Commonwealth Fusion Systems

Accelerating

Bob Mumgaard

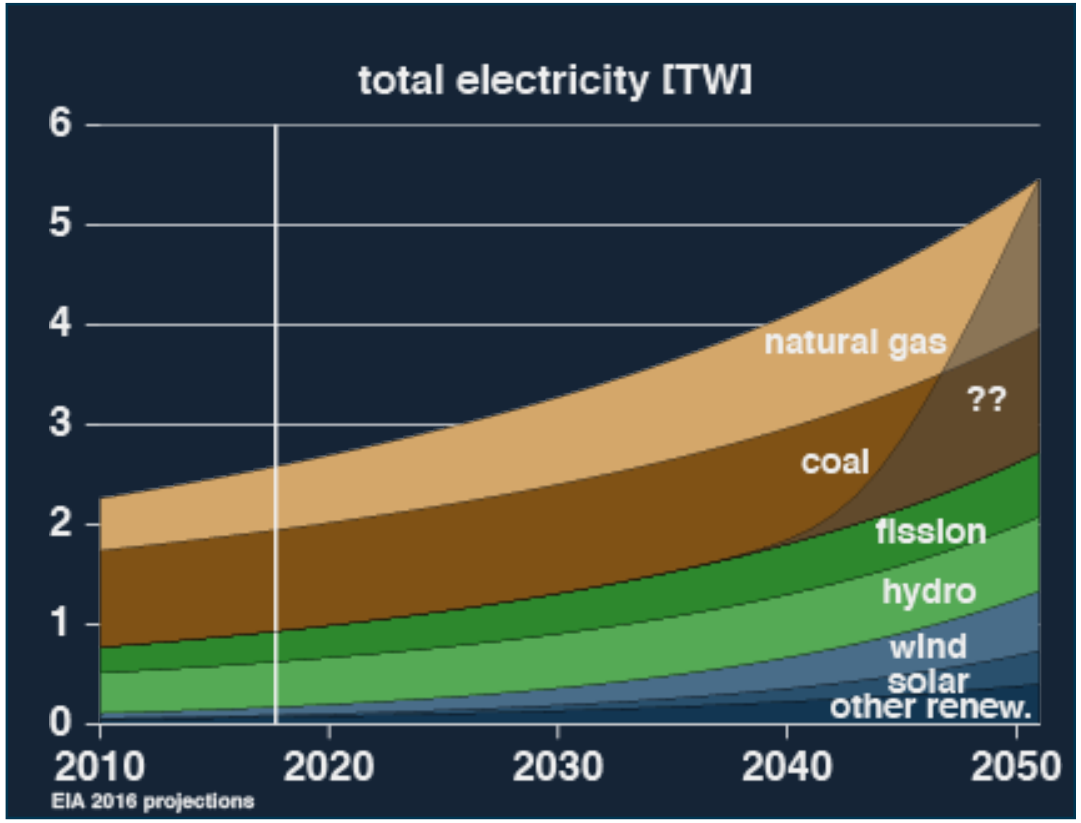
Fusion Power is a product

…. it is not an end in itself

- It must compete in a market place
- People must choose to buy it
- Those that buy it must make money
- It will take an industry and ecosystem to do this

Good news: It's a pretty good product and an eager market

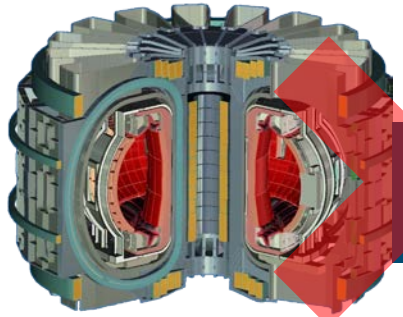
- There is a lot going for fusion as a power source and people understand it
- Our experience is that those in energy are excited to see a fusion-like solution
- The energy market will/must undergo the most drastic shift in any market in history over the next 3 decades
- Fusion could be a major player in that market



The market will decide

Bad news: Act quick or we'll miss this opportunity

- Our concepts must lead to a commercial product for it to have widespread impact
- We must leverage innovation across all areas
- We must find ways to broaden the participation – to build an ecosystem and an industry
- We must move with urgency to deliver in a timescale that matters to decision-makers

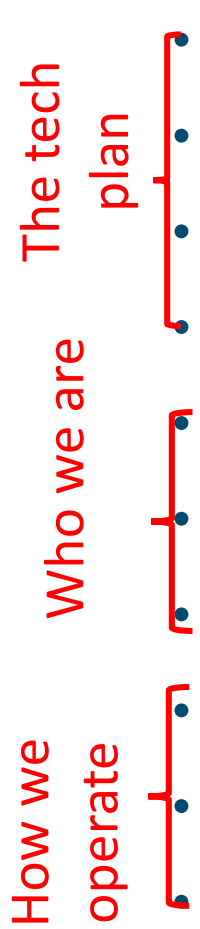


>1GW, >5m

Past 2050

CFS was built to fast track fusion

Speed is the driver -- ways to get speed:



- Decrease the capital outlay required to retire risk – make it 10x smaller
- Use established physics concepts – engineering over science projects
- Minimize technology interdependencies – modularize and parallelize
- Make it economically attractive – increase the TAM
- Increase private capital participation – success acts as accelerator
- Decrease the number of stakeholders – keep them aligned
- Recruit outside expertise – people have done similar things
- Demonstrate by building – roadmaps and plans are easy
- Build momentum with early success – hit meaningful milestones
- Focus on unique value creation – leverage work done elsewhere

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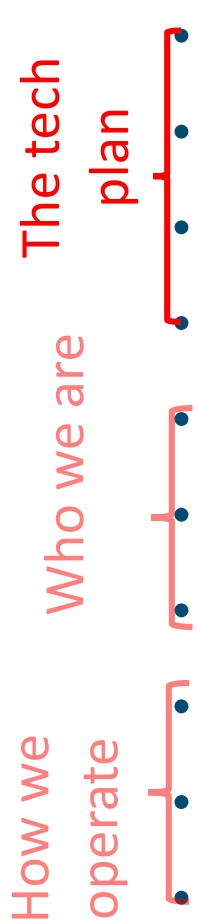

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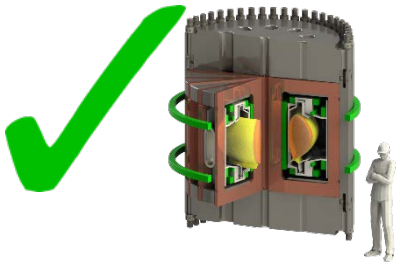
CFS and MIT are now executing a 15 year plan to fusion

Phase 1: Technology Development



C-Mod

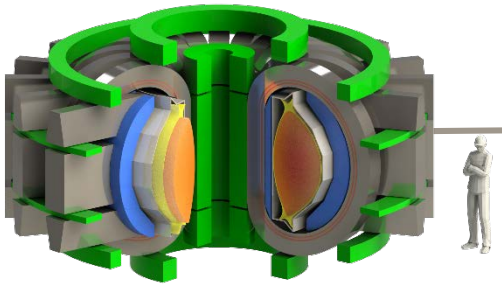
IN PROGRESS

HTS magnets

Full-scale TF by Q2 2021

Phase 2: Demonstration

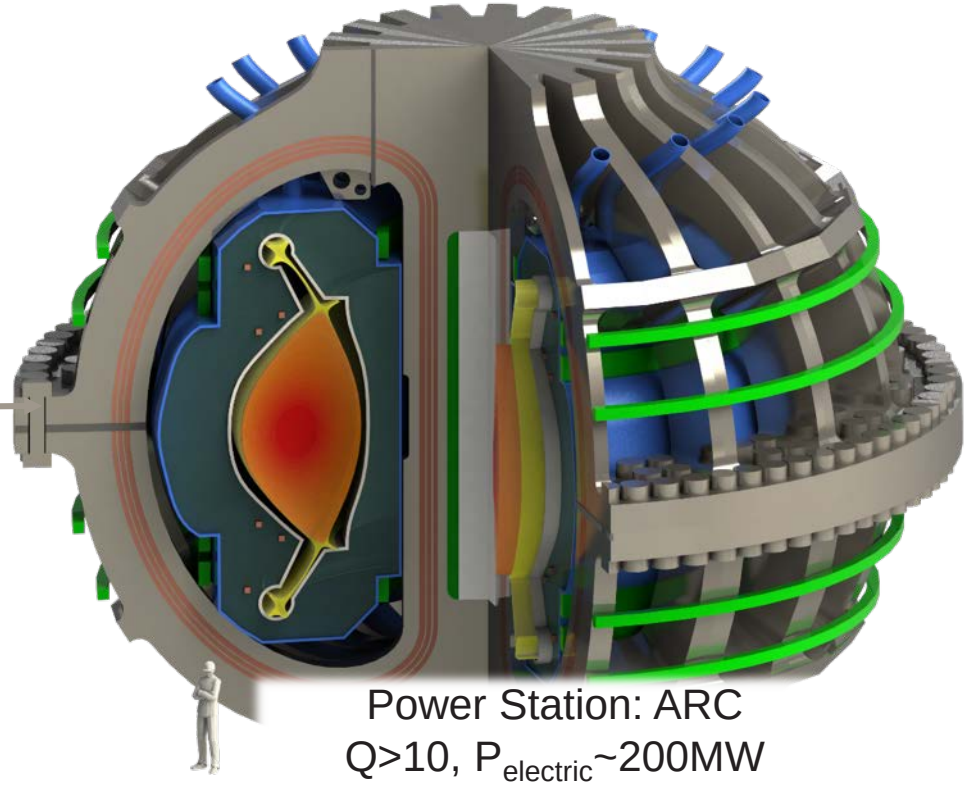
Fusion "Kitty Hawk"



Prototype: SPARC
Q>2, P_{fusion}>50MW

First plasma: 2025
DT: 2026

Phase 3: Commercialization



Power Station: ARC
Q>10, $P_{electric}$~200MW

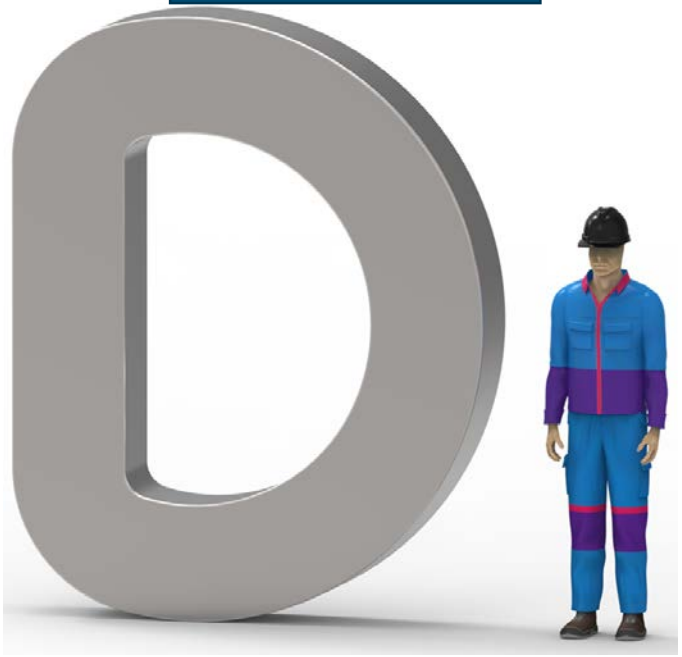
First plasma: Early 2030s
Power on the grid ASAP

SPARC HTS magnet R&D on track for June 2021 Toroidal Field Model Coil (TFMC) demonstration

- Prototype cables and magnets tested externally and in-house
- First-year TF winding pack R&D hit milestones and retired major risks:
  - Relevant JxB forces
  - Cyclic loading
  - Quench detection
  - Fabrication methods
- Publication in preparation with detailed results, also shown at MT26 last month
- Team working hard to design, build, and operate TFMC by June 2021 to retire major risks of SPARC TF magnet system
  - HTS ordered, first deliveries already in
  - Cutting metal

SPARC test cable at the SULTAN test facility

SPARC Toroidal Field Model Coil



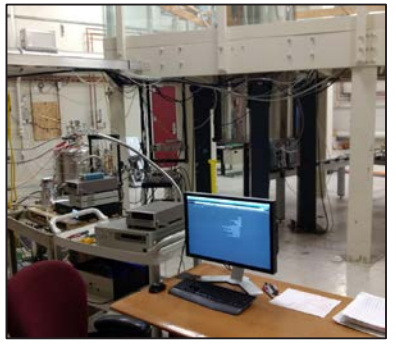
- Operate with magnetic field and JxB forces at or above SPARC
- Demonstrate safe management of quench
- Winding pack design and manufacturing processes are representative of and transfer to SPARC

Project is driving the HTS industry

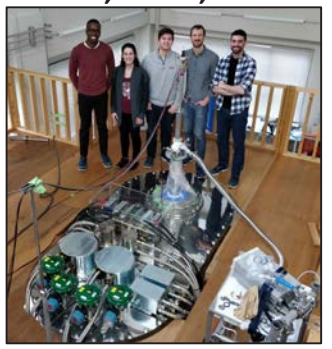
- ~20 km of evaluation orders from 7 HTS manufacturers
  - Several improved manufacturing processes to meet SPARC specifications: $J_e(20K,20T,\theta_{worst}) > 700\ A/mm^2$
- Contracts closed for ~500 km for TFMC project
  - Deliveries already arriving
  - Average performance exceeding specifications
- Continue working with industry to ensure it is ready for 20x scale-up to SPARC in 2 years
- Project implementing rigorous QA and characterization process
  - High-throughput assessment of all HTS at 77 K and self-field
  - Witness samples tested through hierarchy of systems at higher fields, lower temperatures, and multiple angles
  - Provides key data for inputs to models
  - Gives feedback to manufacturers on process improvements

THEVA TapeStar
(CFS)
77K, SF

SuperCurrent
(RRI, HTS110, CFS)
15-77K, 0-12T, 0-240°



High-field Test Rig
(MIT PSFC)
20K, 16T, 0°



Tohoku Univ.
(Japan)
4-77K, 25T, 0-180°

SPARC siting process is well under way

Our Process:

- Cast a wide net for sites in Agreement States (states with an NRC agreement to license radioactive materials)
- Site identification meetings/site visits with state governments, economic development offices and authorities, chambers of commerce, private land owners
- Due diligence to determine if sites meet necessary criteria

Timeline:

- March – July 2019: Meetings with with site stakeholders
- July – August 2019: Due diligence on sites
- August 22, 2019: Present top candidate sites to site selection committee for down select of top 3
- September 2019: Further due diligence on top sites
- October 2019: Start negotiations with top site
- December 2020: Finalize permitting/licensing process
- June 2021: SPARC site ground breaking

What we look for in a site:

- Ease of permitting/licensing process
- Proximity to MIT/Cambridge
- Access to sufficient power or the ability to get it by 2024
- Sufficient site size
- Geographical features – will the site work for construction of the SPARC facility?
- Features of surrounding area – is there anything that could slow or block the process?
- Potential state/local incentives
- Supportive state/municipality
- Access to public transportation
- Access to paved roads/highways
- Cost considerations associated with the site and construction

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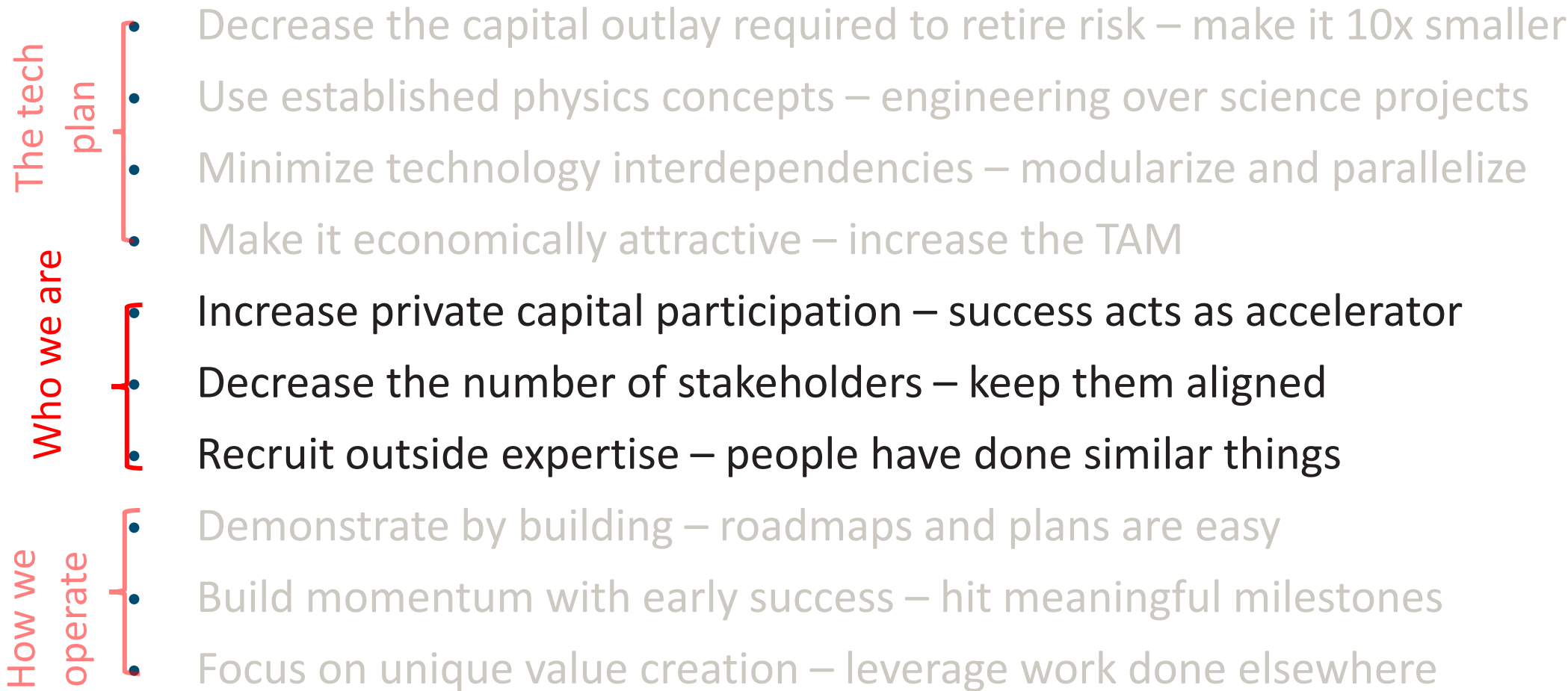
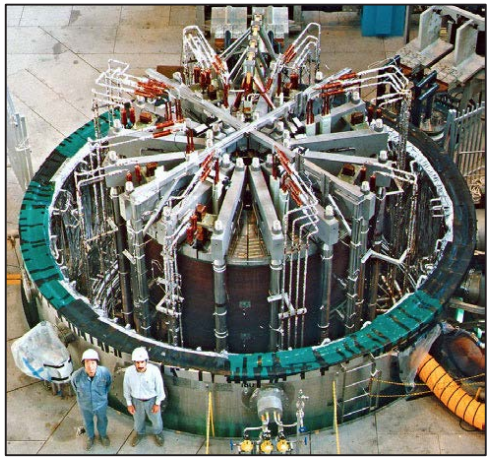


Backed by capital to get it done

- Investors committed to displacing CO2 and building a fusion business
  - Large industrial and energy companies who know how to deliver energy at scale
  - Early investors in Google, SpaceX, Tesla, Amazon
- Enough capital to get it done and to accelerate while doing it
- Understanding of and appetite for the technical risks
- Anything less than power on the grid is a failure
- They are activists for the fusion program

Gathering the skilled, experienced team

- >70 FTE, >100 people (CFS, MIT, contractors/collaborators) working on magnet R&D and SPARC design
- Proven, diverse expertise:
  - High-field fusion science and engineering from Alcator C-Mod
  - High-field HTS cables and magnets at MIT PSFC
  - ITER CS Model Coil
  - Fusion collaborators around the world
  - SpaceX manufacturing
  - GM high-performance engineering
  - COMSOL multi-physics simulations
  - TerraPower project management
- Hiring 20+ engineers over next year, many early-career



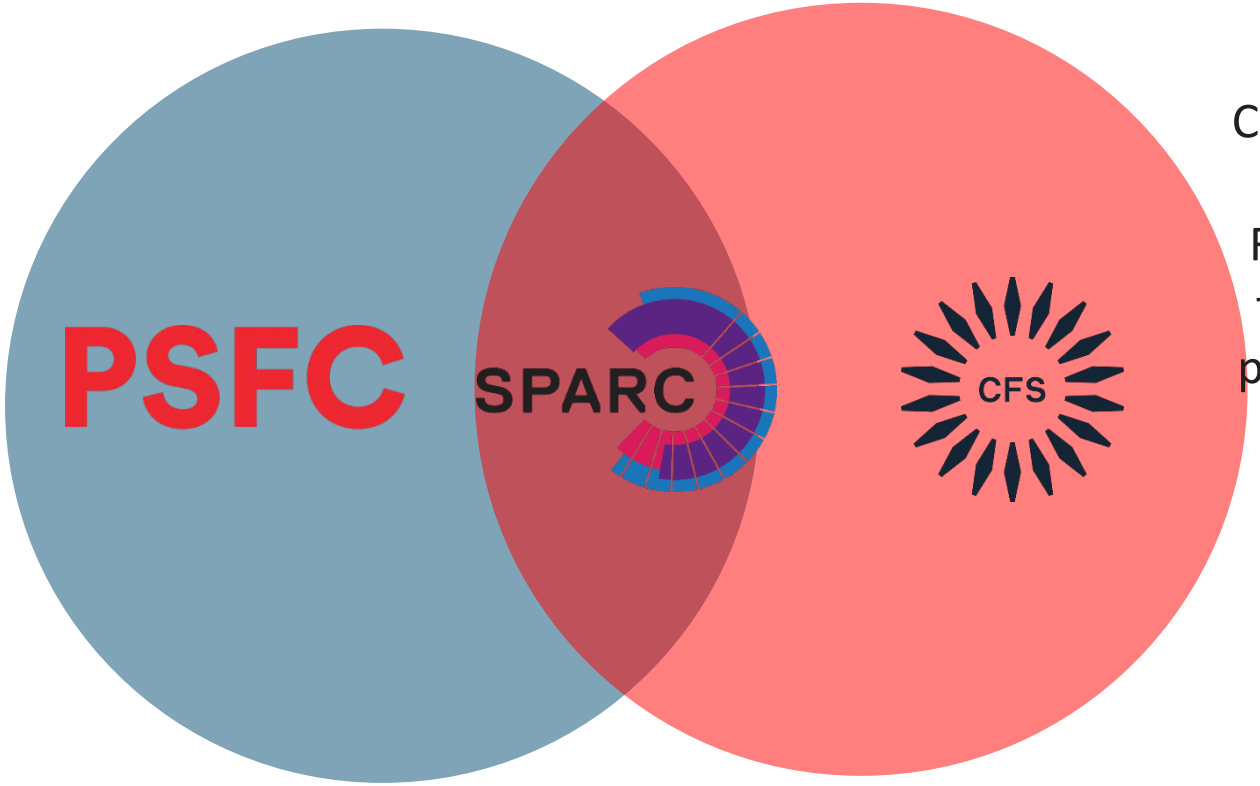
TerraPower™

COMSOL

Partnered with the MIT PSFC and adding others

MIT PSFC remains an independent research establishment

Providing scientific and R&D to the joint project



CFS is a private company

Focused on developing the commercial fusion product in time to make a difference

Bringing the best of all worlds together:
The scientific underpinnings from tokamak research and the speed, capital and drive of the private sector and the capabilities around the world

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

APS DPP town hall on SPARC last week

16

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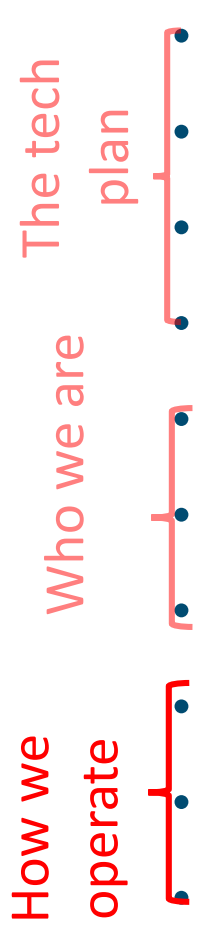

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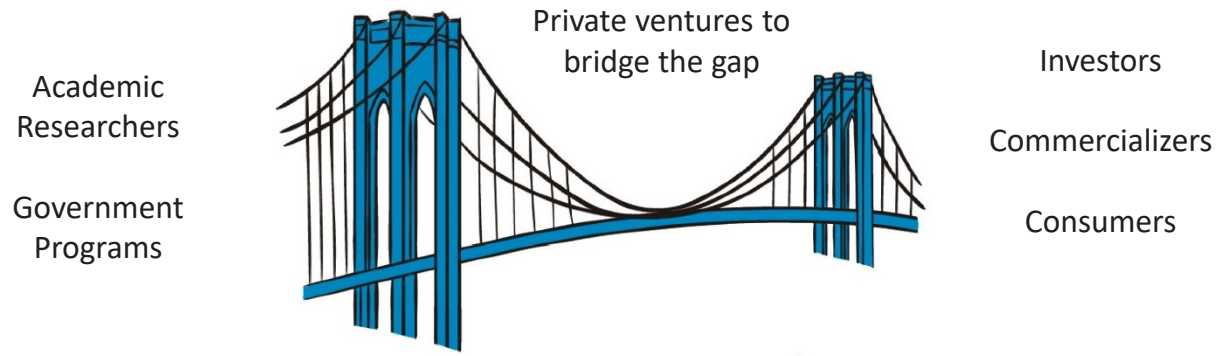
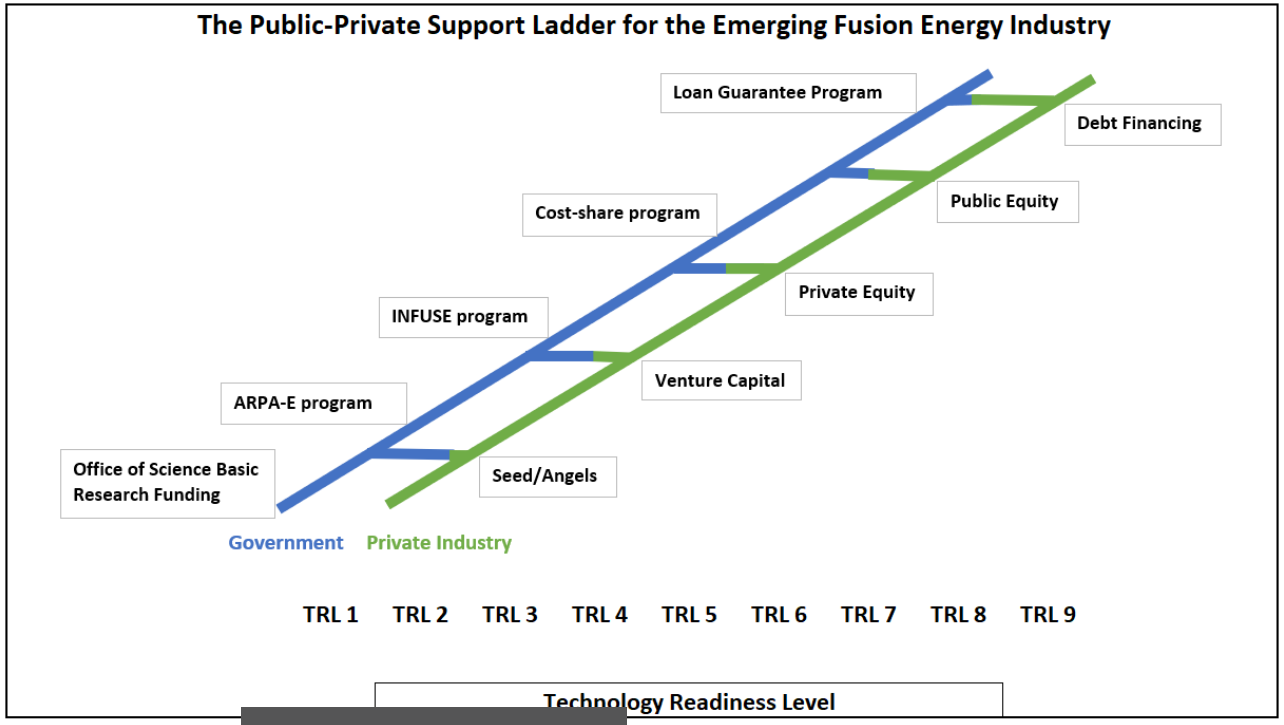
Technology gets to market using the whole ecosystem

- The entire funding environment is evolving
- Fusion is following a well-worn tech-development arc
  - Computers, AI, Robotics, Drugs, Aerospace, Energy, Quantum, Materials, etc.
- **An evolving pathway is how fusion is going to get on the grid**
  - The US government doesn't build reactors, pilot plants, etc. – industry does
  - Look to fission, fossil, ARPA-E, EERE, New Space
- Each side does what it is good at
  - Government does basic research, deep expertise, tool sets, seeds innovation
  - Private finds market fit, selects architectures, scales solutions, manages costs



A ladder for gov’t and industry to climb together

- The US is very good at industry –academia – government
- There are many relevant precedents, look to commercial space for example
- We need to build a ladder that builds up capabilities
- A vibrant fusion ecosystem supports all of fusion



Fusion Science and Technology

Fusion Energy Development

Fusion Energy Industry

- NASA COTS: From Shuttle to SpaceX

Diversifying the funding and partnerships

INFUSE Innovation Network for Fusion Energy

4 INFUSE grants in 2019

1. BNL: HTS cable quench
2. ORNL: Divertor materials tests
3. LLNL: Divertor plasma siumlations
4. PPPL: Alpha particle simulations

SBIR

Applying to SBIRs to support spin-out R&D

arpa·e

FOA: BETHE (Breakthroughs Enabling Thermonuclear-Fusion Energy) submitting applications

COTS

COTS-like (Commercial Orbital Transportation Services) cost share working way through Congress, potential to support SPARC and collaborations

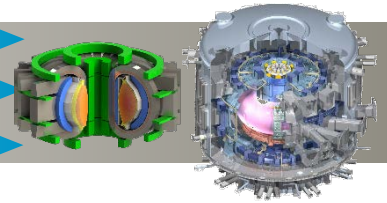
ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics

Fast particles — NSTX-U

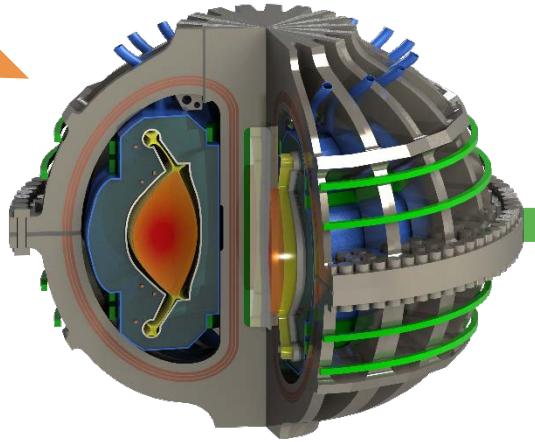
HTS magnet development



SPARC+
ITER

Burning-plasma physics

ARC:
Compact fusion
Power Plant



Show fusion makes more power as soon as possible:
Burning plasmas are key.

TODAY — 2025+ — 2030+

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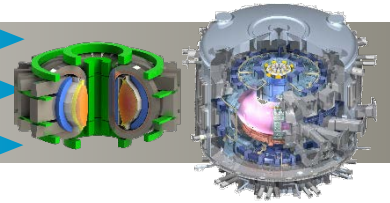

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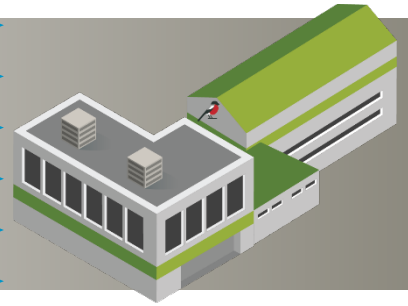
Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



Nuclear qualified components, materials, and systems, minus the burning plasma

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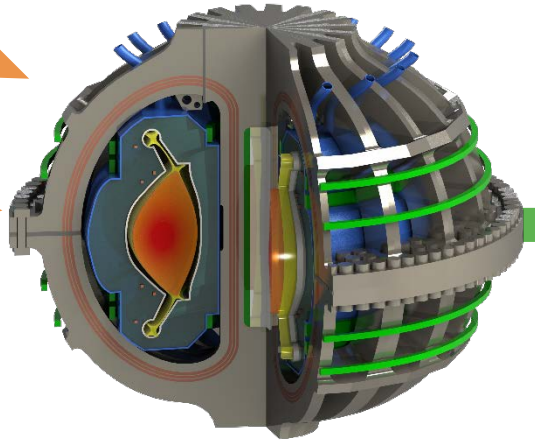
Compact fusion
Power Plant



But without nuclear-compatible materials and components the first fusion system is very sub-optimal.
Its been 25 years since the US did DT– do it now for FM&T.

TODAY → 2025+ → 2030+

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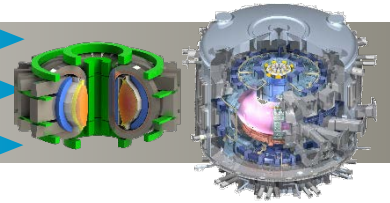

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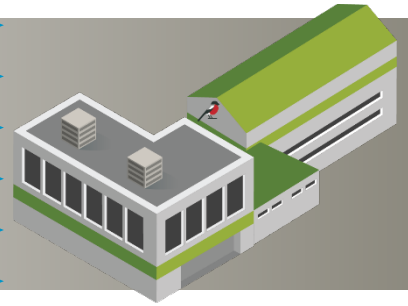

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Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

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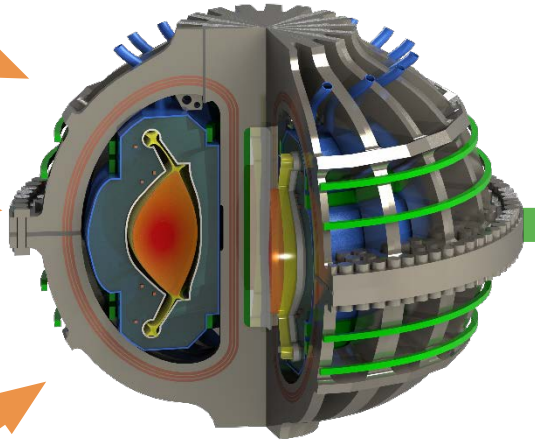

The divertor and boundary are long-identified show-stoppers. They are rich in science for all of fusion. We need a modest, modular, flexible, near-term test bed.

TODAY

2030+

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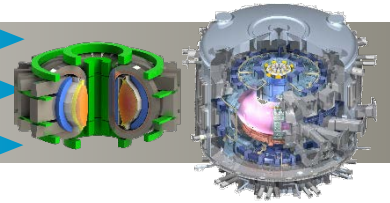

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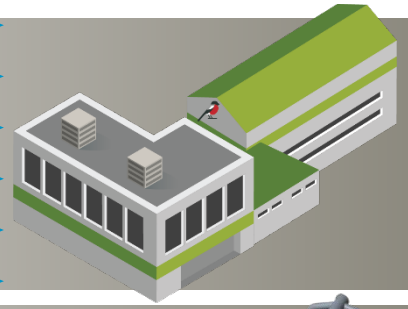

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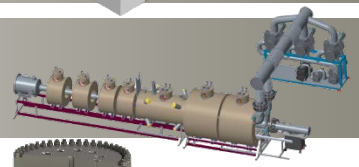

MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations
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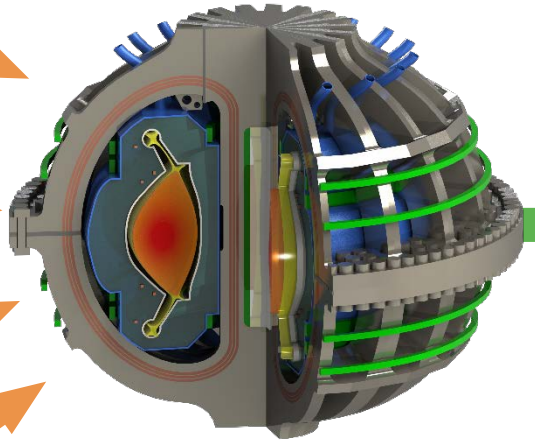

We need the materials for the first wall qualified in long pulse to match to any plasma solution.
Do MPEX now.

TODAY

2030+

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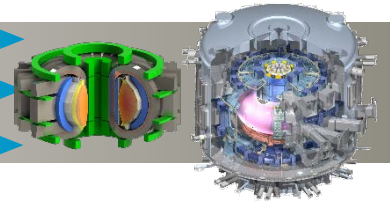

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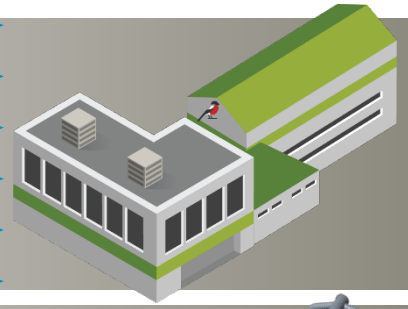

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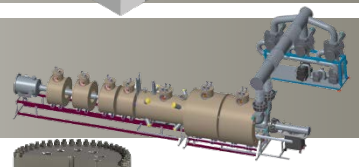

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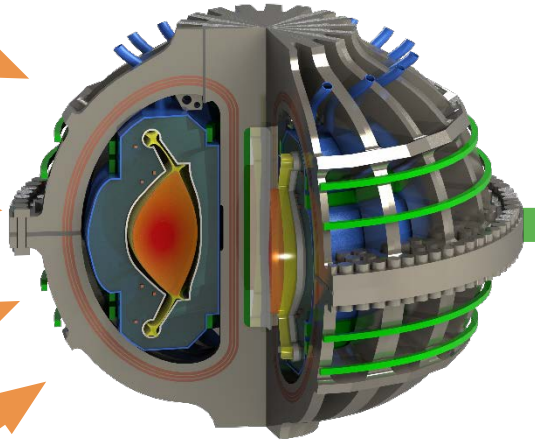

For EVERYTHING we need validated mod-sim.
Data + Simulation = design tools. FM&T, boundary, core.

Modeling and Simulation → Full device modeling → Validation

TODAY → 2025+ → 2030+

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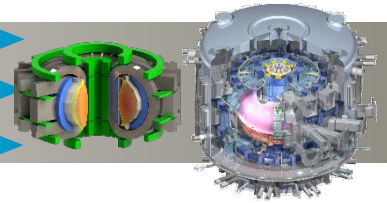

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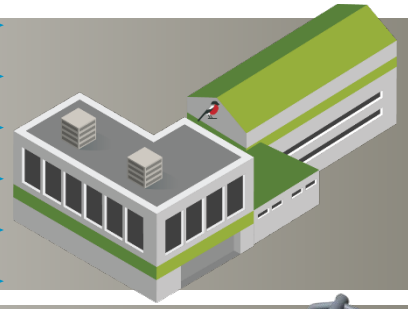
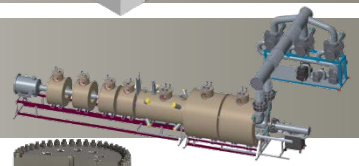


Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

Fusion power plant:

A black box that confines plasmas to get to burning conditions, captures the energy, breeds the fuel, survives long enough, designed with validated design tools, that fits a market.

This path is almost entirely architecture independent.
We don't need to decide power plant now, we need to get decision quality data now.

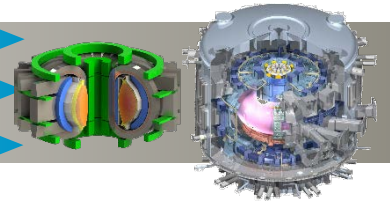
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

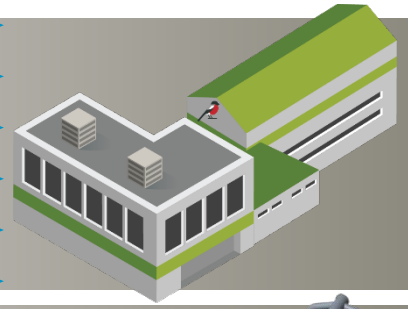
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



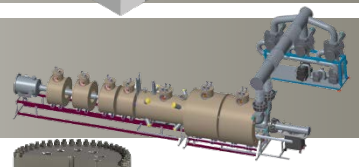
SPARC+
ITER

Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

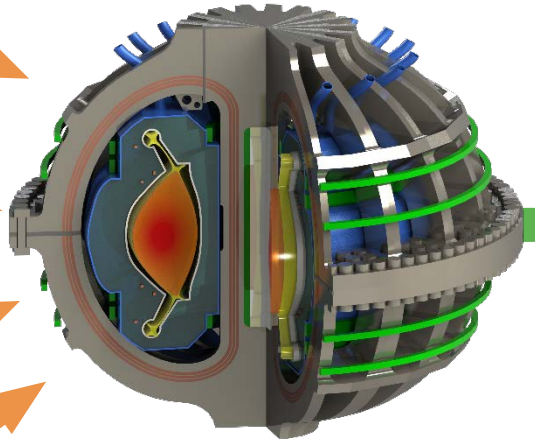
Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

ARC:
Compact fusion
Power Plant



We will need all the same things to do a high-field tokamak.
We don't need to decide power plant now, we need to get decision quality data now.

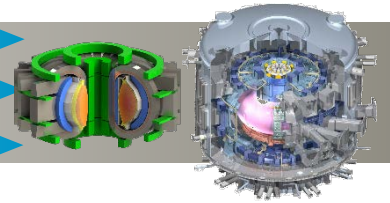
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

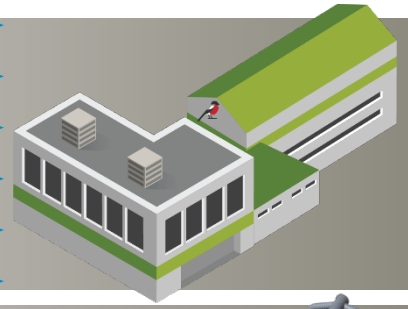
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



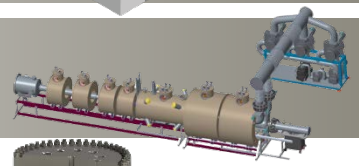
SPARC+
ITER

Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

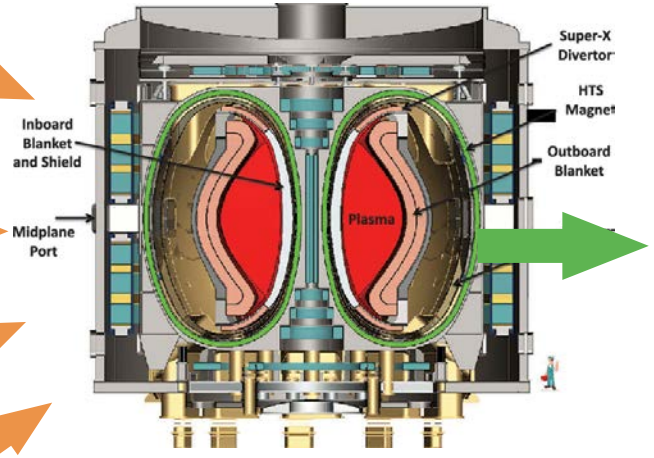
Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

ST-based Compact Fusion Power Plant



We will need all the same things to do an ST. We'll also have NSTX-U, MAST-U, ST-40.
We don't need to decide power plant now, we need to get decision quality data now.

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

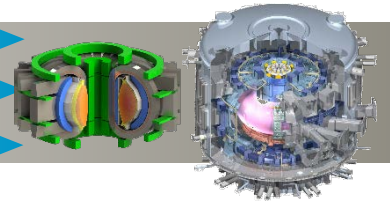
US FUSION PROGRAM

Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR

Confinement Physics

Fast particles — NSTX-U

HTS magnet development



SPARC+
ITER

Burning-plasma physics

Volumetric neutron source development

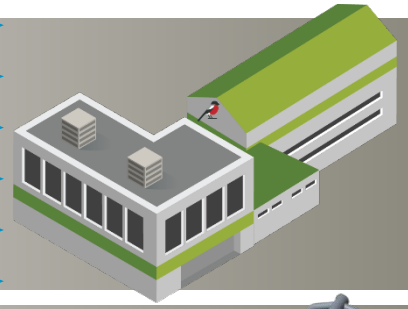
Blanket test stands

Tritium extraction technologies

Materials characterization tools — LAMBDA

Fusion Prototypical Neutron Source

Fusion-relevant materials program



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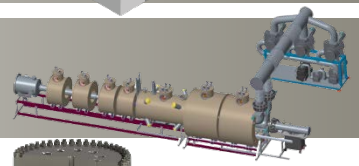


MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations

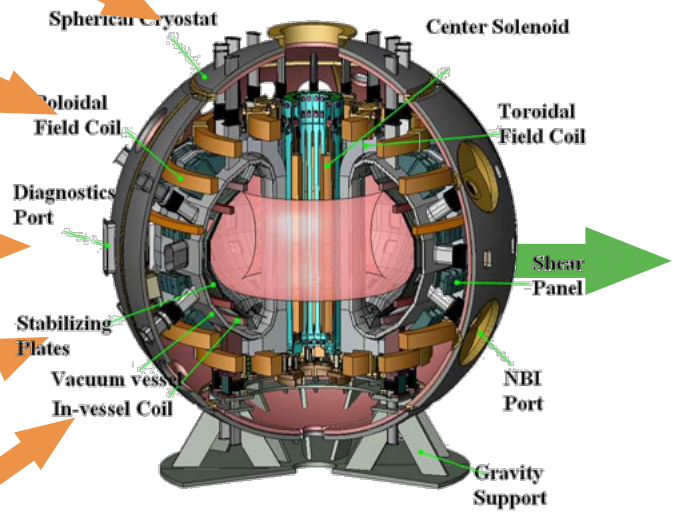
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

AT option

AT-based Compact Fusion Power Plant



We'll need all the same things if we do AT. And we'll have JT-60SA + DIII-D results.
We don't need to decide power plant now, we need to get decision quality data now.

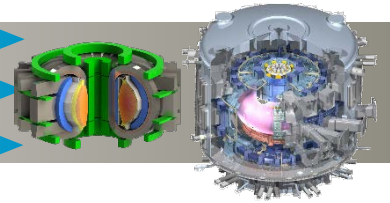
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

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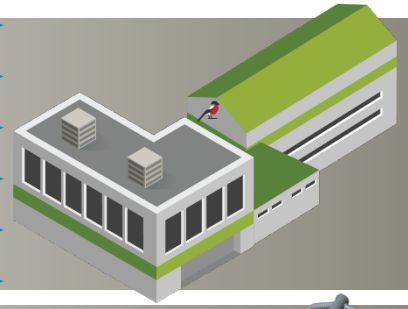
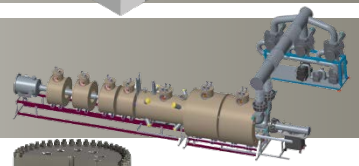
Fusion-relevant materials program



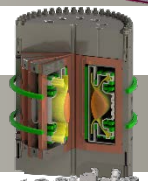
Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

Fusion-qualified first wall materials

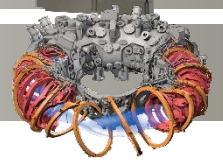
Boundary simulation and collaborations
Liquid metals — NSTX-U



US-DTT

Fusion-qualified plasma exhaust scenarios

Stellarator optimization — W7-X, LHD

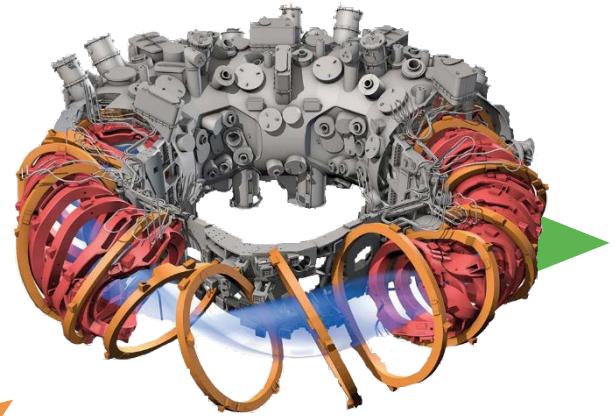


Mid-scale
STELLARATOR

Inherently steady-state fusion system

High-Q stellarator

Stellarator-Based Compact Fusion Power Plant



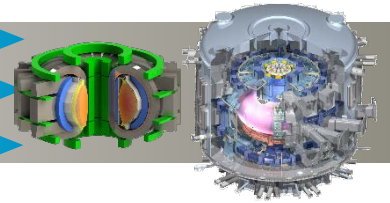
TODAY

We'll need all the same things if we do a Stellartor. And we should do a mid-scale one.
We don't need to decide power plant now, we need to get decision quality data now.

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

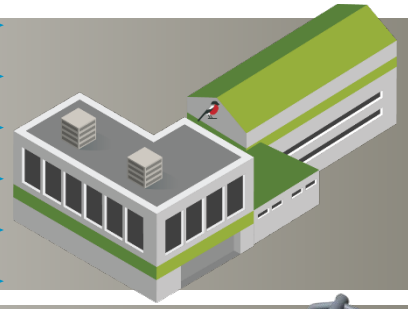
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



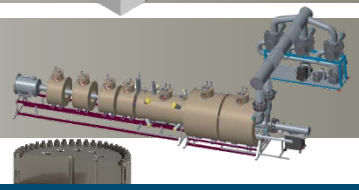
SPARC+
ITER

Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



Nuclear qualified components, materials, and systems, minus the burning plasma

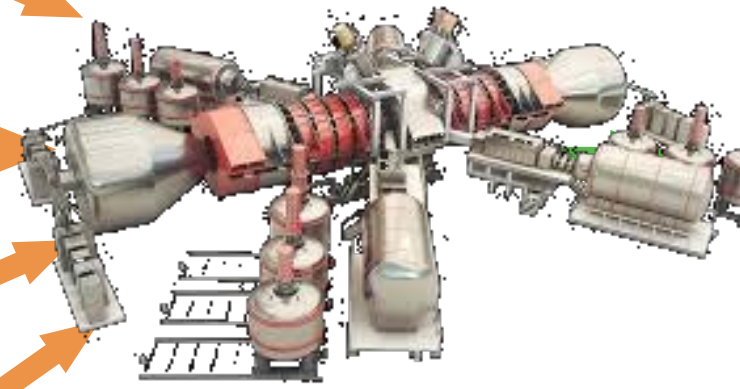


MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations

FRC-based
Compact Fusion
Power Plant



We'll need all the same things if we do a an alternate. Let's keep seeding this area.
We don't need to decide power plant now, we need to get decision quality data now.

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

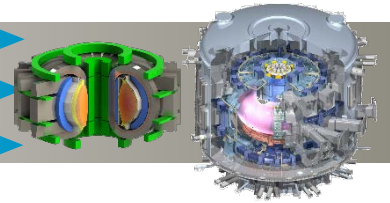
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

Burning-plasma physics

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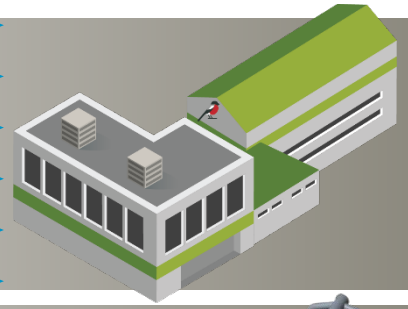
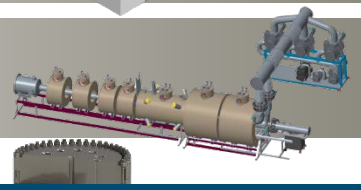
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations

MIF- based Compact Fusion Power Plant

We'll need all the same things if we do MIF. Let's keep seeding this area.
We don't need to decide CPP now, we need to get decision quality data now.

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

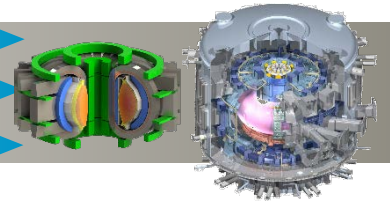
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

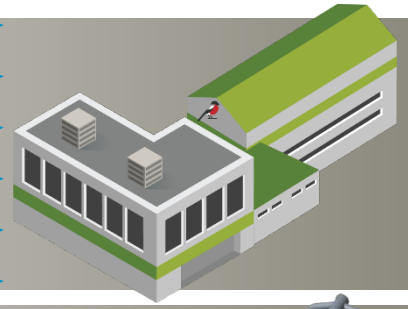
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



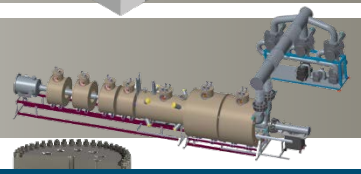
SPARC+
ITER

Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



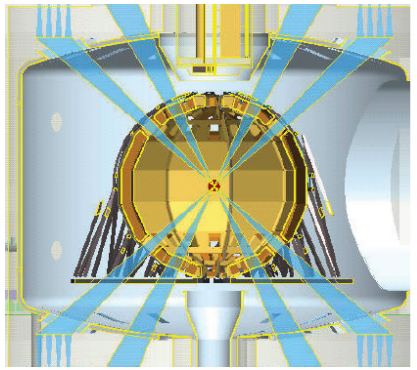
Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

Fusion-qualified first wall materials

ICF- based Compact Fusion Power Plant



We'll need most of the same things if we do ICF.
We don't need to decide CPP now, we need to get decision quality data now.

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

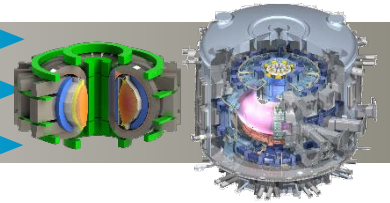
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

A ROADMAP TO FUSION ENERGY THAT CFS WOULD SUPPORT

US FUSION PROGRAM

Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR → AT option

Confinement Physics
Fast particles — NSTX-U
HTS magnet development

SPARC+
ITER
→ Burning-plasma physics

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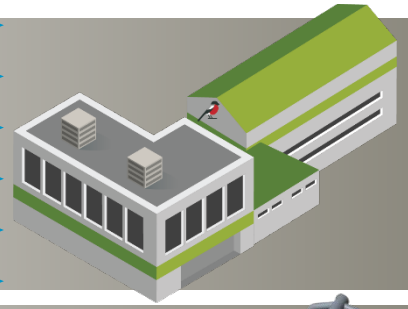
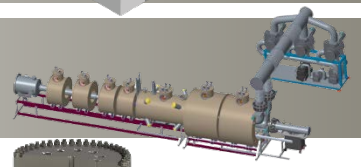
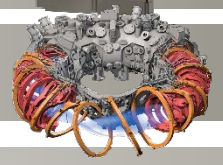

→ Nuclear qualified components, materials, and systems, minus the burning plasma


MPEX
→ Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT
→ Fusion-qualified plasma exhaust scenarios

Stellarator optimization — W7-X, LHD

Mid-scale
STELLARATOR
→ Inherently steady-state fusion system → High-Q stellarator

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

Modeling and Simulation → Full device modeling → Validation

TODAY → 2025+ → 2030+

Compact Fusion

We support a program that supports as broadly as possible fusion concepts in a flexible manner.

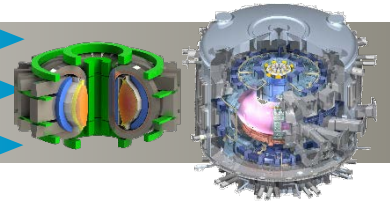
Put options on the table, don't focus on down-selecting.

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

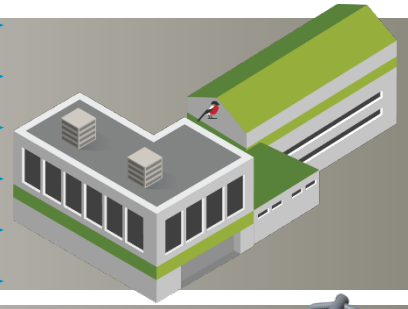
Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR → AT option

Confinement Physics
Fast particles — NSTX-U
HTS magnet development

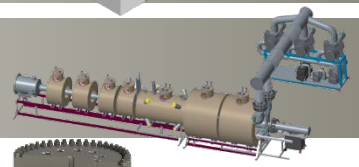


SPARC+ ITER → Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



Nuclear qualified components, materials, and systems, minus the burning plasma

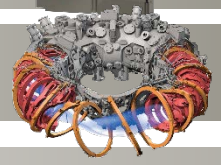


MPEX → Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT → Fusion-qualified plasma exhaust scenarios

Stellarator optimization — W7-X, LHD



Mid-scale STELLARATOR → Inherently steady-state fusion system

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

The important thing is that we start NOW.

If we wait and don't do the early things then we will lose.

It would be a travesty for somebody to have a concept that works and have fusion stall because we, *CHOSE* not to prioritize the parts that help everybody.

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR

Confinement Physics

Fast particles — NSTX-U

HTS magnet development

Volumetric neutron source

Blanket test stands

Tritium extraction technol

Materials characterization

Fusion Prototypical Neutr

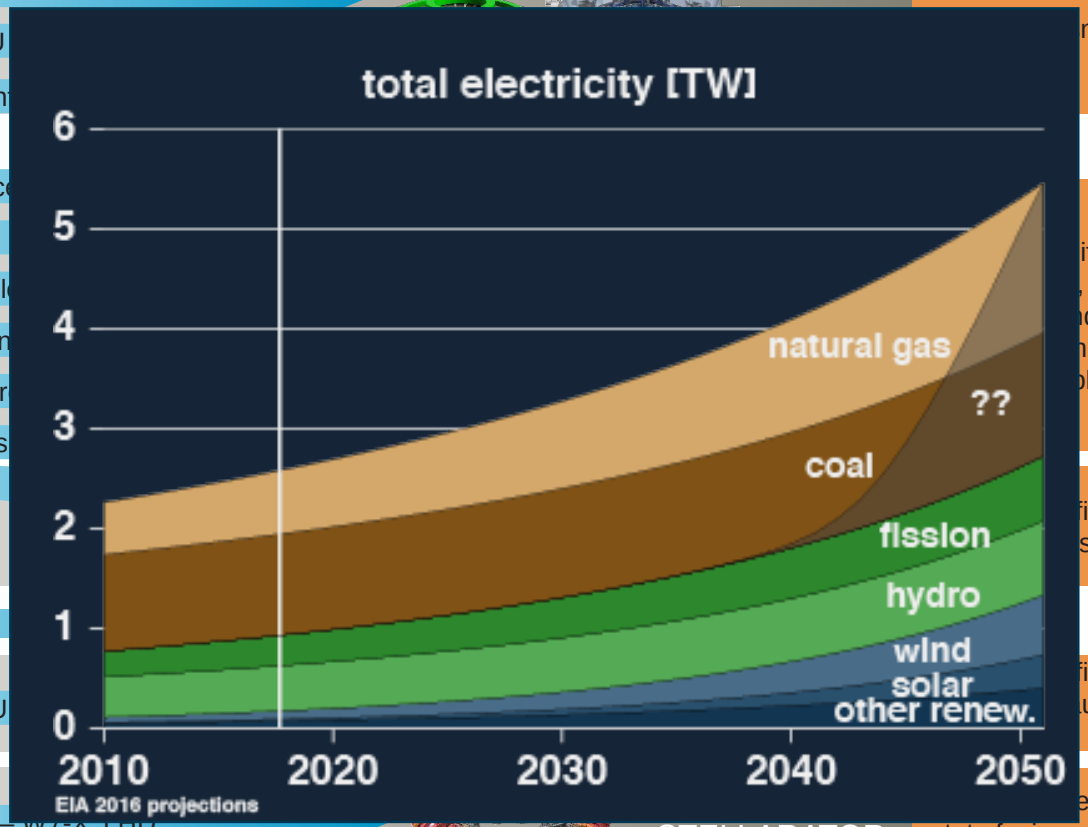
Fusion-relevant materials

Boundary simulation and

Liquid metals — NSTX-U

Stellarator optimization — W7-X, LHD

Innovative concepts — Z-pinch, FRC, Spheromak, RFP



STELLARATOR

AT option

ma

ified

d

nus

lasma

fied first

s

fied

ust

eady-

state fusion system

Waiting is a CHOICE

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+


Commonwealth Fusion Systems
The fastest path to
limitless, clean energy.