A new approach to funding, accelerating, and commercializing fusion

R. Mumgaard
CEO --Commonwealth Fusion Systems

NAS comments, PPPL, April 12, 2018

Your charge to me:

1. The capabilities and prospects of private-sector ventures

2. The short-term and long-term plans of CFS

3. What should the government-funded program do with all of this?*

* Mumgaard addition

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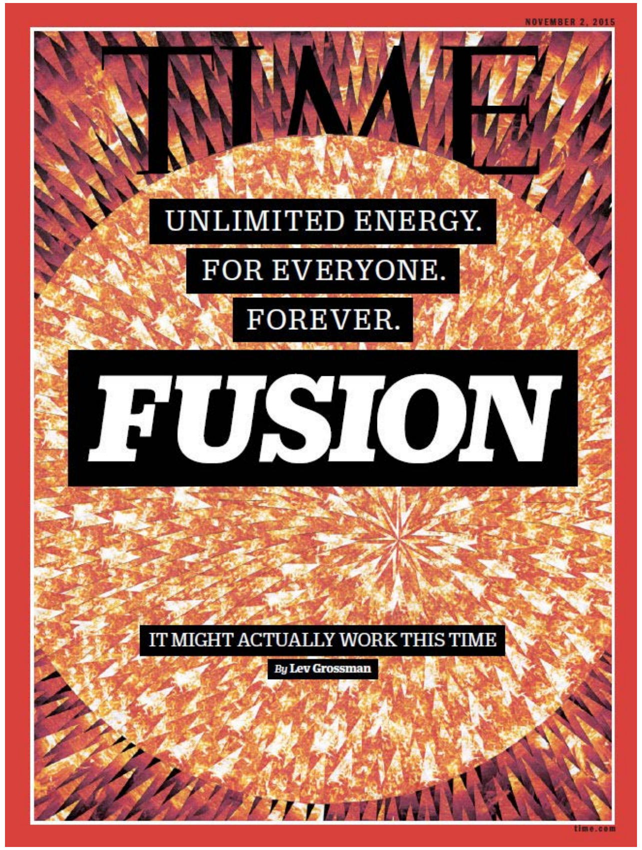
*There is a nascent fusion industry**

- There are many companies, the list is growing
- They are optimizing for things beyond physics
  - Indicators about the fusion value proposition
- They can be extremely capable organizations
  - Move faster than gov’t programs
  - Tight focus on deliverables and milestones
  - With less $ (now) and different resources than gov’t
  - High-growth potential
- They are serious and thoughtful

*Private companies investing significantly in fusion R&D, not just performing gov. research.

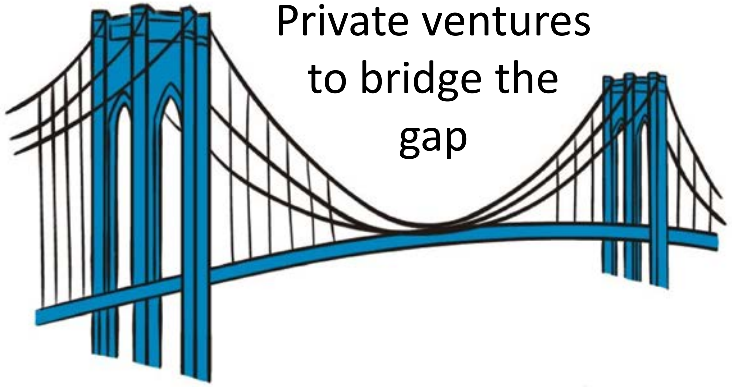
This is a good thing

- Our basic research is being used! It is important!
- Attracting new stakeholders
- Energizing the public and adjacents
- Building momentum as success builds success
- Diversity of tolerance to risk –not everything has to work
- Diversity of physics approaches –fusion is too important for one architecture
- Diversity of organizational approaches –fusion is too important for one team



This is how new technology gets to market

- The private funding environment is evolving
- Fusion is following a well-worn tech-development arc
    - Computers, AI, Robotics, Drugs, Aerospace, Energy, Quantum, Materials, etc
- **This is how fusion is going to get on the grid**
    - The US government doesn't build reactors, pilot plants, etc – it does basic research
    - Look to fission, fossil, ARPA-E, EERE
- How does the government program fill its role?
    - The mandate is basic research
    - To support a fusion industry



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A lot of excitement….

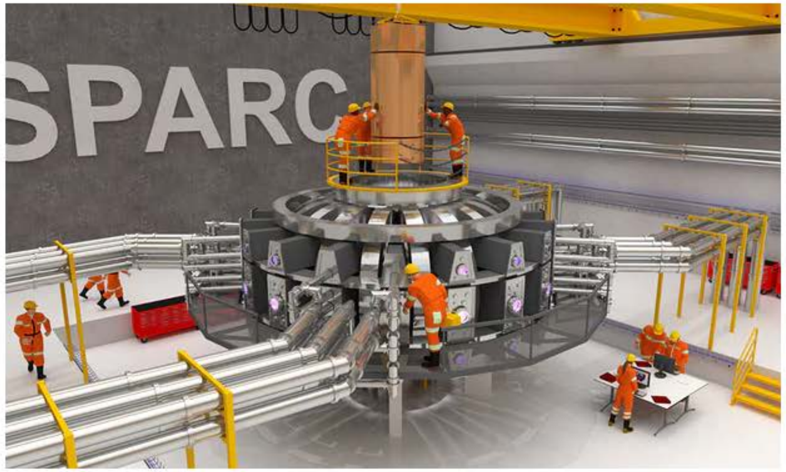
Nuclear power

Nuclear fusion on brink of being realised, say MIT scientists

Carbon-free fusion power could be 'on the grid in 15 years'

Hannah Devlin *Science correspondent*
@hannahdev
Fri 9 Mar 2018 00.01 EST

40,022



▲ A visualisation of MIT's planned fusion experiment. Photograph: Ken Filar/MIT

The dream of nuclear fusion is on the brink of being realised, according to a major new US initiative that says it will put fusion power on the grid within 15 years.

The project, a collaboration between scientists at MIT and a private company, will take a radically different approach to other efforts to transform fusion from an

AMERICAN VOICES

MIT Aims To Build Fusion Power Plant Within 15 Years

3/14/18 9:47am

SEE MORE: OPINION

The Massachusetts Institute of Technology plans to bring nuclear fusion to market in the next 15 years after receiving a $50 million investment, a development that could offer the world massively more efficient and cleaner energy. What do *you* think?

"But when will the new dining hall be finished?"

GREG THOMAS • STUDENT

"Wait, are we not scared of nuclear power anymore? I thought we were still scared of it."

WILLIAM PECK • WAX FRUIT PAINTER

"Those MIT fellas, they're always building stuff!"

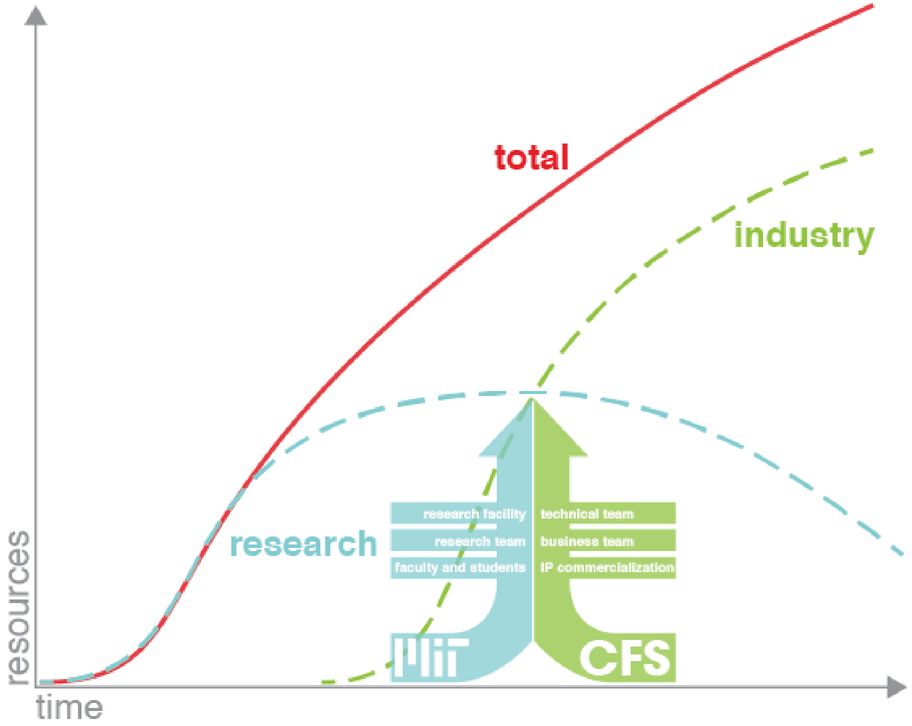
ALICIA BURTON • MINIGOLF COURSE DESIGNER

What's the real story….

Commonwealth Fusion Systems Basics

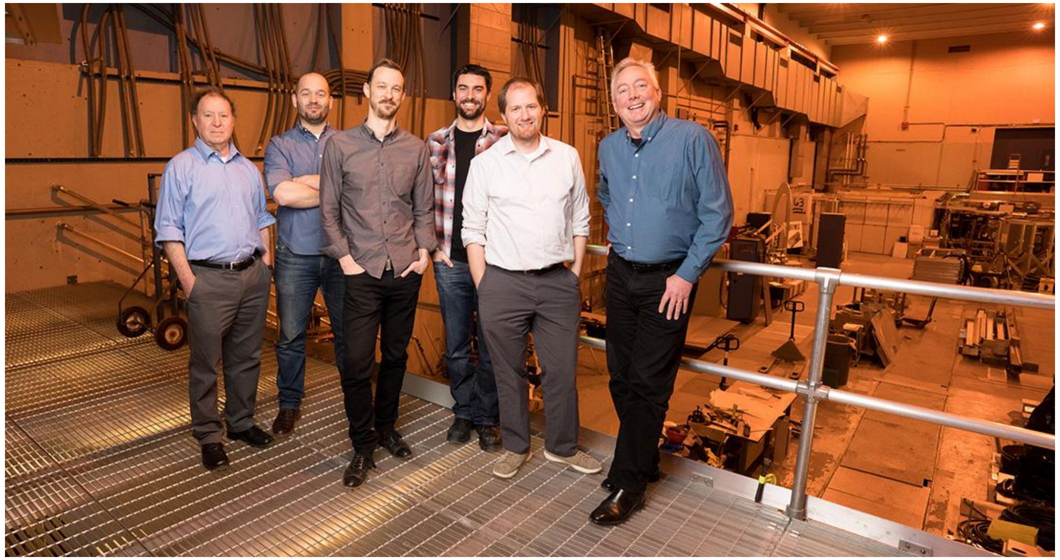
- Why
  - Fusion is important and can make a difference
  - It is our responsibility to make the best attempt at it using all the tools available
  - With an express purpose to make it a commercially viable energy source
- What
  - A private company in tight collaboration with MIT

CFS combines the lean, fast mentality of a startup with the deep talent pool of academia and the world's leading investors in science and energy to develop the fastest path to commercial fusion that will provide clean energy to all.



Commonwealth Fusion Systems Basics

- Who
  - Team – A combination of deep physics experience with talent drawn from other sectors
  - Investors – Visionary, long-term, highly technical, high-capital, risk-tolerant individuals and organizations
  - Partners– Those that share our vision and want to work together to get fusion to impact
  - Serious people taking fusion seriously
- Where
  - Massachusetts based
  - Global market, partners, investors, talent



Commonwealth Fusion Systems Basics

- When
  - Now!
  - There is a moral imperative
  - There is a window in the energy transition
  - HTS offers a breakthrough
  - Now is the time to punch forward
- How
  - High-field approach based on HTS
  - Science + Scale + Speed + System

We know the technical gaps

CFS

US studies:

- US community report on research gaps (2007)
- US community report on research needs (2009)
- Technical readiness evaluation (2009)
- EPRI assessment on fusion (2012)
- PPPL study (2012)
- AAAS report on pathways (2013)

International:

- IOP report (2008)
- Korean fusion roadmap (2009)
- EU fusion roadmap (2012)
- Chinese fusion roadmap (2014)
- Japanese fusion roadmap (2015)

- These have been extensively studied: Good!
- We don't have solutions, yet
- Having a strategy is key
    - Reduce the scale to move quickly
    - Be innovation-driven, leverage other fields
    - Evaluate work-arounds to build momentum
- But there are MANY identified innovations that can help for all the fusion concepts, but we haven't pulled the trigger

Tokamak fusion reactor to do list

- ❑ Net energy gain
- ❑ High-gain plasma physics
- ❑ Superconducting magnets
- ❑ Long-pulse core plasma physics
- ❑ Steady state actuators
- ❑ Divertor heat flux mitigation
- ❑ Low first wall erosion
- ❑ Blanket and shield
- ❑ Feasible maintenance scheme
- ❑ T breeding and separation
- ❑ Neutron resistant materials
- ❑ Long lifetime components
- ❑ Licensed, safe, and accepted
- ❑ High availability
- ❑ Energy conversion to electricity

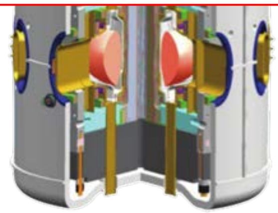
Commonwealth Fusion Systems Plan

Academia | Collaboration | Commonwealth Fusion Systems

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9

Basic research · Prove feasibility · Tech Demonstration · System and subsystem dev. · Pilot plant · Market launch

Science proof-of-principle



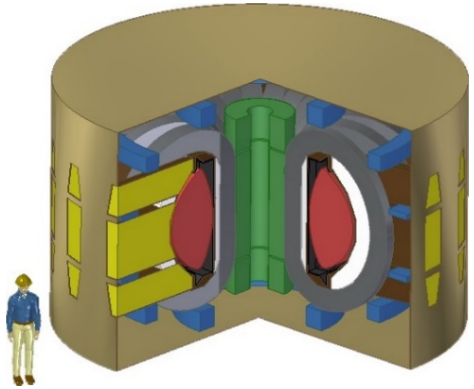
Alcator C-Mod

Complete

Technology proof-of-principle

SPARC
TF magnet

Science and technology demonstration and development testbed



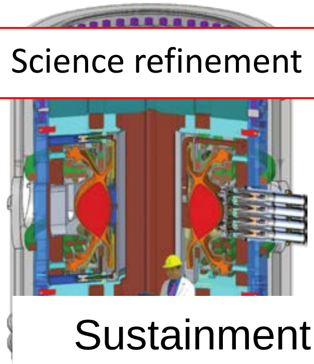
SPARC

Energy gain > 2

P_{fusion} > 50 MW

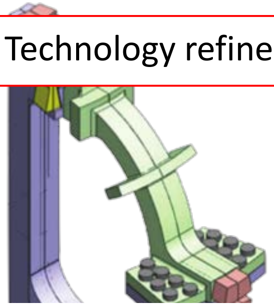
Pulsed

Science refinement



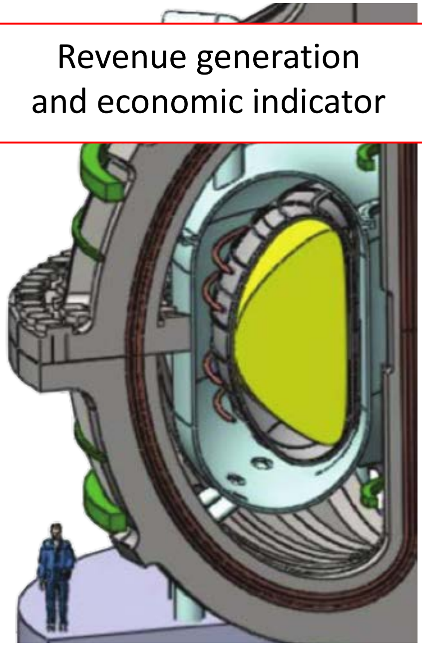
Sustainment R&D

Technology refinement



Component engineering R&D

Revenue generation and economic indicator



ARC pilot plant:

Energy gain > 10

$P_{electric}$ ~200 MW

Focus on HTS magnets

Academia	Collaboration	Commonwealth Fusion Systems

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Basic research		Prove feasibility	Tech Demonstration		System and subsystem dev.		Pilot plant	Market launch

Phase 1: 3 years

- Develop HTS magnets at scale
  - Including manufacturing systems
  - Supply chain
  - Structures
  - Quench
- Design SPARC and critical R&D
- This is well-underway now

Then quickly get to net energy

Academia | Collaboration | Commonwealth Fusion Systems

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9

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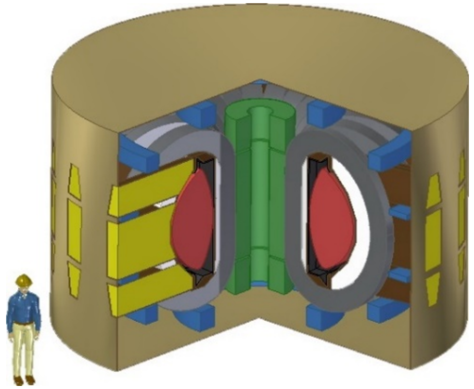


SPARC

Energy gain > 2

P_{fusion}> 50 MW

Pulsed

Science refinement

Component engineering R&D

Energy gain > 10

$P_{electric}$ ~200 MW

Phase 2: 4 years

- Build and operate SPARC
    - Net energy
    - Change the narrative
    - Explore higher Q
- R&D on ARC issues
- ARC conceptual design

Then quickly get to net electricity

Academia
Collaboration
Commonwealth Fusion Systems

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9

Basic research | Prove feasibility | Tech Demonstration | System and subsystem dev. | Pilot plant | Market launch

Science proof-of-principle

Science and technology

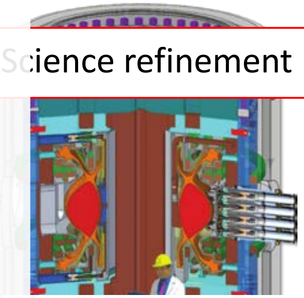
Phase 3: 8 years

- Prototype ARC subsystems
- Build and operate ARC
  - Net electricity
  - Refinement of concept through successive upgrades

SPARC
TF magnet

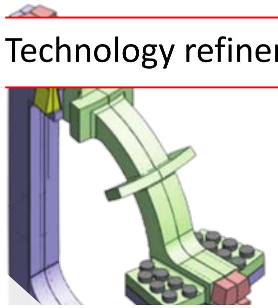
Pulsed

Science refinement



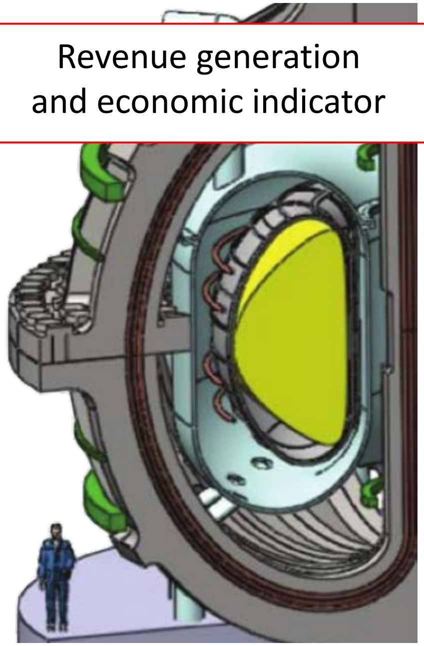
Sustainment
R&D

Technology refinement



Component engineering
R&D

Revenue generation
and economic indicator



ARC pilot plant:
Energy gain > 10
$P_{electric}$ ~200 MW

This is the plan we're funded to do

- Solutions are not all in-hand
  - But strategies identified
- The plan is aggressive
  - Fusion is worth being aggressive
  - We'd like to move even faster
  - Of the private plans it is the least aggressive
- It assumes success
  - Because we know the talent level
- It takes on risks sooner rather than later
  - "Waiting to solve problems" is not a program
- Given more resources it could be parallelized
- **Our investors and partners have bought into this**

We are headed to 88mph….

Lets talk about 15 years…

- Our aim is to put fusion electricity on the grid in this timeframe
- Why do we think we can do this?
- **15 years is a long time in the real world!**
  - **– Especially when there is a breakthrough + a substantial need**

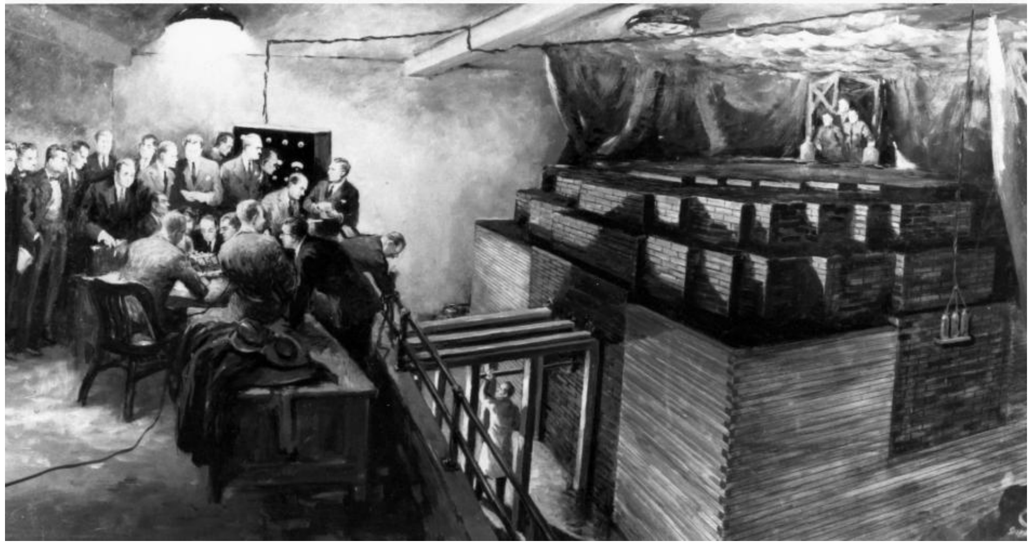
Game changer definition:
a newly introduced element or factor that changes an existing situation or activity in a significant way

Breakthrough definition:
A sudden advance especially in knowledge or technique

An act or instance of moving through or beyond an obstacle

Lets talk about 15 years… Fission power

1942 – Pile 1
0.5 W thermal



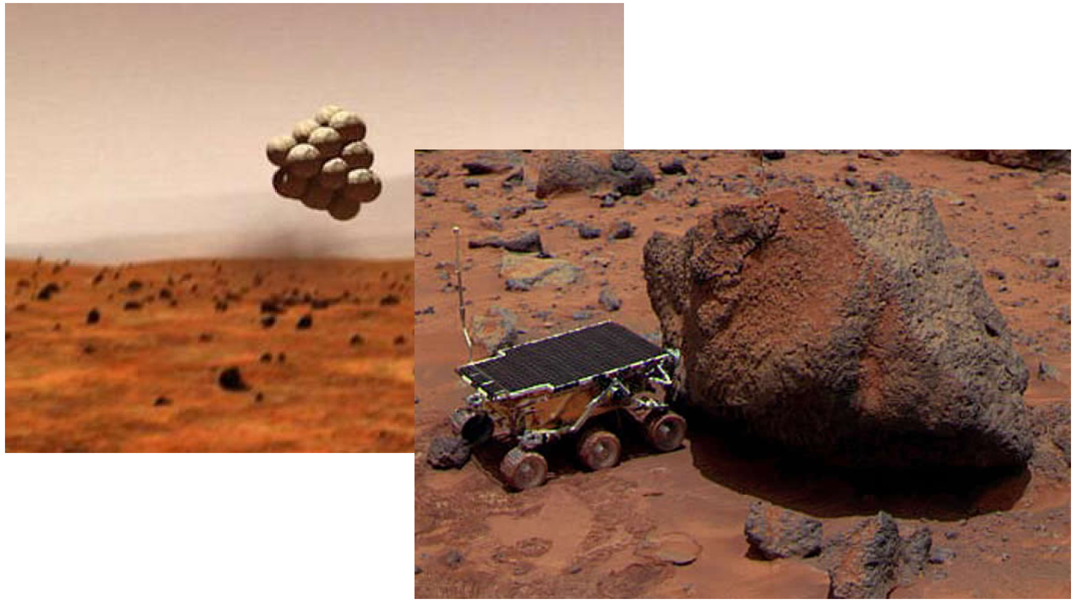
War drives science.
Very basic nuclear physics, no materials knowledge, no applications, no industry

1957 – Shippingport
60 MW electrical, public-private
Market drives engineering

+ 2 fully-private full-scale plants under construction
Architecture fixed, soon to scale to 20% of US power

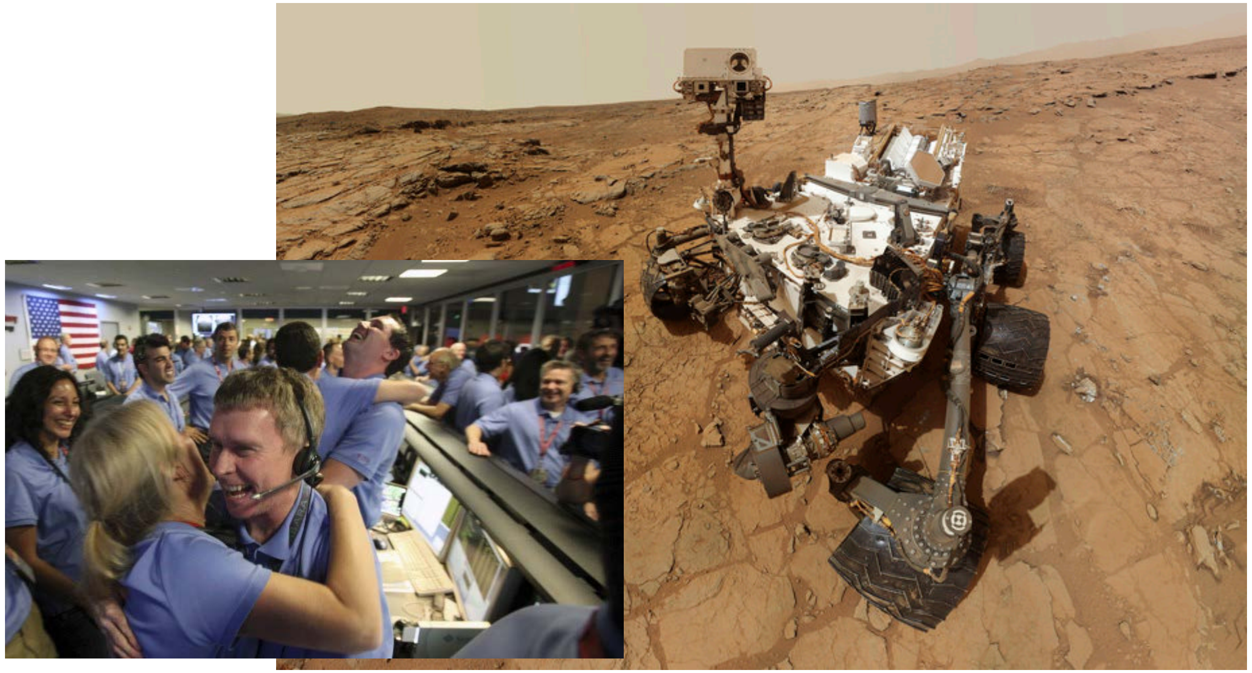
Lets talk about 15 years… Mars

1996 – Mars Pathfinder lands



Organizational innovation pushes the cost of landing something on Mars down a factor of 20 and shortens the development time by a factor of 3.

2012 – Curiosity, a nuclear-powered SUV roving on Mars
Success breeds success



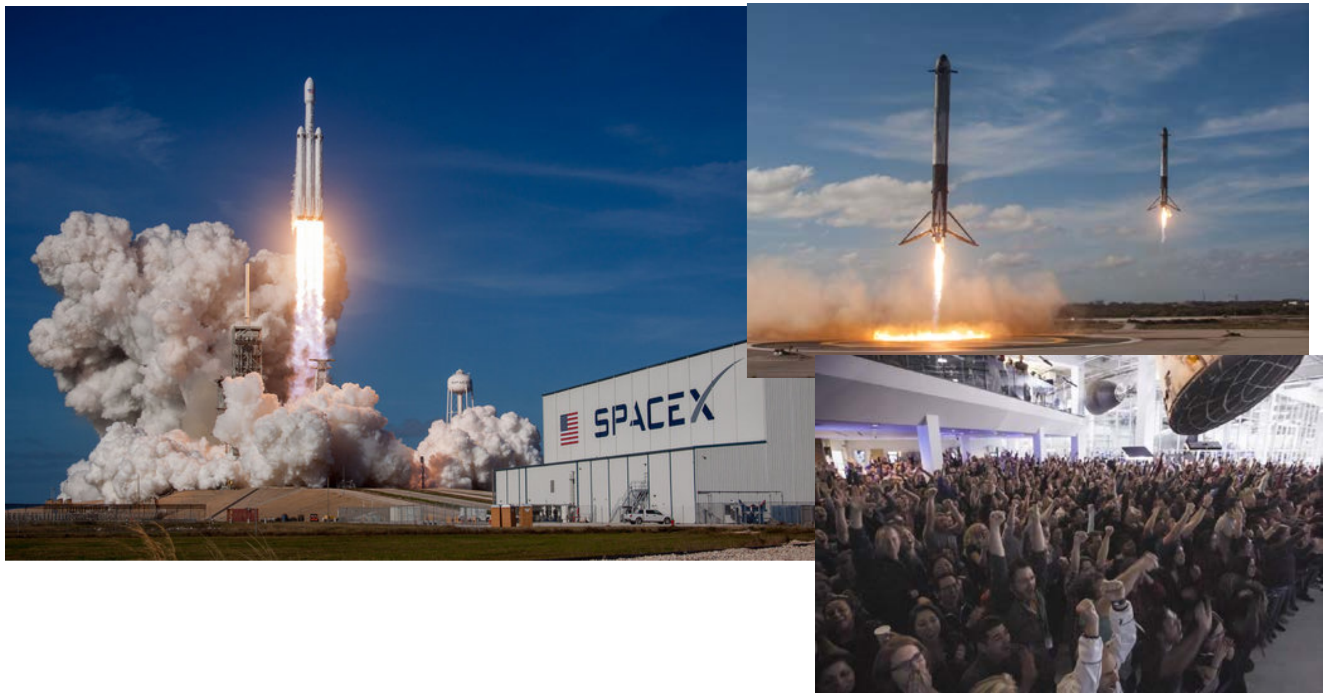
Over 20 spacecraft operating at Mars. Budget up a factor of 15. Program attracts the best and brightest and captures imaginations.

Lets talk about 15 years… SpaceX

2002 – SpaceX founded

Launch is a very expensive, hide-bound program dominated by government-funded contractors with very little innovation.

2018 – Falcon Heavy
Innovation applied to orgs and tech, supercharged by finance

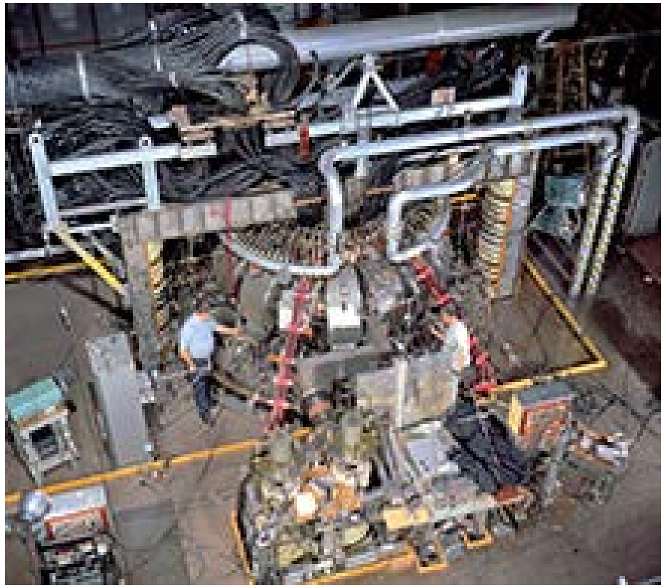


Falcon 9: 4 years + $300M from napkin to launch
Cuts the cost to orbit by factor of 10, built a market

This is what our investors expect

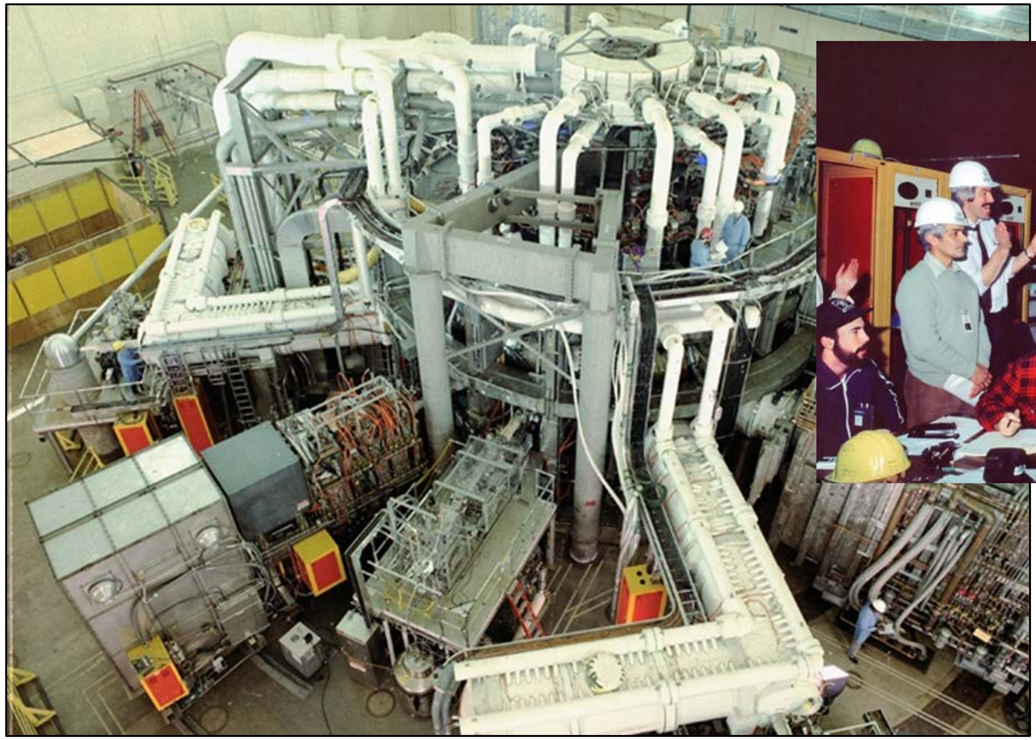
Lets talk about 15 years… Fusion

1971 – ST shows tokamaks work



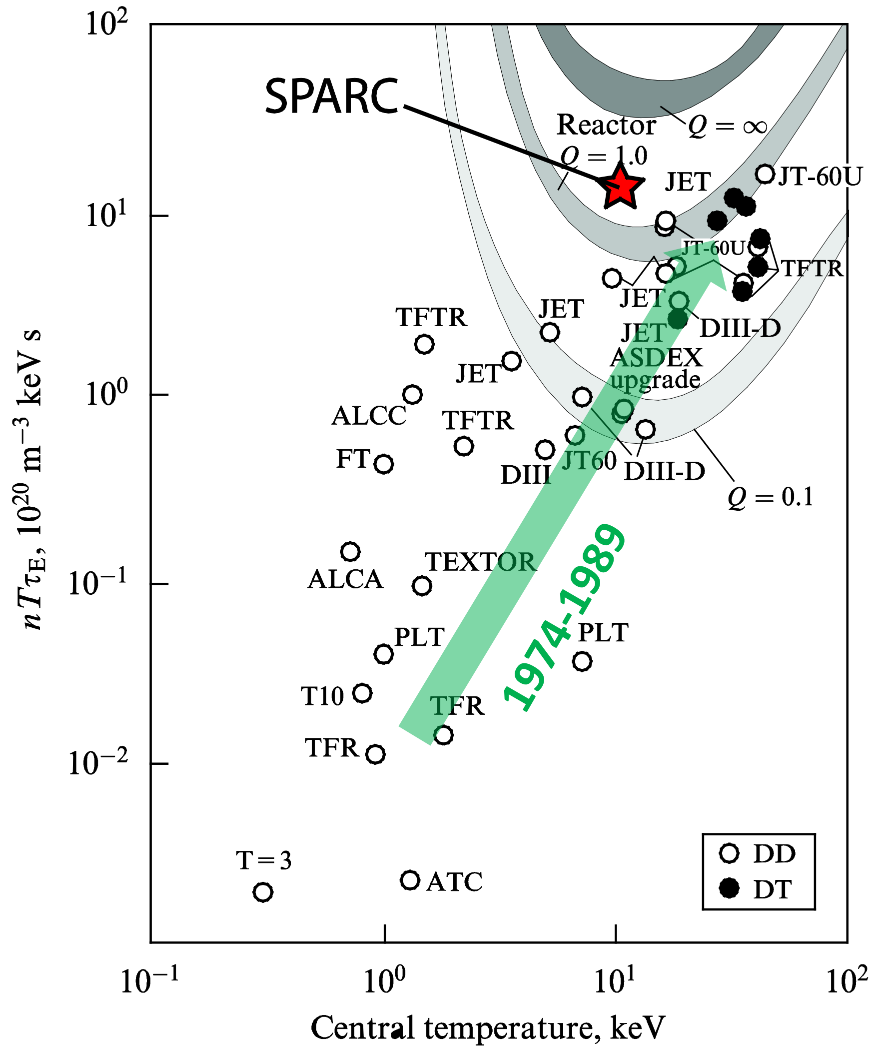
Tokamaks are performing good enough, the world needs energy, we have sights on the technology.
Make push for DT.

1986 – JET, JT-60, TFTR running, supershots, prepping DT



Drastically expanded the operating space for tokamaks, developed most of the technologies we now use.
It wasn't that expensive.

Lets talk about 15 years… Fusion

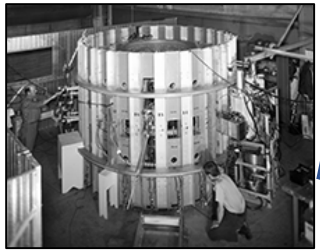


Extrapolations in performance		
Parameter	1974-1989	Today-ARC
Plasma current	10	1.5
Toroidal field	2	1
Magnetic energy	100	18
Pulse length	1000	??
Auxiliary heating	100	0.75
Ion temperature	10	0.5
Triple product	1000	~2-5
D-T fuel	DT	Done
Fusion power	10000000	>15
Q	10000000	>10

Why can't we do this again?... We don't have so far to go.

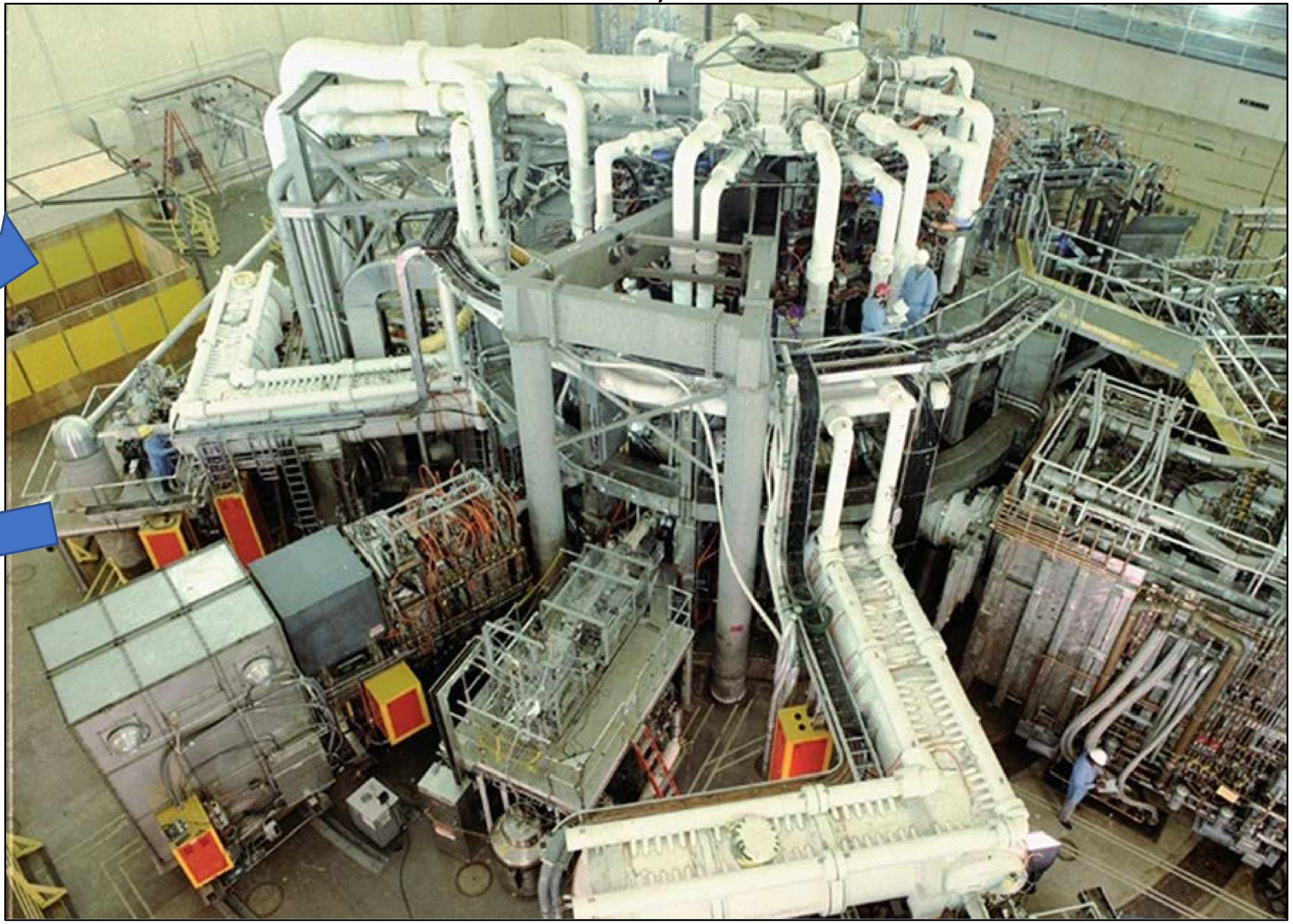
Lets talk about 15 years… Fusion

ATC, 2T



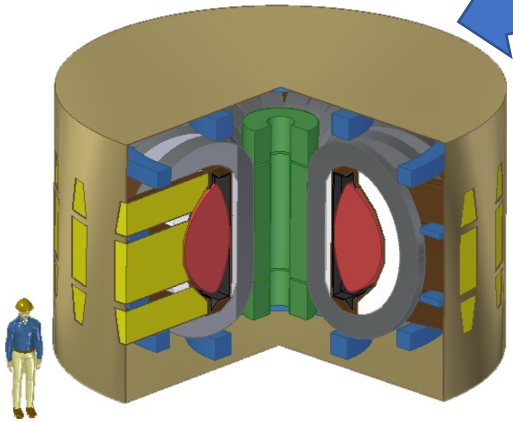
1974:
Tokamak physics mature *enough* to try DT

TFTR, 6T



2016:
HTS mature *enough* to build a tokamak

SPARC V0, 12T



Approximately to scale

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* Mumgaard addition

1. Everybody should be incredibly excited

- There may not be consensus on everything… except on how awesome this could be
- Everyone we talk to is extremely excited
    - Investors who invested and those who didn't
    - Government officials
    - Talent and partners
    - Other fusion companies
    - The public
- This is additive to other programs
    - Do no harm – not a competition, we all want fusion to work

2. Find ways for gov't and industry to work together

- The US is very good at industry –academia –government
- Each side does what it is good at
  - Government does basic research, deep expertise, tool sets, seeds innovation
  - Private selects architectures, finds market fit, scales solutions, manages costs
- There are many ways to do this
  - Expert reviews, running codes on industry configurations
  - Access to experts, seconding equipment, diagnostics
  - In-kind contribution
  - Help with siting, cost sharing components
  - Joint development projects
- There are many relevant precedents
- This will support all of the fusion concepts

3. Solve problems –With urgency

- There are plenty of problems and potential solutions identified
  - More efficient and better actuators
  - Integrated simulation, AI, control, predictive modeling
  - Advanced divertors and power handling
  - PMI, liquid metals, addative manufacturing
  - Nuclear materials, fuel cycle, tritium breeding
  - Advanced concepts
- All of this is ready to go, people want to work on it
- It is all fairly low cost –there will need to be reprogramming
- Staying static will not be supported by industry
- This helps all of the fusion concepts –if done soon
- Windows for the US to lead on this are closing as others solve problems

4. Do what only gov't can do- With urgency

- There are some things only gov't can do
  - Developing the appropriate regulatory structure
  - Help with siting
  - Pathways to provide tritium
  - Convening stakeholders
  - Developing a workforce and academic
- These are independent of configuration
- Industry will help
- This needs to be ready in time if we are to get fusion to impact

This is what leadership looks like:

- New experiments and programs
- New programs at new places with new people attracted to the field
- Working on innovative ideas that can make a difference for fusion
- Working across sectors from private to public to academic
- Unique capabilities
- Pushing the boundary
- Engaging the public

These are bold times for fusion
We need to match the times

We have the good ideas!

We have people and institutions that want to do them!

We have enough money, just in the wrong places

What is stopping us?

Imagine in 10 years we have:

Demonstration of Reactor-Relevant Steady-State Scenarios with Reactor-Relevant RF Actuators and Sensors in the DIV tokamak

ZetaScale Computing of Turbulent Simulations of a Tokamak: From the Core to the Wall

CFS

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

THE UNIVERSITY OF TEXAS AT AUSTIN

PRINCETON UNIVERSITY

PPPL

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

UNIVERSITY OF MARYLAND 1856

MIT PSFC Plasma Science and Fusion Center

GENERAL ATOMICS

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UAF UNIVERSITY OF ALASKA FAIRBANKS

Lawrence Livermore National Laboratory

Performance of Fusion Structural Materials Irradiated in the National Gas Dynamic Trap Facility

First Plasma in the National Optimized Stellarator Experiment

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MIT | PSFC Plasma Science and Fusion Center

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AUBURN UNIVERSITY

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

PRINCETON UNIVERSITY

OAK RIDGE National Laboratory

NYU

Los Alamos NATIONAL LABORATORY EST.1943

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Lawrence Livermore National Laboratory

Attainment of Passively Stable Divertor Power Exhaust at Reactor-Relevant Conditions

Progress in the ARPA-E Industry-Lab-University Alternates Partnership

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CHANGING WHAT'S POSSIBLE

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ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Confinement Scaling to Reactor-Relevant Collisionality with Liquid Metal Walls in ST40-U