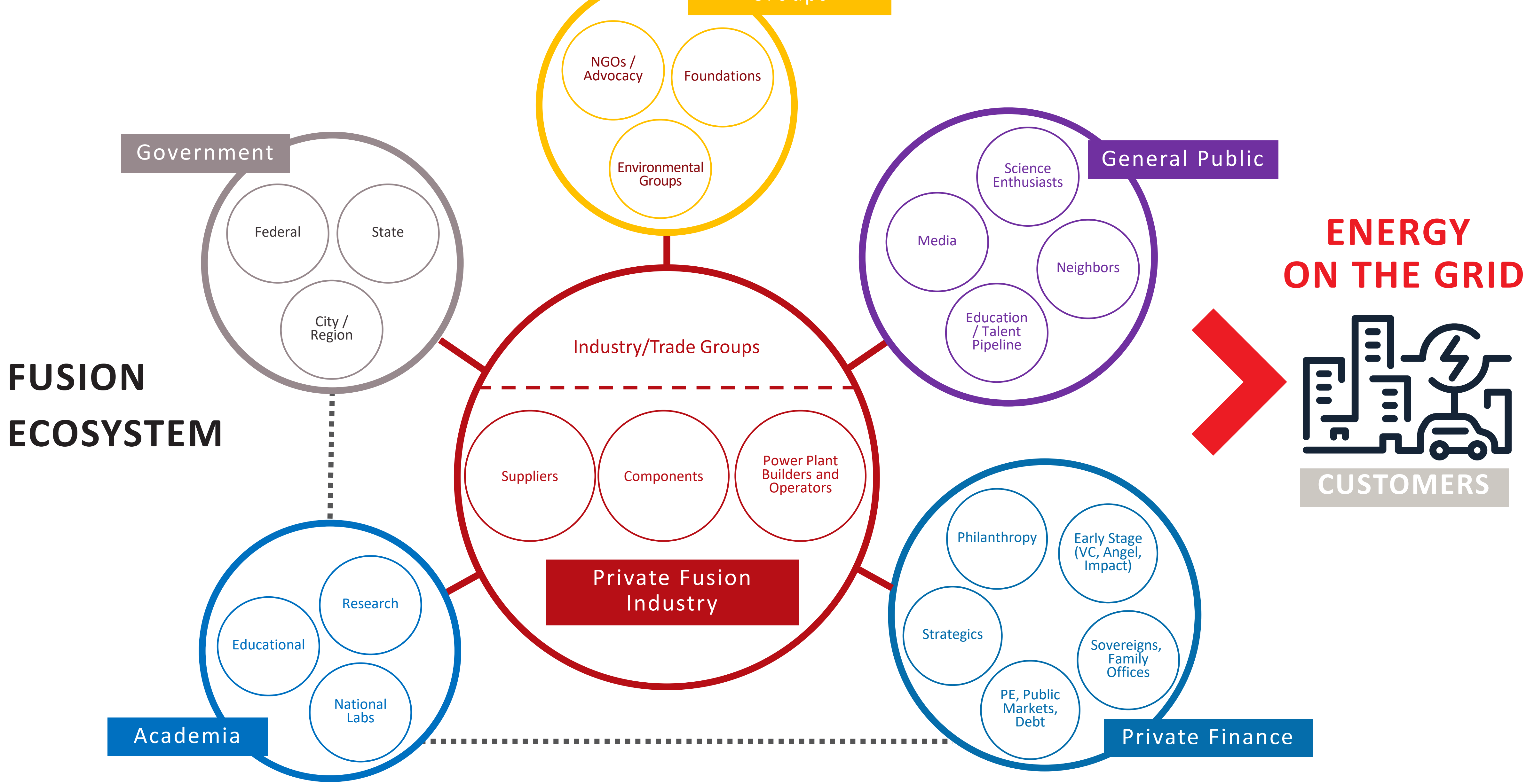
# The fusion ecosystem a few years ago




- Just as the context of bringing commercial fusion energy changed our technology and science strategy, it also had to affect our organizational strategy
- While there were external forcing functions, in the end we committed as a team to a new way to accomplish our collective goals.

# … must change

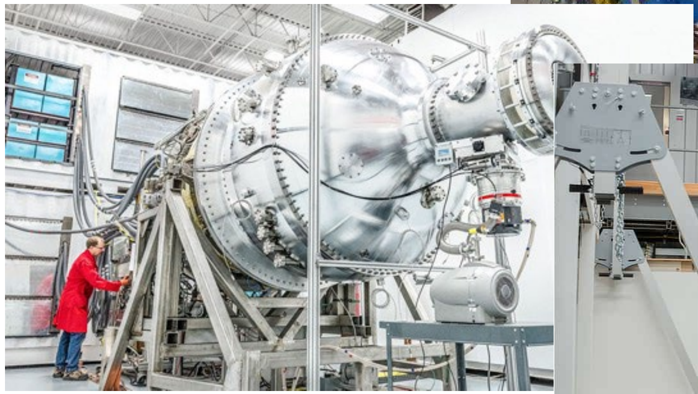

FUSION ECOSYSTEM
Special Interest Groups
NGOs / Advocacy
Foundations
Environmental Groups
Government
Federal
State
City / Region
General Public
Science Enthusiasts
Media
Neighbors
Education / Talent Pipeline
Industry/Trade Groups
Suppliers
Components
Power Plant Builders and Operators
Private Fusion Industry
Academia
Research
Educational
National Labs
Private Finance
Philanthropy
Early Stage (VC, Angel, Impact)
Strategics
Sovereigns, Family Offices
PE, Public Markets, Debt
ENERGY ON THE GRID
CUSTOMERS

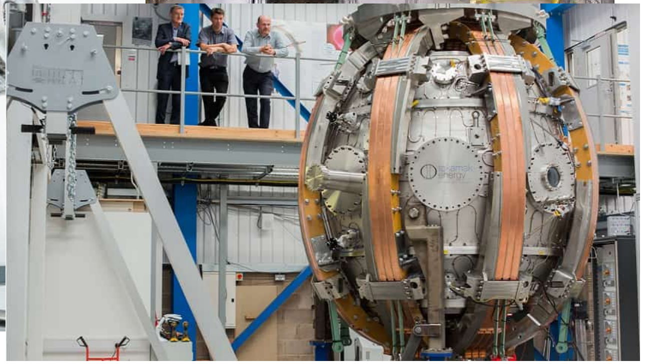
# MIT-CFS partnership

- Leverages existing MIT infrastructure — people, expertise, space
- Leverages CFS expertise in supply chain, finance, manufacturing,
- Currently have over 275 people working on this project (CFS+MIT)
- The best from both academia and industry working together
- Flexible invention and licensing agreement, expedited tech-transfer

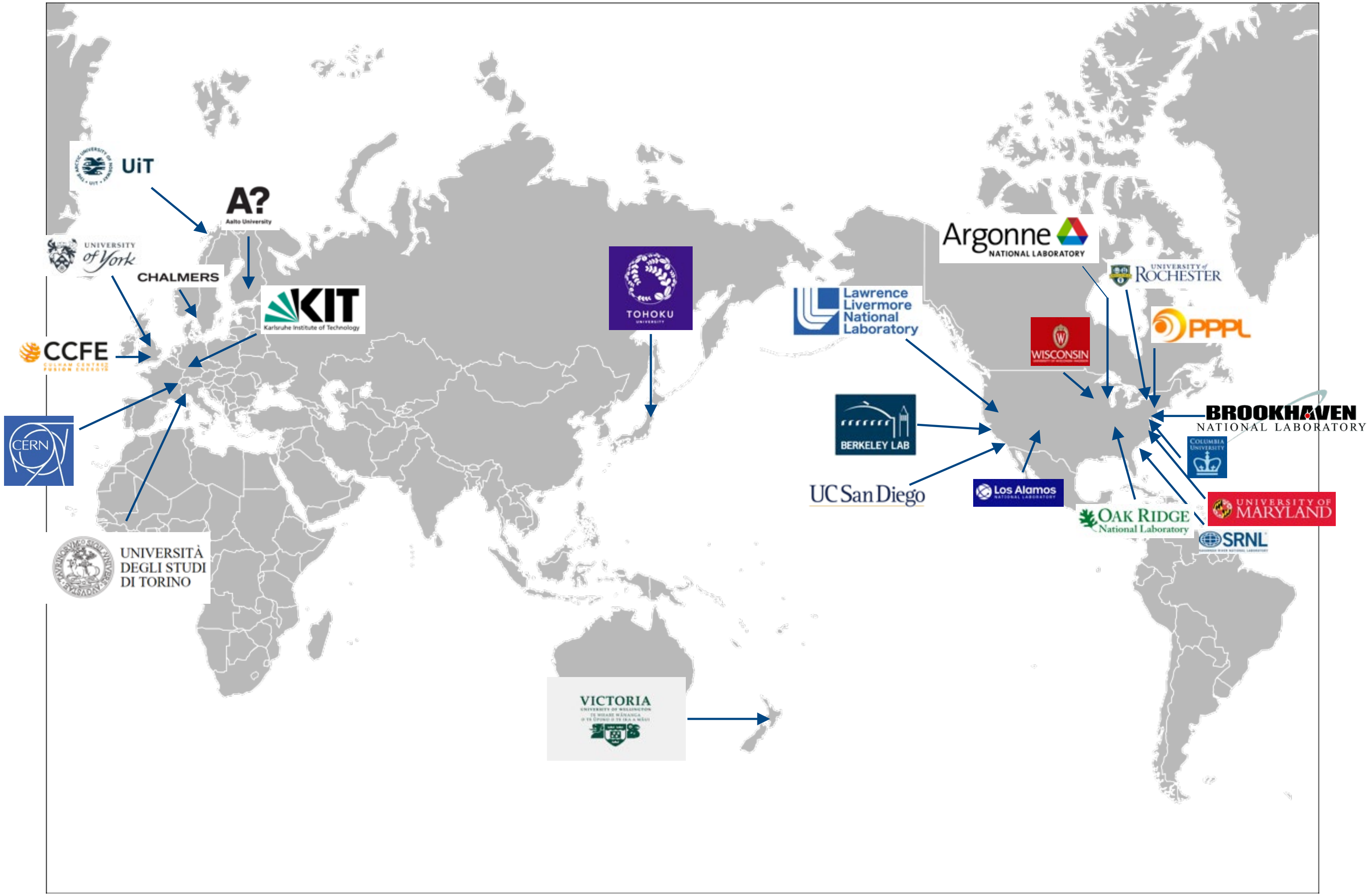
# Part of a growing fusion industry

- Deliver products that reflect the fusion value proposition
- They can be extremely capable organizations
  - Tight focus on deliverables and milestones
  - With less $ (now) and different resources than gov’t
  - High-growth potential
- Academic researchers couple to such companies in all applied disciplines





# Private fusion is an organizational forcing function




- CFS/MIT/SPARC has >50 collaborations, >40 institutions, >10 countries
- Includes National Labs, universities, governmental orgs, private companies
- 10 INFUSE awards, premier FES PPP program, most of any company
- ARPA-E awards as prime, sub-recipient, industrial partner

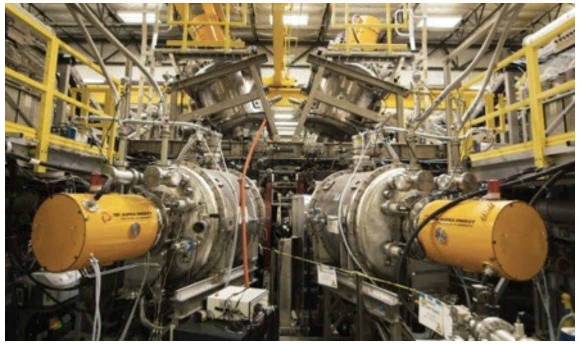
# Private fusion add speed…and resources w/ success!

tae TECHNOLOGIES

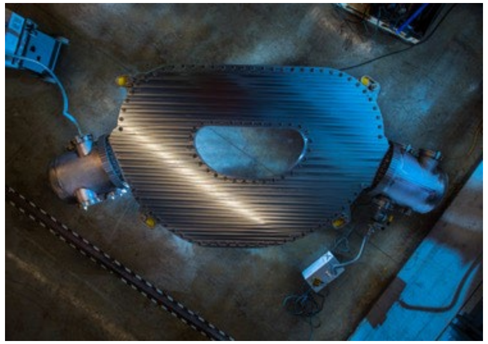
CFS

generalfusion

tokamak energy

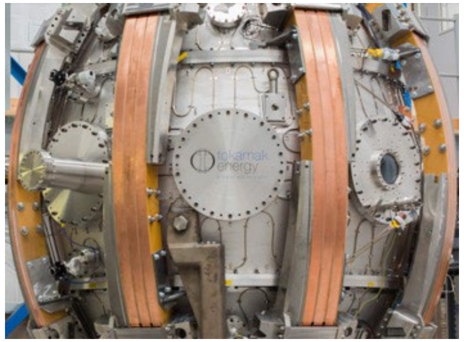


Norman



TFMC

Plasma Injector



ST-40

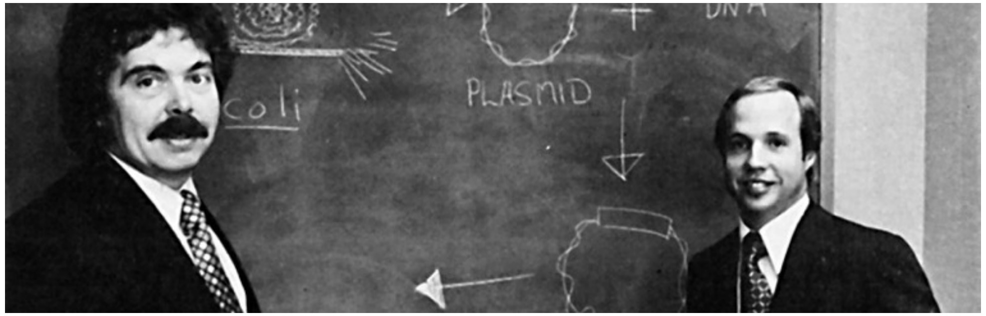
*Proven capability to deliver big hardware quickly*

# How do we work together?

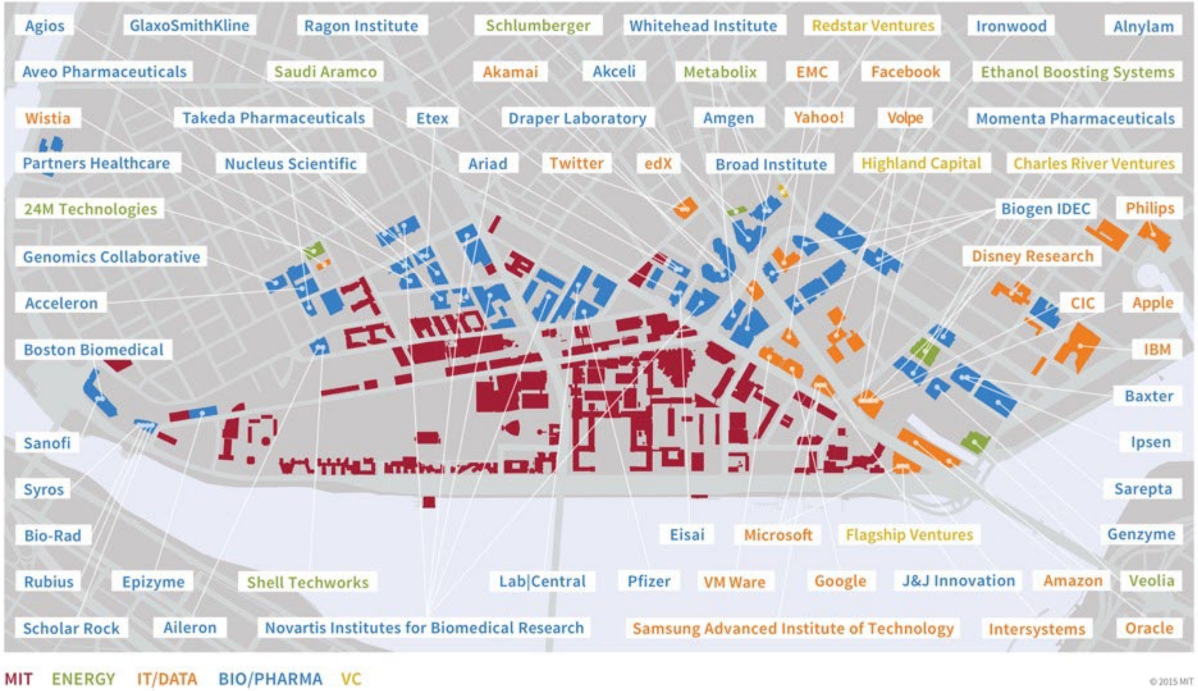
*We each do what we're good at*

| Public Programs, Academia | Private Industry |
| --- | --- |
| Basic science | Industrial engineering |
| Test stands and user facilities | Scaling |
| Training and education | Interfacing with customers and suppliers |
| Simulation and validation | Robust supply chain |
| Cross-cutting research | At-risk development |
| Community toolsets | Commercial regulation |
| Foundations through peer-review | Systems integration |

# This has all happened before






- ~1000 biotechs in Boston area
- Dominant technology in MIT cluster
- Natural evolution of industry: pie gets bigger

# This has all happened before

The New York Times July 8, 2011

*Atlantis Lifts Off for Last Space Shuttle Mission*

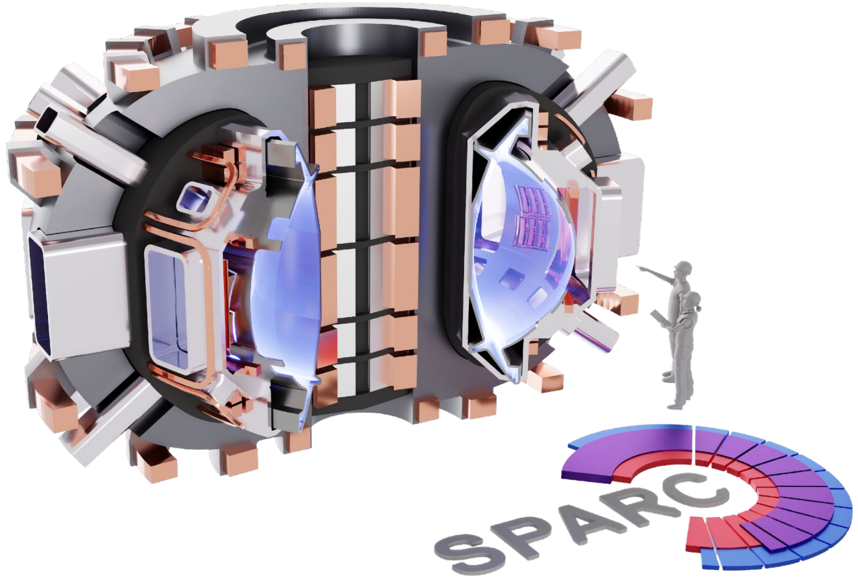
- NASA built low-Earth orbit industry at fractional cost
- Used PPPs w/ milestone-based cost share, risk sharing
- NASA: “We would encourage …other Government agencies to consider adopting similar approaches where possible.”
- *Fusion version of COTS has been passed into law*

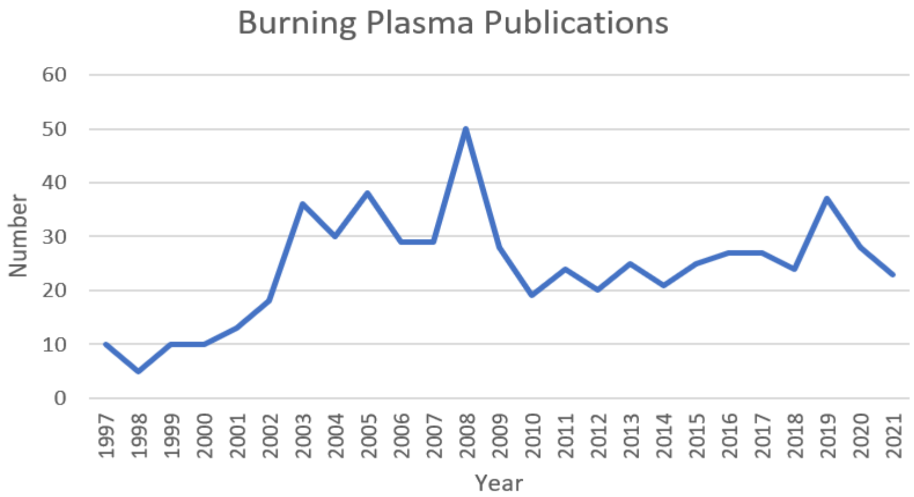
# Outline

- The high field burning plasma plan & the energy transition
- SPARC and its mission
- The public-private ecosystem
- ARC as a Fusion Pilot Plant platform

# SPARC is domestic burning plasma experiment using known science, but its context is new

- Designed and built using a new PPP
- The pursuit of BP/net-energy science is a necessary but insufficient part of delivering fusion energy.
- SPARC evolved alongside the ARC pilot plant design to assure that they were both leveraged to accelerate the timeline
  - Parallel development
  - Technology development risk preferred to integrated plasma risk
  - With an unsentimental view of using the technology to deliver fusion energy



# ARC – a platform for fusion energy development

- Only a few  set boundary conditions
  - REBCO-based high B magnets → ~JET size
  - Liquid immersion blanket → neutron physics
  - Modular design → replaceable thin VV/first wall

- Set by market: economics ($/W) and need to have a flexible platform that can provide integrated answers to plant availability

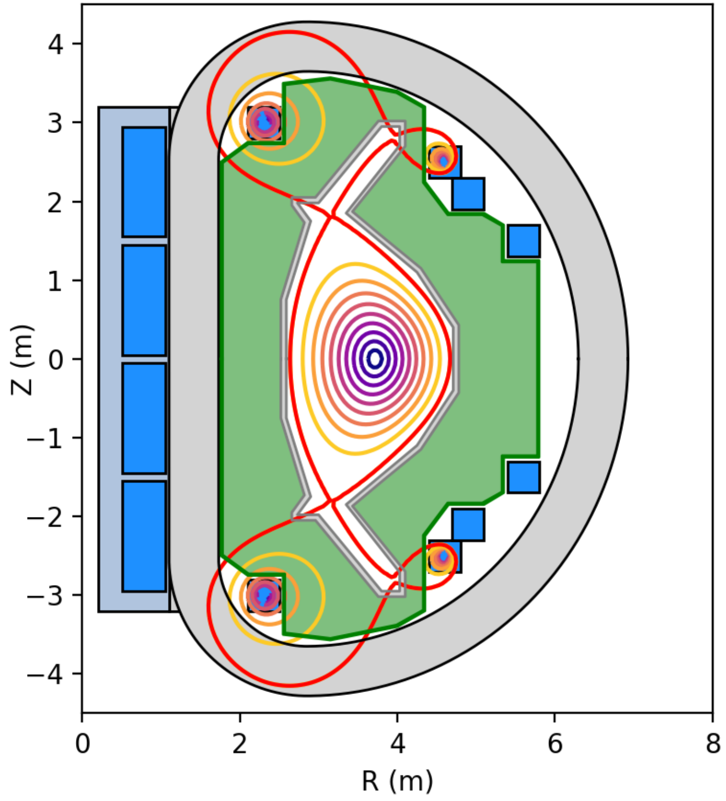
- Highly flexible core plasma scenarios because high B allows for ops in huge parameter space…these are tools, not the reason to build ARC!
  - Standard H-mode, inductive
  - Non-inductive, higher H, high recirculating powe
  - Radiative L-mode, higher $I_p$ (negative triangularity?)

# The current ARC design point → Market informed

- ARC is a **class** of machines driven by **market needs**
- Characteristics:
  - Nearly ignited
  - Pulsed with 30min on/1min off
  - Very similar to SPARC
  - Very far from plasma limits
  - $P_{elect}$ ~200MWe
- Reference design is not overly sensitive to assumptions

| Parameter | ARC V1 |
|---|---|
| $B_0$ (T) | 11.5 |
| $R_0$ (m) | 3.45 |
| a (m) | 0.93 |
| $\epsilon$ | 0.27 |
| $V_p$ ($m^3$) | 91 |
| $\kappa_a$ | 1.60 |
| $\kappa_{sep}$ | 1.80 |
| $\delta_{sep}$ | 0.50 |
| $I_p$ (MA) | 9.9 |
| $q^*$ | 3.05 |
| $H_{98,y2}$ | 1.15 |
| Q | 107 |
| $P_{fus}$ (MW) | 521 |
| $P_{rf,coup}$ (MW) | 4 |

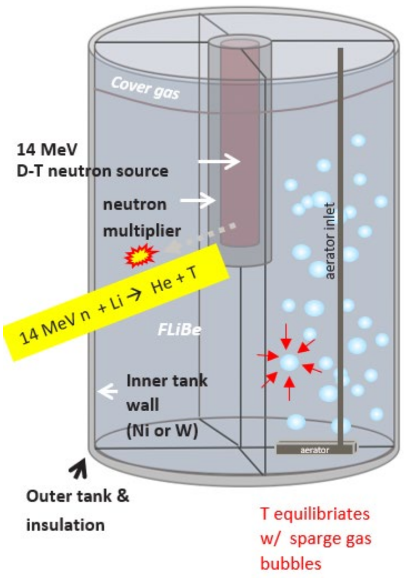
| Parameter | ARC V1 |
|---|---|
| $Z_{eff}$ | 1.5 |
| $P_{rad}$ (MW) | 24 |
| $<T_e>$ (keV) | 11.8 |
| $<n_e>$ ($10^{20}$) | 1.7 |
| $f_g$ | 0.49 |
| $\beta_N$ | 1.4 |
| $f_{bs}$ | 0.10 |
| PB/R (MW T/m) | 284 |
| Pulse Len. | ~30 min |
| $\Phi_{total}$ (V-s) | 125 |

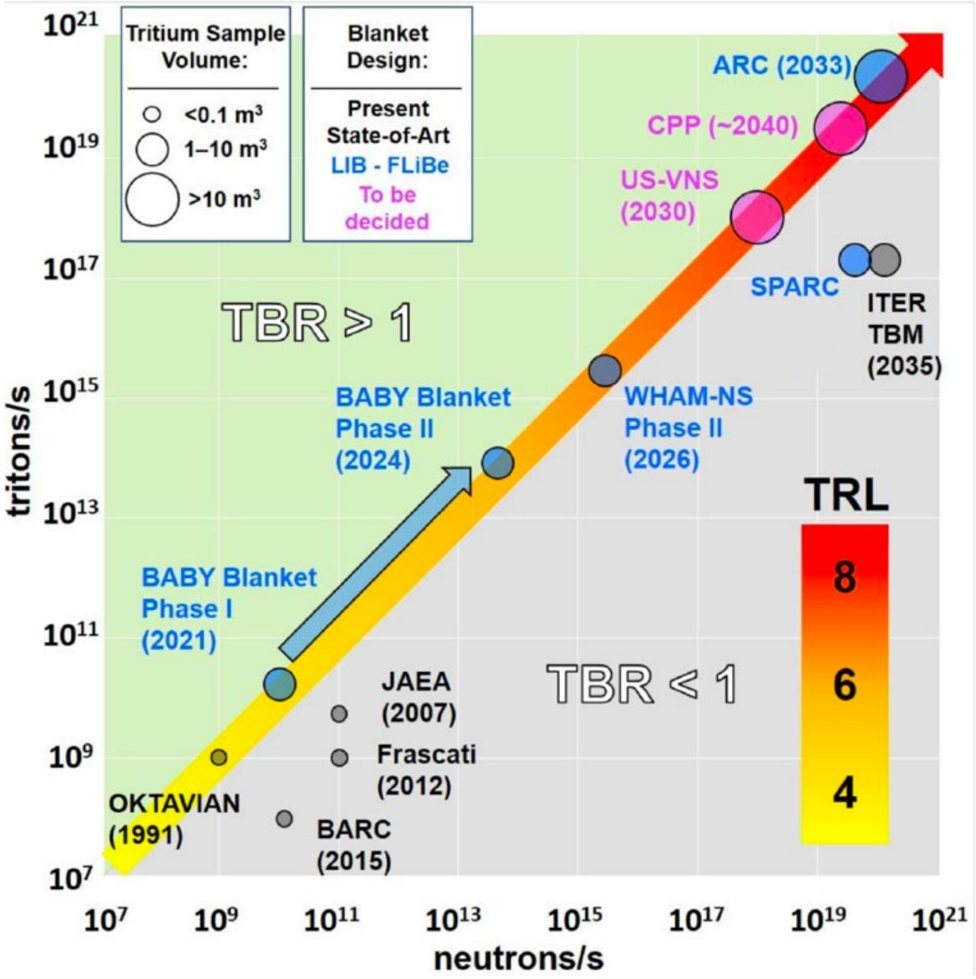


# Leveraging technology innovations: liquid immersion blanket TRL can be greatly advanced without a tokamak!

- Proposed "mini" LIB blanket at MIT
- Significant milestones:
  - TBR>1 at increasing amounts of breeding
  - Tritium extraction at rep. rate
  - Corrosion control
  - FLIBE material handling and sourcing
- Collaboration opportunities outside usual fusion community expertise
  - FLiBe impurity control, purification
  - Active corrosion monitoring and control
  - MHD heat transfer coefficients of FLiBe under fields
  - Heat exchange materials, performance
  - Tritium accountancy

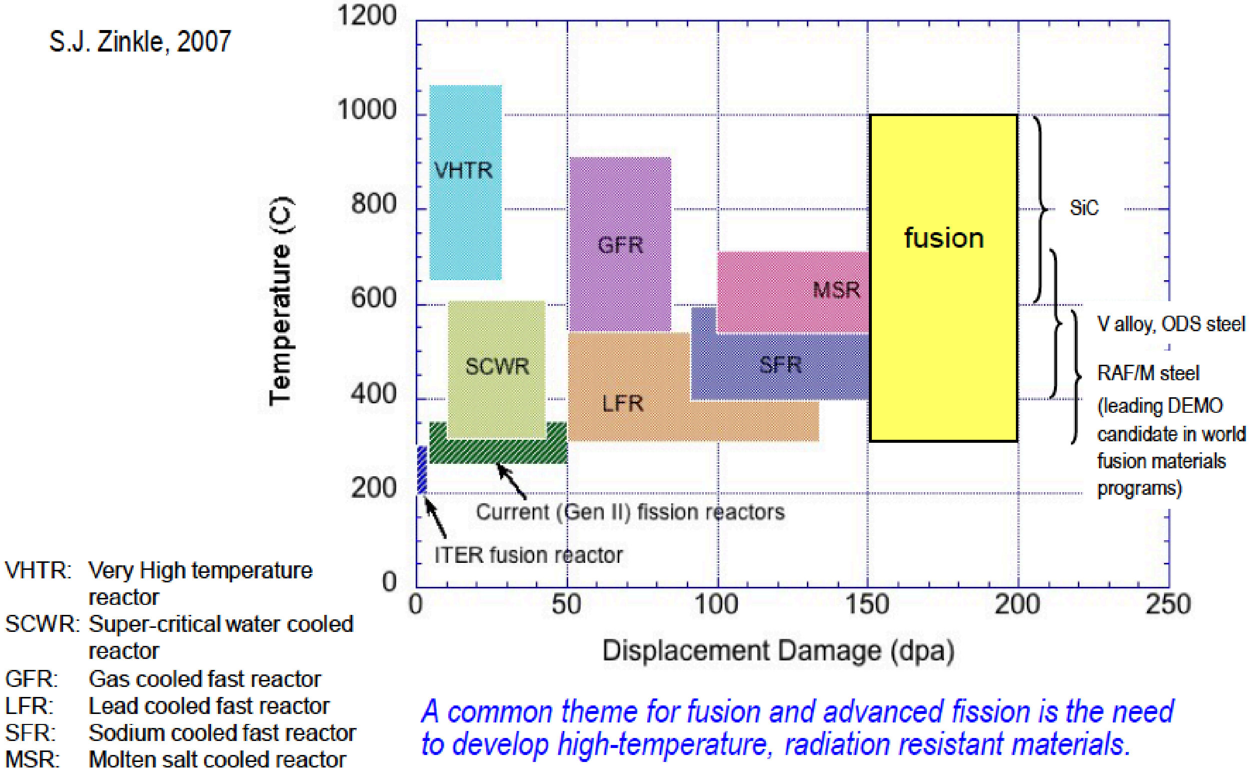
The MIT LIBRA experiment



# Materials strategy → Use something that works today to start

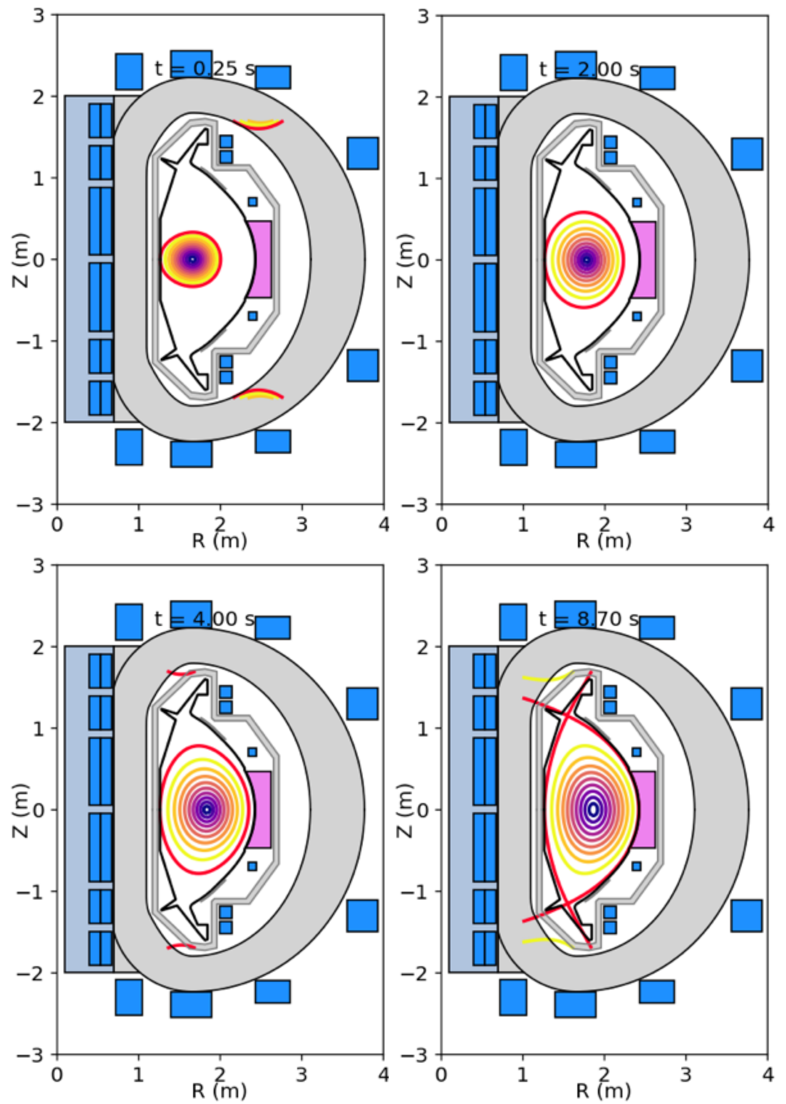
- ARC will have replaceable VV: materials don't need to last forever
- We will require only ~50 DPA lifetimes and 500 ppm of helium to start.
- Small volume ~few $m^3$
- RAFM and D9 steels could build an ARC vacuum vessel today.
  - Advanced materials to improve economics e.g. higher $T_{op}$
- Materials roadmap instead of silver bullet: bootstrap, learn as we go




*A common theme for fusion and advanced fission is the need to develop high-temperature, radiation resistant materials.*

# Physics → Use SPARC to close key gaps

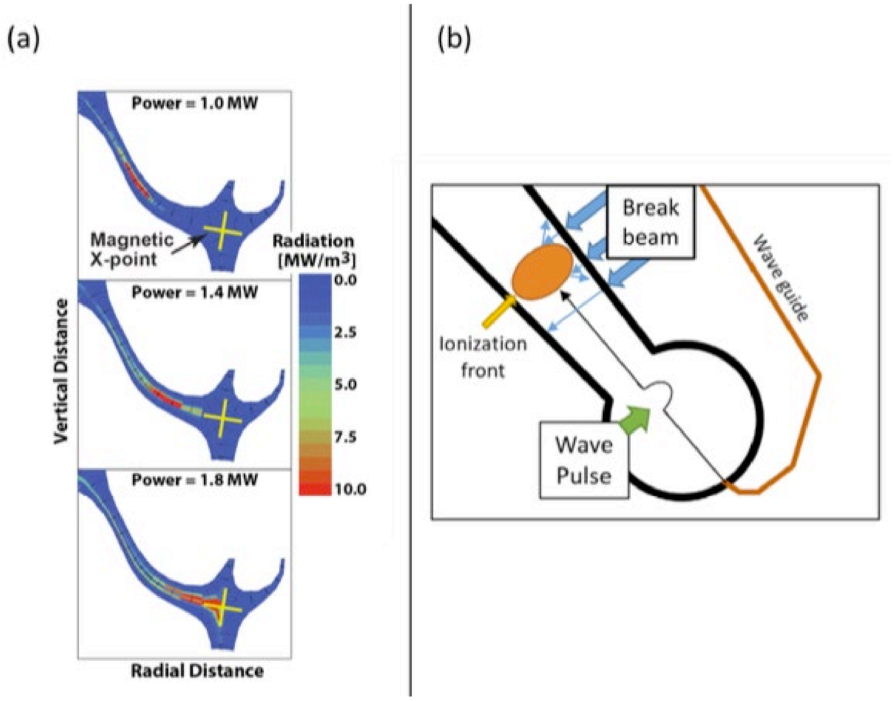
- SPARC physics basis published, refereed, conservative: discharge is ~non-dimensional match to JET.
- H-mode reference discharge has a wide operational window in temperature and density
- Operational point is far from density and pressure limits with reasonable safety factor
- ARC will have substantially similar physics
- Collaboration opportunities:
  - Modern tokamak scenario design tool
  - Divertor physics simulation
  - Disruptions and transients



SPARC Scenario from TSC

# Diagnostics -> Start with full set, then reduce

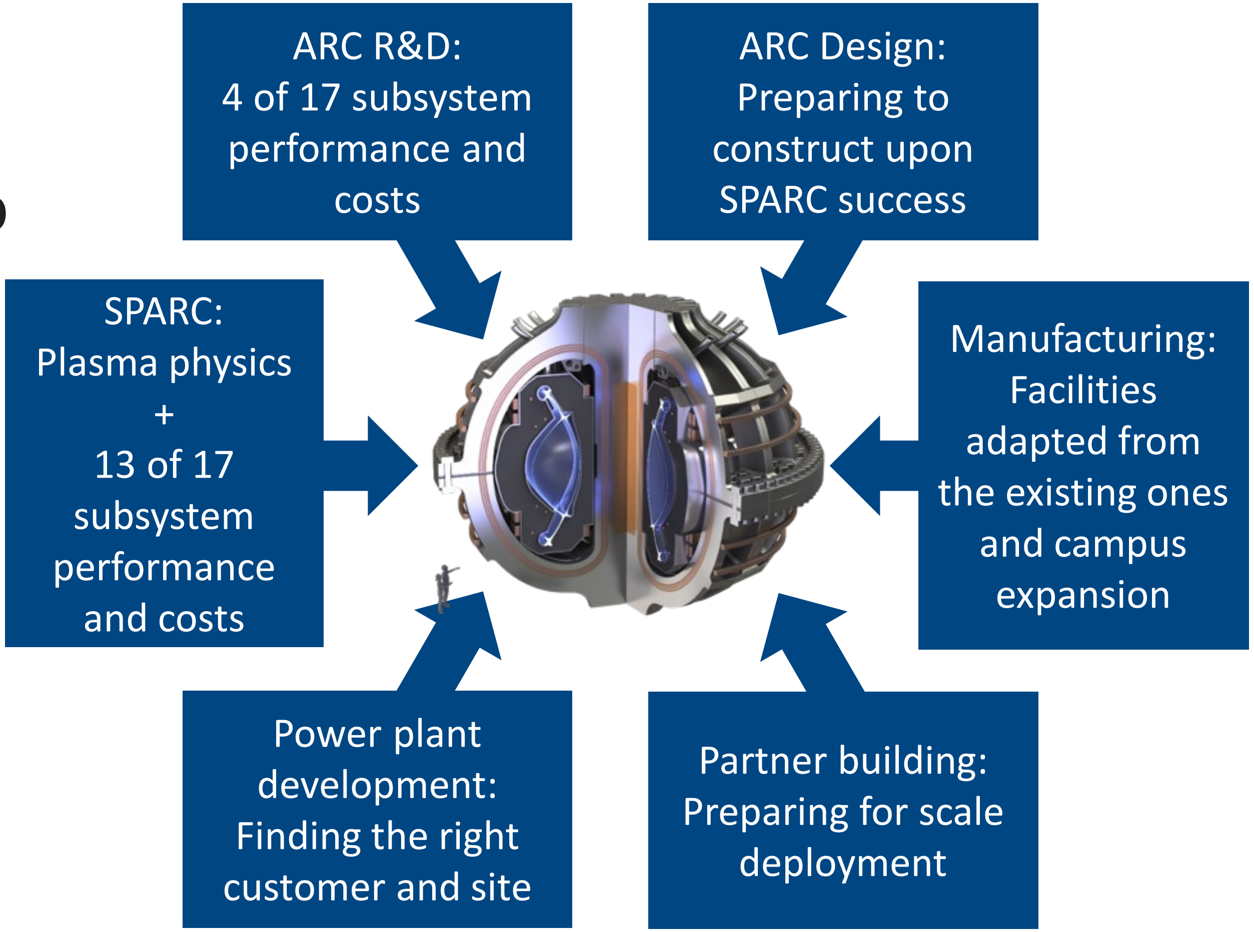
- Present-day tokamaks are generally very well diagnosed and have many observations with which to control the plasma.
- A power plant, on the other hand, will be constrained in diagnostic coverage, as many present-day diagnostics would not survive
- While SPARC will have the capability to install many diagnostics, it shall have the capability to prepare for ARC operation
- Collaboration opportunities:
  - Diagnostics survivability
  - Control systems modeling
  - Feedthrough designs




Some early scoping work already done for ARC [Kuang 2018]

# 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
- Manufacturing using our facilities




**Set up to move to ARC construction immediately after SPARC demonstrated**

# Burning plasma science is a key part of the path to fusion energy having an impact on decarbonization

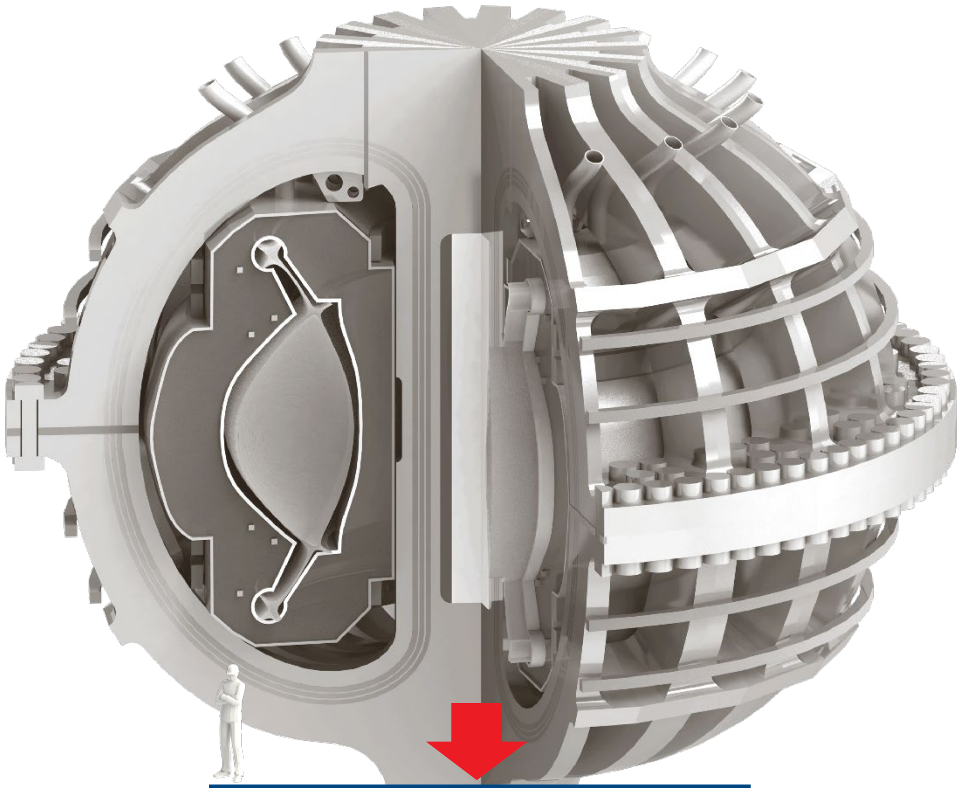
**COMPLETED:**
Alcator C-Mod

**COMPLETED**
TFMC demonstrated
September 5, 2021

**CONSTRUCTION PLANNING UNDERWAY for 2025 LAUNCH**
SPARC achieves net energy

**Net energy**

**Early 2030s**
ARC fusion power on the grid



**Carbon-free scalable commercial power**

# Thank you

www.psfc.mit.edu

www.cfs.energy