SPARC

SPARC and the high-field path to commercial fusion energy

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MIT Plasma Science and Fusion Center

Strategies and Expectations through the 2020s

It is a critical time for energy -- are we going to be a part of the conversation?

Themes:

Moving toward energy relevance

The high-field approach

Moving together

Moving with purpose

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Start with the why

THE HILL

Climate change is no longer a future problem

BY SHAHIR MASRI, OPINION CONTRIBUTOR — 12/03/18 03:30 PM EST
THE VIEWS EXPRESSED BY CONTRIBUT

484 COMMENTS

6 SHARES

Just In...

HUFFPOST

David Attenborough's Dire Climate Warning: ‘Our Greatest Threat In Thousands Of Years'

The Washington Post
Democracy Dies in Darkness

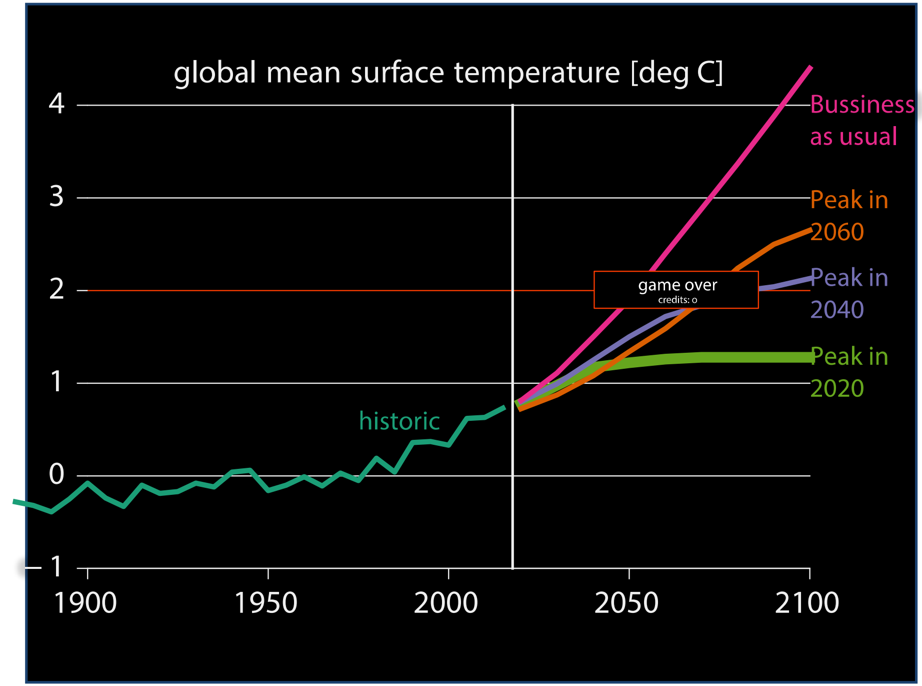
Opinions

The world is moving forward on climate — with or without Trump

COP24·KATOWICE 2018
UNITED NATIONS CLIMATE CHANGE CONFERENCE

Is fusion relevant to climate change?

- If so, this sets the timing:



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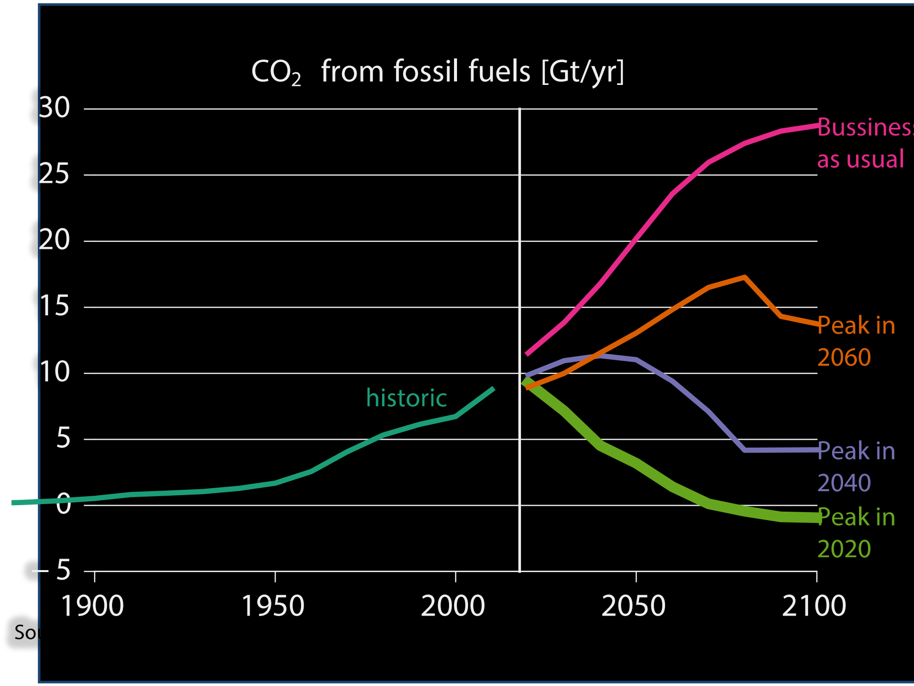

So

Is fusion relevant to climate change?

- If so, this sets the timing:
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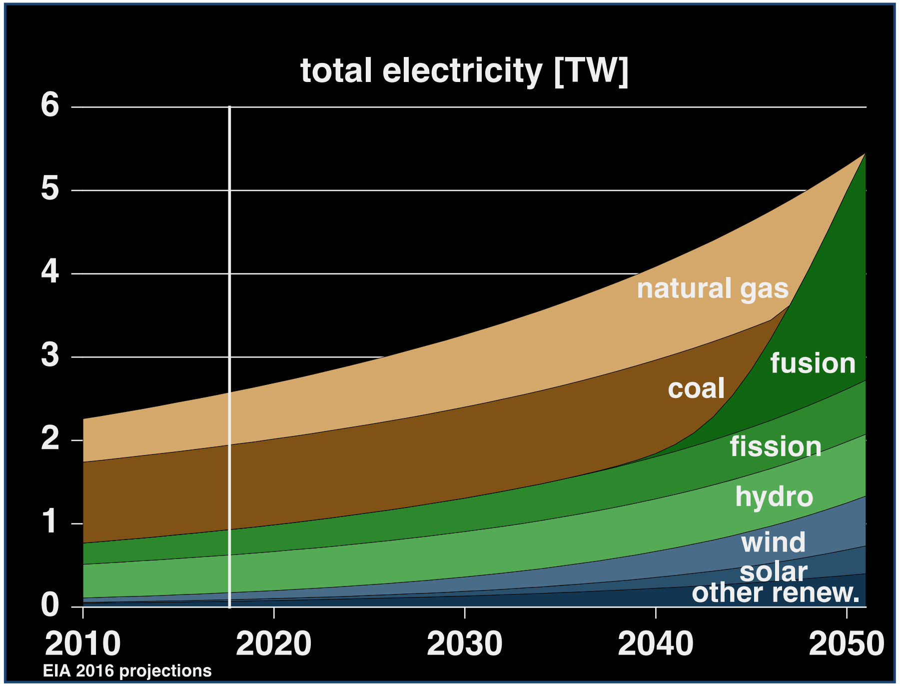

Is fusion relevant to climate change?

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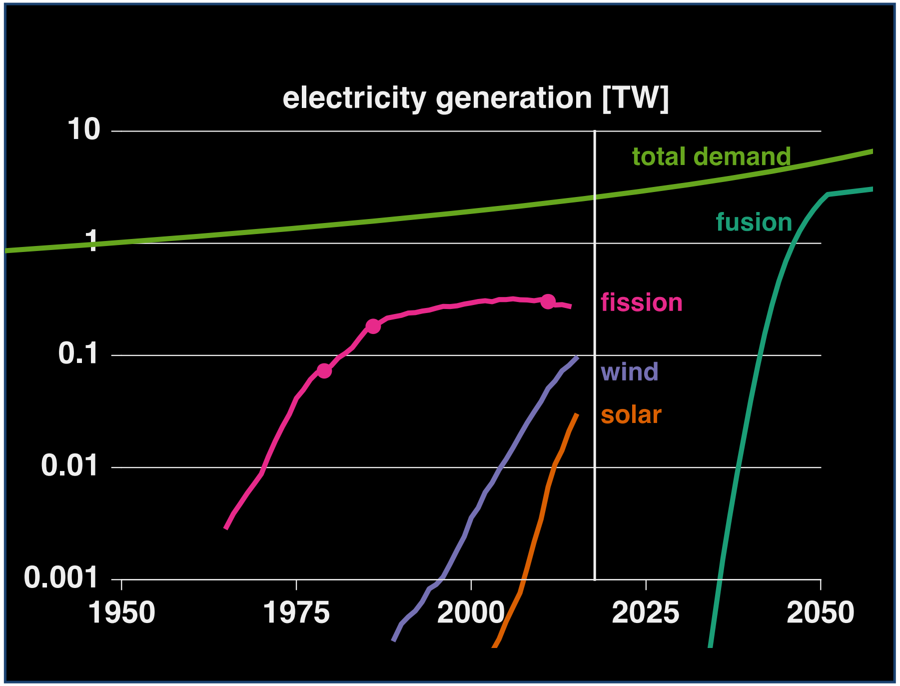
  - Deploying first plants in 2030s



Is fusion relevant to climate change?

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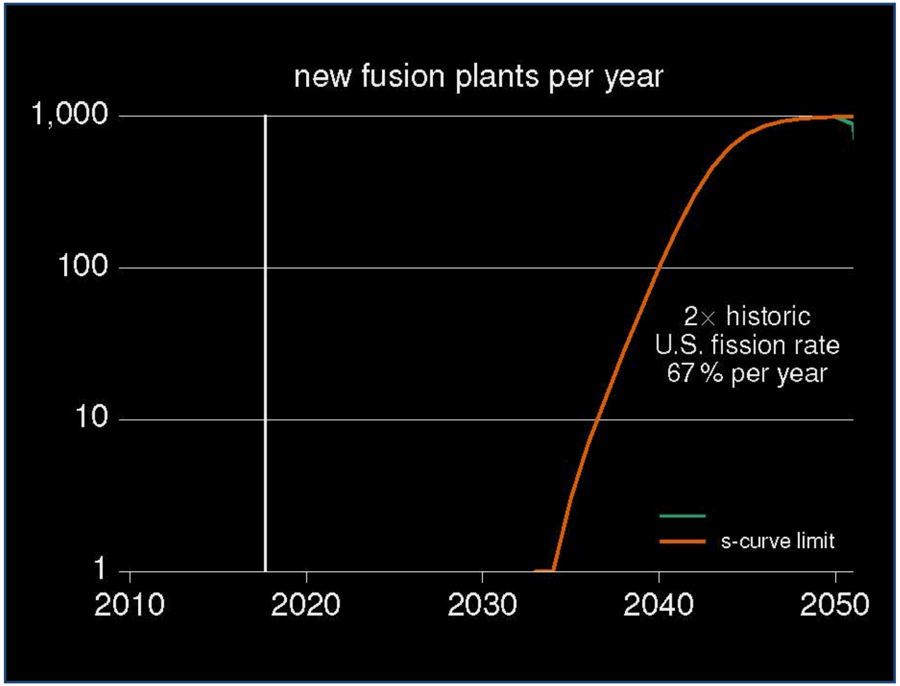
  - Deploying first plants in 2030s
  - Demonstrating market-indicators in 2020s



Is fusion relevant to climate change?

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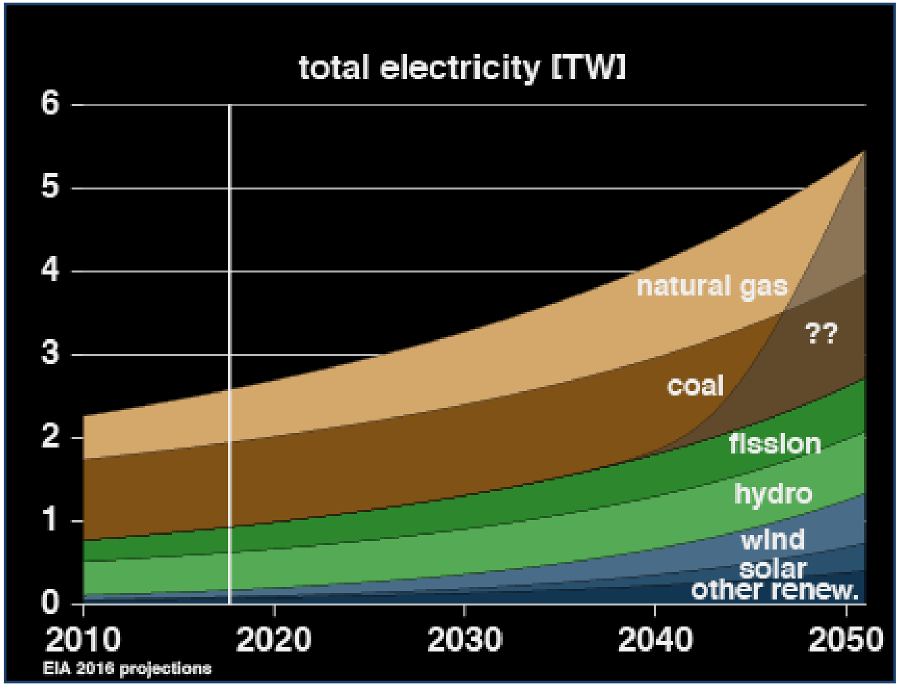
  - Something else will, or things won't go well



The market will decide

Is fusion relevant to climate change?

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  - Deploying first plants in 2030s
  - Demonstrating market-indicators in 2020s
- If we can't hit the timing:
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  - Why do we do fusion?

If fusion does not have a plan to participate in the climate change mitigation we need to be honest with our stakeholders:

- The public
- Governments
- Our young people
- Ourselves

Speed is the driver -- what are the ways to get speed?

The tech plan

- 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

Who we are

- Increase private capital participation – success acts as accelerator
- Decrease the number of stakeholders – keep them aligned
- Recruit outside expertise – people have done similar things

How we operate

- 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

Feedback from the energy world:

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

Many of the current government-driven fusion plans are not aligned with them

What they need to see:

- Show net-energy high power production ASAP – net electricity if possible
- In a package that scales to an economical and market-relevant power plant
- In a robust and simple as possible configuration
- In a market-relevant timeframe
- With concrete risk retirement milestones to track progress

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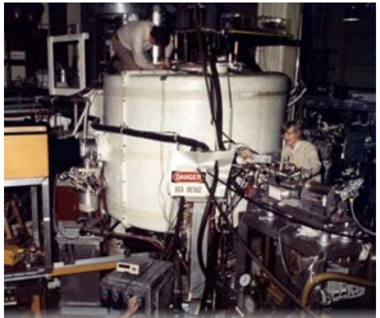
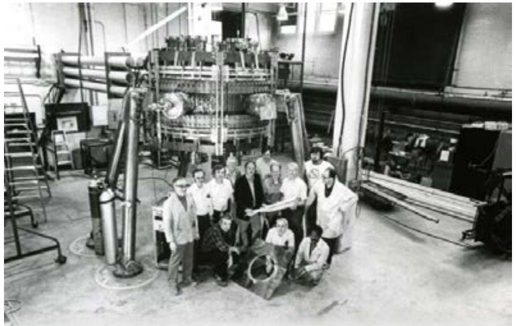
Tokamaks don’t have to be big, expensive, slow, unwieldy programs

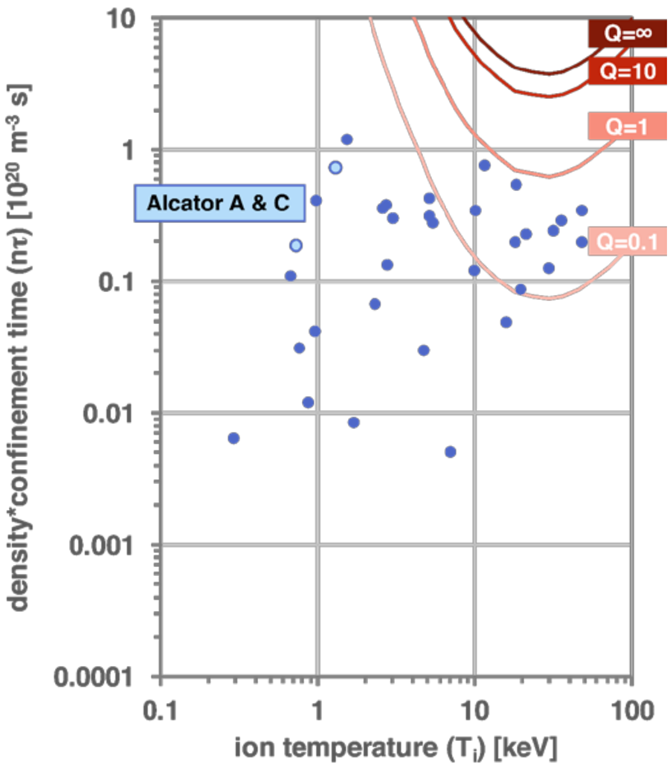
- There are some small very high performance early tokamaks



Alcator A
MIT 1969
10 Tesla

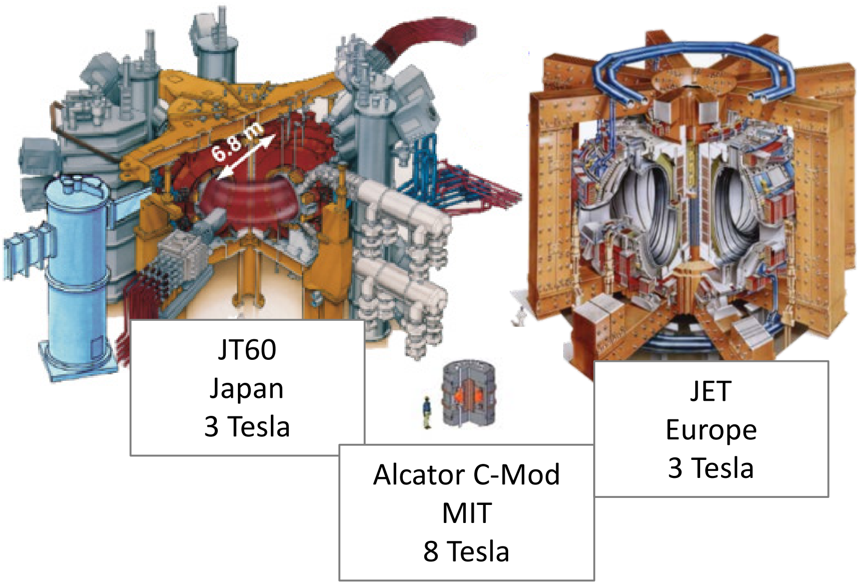


Alcator C
MIT 1978
12 Tesla

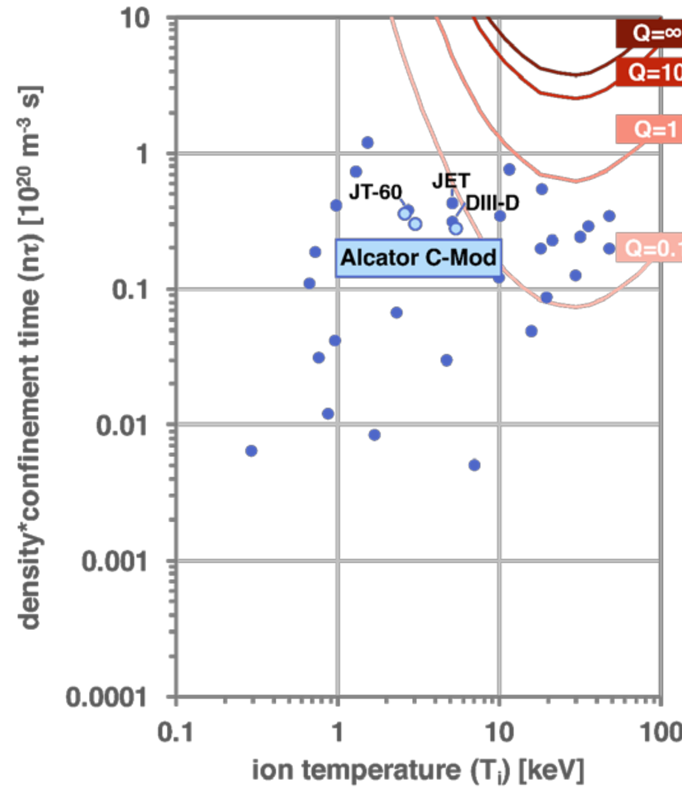


- These were enabled by a cutting edge technology at the time
  - High-field, cryogenically-cooled, high-strength copper magnets developed for magnetic science (MRI, NMR, etc)
- They were early, inexpensive, small, team-oriented, and quickly constructed on a university campus
- These, what might qualify as “startups”, beat the large devices at the national labs to get the Lawson criteria above breakeven

Compact high-performance tokamaks: Demonstrated high absolute performance in small package

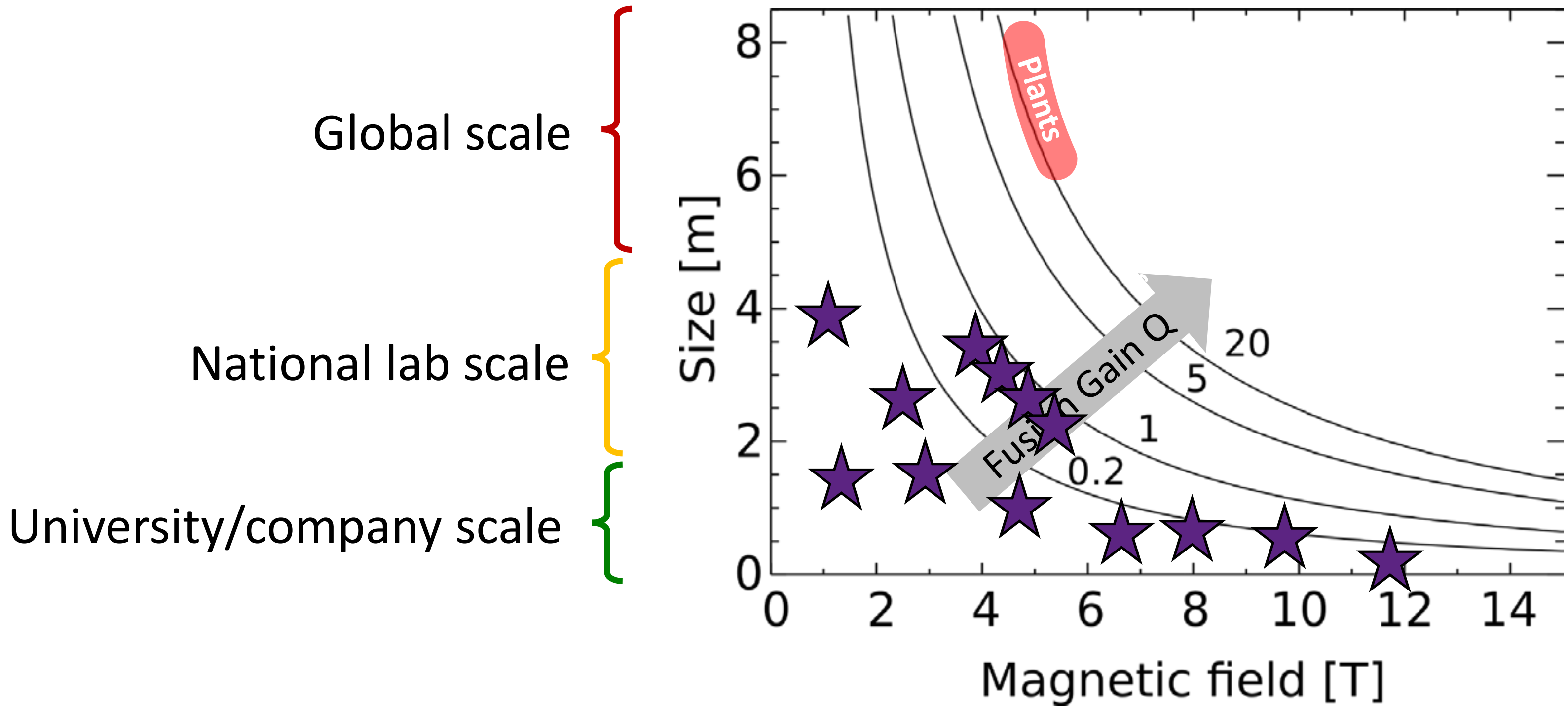


- C-Mod finished a successful 23 year career
- Extended physics basis for tokamak operation at high-field
- Data is still providing insights



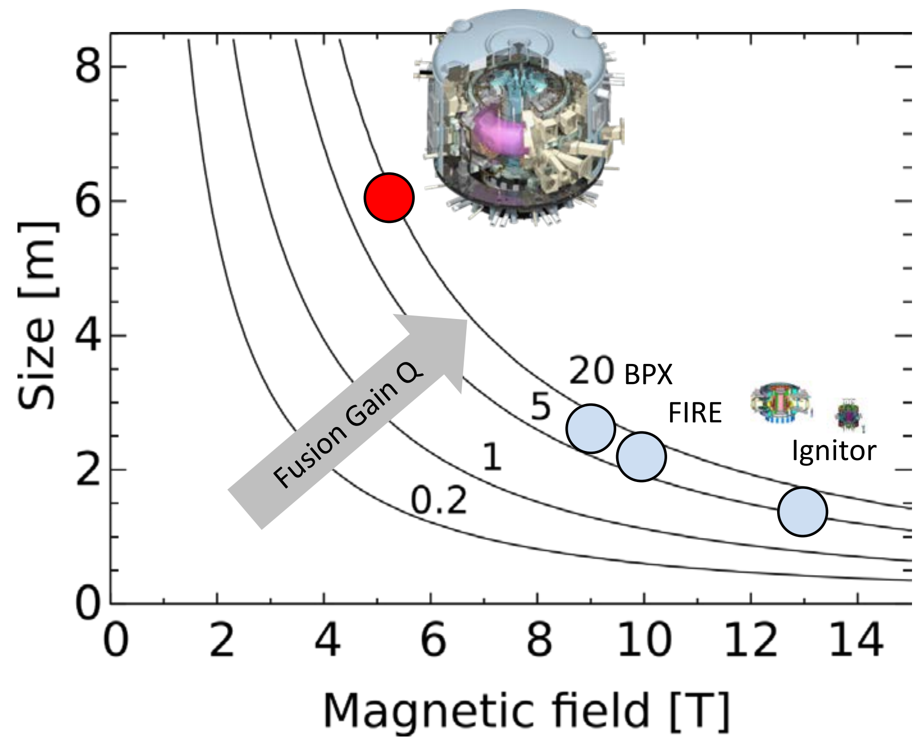
60 years of research shows the magnetic field plays a central role in the size of tokamaks

Curves of constant Q from experiments and simulations.   Only tokamaks can draw these with confidence. Results of decades of hard-won science.

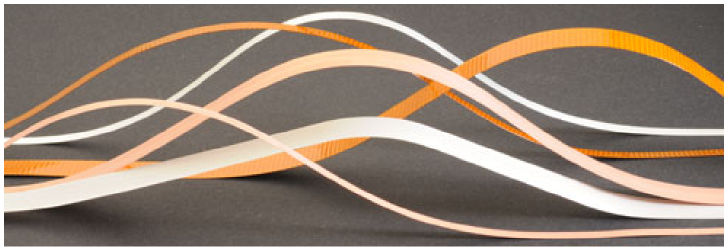


The road not taken: Compact, High-field, Copper

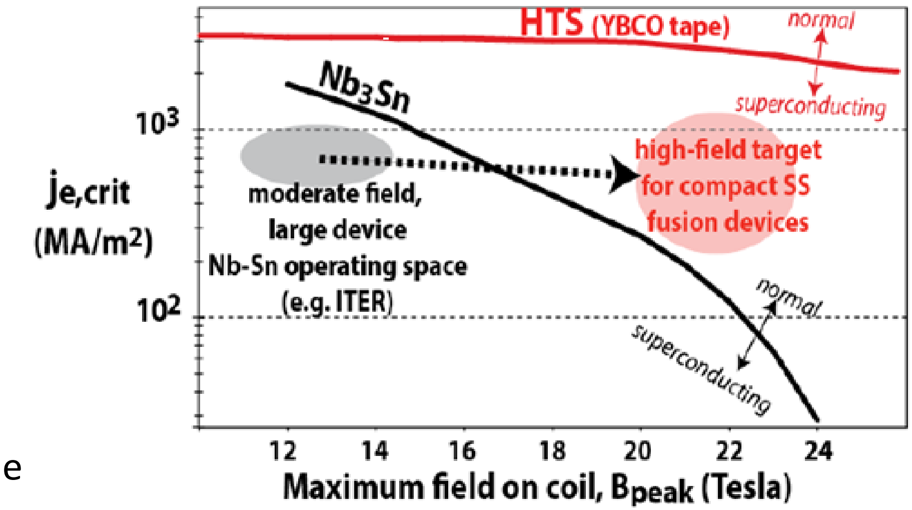
- Concepts validated by extensive review by FESAC, NAS, workshops.
- ITER was chosen and the U.S. program was down-selected.
- There were compelling reasons to go with ITER over FIRE and vice-versa.
- These copper machines would never scale to a power plant due to the magnet power consumption.



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

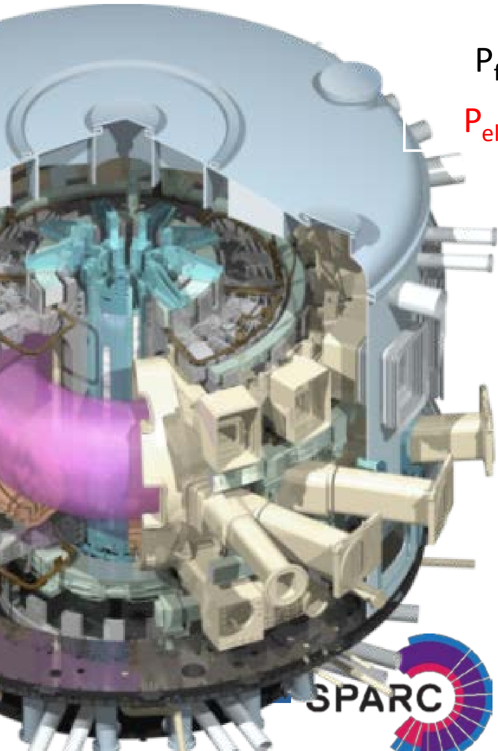


This is ambitious. A high-field large-bore HTS coil has not been demonstrated. Yet.

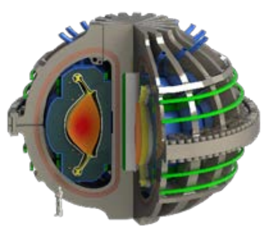
With this magnet technology one can build smaller fusion tokamaks

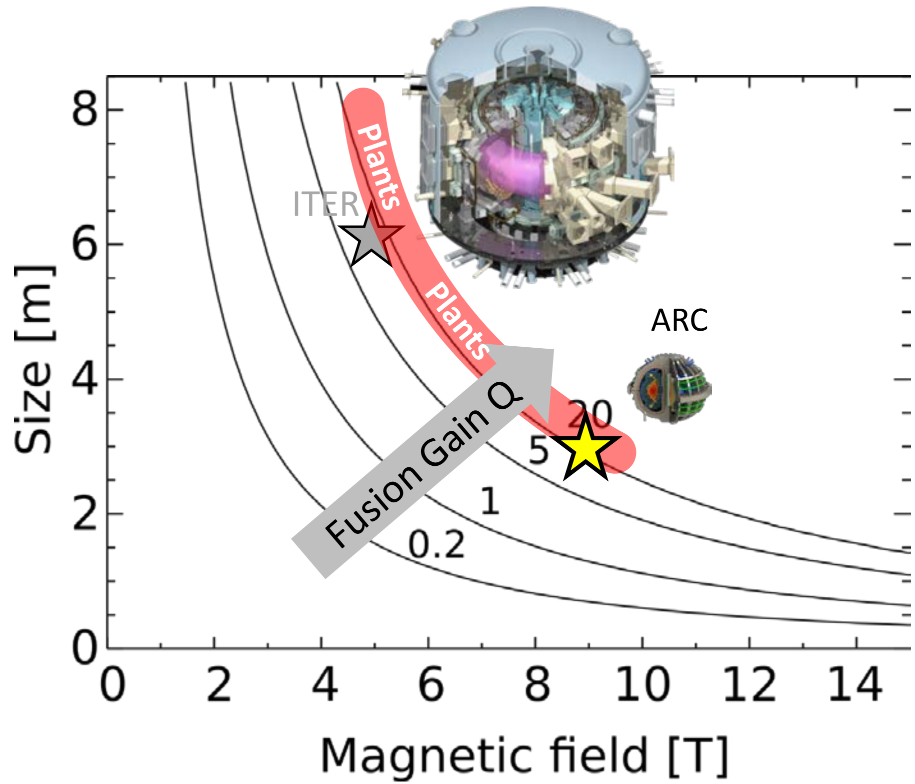
	ITER	ARC
R [m]	6.2	3.2
Magnet	LTS	HTS
B [T]	5.3	9.2
P_{fusion} [MW]	500	500
$P_{electric}$ [MW]	0	200

ITER



ARC



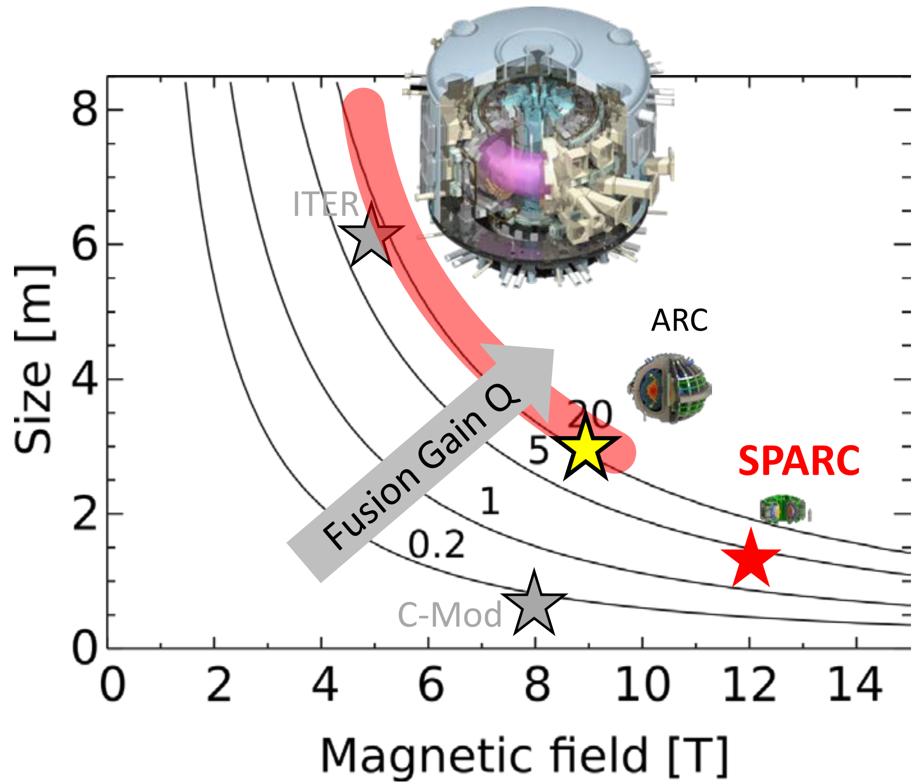


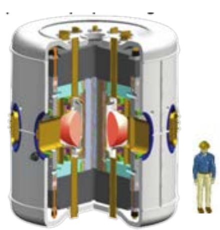
… and we can now build really small net-energy fusion demonstrations to retire risk early and at lower cost

If higher magnet fields enable ARC to rethink how fusion energy tokamaks are designed … why stop there?

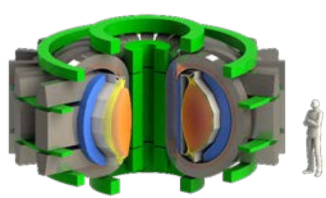
SPARC is the logical next step and be about twice the size of the current experiment at MIT.

It can prove the feasibility of fusion and demonstrate the key technologies. At a small scale.





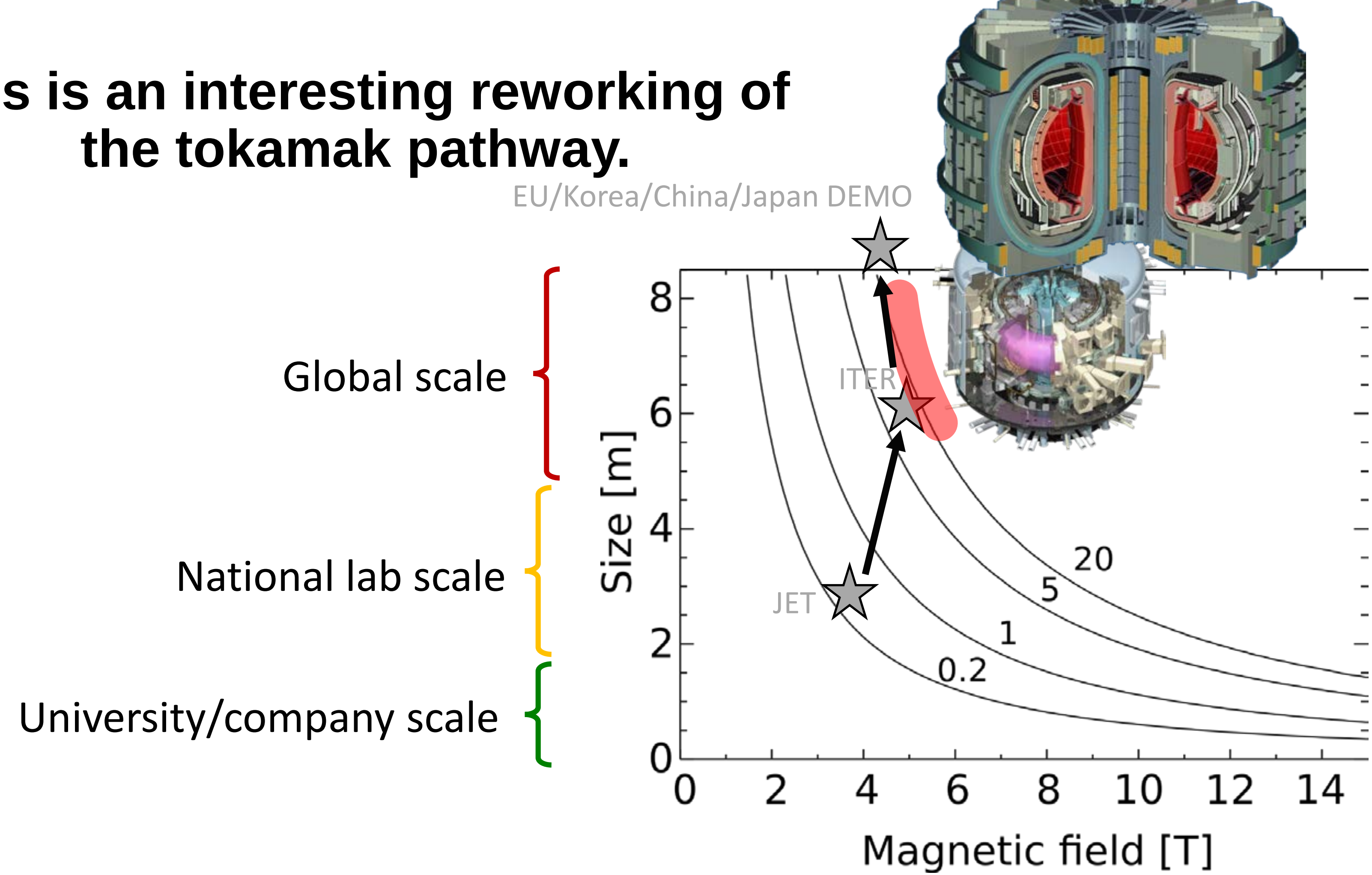
Alcator C-Mod
(MIT PSFC today)



SPARC
(MIT PSFC tomorrow)

SPARC

This is an interesting reworking of the tokamak pathway.

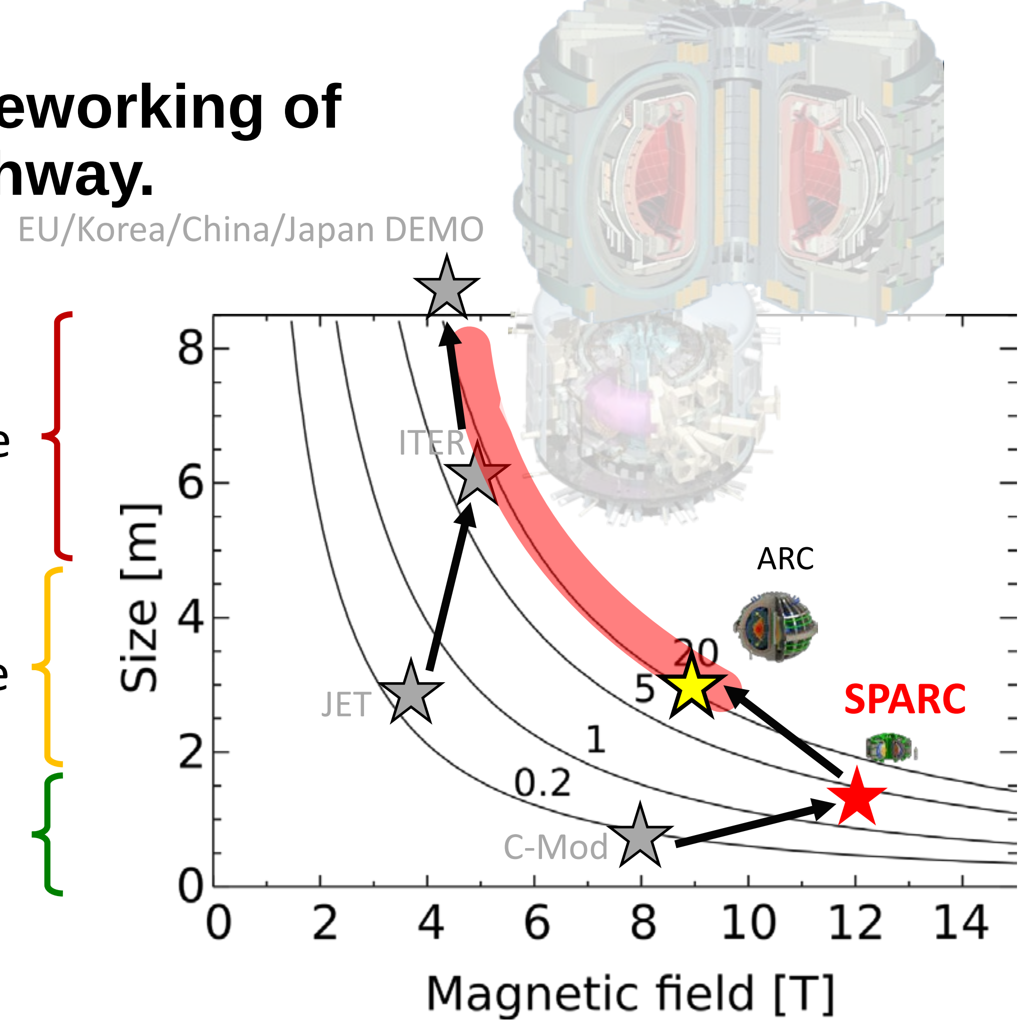


This is an interesting reworking of the tokamak pathway.

Global scale

National lab scale

University/company scale



How we get there: Risk retirement in concrete steps

Phase 1: Technology Development

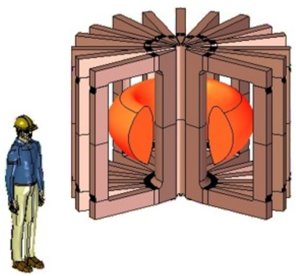
Phase 2: Demonstration

Phase 3: Commercialization

How to structure a concrete risk retirement plan?

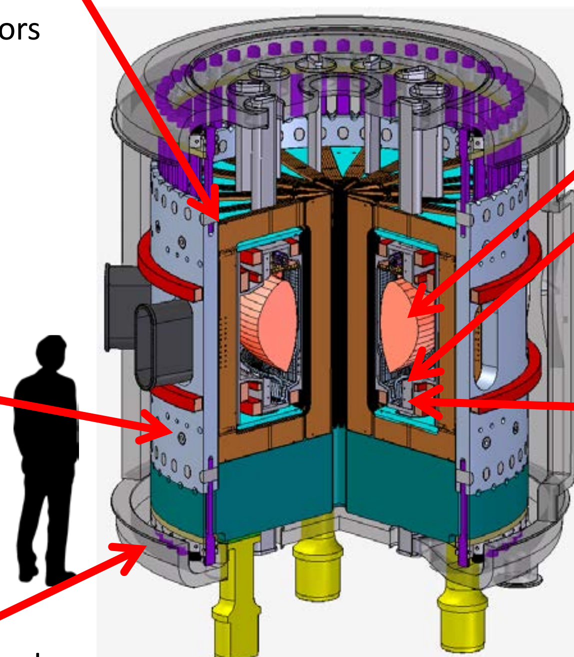
Start with a team that has built fusion devices

Toroidal field (TF) magnetic coils
The heart of any tokamak
LN2 cooled copper to enable B_{coil} > 16T
- Cu works for experiments but not reactors



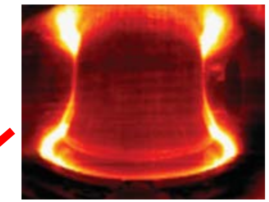
Forged superstructure supports large electromechanical forces

Alcator C-Mod, MIT:
R= 0.68m
8T Cryogenic Cu

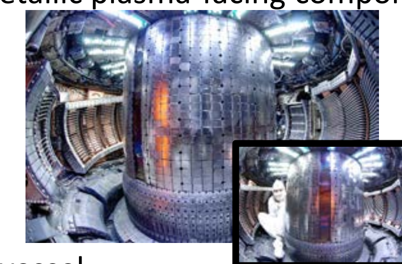


Cryostat cools coils to 77K

Plasma >80 Million degrees



Metallic plasma-facing components



Vacuum vessel

Housed in an experimental cell

Risk retirement in concrete steps

Phase 1: Technology Development

Phase 2: Demonstration

Phase 3: Commercialization

C-Mod

Need to develop the HTS magnets

Risk retirement in concrete steps

Phase 1: Technology Development

Phase 2: Demonstration

Phase 3: Commercialization

C-Mod

IN PROGRESS

HTS magnets

Couple the accomplishments

Risk retirement in concrete steps

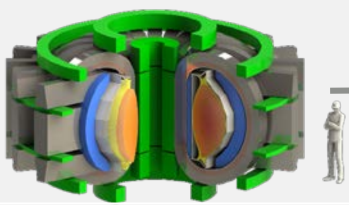
Phase 1: Technology Development

Phase 2: Demonstration

Phase 3: Commercialization

C-Mod

HTS magnets



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

Make into a product

Risk retirement in concrete steps

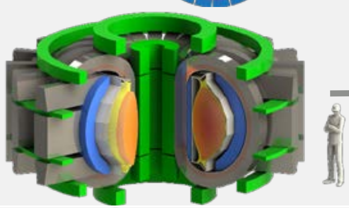
Phase 1:
Technology
Development

C-Mod

HTS magnets

Phase 2:
Demonstration

SPARC



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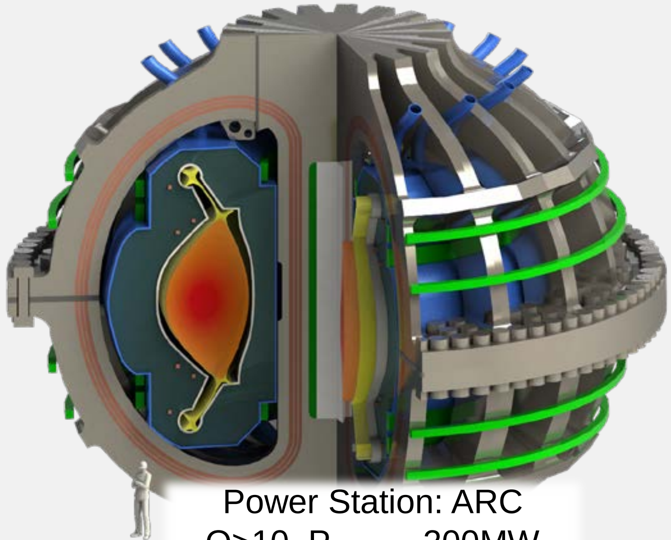
Phase 3:
Commercialization

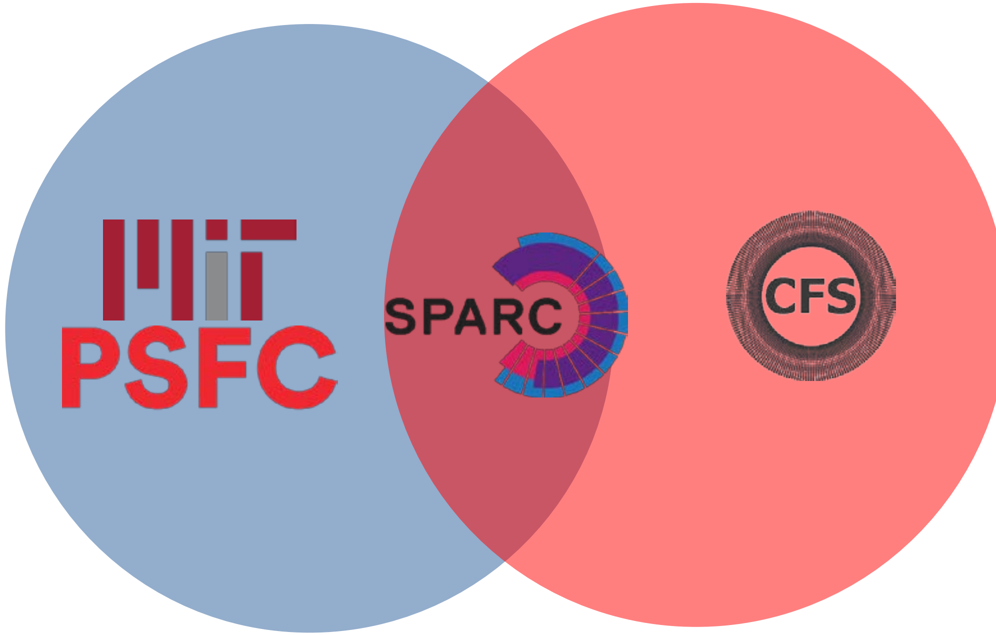


Power Station: ARC
Q>10, $P_{electric}$~200MW

A new model for fusion commercialization

MIT PSFC remains an independent research establishment

Providing scientific and R&D to the joint project



CFS is a private company

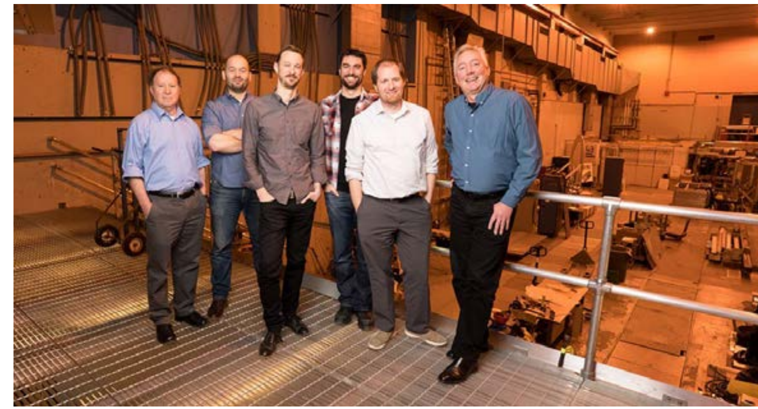
Investor-backed with the aim of commercializing the high-field pathway

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

Commonwealth Fusion Systems Fundamentals

- Team – A combination of deep physics experience with talent drawn from other sectors
  - Google, SpaceX, Tesla, Terrapower leadership
  - Expanded academic disciplines
  - Expanded workforce diversity
- 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**



eni

Breakthrough Energy VENTURES

khosla ventures

THE ENGINE
Built by MIT

SPARC

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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

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

tokamak energy
a faster way to fusion

tae TECHNOLOGIES

PHOENIX NUCLEAR LABS

LOCKHEED MARTIN SKUNK WORKS

generalfusion

HYPERJET FUSION CORPORATION

Helion Energy

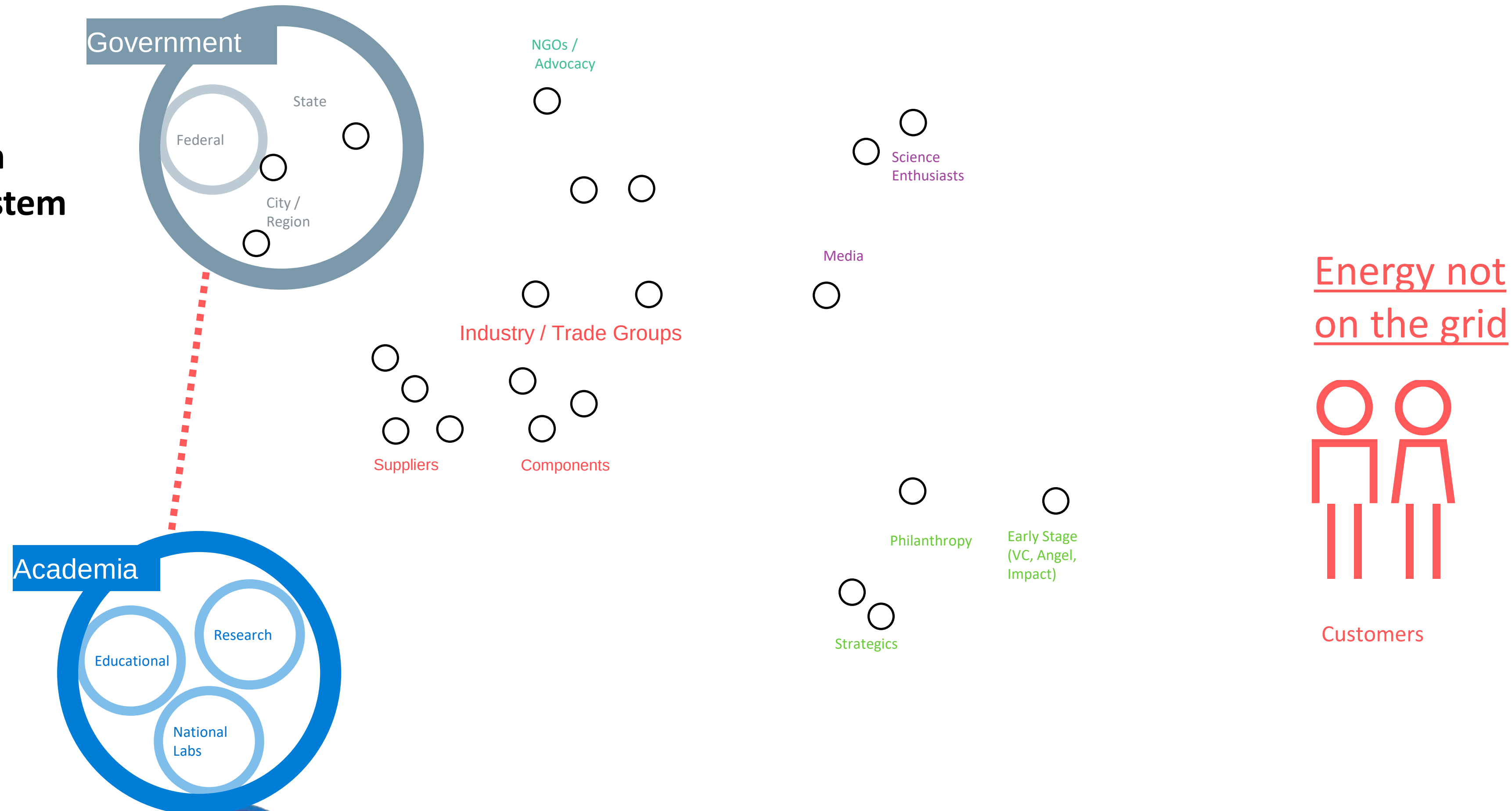
MIFTI

SPARC

Part of a new industry association

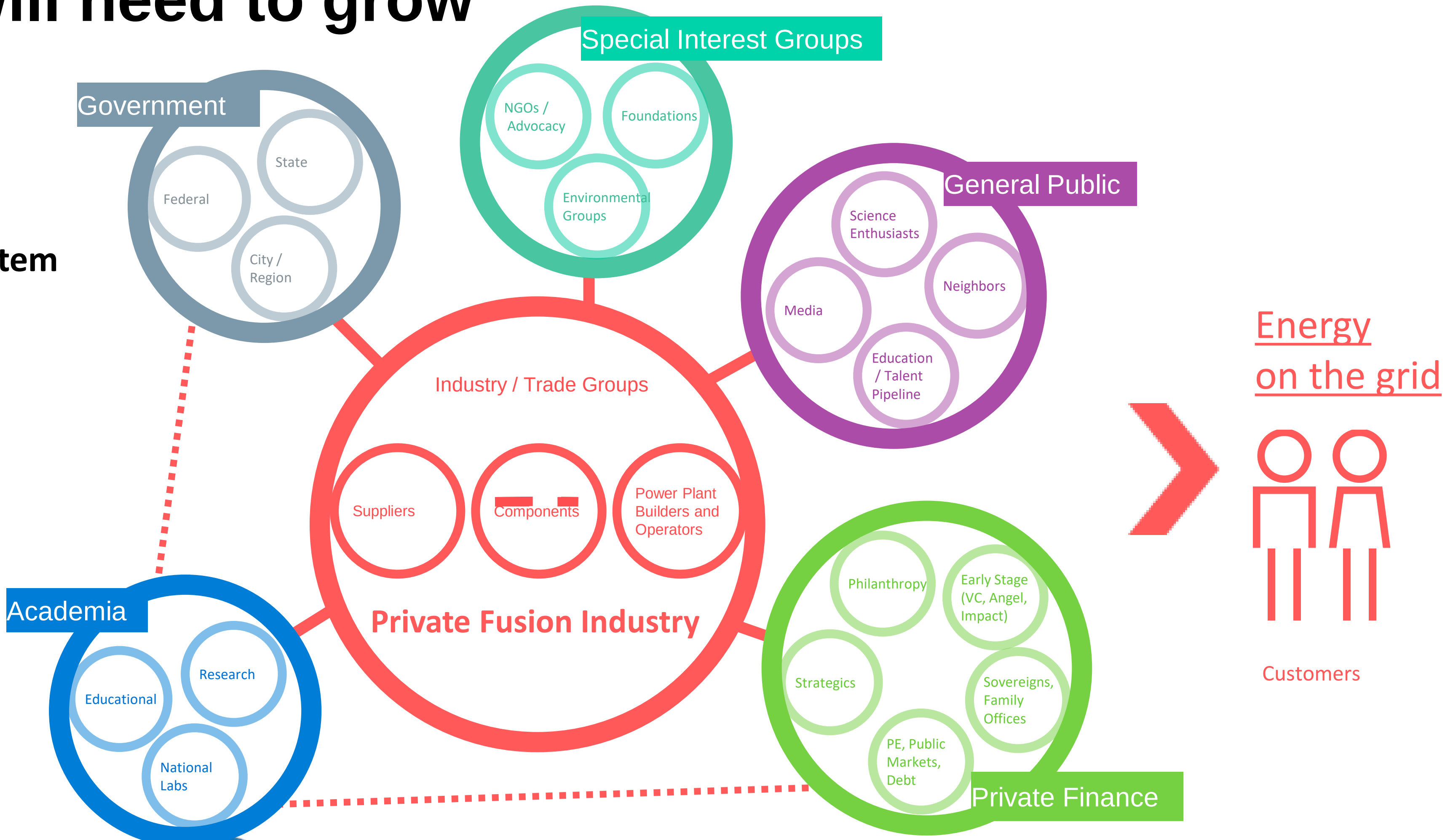
The ecosystem is changing

Fusion Ecosystem



It will need to grow

Fusion Ecosystem

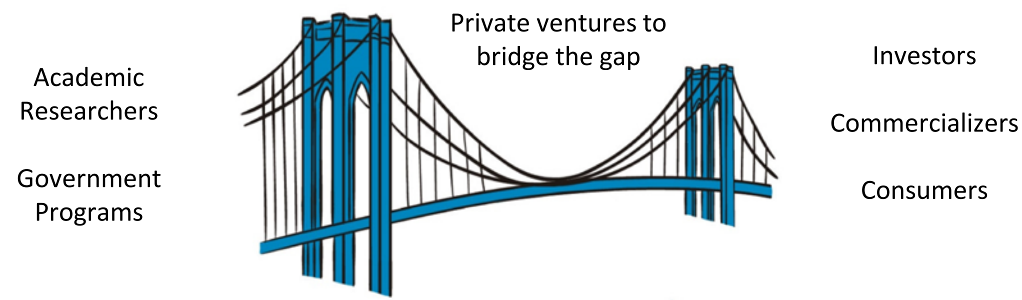


Find ways for gov't and industry to work together

- 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

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, New Space
- How does the government program fill its role?
  - The mandate is basic research
  - To support a fusion industry



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We know the technical gaps

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

Majority of gap work is independent of roadmap

- Every program around the world needs the same basic building blocks (community has done countless reviews)
- Don't get side-tracked into building a single machine to do them all in 30 yrs (it becomes an excuse to not make progress on individual issues now)
- Don't get side-tracked into first settling on a unified global lock-step 50yr roadmap (We have that in ITER already)
- Work on these! Take steps now! Break the problems down as much as possible!
- If labs are retiring these risks we want to collaborate/coordinate with you
- Be part of the solution. Not a brake on progress.

But there is plenty to do in parallel!

Private interest motivates increased science efforts

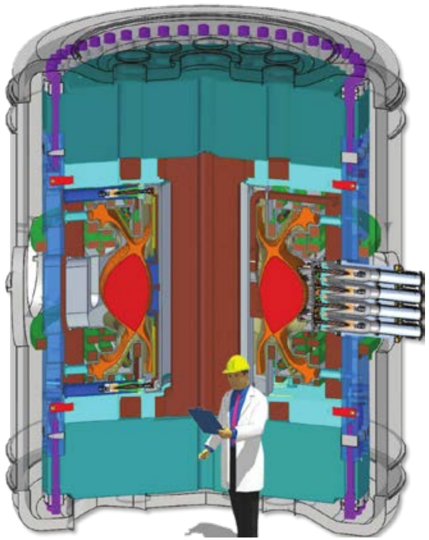
Not necessary for SPARC– but helpful for ARC:

- 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

U.S. program should do them

…. sooner rather than later



- A divertor test tokamak is desired.
- Must be at relevant heat flux, geometry, and field.
- An opportunity for US leadership.

What fusion leadership looks like:

- On a path to deliver value to citizens and industry – solving a problem
- New and unique capabilities
- Courage to retire & replace well-explored capabilities
- New programs at new places with new people attracted to the field
- Working on innovative ideas – pushing the boundary
- Working across sectors from private to public to academic
- Engaging the public

These are bold times for energy
Fusion needs to match the times

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

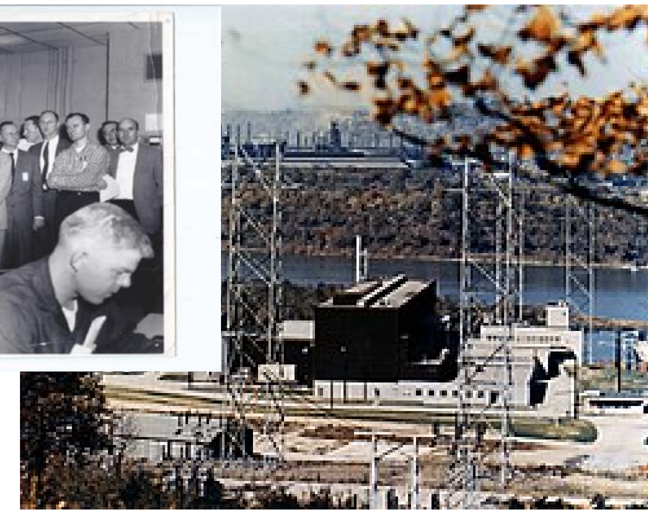
An act or instance of moving through or beyond an obstacle

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

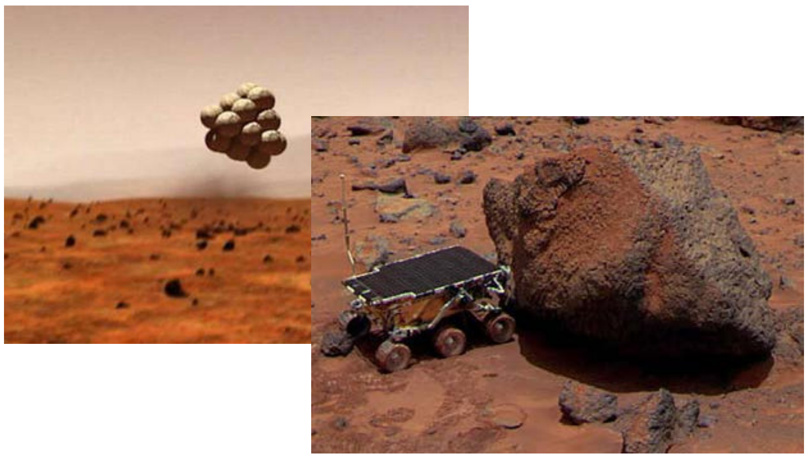
1957 – Shippingport.
60,000,000 W electrical, public-private.
Market drives engineering.



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

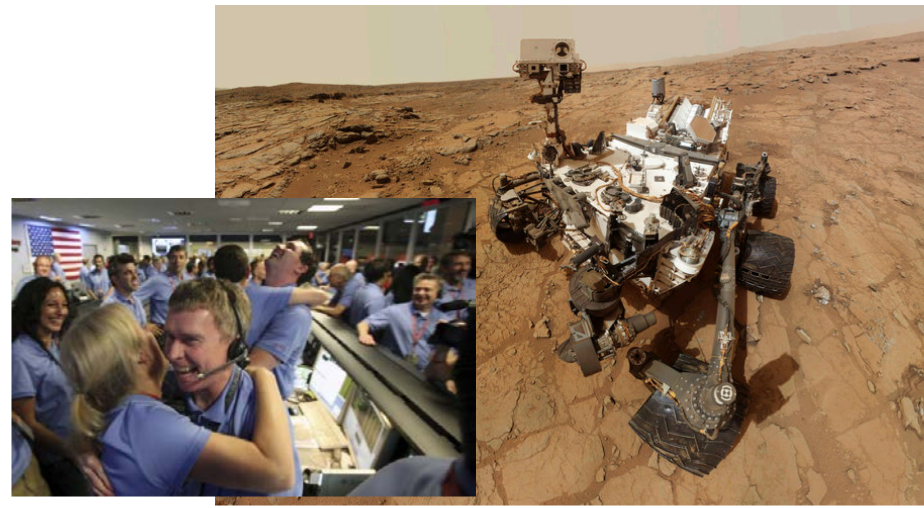
Lets talk about 15 years… Mars

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.

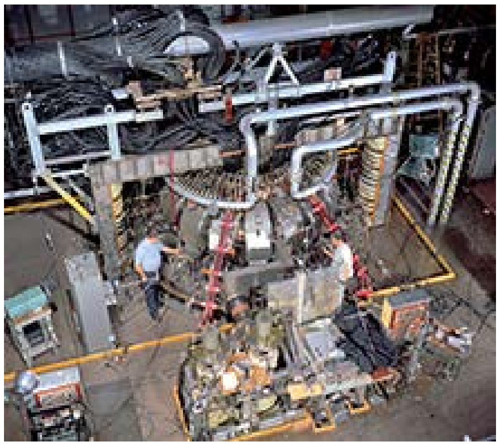
2018 – Falcon Heavy
Innovation applied to orgs and tech, supercharged by finance.

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

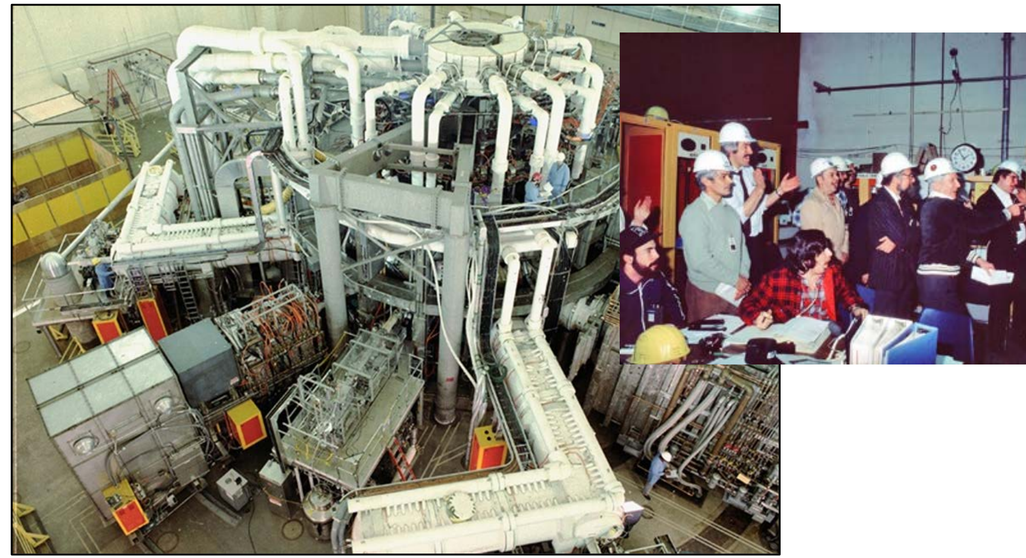
Lets talk about 15 years… Fusion

1971 – ST shows tokamaks work



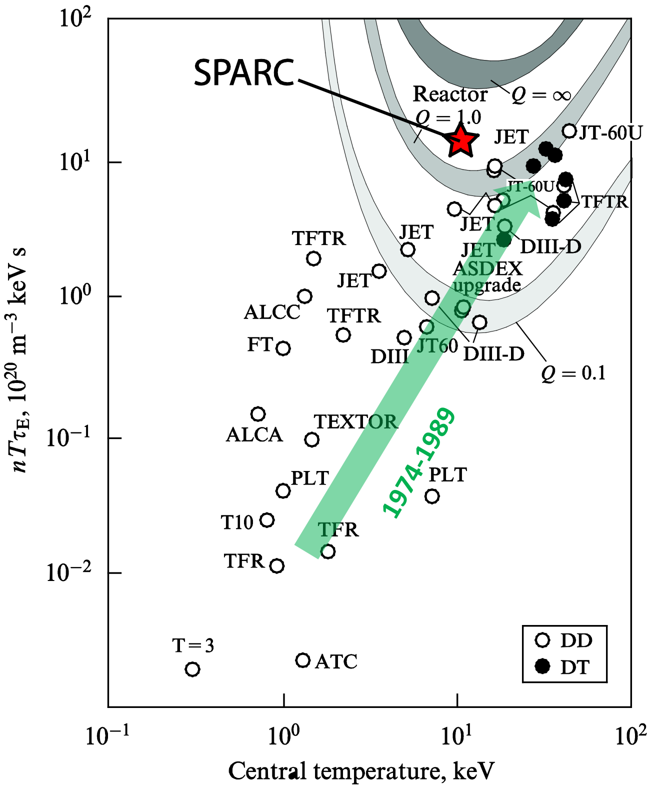
Tokamaks are performing good enough, the world needs energy, we have sights on the technology.
Make push for DT.

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

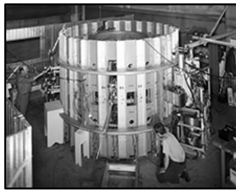


Extrapolations in performance		
Parameter	1974-1989	Today-ARC
Plasma current	10	1.5
Toroidal field	2	1
Magnetic energy	100	18
Pulse length	1000	??
Auxiliary heating	100	0.75
Ion temperature	10	0.5
Triple product	1000	~2-5
D-T fuel	DT	Done
Fusion power	10000000	>15
Q	10000000	>10

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

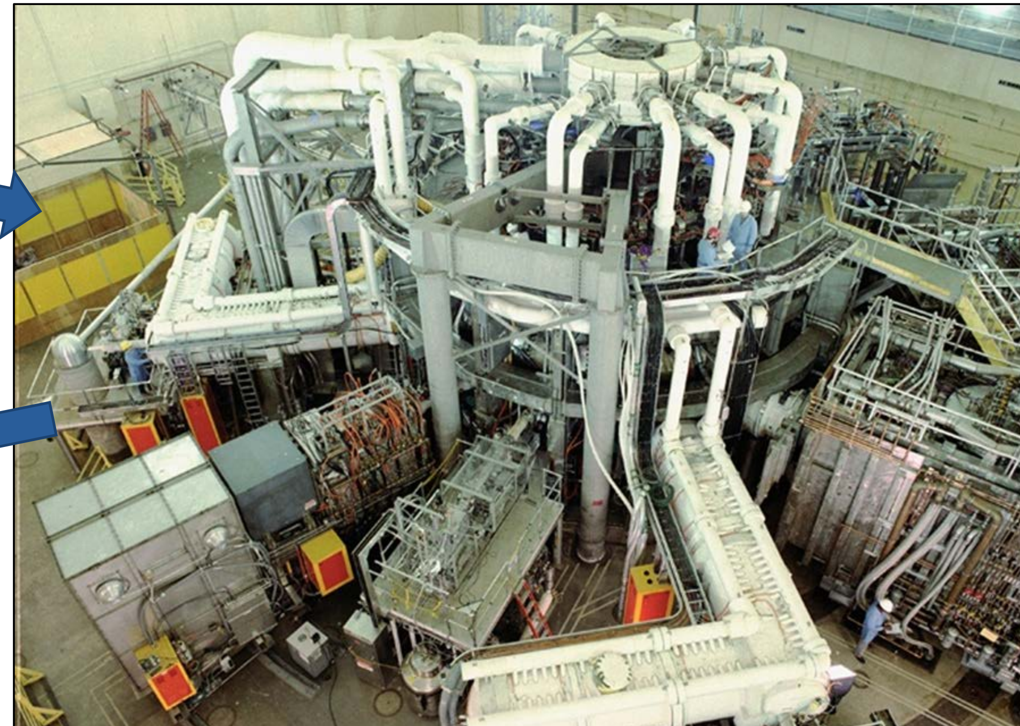
Lets talk about 15 years… Fusion

ATC, 2T



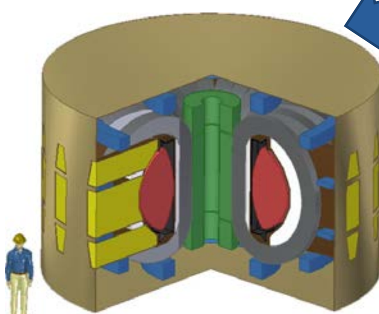
1974:
Tokamak
physics mature
enough to try
DT

TFTR, 6T



2016:
HTS mature
enough to build
a tokamak

SPARC V0, 12T



Approximately to scale

Questions?