SPARC and the high-field strategy to fusion energy

Dennis Whyte, Zach Hartwig for the SPARC team

Commonwealth Fusion Systems
MIT Plasma Science and Fusion Center
What we found out in the clean energy world

We have worked extensively with utilities, investors, energy companies, manufacturers around fusion. They are excited to participate in a commercialization effort.

What needs to be done:
• Show net-energy high power production ASAP
• In a package that scales to an economical and market-relevant power plant
• In a relevant timeframe
• With concrete risk retirement milestones
Compact high-performance tokamaks: Demonstrated high absolute performance in small package

- C-Mod finished a successful 23 year career
- Extended physics basis for tokamak operation at high-field
The road not taken: Compact, High-field, Copper

<table>
<thead>
<tr>
<th>Device</th>
<th>B</th>
<th>R</th>
<th>a</th>
<th>Ip</th>
<th>Q</th>
<th>Pfus</th>
<th>Pulse</th>
<th>Pext</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignitor</td>
<td>13T</td>
<td>1.3 m</td>
<td>0.4 m</td>
<td>11 MA</td>
<td>??</td>
<td>530MW</td>
<td>5 s</td>
<td></td>
</tr>
<tr>
<td>CIT</td>
<td>10.4T</td>
<td>1.2 m</td>
<td>0.46 m</td>
<td>10 MA</td>
<td>5</td>
<td>530MW</td>
<td>3.8 s</td>
<td></td>
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<tr>
<td>BPX</td>
<td>9T</td>
<td>2.6 m</td>
<td>0.8 m</td>
<td>11.8 MA</td>
<td>5-25</td>
<td>100-500MW</td>
<td>10 s</td>
<td>20MW</td>
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<tr>
<td>FIRE</td>
<td>10T</td>
<td>2.14 m</td>
<td>0.595 m</td>
<td>7.7 MA</td>
<td>10</td>
<td>100-200MW</td>
<td>20 s</td>
<td>20MW</td>
</tr>
</tbody>
</table>

These high-field tokamaks were the main thrust of the U.S. Next Step Options
Had they been built: They would have burned

- Concepts validated by extensive review by FESAC, NAS, workshops.
- ITER was chosen and the U.S. program was down-selected.
- There were compelling reasons to go with ITER over FIRE and vice-versa.
- These copper machines would never scale to a power plant due to the magnet power consumption.
What has changed: High-field superconducting with HTS

- High-temperature superconductors (HTS) are transformative [FESAC TEC report 2018]
  - Enable much higher magnetic fields
  - Higher current densities
- Only recently commercialized on a relevant scale
- Opens new options for power plants
- Commercially interesting on their own

This is ambitious. A high-field large-bore HTS coil has not been demonstrated. Yet.
ARC: An innovative high-field power plant

Recent publication explores heat exhaust and other issues [Kuang, FED 137 221-242, 2018]

This is at a scale and cost that is commercially interesting

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>ARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>R [m]</td>
<td>6.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Magnet</td>
<td>LTS</td>
<td>HTS</td>
</tr>
<tr>
<td>B [T]</td>
<td>5.3</td>
<td>9.2</td>
</tr>
<tr>
<td>$P_{\text{fusion}}$ [MW]</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>$P_{\text{electric}}$ [MW]</td>
<td>0</td>
<td>200</td>
</tr>
</tbody>
</table>
SPARC: A fast-track HTS-based net-energy machine

Principles of program:

- Go fast
- Use established plasma physics
- Require no breakthroughs beyond magnet
- Leverage private experience in delivering programs
- Avoid mission scope creep
**SPARC: A fast-track HTS-based net-energy machine**

**SPARC V0 technical requirements:**
- Burn D-T fuel
- $Q > 2$ (with headroom)
- $P_{fus} > 50$ MW up to 100 MW
- Pulsed with 10s flattop burn
- $\sim1,000$ D-T pulses, $>10,000$ D-D pulses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>1.65 m</td>
</tr>
<tr>
<td>$a$</td>
<td>0.5 m</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>0.33</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.8</td>
</tr>
<tr>
<td>$B_0$</td>
<td>12 T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>7.5 MA</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>20.9 T</td>
</tr>
<tr>
<td>$P_{fus}$</td>
<td>50-100 MW</td>
</tr>
<tr>
<td>$P_{ext}$</td>
<td>30 MW</td>
</tr>
</tbody>
</table>

**SPARC programmatic requirements:**
- Demonstrate break-even fusion energy production
  - Should $Q$ be higher?
- Demonstrate fusion-relevant HTS magnets at scale
- Demonstrate high-field fusion plasma scenarios for an ARC scale device

**A net-energy device at the scale of DIII-D**
A smaller, sooner machine offers physics advantages

<table>
<thead>
<tr>
<th>Design:</th>
<th>ITER: 5.3T, 6.2m</th>
<th>12T, 1.65m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>400 s</td>
<td>10 s</td>
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<tr>
<td>Fusion power</td>
<td>500 MW</td>
<td>100 MW</td>
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</table>

**Physics learning:**

<p>| | | |</p>
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<thead>
<tr>
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<tbody>
<tr>
<td>Pulse length/Plasma equilibrium</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>Energy confinement time</td>
<td>133</td>
<td>17</td>
</tr>
<tr>
<td>Pulse length/Helium confinement</td>
<td>25</td>
<td>3</td>
</tr>
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</table>

**Engineering systems:**

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<tbody>
<tr>
<td>Pulse length/Wall thermal</td>
<td>40</td>
<td>0.5</td>
</tr>
<tr>
<td>equilibration time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy in/pulse</td>
<td>20 GJ</td>
<td>0.3 GJ</td>
</tr>
<tr>
<td>Energy out/pulse</td>
<td>220 GJ</td>
<td>1.3 GJ</td>
</tr>
<tr>
<td>Plasma thermal energy/surface</td>
<td>0.5 MJ m⁻²</td>
<td>0.4 MJ m⁻²</td>
</tr>
<tr>
<td>area</td>
<td></td>
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</table>

**Nuclear systems:**

<p>| | | |</p>
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<tr>
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</thead>
<tbody>
<tr>
<td>Tritium burned/pulse</td>
<td>350 mg</td>
<td>1.8 mg</td>
</tr>
<tr>
<td>Gas throughput/pulse</td>
<td>1,500 Atm-l</td>
<td>2.7 Atm-l</td>
</tr>
<tr>
<td>10²⁰ neutrons produced/pulse</td>
<td>730</td>
<td>3.5</td>
</tr>
<tr>
<td>10²⁰ neutrons fluence/pulse</td>
<td>1 m⁻²</td>
<td>0.08 m⁻²</td>
</tr>
</tbody>
</table>

Access to similar physics

With orders of magnitude smaller engineering systems

At orders of magnitude smaller nuclear impacts
The high-field approach to fusion energy

Phase 1: Technology Development
- C-Mod
- Currently prototyping
- HTS magnets
- 3 year project

Phase 2: Demonstration
- SPARC
- Q>2, P_{fusion}>50MW
- Starting design
- 4 year project

Phase 3: Commercialization
- Power Station: ARC
- Q>10, P_{electric}~200MW
- Concept

This path is backed by our investors financially, and by MIT institutionally for R&D. We are executing now.
Opening a new path to fusion risk-retirement at much smaller scale = faster

![Diagram showing the size and magnetic field of different fusion reactors, including ITER, ARC, C-Mod, and SPARC.]
A new model for fusion R&D and commercialization

MIT PSFC remains an independent research establishment

Providing scientific and R&D to the joint project

CFS is a private company

Investor-backed with the aim of commercializing the high-field pathway

Investors are in it for the long haul with capital to see it through

Bringing the best of both worlds together:
The scientific underpinnings from tokamak research and the speed, capital and drive of the private sector
CFS & MIT created a novel framework, enabled by MIT Energy Initiative

- CFS provides funding to MIT
- Collaborative R&D
- CFS is MITEI member

A framework that can be applied throughout MIT & academia for tough tech development
CFS closed its initial financing on 6/1/18

- $50M strategic investment from ENI

- Additional investments from world-leading financial investors

- Currently discussing additional investments
Our timeline motivates increased science efforts

Not necessary for SPARC— but helpful for ARC:

- Advanced divertors for higher power handling
- First wall plasma material interactions
- Radiation tolerant materials
- Blankets and power conversion
- Tritium processing

These have long been identified as important

The U.S. program should do them

.... sooner rather than later

- A divertor test tokamak is desired, ADX is an example.
- An opportunity for US leadership.
We are growing and diversifying MIT engagement in fusion

• A new generation of interdisciplinary students being attracted by SPARC, funded by CFS, ENI and donations

Erica Salazar
NSE
Magnet cables

Caroline Sorenson
MechE
Molten salt heat transfer

Patrick White
NSE
Fusion licensing

Libby Tolman
Physics
Energetic particle stability

Theo Mouratidis
Aero/Astro
Magnet structure

J. Brisson
MechE
PSFC Division Head

M. Short
Nuclear Eng
Fusion Materials

MI. K. Emmanuel
EAPS
Climate policy

A. Lo
Sloan
Financing
We’re taking a collaborative approach

- Engaging with fusion community on SPARC physics
- SPARC physics basis will be published and available
- An opportunity to test our blind prediction capabilities
- Operating machine intended to be long-term science asset
- DOE FES establishing framework for broader community participation in program
Technical objectives:

- Burn D-T fuel
- $Q > 2$ (with headroom)
- $P_{\text{fusion}} > 50\text{MW}$ up to 100MW
- Pulsed with 10s flattron burn (about $2\times \tau_{\text{CR}}$)
- ~1,000 D-T pulses, >10,000 D-D full-power pulses
- ~1 hr D-T pulse repetition rate
- ~15 minutes between D-D shots

<table>
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<tr>
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<th>12</th>
<th>T</th>
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<tbody>
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<td>7.5</td>
<td>MA</td>
</tr>
<tr>
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<td>m</td>
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Desired schedule:

- R&D: 3 yrs (mainly HTS magnets)
- Construct: 4 yrs
Make the large-bore HTS Magnets Work?

REBCO tapes are already at performance needed

Challenges: \( j \times B \) forces  cooling  quench protection

We are up and going on these with team of 50+ designing, building & testing

But cannot reveal details before IP disclosures

How Confident Are We That A “SPARC Class” Tokamak Will Achieve Its Objectives IF magnets work?
SPARC: Nominal Operating Space; $Q_{FUS}$ up to 3.6

- Use ITER Performance Rules
  - Confinement $H_{98} = 1$
  - Profile peaking factors
  - Fuel mix
  - Fuel dilution
- Operating Space Defined by
  - $Q_{FUSION} > 2$
  - $P_{LOSS} > P_{L-H}$ (Threshold)
  - $P_{HEATING} < 30$ MW
  - $P_{FUSION} < 100$ MW
The $H_{98} = 1$ Confinement Assumption Puts SPARC Within the Footprint of the Existing Tokamak Database

Of course, this doesn’t reveal much about the physics
In Plasma Physics Variables, the SPARC Operating Point Is Generally Closer to the Mean of the H-mode Confinement Database than ITER

- ITERDB data using criteria from $H_{98}$ scaling and ITER-like geometry
- Exception: some records don’t contain the kinetic information required to calculate $\nu^*$ or $\rho^*$
For Example, SPARC operates in a well explored region of normalized density

Running comfortably below the density limit has a strong advantages

- Less susceptibility to disruptions
- Easier, generally, to get good confinement

The level of plasma fluctuations and convective losses are dramatically lower

- Strongly reduced main chamber wall interactions
- Less scattering of RF waves by edge fluctuations
We Can Find Discharges That Are Very Close To Matching, Simultaneously, All SPARC Dimensionless Plasma Parameters and Geometry ($\beta_N$, $\nu^*$, $\rho^*$, $q_{95}$, $n_G$, $\varepsilon$, $\kappa$, $\delta_L$)

The same 20 (JET) discharges are shown in red
- $B_T = 3.0 – 4.0$ T
- $I_p = 3.0 – 4.2$ MA
- $P = 8.2 – 15.8$ MW
- $H_{98} = 0.82 – 1.08$
We Can Find Discharges That Are Very Close To Matching All SPARC Dimensionless Plasma Parameters \((\beta_N, \nu^*, \rho^*, \mathbf{q}_{95}, n_G, \varepsilon, \kappa, \delta_L)\) Simultaneously

The same 20 (JET) discharges are shown in red
- \(B_T = 3.0 - 4.0\; T\)
- \(I_p = 3.0 - 4.2\; MA\)
- \(P = 8.2 - 15.8\; MW\)
- \(H_{98} = 0.82 - 1.08\)

Thus: Much of the Core Plasma Physics Has Been Already Observed
We Can Find Discharges That Are Very Close To Matching All SPARC Dimensionless Plasma Parameters \((\beta_N, \nu^*, \rho^*, q_{95}, n_G, \varepsilon, \kappa, \delta_L)\) Simultaneously

The same 20 (JET) discharges are shown in red – \(BT = 3.0 – 4.0\) T – \(IP = 3.0 – 4.2\) MA – \(P = 8.2 – 15.8\) MW – \(H_{98} = 0.82 – 1.08\)

Why didn’t those JET discharges generate 100 MW of fusion?

Fusion is nuclear physics – Doesn’t scale with dimensionless plasma parameters

• In fact, we’re eagerly looking forward to experiments in the regime where plasma physics and nuclear physics are coupled – this will be new

\(- I_p = 3.0 – 4.2\) MA
\(- P = 8.2 – 15.8\) MW
\(- H_{98} = 0.82 – 1.08\)
Lots of Upside Potential
Performance Estimates Robust With Respect To Confinement Assumptions

- $Q = 2 - 3.6$ With $H_{98} = 1$: Nominal
- $Q$ up to 5 One standard deviation above database mean, $H_{98} = 1.1$:
  - Perhaps higher in I-mode
- $Q > 2$ One standard deviation below database mean, $H_{98} = 0.9$:
  - $Q \approx 1$ in L-mode $H_{89} = 1$
  - $Q > 2.6$ Under slightly improved L-mode, $H_{89} = 1.4$
  - Enhanced Confinement with reduced magnetic shear, hybrid regime should be accessible transiently
We’ve established physics plausibility for SPARC V0 - but just started to explore the design space

We Need to Continue to Build the Physics Basis For SPARC

Given the SPARC mission, We pose three questions:

• What the best configuration for a SPARC-class device? – is there something better than Version 0 in the same neighborhood?
• When we build a SPARC-class device, what level of performance do we predict?
  – What do we need to build in to the design to ensure success?
• What new and important physics questions will SPARC allow us to address?
  – What should the physics program look like?
Main Physics Topics

• Plasma Startup, Equilibrium & Control

• ICRF Heating – Getting power in

• Plasma Exhaust – Getting the power out

• Core & Pedestal – Predicting profiles & fusion power

• MHD/Fast Particle Physics – Disruptions & Confining fusion products

• Nuclear Issues – Managing tritium & neutrons

• Diagnostics – Measuring & validating progress
Simple estimates of PFC response indicate inertial cooling is feasible in SPARC, but not ITER

ITER: \( P_{\text{exh}} = 150 \text{ MW}, \ S_{\text{plate}} = 5\% \ S_{\text{plasma}} \sim 45 \text{ m}^2 \)

SPARC: \( P_{\text{exh}} = 53 \text{ MW}, \ S_{\text{plate}} = 5\% \ S_{\text{plasma}} \sim 2.6 \text{ m}^2 \)

\[ \Delta T_{Vol} = \frac{q \ t}{\rho c_v V} \]

\[ \tau_{CR} [s] \approx \frac{1.4}{Z_{\text{eff}}} \left( \frac{T_{keV}}{2} \right)^3 a [m]^2 \]
Case study: Double null divertor with strikepoint sweeping, 2 cm thick, inertial cooled divertor is viable

- SOL radiation fraction: 0.9

![Diagram of divertor with labels](image)

- Double null to spread heatflux to upper and lower outer divertors
- Aggressive strikepoint sweeping to spread energy over the entire surface, minimize peak temperature

![Graph of maximum surface temperature](image)

- Maximum Surface Temperature (K)
- Time (s)
- Tungsten
- Molybdenum
- Graphite
A large strategic advantage to assess dissipative divertor physics solutions: **SPARC** can operate at high and variable core density, but at low Greenwald fraction.
SPARC boundary plasma physics solutions relevant for ARC and other fusion power plant designs
New design study: demountable REBCO coils + immersion salt blanket very attractive for innovative divertor

- Minimal solid materials!
- Internal PF coils allow advanced long-leg divertor...we focused on the X-point target divertor [LaBombard]
- Modeling shows this has 10x larger detachment window for low-density, LHCD non-inductive core.

Kuang et al FED 2018
And in turn the long-leg divertor + blanket dramatically decreases neutron damage rate for divertor high heat flux components

~ 5 dpa / year

<table>
<thead>
<tr>
<th>Coil</th>
<th>Lifetime [FPY]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF1</td>
<td>11.3</td>
</tr>
<tr>
<td>PF2</td>
<td>76.2</td>
</tr>
<tr>
<td>PF3</td>
<td>12.5</td>
</tr>
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Kuang et al FED 2018
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Phase 2: Demonstration
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Have Good Ideas? Want to Help Make The Design Even Better?

• Contact
  – Martin Greenwald g@psfc.mit.edu
  – Nathan Howard nthoward@psfc.mit.edu
  – Bob Mumgaard bob@cfs.energy
Thank you!

Dennis Whyte
whyte@mit.edu