The path to commercial fusion energy
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
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
New magnet test facility at MIT
World's strongest HTS magnet demonstrated

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.”

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," Murguia said. "We really pushed hard on the magnet side so that we could get some relief on these other types of issues."

Magnet milestones move dream of nuclear fusion closer

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 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

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<tr>
<th>Parameter</th>
<th>ARC</th>
<th>ITER</th>
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<td>$Q$</td>
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<td>$P_{\text{electric}}$ [MW]</td>
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</table>

ARC – fusion power plant using known physics + new magnets

ITER – to scale
Opening a new development pathway

Uneconomic

Power plant

Start-up scale

ITER – to scale

C-Mod and SPARC
Risk retirement in concrete steps

**COMPLETED:**
- Alcator C-Mod
- Record-setting tokamak

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

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

**EARLY 2030s:**
- ARC deployed
  ~400 MW

- Early revenue from magnet platform
- Commercially-relevant net fusion energy for the first time
- 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
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


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


Divertor heat flux challenge and mitigation in SPARC


Predictions of core plasma performance for the SPARC tokamak


Physics basis for the ICRF system of the SPARC tokamak

Y. Lin, J. C. Wright and S. J. Wukitch

MHD stability and disruptions in the SPARC tokamak


Fast-ion physics in SPARC

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
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

Performance is based on extensive tokamak database

References:
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 $Q_{\text{physics}}$ that’s remarkably close to empirical prediction: ~8 and ~11, respectively


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

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
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
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

Government plans

- **JET (UK)**: Largest operating tokamak
- **ITER (World)**: Net-energy experiment
- **DEMO (World)**: First power plant

**CFS plan**

- **2015**: C-MOD (MIT) Plasma physics
- **2020**: SPARC (CFS)
- **2025**: ARC (CFS) First power plant
- **2030**: ~ to scale

Government plans timeline:

- **2015**: C-MOD (MIT) Plasma physics
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**CFS plan**

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