SPARC and the high-field strategy to fusion energy

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for the SPARC team

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MIT Plasma Science and Fusion Center

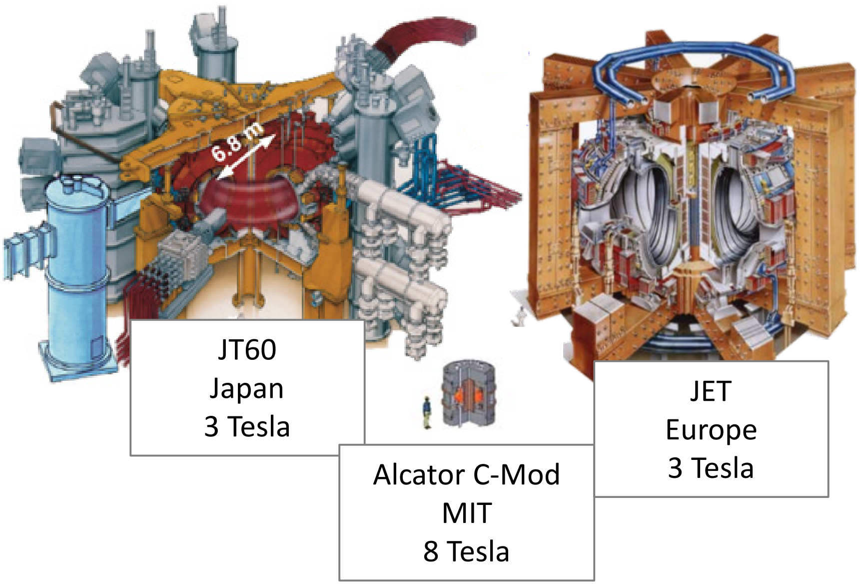
What we found out in the clean energy world

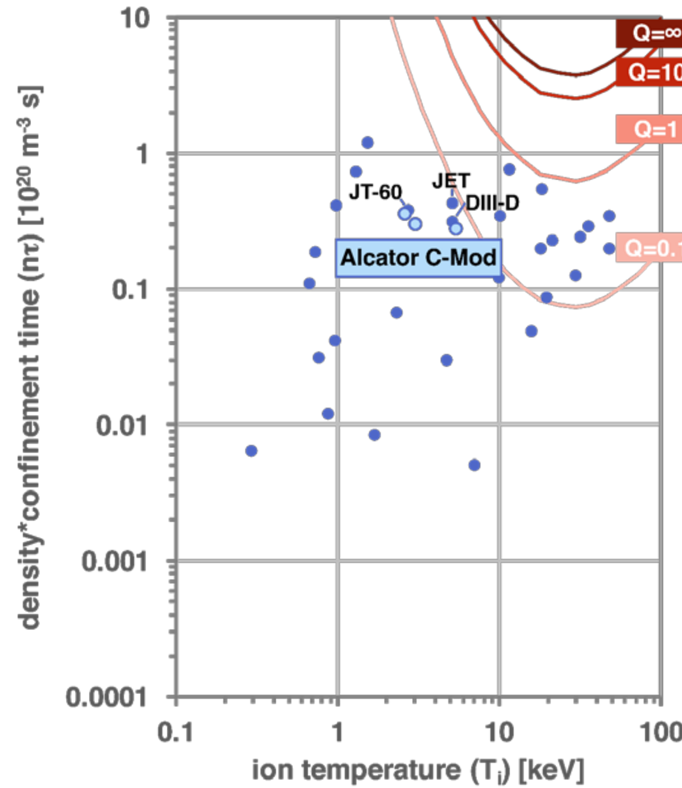
We have worked extensively with utilities, investors, energy companies, manufacturers around fusion. They are excited to participate in a commercialization effort.

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

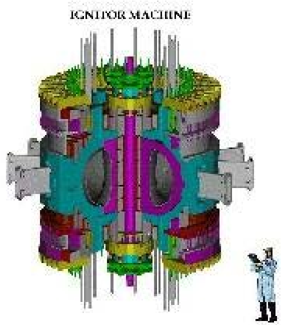




- C-Mod finished a successful 23 year career
- Extended physics basis for tokamak operation at high-field

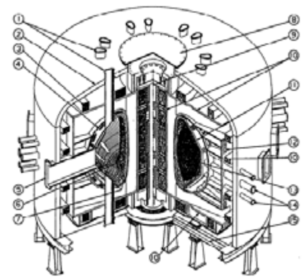
The road not taken: Compact, High-field, Copper

Ignitor



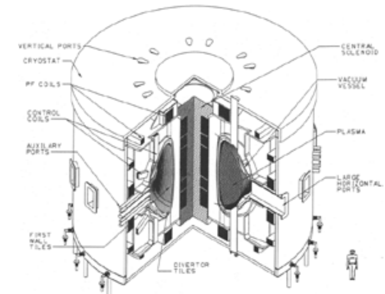
International study
~1985- present

CIT



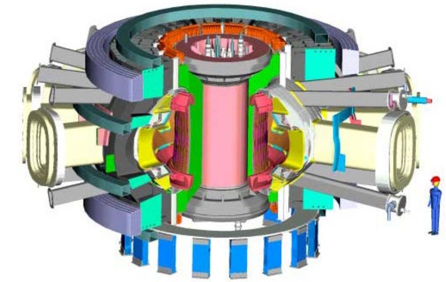
US study (MIT, Oak Ridge, PPPL)
~1985-1990
Alcator C-Mod was a prototype

BPX



US study (PPPL)
~1990- 1995
[Special issue, FST 21 3P1]

FIRE



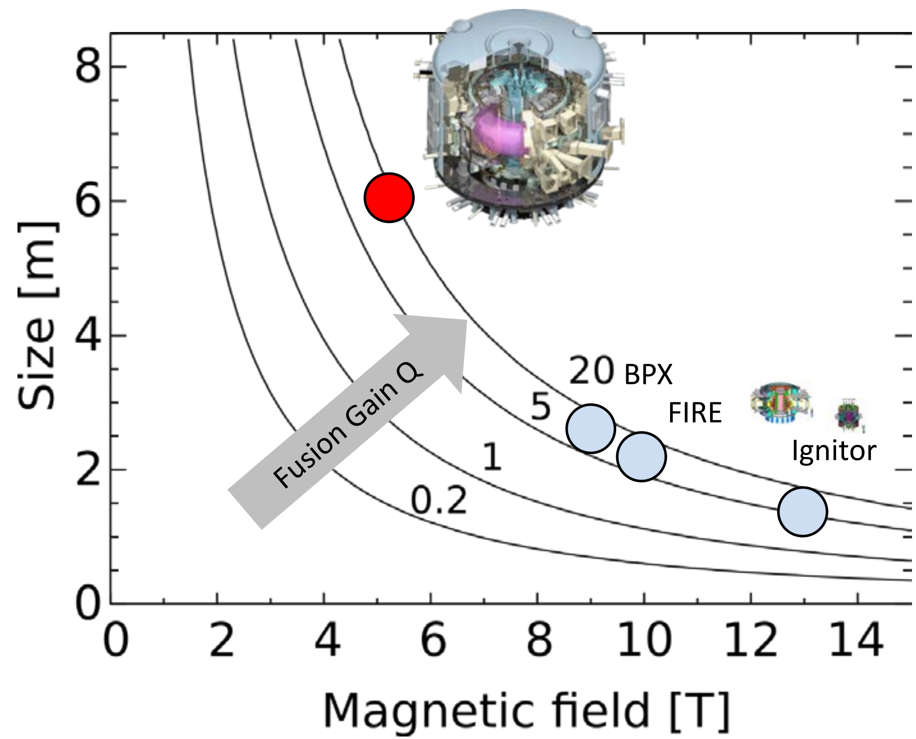
US study (MIT, PPPL)
~1998-2005
[Meade, D. "FIRE" Fusion engineering and design 63-64 (2002): 531-540.]

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

These high-field tokamaks were the main thrust of the U.S. Next Step Options

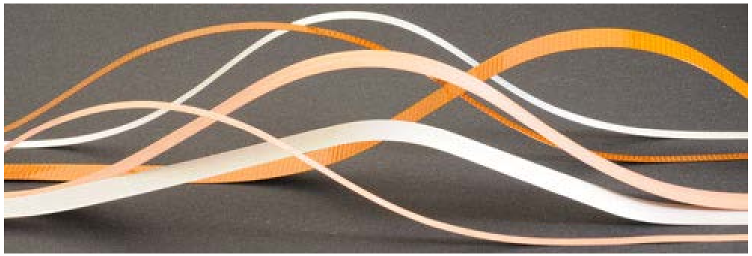
Had they been built: They would have burned

- 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.

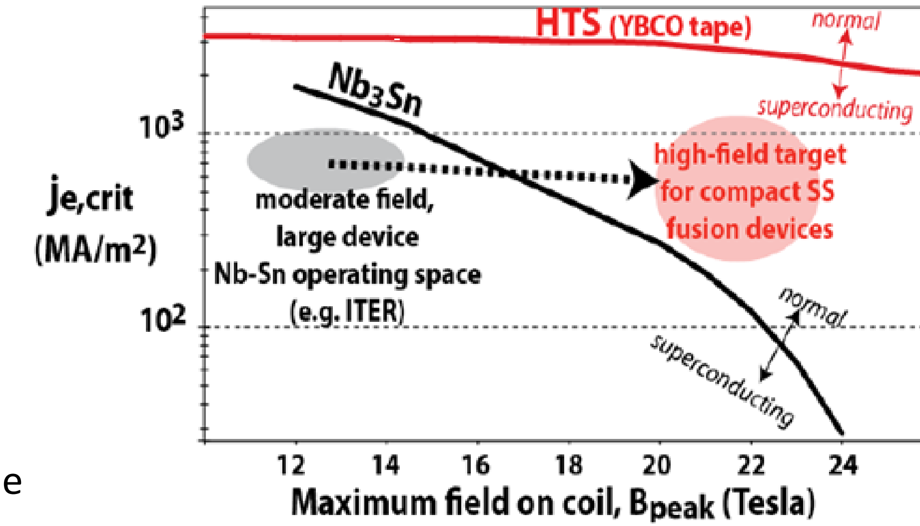


SPARC

What has changed: High-field superconducting with HTS

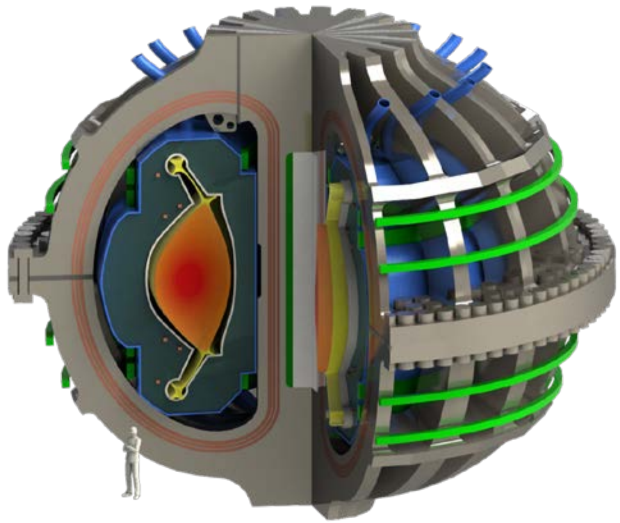


- High-temperature superconductors (HTS) are transformative [FESAC TEC report 2018]
  - Enable much higher magnetic fields
  - Higher current densities
- Only recently commercialized on a relevant scale
- Opens new options for power plants
- Commercially interesting on their own

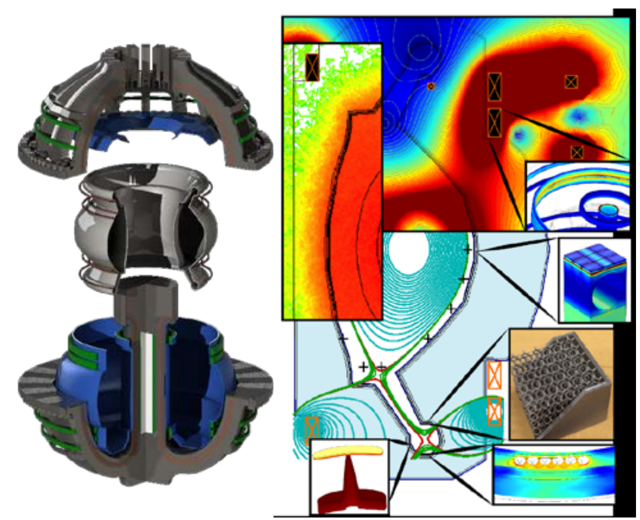


This is ambitious. A high-field large-bore HTS coil has not been demonstrated. Yet.

ARC: An innovative high-field power plant



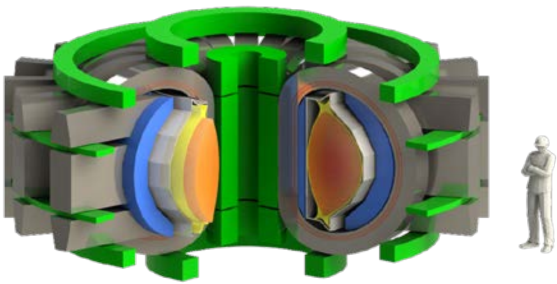
	ITER	ARC
R [m]	6.2	3.2
Magnet	LTS	HTS
B [T]	5.3	9.2
P_{fusion} [MW]	500	500
$P_{electric}$ [MW]	0	200



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

SPARC: A fast-track HTS-based net-energy machine

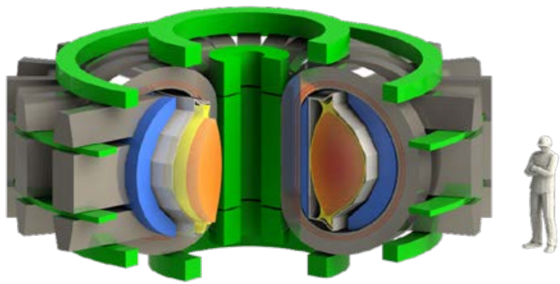


A net-energy device at the scale of DIII-D

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



A net-energy device at the scale of DIII-D

R_0	1.65	m
a	0.5	m
ε	0.33	
κ	1.8	
B_0	12	T
I_P	7.5	MA
B_{max}	20.9	T
P_{fus}	50-100	MW
P_{ext}	30	MW

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

SPARC V0 technical requirements:

- Burn D-T fuel
- Q > 2 (with headroom)
- P_{fusion} > 50MW up to 100MW
- Pulsed with 10s flattop burn
- ~1,000 D-T pulses, >10,000 D-D pulses

SPARC

A smaller, sooner machine offers physics advantages

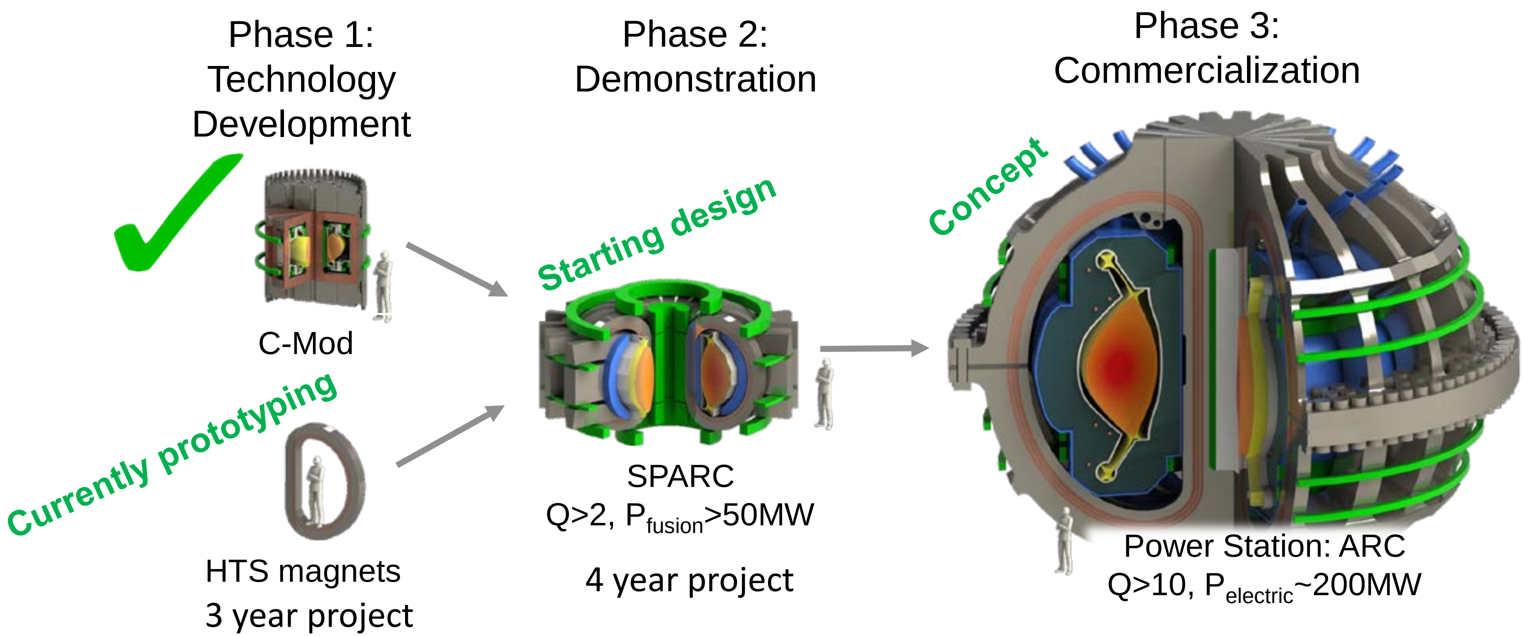
Design:	ITER: 5.3T, 6.2m	12T, 1.65m
Pulse length	400 s	10 s
Fusion power	500 MW	100 MW
Physics learning:		
Pulse length/Plasma equilibrium time	2	1.7
Pulse length/Energy confinement time	133	17
Pulse length/Helium confinement time	25	3
Engineering systems:		
Pulse length/Wall thermal equilibration time	40	0.5
Energy in/pulse	20 GJ	0.3 GJ
Energy out/pulse	220 GJ	1.3 GJ
Plasma thermal energy/surface area	0.5 MJ m^{-2}	0.4 MJ m^{-2}
Nuclear systems:		
Tritium burned/pulse	350 mg	1.8 mg
Gas throughput/pulse	1,500 Atm-l	2.7 Atm-l
10^{20} neutrons produced/pulse	730	3.5
10^{20} neutrons fluence/pulse	1 m^{-2}	0.08 m^{-2}

Access to similar physics

With orders of magnitude smaller engineering systems

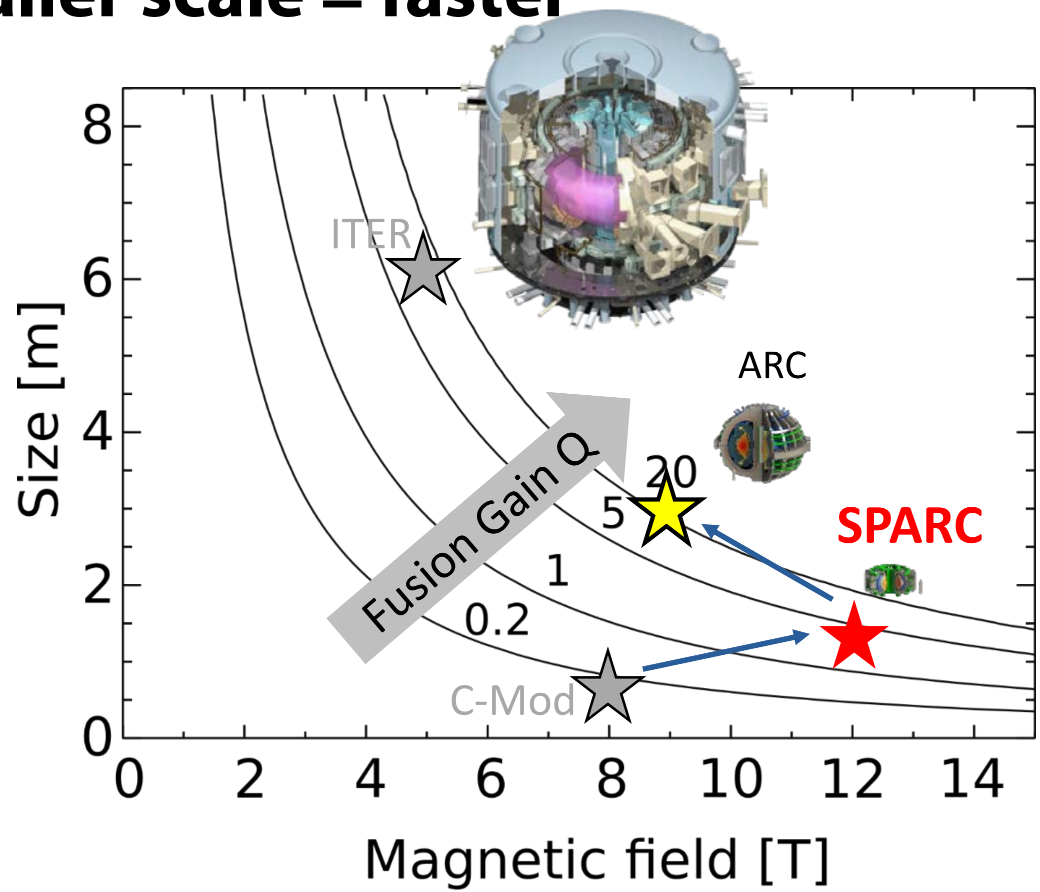
At orders of magnitude smaller nuclear impacts

The high-field approach to fusion energy



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

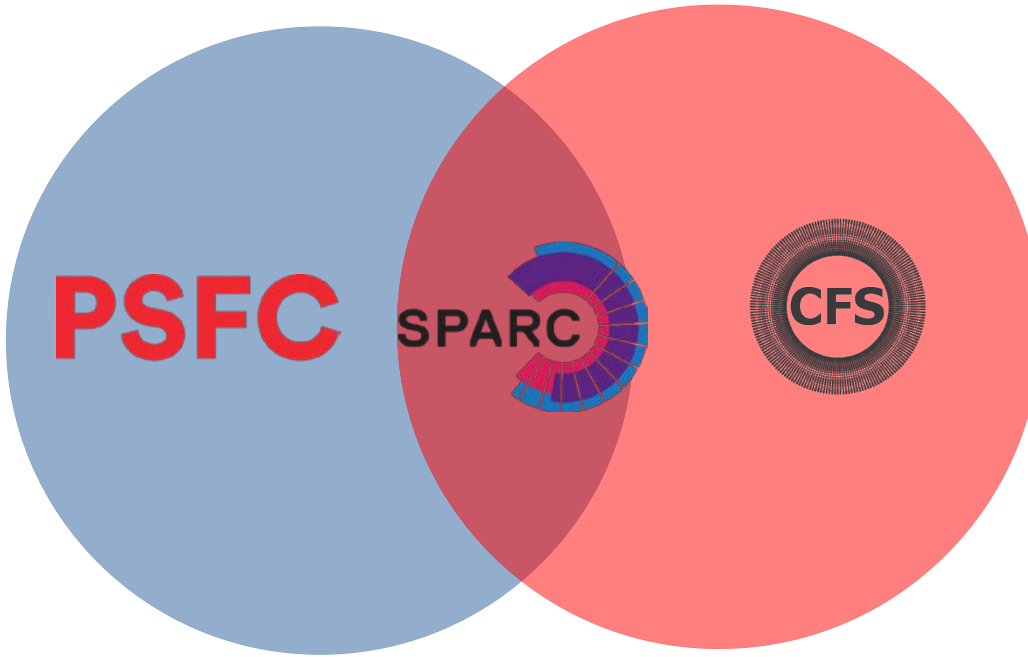


SPARC

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

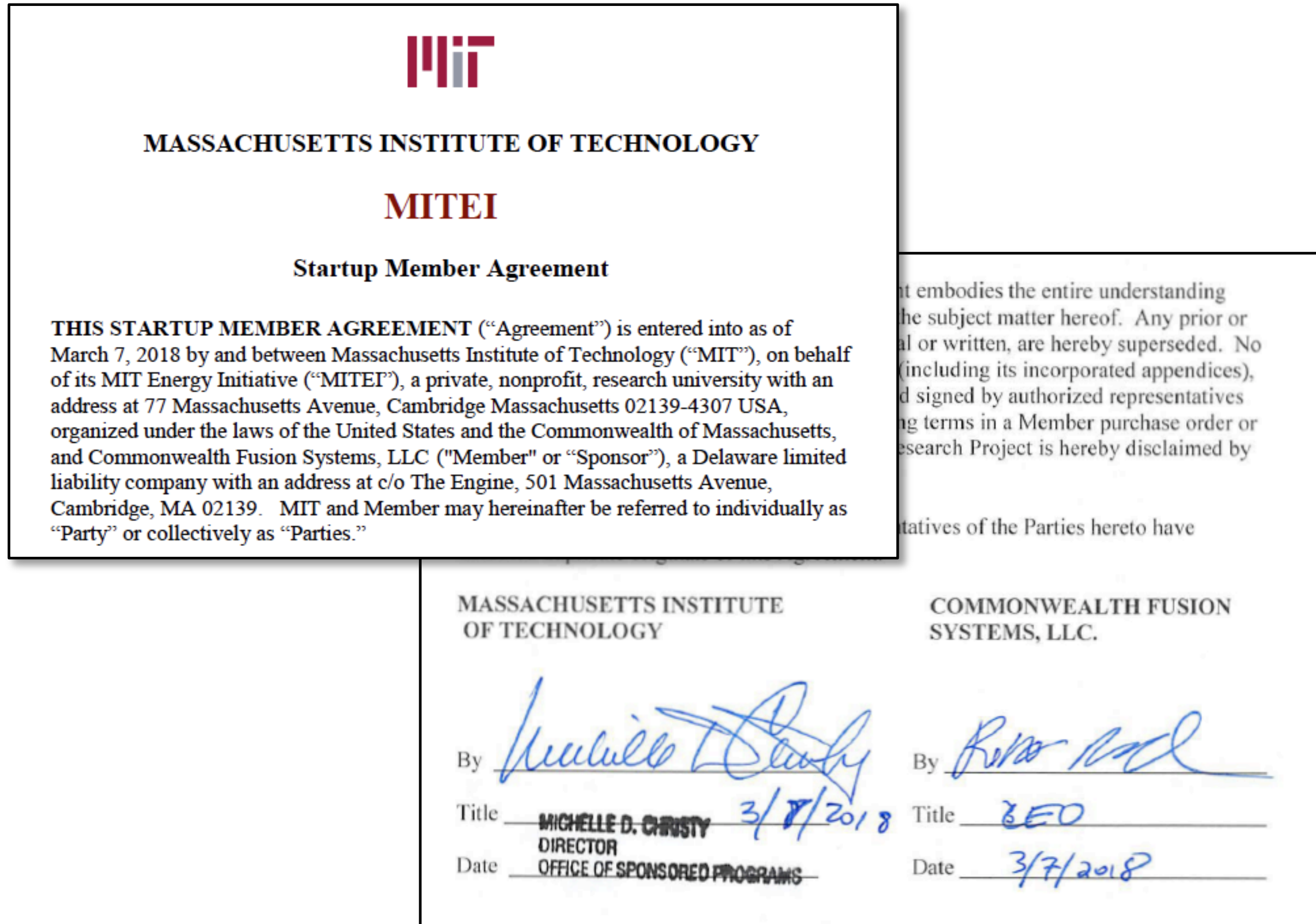
Investor-backed with the aim of commercializing the high-field pathway

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


MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MITEI

Startup Member Agreement

THIS STARTUP MEMBER AGREEMENT (“Agreement”) is entered into as of March 7, 2018 by and between Massachusetts Institute of Technology (“MIT”), on behalf of its MIT Energy Initiative (“MITEI”), a private, nonprofit, research university with an address at 77 Massachusetts Avenue, Cambridge Massachusetts 02139-4307 USA, organized under the laws of the United States and the Commonwealth of Massachusetts, and Commonwealth Fusion Systems, LLC ("Member" or “Sponsor”), a Delaware limited liability company with an address at c/o The Engine, 501 Massachusetts Avenue, Cambridge, MA 02139. MIT and Member may hereinafter be referred to individually as “Party” or collectively as “Parties.”

...t embodies the entire understanding ...he subject matter hereof. Any prior or ...l or written, are hereby superseded. No ...(including its incorporated appendices), ...d signed by authorized representatives ...ng terms in a Member purchase order or ...esearch Project is hereby disclaimed by

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY	COMMONWEALTH FUSION SYSTEMS, LLC.
By	By
Title MICHELLE D. CHRISTY DIRECTOR OFFICE OF SPONSORED PROGRAMS	Title CEO
Date 3/8/2018	Date 3/7/2018

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

gtm: Solar Grid Edge Storage Wind More Trending Podcasts Resources

FINANCE & VC

Billionaire-Backed Breakthrough Energy Ventures Makes 7 More Investments

The fund started by Bill Gates backs R&D into fusion power, capturing water from the air and carbon in concrete, and other long-range efforts.

JEFF ST. JOHN | OCTOBER 01, 2018

Billionaire-Backed Breakthrough Energy Ventures Makes 7 More Investments

Breakthrough Energy Ventures has made seven more long-range bets on startups promising everything from fusion power to solar panels that capture water from the atmosphere — as

Our timeline motivates increased science efforts

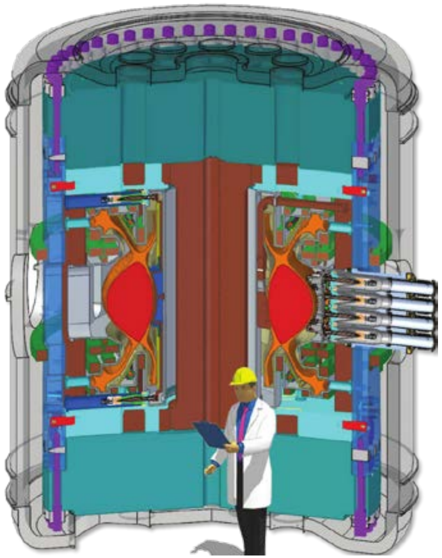
Not necessary for SPARC– but helpful for ARC:

- 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

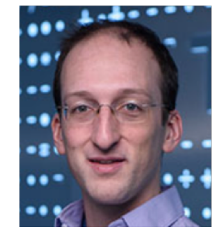
- A new generation of interdisciplinary students being attracted by SPARC, funded by CFS, ENI and donations

J. Brisson
MechE
PSFC Division Head

Caroline Sorenson
MechE
Molten salt heat transfer

Erica Salazar
NSE
Magnet cables

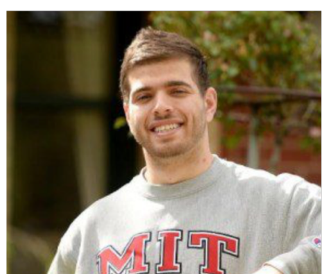
M. Short
Nuclear Eng
Fusion Materials



Patrick White
NSE
Fusion licensing

MI. K. Emmanuel
EAPS
Climate policy

Libby
Tolman
Physics
Energetic
particle
stability



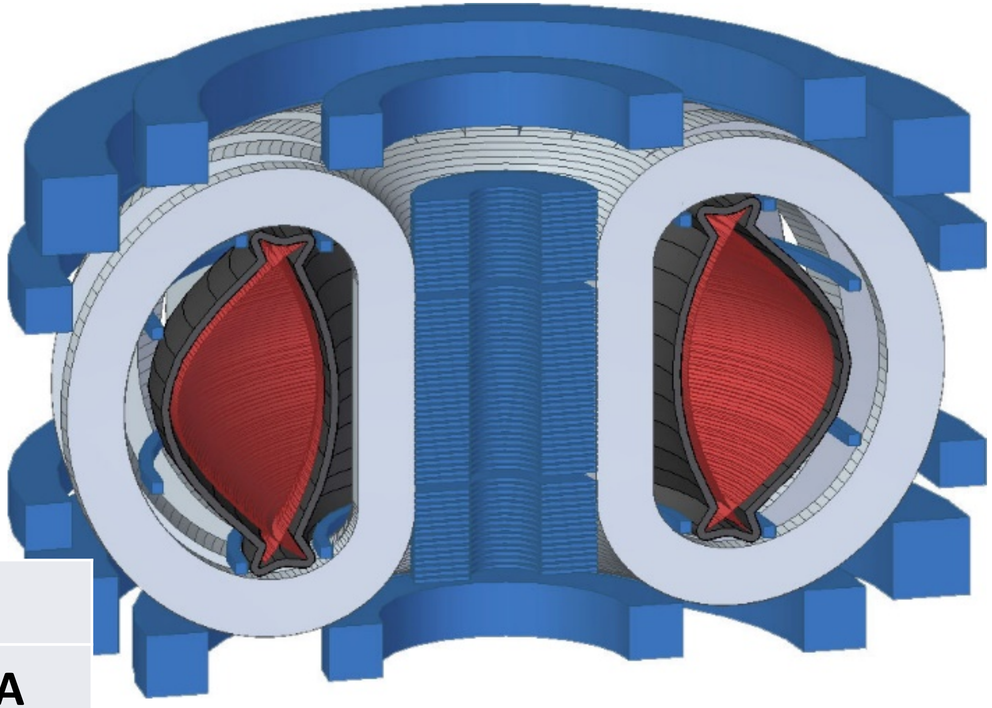
Theo Mouratidis
Aero/Astro
Magnet structure

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

SPARC V0: Nominal Starting Point



Technical objectives:

- Burn D-T fuel
- Q > 2 (with headroom)
- P_{fusion} > 50MW up to 100MW
- Pulsed with 10s flattop burn (about 2x τ_{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

B_0	12	T
I_P	7.5	MA
Ro	1.65	m
a	0.5	m
ε	0.33	
κ	1.8	
P_{fus}	50-100	MW
P_{ext}	30	MW

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: jxB forces cooling quench protection

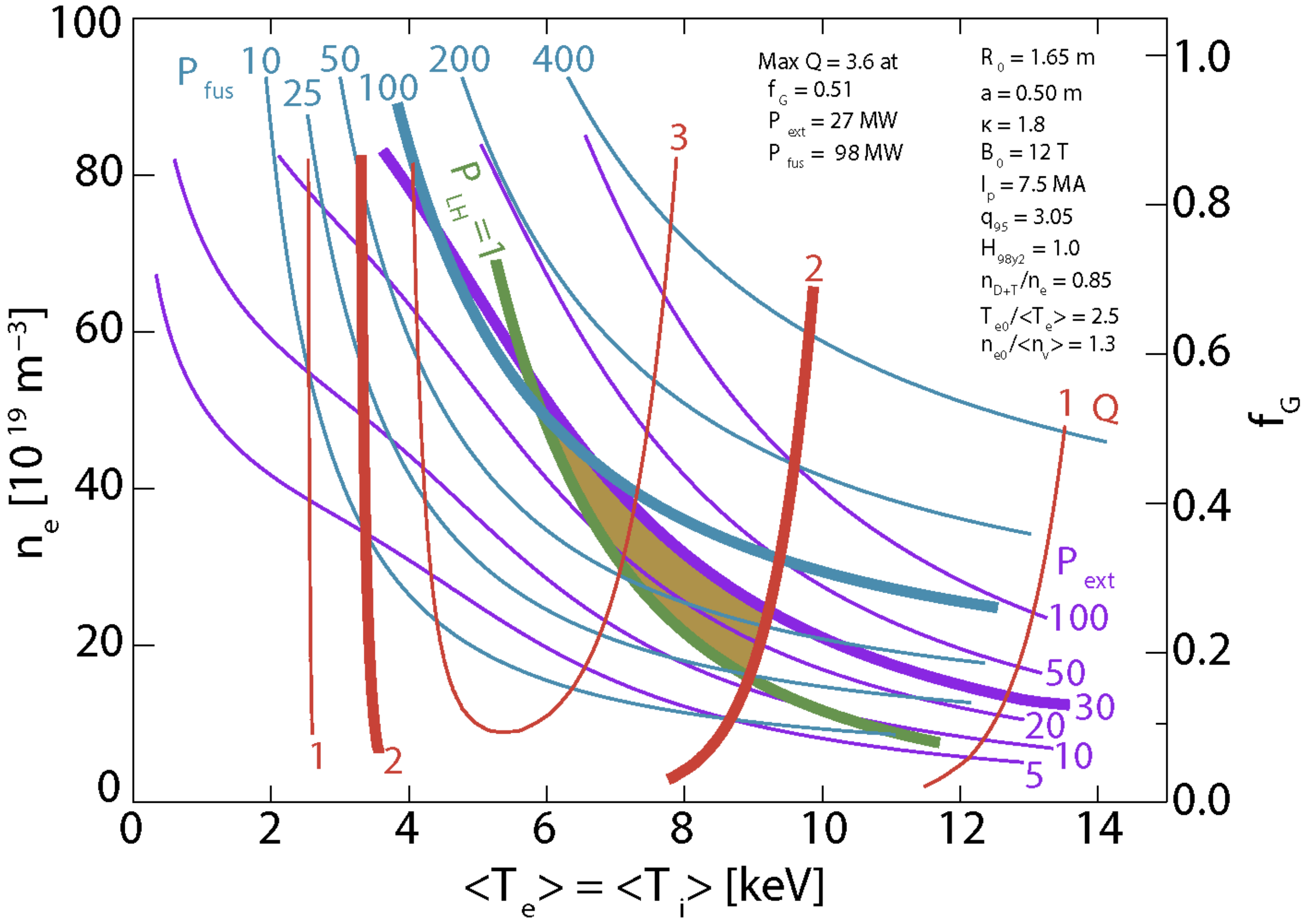
We are up and going on these with team of 50+ designing, building & testing

But cannot reveal details before IP disclosures

How Confident Are We That A "SPARC Class" Tokamak
Will Achieve Its Objectives IF magnets work?

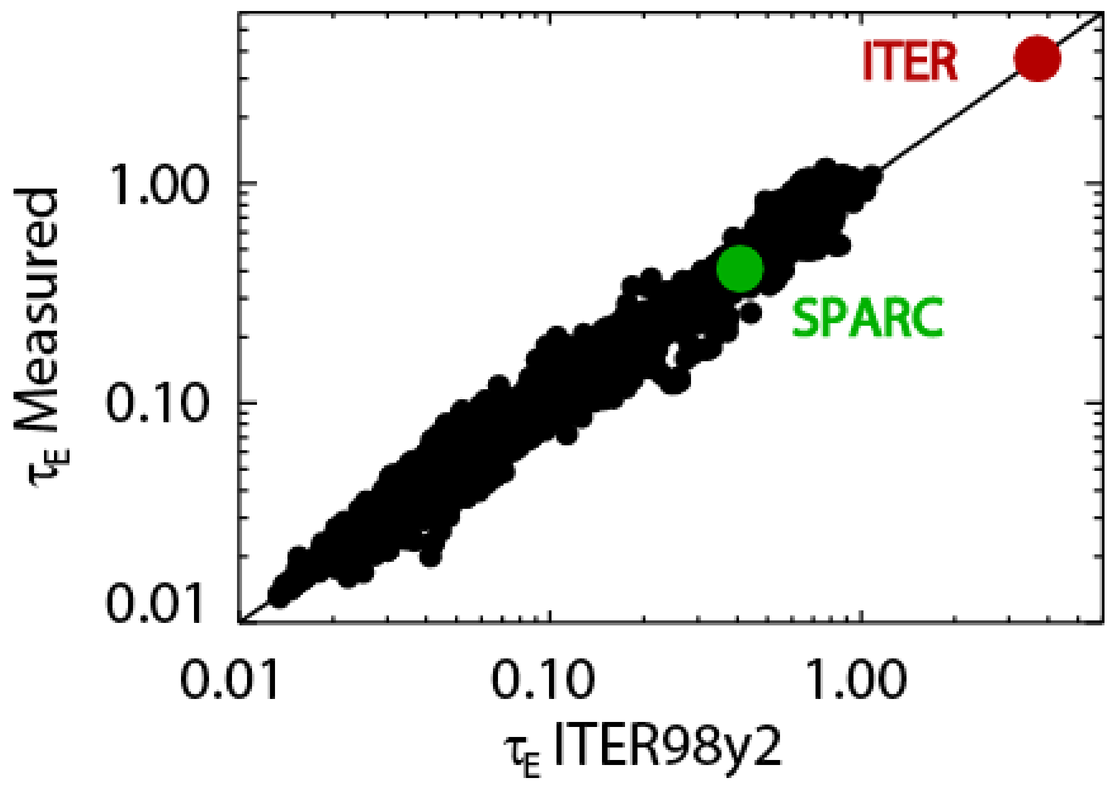
SPARC: Nominal Operating Space; Q_{FUS} up to 3.6

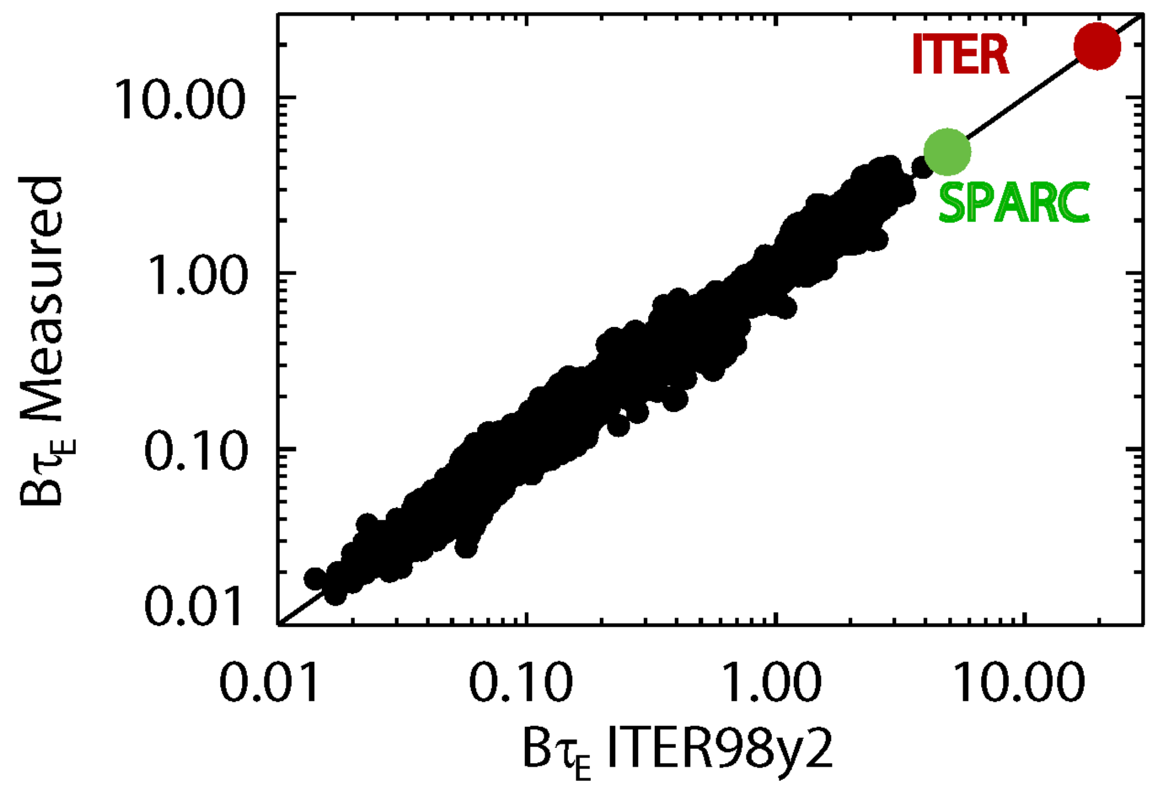
- **Use ITER Performance Rules**
  - Confinement $H_{98} = 1$
  - Profile peaking factors
  - Fuel mix
  - Fuel dilution
- **Operating Space Defined by**
  - $Q_{FUSION} > 2$
  - $P_{LOSS} > P_{L\text{-}H}$ (Threshold)
  - $P_{HEATING} < 30$ MW
  - $P_{FUSION} < 100$ MW



SPARC

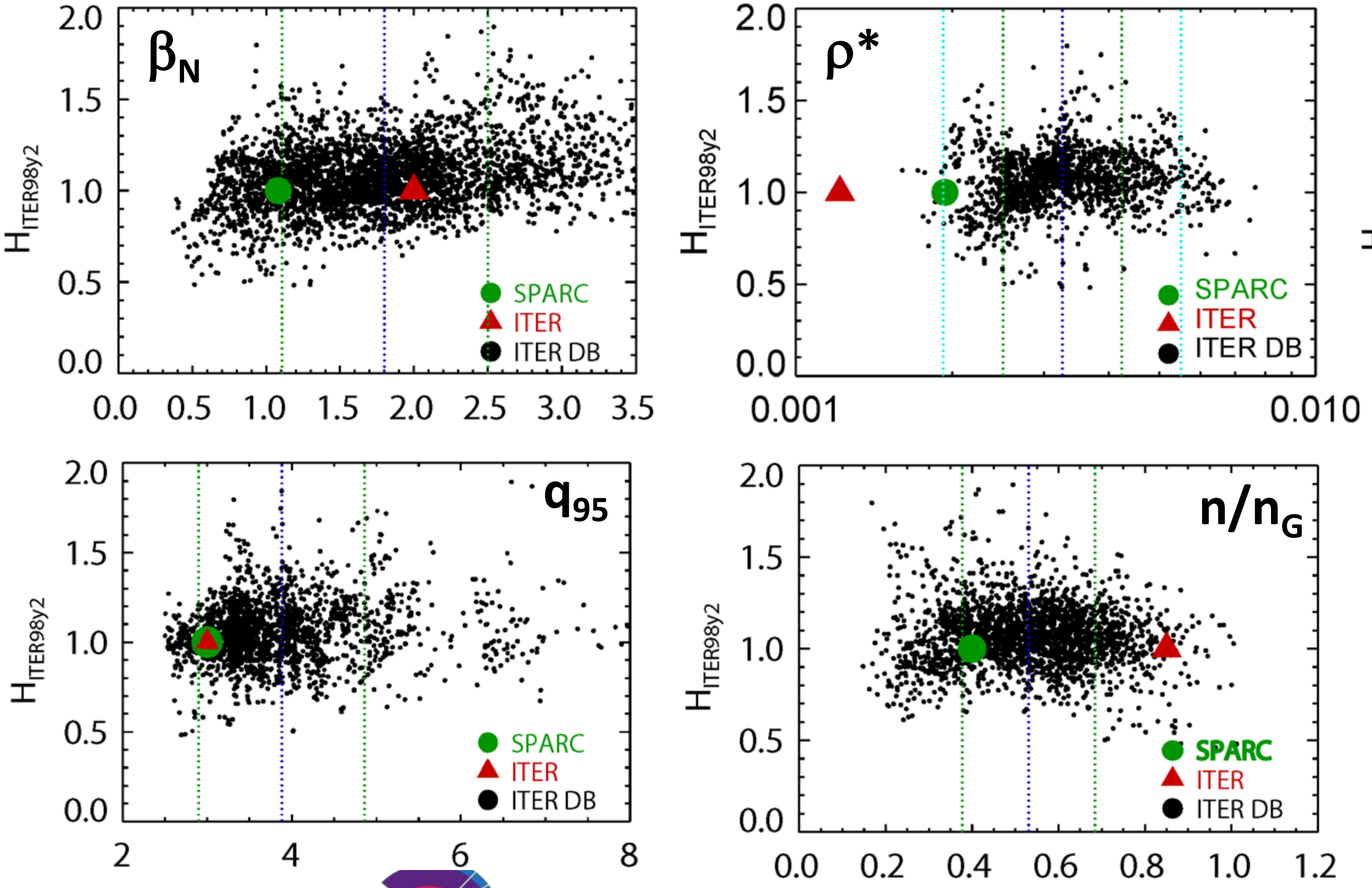
The $H_{98} = 1$ Confinement Assumption Puts SPARC Within the Footprint of the Existing Tokamak Database





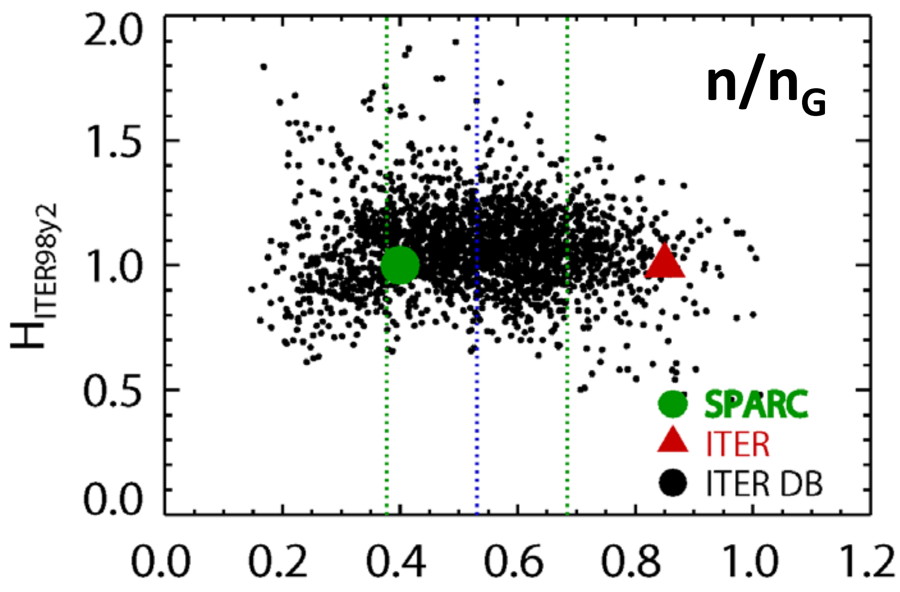
Of course, this doesn't reveal much about the physics

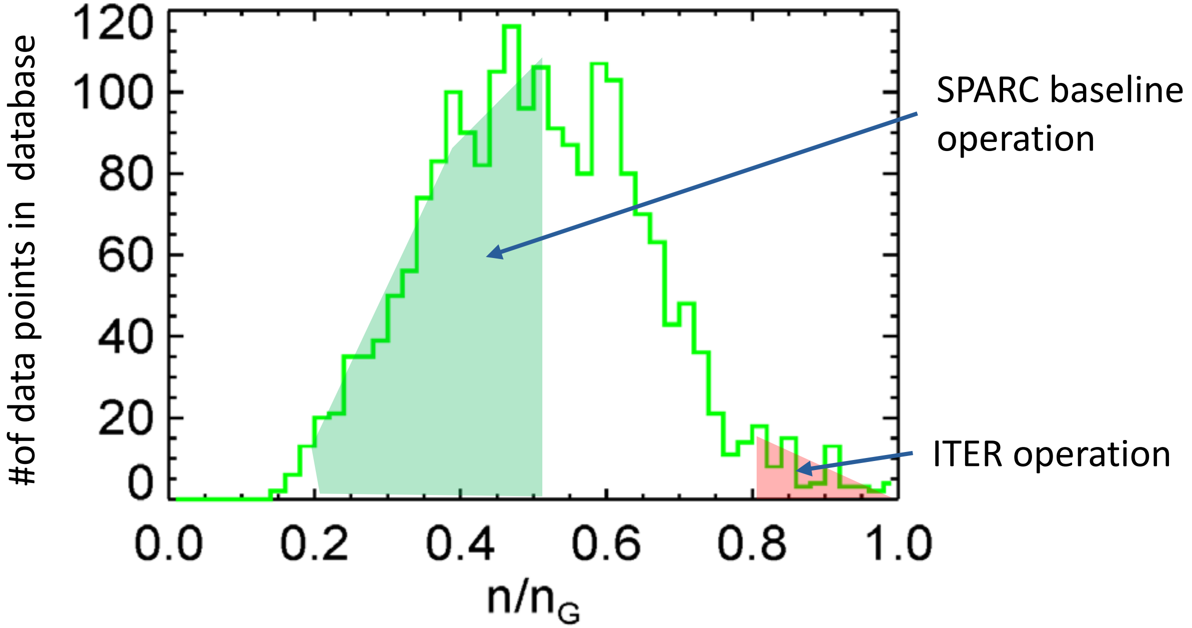
In Plasma Physics Variables, the SPARC Operating Point Is Generally Closer to the Mean of the H-mode Confinement Database than ITER



- ITERDB data using criteria from H_{98} scaling and ITER-like geometry
- Exception: some records don't contain the kinetic information required to calculate ν^* or ρ^*

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

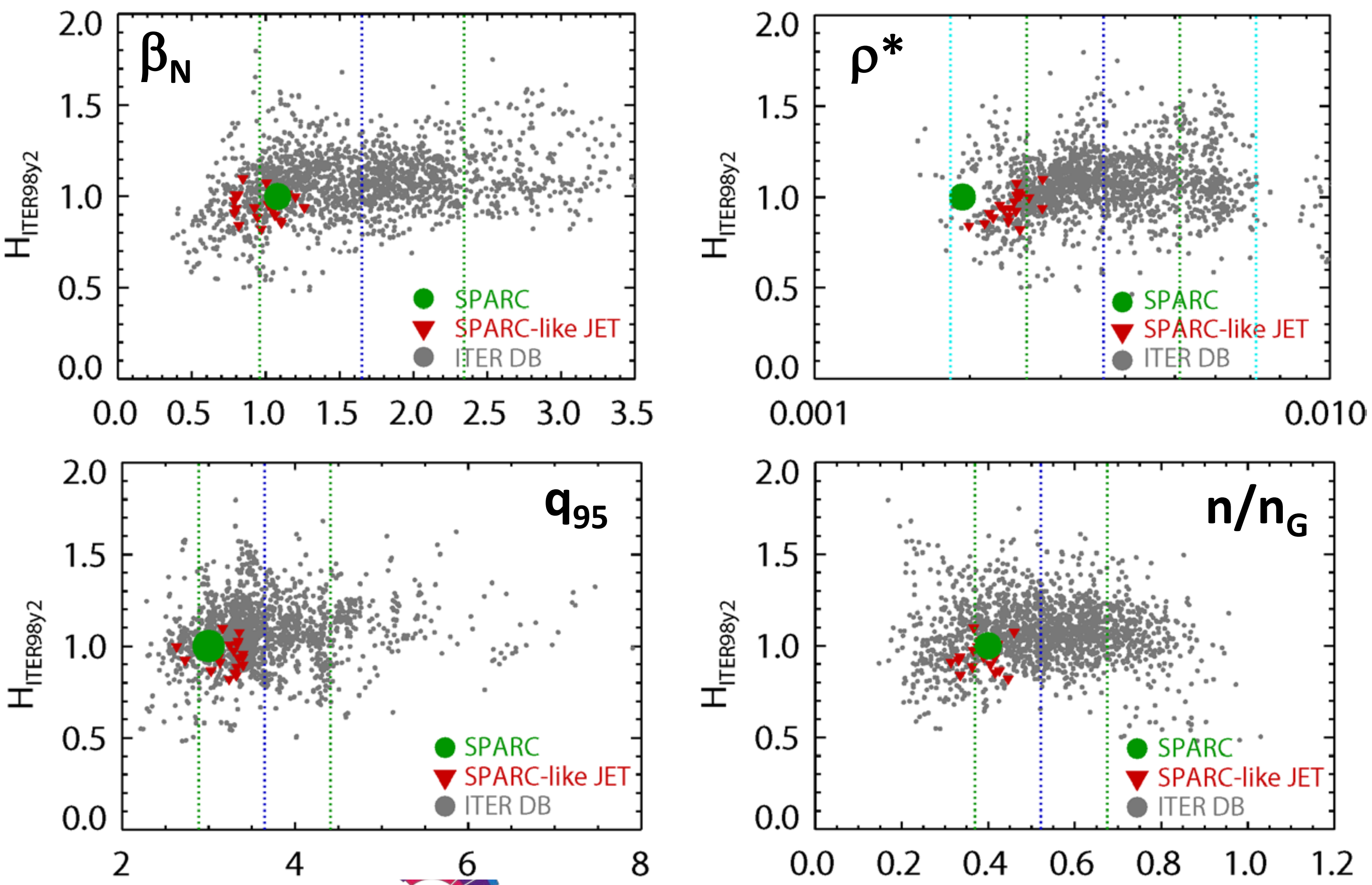
– Easier, generally, to get good confinement

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

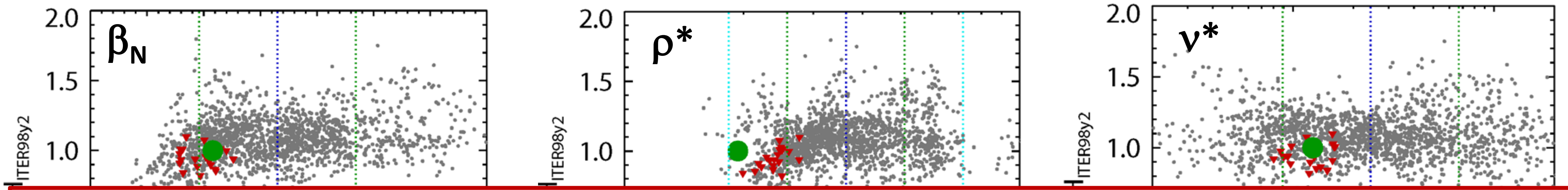
We Can Find Discharges That Are Very Close To Matching, Simultaneously, All SPARC Dimensionless Plasma Parameters and Geometry (β_N, ν^*, ρ^*, q_{95}, n_G, ε, κ, δ_L)



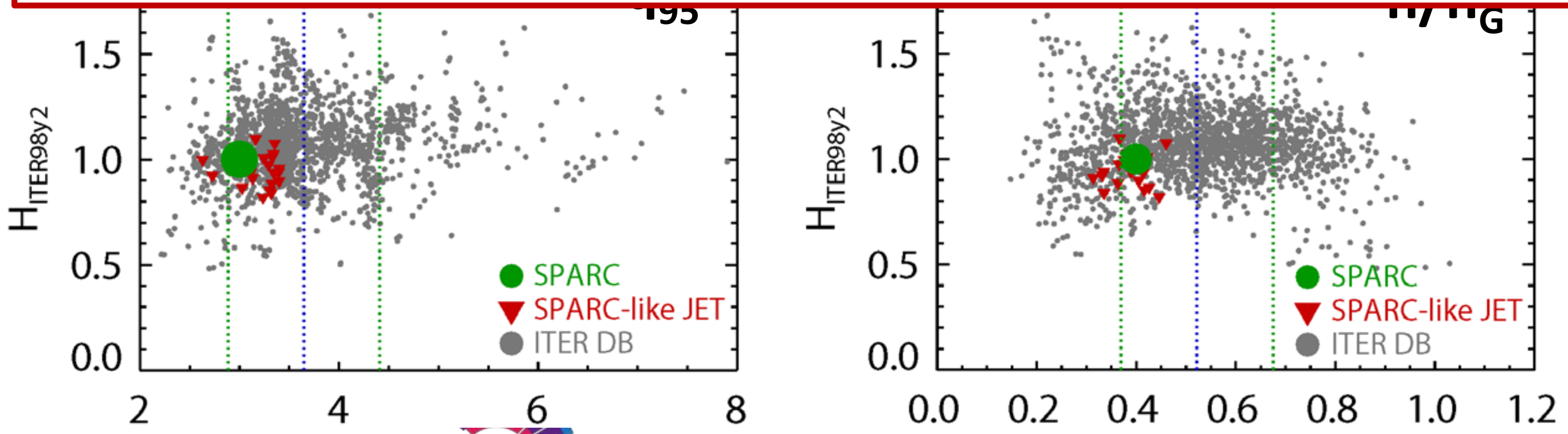
The same 20 (JET) discharges are shown in red

- 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 (β_N, ν^*, ρ^*, q_{95}, n_G, ε, κ, δ_L) Simultaneously



Thus: Much of the Core Plasma Physics Has Been Already Observed



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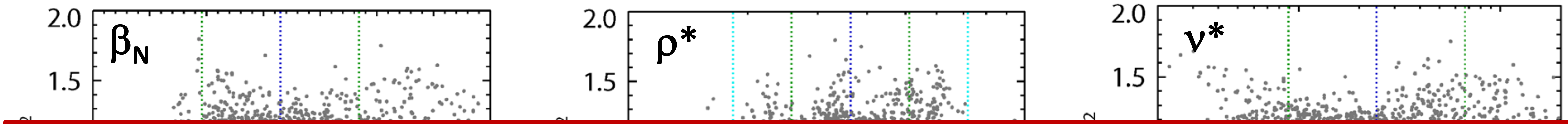
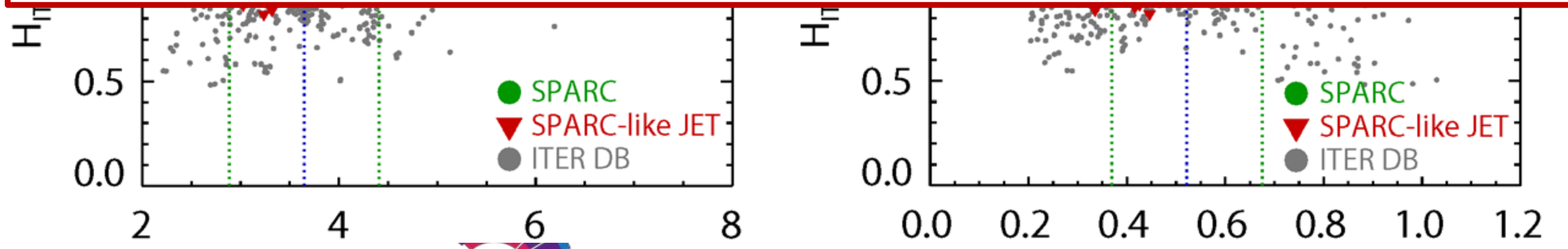


Why didn't those JET discharges generate 100 MW of fusion?

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**

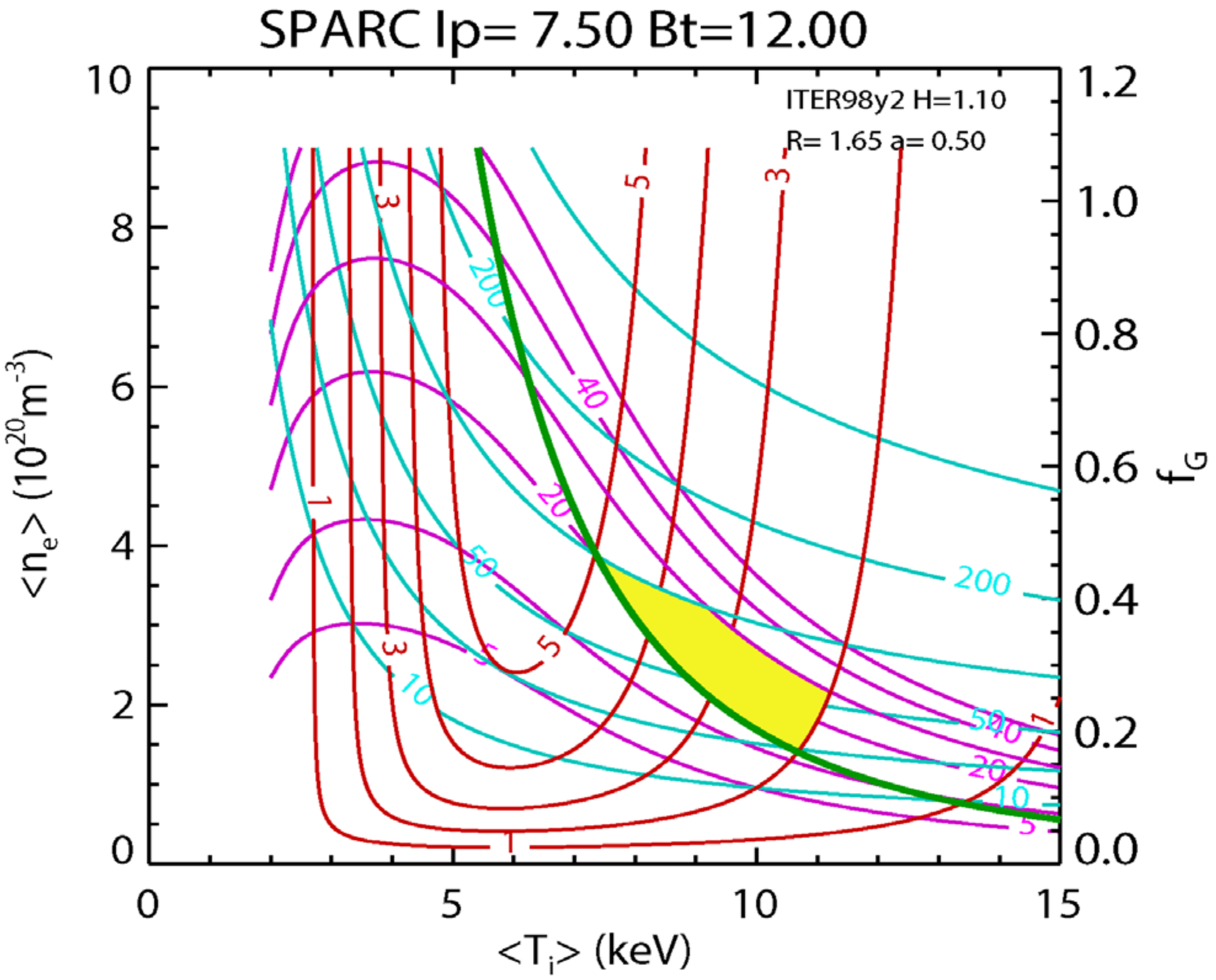


– I_P = 3.0 – 4.2 MA
– P = 8.2 – 15.8 MW
– H_{98} = 0.82 – 1.08

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 ≈ 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

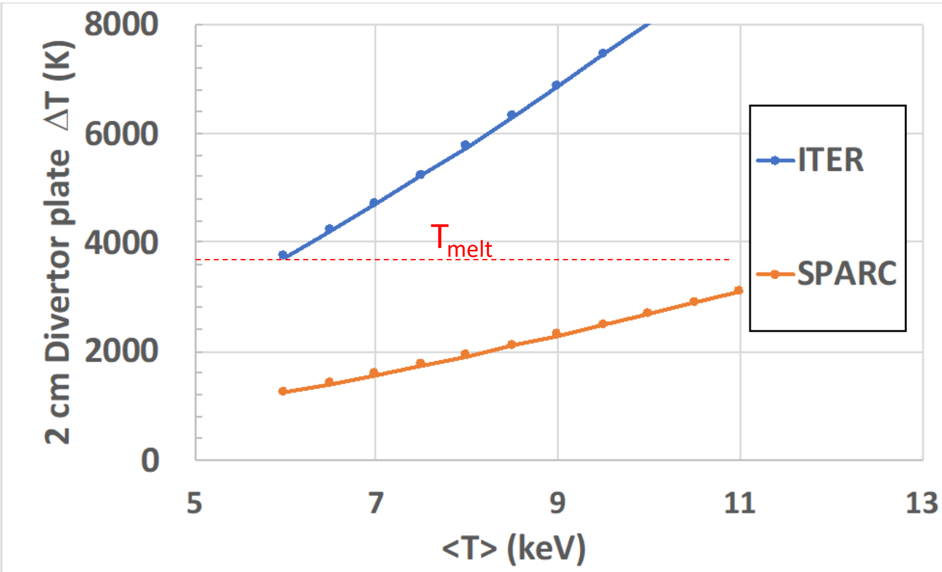
Simple estimates of PFC response indicate inertial cooling is feasible in SPARC, but not ITER

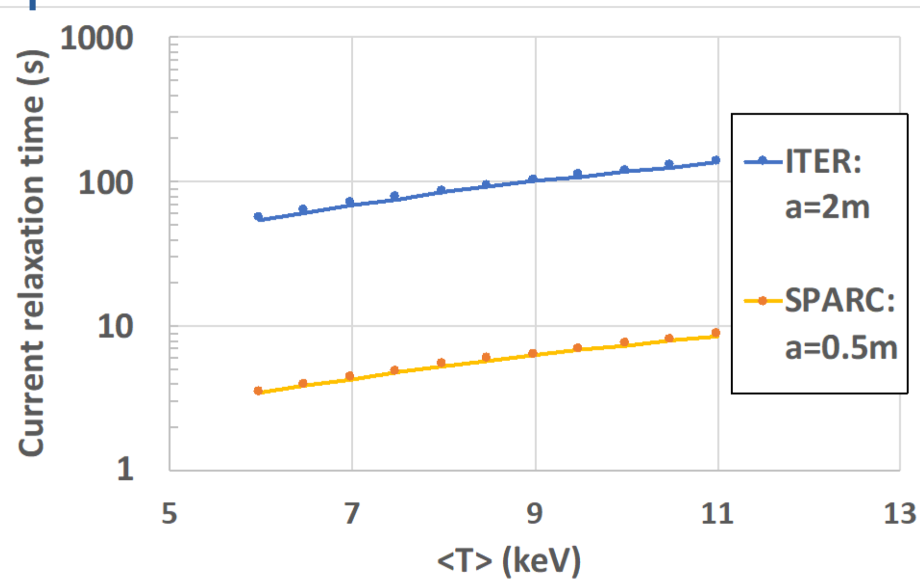
ITER: P_{exh}=150 MW, S_{plate}=5% S_{plasma}~45 m^2

SPARC: P_{exh}=53 MW, S_{plate}=5% S_{plasma}~2.6 m^2

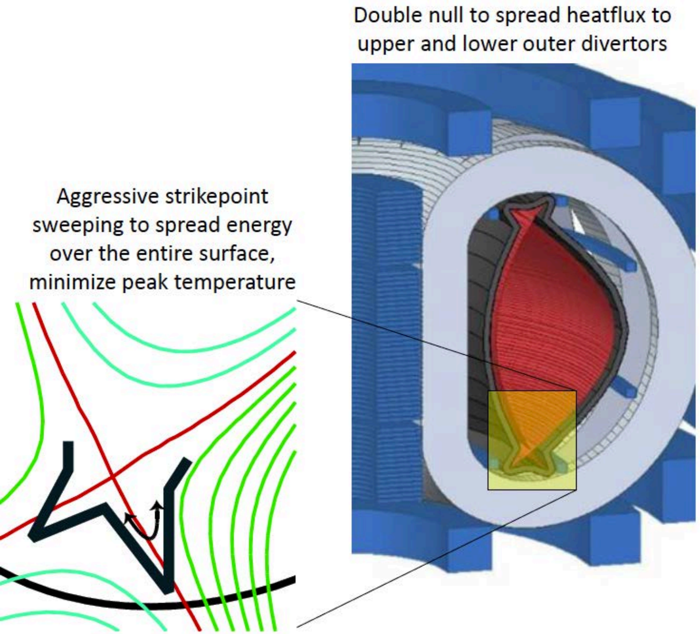
$$\Delta T_{Vol} = \frac{q\ t}{\rho c_v\ V}$$

$$\tau_{CR}[s] \cong \frac{1.4}{Z_{eff}} \langle T_{keV} \rangle^{\frac{3}{2}} a[m]^2$$

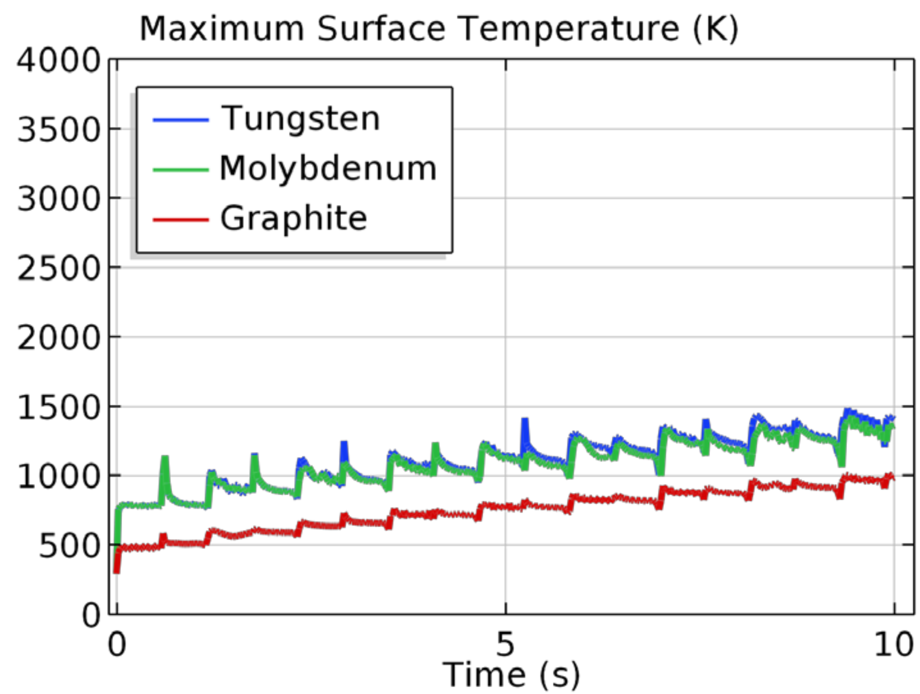




Case study: Double null divertor with strikepoint sweeping, 2 cm thick, inertial cooled divertor is viable

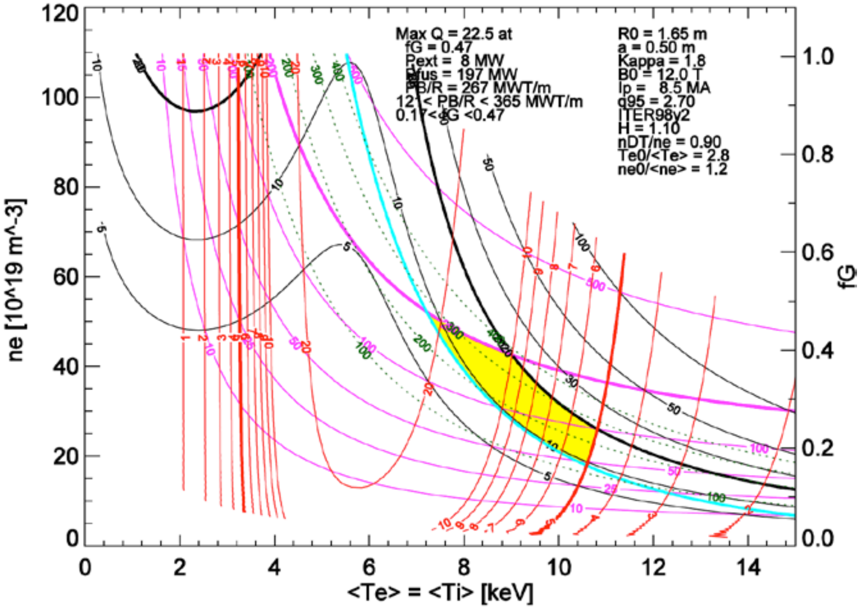


- SOL radiation fraction: 0.9

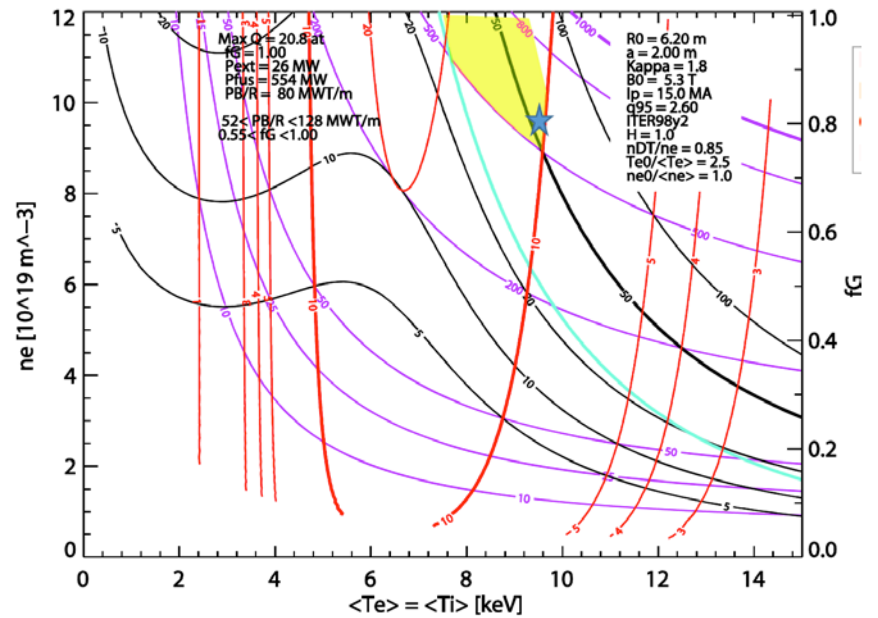


A large strategic advantage to assess dissipative divertor physics solutions: SPARC can operate at high and variable core density, but at low Greenwald fraction

SPARC, H=1.1, Q=5-10, P_f < 200 MW

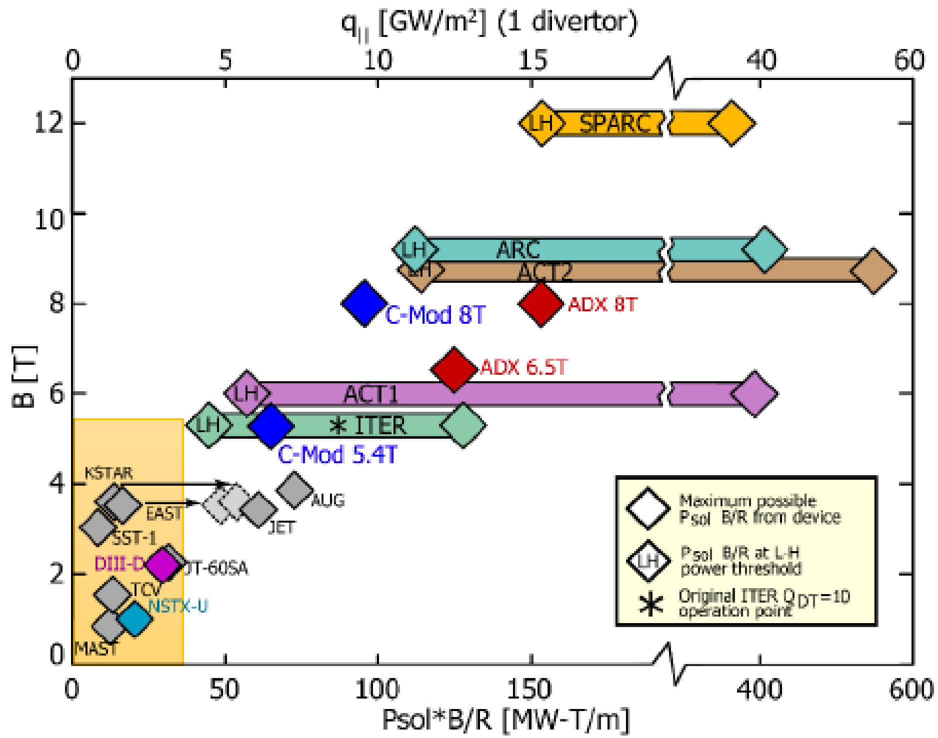


ITER Q=10



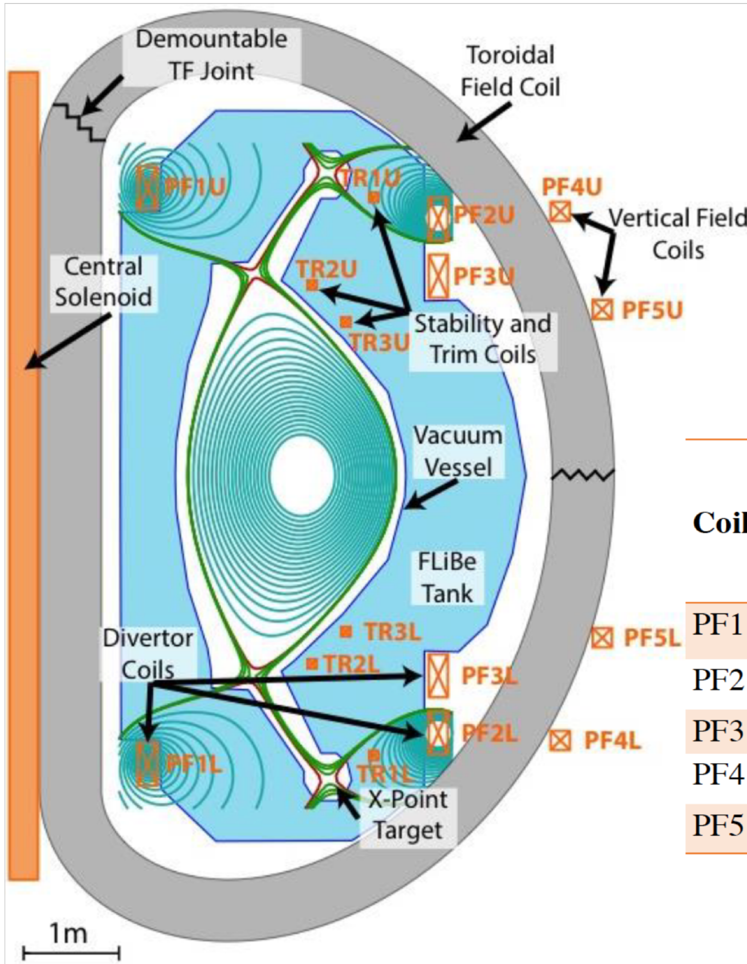
SPARC

SPARC boundary plasma physics solutions relevant for ARC and other fusion power plant designs



Adopted from ADX NF paper (LaBombard et al.)

New design study: demountable REBCO coils + immersion salt blanket very attractive for innovative divertor

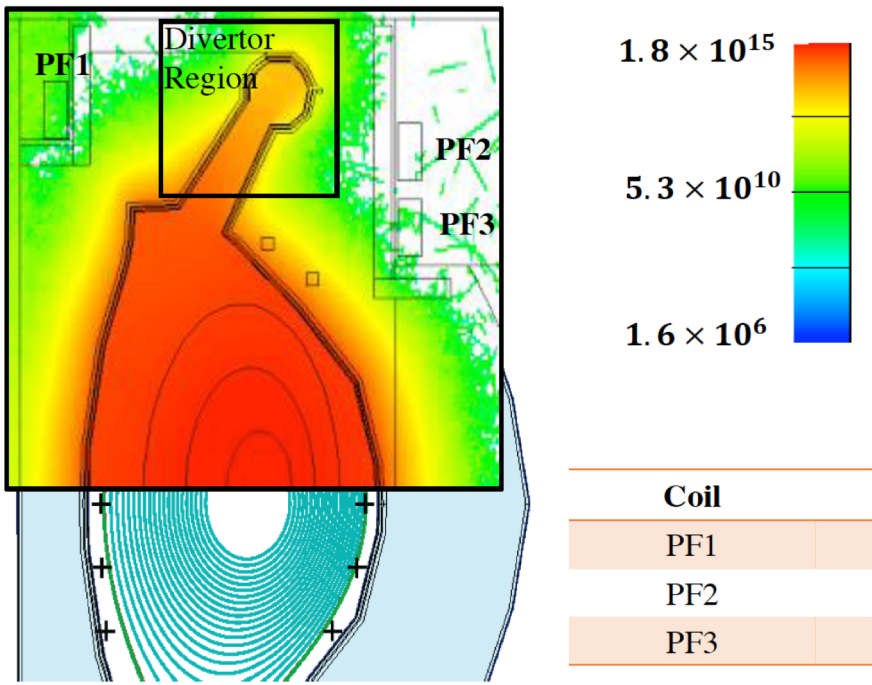


Coil	Current-Turns [MA-turns]
PF1	3.9
PF2	5.2
PF3	4.4
PF4	1.4
PF5	3.5

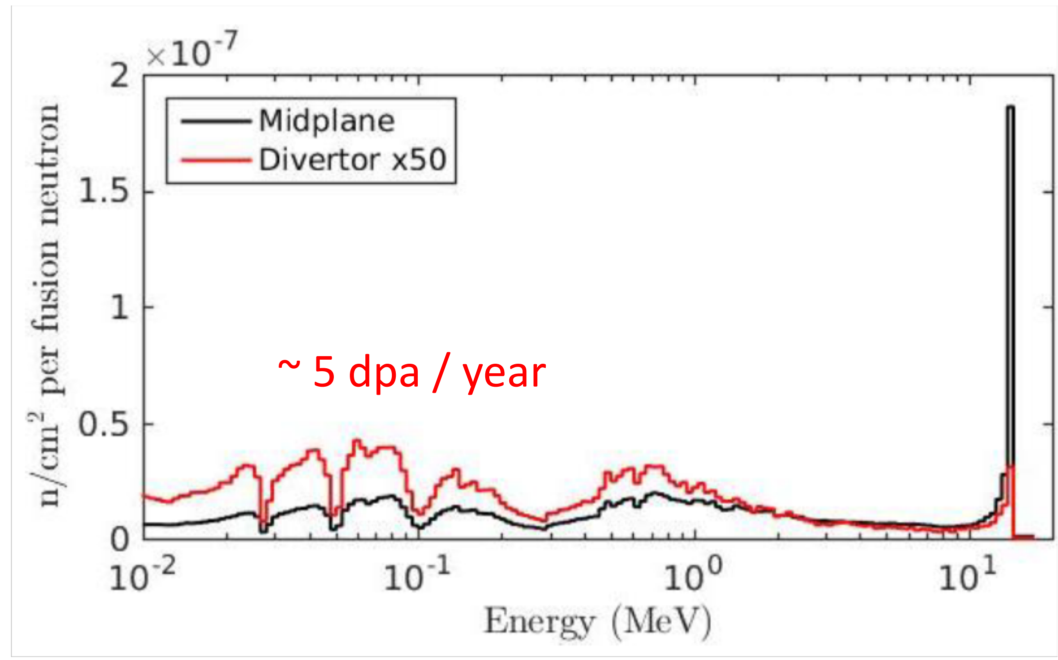
Kuang et al FED 2018

- 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.

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

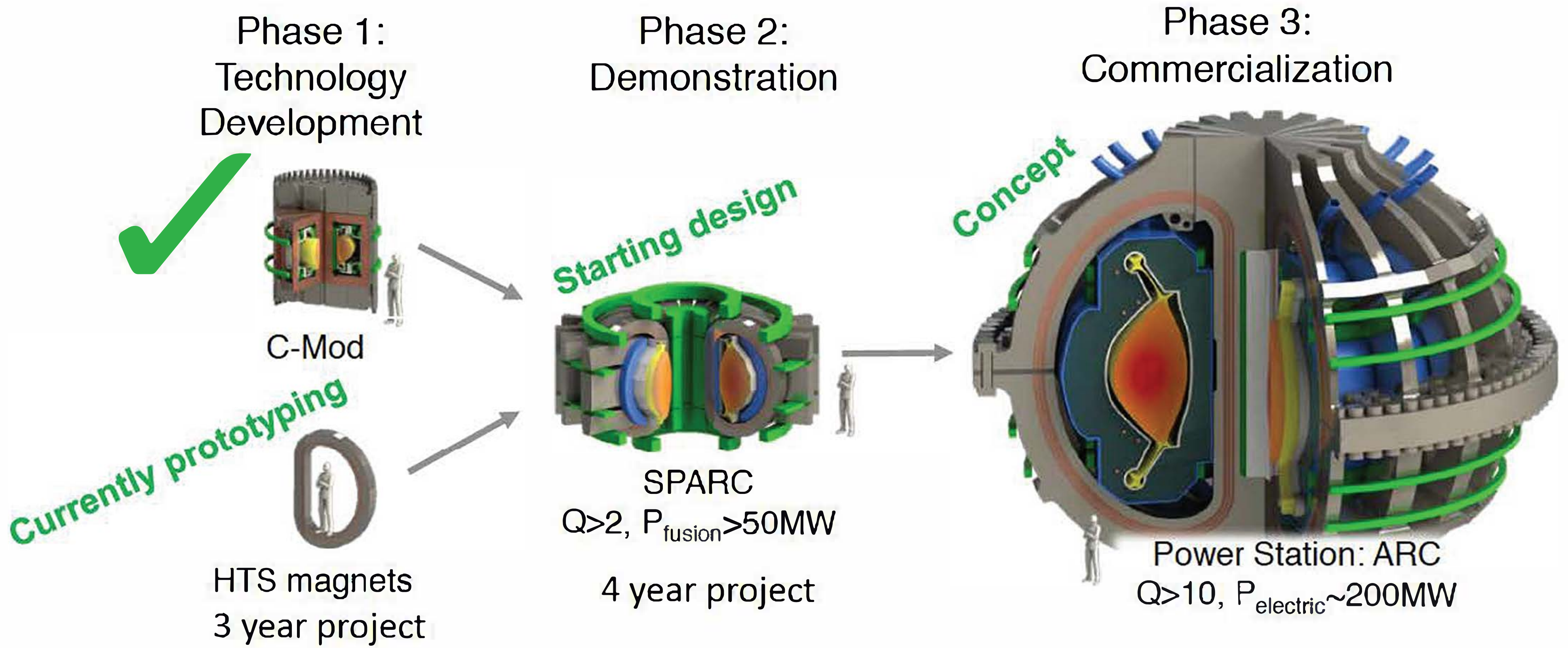


Coil	Lifetime [FPY]
PF1	11.3
PF2	76.2
PF3	12.5



Kuang et al FED 2018

The high-field approach to fusion energy



This path is backed by our investors financially, and by MIT institutionally for R&D. We are executing now.

Have Good Ideas?   Want to Help Make The Design Even Better?

- Contact
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SPARC

Thank you!

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