SPARC and the Hig
Magnetic Field Pat
Fusion Energy

Presented by Martin Gre
MIT – Plasma Science & Fusion C

LLNL HEDSC Seminar – March 25,

Acknowledgements – The SPARC Team, Particularly

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- Alex Creely*
- Chris Chrobak*
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Collaborating Ins

- Aalto U.
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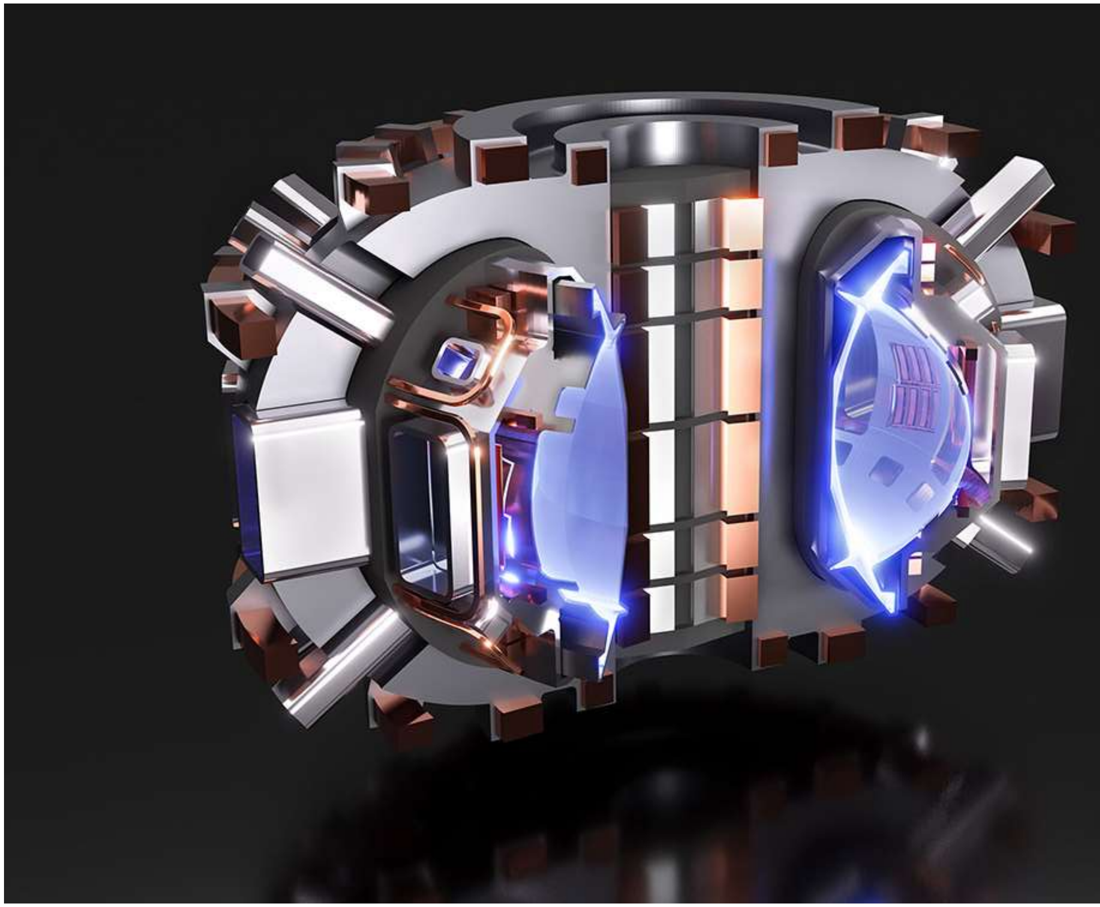
*Commonwealth Fusion Systems

Outline

- Quick introduction to fusion energy and magnetic confinement
- High Temperature Superconductors – a game-changing technology
- Plans, projections and physics for the SPARC device
- The role of private industry



SPARC – planned as the first magnetic confinement wh
would make net energy

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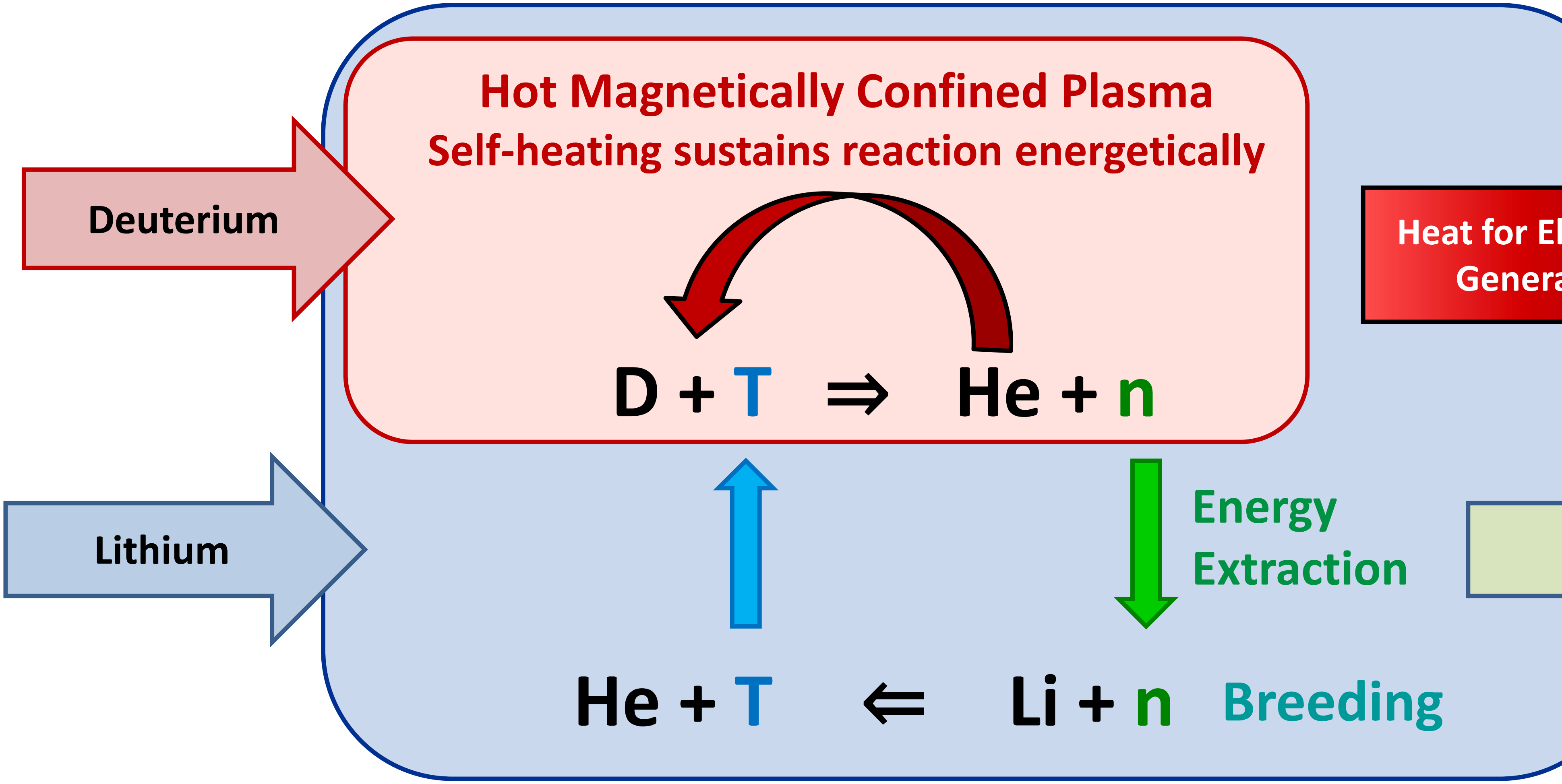
Can Fusion Contribute To The Solution?

The Technical Challenges Are Well Understood

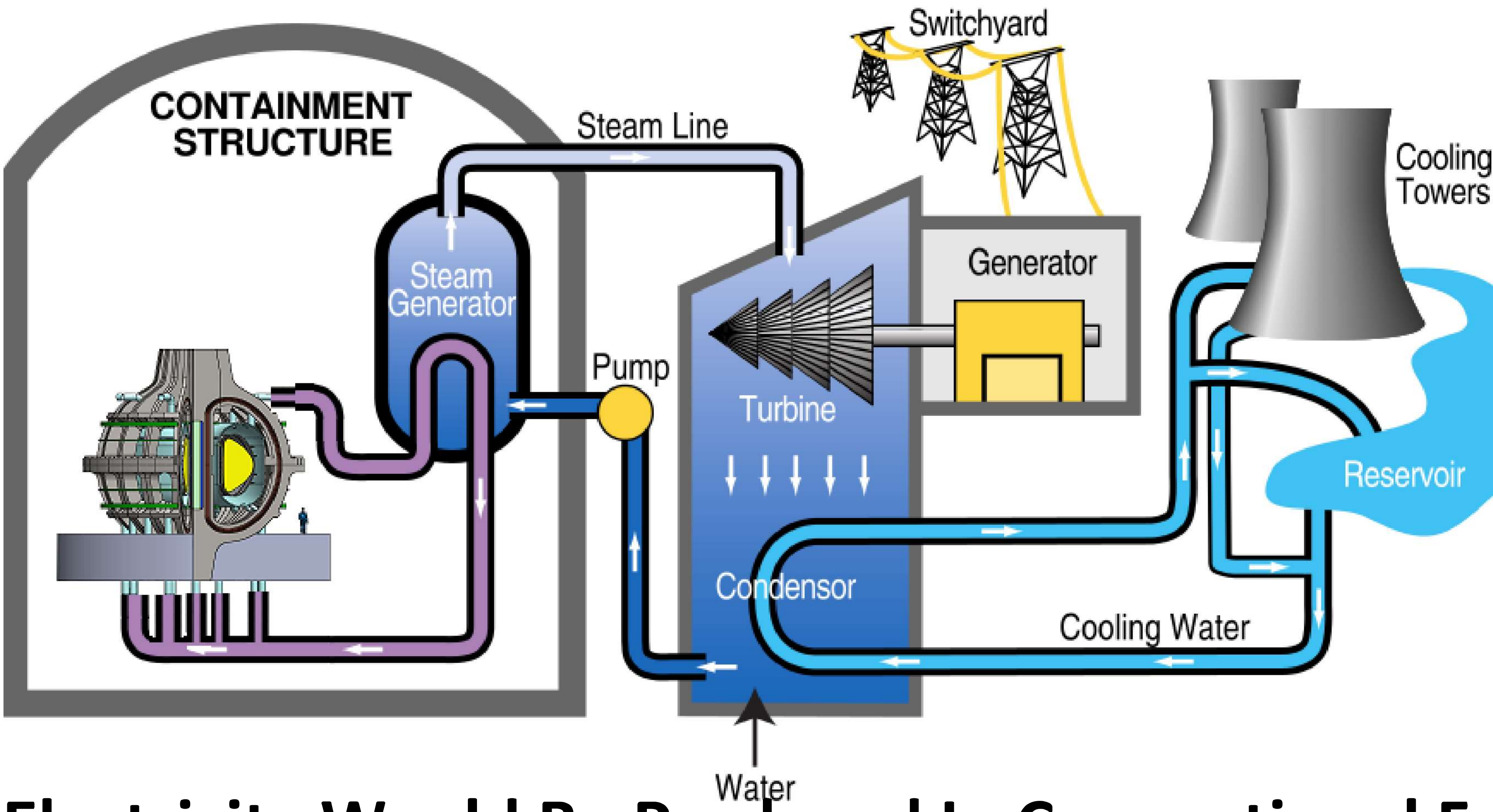
1. **Plasma physics**
   - Create, confine and sustain hot plasmas that produce net energy
2. **Taming the plasma material interface**
   - Minimize heat and particle loads
   - Develop materials and strategies to handle what remains
3. **Harnessing fusion energy**
   - Fuel cycle – tritium breeding, inventory control
   - Structural materials – maintaining structural, thermal and electrical properti intense neutron bombardment
   - Reliability, Availability, Maintainability, Inspectability



Net reaction: $_1D^2 + {}_3Li^6 \Rightarrow {}_2He^4 + {}_2He^4 + \sim 20$

Beyond the Fusion Core

Electricity Would Be Produced In Conventional Fash

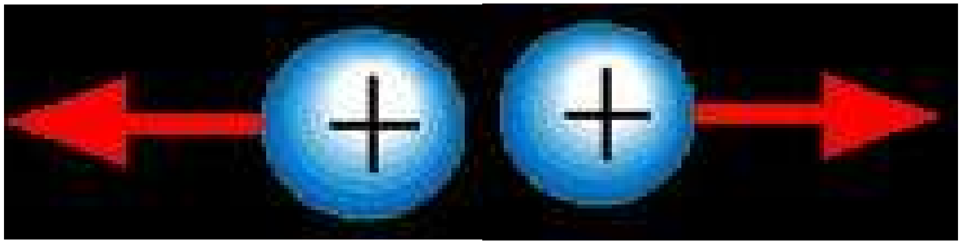


Electricity Would Be Produced In Conventional Fa

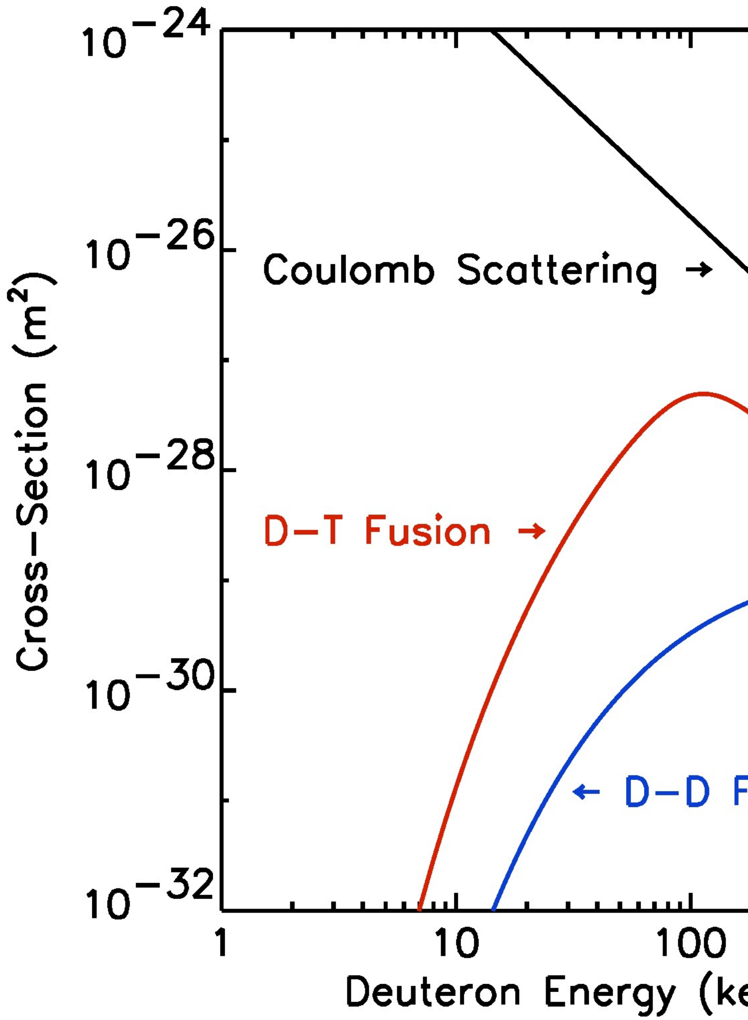
The Physics Challenge:
Very High Kinetic Energies Are Needed To Overcome Electrostatic

Fusion is mediated by the strong nuclear force – with a range of 10^{-15} m

So we need significant wave function overlap at that range

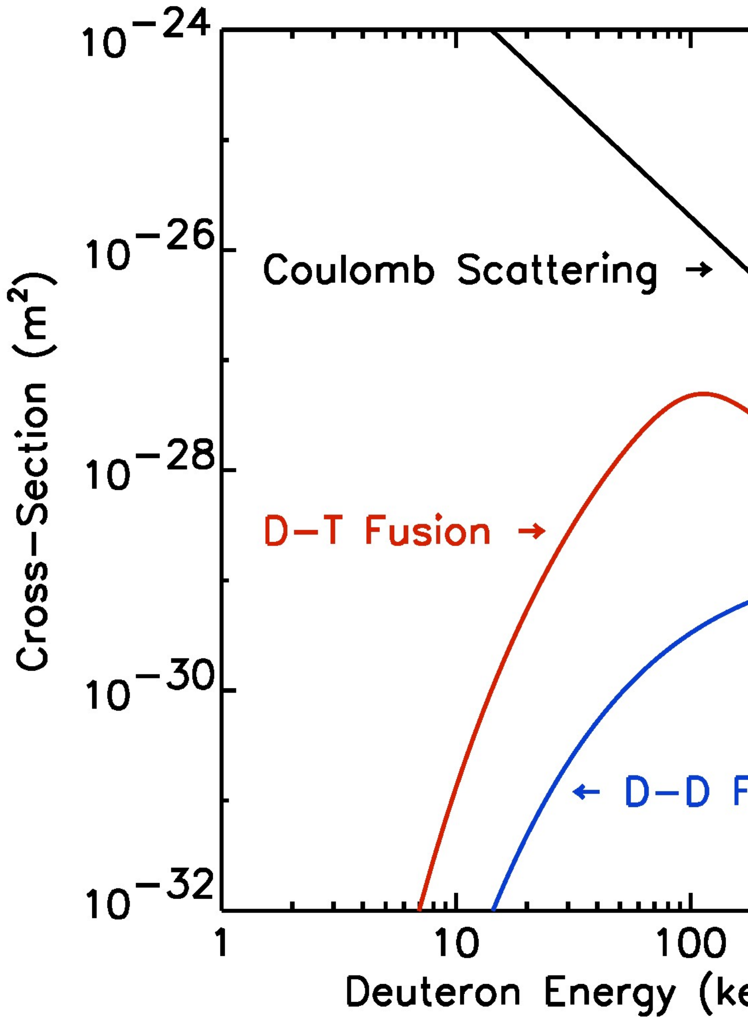


Nuclei are charged ⇒ Fusion requires ion energies on the order of 100 keV



The Physics Challenge:
Very High Kinetic Energies Are Needed To Overcome Electrostatic

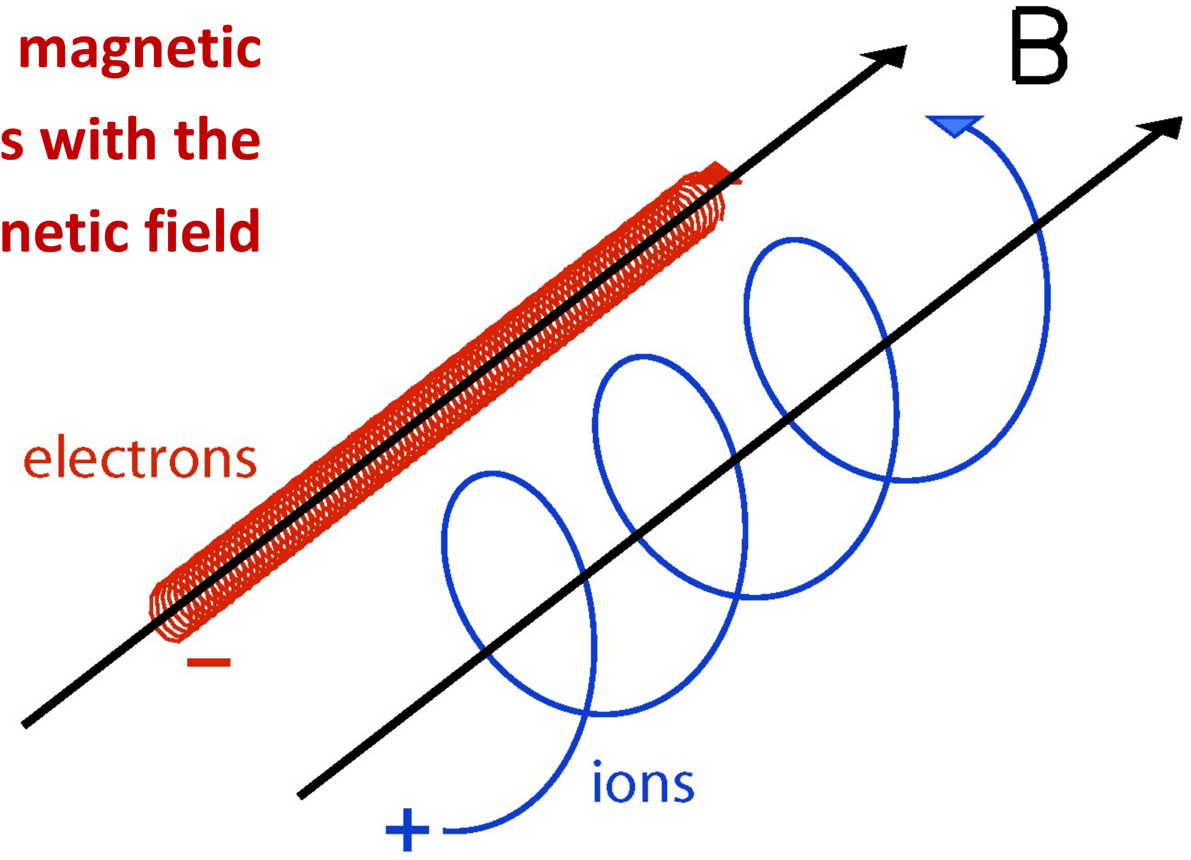
- But, even at the optimum energy, the nuclei are much more likely to scatter elastically than to fuse
- Particles rapidly thermalize, equilibrate
- We need to confine hot plasmas for many collision times
- Fusion plasmas need to reach temperatures on the order of 20 keV ≈ 200,000,000 K
- Must be isolated and insulated from ordinary matter



Plasma Can Be Confined by the Gyration Of Charged Particles in a Magne

Magnetic Confinement = Thermal Insulation Perpendicular To Fiel

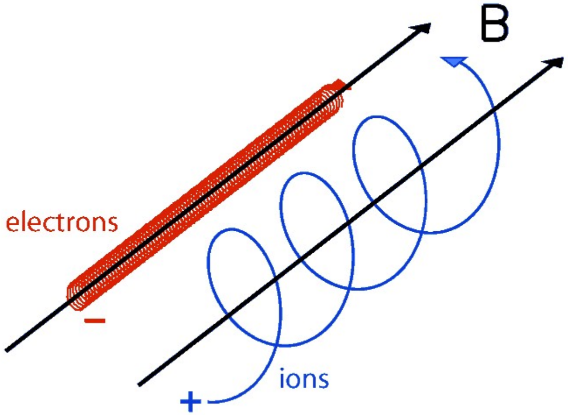
The quality of the magnetic insulation increases with the strength of the magnetic field



At B = 10

- ρ_e = 0.
- ρ_i = 1.
- We ne
  ~500 -
  - i.e.
  - (Bre
    requ

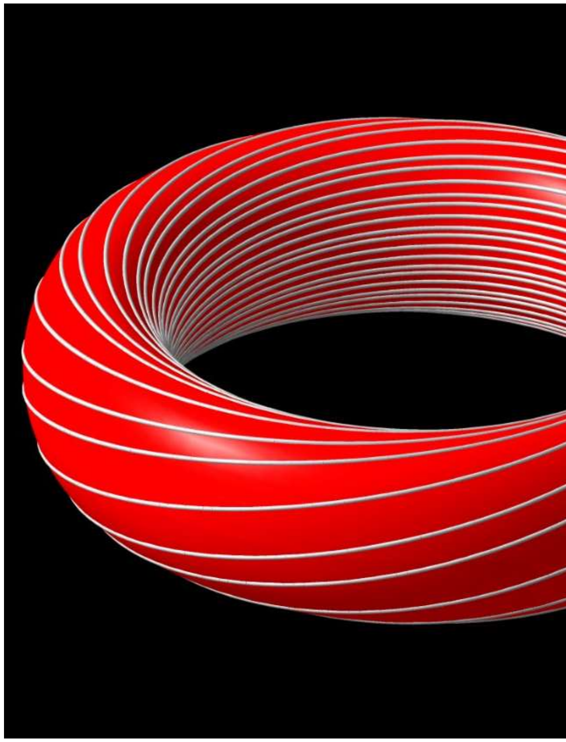
Magnetic fields confine charged p
in the perpendicular di



- At the temperatures involved, ions are moving at over 1,000 km/s
- But, even at these temperatures, the average time for an ion to fuse ~ 25 seconds
- For a practical device, the end losses must be eliminated

Voila!

Eliminate the ends



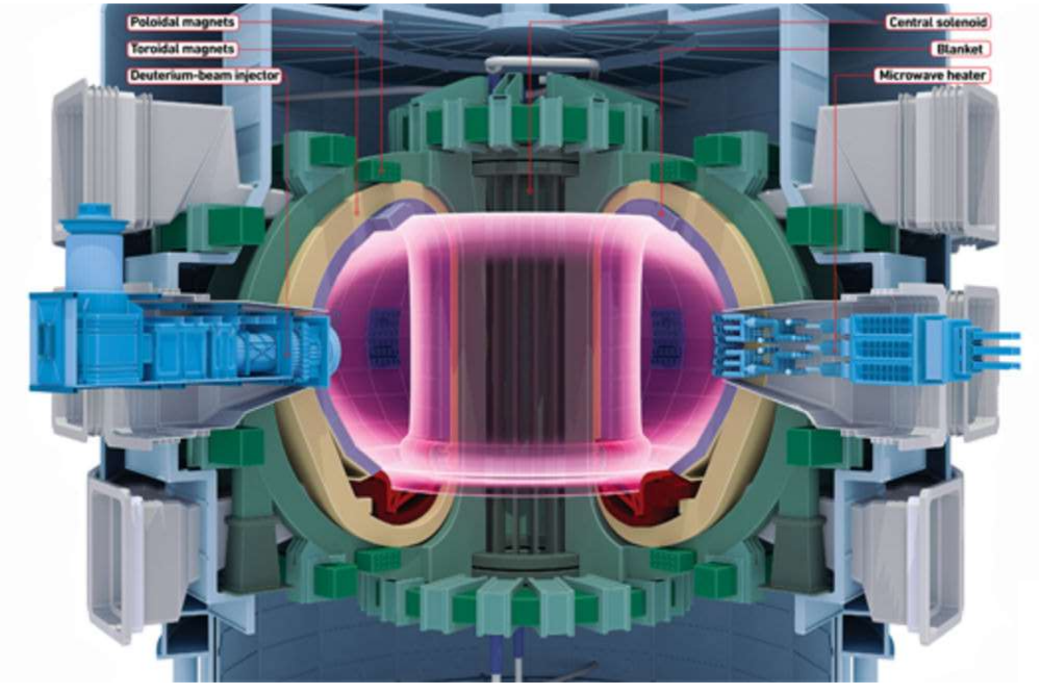
A torus is unique topologically. It is the only 3D shape whe vector field (B in our case) can be tangent to the sur

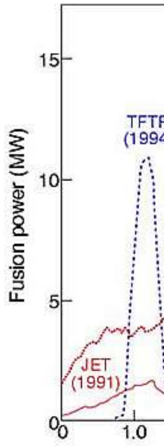
The Tokamak is the Leading Concept in the Race for Practical Fusion Energy

Nature provides a well-founded and quantitative set of metrics for progress in fusion energy in the Lawson criteria (1955): $n\tau_E$ **and** T_i

(Density x confinement time and temperature)

We've achieved the required $n\tau_E$ **and** T_i individually, but not both together - YET





Toka
produ
MW of

Tokamaks Demonstrated Enormous Progress For 3 Decades, Bu


HT-7 (CN)

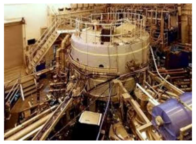

JT-60U (JP)


KSTAR (KR)


MAST-U (UK)


NSTX-U (US)

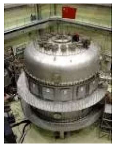

Tore Supra (FR)


Alcator C-Mod (US)


ASDEX-U (DE)


COMPASS (CZ)

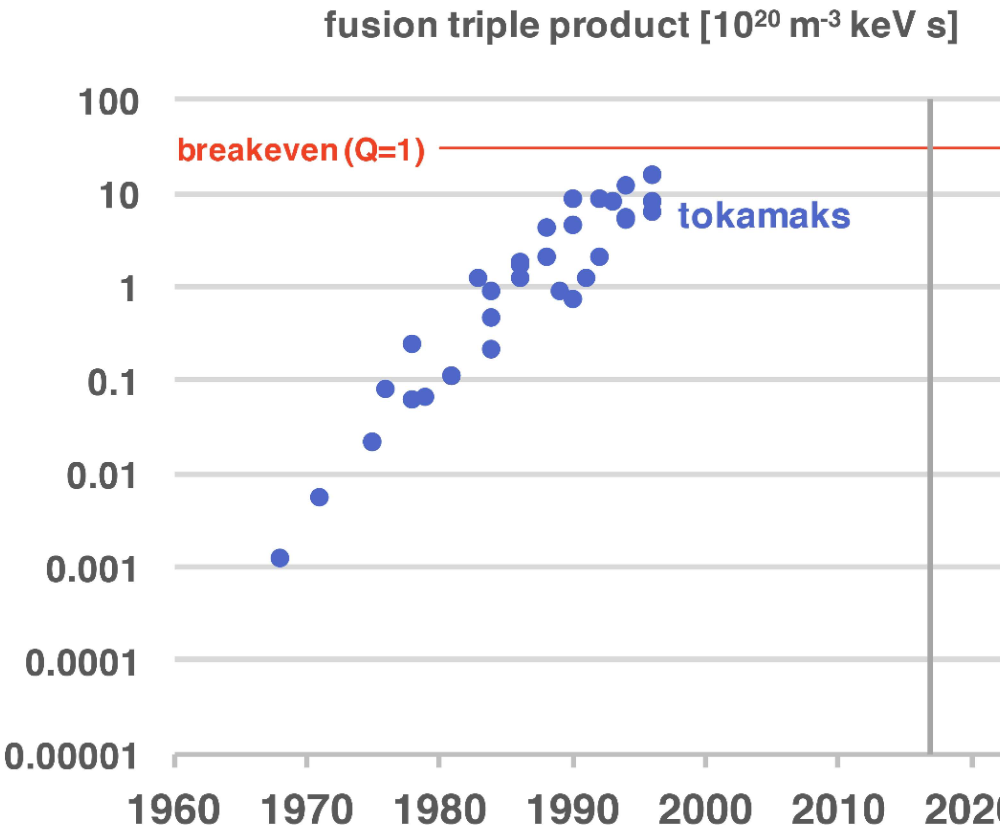

DIII-D (US)


EAST (CN)


FTU (IT)

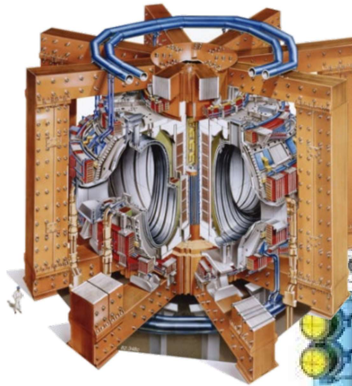
+ 160 other tokamaks across 60 years

Enormous technical and scientific base

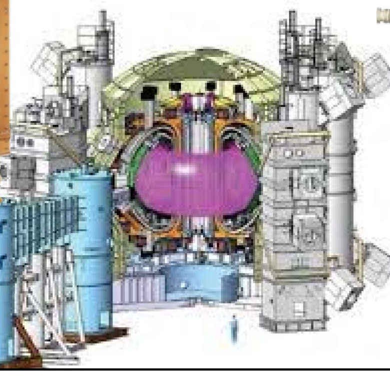


Progress Exceeded Moore's Law

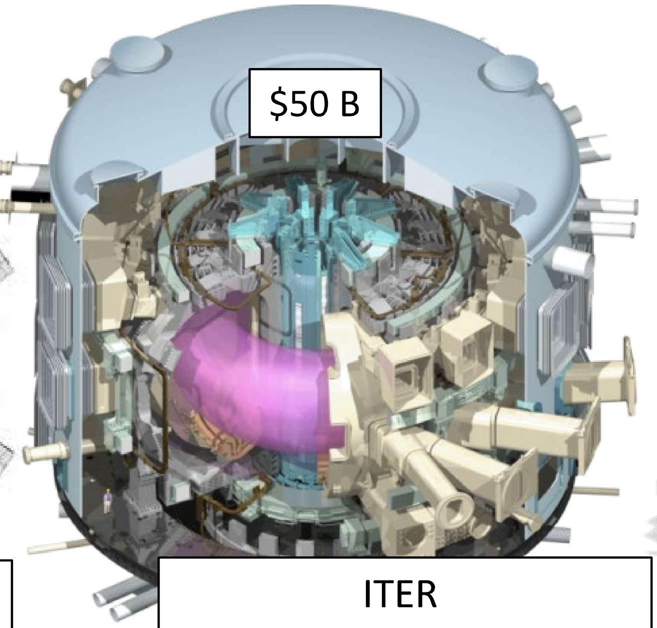
Progress Slowed As The Devices Got Too Big, Too Expensive



JET
Now operating

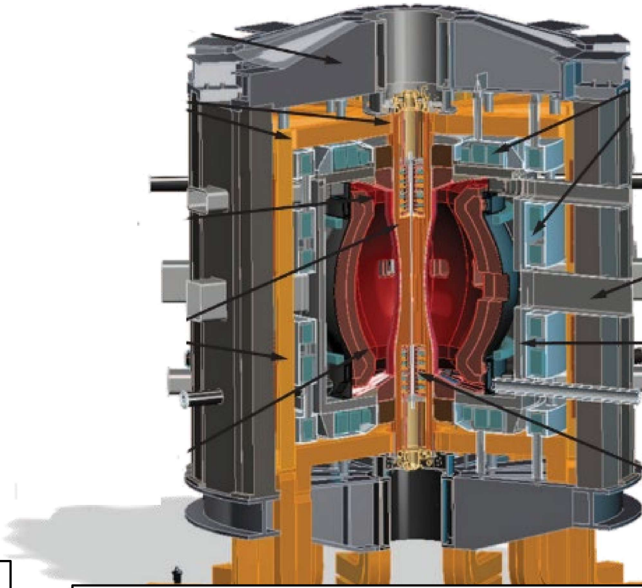


JT-60SA
Commissioning, 2021



$50 B

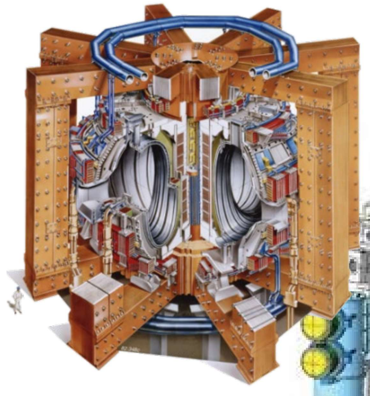
ITER
US-USSR Agreement 1985
Research 2030
D-T 2035-2040



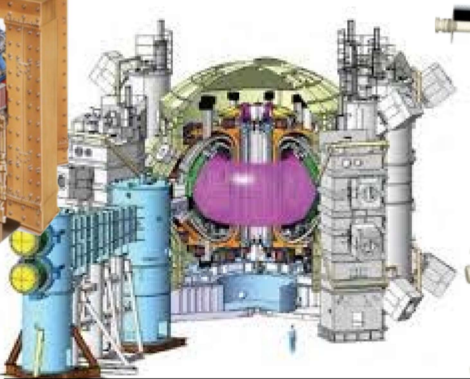
FNSF/Pilot (US)
Construction Start 2040-2045?
Operation 2050?

2015 2020 2025 2030 2035 2040 2045 2050

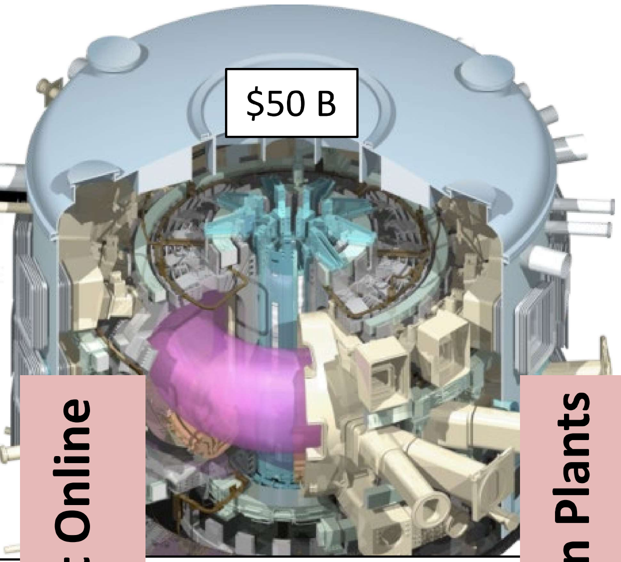
Progress Slowed As The Devices Got Too Big, Too Expensive



JET
Now operating



JT-60SA
Under construction, 2019



$50 B

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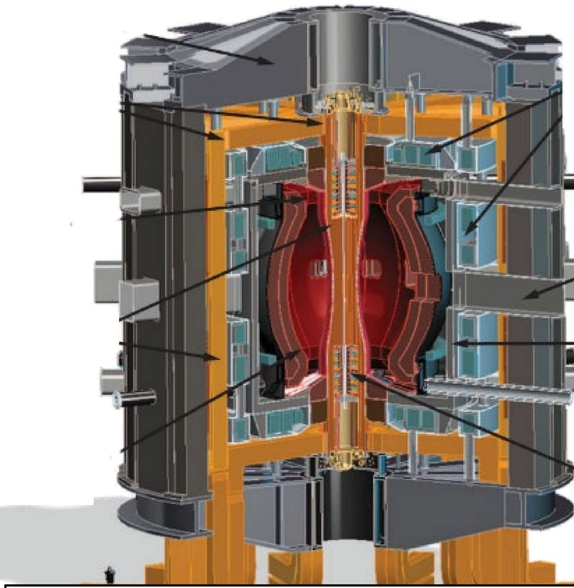


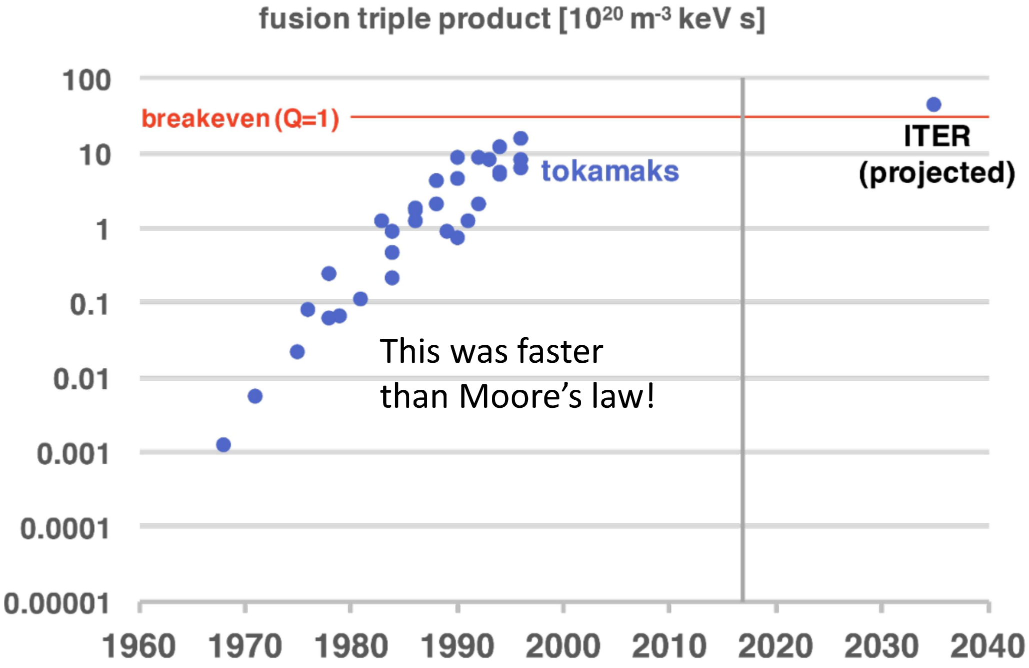
FNSF/Pilot (US)
Construction Start 2040-2045?
Operation 2050?

First Plant Online

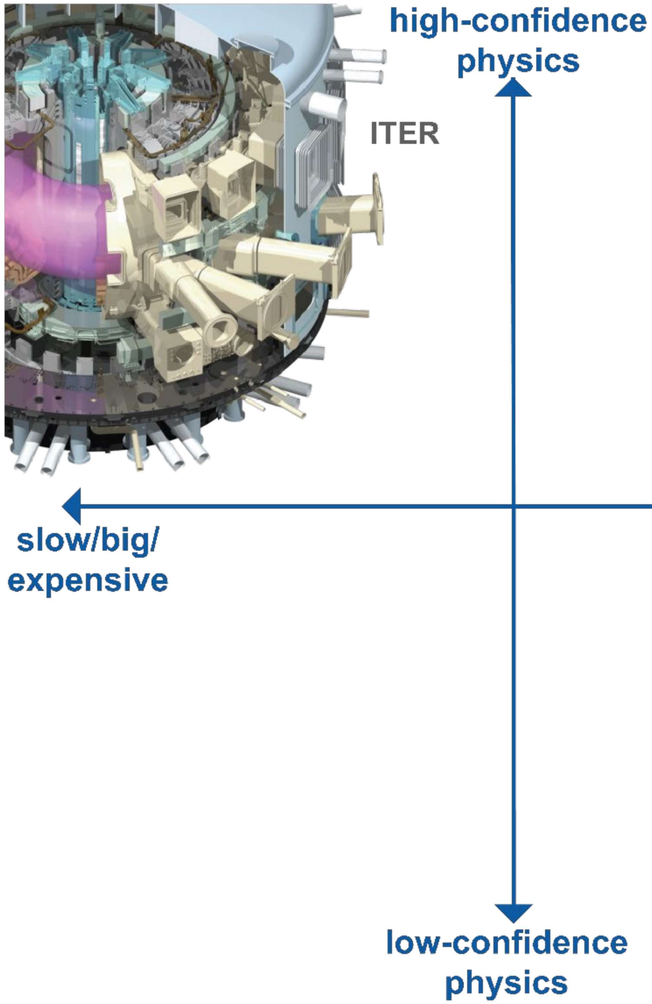
Deploy Ten Plants Per year

2015 2020 2025 2030 2035 2040 2045 2050

What Can We Do About This?



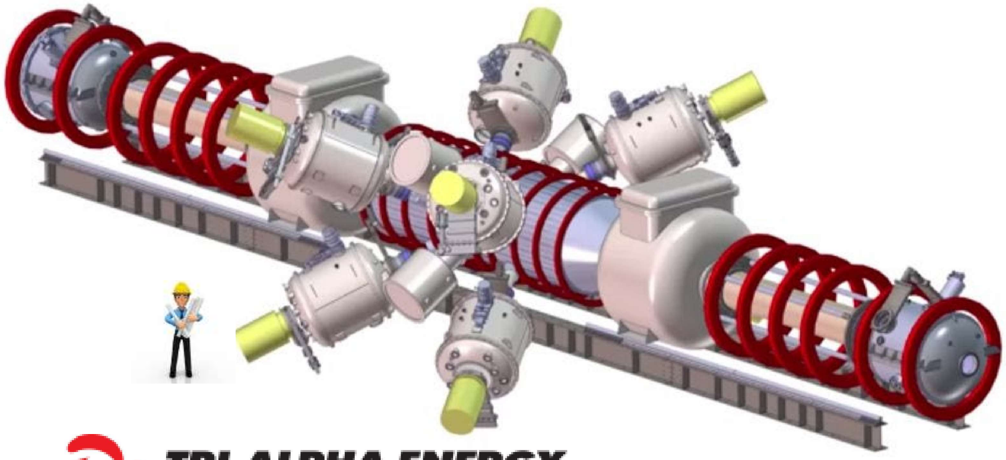
This was faster than Moore's law!



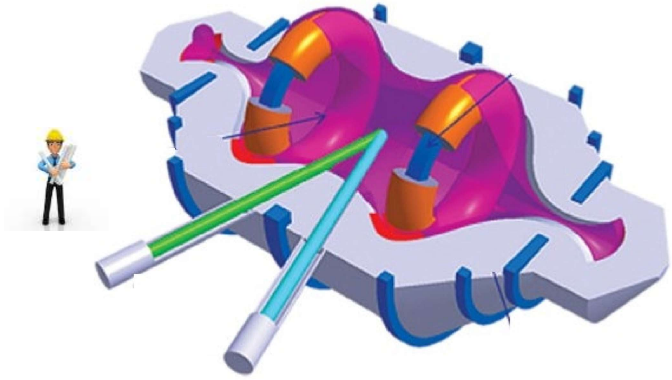
- Tokamaks: Impressive and unparalleled fusion performance
- Stagnating due to size & cost, not saturation due to physics
- Can they be fielded in time to deal with global warming?

Private Companies Have Attracted $$$ On Small But Risky Co

- Small enough to carry out without government funding
- Can be built quickly
- Raise the profile of fusion
- Have been innovative and nimble
- But – are taking a big leap into unknown physics and engineering

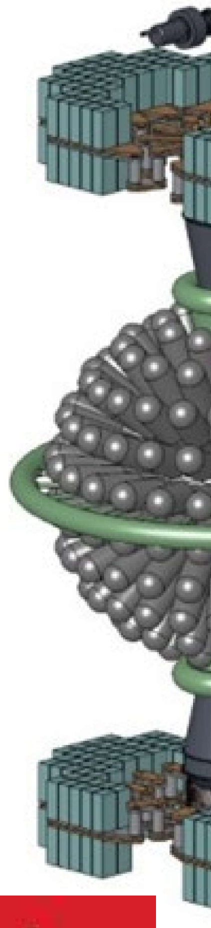


TRI ALPHA ENERGY
THE POWER OF INGENUITY



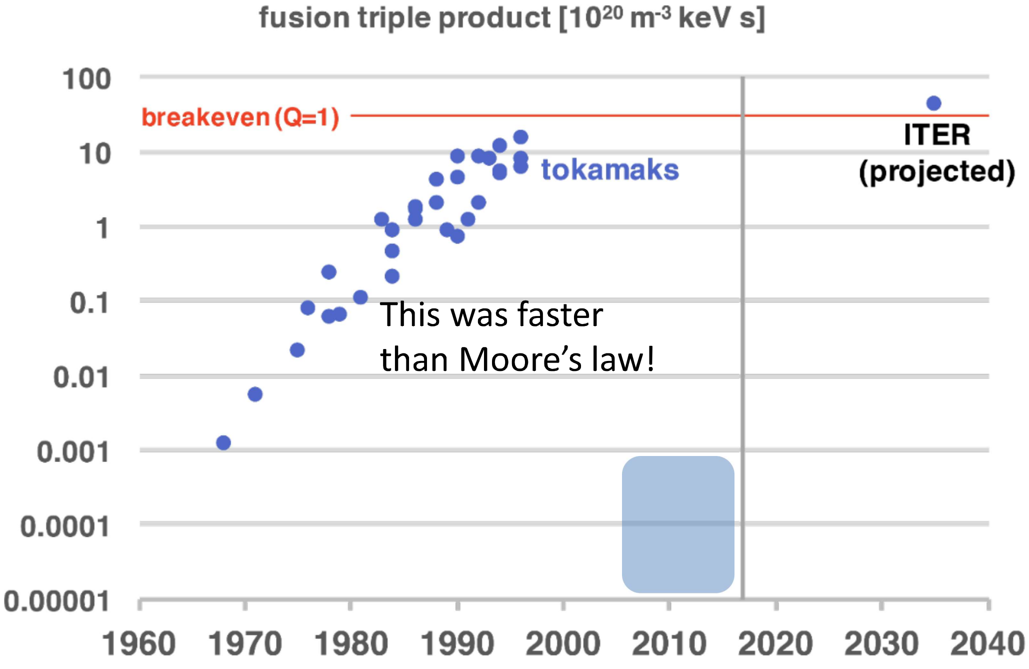
LOCKHEED MARTIN

(all figures to scale)



generalfusion

These Alternates Currently Fall Far Short of What's Need



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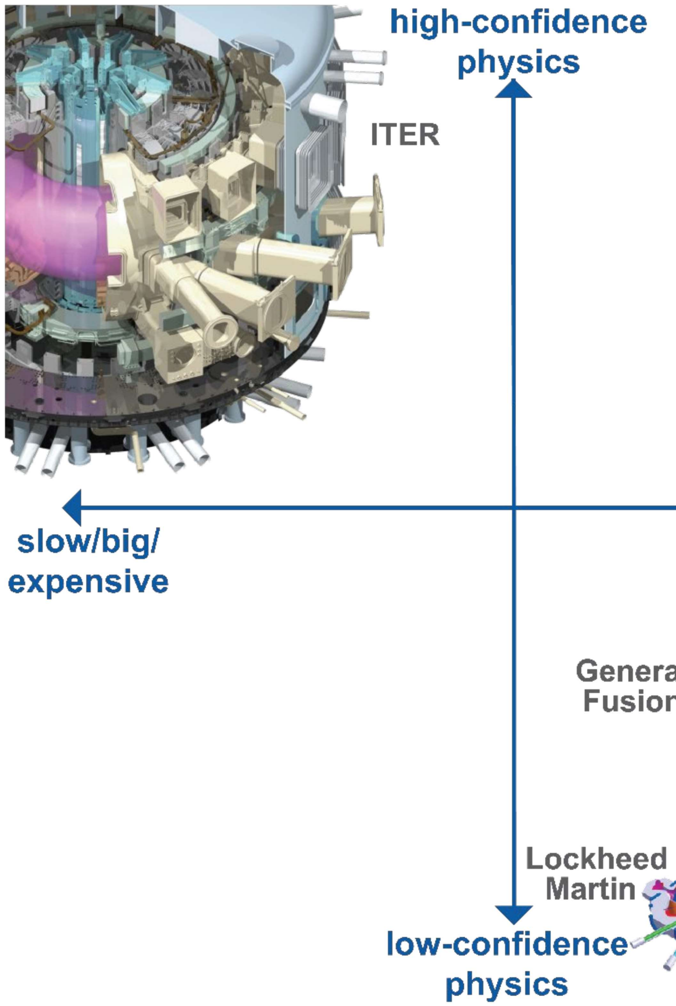


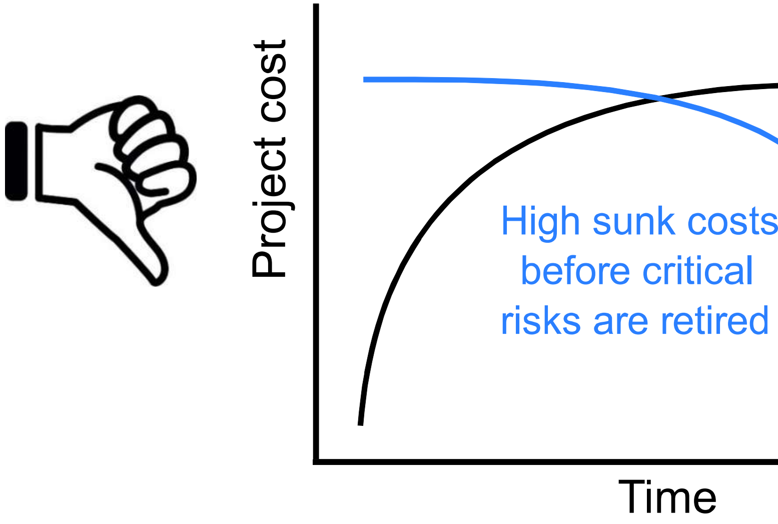
Moreover Can We Follow a Development Path That Retires Ris

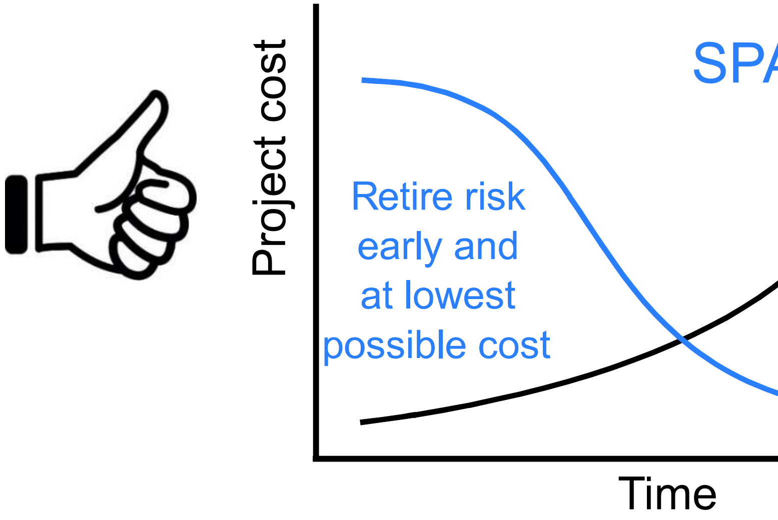
What should the risk retirement and cost curves look like?

- Retire the largest portion of the risk at lowest expenditure
- If the risk is in the physics then the entire device must be built before that risk is retired
- But if the risk is in the enabling technology, that can be retired early leaving high confidence the device will operate as designed

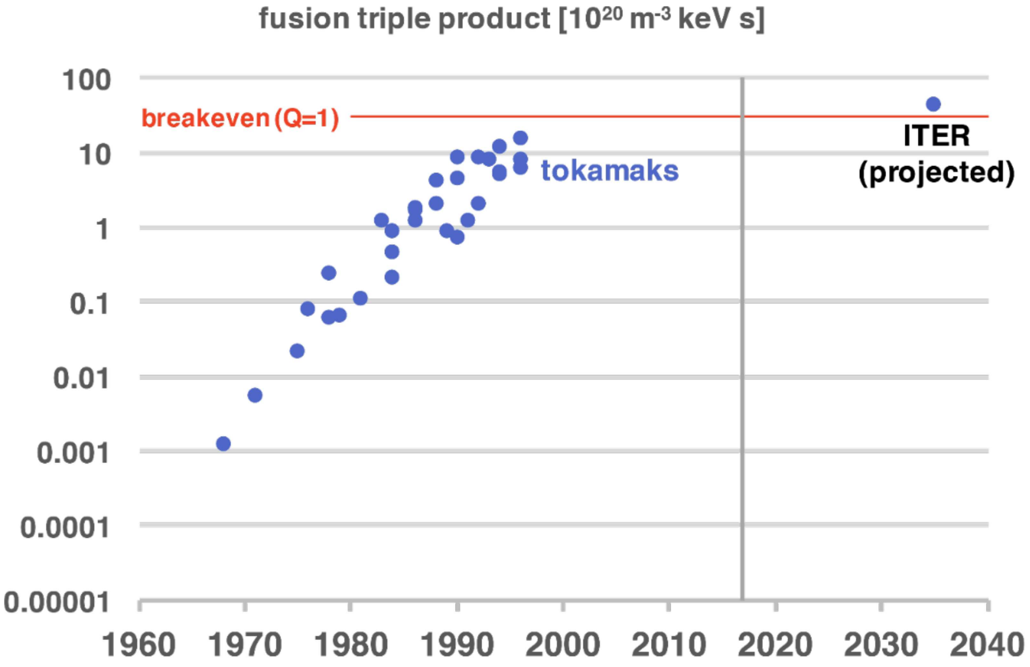
- **Innovate in the areas of highest return**

- **Avoid putting all innovation on unproven physics and instead innovate in engineering of new components to make proven physics work better**



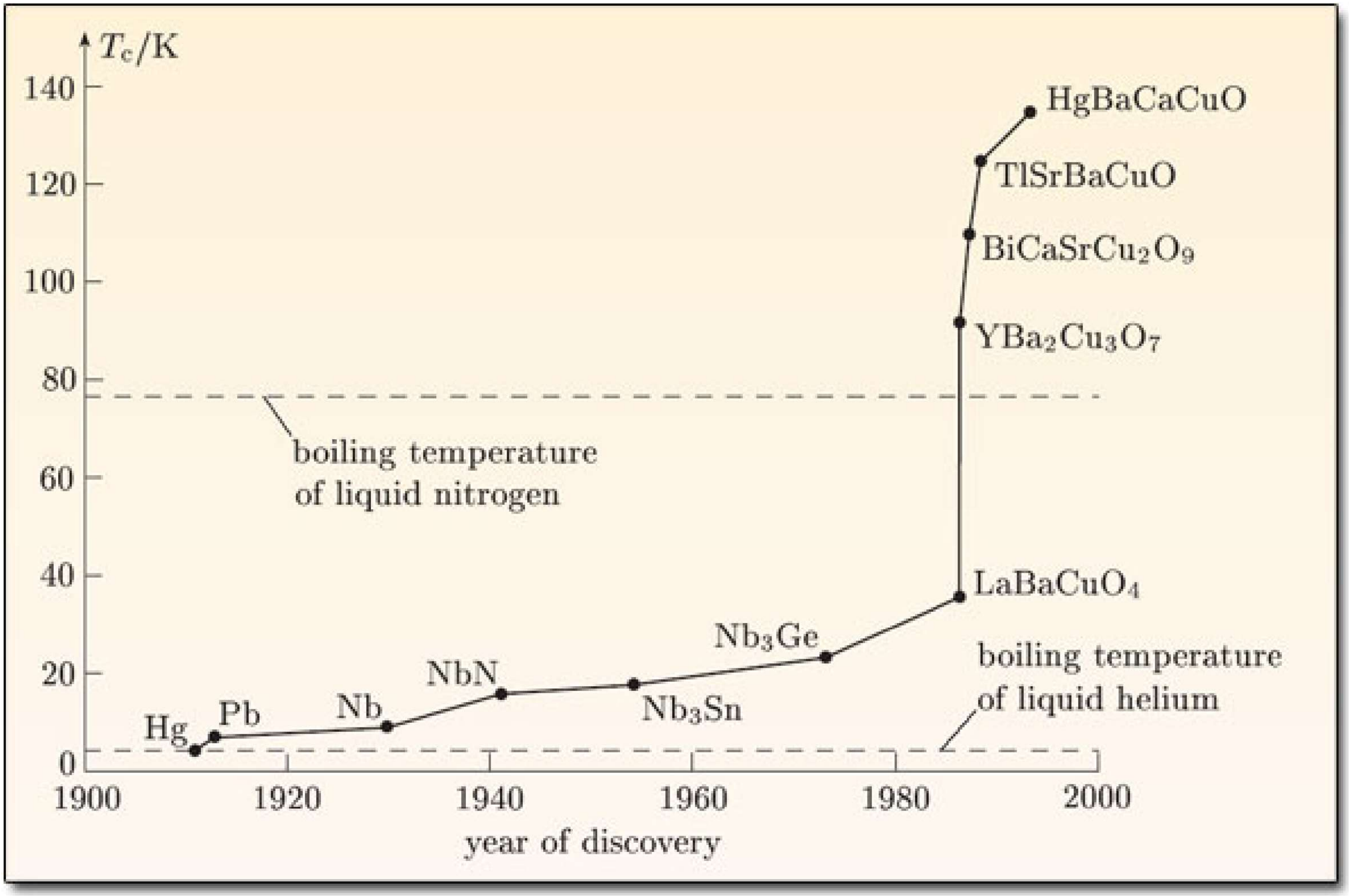


We Need To Consider Another Approach



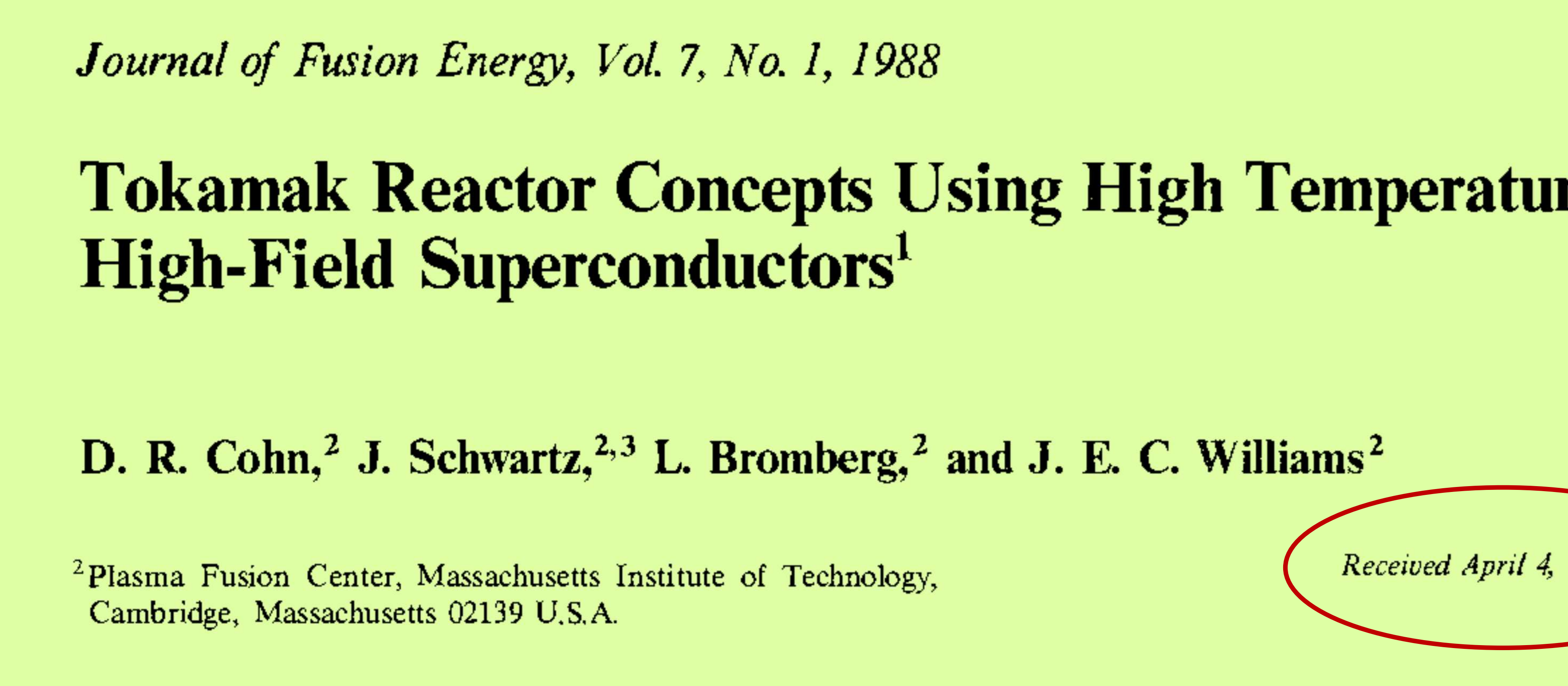
- **We're looking for a path which builds on the progress and knowledge built by decades of research on the tokamak**
- **Reduced in scale to learn fast**
- **Focused on fusion power plants that are practical and economical**

We Think The Basis For Breakthrough Is Here – High Temperature Superc



- Discovered mor
  years ago – 198
  - Nobel prize fo
    Muller 1987
- High T_C was a su
  theory still inco
- Ceramic form –
  too brittle for p
  applications by

Some People Understood The Implications Right Av



Journal of Fusion Energy, Vol. 7, No. 1, 1988

Tokamak Reactor Concepts Using High Temperatu High-Field Superconductors[1]

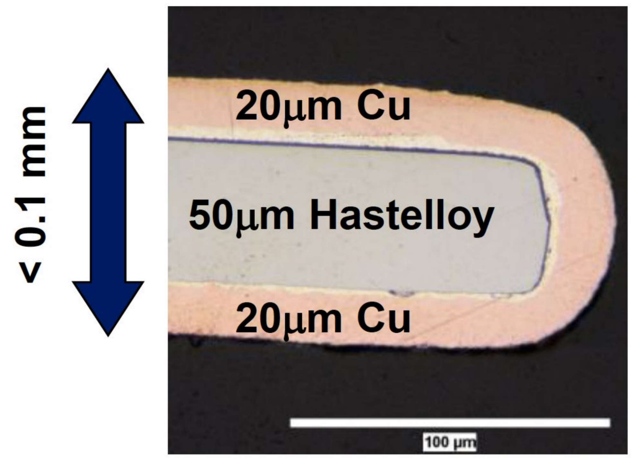
D. R. Cohn,[2] J. Schwartz,[2,3] L. Bromberg,[2] and J. E. C. Williams[2]

[2] Plasma Fusion Center, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139 U.S.A.

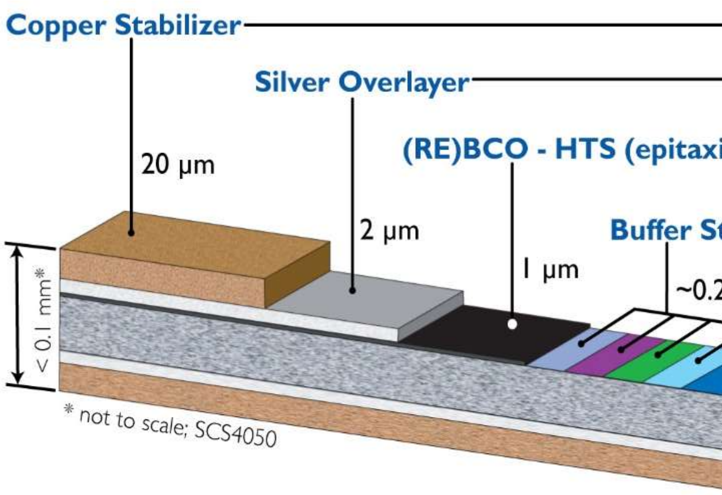
Received April 4,

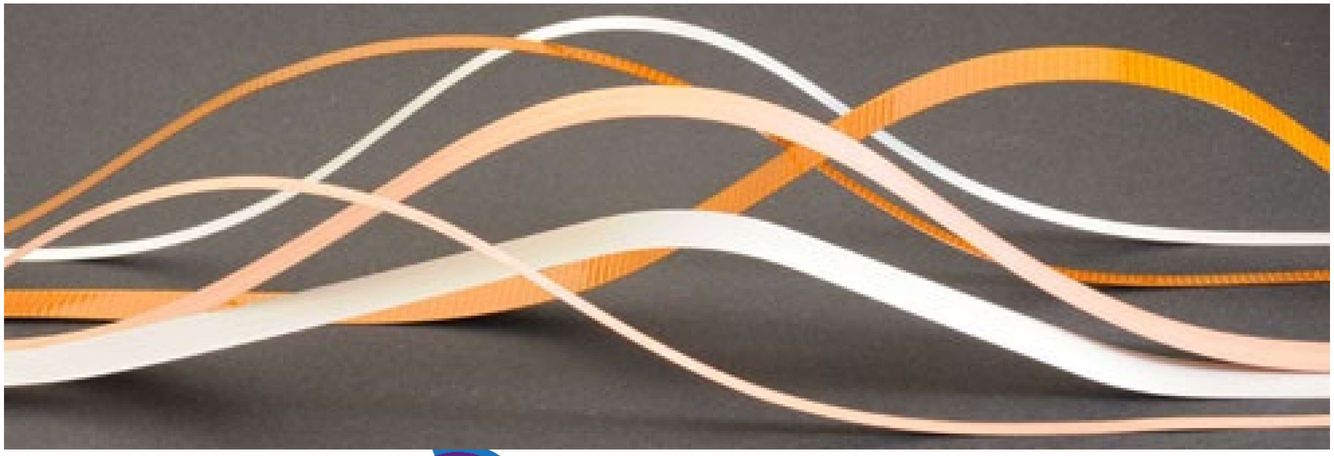
The rest of us took a bit more time to appreciate the

High Temperature Superconductors
Out of the Lab and into Industrial Production



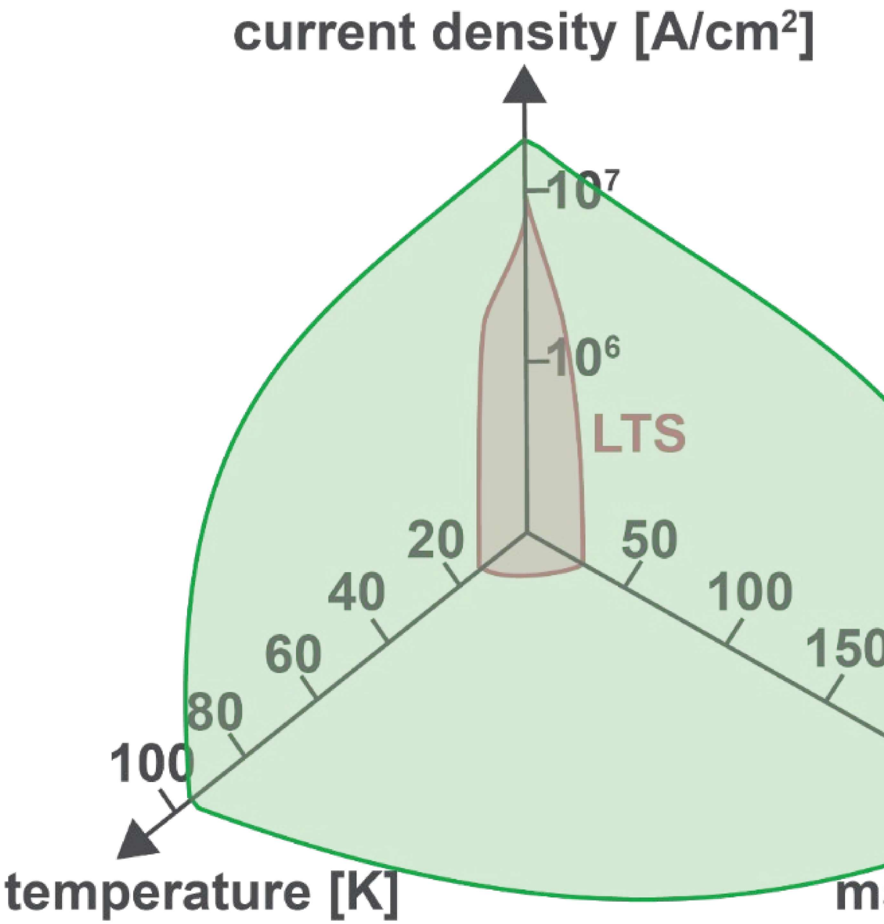
- Deposited as a thin film on a steel substrate
- Over-coated with copper for stability





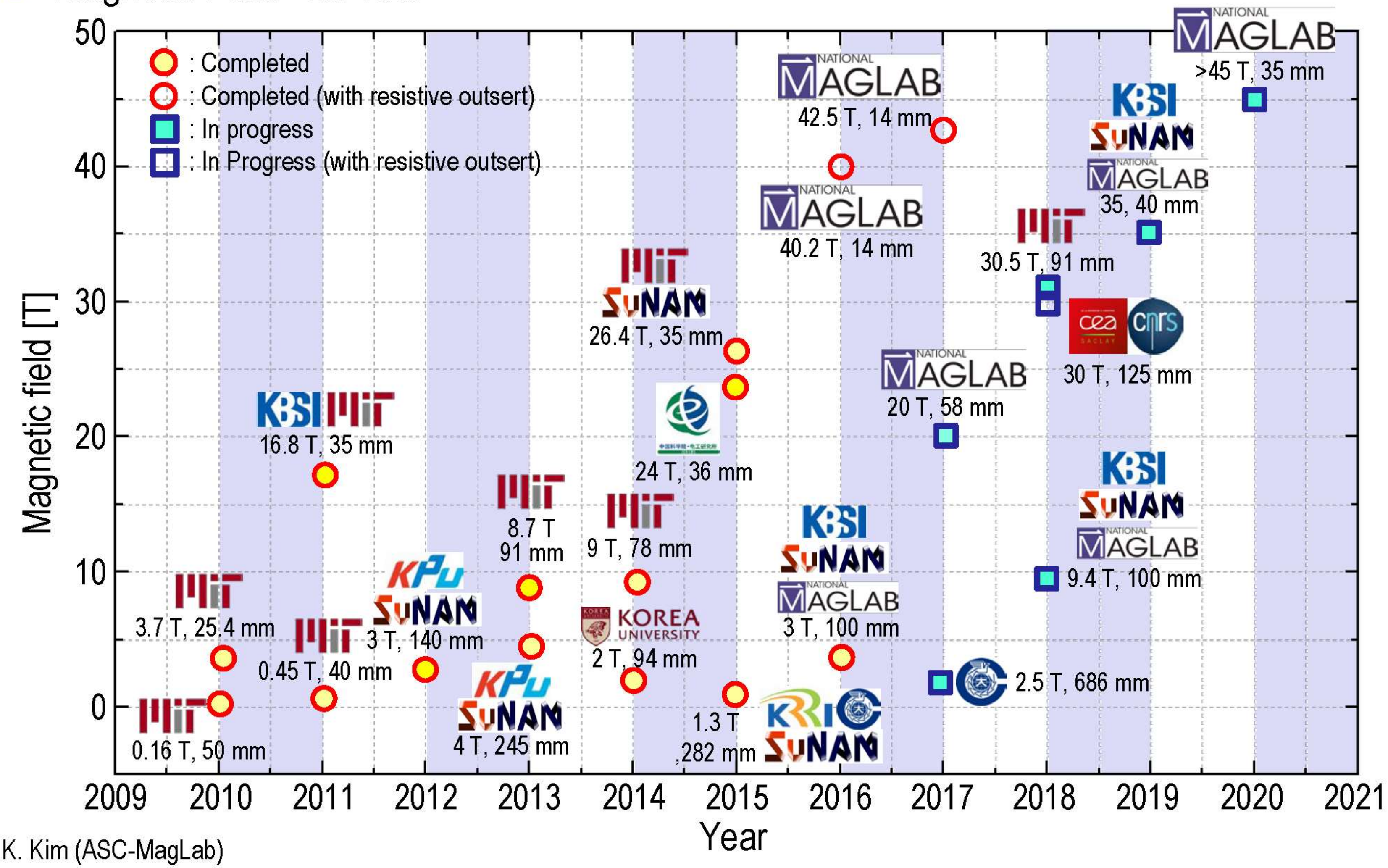
These New Superconducting Materials Are Ideal For Large-V
High-Field Fusion Magnets

- Much wider operating space in field, current density and temperature
- Higher current densities – more compact magnets
  - Strong structure - substrate is mainly steel
- Operation at higher temperatures
  - New cryogenic options
  - Better stability against quench
  - Higher heat capacity should enable magnets with demountable joints
- No reaction process as part of winding



Capabilities of HTS Magnets Are Rapidly Increasing, Costs Dec

- Magnetic Field vs. Year



K. Kim (ASC-MagLab)

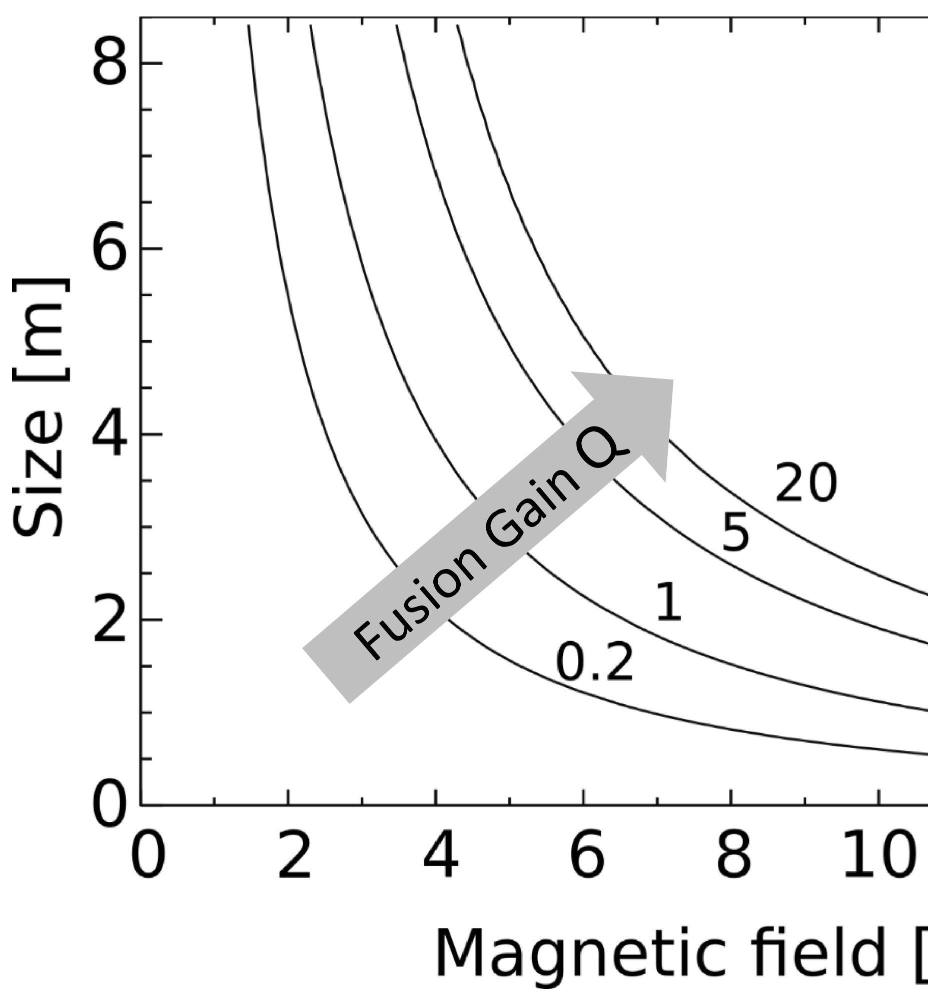
26 T

S. Hahn
NHMFL,

Why Do We Care? At Higher Fields, Fusion Reactors Can Be

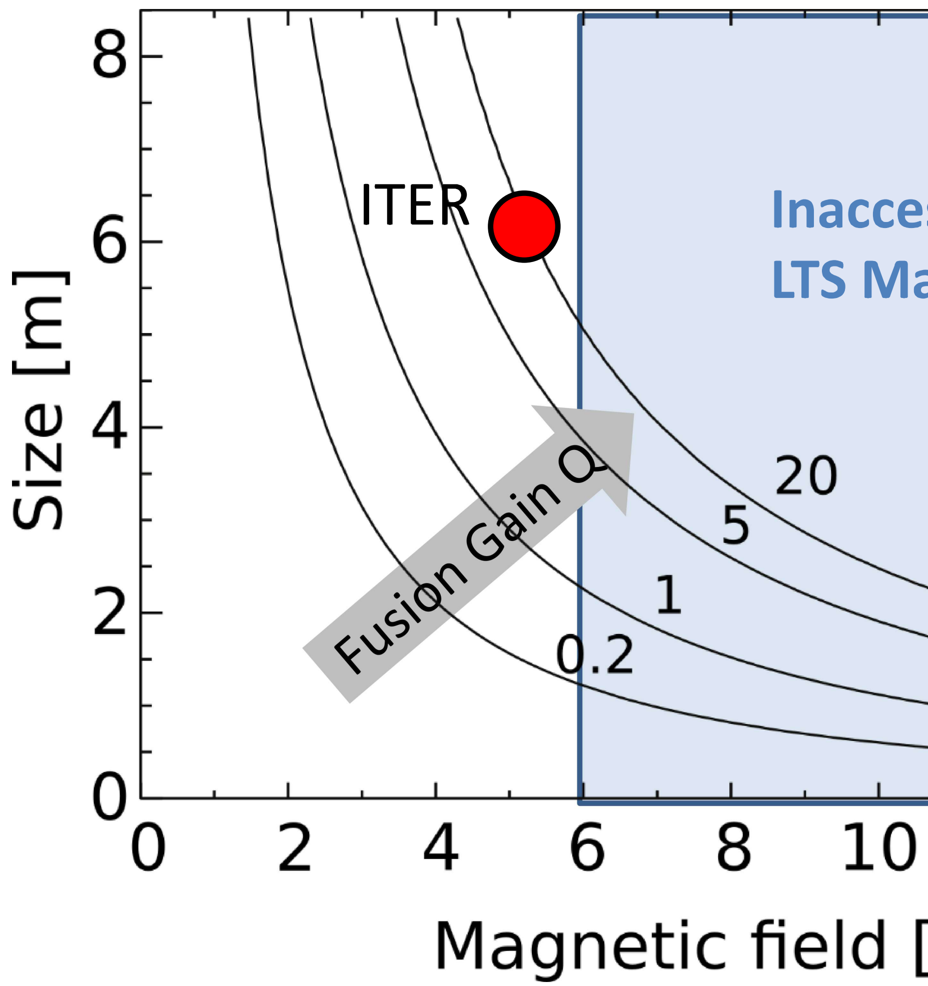
- The “size” of the plasma is properly measured in ion gyro-radii, $R/\rho_i \propto BR$
- Higher power density
  - $R_{Fusion} \propto n^2T^2 \propto p^2 \propto B^4$
  - Fusion gain: $n\tau_E T \propto B^3$
- Using “Standard” physics assumptions we can map out fusion performance and see the quantitative trade-off between field and size

- $H_{98} \sim 1$
- $A \sim 3$
- $\kappa \sim 1.8$
- $q \sim 3$
- $D/(D+T) \sim 0.5$



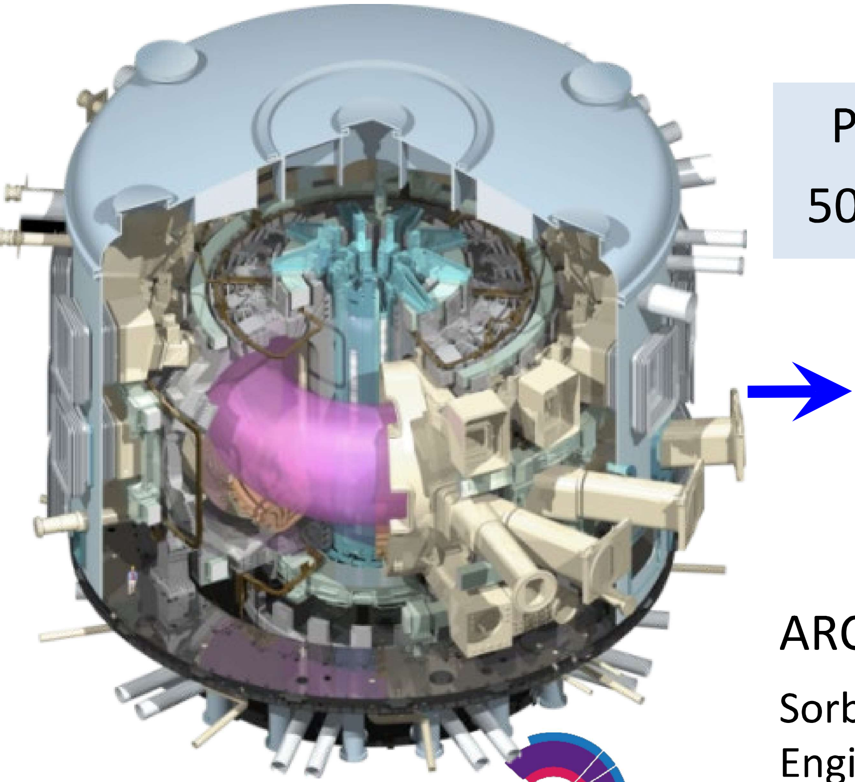
But - With Conventional Superconductors, Machines Have To

- Practical fusion needs superconducting magnets
- "Best" LTS (Low Temperature Superconductors) is Nb_3Sn
- Large-volume fusion magnets can't have much more than 5-6 T on axis
- That set the size for ITER
- Requires the combined resources of the entire industrialized world to build
  - ~50 years from Reykjavik summit (1985) to DT operation (2035)

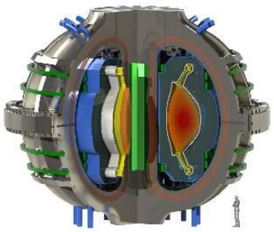


The New HTS Magnet Technology Relaxes That Constraint
At Higher Fields, We Can Go Smaller

- Doubling the field allows the size to drop in half
- The volume, weight decrease by a factor of 8
- **Enables a new class of devices**

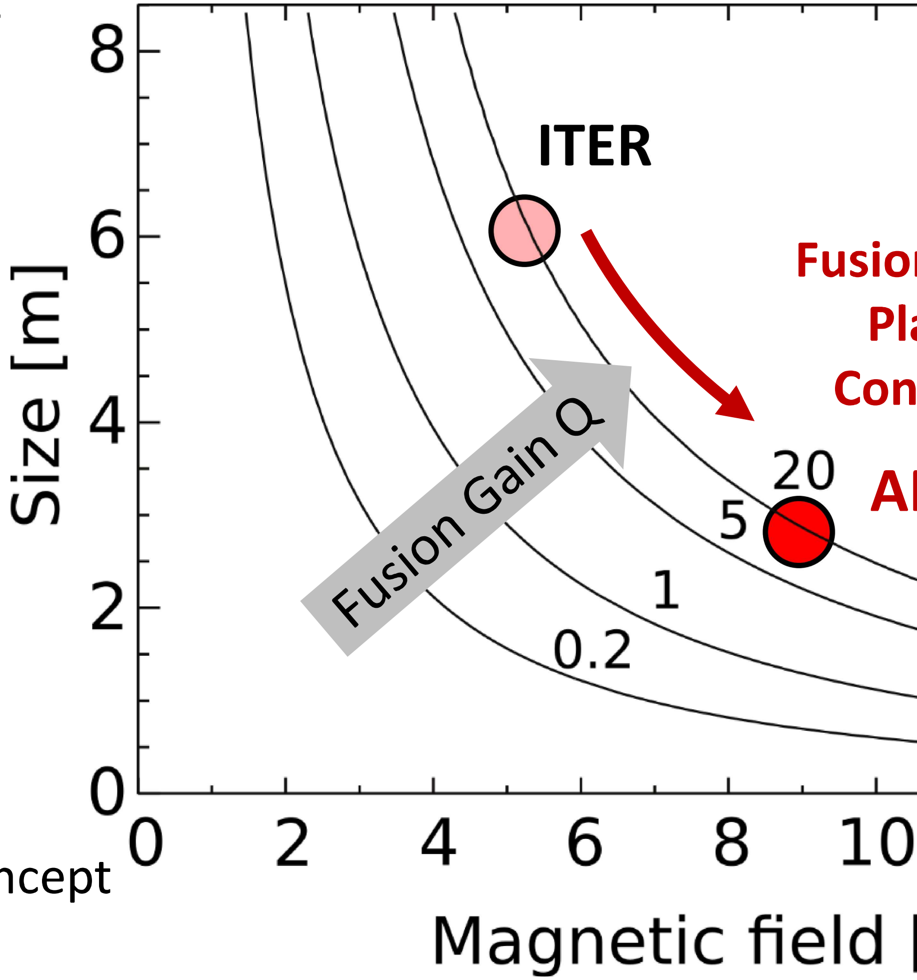


P_{FUSION}
500 MW

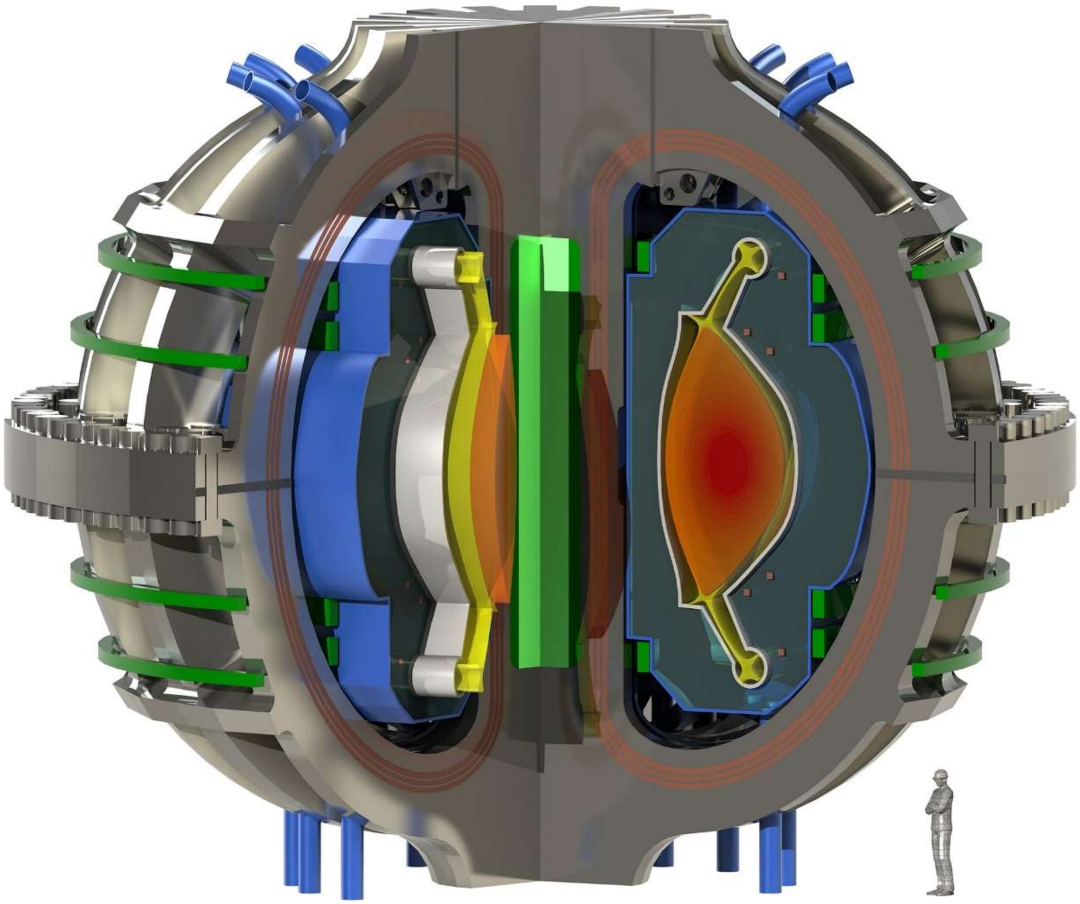


ARC: Pilot Plant Concept

Sorbom et al., Fusion Engineering and Design 2015



ARC: Concept for Class of Modular Fusion Pilot Plants

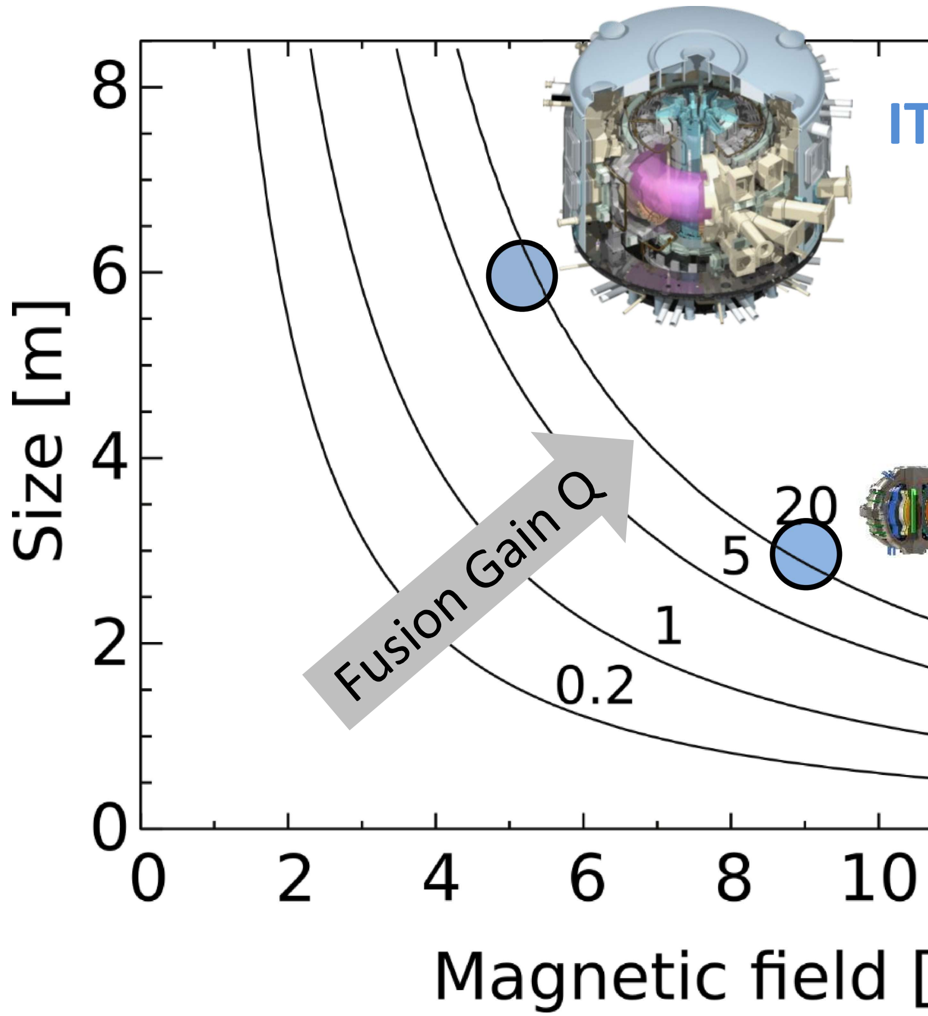


- Originated in a Graduate design class
- **Not** an engineering design (yet)
  - Though sufficient mechanical, hydraulic, electrical calculations were performed t engineering plausibility for this class of c

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

We’re Not Ready To Build A Machine in the ARC Class
SPARC: An Intermediate Step From Today’s High-Field Experi

- Burn DT to demonstrate Q_{FUS} robustly above 1 and with significant fusion power
- Same B_{COIL} as ARC – same technology
- Think of as a 12T, HTS version of AUG or DIII-D (currently operating expts.)
  - About 1/64 volume, weight, cost of ITER
  - Small enough to be built by a university/industry team



SPARC Mission

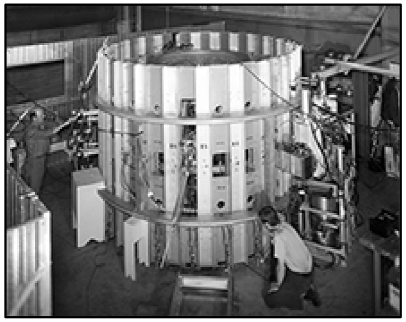
- **Make a plasma with (robustly) break-even fusion energy gain, Q > 2**
  - At long last, the Kitty Hawk moment for fusion
  - Our hypothesis – this would be a sufficient demonstration to put fusion firml national energy plans and to attract investments for the next step
- **Demonstrate fusion-relevant HTS magnets at scale**
  - Integrated with high-performance tokamak operation
- **Provide the physics basis for high-field pathway**
  - Demonstrate high-field, burning fusion plasma scenarios

That Is the Aspiration: What is the Plan?
The SPARC Project

- **Privately funded – official start March 2018**
  - Bolster fusion research and education at MIT while building a strong industrial (Commonwealth Fusion Systems - CFS) that aims to commercialize fusion ener
  - Combined team now ~ 240 people, capital raised so far $215M
  - Go fast, accept risks, learn from mistakes
- **Phase I**
  - R&D & Demonstration of HTS fusion magnets **at scale**
  - Development of physics & engineering design for SPARC tokamak
- **Phase II**
  - Construction & Operation of SPARC
- (**Phase III**: CFS Builds the world's first fusion pilot plant – an ARC-class device)

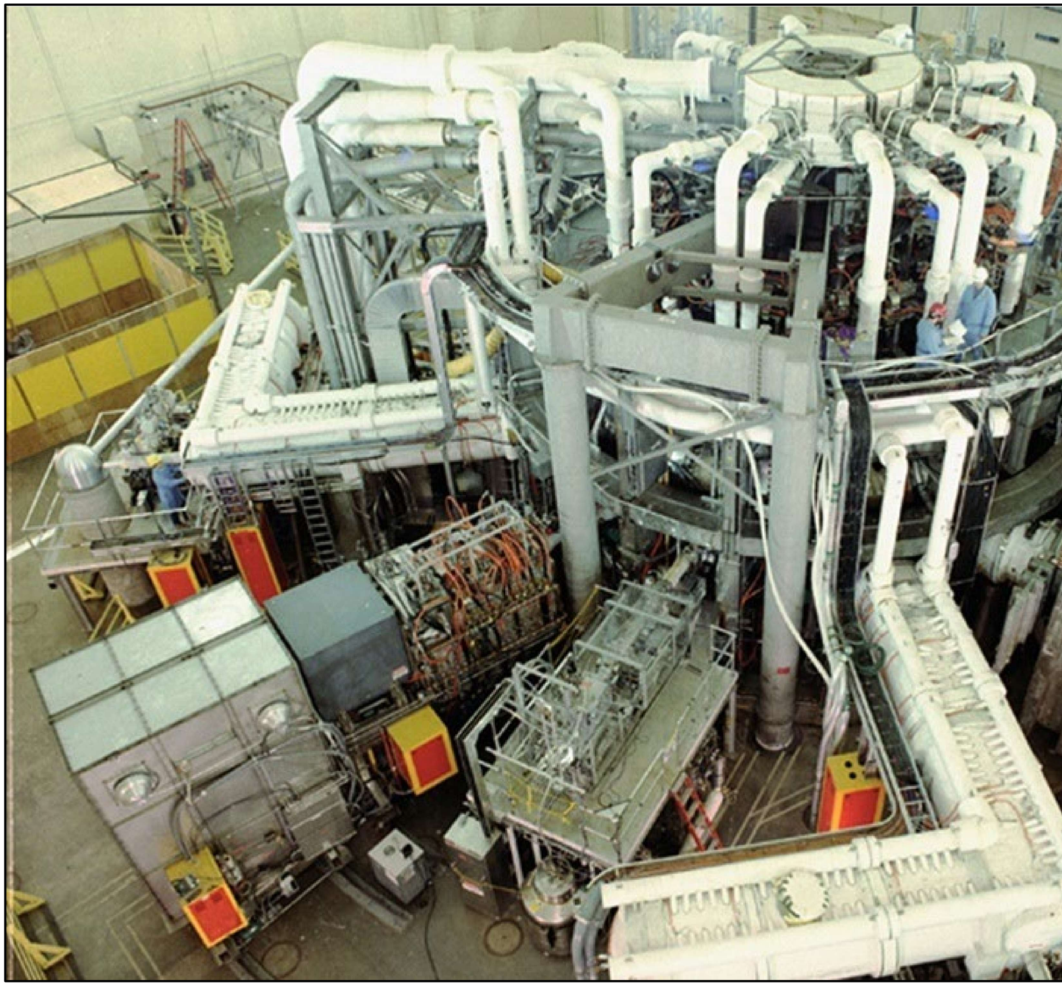
Audacious? Yes, But Consider Some History…

ATC, 2T



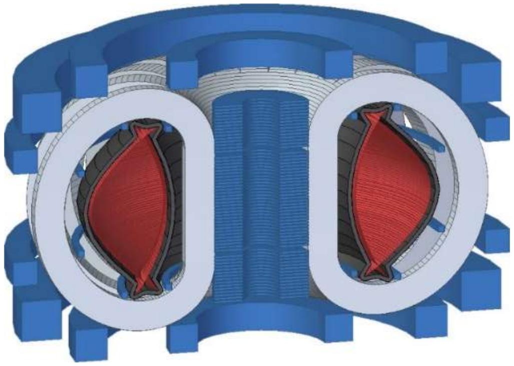
July 1974:
Tokamak physics
mature *enough*
to try DT

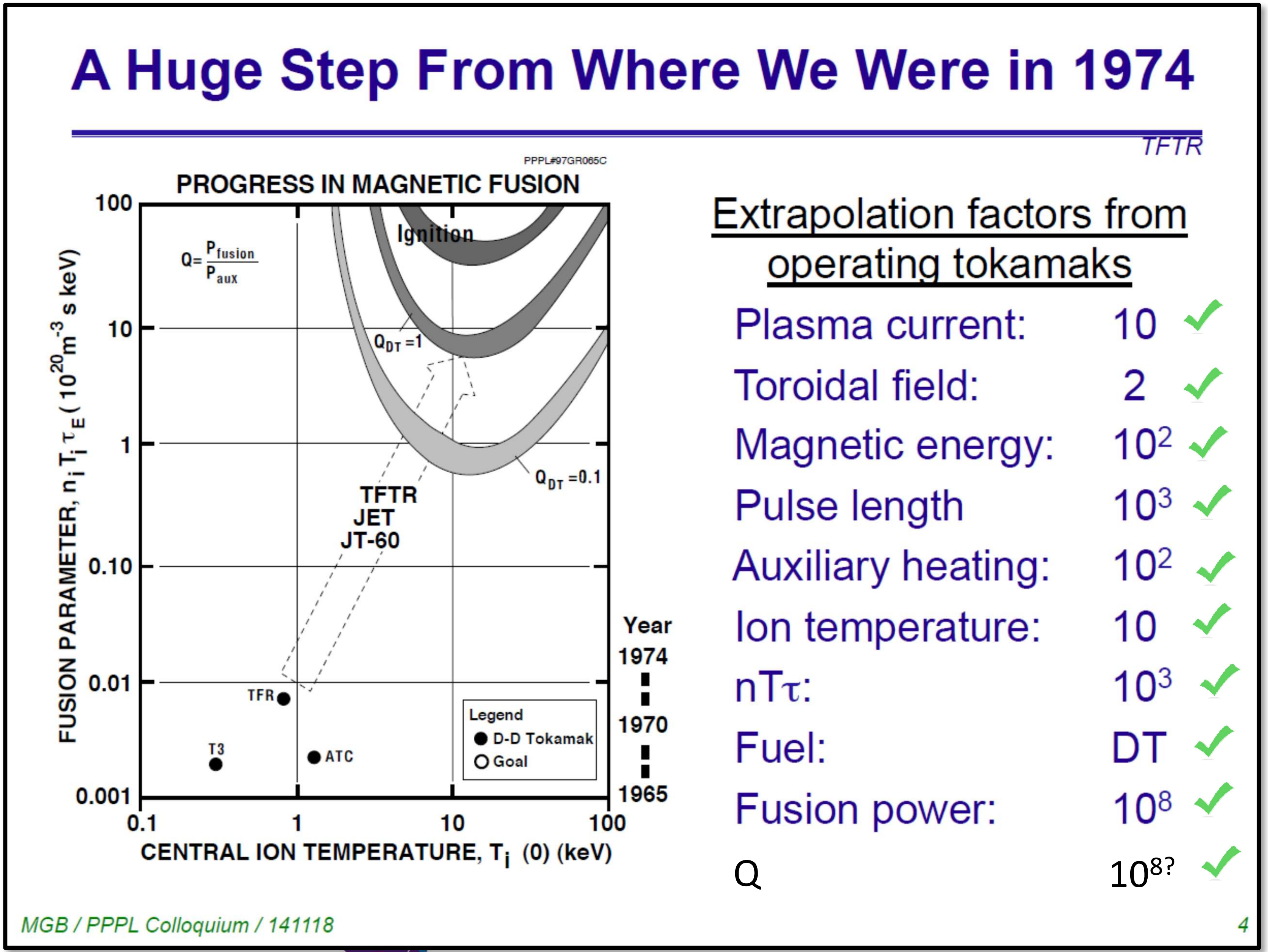
TFTR, 6T Construction approved 1976; 1st plasm



2018:
HTS mature
enough to build a
tokamak

SPARC V2, 12T





A Huge Step From Where We Were in 1974

TFTR

Extrapolation factors from operating tokamaks

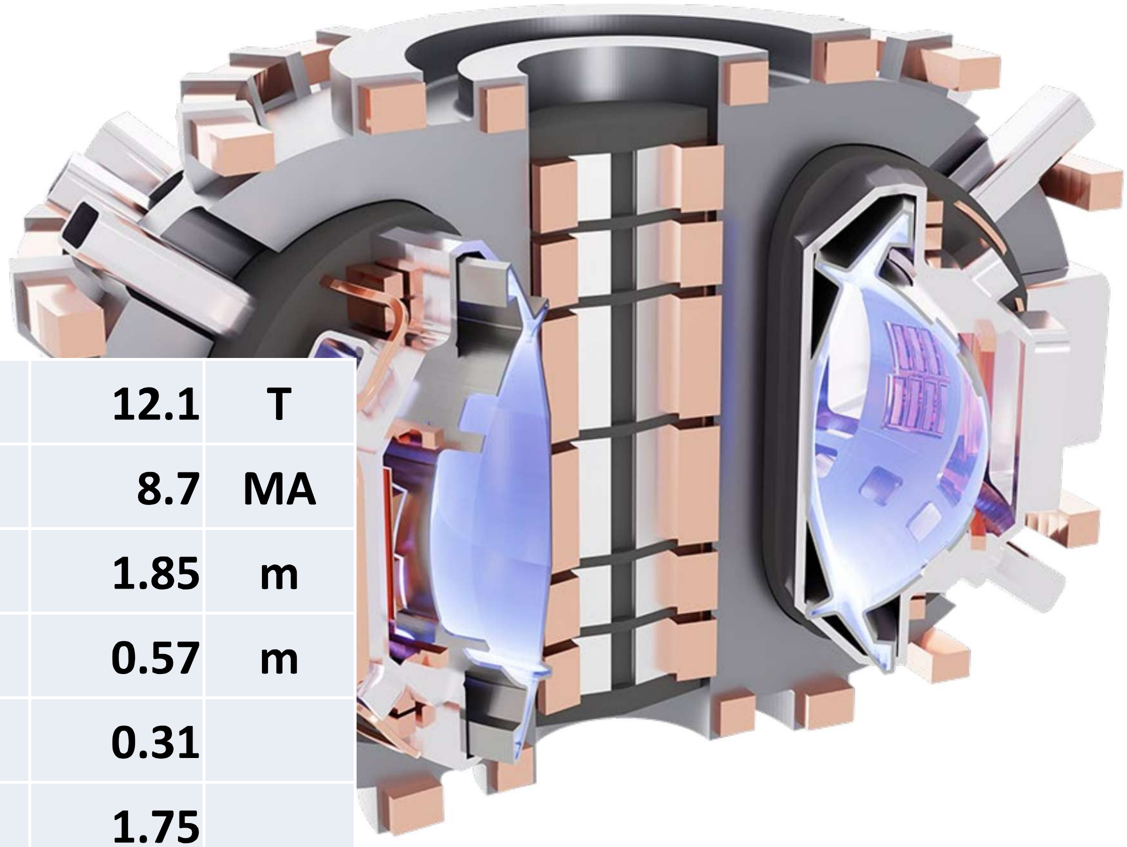
Plasma current:	10	✓
Toroidal field:	2	✓
Magnetic energy:	10^2	✓
Pulse length	10^3	✓
Auxiliary heating:	10^2	✓
Ion temperature:	10	✓
$nT\tau$:	10^3	✓
Fuel:	DT	✓
Fusion power:	10^8	✓
Q	$10^{8?}$	✓

MGB / PPPL Colloquium / 141118

**Today, SPARC i
step compared
decision to bu**

SPARC extrapola from operat
Plasma current
Toroidal field
Magnetic energy
Pulse length
Auxiliary heating
Ion temperature
Triple product
D-T fuel
Fusion power
Q

SPARC V2: Starting Point for Detailed Engineering Desig



B_0	**12.1**	**T**
I_P	**8.7**	**MA**
Ro	**1.85**	**m**
a	**0.57**	**m**
ε	**0.31**	
κ (area)	**1.75**	
P_{fus}	**50-140**	**MW**
P_{ext}	**25**	**MW**

SPARC V0 technical requi

- Burn D-T fuel
- Fusion Gain: Q > 2
- P_{fusion} > 50MW up to 14
- Pulsed with 10s flattop

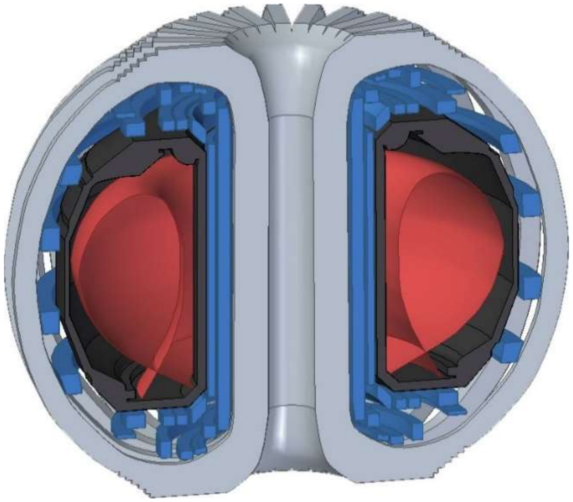
Desired schedule:

- R&D: 3yrs (mainly HTS
- Construct: 4 yrs
- Operate: 5 yrs
- Decommission: 4 yrs

Desired construction cost:

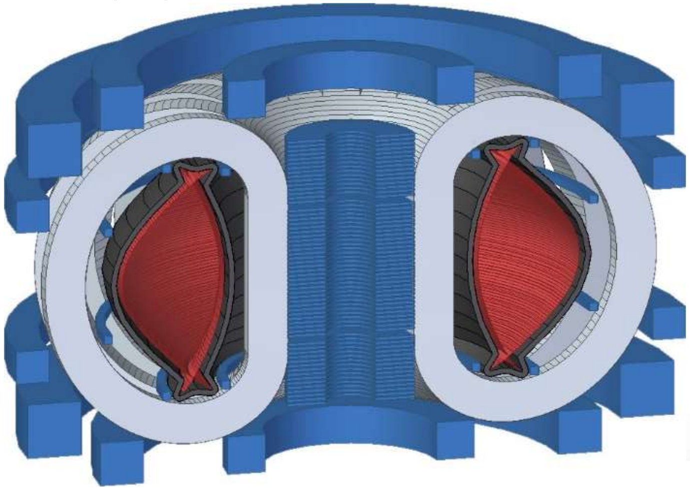
SPARC – Similar In Size To Machines We've Built

DIII-D, General Atomics:
1.66m, 2.1T, <2.0MA
Water cooled Cu

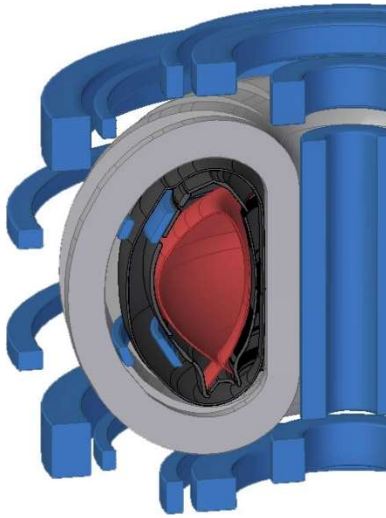


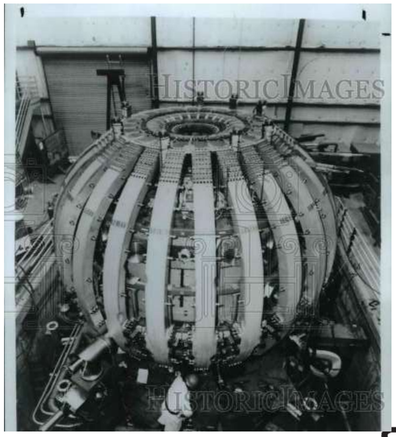
SPARC V0, MIT:
1.85m, 12T, 8.7 MA
Cryogenic HTS

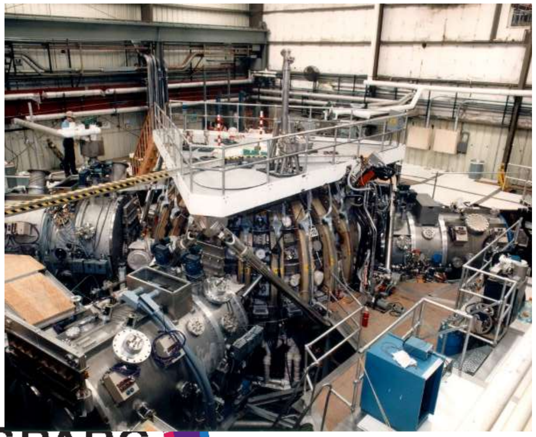
To scale



ASDEX-Upgrade, IPP G
1.65m, 3.1T, 1.6MA
Water cooled Cu







There are many others at this size: KSTAR, EAST, WEST, TEXTOR, PDX, PLT (and several bigger – TFTR, JET, JT60, JT60-SA, Tore-Supra)

What Are The Principles Behind The SPARC Design Point

- Use the ITER plasma physics basis
  - As far as possible, stay close to regimes and parameters where we have data
  - Be less of an extrapolation from existing experiments than ITER
- Use proven heating & control techniques
- Ensure robust operating windows
  - Stay away from known operational limits (β, n/n_G)
  - Operate away regimes requiring complicated or expensive control systems
- Keep pulse short to avoid other engineering complications (current drive, heat removal) for the mission
  - But long enough for the plasma to reach steady state
- Keep nuclear envelope within fusion precedence (TFTR, JET) – no blanket

Leverage As Much Mature Technology As Possible

Mature knowledge utilized for SPARC

Plasma Physics:
From 170+ tokamaks
over the last 50+ years

PF/CS design:
From FIRE, BPX, CIT

Power supply design:
From C-Mod,
Smaller than DIII-D, AUG

Plasma heating design:
From TFTR, JET, FIRE, C-Mod

Licensing:
From accelerators, TFTR, JET

Heat exhaust:
From C-Mod

Cryo systems:
From rocket industry

Site size:
From TFTR/JET/FIRE

Cell size:
From AUG

Shielding:
From accelerators, TFTR, JET
fission reactors

Tritium handling, processing:
From TFTR, JET, LANL, Sandia, Bates

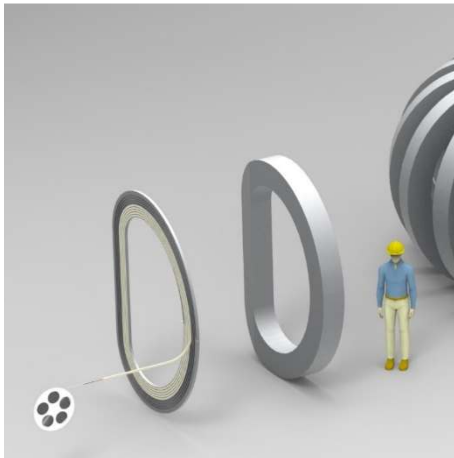
Decommissioning:
TFTR, accelerators

SPAR

One Key Inn

High Field M

New HTS Tec



The SPARC HT
(12 T on axis;

SPARC: How Do We Estimate Fusion Performance?

- **Hierarchy of models – No closed-form solutions for turbulent transport**
- **Empirical Scaling: 0D – Transport is characterized by τ_E = energy confineme**
  - For ITER design, a large data set was assembled
  - Regress τ_E against “engineering” parameters (plasma size, input power, magnetic field,
- **Dimensionless identity:**
  - Plasma physics equations can be cast in dimensionless form
  - With identical dimensionless parameters, plasma physics should be identical
- **Time-dependent simulation – quasi-linear transport model**
  - Quasilinear = calculate linear growth rates at all wavenumbers and normalize transport saturation “rule” calibrated to nonlinear GK simulations
- **Nonlinear gyro-kinetic simulations**
  - GK = Boltzmann equation averaged over gyro-motion (equation of motion in 5D phase sp

0D Analysis From Empirical Scaling Laws

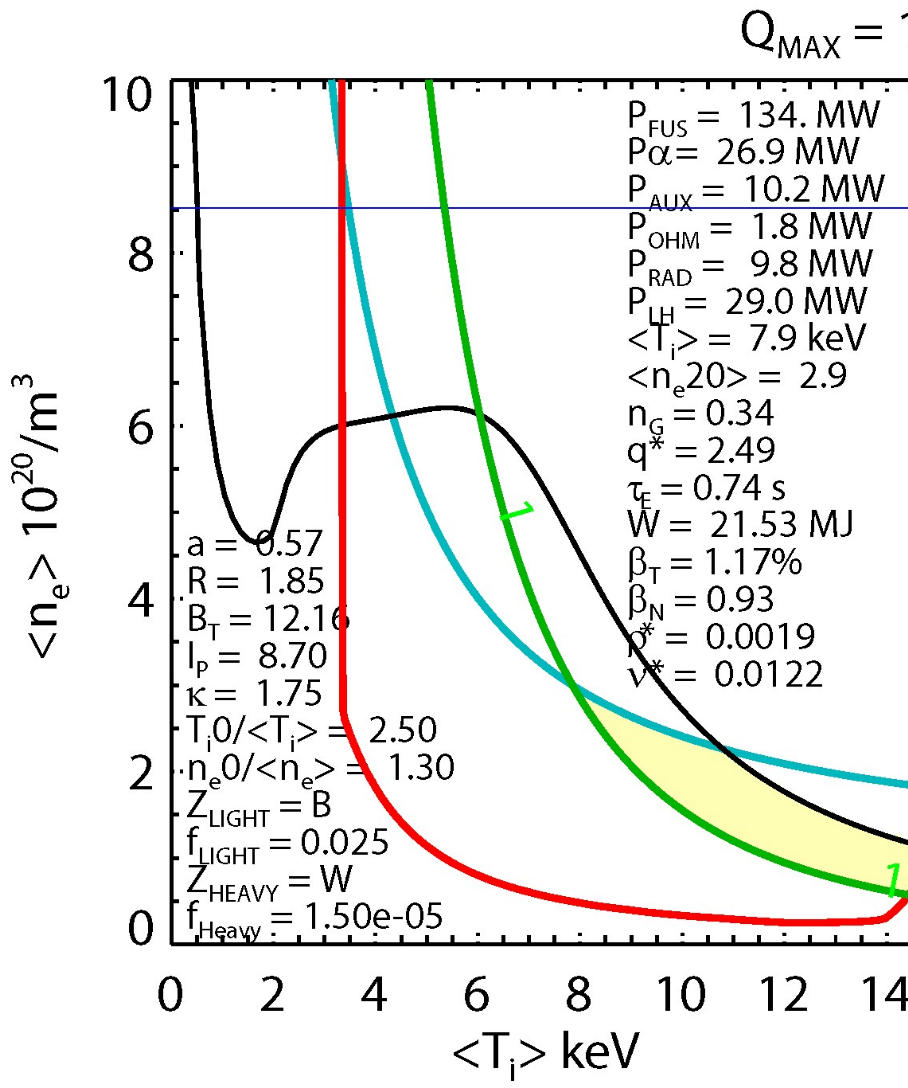
- **Use ITER Performance Rules**
  - Energy Confinement: $H_{98} = 1$
  - Profile peaking factors
  - Fuel mix
  - Fuel dilution
- **Operating Space Defined by**
  - $Q_{FUSION} > 2$
  - $P_{LOSS} > P_{L\text{-}H}$ (Threshold)
  - $P_{HEATING} < 30$ MW
  - $P_{FUSION} < 100$ MW

Calculation Proceeds in the <n>, <T>

1. Compute fusion power using n, T, fue dilution, profile peaking factors
2. Compute radiated power (Bremms, L radiation, synchrotron) using Z_{EFF}, pla B_T, profile factors
3. Compute total input power required confinement law (from empirical scal
4. Compute aux power required from p balance $P_{AUX} + P_{\alpha} + P_{OH} = P_{Loss} + P_{RA}$
5. Compute operational limits (β, n/n_G,

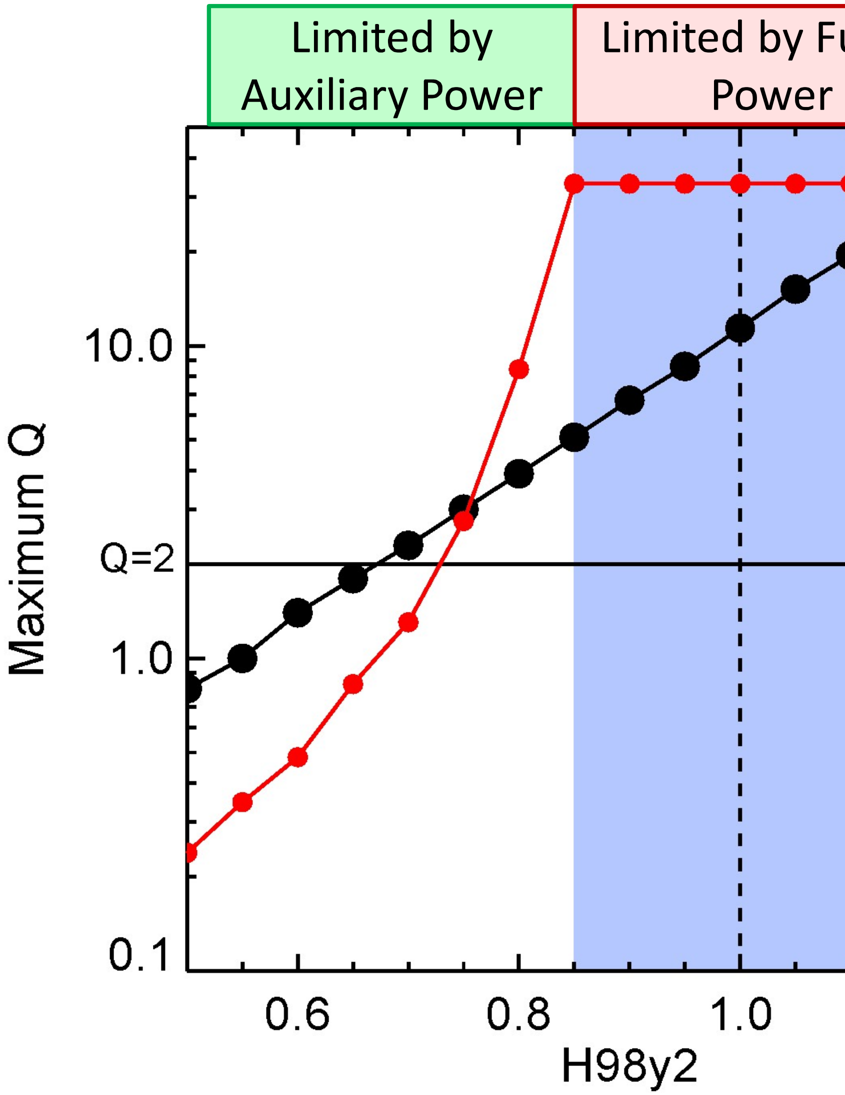
SPARC: Nominal Operating Space; Q_{FUS} up to 11

- **Use ITER Performance Rules**
  - Energy 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)
  - $P_{HEATING} < 25$ MW
  - $P_{FUSION} < 140$ MW

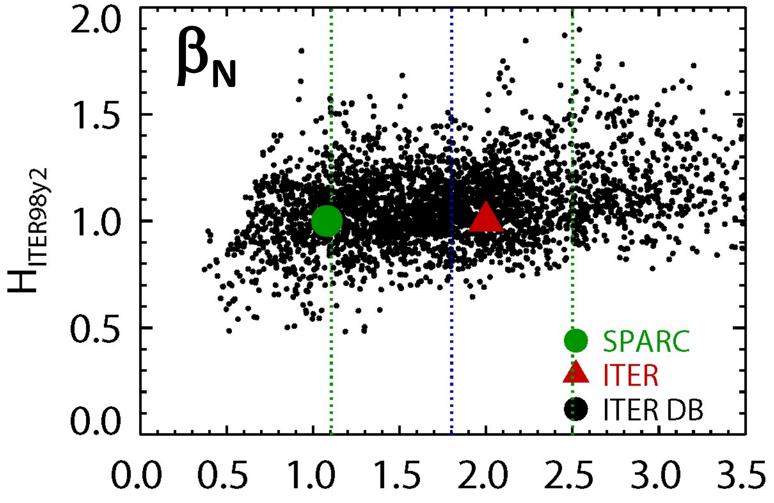


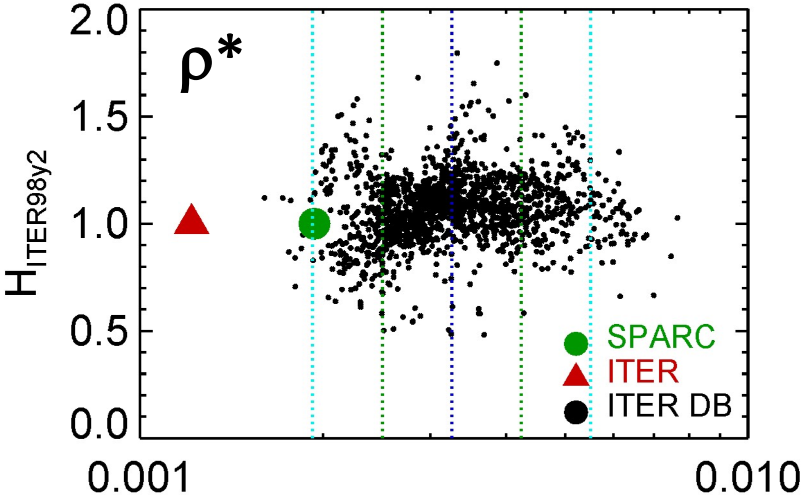
As Planned, SPARC Has Performance Margin

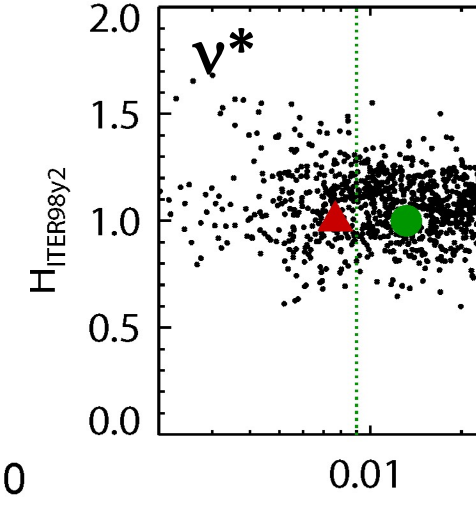
- Limited by auxiliary power at low confinement
- Engineering limits on fusion power output at high confinement
- Exceeds Q=2 at H ≈ 0.7
- Provides margin against confinement uncertainty or
- Reduced pedestal height
  - i.e. margin against peeling-ballooning (ELM suppression)

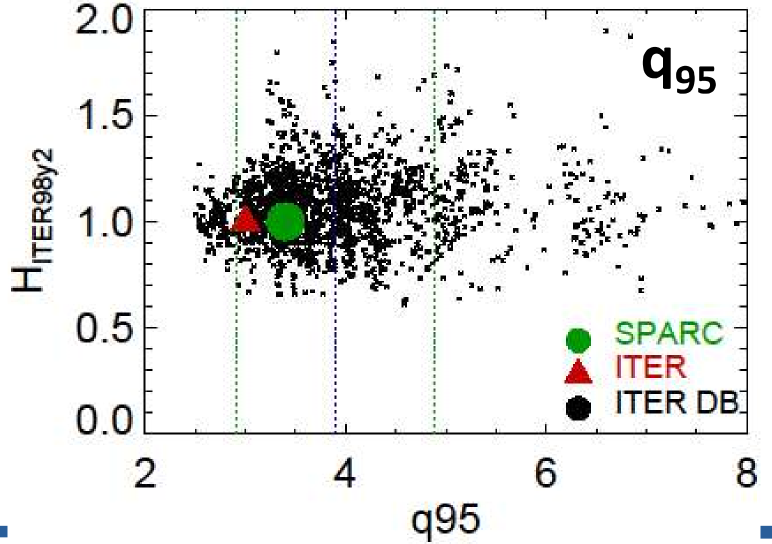


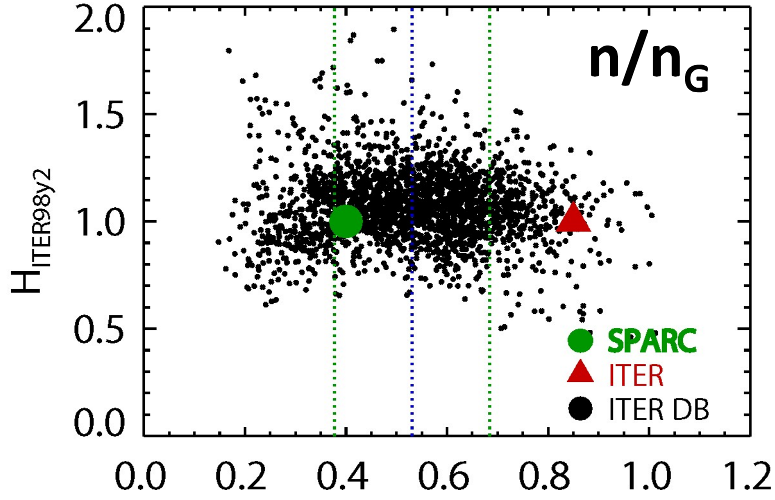
In Dimensionless Variables, the SPARC Operating Point Is Ge
Closer to the Mean of the H-mode Confinement Database th





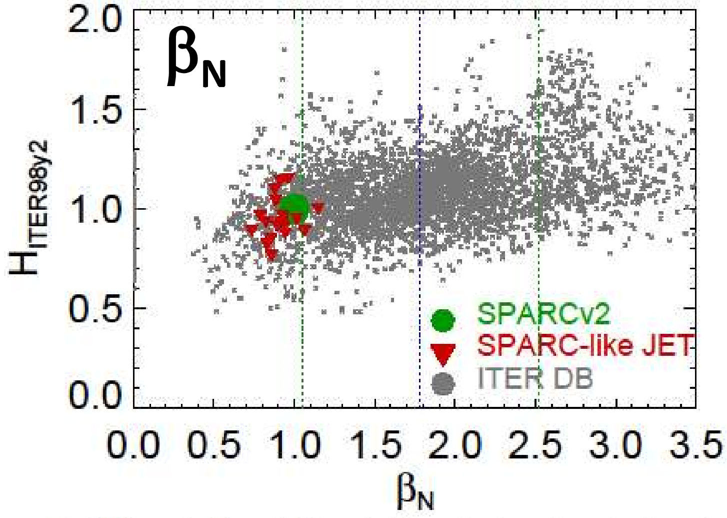


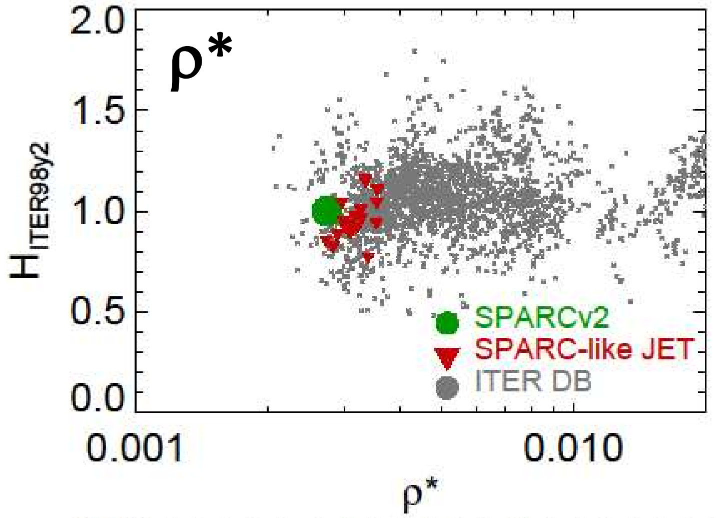


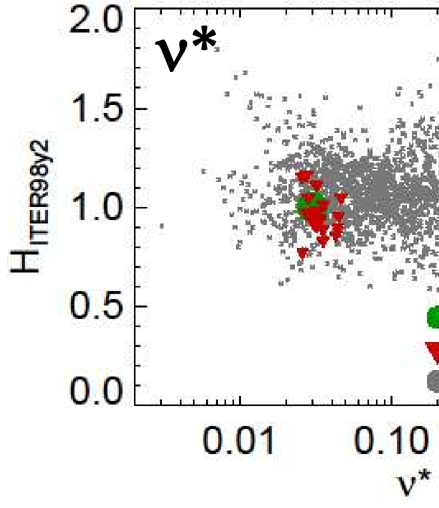


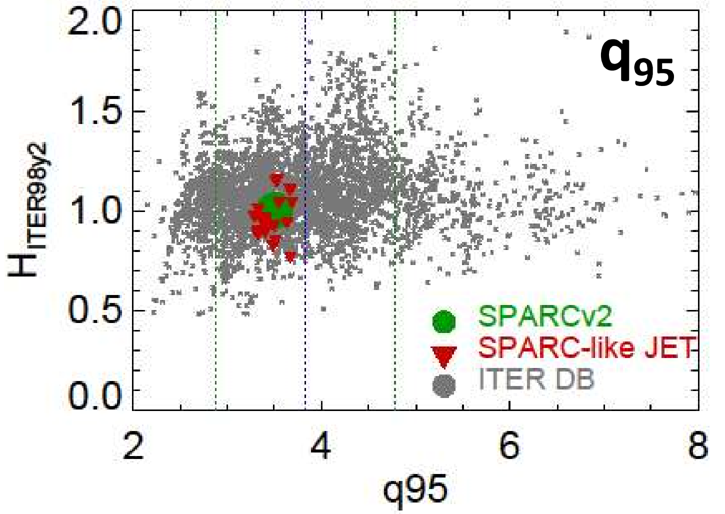
- ITERDB data
  from H_{98} scal
  like geometr
- Exception: som
  contain the kir
  required to cal

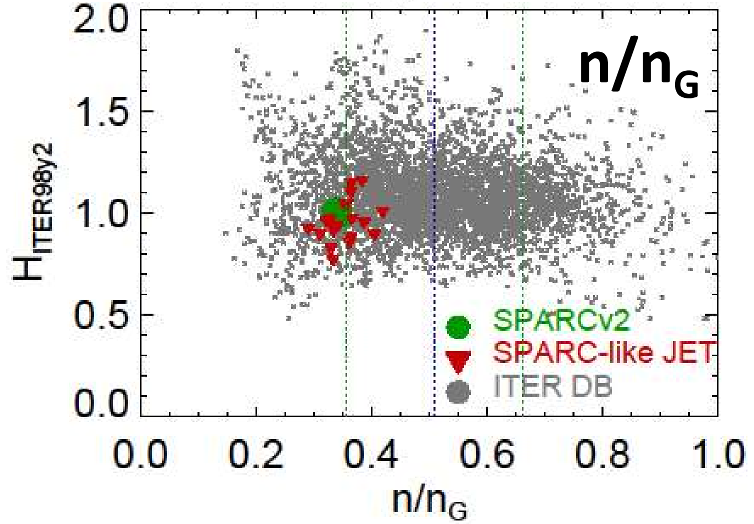
We Can Find Discharges That Are Very Close To Matching All SPARC Dime Plasma Parameters (β_N, ν^*, ρ^*, q_{95}, n_G, ε, κ, δ_L) Simultaneously







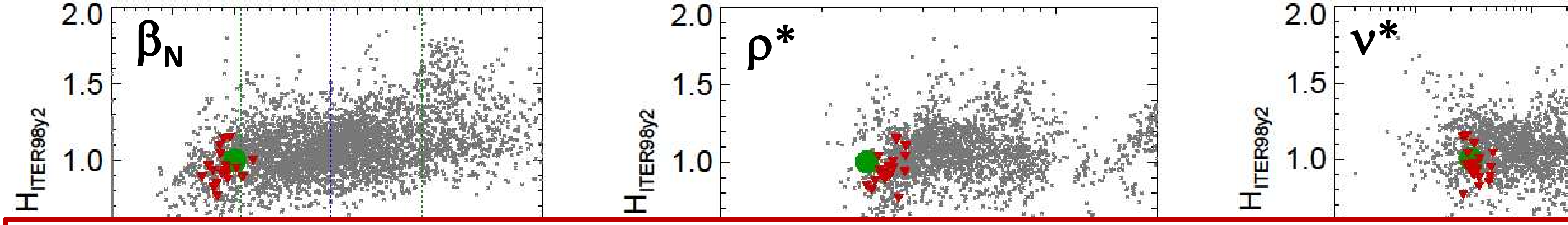




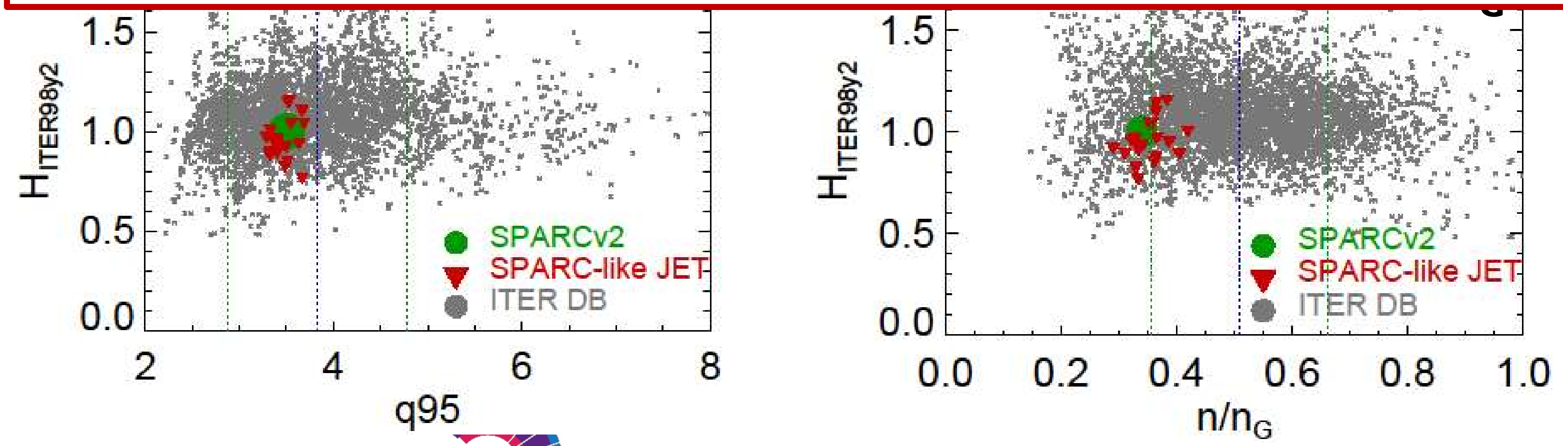
The same 20 (JET are shown in red

- $B_T = 3.0 - 4.$
- $I_P = 3.0 - 4.2$
- $P = 8.2 - 15.$
- $H_{98} = 0.82 -$

We Can Find Discharges That Are Very Close To Matching All SPARC Dime
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



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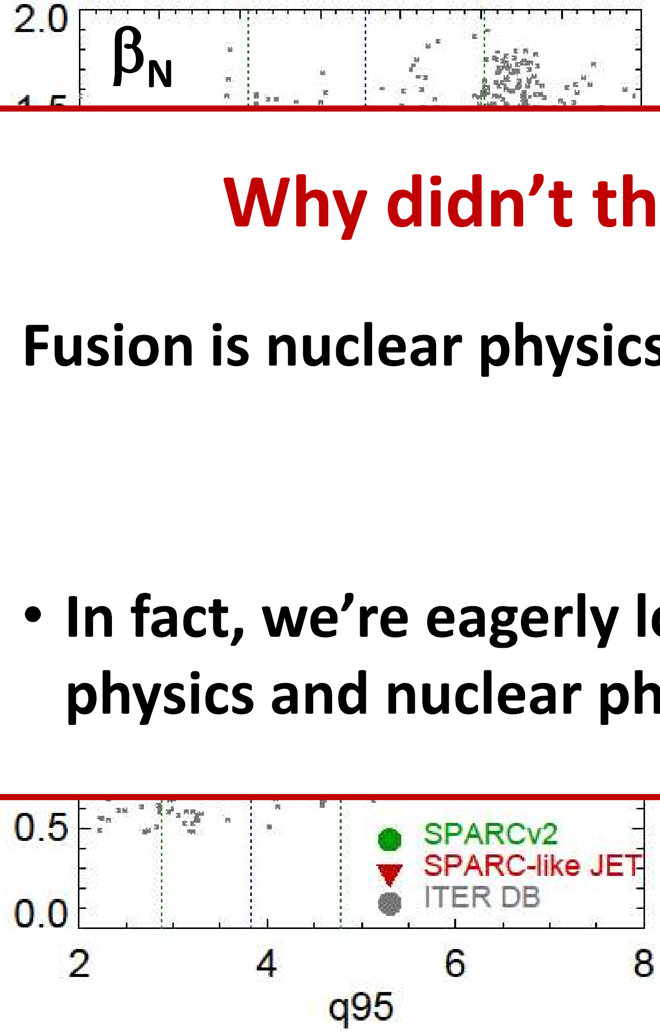
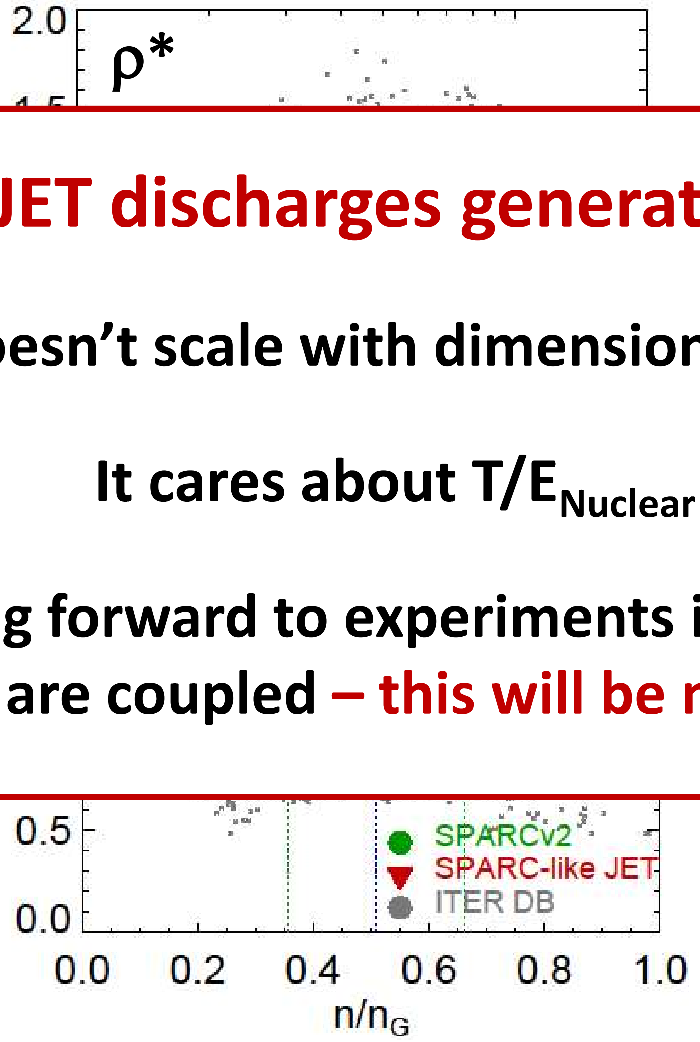
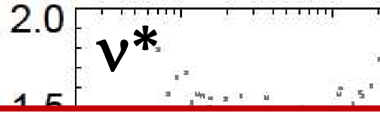






Why didn't those JET discharges generate 100 MW of fu

Fusion is nuclear physics – Doesn't scale with dimensionless plasma param

It cares about T/$E_{Nuclear}$

- **In fact, we're eagerly looking forward to experiments in the regime wher physics and nuclear physics are coupled – this will be new**

- $P = 8.2 – 15.$
- $H_{98} = 0.82 –$

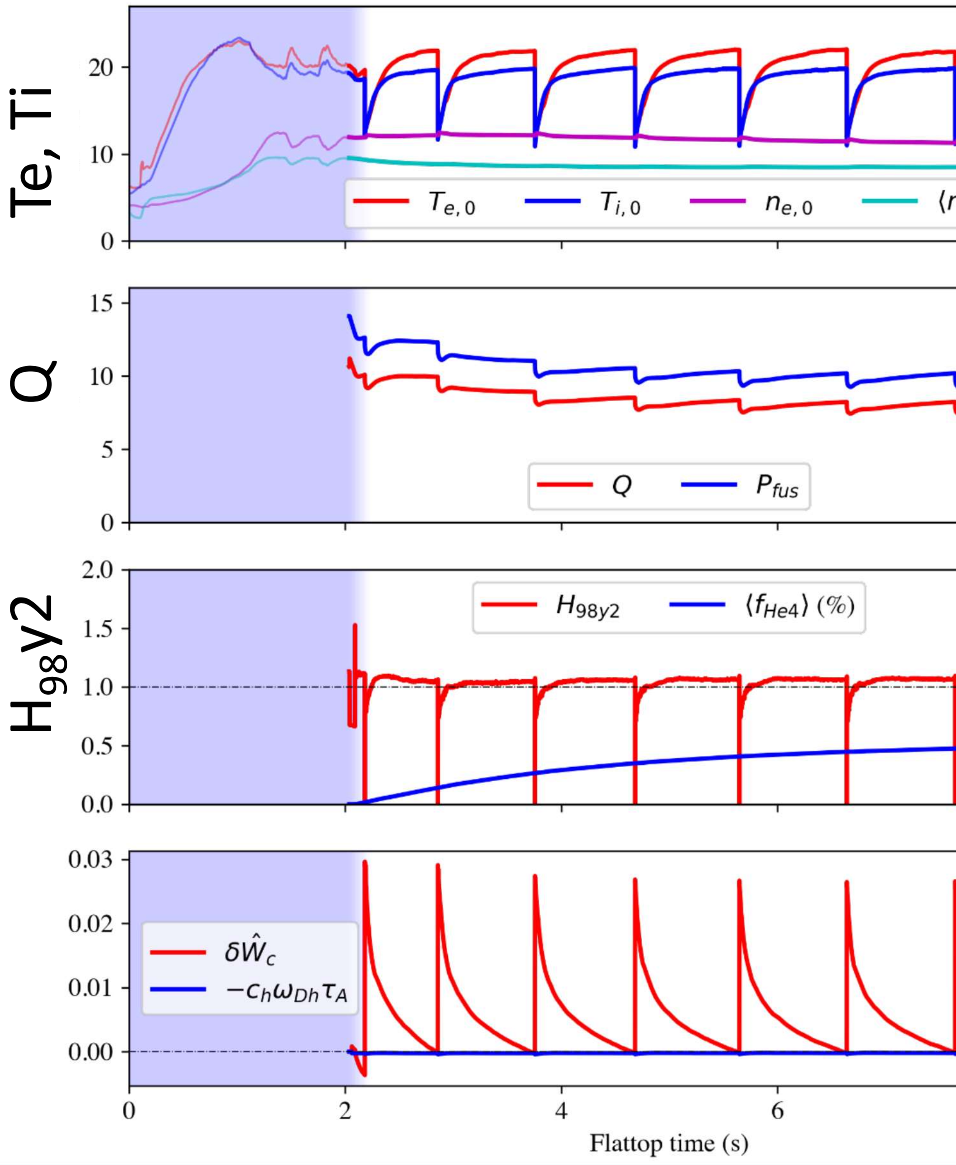
Ensuring Performance : Time-dependent Plasma Simulati

- Compared to empirical scaling which is **ALL DATA** and minimal physi
- These simulations are **ALL PHYSICS** (reduced models where necessar minimal data
  - 2D MHD equilibrium, (1D radial profiles = 1.5D)
  - Plasma Profiles - Quasi-linear transport to calculate
  - Heating - RF wave propagation & damping
  - Heating – Fusion reaction rate and alpha power deposition
  - + lots more…

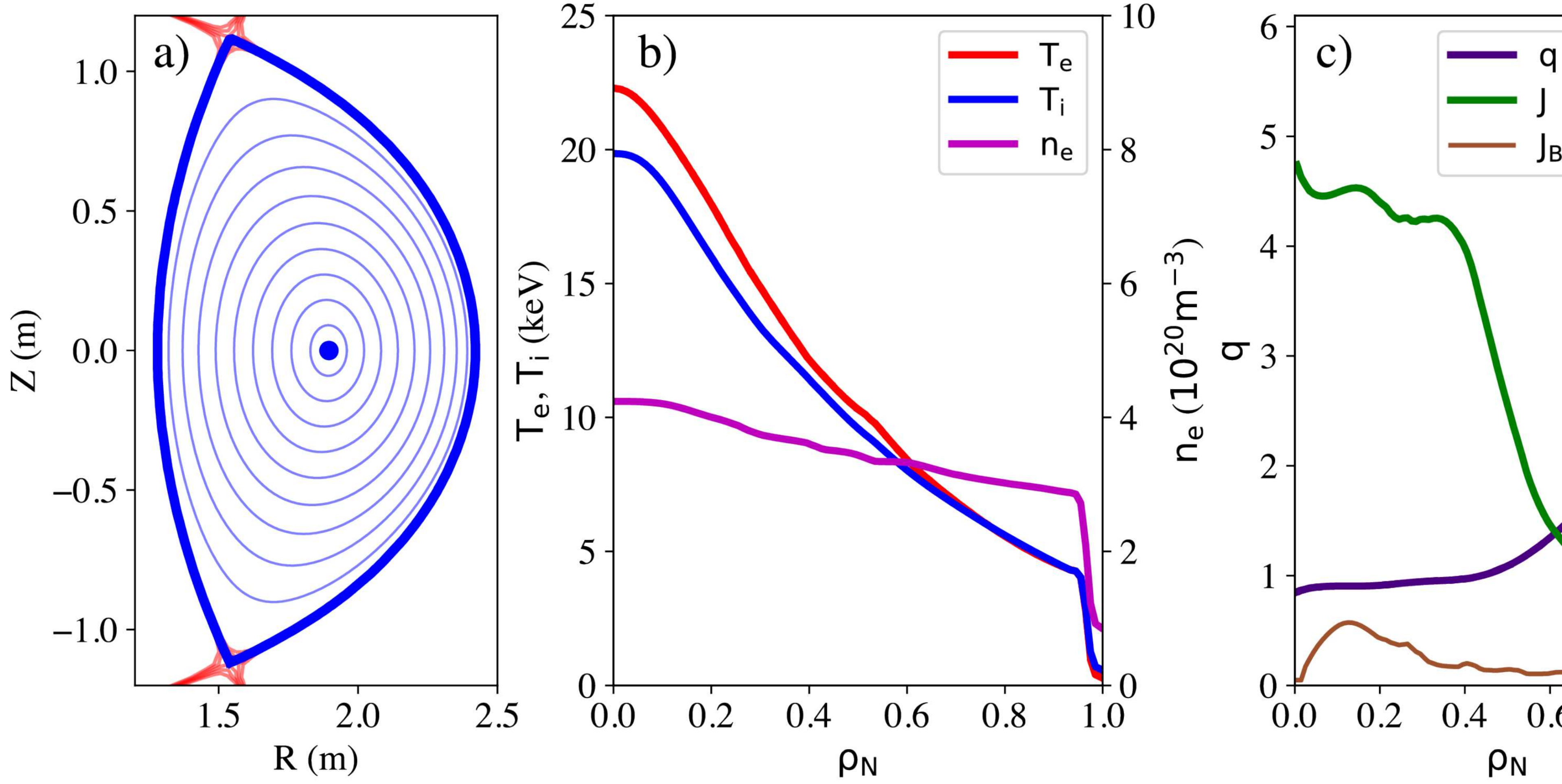
Remarkable Agreement Between 0D and 1.5 D Time-dependent

- For this calculation, the energy confinement time, H factor, temperatures, fusion power, Q are all outputs
- Methods are entirely independent
- However, results are remarkably close

	TRANSP	Empirical
H_{98}	1.0	1.0
<Ti>	7.8 keV	7.9 keV
Ti(0)/<Ti>	2.5	2.5
P_{RAD}	13.2 MW	10.4 MW
P_{FUS}	105 MW	140 MW
Q	9	11

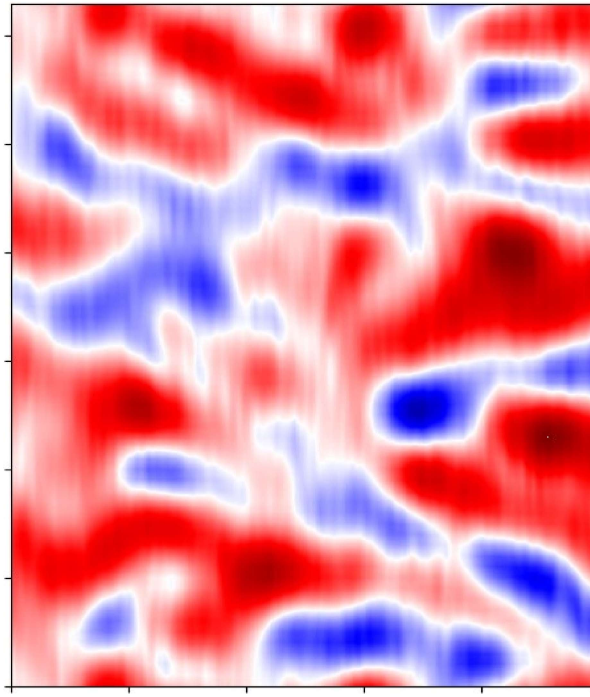


1.5 D Predictions of Plasma Profiles For SPARC



Next Steps - Nonlinear Simulation of Gyrokinetic Turbule

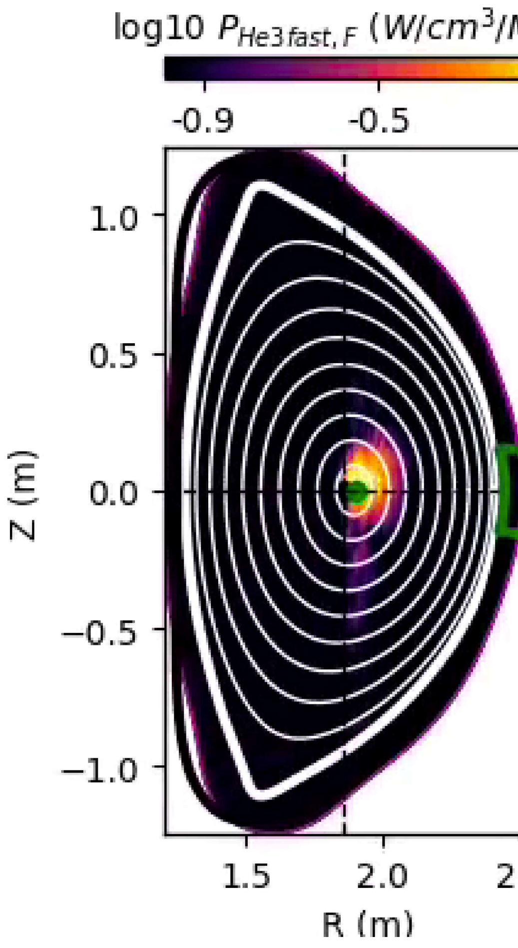
- Quasi-linear model has been benchmarked against experiments and gyrokinetic codes
- We've sampled the profile at a few points and looked at the expected turbulence
  - No surprises – SPARC should be in turbulence regimes similar to other devices
- Still, we want to take the next step
- We're in the process of launching a fully nonlinear gk prediction of profiles – a "heroic" simulation
  - Constrain gradients at each radii with nonlinear GK



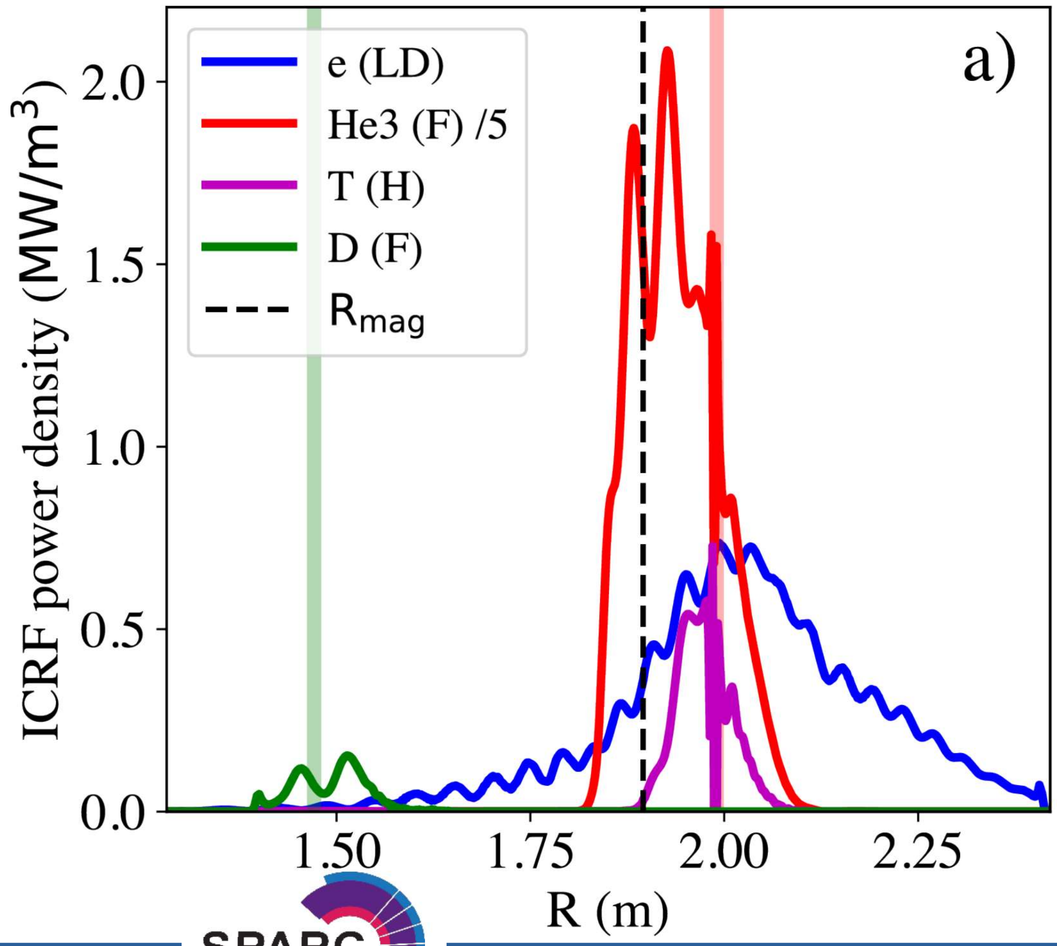
Getting Power In: Plasma Heating - 25 MW ICRF

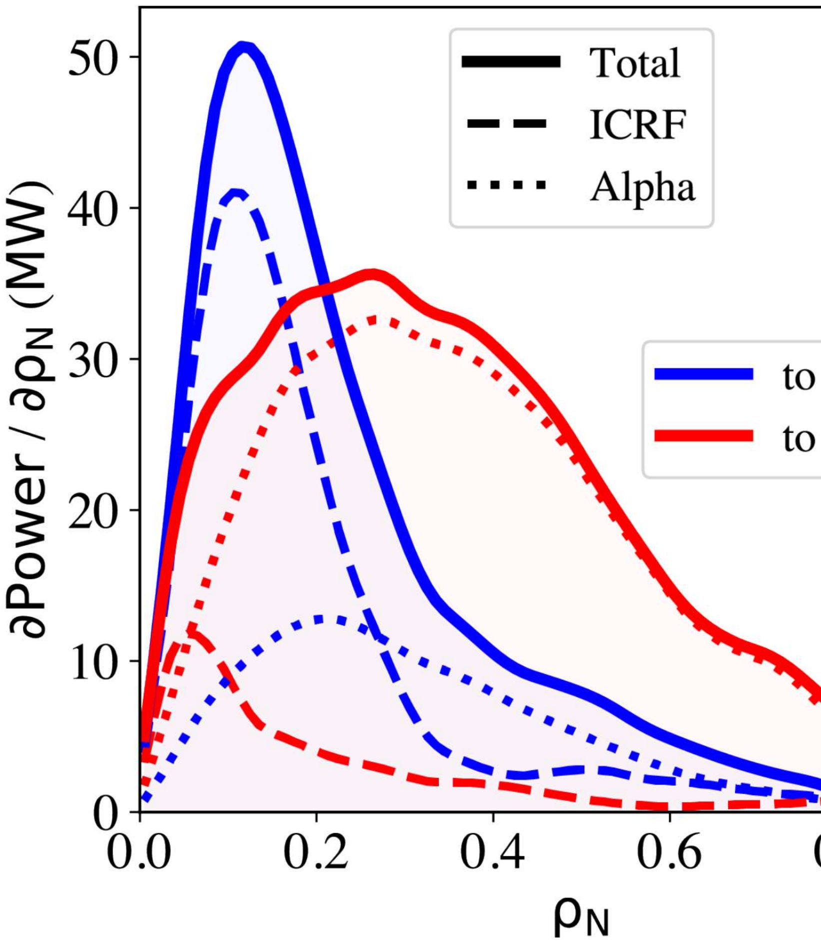
- **Simplicity: Utilize a single type of heating**
  - Proven to work on C-Mod (at required plasma density) and on DT devices (TFTR & JET)
- **Heating scenarios at 120 MHz look promising**
  - Options for DD (H minority at 8T)
  - DT (He^3 minority at 12T) operation (+ perhaps 2^{nd} harmonic T)
  - Good single pass absorption predicted
- **Optimum antenna spectrum is a balance between coupling and absorption**

ICRF scoping calculations

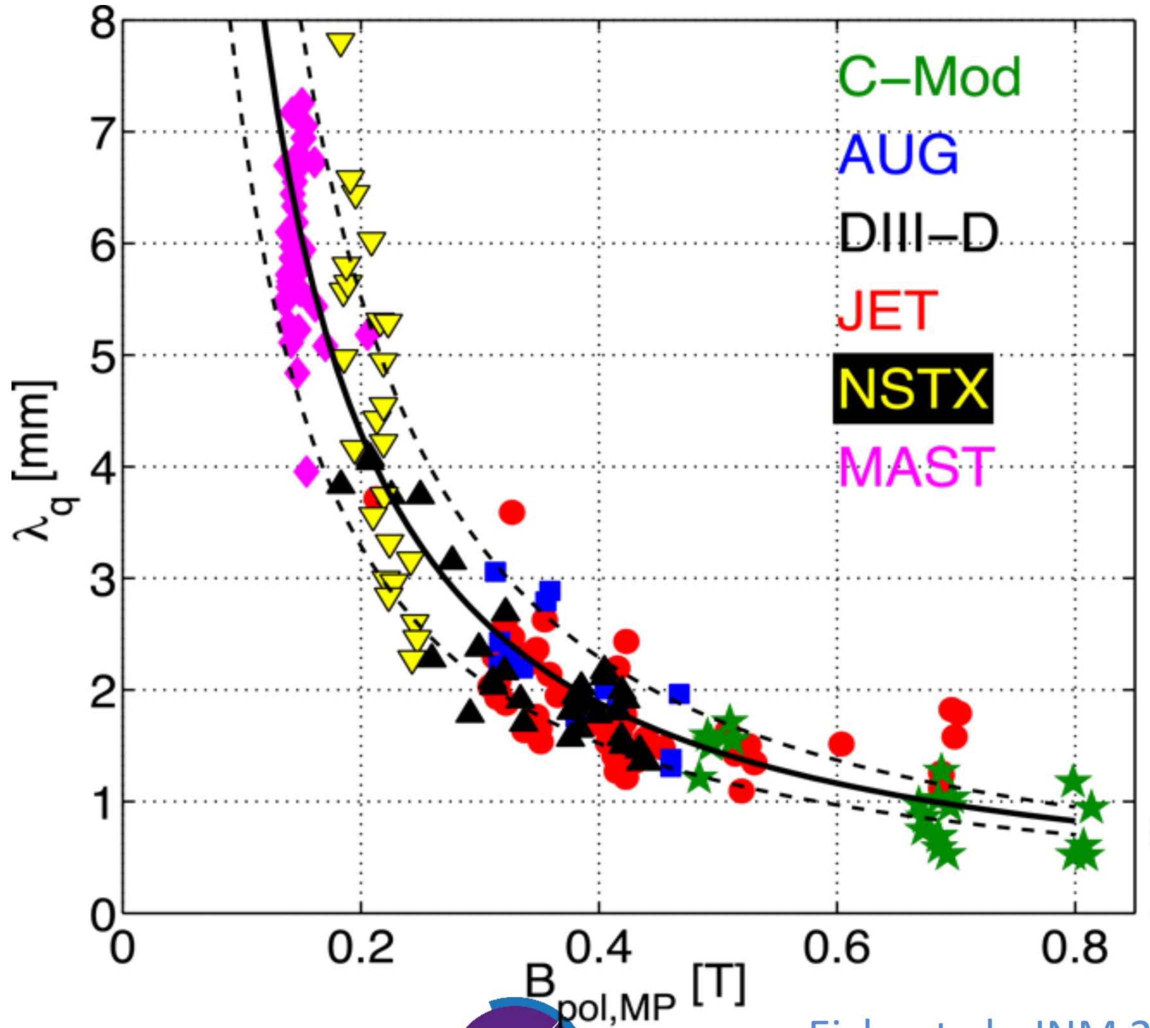


ICRF Heating Is Well Localized In Plasma Core
Most ICRF Power into Ions, Alpha power to electrons





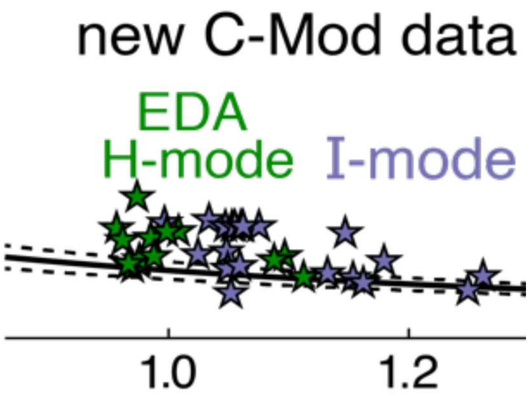
Getting Power Out: Divertor Loading –A Challenge At High Perfo



Eich, et al., JNM 2011

We need to manage the interface b
hot plasma and ordinary matter

- For "attached" divertor, the heat fl
  scales like 1/B
- Detachment scales like PB/Rn_{SEP}^2

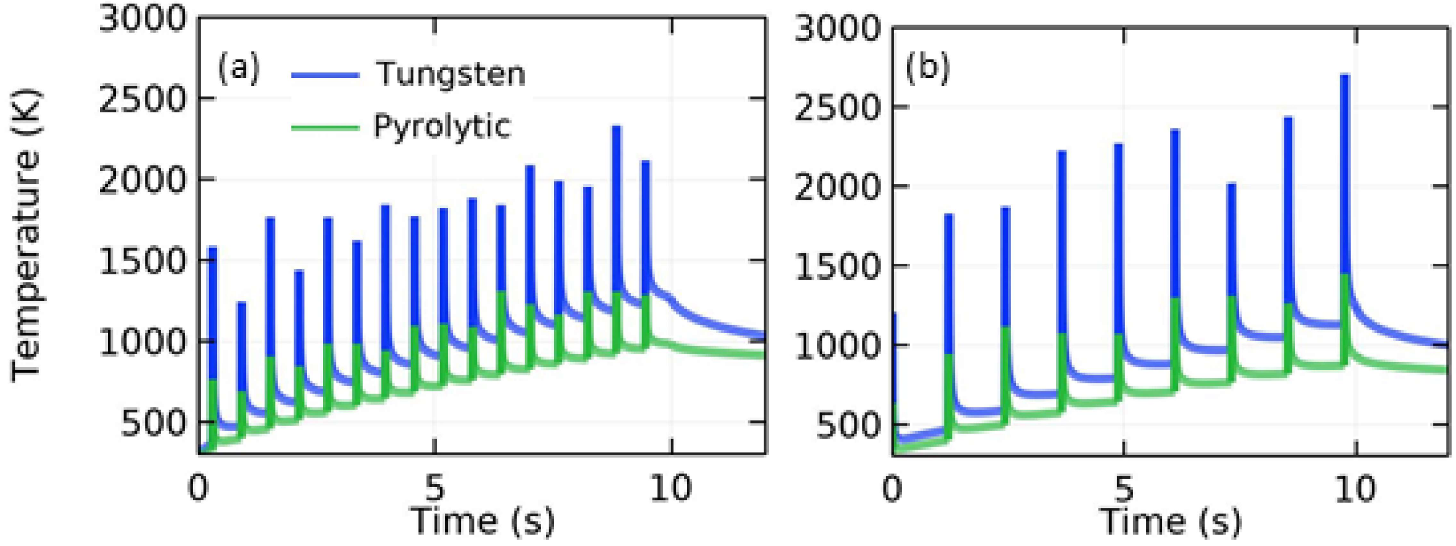


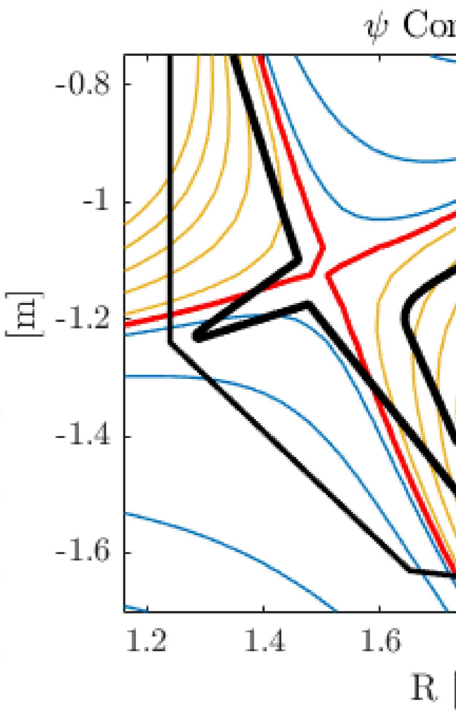
Brunner, 2017

(Though rec
for ITER sug
beneficial, l
dependenc
count this)

Boundary power exhaust challenging but not a show-stopper for SPA
Simulations show that heat flux can be handled with aggressive strike point

- With standard (C-Mod, ITER) vertical target divertor, 10 sec pulse
  - At typical and acceptable radiation fraction (50%), target materials survive full power pulse. (assumes fully attached, single null)
  - Radiation fractions of > 90% have been demonstrated on C-Mod, AUG, JET while maintaining good core confinement



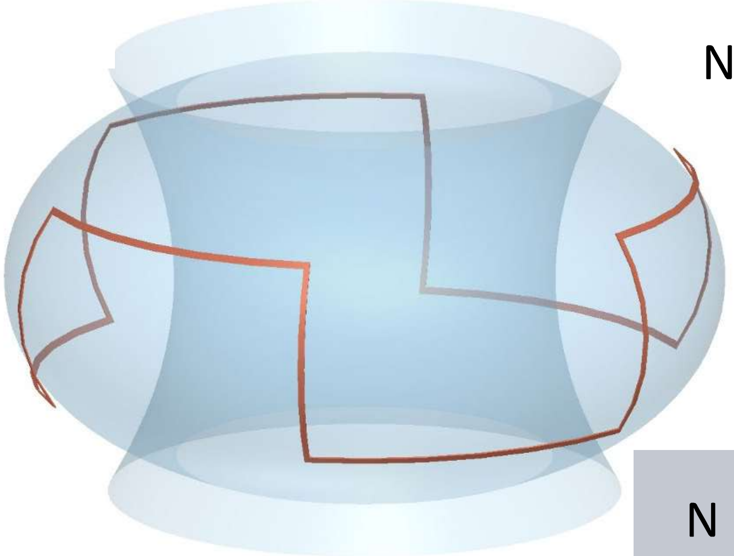


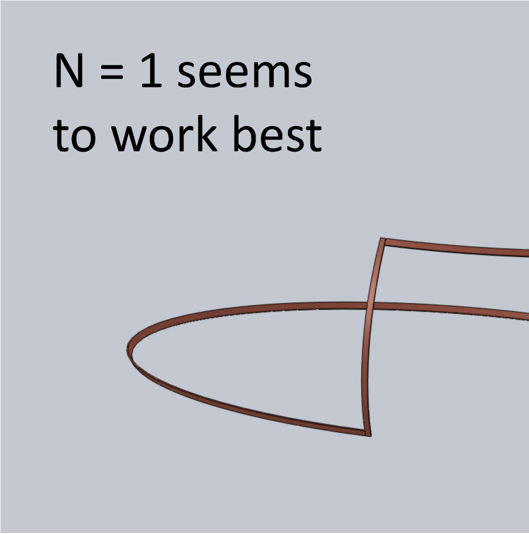
Disruptions: A Challenge For All High-Performance Tokam
Compact, High-Field Has Some Advantages

- **Operating away from limits**
  - ↑ Staying further away from limits (especially pressure, density) should reduce disruptio
- **Disruption forces are not obviously more difficult for compact, high-field**
  - ○ IxB and stresses about the same
  - ↑ distances can be smaller for mitigation actuators (gas, pellets)
  - ↓ But, quench times faster for compact devices
- **Runaway electron growth rate reduced, damping enhanced**
  - ↑ Runaways more strongly damped by collisions and synchrotron radiation
  - ↑ Growth (Coulomb Avalanche) exponential with plasma current $(I_{runaway}/I_{seed}) \propto e^{2}$

To Mitigate Disruption Runaways, We Will Try Out A Novel 3

- From an original idea by A. Boozer
- Current driven inductively by dI_P/dt of disruption
- Non-axisymmetric coil creates 3D fields which break up flux surface, leading to rapid loss of "seed" electrons

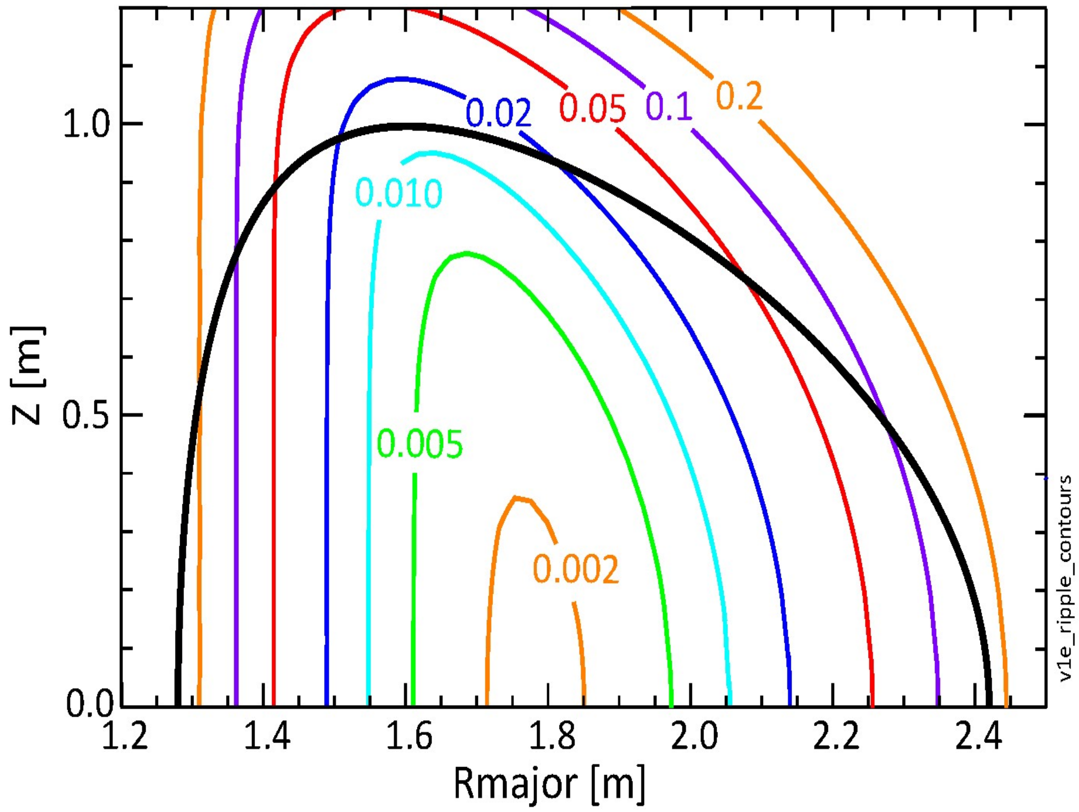

N = 3


N = 1 seems to work best

- Analysis of plasma response by V. Izzo – with NIMROD – extended MHD code
- Looks very promising
- Offers possibility of passive safety wrt runaways!

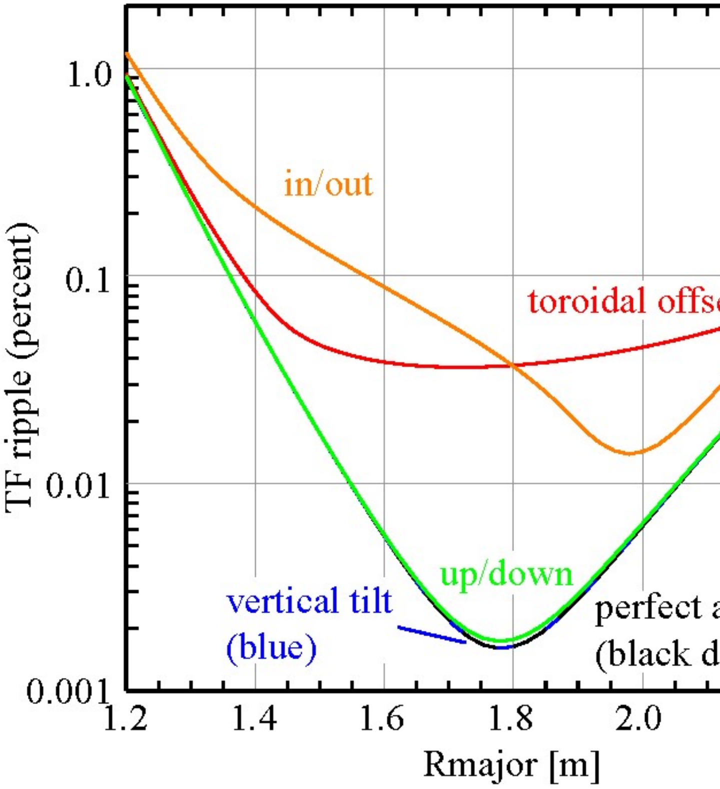
Loss of Fast Alphas from Ripple Transport Should Be Mini

Ripple contours (%) 18 coils perfect alignment



- Ripple loss 0.25 %
- Neoclassical loss 2.8%

Ripple Profile With Significant



- Ripple loss 1 % (all fro

How About Transport of Fast Alphas by MHD?

- Perhaps the most important new physics that the SPARC experiment will address
- The fully self-consistent, nonlinear interaction of fast particle distributions and MHD in a plasma is a cutting edge research problem – need a burning plasma experiment to valida
- We've done some linear analysis (Tolman, et al., Nucl. Fusion 59, 046020, 2019.)
  - $n_\alpha/n_e \propto T^{3.5}$
  - Drive to damping ratio for Alfvenic modes $\propto \beta_\alpha/\beta_e \propto T^{2.5}$
  - Bottom line – with similar temperatures, alpha physics in SPARC will be similar to what expected on ITER - good for baseline H-mode operation
  - Higher field will push the spectrum of AE modes to higher n, m
- Diagnostics are planned to look at fusion rate, confined alpha distributions and fast MHD
  - Neutron detectors and neutron spectrometers look like promising tools

There's Lots More Physics – See JPP Special Issue on SPARC Physics

Overview of the SPARC tokamak, **A.J. Creely** et al,
J. Plasma Phys. 86 (5), 865860502 (2020). http://doi.org/10.1017/S002237782000125

Predictions of core plasma performance for the SPARC tokamak, **P. Rodriguez-Fernan**
J. Plasma Phys. 86 (5), 865860503 (2020). https://doi.org/10.1017/S002237782000107

Projections of H-mode access and edge pedestal in the SPARC tokamak, **J.W. Hughes**
J. Plasma Phys. 86 (5), 865860504 (2020). https://doi.org/10.1017/S002237782000130

Divertor heat flux challenge and mitigation in SPARC, **A.Q. Kuang** et al,
J. Plasma Phys. 86 (5), 865860505 (2020). https://doi.org/10.1017/S002237782000111

Physics basis for the ICRF system of the SPARC tokamak, **Y. Lin** et al,
J. Plasma Phys. 86 (5), 865860506 (2020). https://doi.org/10.1017/S002237782000126

MHD stability and disruptions in the SPARC tokamak, **R. Sweeney** et al,
J. Plasma Phys. 86 (5), 865860507 (2020). https://doi.org/10.1017/S002237782000112

Fast-ion physics in SPARC, **S.D. Scott** et al,
J. Plasma Phys. 86 (5), 865860508 (2020). https://doi.org/10.1017/S002237782000108

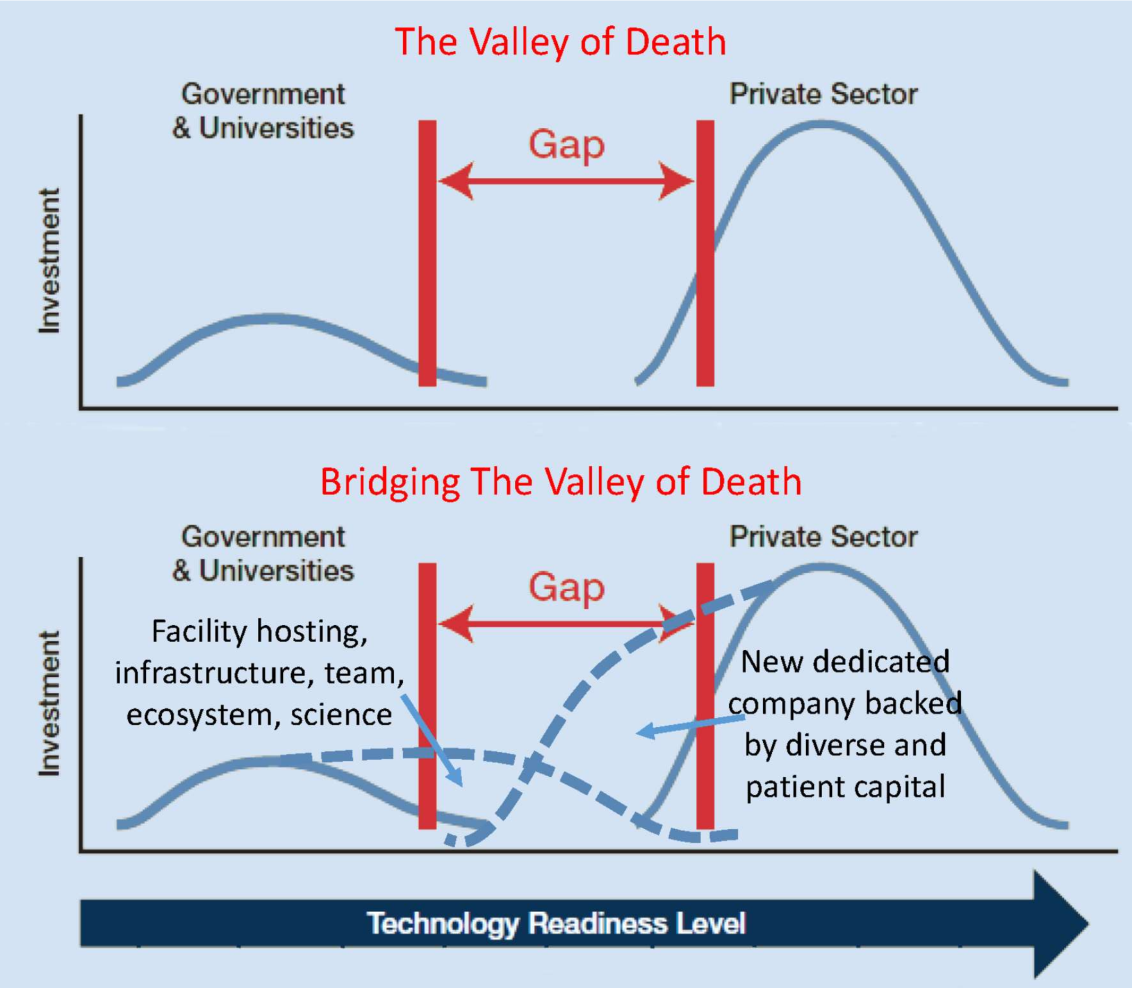
What’s Next?
Device Optimization, Physics Validation, Engineering Revi

- Detailed engineering underway
- Deeper dive into physics validation
- Project reviewed by late spring 2021
- **Leading to “ready for construction” milestone by June 2021**
- Site selected - to be acquired in a few weeks, permitting process well underway
- Tritium supply secured, HTS supply secure

SPARC Is Privately Funded

The Role of Private Industry In Fusion Developm

Bridging the Valley of Death for Fusion



- Government Labs & Universities ar
  basic research
- Outside of defense applications, th
  is reluctant to sponsor research as i
  application
- Private companies are reluctant to
  research if the time scale is long an
  financial returns are too low
- This is a particular problem for "Ha
- MIT spun out a new fusion start-up
  (Commonwealth Fusion Systems)
  - We're partnering to bridge the ga
  - The university "holds on" to the r
    longer, private industry picks it u

CFS, an MIT spinout, Is Part Of A Nascent Fusion Ind

Commonwealth Fusion Systems

- There are many companies, the list is growing
- They serve as indicators of the fusion value proposition
- Most are pursuing more speculative approaches - optimizing economics, maintainability
- Private industry/investors have a greater tolerance for risk than the USG

tokamak energy
a faster way to fusion

PHOENIX NUCLE

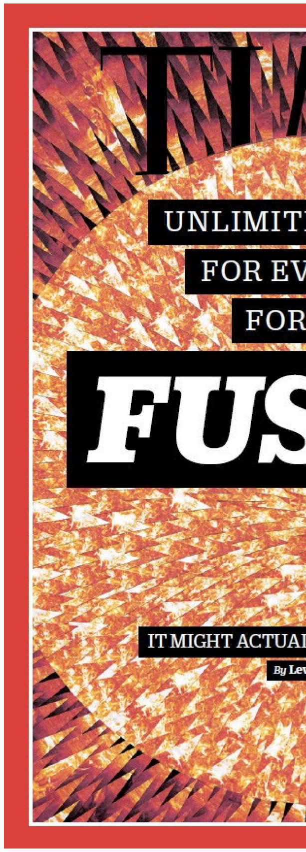
tae TECHNOLOGIES

Helion Energy

MIFTi

We think this is a good thing

- Our basic research is being used! It is important and valued!
  - We’re attracting new stakeholders
  - Energizing the public and adjacents
  - Building momentum, building the ecosystem
- Having more players is good
  - Diversity of physics approaches –fusion is too important for one architecture –not everything has to work
  - Diversity of organizational approaches – fusion is too important for one team
  - Diversity of tolerance to risk



This is how new technology gets to marke

- Fusion is following a well-worn tech-development arc
  - Drugs, Aerospace, Computers, AI, Robotics, Rockets, 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 res
  - 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

Academic Researchers

Government Programs

Partnerships like MIT-CFS, Public-Private

C

Summary

- **Success from our research on HTS magnets and SPARC will open up a compellir for smaller, faster, cheaper fusion development**
  - We should have answers on the magnet technology in less than 6 months
  - Aim to demonstrate the first (controlled) net-energy fusion experiment 4 - 6 ye
  - These steps will be funded by private investment
- As a private initiative, it provides opportunities that the US program can leverage
  - Builds on the solid foundations of decades of publicly funded research
  - Validates the goals and value of fusion research
  - Builds an industry and ecosystem which helps focus the publically funded prog

END