HTS magnets and SPARC:

Paving a pathway towards faster, smaller, and economical high-field fusion energy

Presented by Dr. Erica Salazar

Commonwealth Fusion Systems

Presenting to *PPPL Introduction to Fusion Energy and Plasma Physics Course*

6.20.2022

Commonwealth Fusion Systems

Research sponsored by Commonwealth Fusion Systems

A little bit about me…

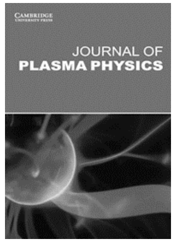
- B.S./M.S. Mechanical Engineering
  - Stanford University
- Engineering, Process Manager
  - General Atomics
- PhD Nuclear Science and Engineering
  - MIT
- Magnet Systems Lead, R&D
  - CFS

CFS

High field path to commercial fusion energy

COMPLETED
Proven science
Alcator C-Mod

COMPLETED
October 2020
Published peer-reviewed SPARC physics basis in Journal of Plasma Physics



COMPLETED
September 2021
Demonstrate groundbreaking magnets

HTS Magnets

HTS CICC-like concepts

No-insulation HTS concepts

CONSTRUCTION UNDERWAY
Operation in 2025
Achieve net energy from fusion

SPARC

Early 2030s
Fusion power on the grid $P_{electric}$~200MW

ARC

High field path to commercial fusion energy

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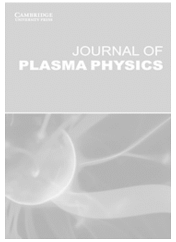
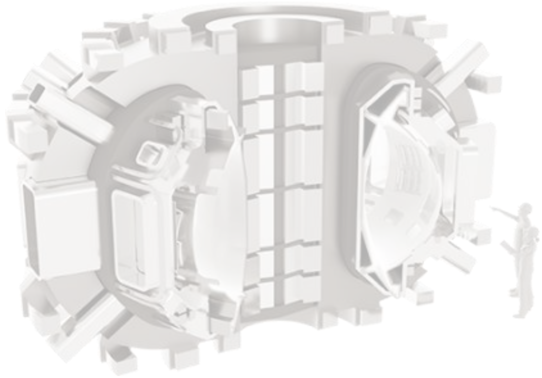
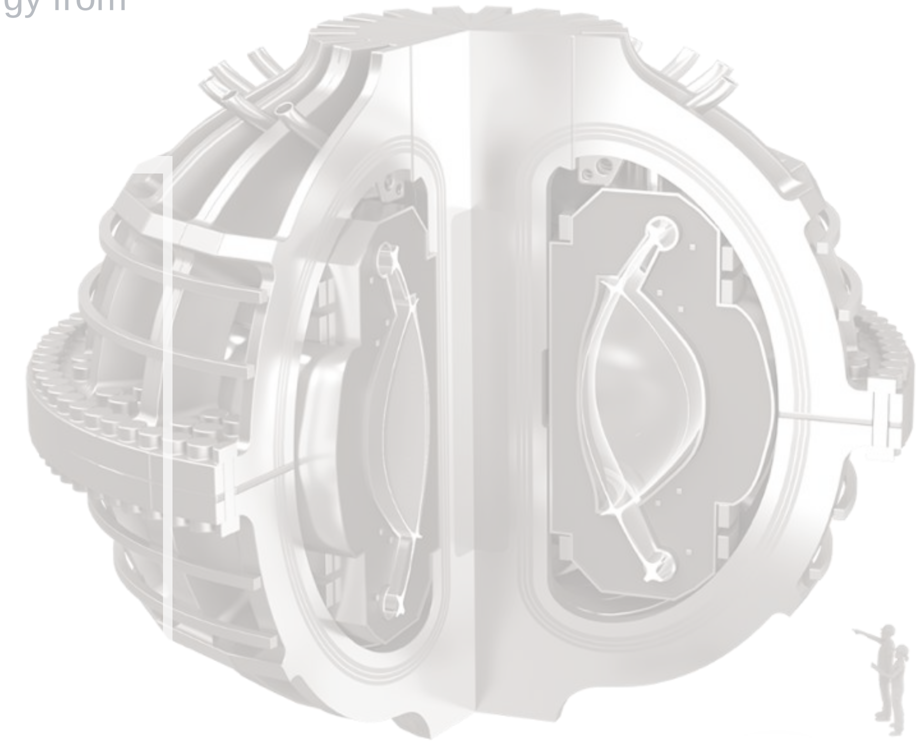


HTS Magnets



SPARC



ARC

HTS CICC-like concepts

No-insulation HTS concepts

Outline

1. Our Motivation: Rapid Global Warming Requires Rapid Solutions
2. The Future of Fusion with High Temperature Superconductors (HTS)
3. The Design Challenges of Using HTS
4. De-risking the Challenges and Proving Technical Feasibility
5. Marching towards a SPARC era

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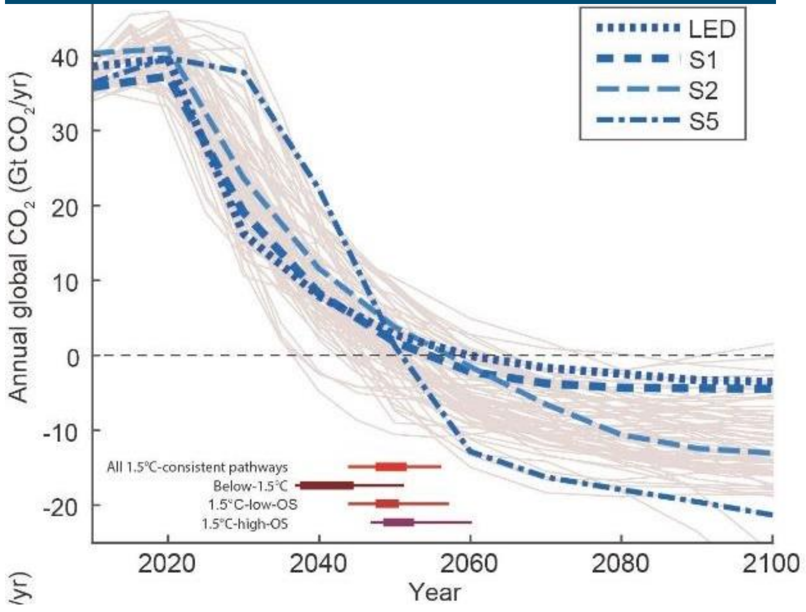
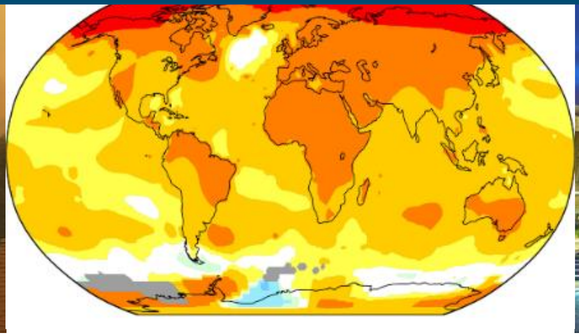
Decarbonization will be the largest macro trend this century

- The verdict is unanimous, we need to decarbonize to net-zero as soon as possible
- This is the largest story in the world and is only growing
- The world is going to act to do what it takes
- Climate, the Energy Transition, and Sustainability are going to be the dominant issue for the next 30 years
- This will require a massive shift in the way we generate and consume energy and will transform ~5-6% of World GDP

What MUST be done

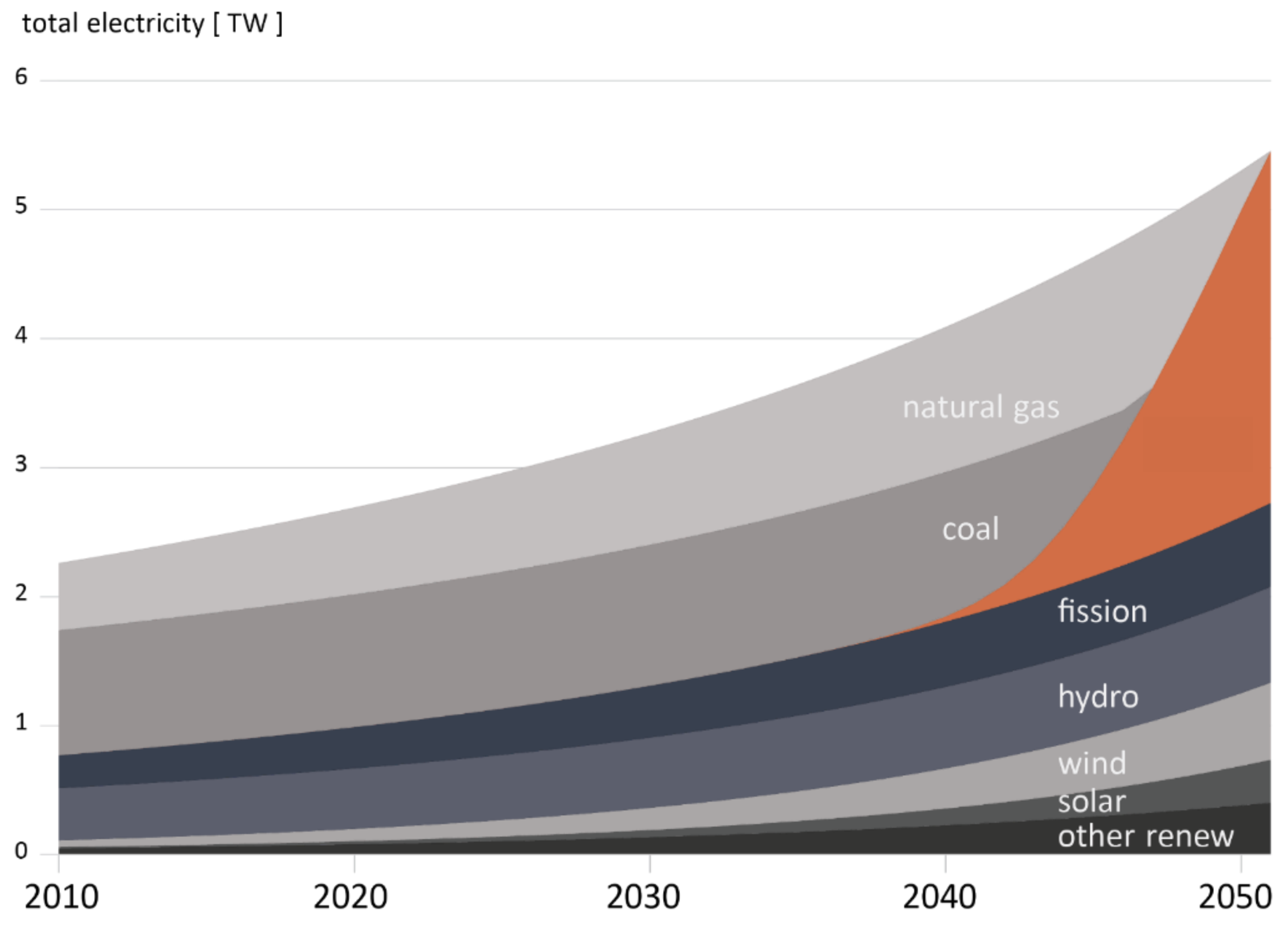


Risk	Science	Finance	Society

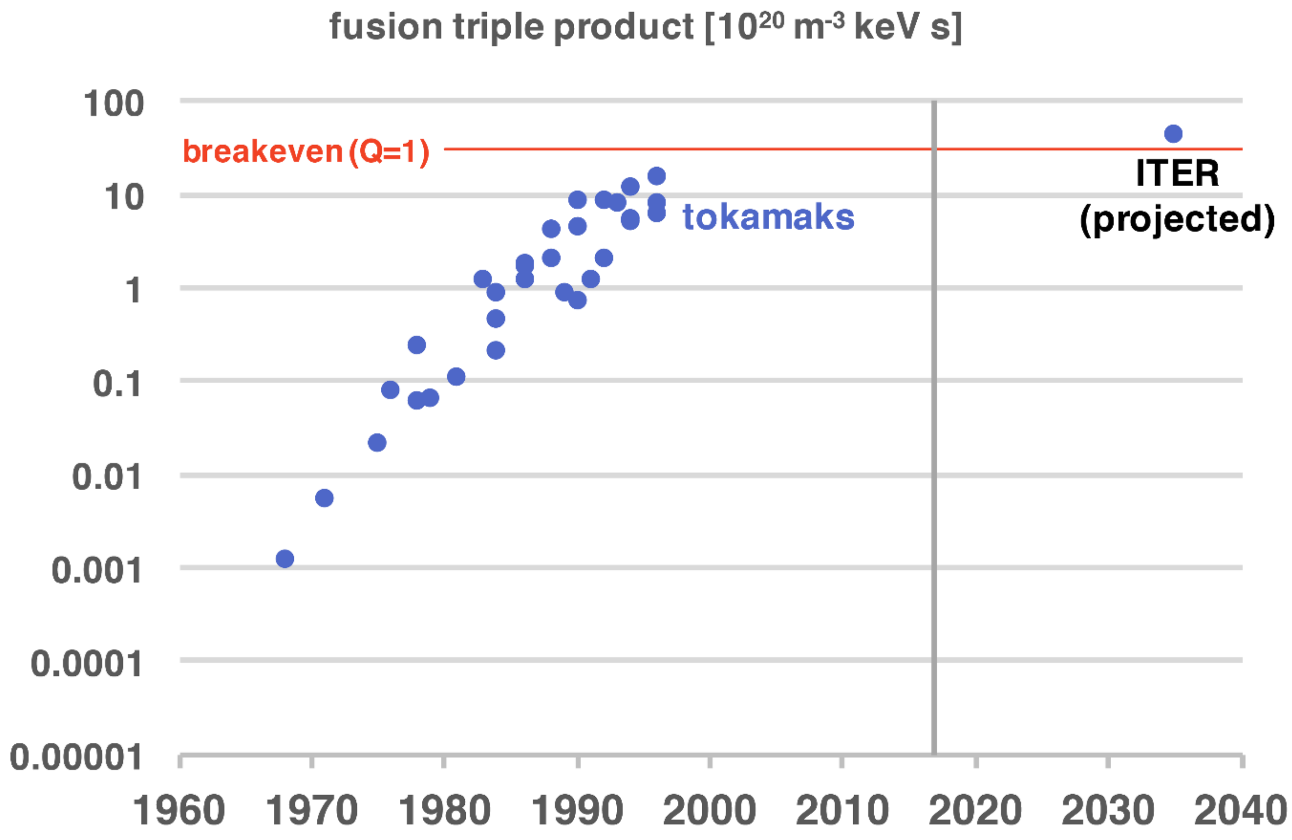


The world needs a fundamental new energy generation technology

- We're not going to get to all our commitments without it
- ~100GW of power plants/yr are required - order of $T of sales/yr
- This is the largest problem and opportunity facing humanity
- Innovation at the source is the highest leverage way to get there



Tokamaks Demonstrated Enormous Progress in their first 3 decades



Progress Exceeded Moore's Law for 30 years


HT-7 (CN)

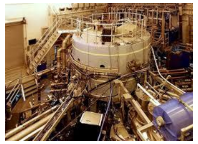

JT-60U (JP)


KSTAR (KR)


MAST-U (UK)


NSTX-U (US)


Tore Supra (FR)

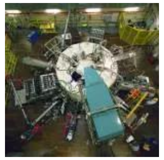

Alcator C-Mod (US)


ASDEX-U (DE)


COMPASS (CZ)


DIII-D (US)

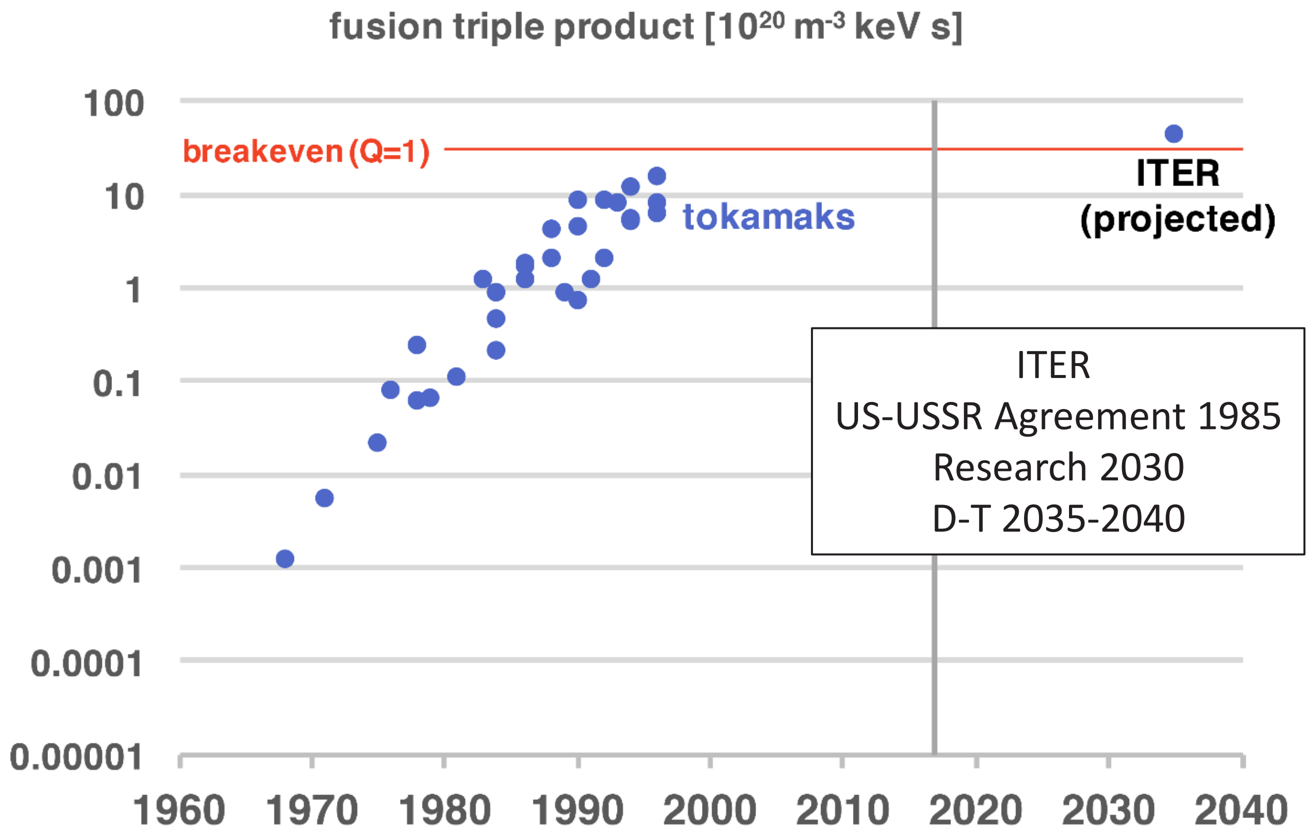

EAST (CN)

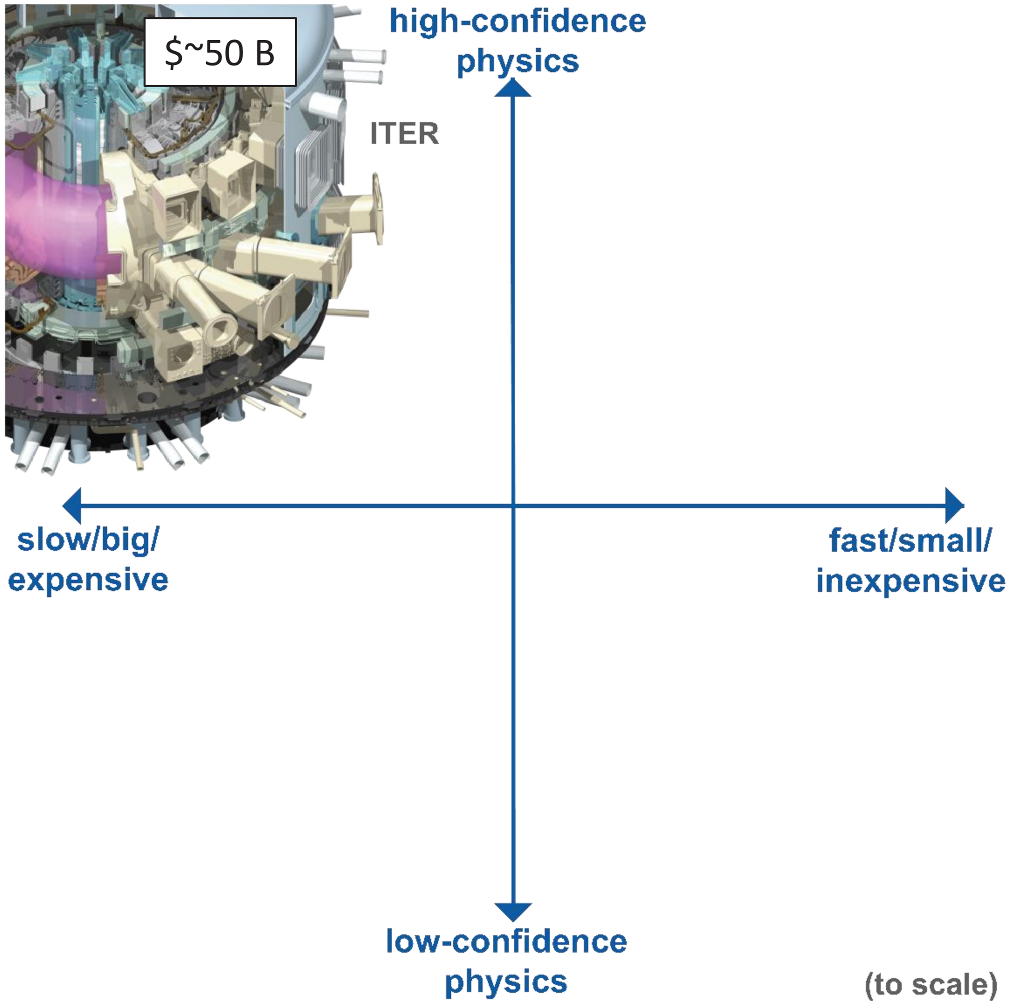

FTU (IT)

+ 160 other tokamaks across 60 years

Enormous technical and scientific base

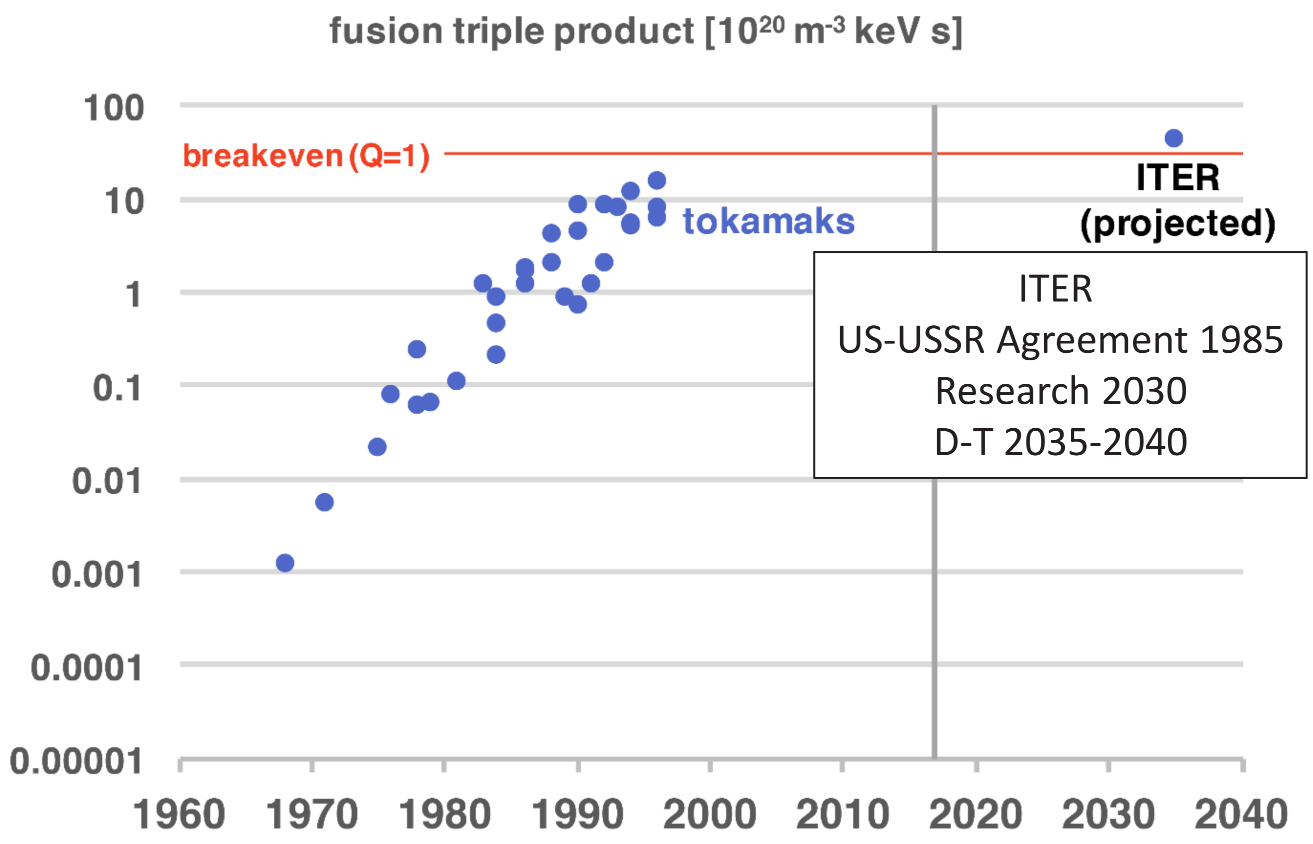
We Need To Consider Another Approach

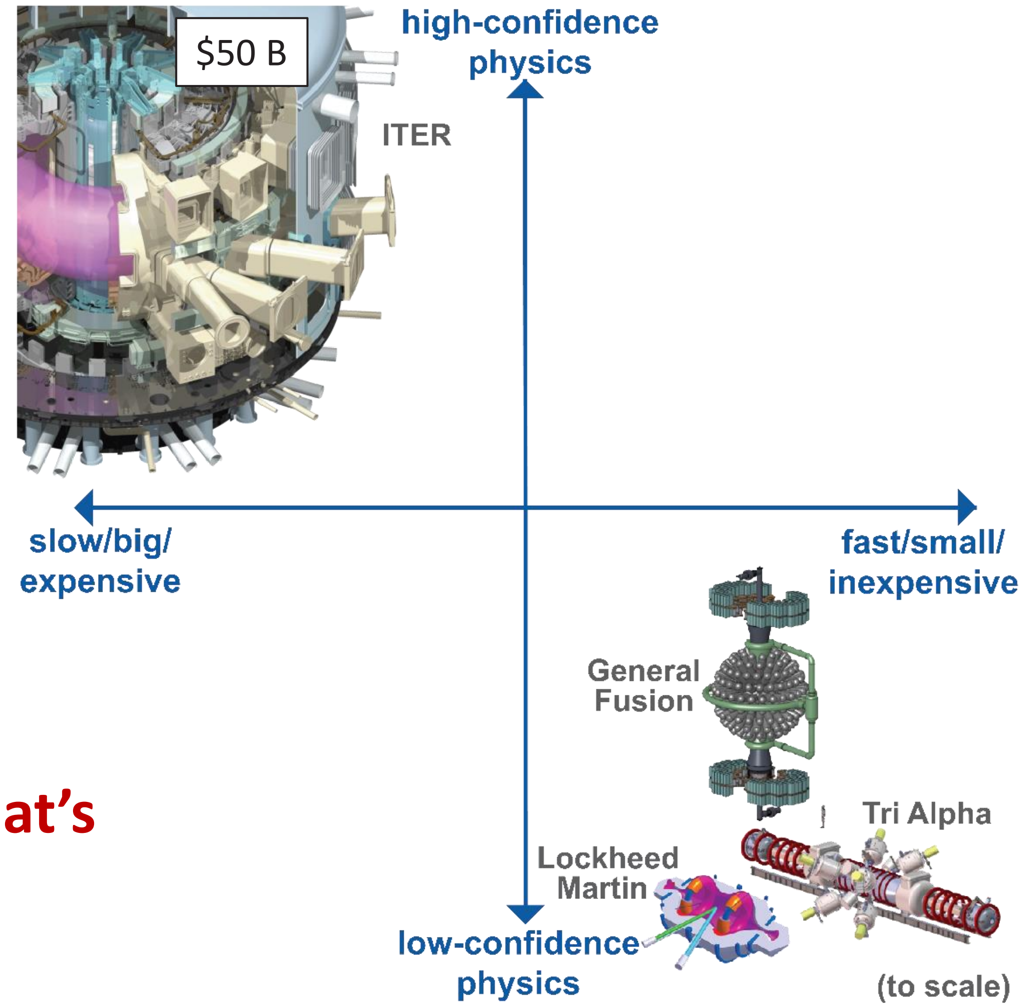




- Impressive and unparalleled fusion performance
- Stagnating due to size & cost, not saturation due to physics
- Can they be fielded in time to deal with global warming?

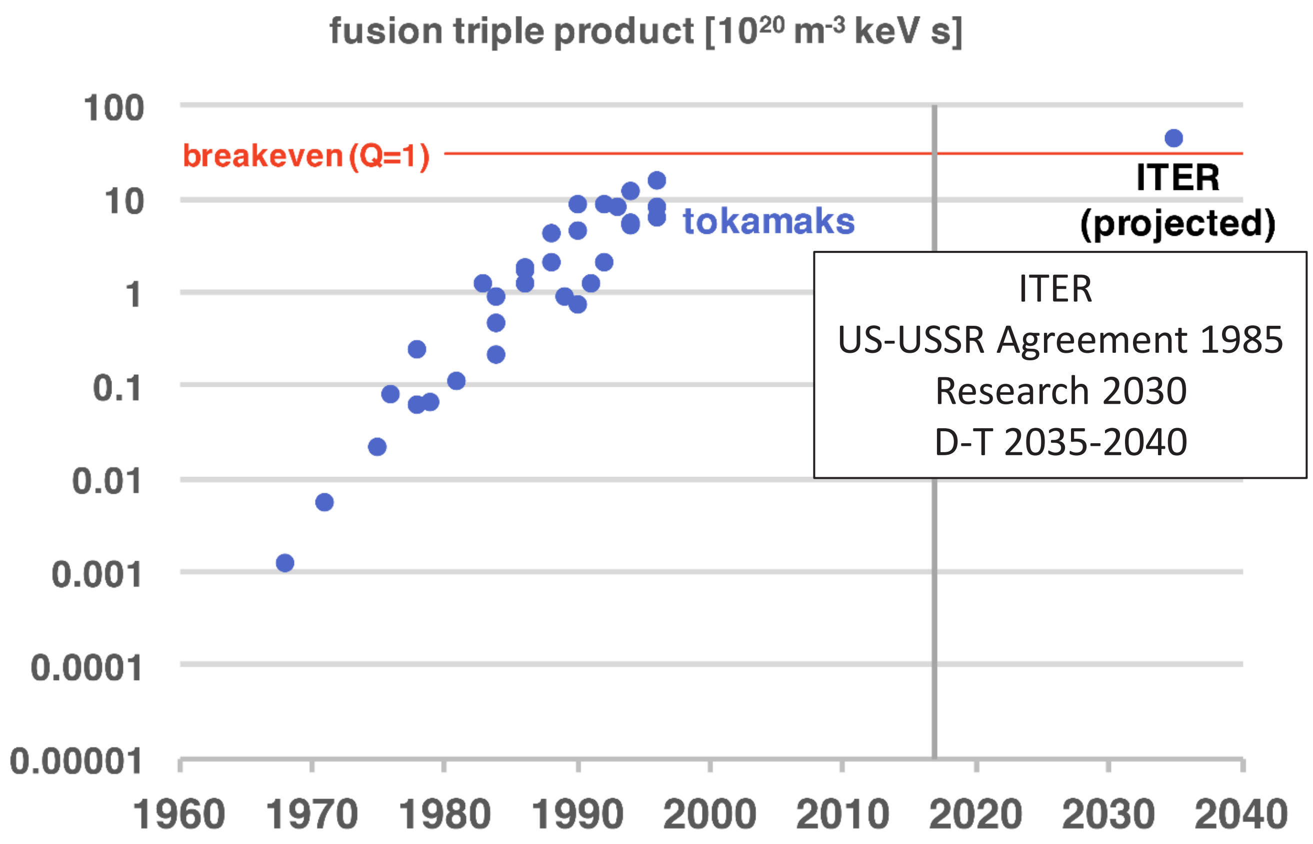
We Need To Consider Another Approach

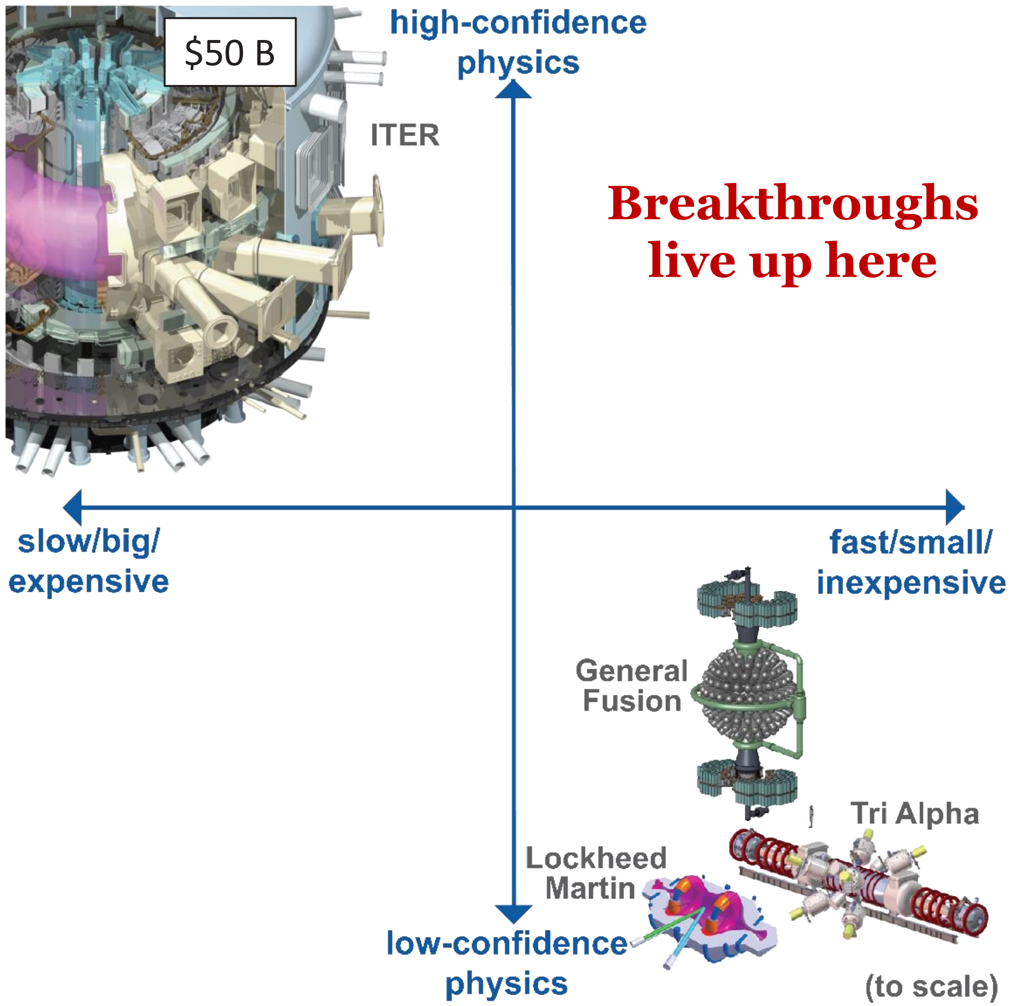




These Alternates Currently Fall Far Short of What's Needed

We Need To Consider Another Approach





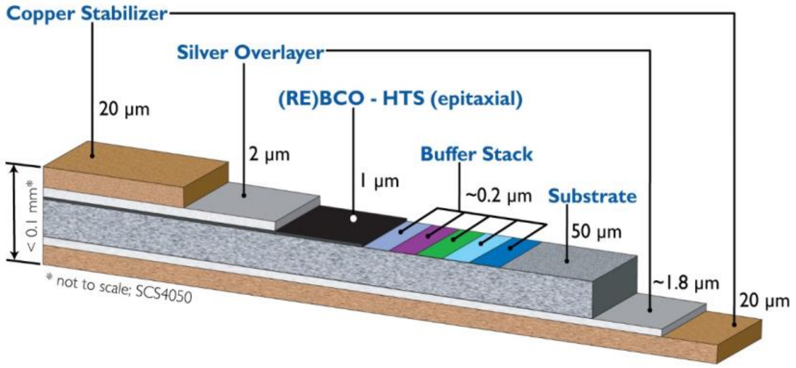
- We're looking for a path which builds on the progress and knowledge built by decades of research on the tokamak
- Reduced in scale to learn fast
- Focused on fusion power plants that are practical and economical

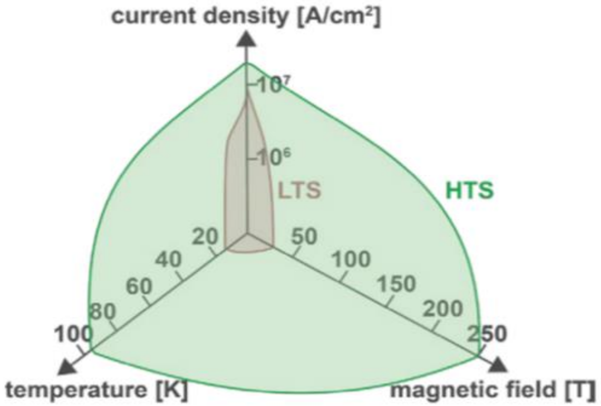
In the 2010s the HTS industry started to build serious HTS magnets

Maturing HTS industry

- Producing REBCO (rare-earth barium copper oxide) high-temperature superconductor at the needed performance
- Scalability and cost reductions within reach

Opened a completely new path to SC magnets

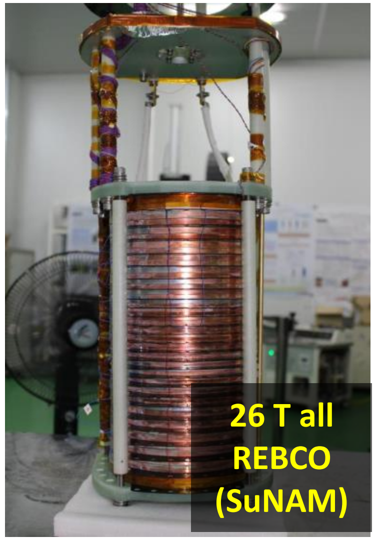




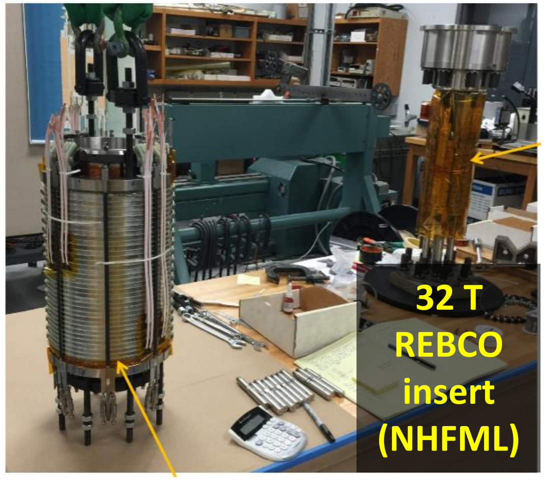
People building high-field HTS magnets

- Ultra-high field, compact HTS magnets were being built for nuclear magnetic resonance (NMR) spectroscopy
- Successful results demonstrated substantial risk retirement in HTS magnet technology

Some big steps on a new path of high-field SC magnets



Seungyong Hahn and SuNAM team



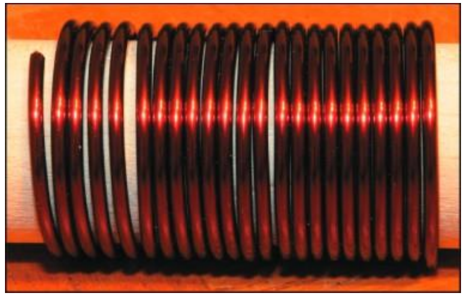
Huub Weijers, Denis Markiewicz, and team

Fusion has pushed to the limits of magnets since the beginning…

1950-1960s:

Copper wire

The pioneers



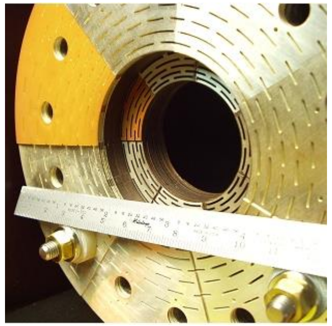
Stellarator A 1953

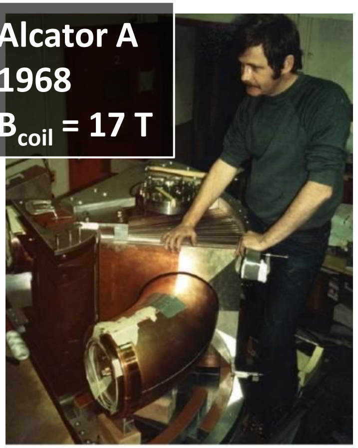
B_{coil} = 0.1 T

1960-1980s:

Cryogenic Bitter plates

The Alcators at MIT





Alcator A

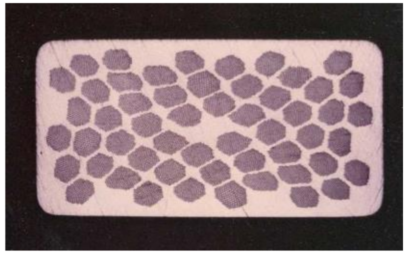
1968

B_{coil} = 17 T

1980-2000s:

NbTi superconductors

First SC fusion devices



Tore Supra 1988

B_{coil} = 9 T

1990s-2010s:

Nb_3Sn for higher field

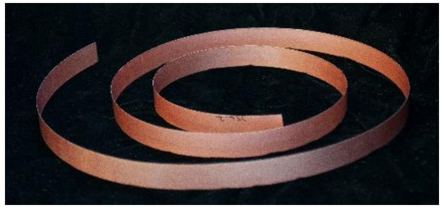
Reactor-class devices

ITER 2015

B_{coil} = 13 T

2010-2020s:

REBCO: very high magnetic fields



? ? ?

B_{coil} > 20 T

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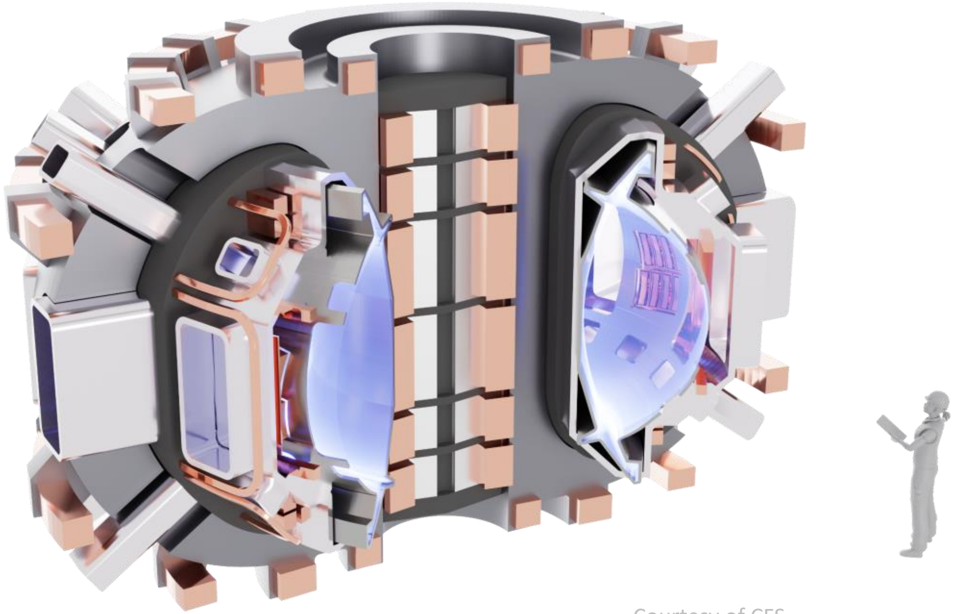
Critical Variables for Magnetic Confinement Fusion

ENERGY GAIN:
(science feasibility)

$$nT\tau_E \sim \frac{\beta_N H}{q^2} R^{1.3} B^3$$

POWER DENSITY:

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{{\beta_N}^2 \varepsilon^2}{q^2} R B^4$$



Courtesy of CFS

P_{fusion} = Fusion power
S_{wall} = plasma wall surface area
n = density
T = Temperature

β_N = Normalized Beta
τ_E = Energy confinement time
q = safety factor

H = confinement factor
R = Major radius
B = Magnetic field

B. Sorbom and e. al., "ARC: A compact, high-field, fusion nuclear science facility anddemonstration power plant with demountable magnets," *Fusion Engineering and Design,* vol. 100, pp. 378-405, 2015.

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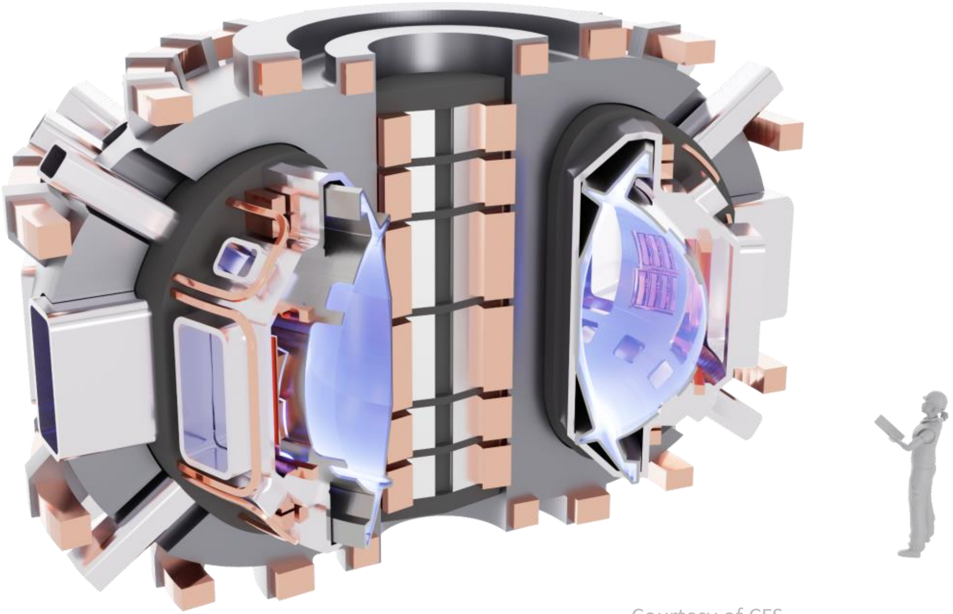

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higher magnetic fields and current density → **smaller magnets** → **smaller, economical fusion devices**

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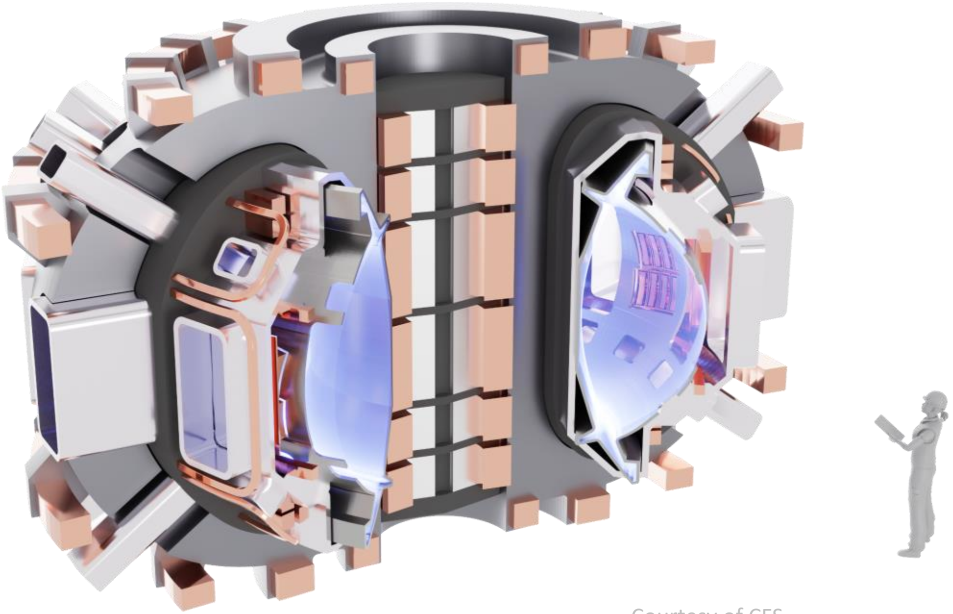

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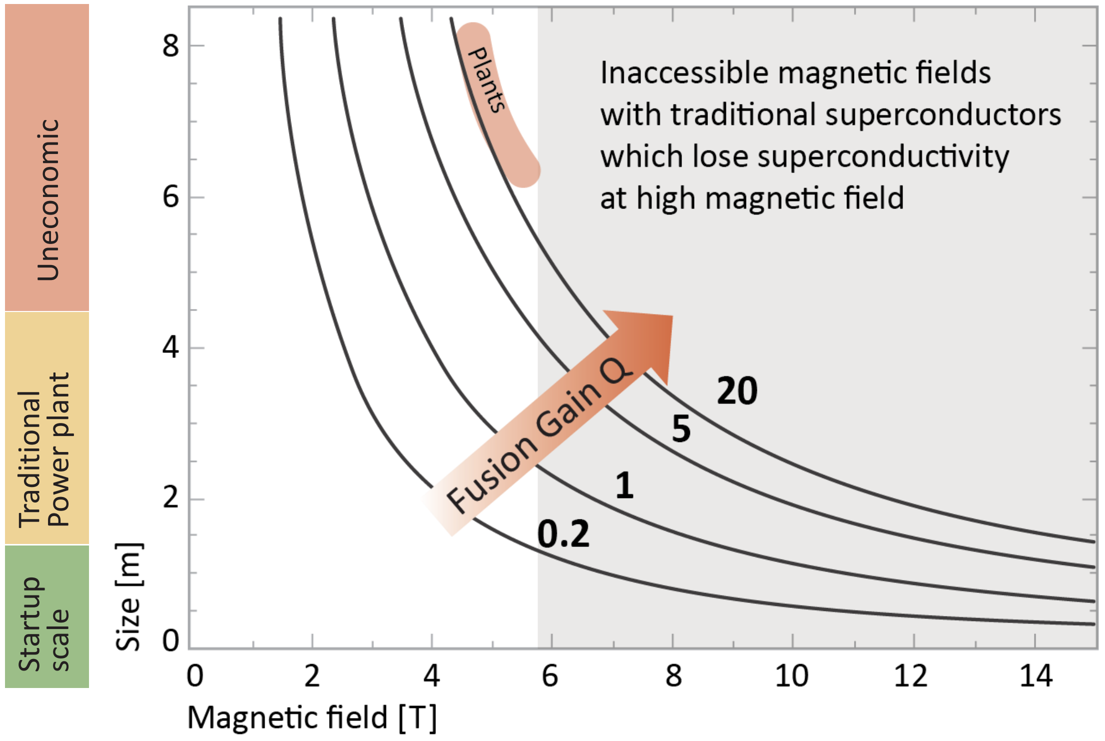

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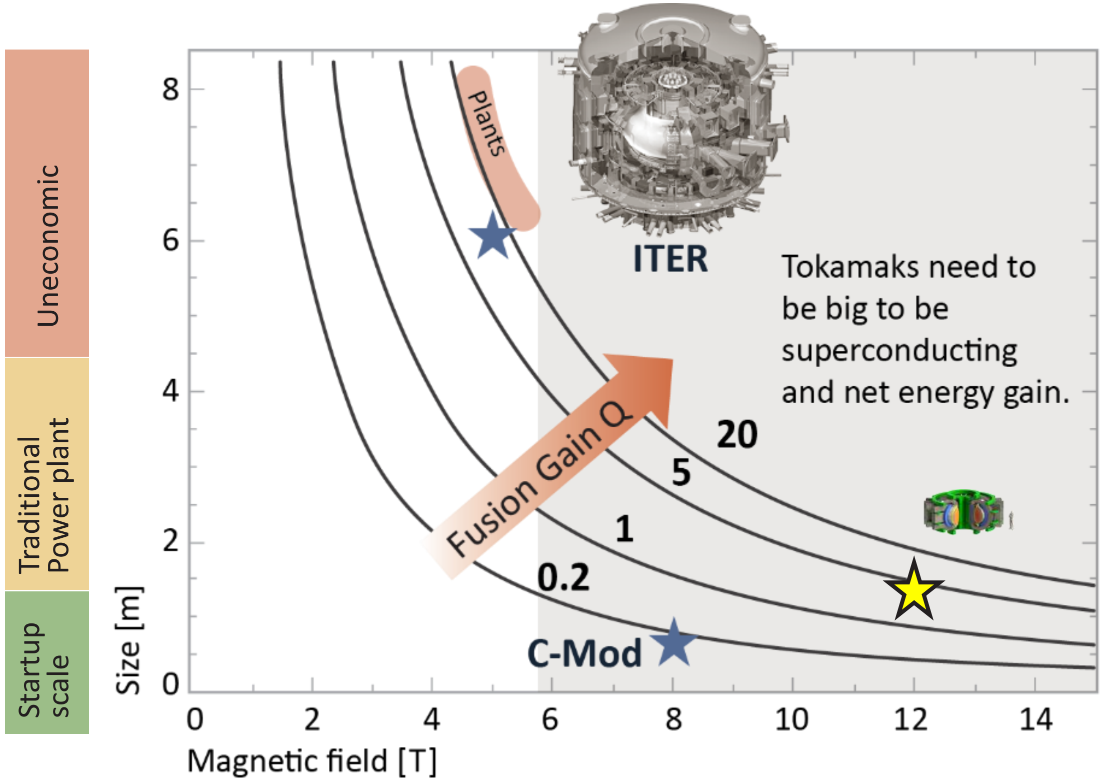

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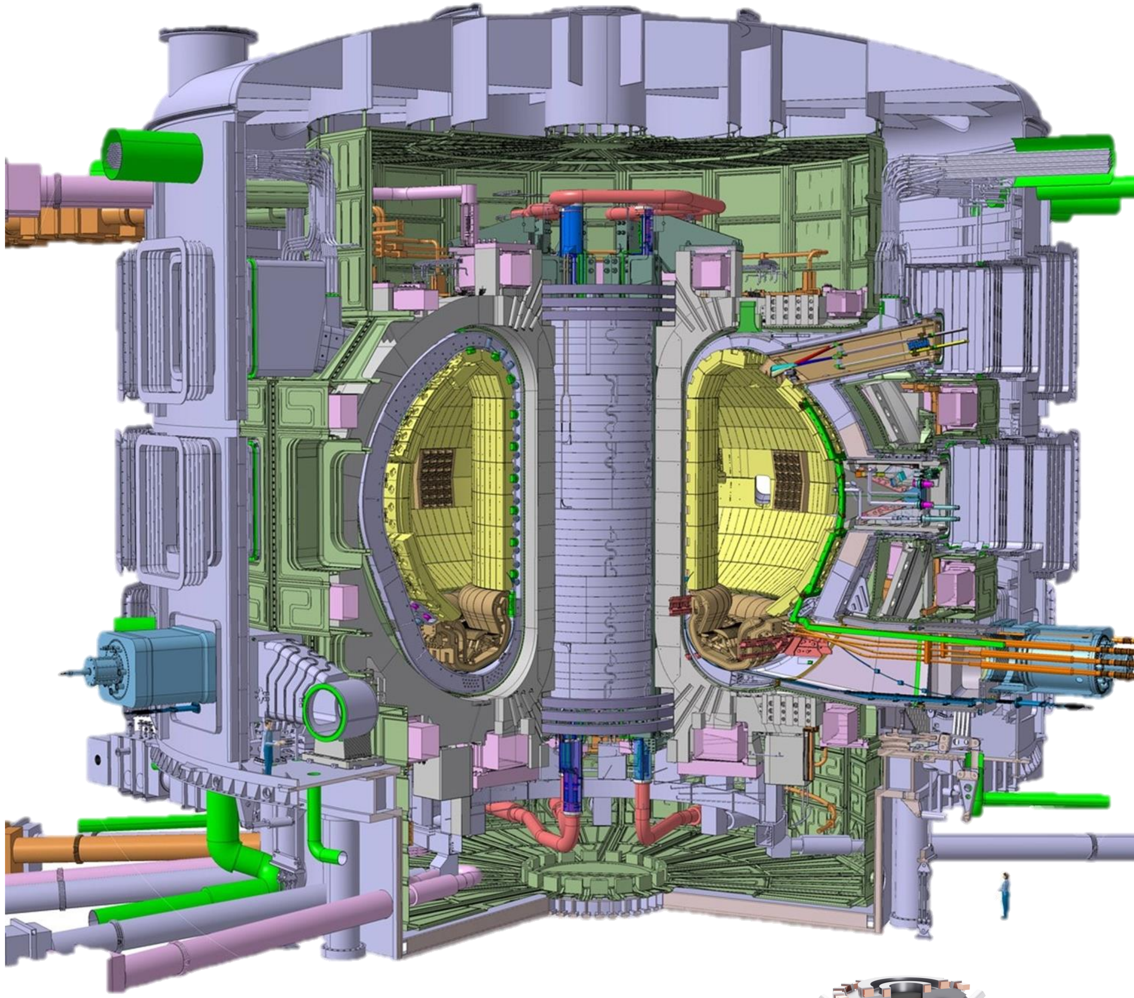
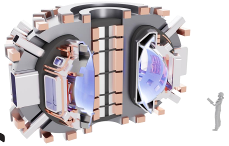


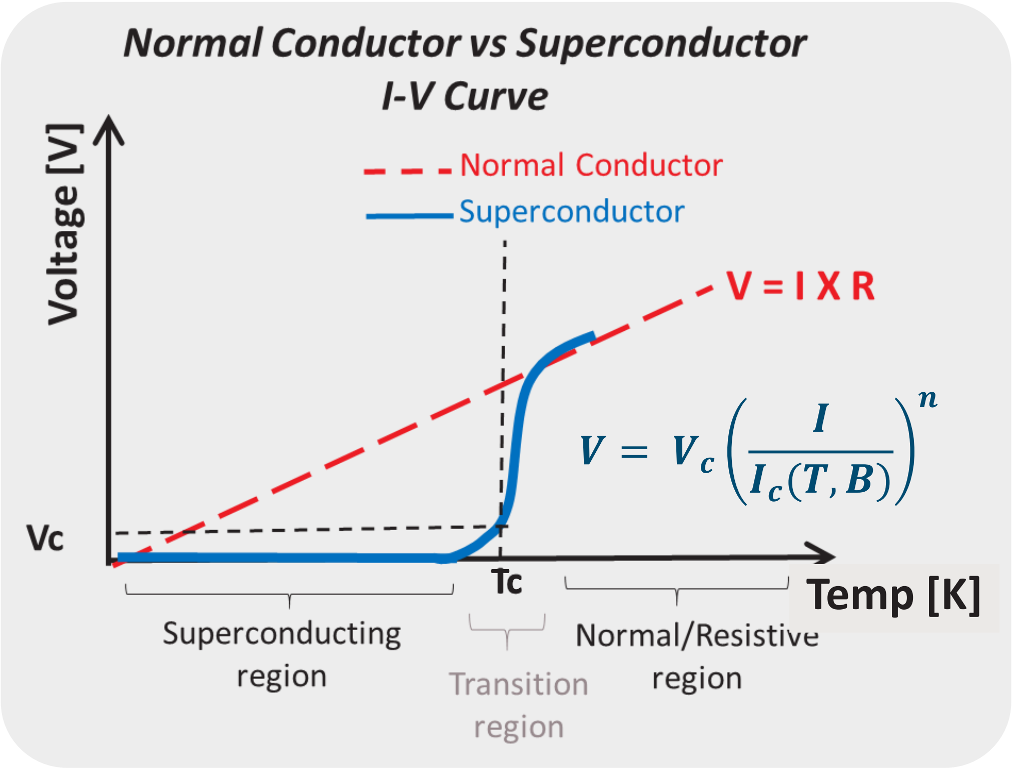
ITER

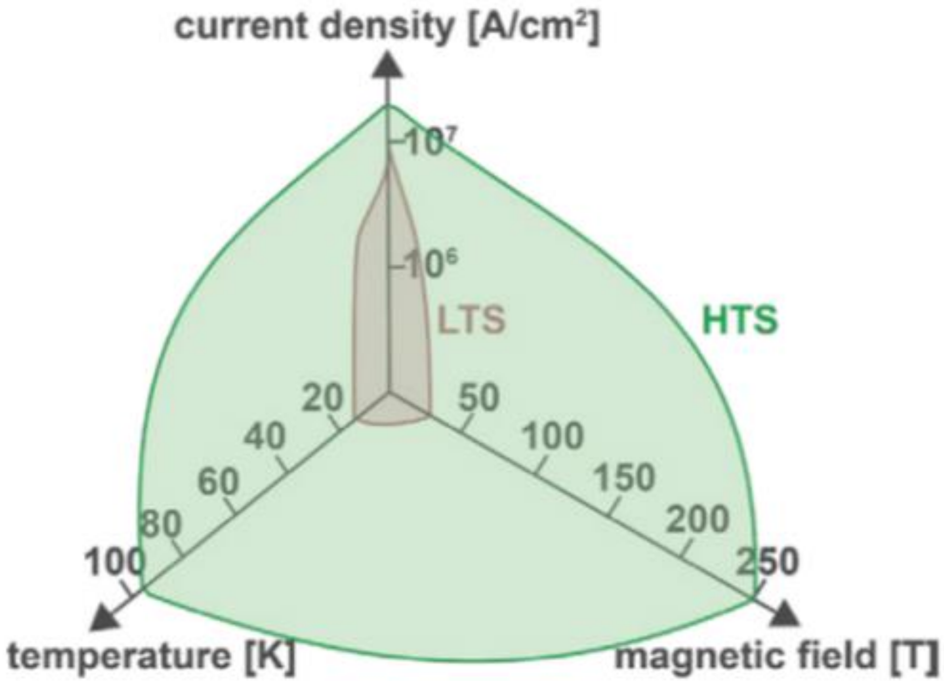


SPARC

What is a superconductor?

A superconductor is an electric conductor that does not exhibit any resistance. If the superconductor exceeds its critical current, temperature or magnetic field, the superconductor becomes a "normal" or resistive conductor.

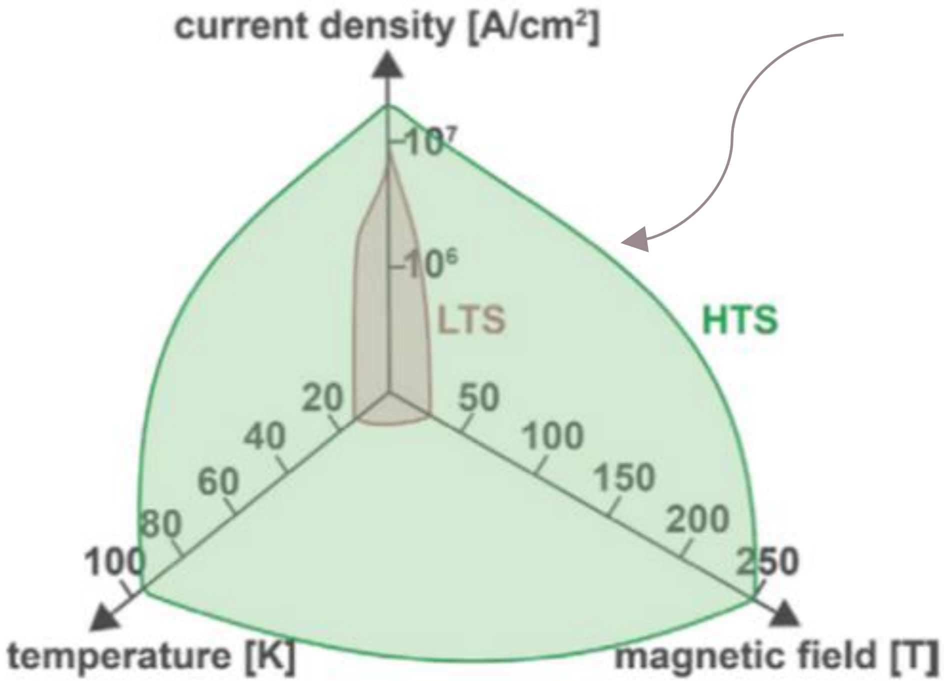




High Temperature Superconductors are a Game-changer

higher magnetic fields and current density → **smaller magnets** → **smaller, economical fusion devices**

HTS can operate at higher current density, temperatures, and magnetic fields



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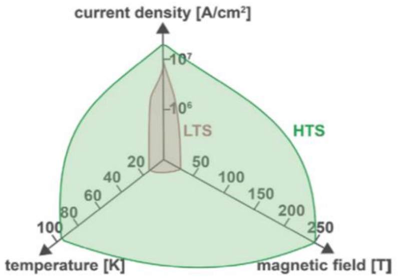
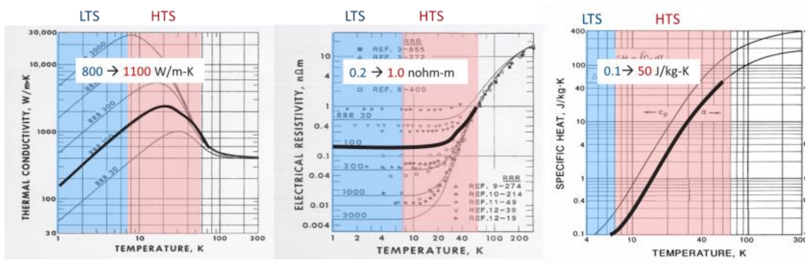
HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → New Scientific Challenges → De-risking: Testing + Modeling

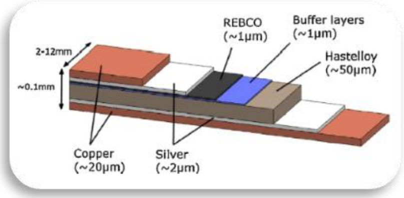
High Current Density + Magnetic Field



Higher operating temperature + larger margin



New manufacturing form factors



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Higher fields + higher current density

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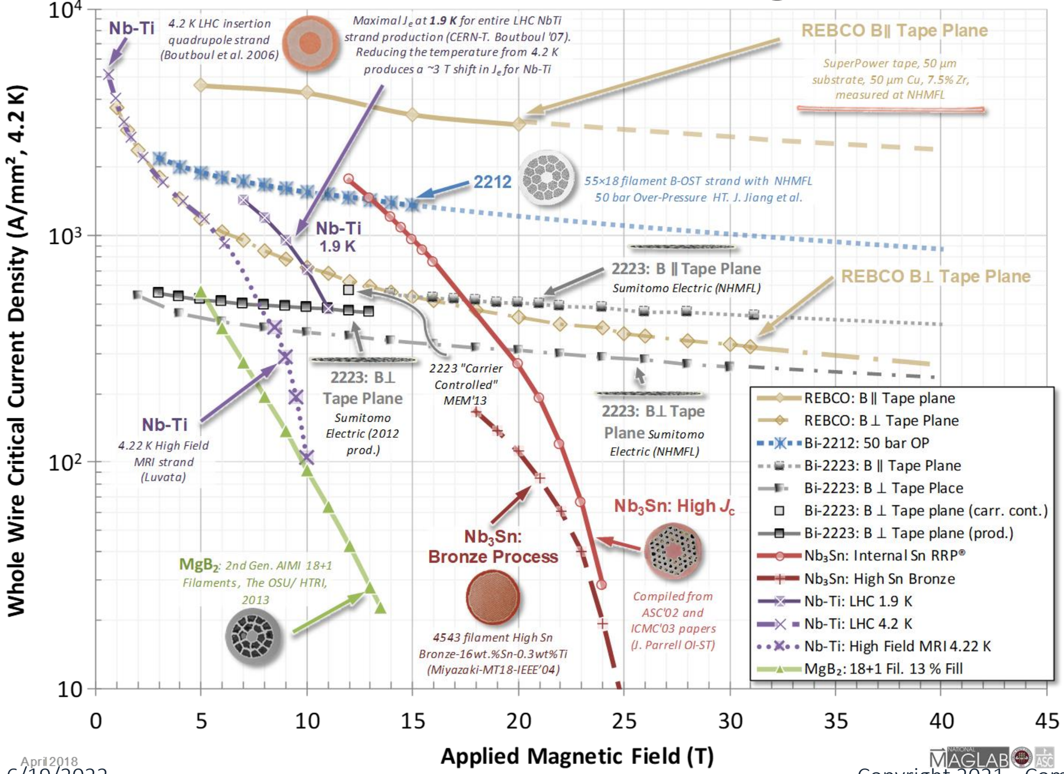
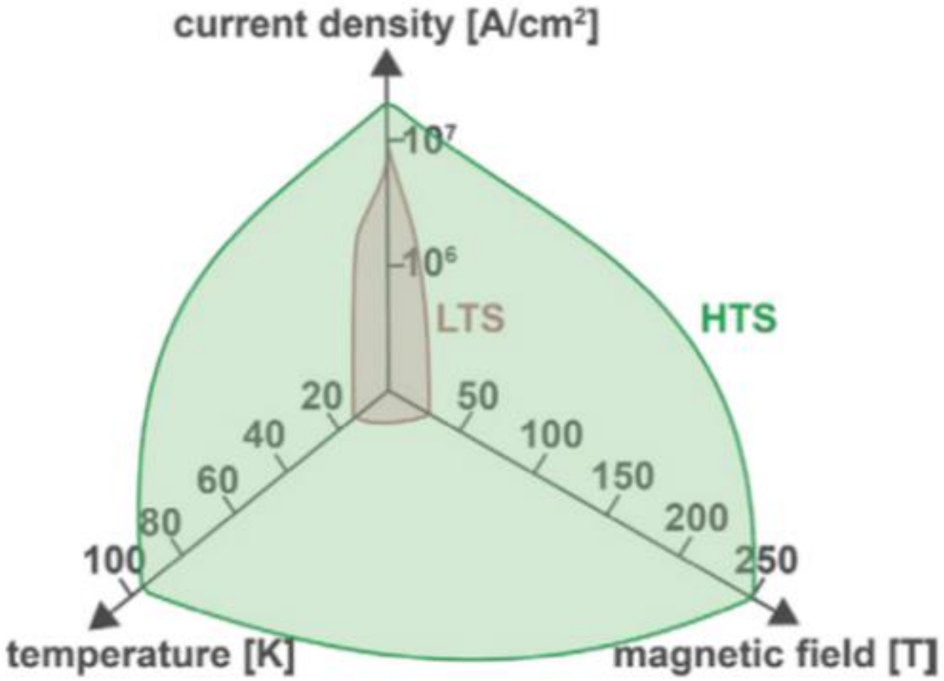
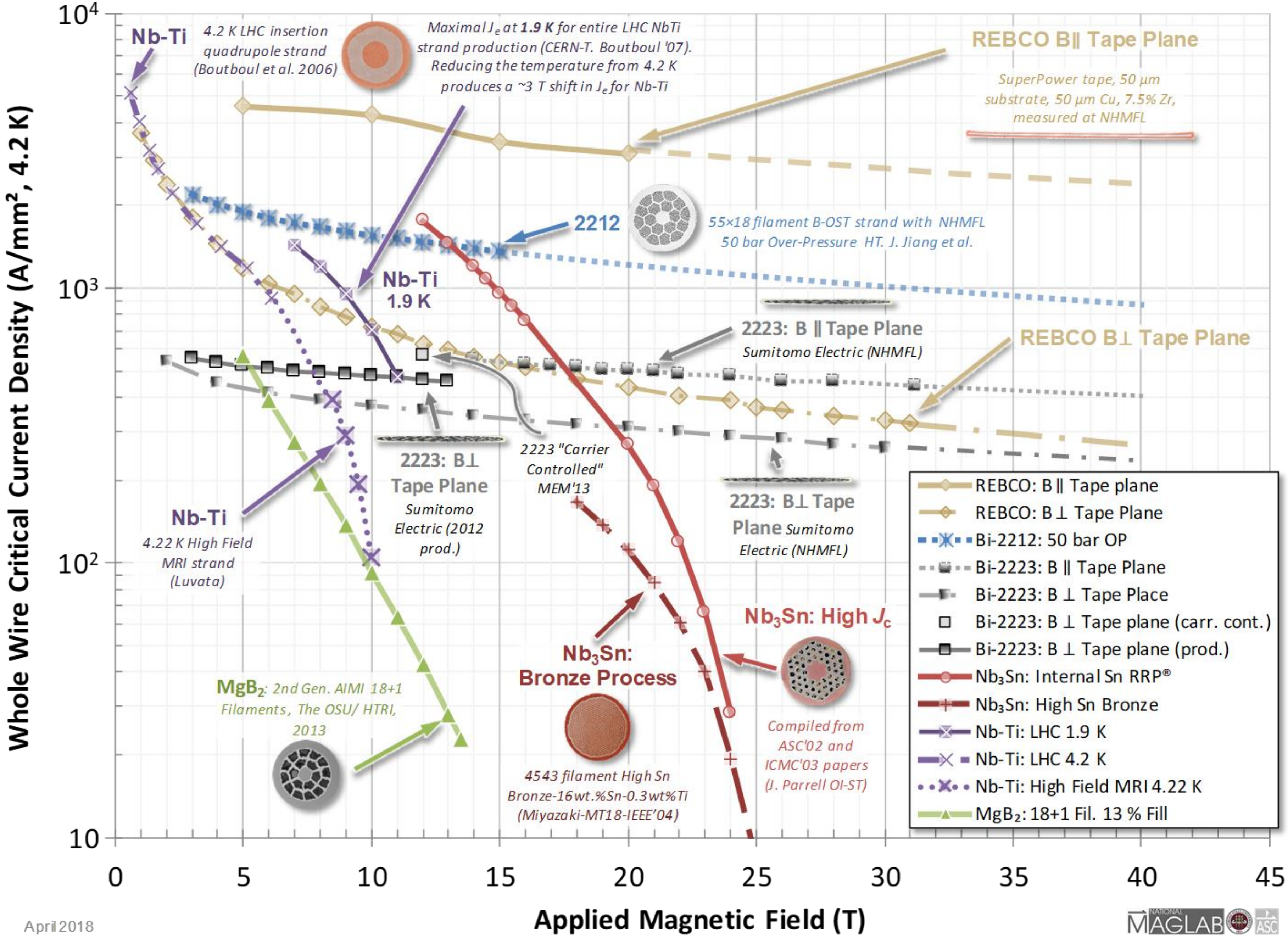
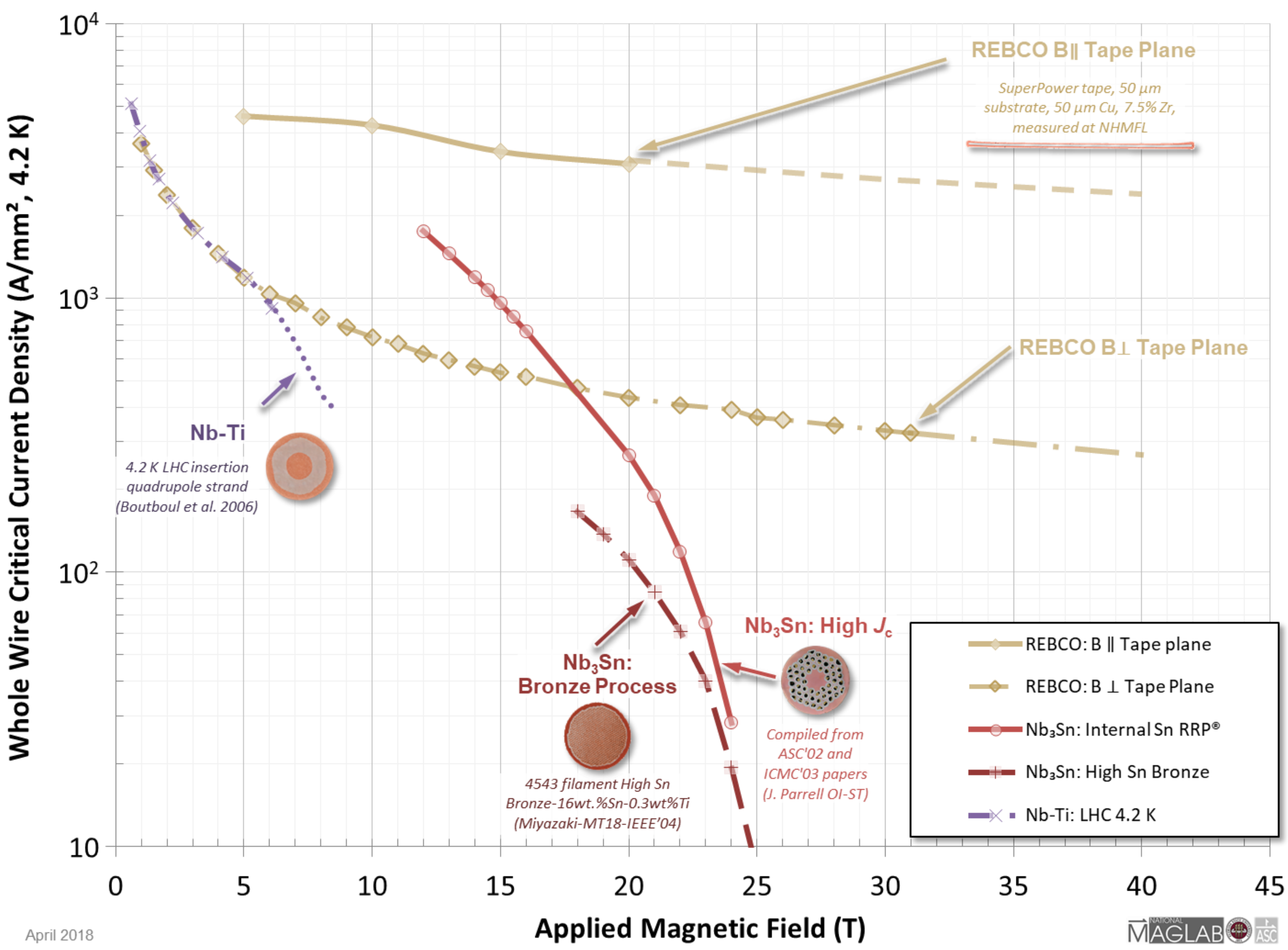






Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Maximal J_e at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in J_e for Nb-Ti
REBCO B∥ Tape Plane
SuperPower tape, 50 μm substrate, 50 μm Cu, 7.5% Zr, measured at NHMFL
2212
55×18 filament B-OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al.
Nb-Ti 1.9 K
2223: B ∥ Tape Plane
Sumitomo Electric (NHMFL)
REBCO B⊥ Tape Plane
2223: B⊥ Tape Plane
Sumitomo Electric (2012 prod.)
2223 "Carrier Controlled" MEM'13
2223: B⊥ Tape Plane Sumitomo Electric (NHMFL)
Nb-Ti
4.22 K High Field MRI strand (Luvata)
Nb_3Sn: High J_c
Nb_3Sn: Bronze Process
MgB_2: 2nd Gen. AIMI 18+1 Filaments, The OSU/ HTRI, 2013
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B ∥ Tape plane
REBCO: B ⊥ Tape Plane
Bi-2212: 50 bar OP
Bi-2223: B ∥ Tape Plane
Bi-2223: B ⊥ Tape Place
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Nb_3Sn: Internal Sn RRP®
Nb_3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
Nb-Ti: LHC 4.2 K
Nb-Ti: High Field MRI 4.22 K
MgB_2: 18+1 Fil. 13 % Fill
Whole Wire Critical Current Density (A/mm², 4.2 K)
10^4
10^3
10^2
10
0
5
10
15
20
25
30
35
40
45
Applied Magnetic Field (T)
NATIONAL MAGLAB
ASC



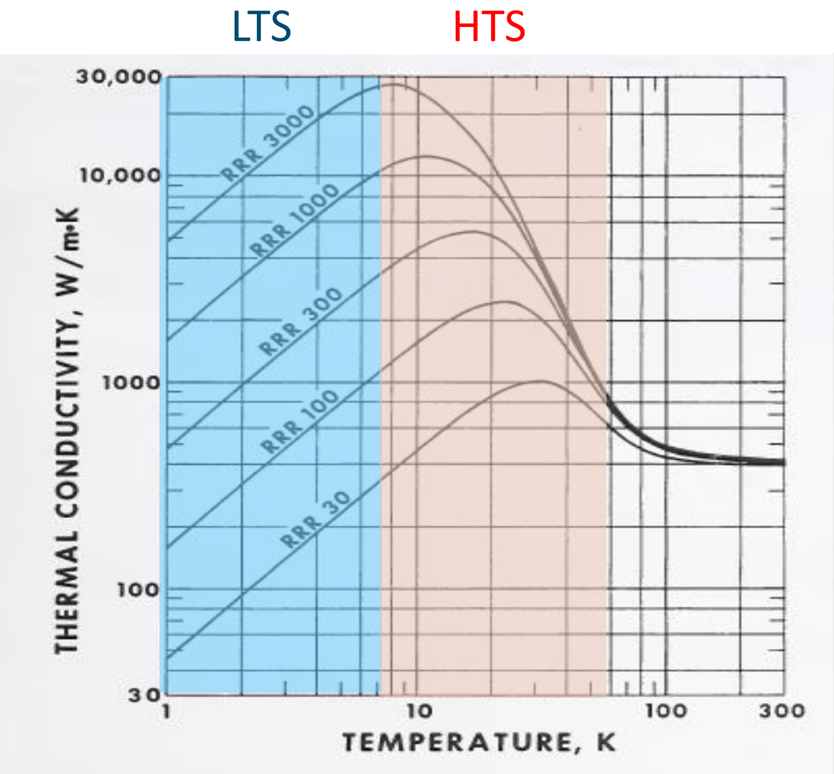
REBCO B∥ Tape Plane
SuperPower tape, 50 µm substrate, 50 µm Cu, 7.5% Zr, measured at NHMFL
REBCO B⊥ Tape Plane
Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Nb$_3$Sn: High J_c
Nb$_3$Sn: Bronze Process
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B ∥ Tape plane
REBCO: B ⊥ Tape Plane
Nb$_3$Sn: Internal Sn RRP®
Nb$_3$Sn: High Sn Bronze
Nb-Ti: LHC 4.2 K
Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
10^4
10^3
10^2
10
0
5
10
15
20
25
30
35
40
45

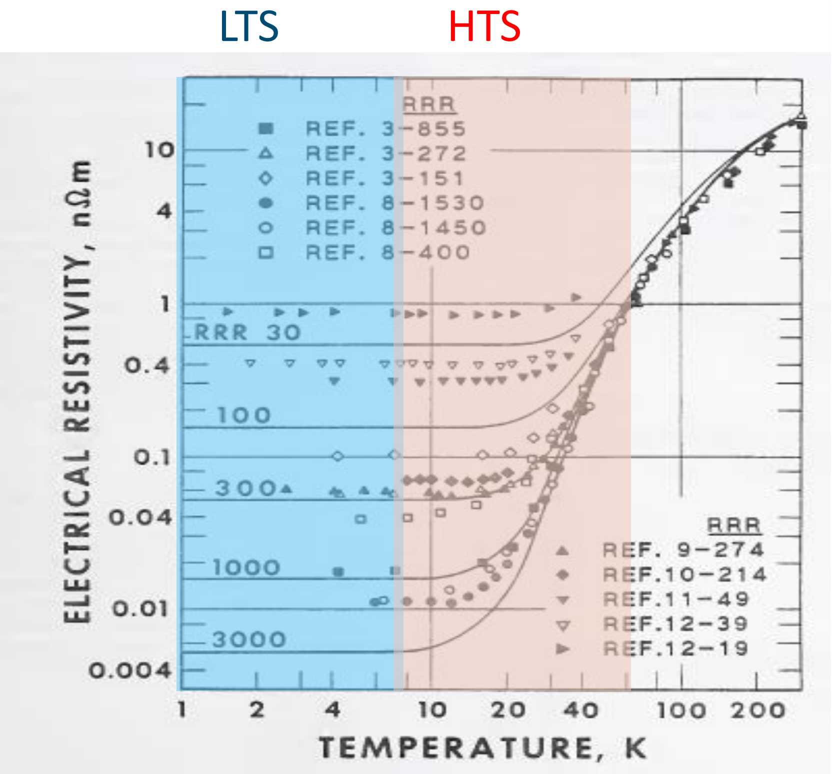
April 2018

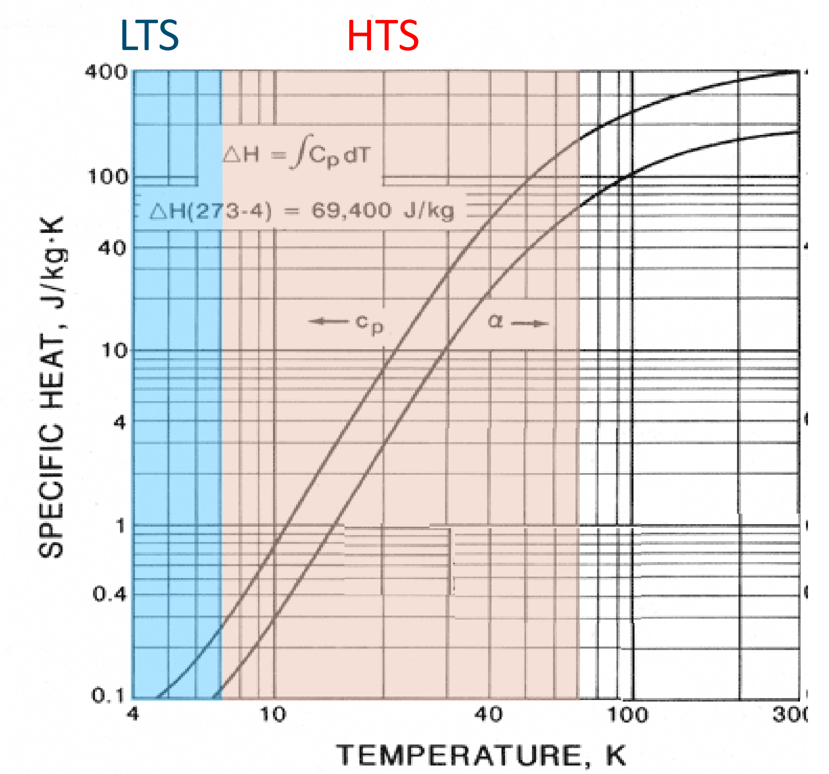
HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → New Scientific Challenges → De-risking: Testing + Modeling

New operating conditions







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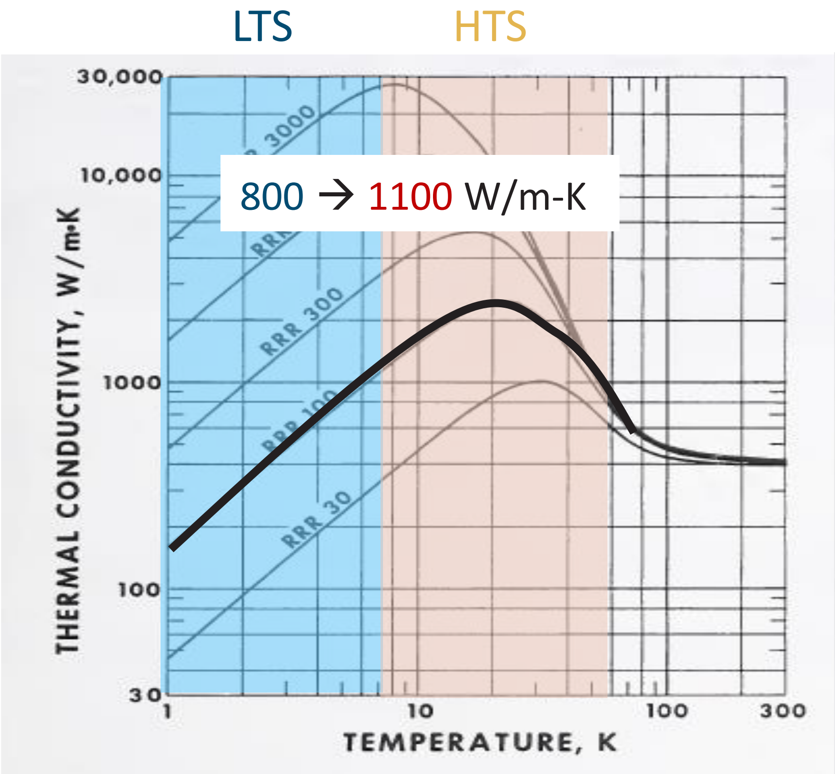

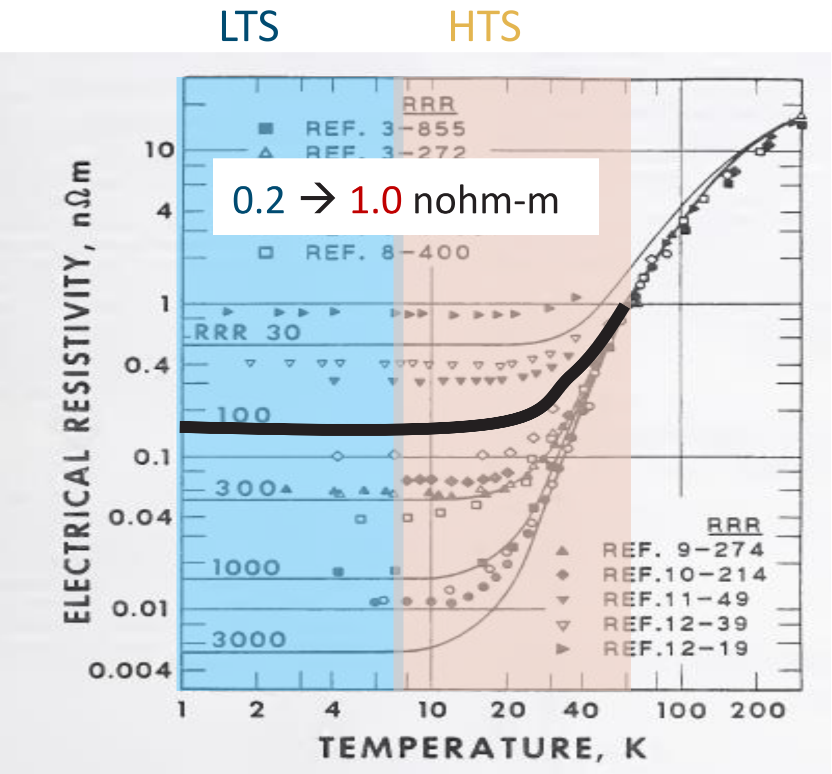

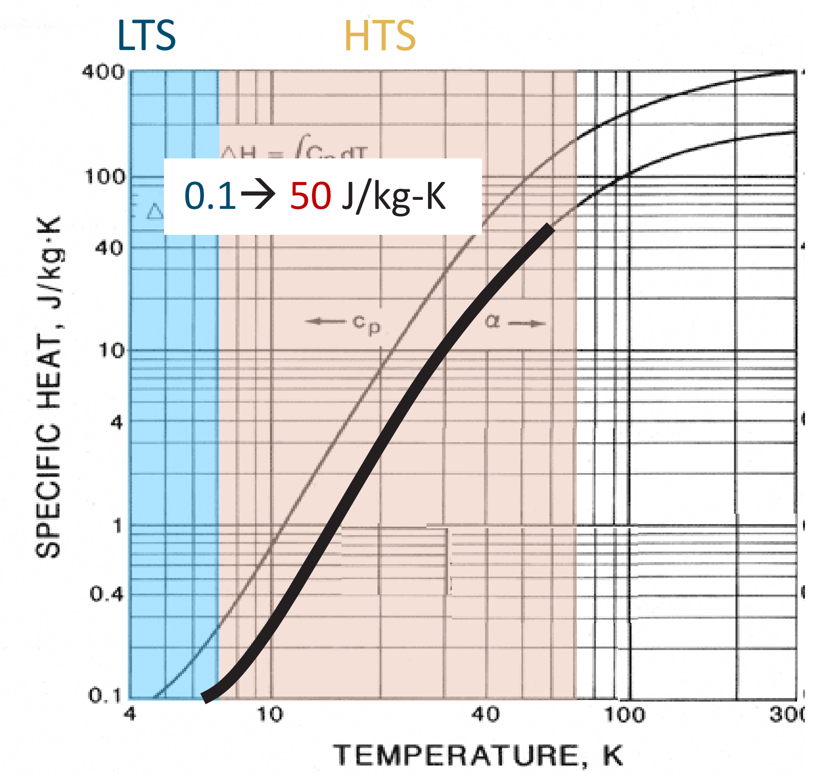

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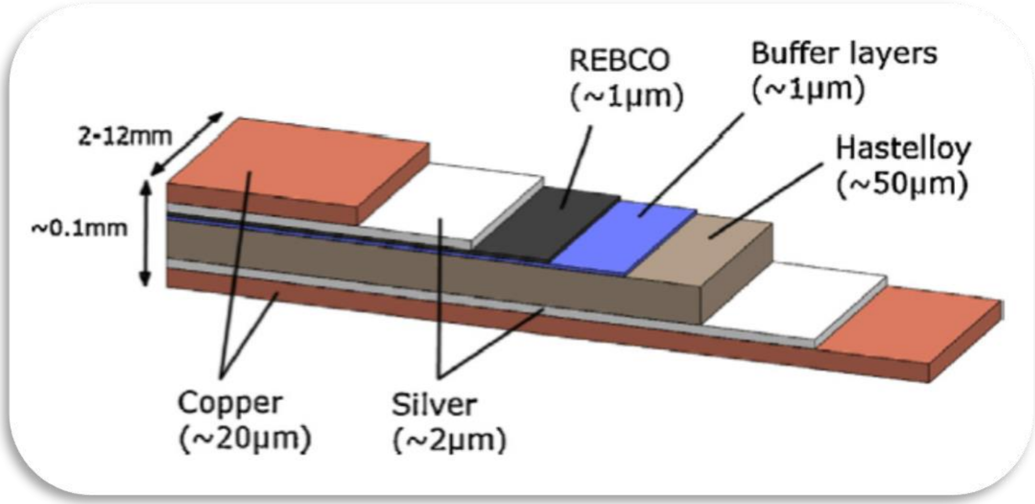
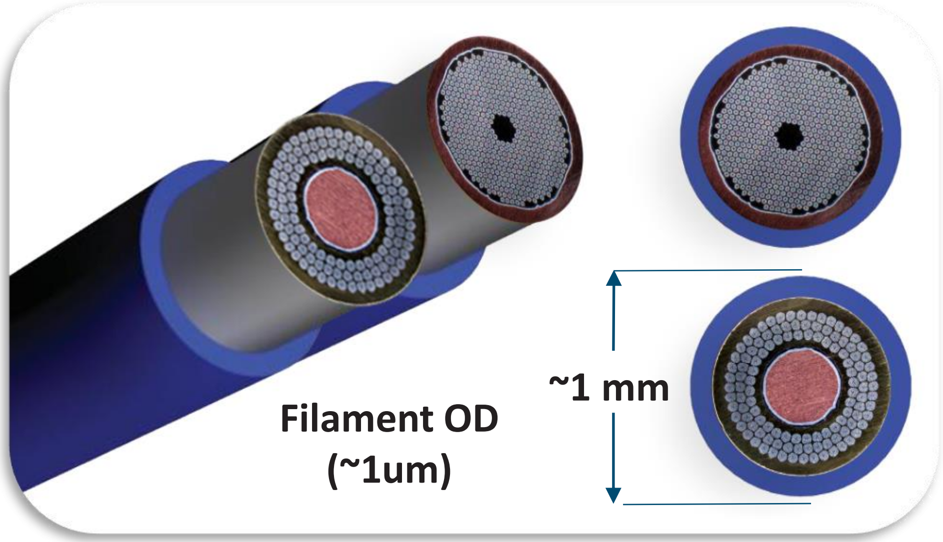
New Technology (HTS) → **New Scientific Challenges** → **De-risking: Testing + Modeling**

New form factors

HTS "tape"



LTS "wire"



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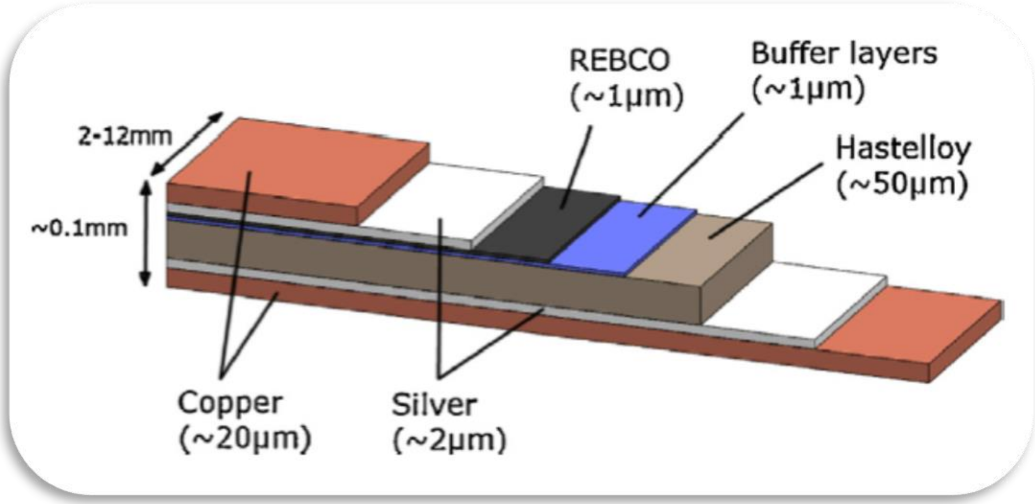
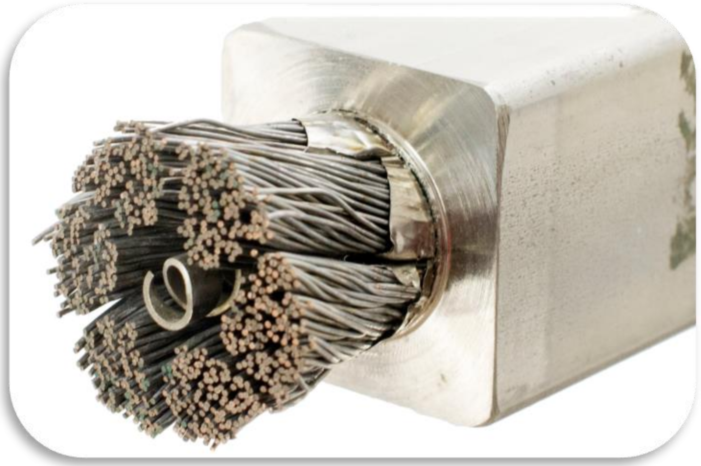
HTS “tape”



LTS Cable-in-Conduit



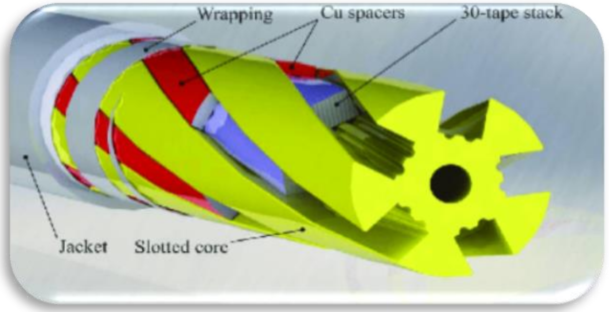
https://nationalmaglab.org

HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → New Scientific Challenges → De-risking: Testing + Modeling

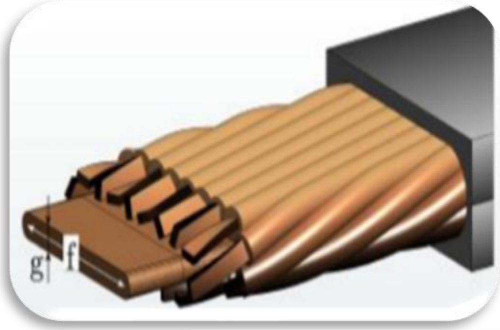
New insulated cable designs

Various HTS designs



G. Celentano and e. al., *IEEE Trans. on App. Superconductivity,*, 2014.

Nikolay Bykovsky et al, EUCAS 2017

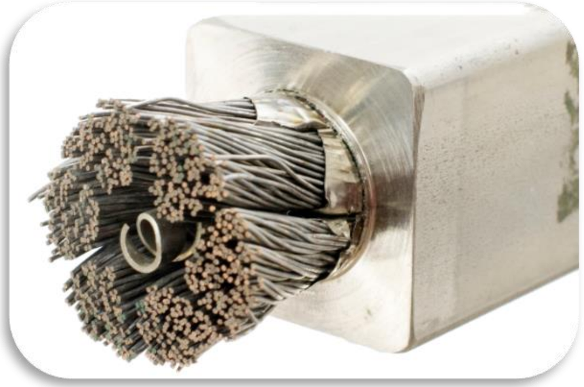


CORC cable.
https://www.advancedconductor.com

Courtesy of M. Takayasu, MIT-

Z. Hartwig et al, *SUST*, 2020

LTS Cable-in-Conduit



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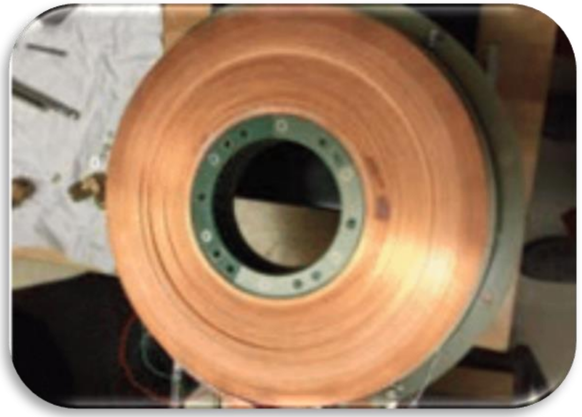
HTS provides superior performance for fusion, but brings new challenges

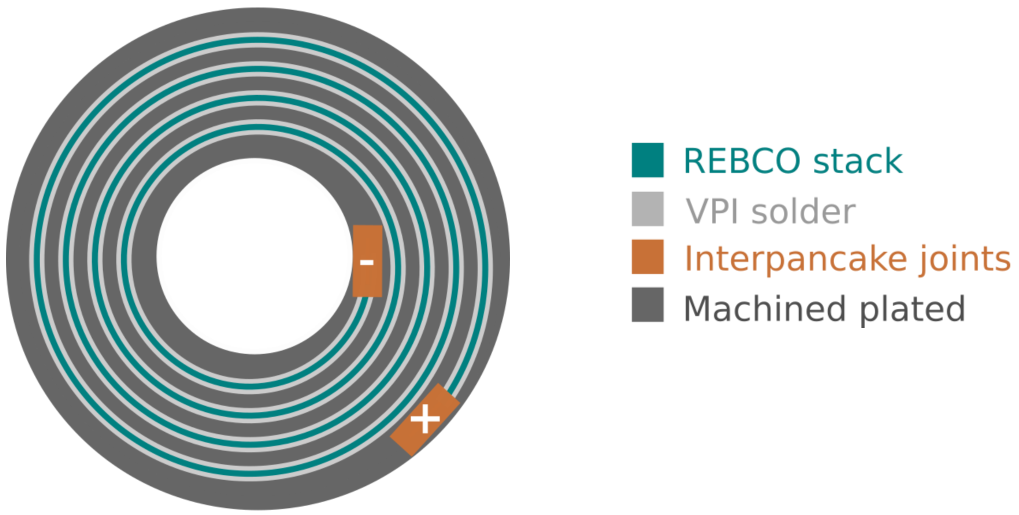
New Technology (HTS) → New Scientific Challenges → De-risking: Testing + Modeling

Innovative non-insulated HTS “pancake” magnet designs

Courtesy of MIT-PSFC, CFS



Courtesy of MIT-PSFC, CFS

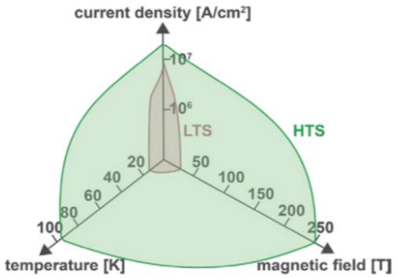


Z. Hartwig, MT27, 2021

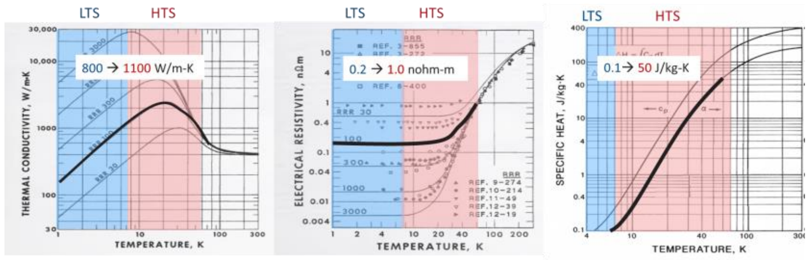
HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → **New Scientific Challenges** → **De-risking: Testing + Modeling**

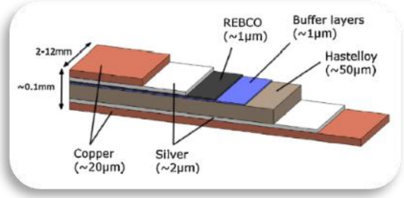
High Current Density + Magnetic Field



Higher operating temperature + larger margin



New manufacturing form factors



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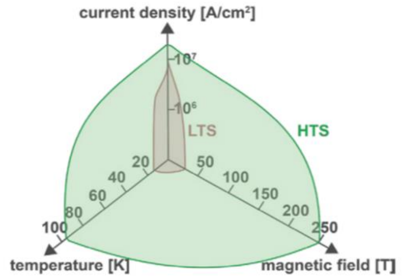
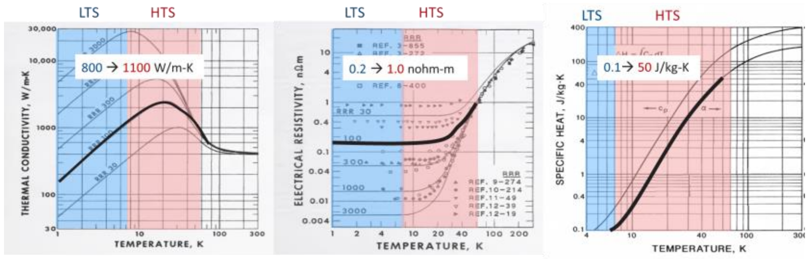
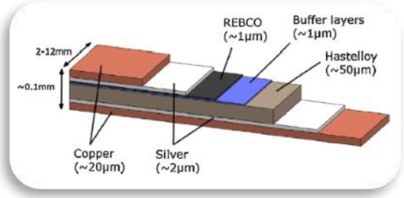
High Current Density + Magnetic Field	Higher operating temperature + larger margin	New manufacturing form factors







High Stresses/Strains (Lorentz Loads)

(Insulated) Slower Quench Propagation

(Non-Insulated) Passive Quench Protection?

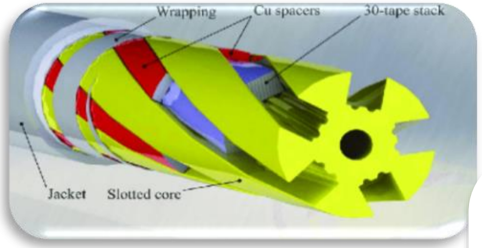
Unknown manufacturing feasibility and scalability

HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → **New Scientific Challenges** → De-risking: Testing + Modeling

Various HTS magnet designs

Courtesy of M. Takayasu, MIT-PSFC



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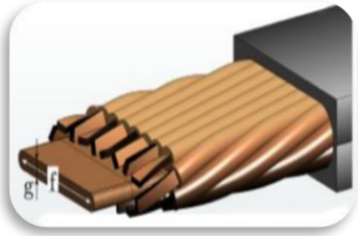
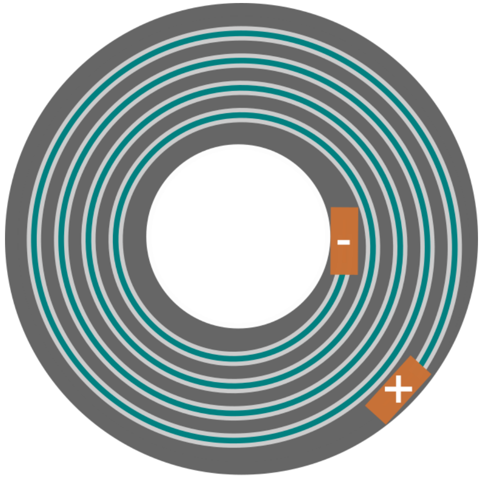
Nikolay Bykovsky et al, EUCAS 2017



CORC cable.
https://www.advancedconductor.com

Z. Hartwig et al, *SUST*, 2020



Z. Hartwig, MT27, 2021

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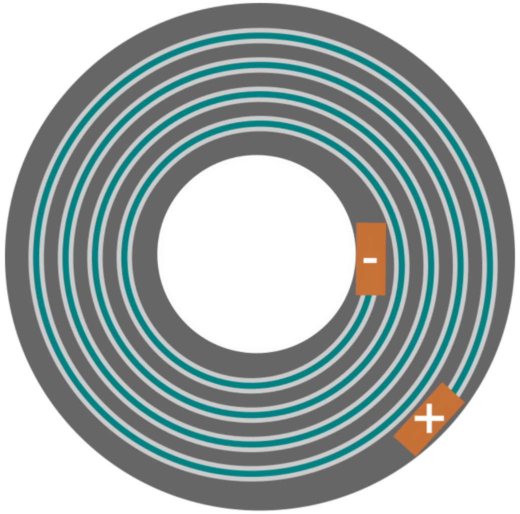
VIPER HTS CABLE

Developed for *multiple* SPARC applications:

- High current feeder cables
- AC magnets: SPARC CS, PF (w/ modifications)

Z. Hartwig et al, *SUST*, 2020

No Insulation No Twist (NINT) Coils



Z. Hartwig, MT27, 2021

Developed for a *specific* SPARC application:

- DC magnet: SPARC TF magnet -> The TFMC

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Developed for *multiple* SPARC applications:

- High current feeder cables
- AC magnets: SPARC CS, PF (w/ modifications)
- DC magnets: back-up for SPARC TF

VIPER HTS CABLE

Z. Hartwig et al, *SUST*, 2020

No Insulation No Twist (NINT) Coils

Z. Hartwig, MT27, 2021

Developed for a *specific* SPARC application:

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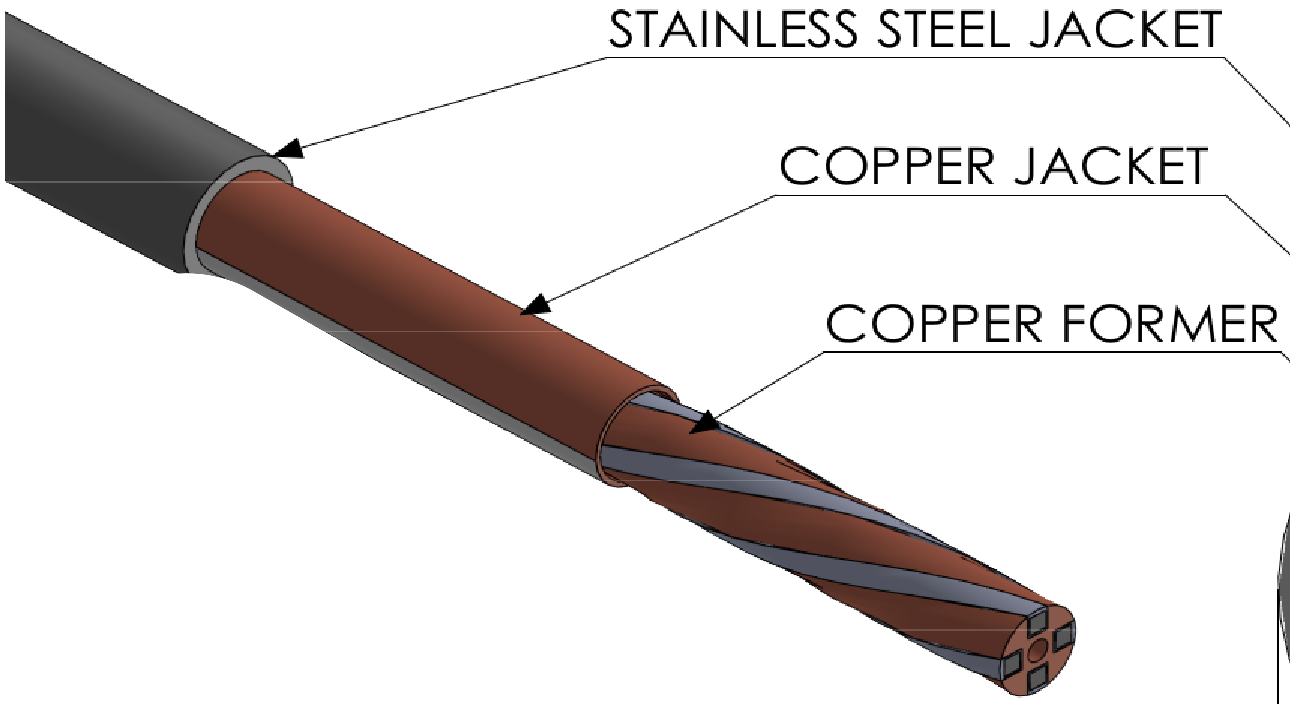
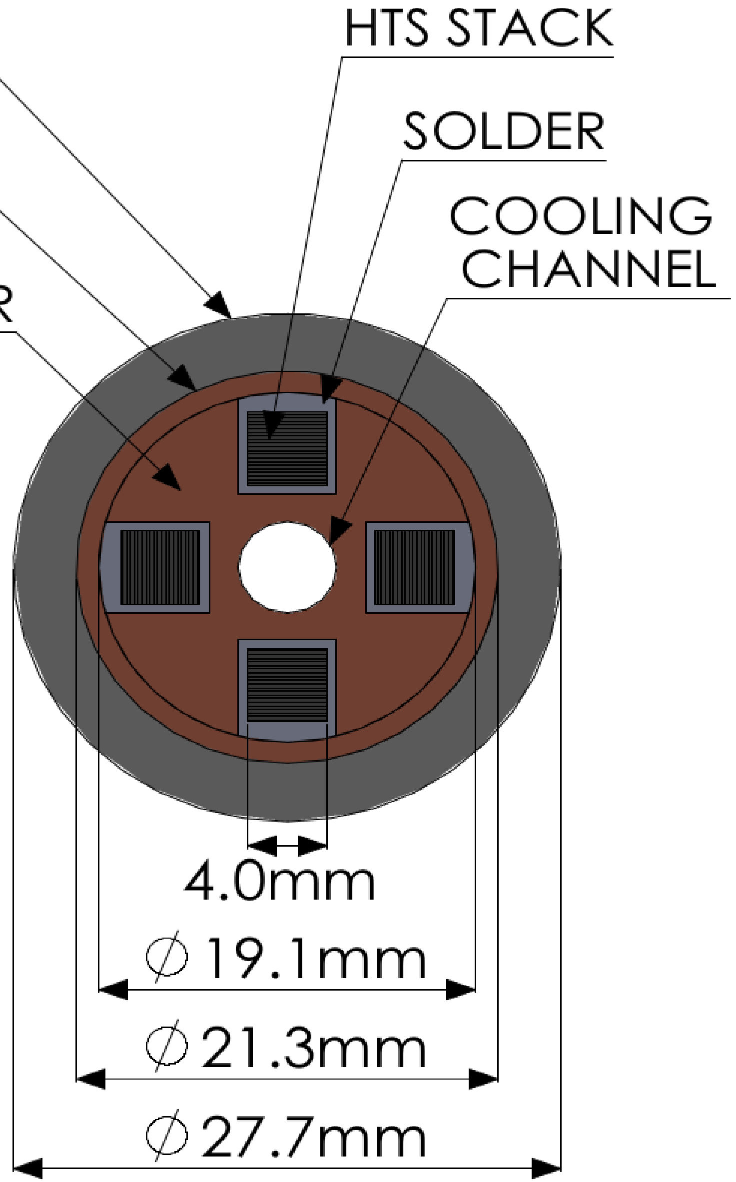
Design overview of the VIPER HTS cable





Based on the TSTC concept originated by Takayasu at MIT, extended by Celentano at ENEA

M. Takayasu *et al.*, IEEE Trans. Appl. Supercond. **21** (2011) 2340.
G. Celantano *et al.*, IEEE Trans. Appl. Supercond. **24** (2014).

Z. Hartwig et al, *SUST*, 2020

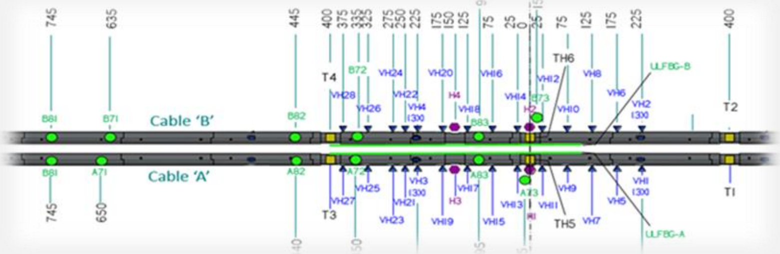
Outline

HTS provides superior performance for fusion, but brings new challenges

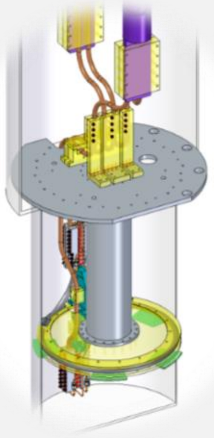
New Technology (HTS) → New Scientific Challenges → **De-risking: Testing + Modeling**

Test prototype in operating conditions under expected Lorentz loads, fatigue cyclic loads, and strain

Quench test prototype in operating conditions to determine cryostability and feasibility tests of novel quench detection systems.



Fabricate prototypes then perform bending tests, scalability tests, etc.



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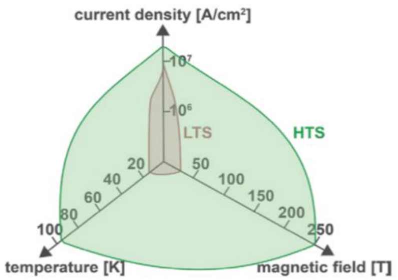

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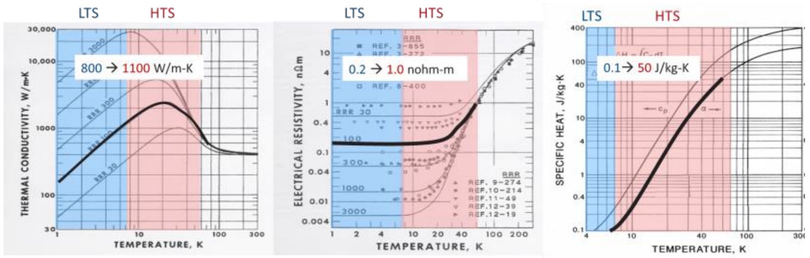
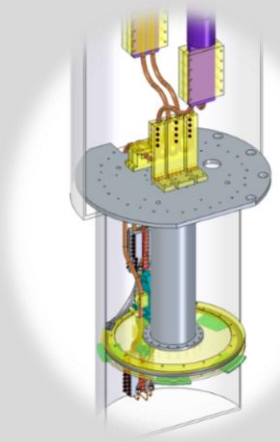


Slower Quench Propagation

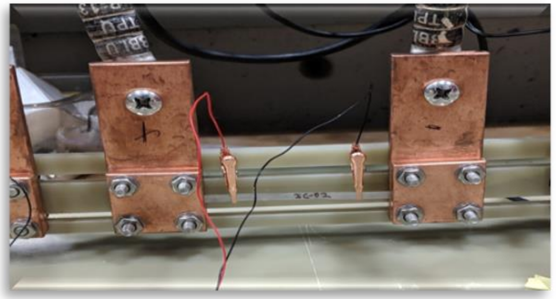
Fabricate prototypes then perform bending tests, scalability tests, etc.



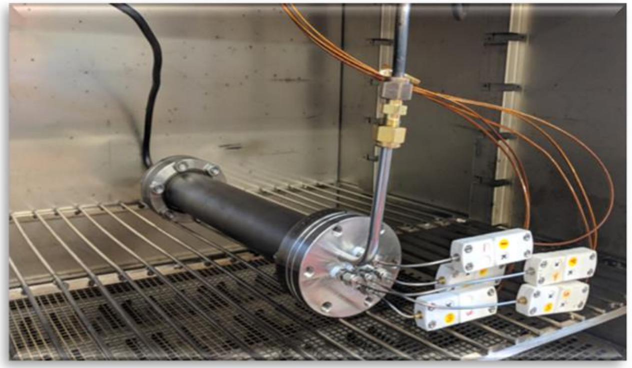
Fabrication at increasing scale built confidence

Small-scale R&D was done to verify key elements of VIPER design

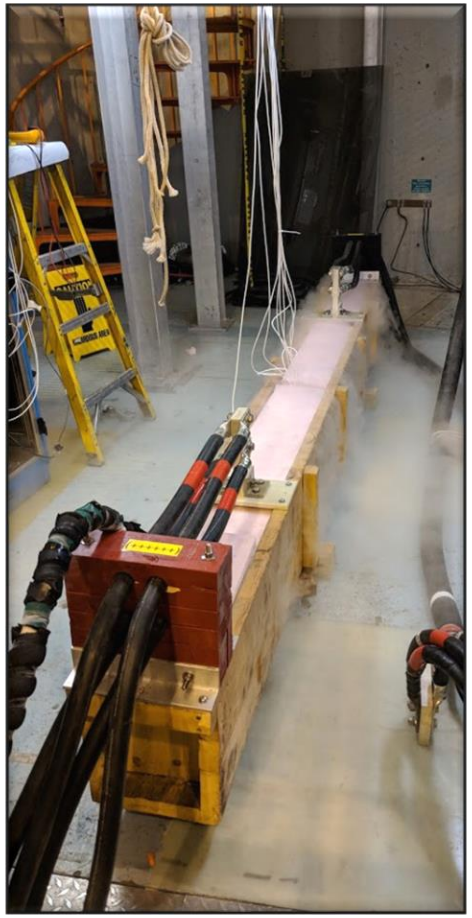
Tape level → Cable level



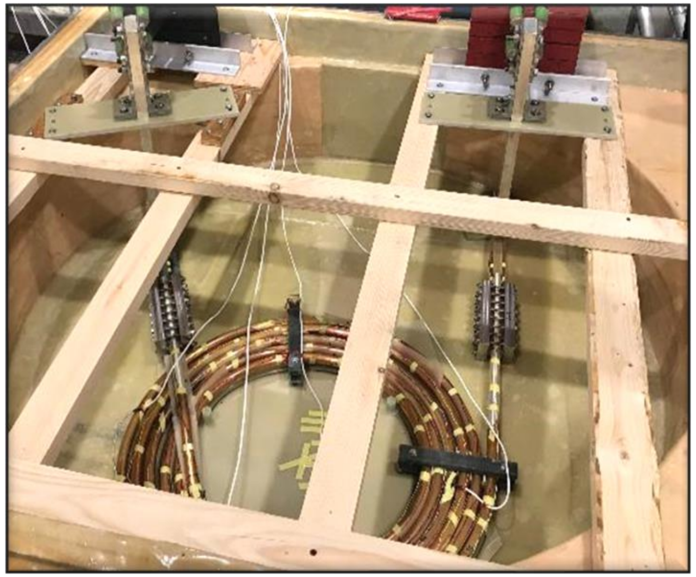
HTS tape Ic characterization test setup



HTS tape oven test rig



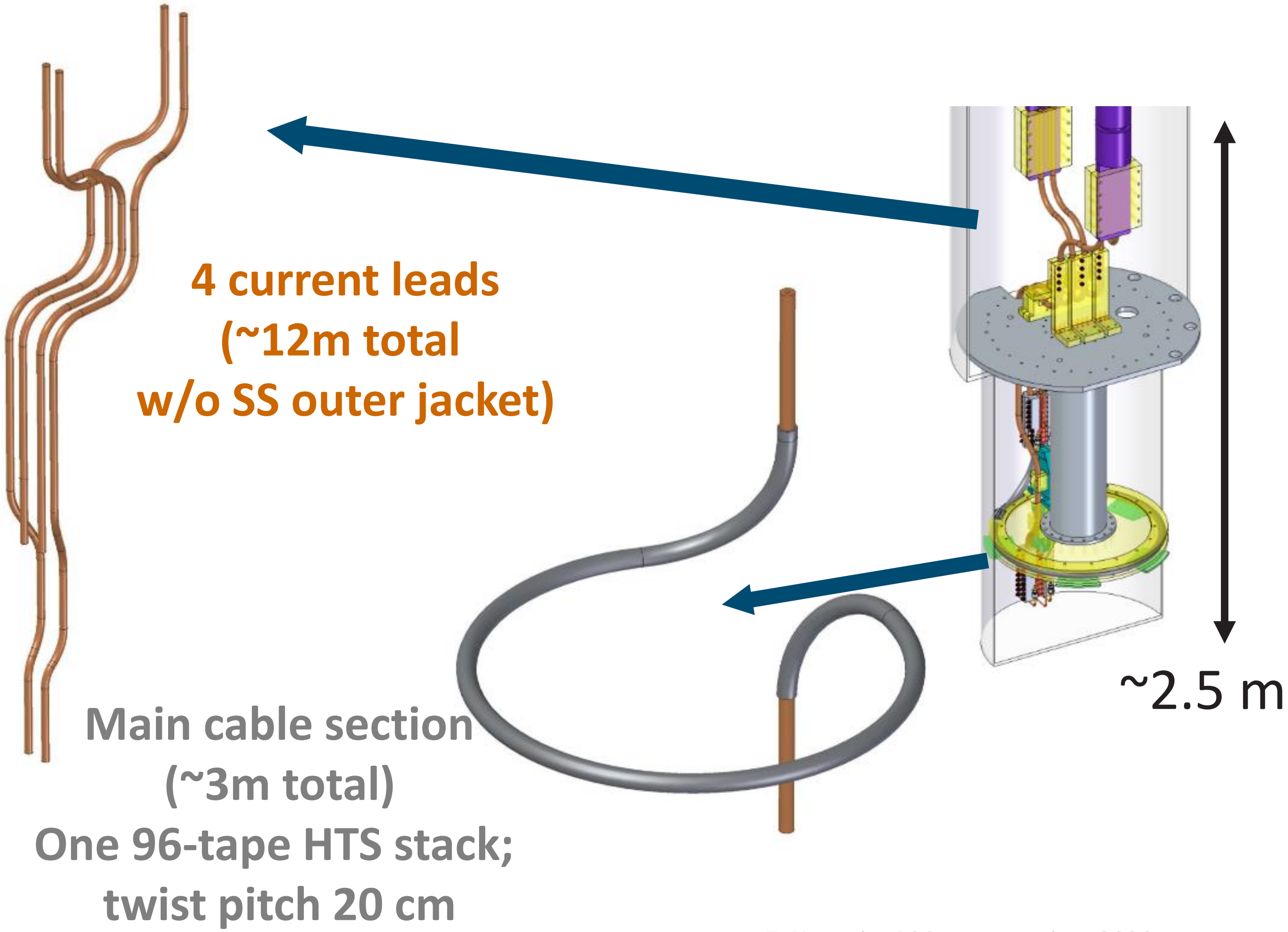
Cable testing in LN2 bath + Testing lead design



12 meter cable tested in LN2 at MIT

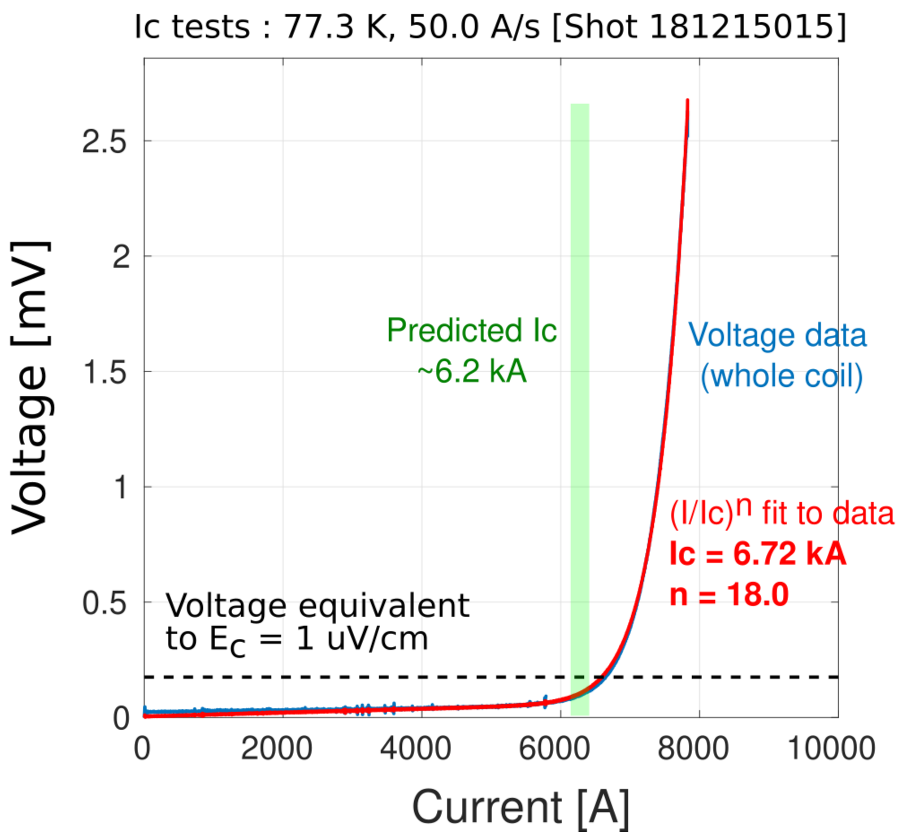
VIPER fabrication proved feasible through prototyping

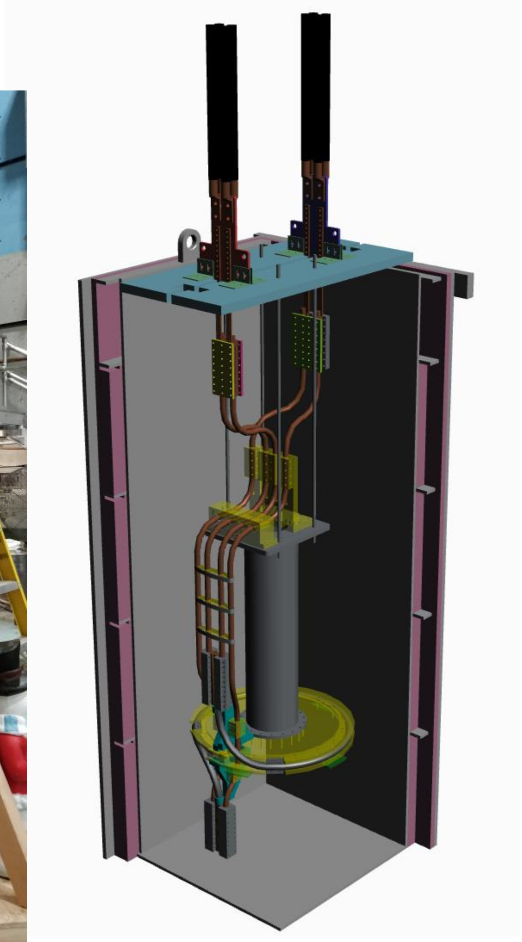
- Complex 3-D bend tests (20 cm bend radius) tested at LN2
  - 5-cable assembly (1 main cable + 4 current leads)
  - intended for in-field testing in large-bore magnet



VIPER fabrication proved feasible through prototyping

- Complex 3-D bend tests (20 cm bend radius) tested at LN2
  - Measured Ic closely matched our predicted Ic!





Z. Hartwig, ASC presentation, 2020

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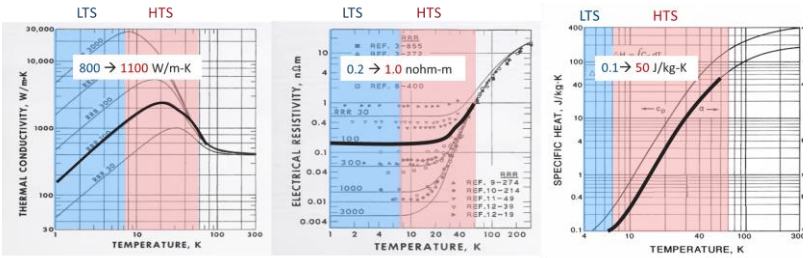

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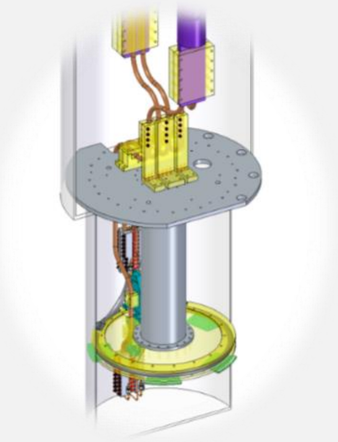
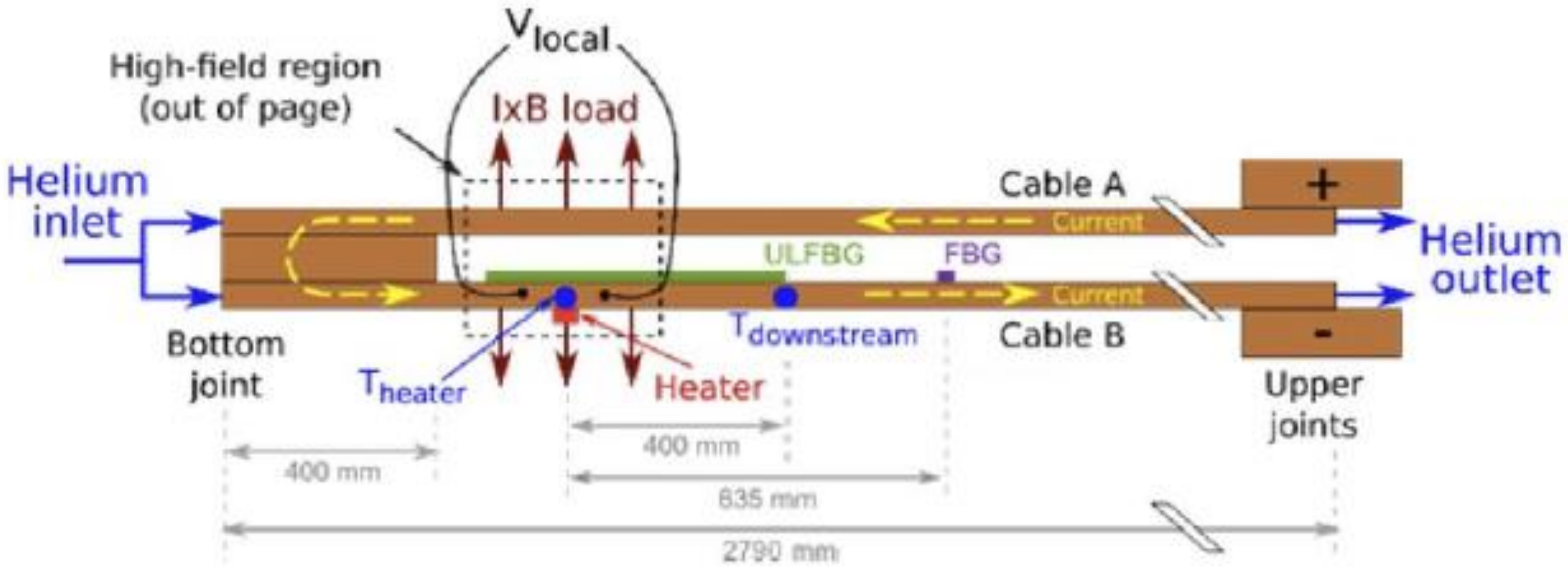


Overview of the VIPER cable tests at SULTAN

Four SULTAN tests (2 identical cables per test) were carried out between Feb 2019 and June 2020

- *Operating Temperatures: 4.5 K - 20 K*
- *Operating Currents : up to 50 kA*
- *Background Magnetic Fields: up to 10.9 T*



Z. Hartwig et al, *SUST*, 2020

Overview of the VIPER cable tests at SULTAN

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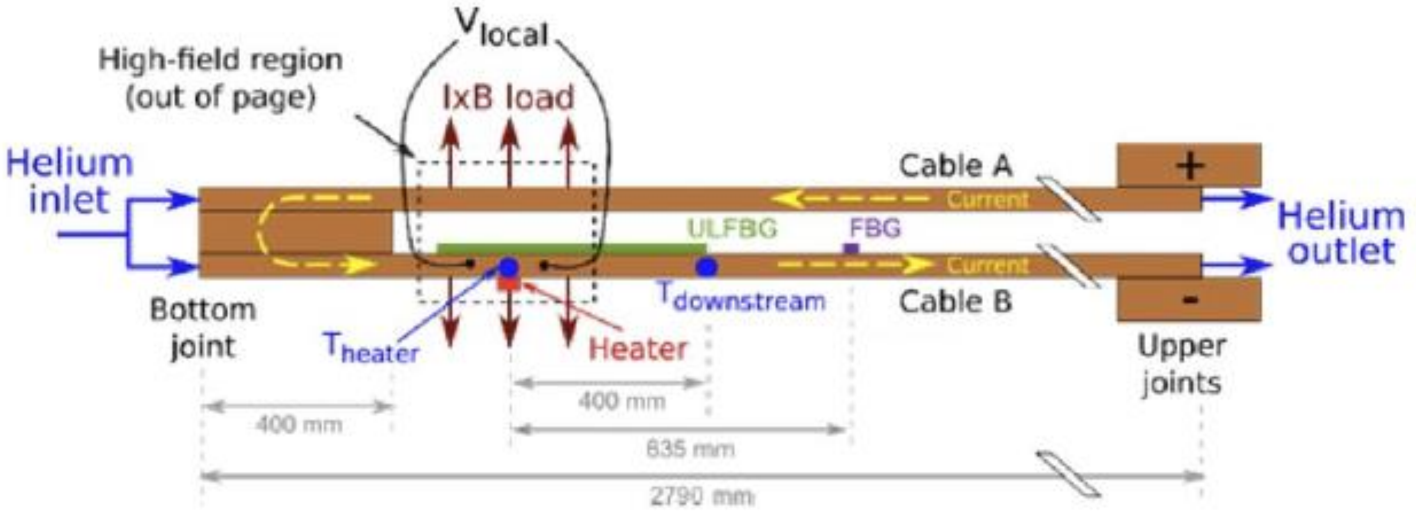
- *Test Alpha*:
- *Test Bravo*:

IxB per HTS stack for loading and cycling

- *Test Charlie*: IxB per HTS stack **PLUS axial strain on HTS**
- *Test Delta*: **Quench tests** and qualification of quench detection techniques



Z. Hartwig et al, *SUST*, 2020

Cable	HTS channels filled with:
Alpha	1 of 4 w/ low Ic HTS
Bravo	1 of 4 w/ high Ic HTS
Charlie	1 of 4 w/ high Ic HTS; 3 w/ dummy
Delta	4 of 4 w/ with low Ic HTS

Overview of the VIPER cable tests at SULTAN

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- *Test Alpha*:
- *Test Bravo*:

} **IxB per HTS stack** for loading and cycling

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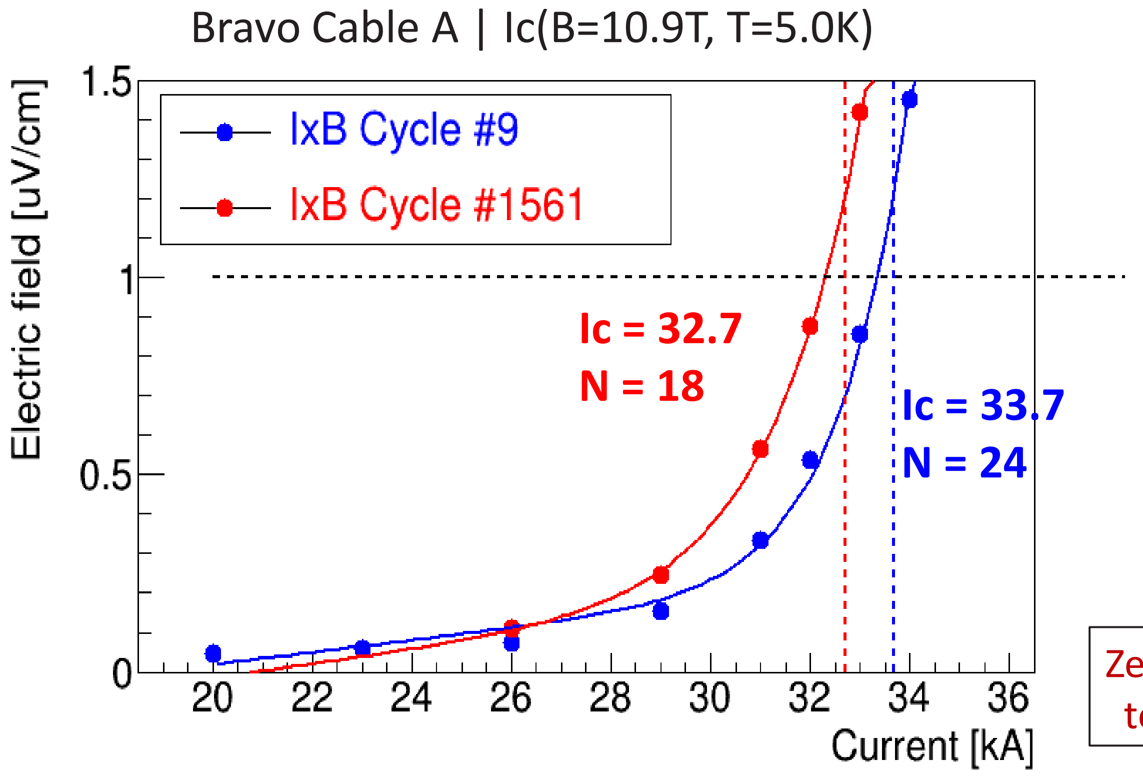
- *Test Delta*: **Quench tests** and qualification of quench detection techniques

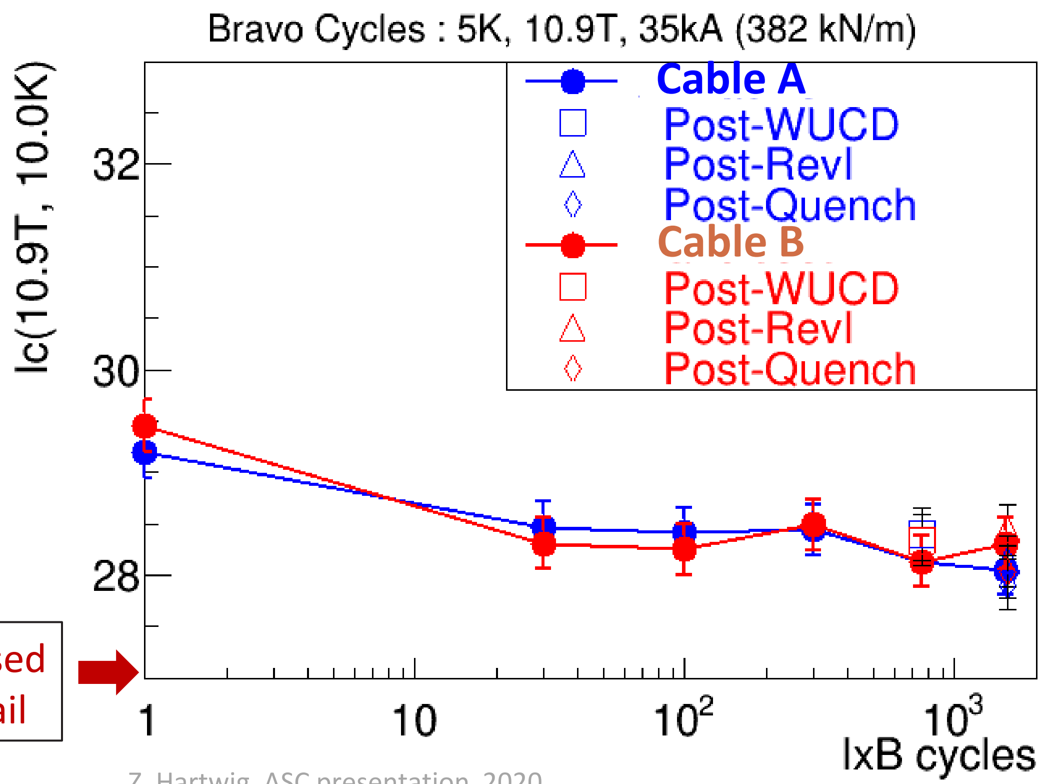
Bravo: Proving minimal degradation with high IXB loading

Minimal degradation under SPARC-relevant IxB per HTS stack for loading and cycling

- Cycling load: **IxB = 382 kN/m** (10.9T x 35.0 kA)
- Total cycles: **1550**
- Total Ic degradation **~3.8 - 4.1%**



Zero suppressed to show detail



Z. Hartwig, ASC presentation, 2020

Charlie: Novel approach for IxB + strain in straight cables

Total external strain applied:

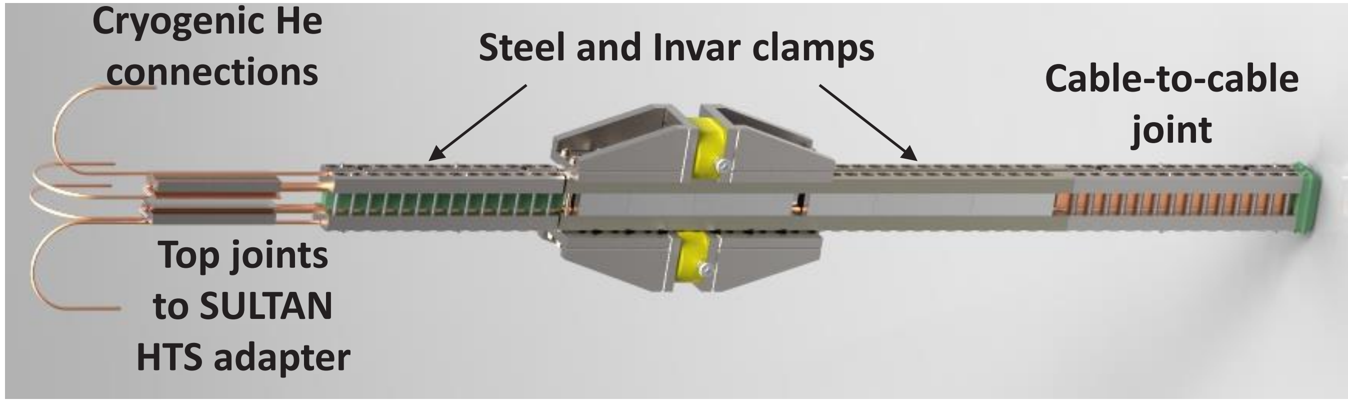
- Cable A = 0.51%, Cable B 0.53% → ~**0.4% HTS strain**

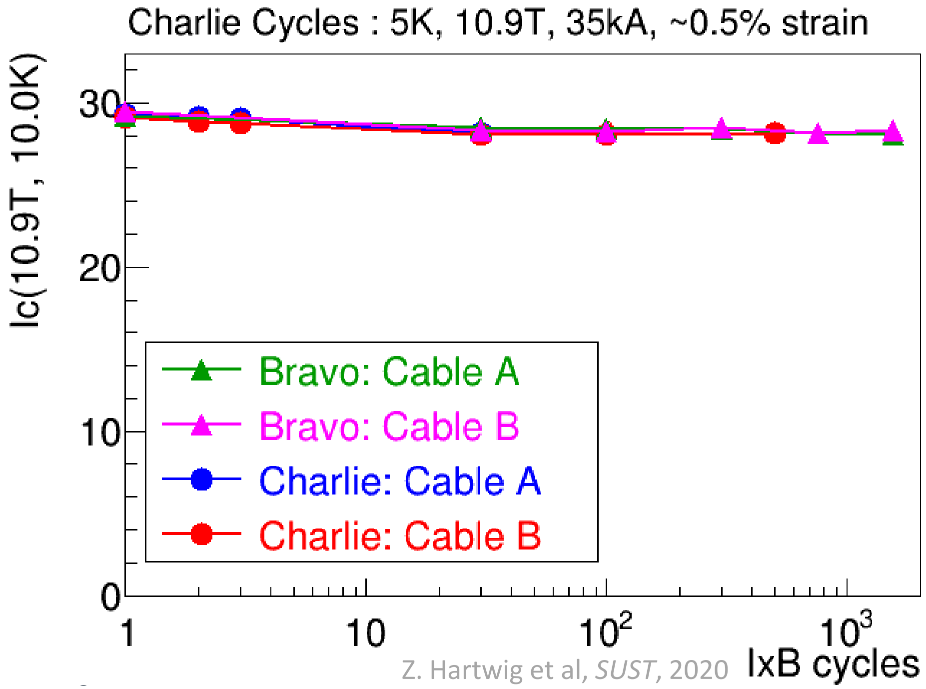
After DC Characterization, IXB and cyclic loading applied:

- Cycling load: **IxB = 382 kN/m** (10.9T x 35.0 kA)
- Total cycles: 500
- ~**3.4 % Ic degradation**

Observations:

- Charlie cables showed similar Ic degradation to Bravo cables
- SEM imaging showed no significant difference in HTS-solder interface between unloaded and IxB+strained regions
- Best joint resistance of 1.9 nΩ (self-field, 5 K)





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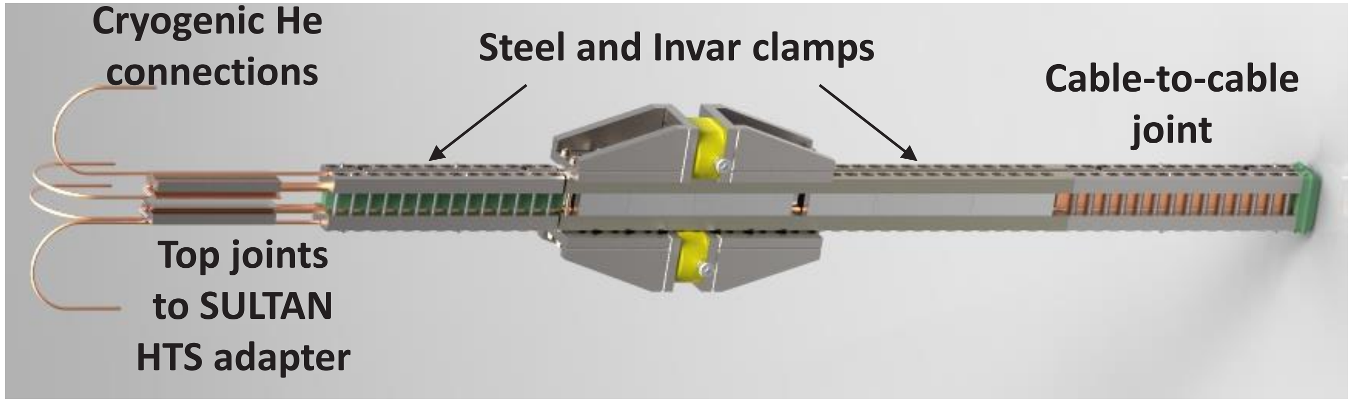

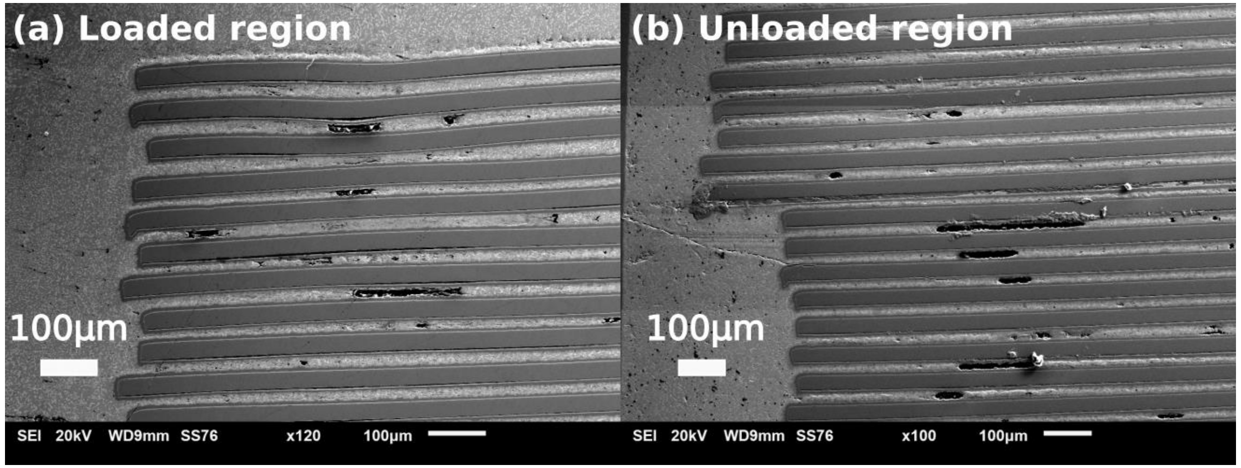

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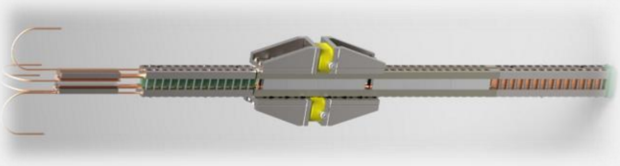
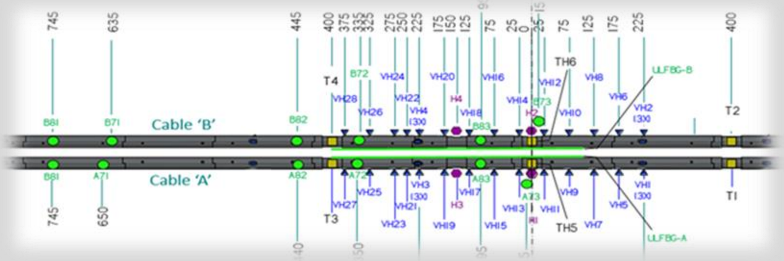
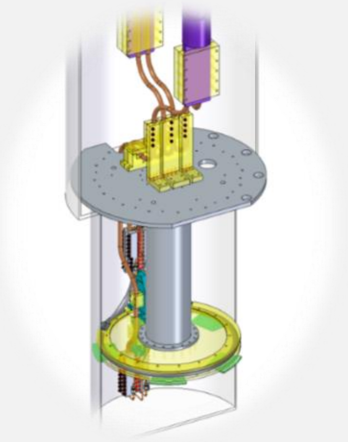


Quench test prototype in operating conditions to determine cryostability and feasibility tests of novel quench detection systems.

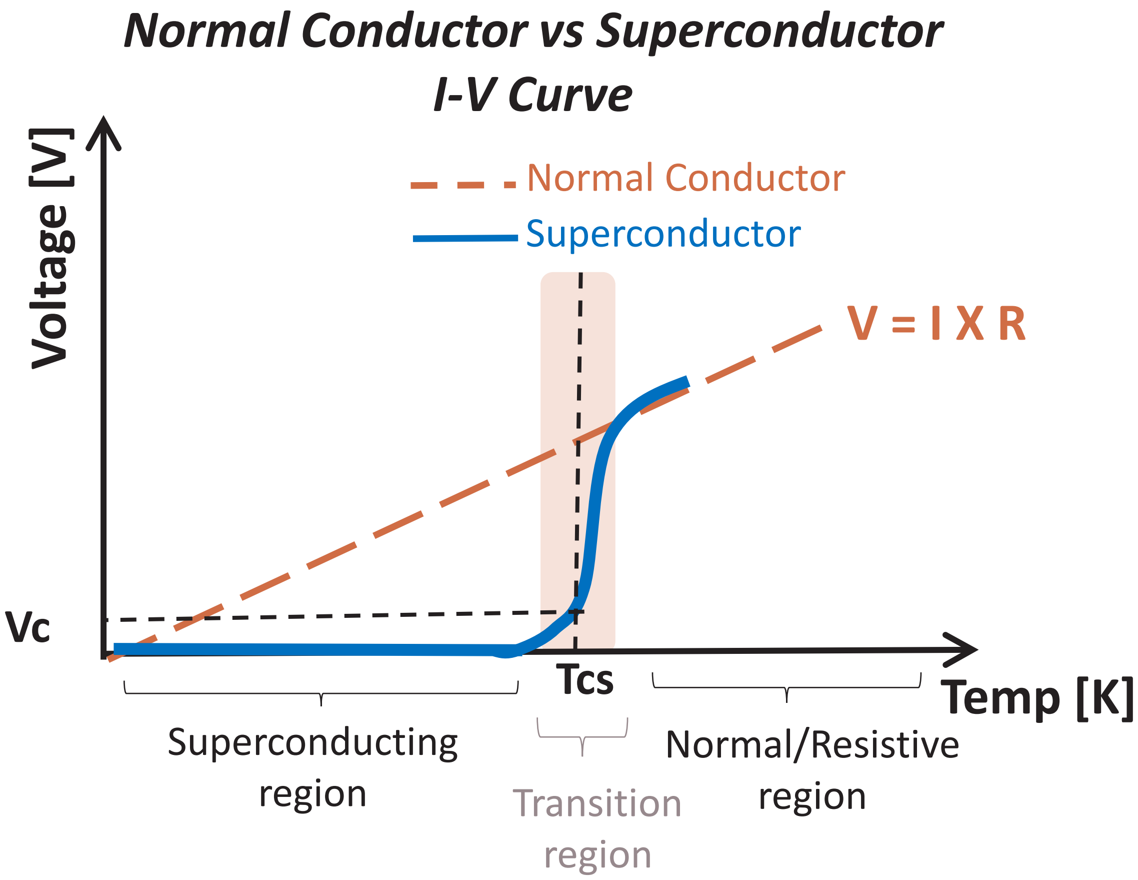


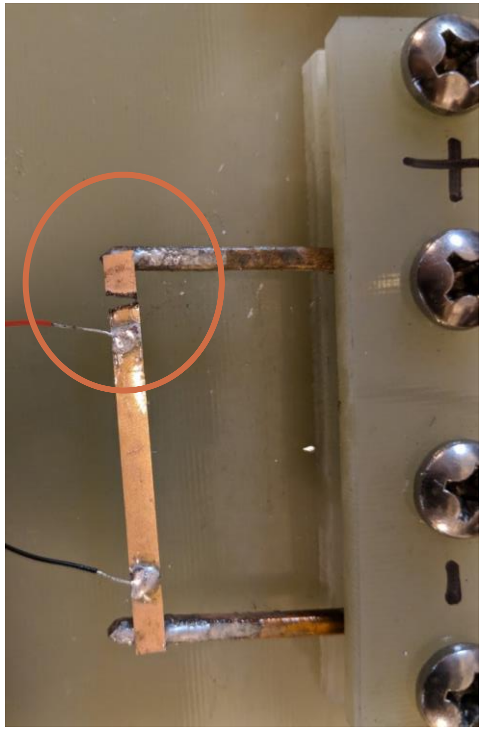
Fabricate prototypes then perform bending tests, scalability tests, etc.



What is quench?

Quench – a sudden loss of superconductivity which may result in a thermal runaway event





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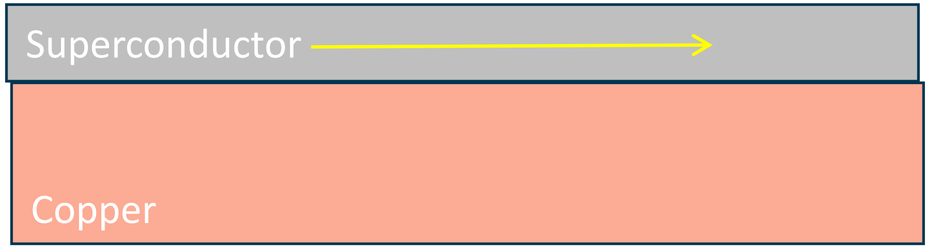

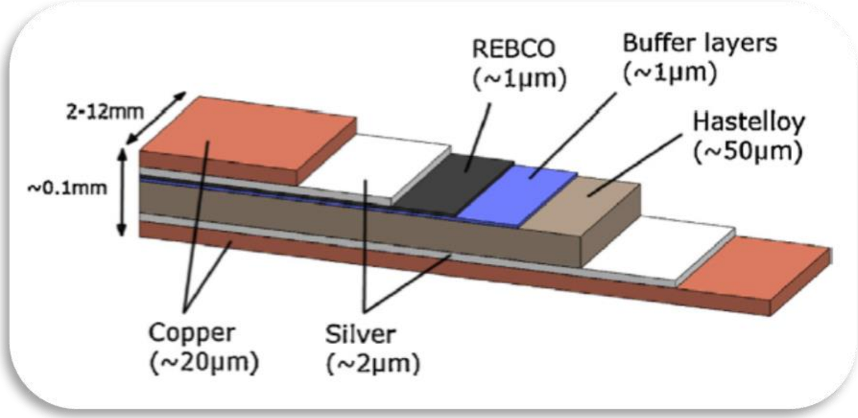

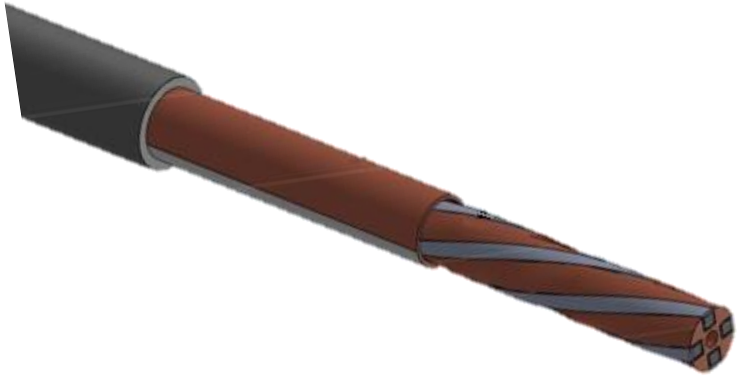

R. G. Sharma, Superconductivity : basics and applications to magnets., vol. 214, Cham: Springer, 2015.

Courtesy of M. Takayasu, MIT-PSFC

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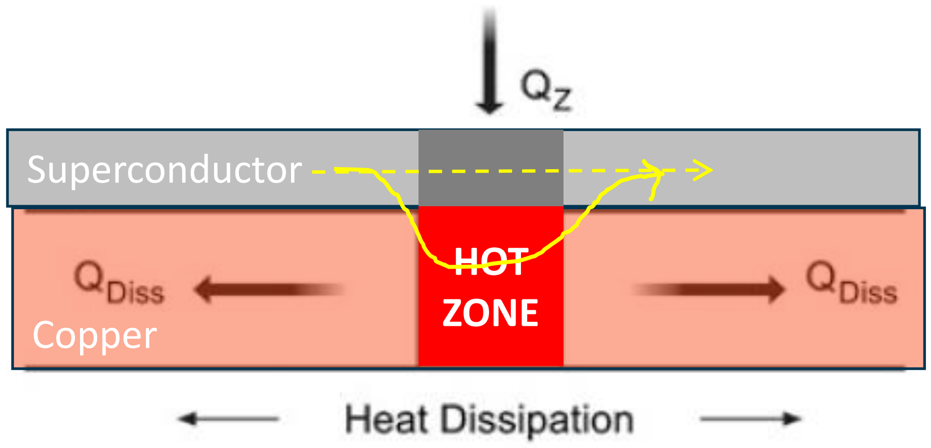

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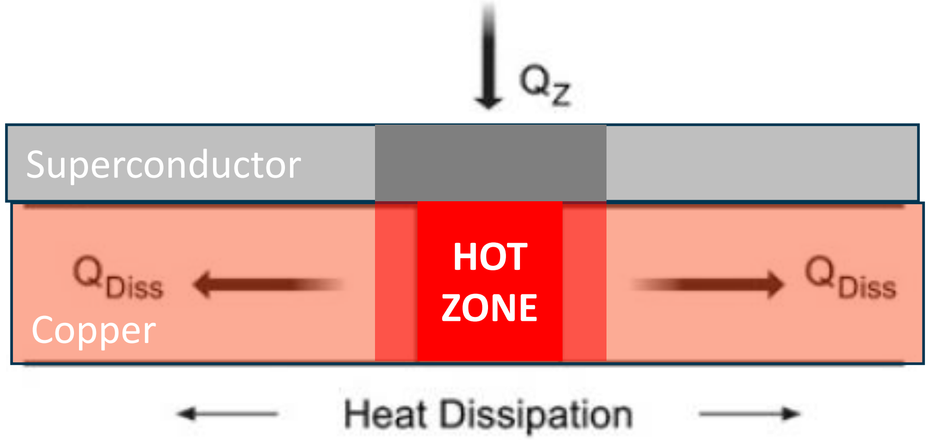

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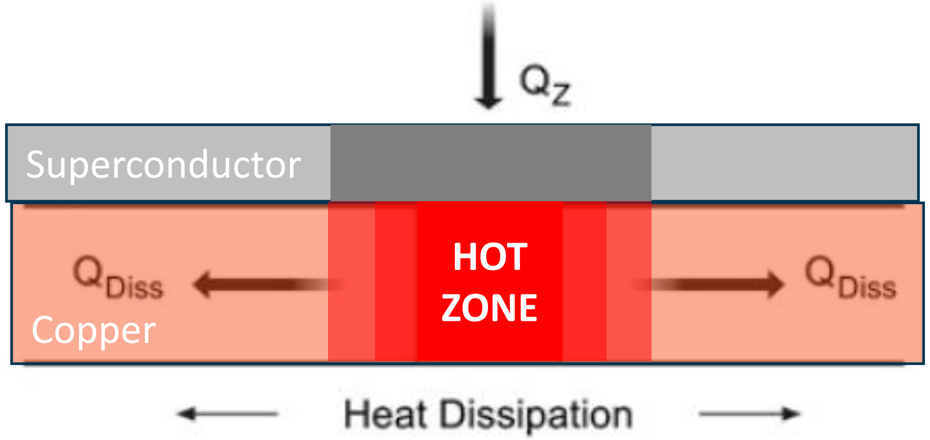

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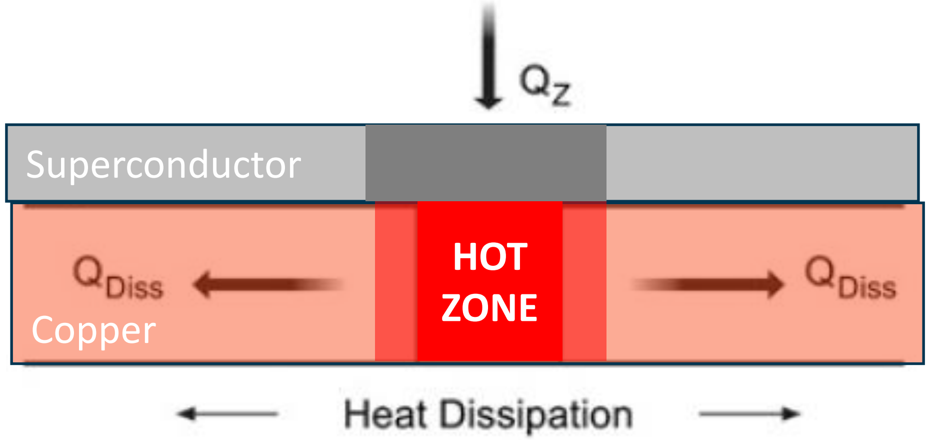

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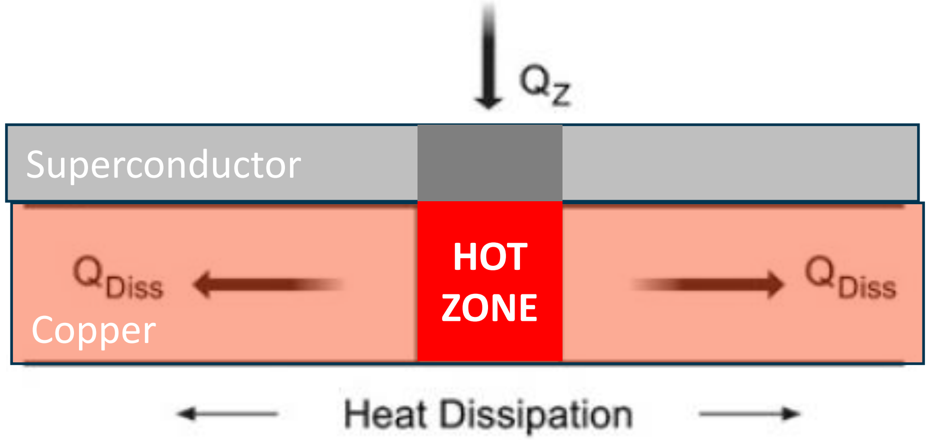

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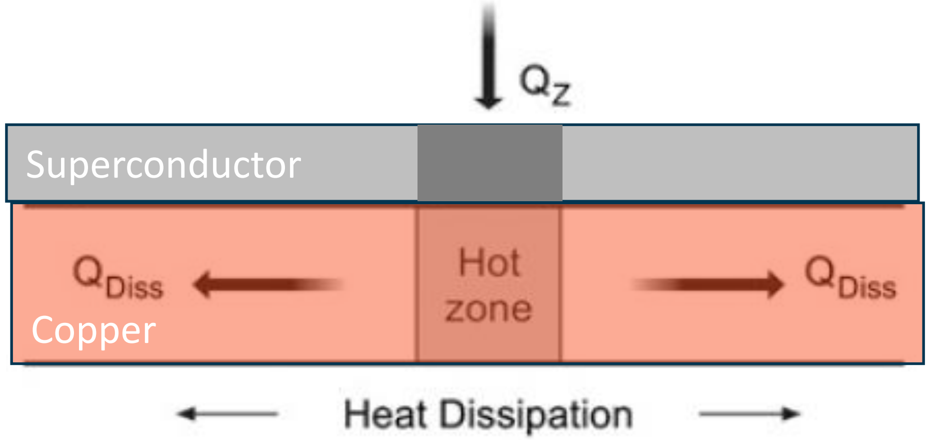

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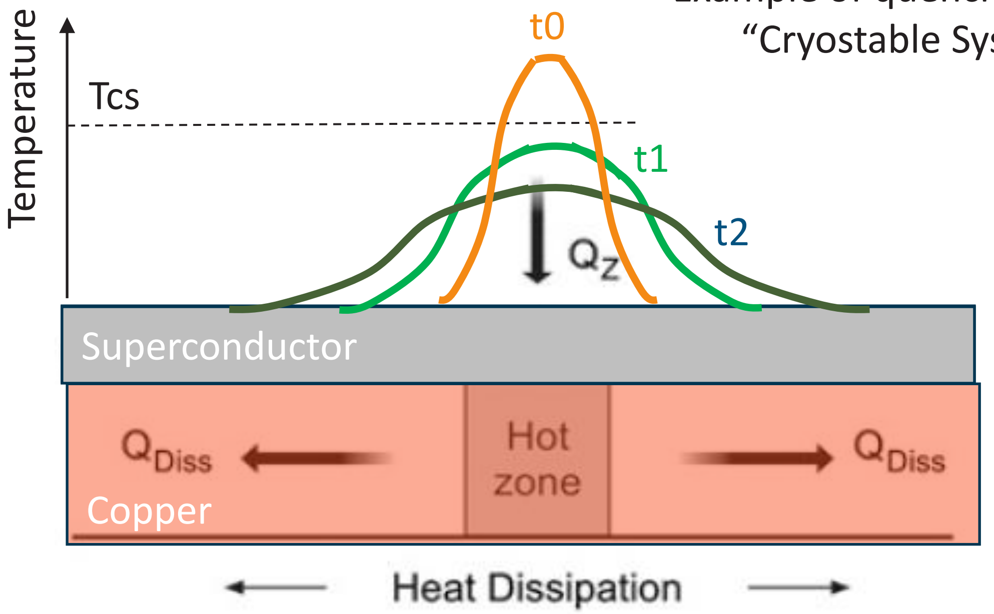
Example of quench recovery
"Cryostable System"



Heat Balance Equation (1D)

$$\frac{d}{dx}\left(k(T)\frac{dT}{dx}\right) + \rho(T) * J(T)^2 + Q_{in} - \rho c_p(T) * \frac{dT}{dt} - Q_{out} = 0$$

- Heat conduction
- Joule Heating
- Externally applied heat into system
- Heat stored
- Additional cooling

$J = current\ density\ \left[\frac{A}{m^2}\right]$

$\rho = resistivity\ [\Omega * m]$

$k = thermal\ conductivity\ \left[\frac{W}{m * K}\right]$

$C = heat\ capacity\ \left[\frac{J}{K}\right]$

$T = temperature\ [K]$

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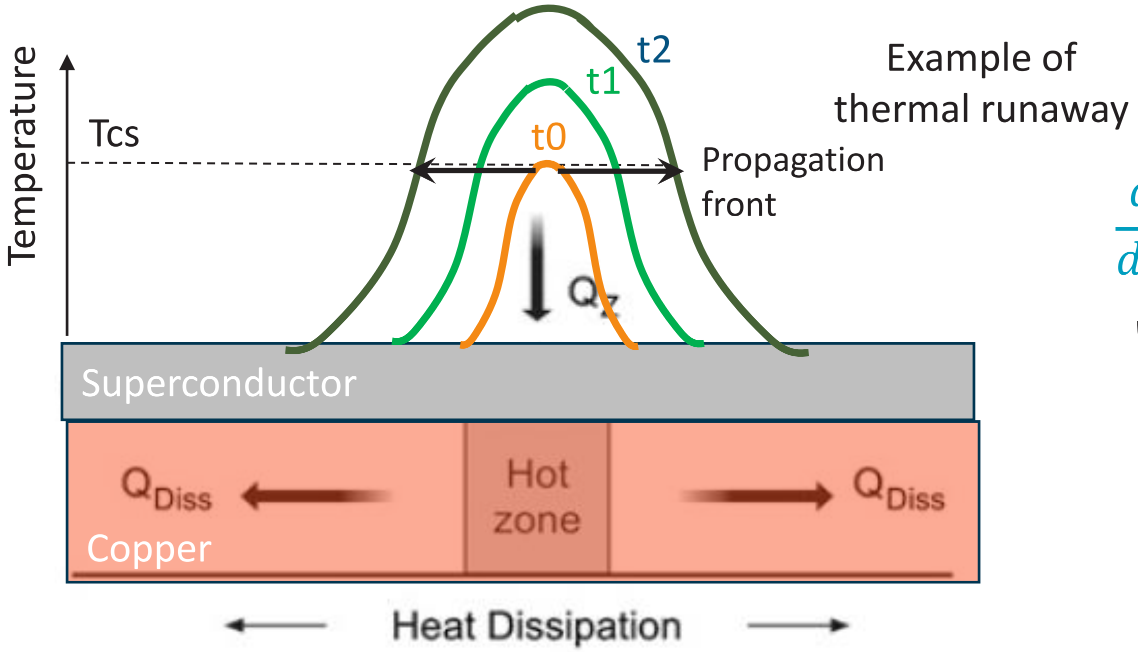

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Heat conduction | **Joule Heating** | **Externally applied heat into system** | Heat stored | Additional cooling

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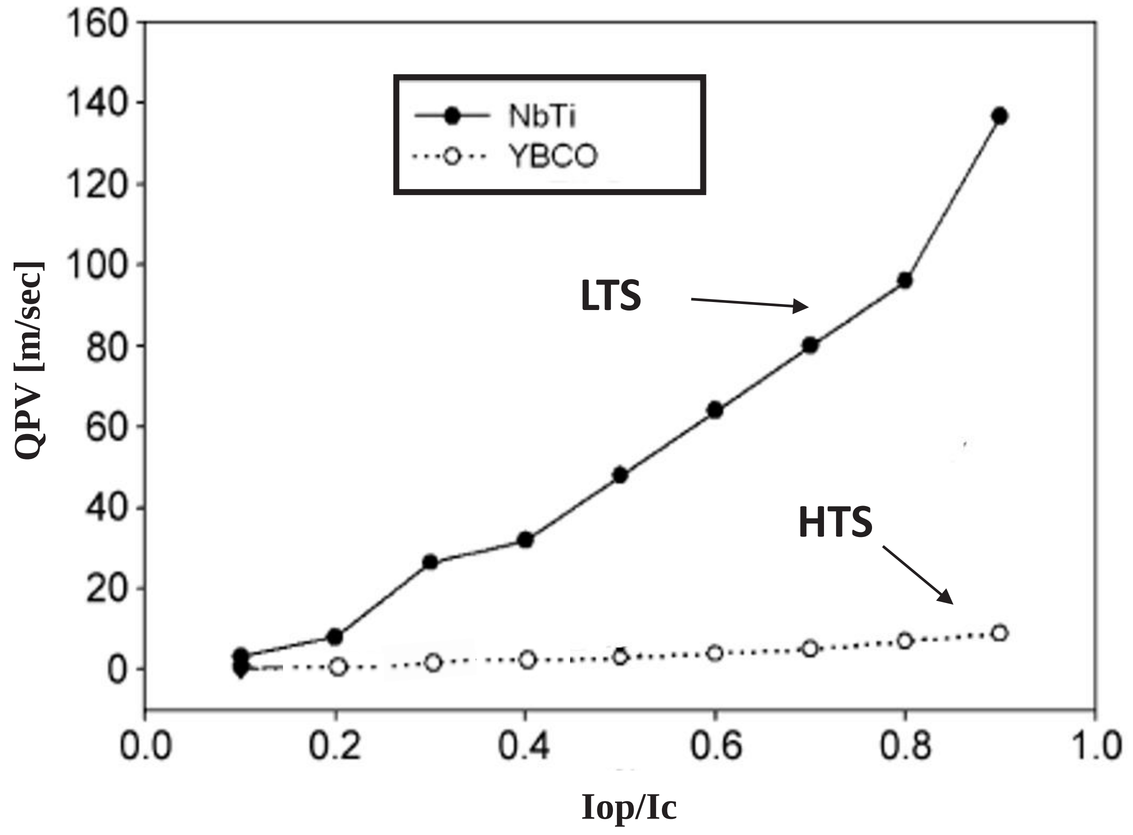
Challenge for HTS: Quench Propagation Velocity

- HTS *tape-level* studies show that Quench Propagation Velocity (QPV) can be 2-3 orders of magnitude slower than LTS
- Slow QPV → Serious Quench Detection Challenge!

QPV vs. Normalized Operating Current

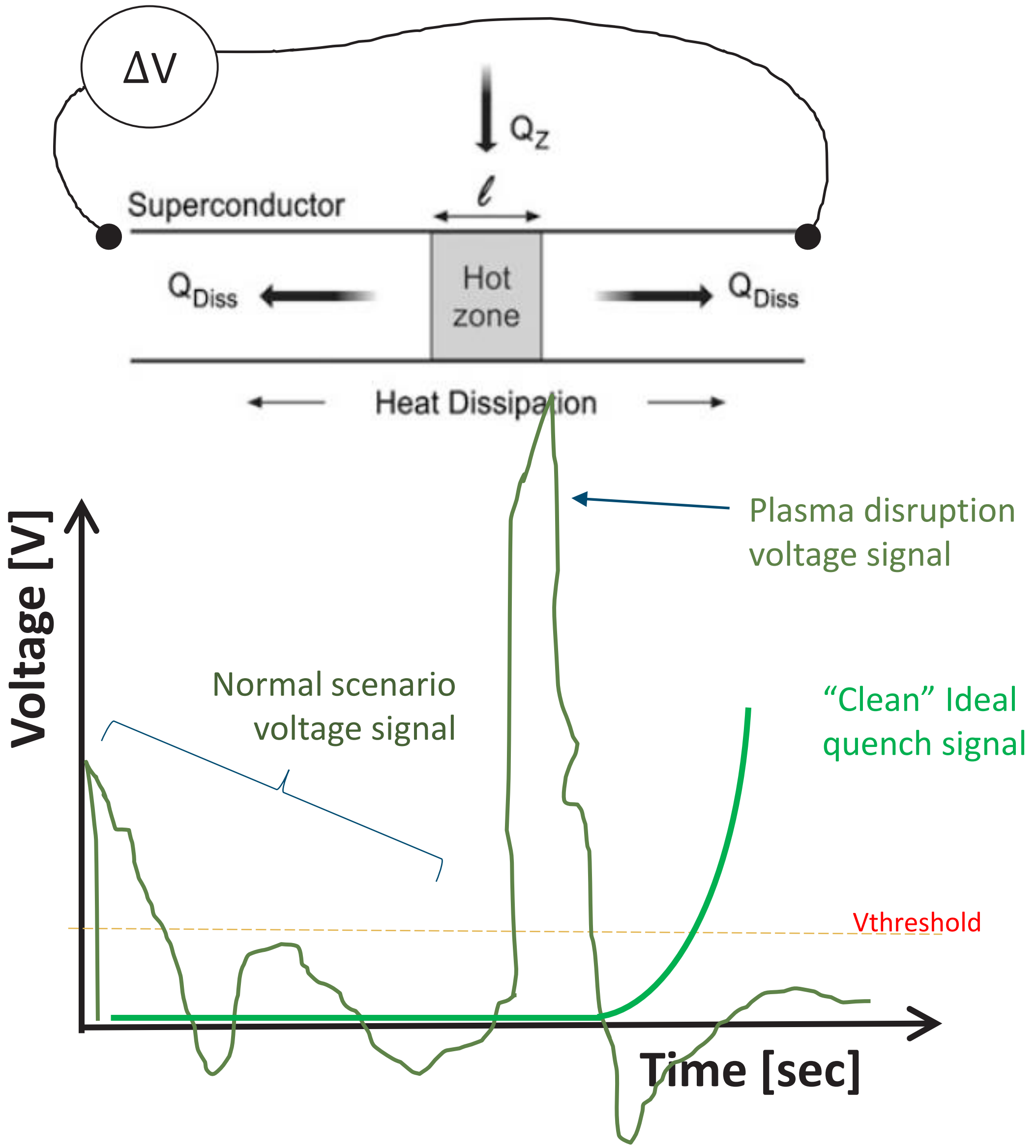


Wei Pi Yinshun Wang Lei Chen Chengrong Li, "Numerical Study of Current Distribution and Stability of LTS/HTS Hybrid Superconductor", IEEE Trans. Appl. Supercond. volume 20 issue 3 (2010)

Alternative quench detection methods worth considering!

Conventional: Voltage-based method

- Electromagnetically induced signal → False positive filtering will be challenging

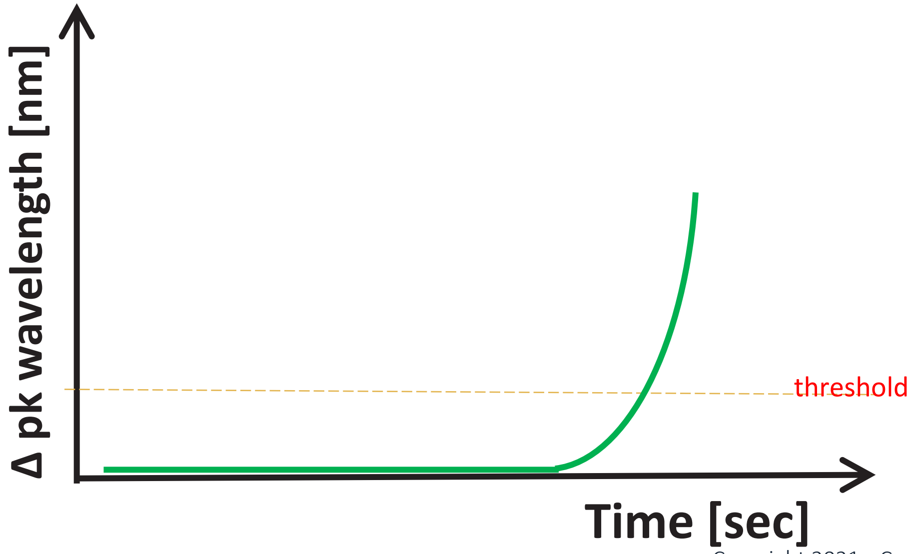


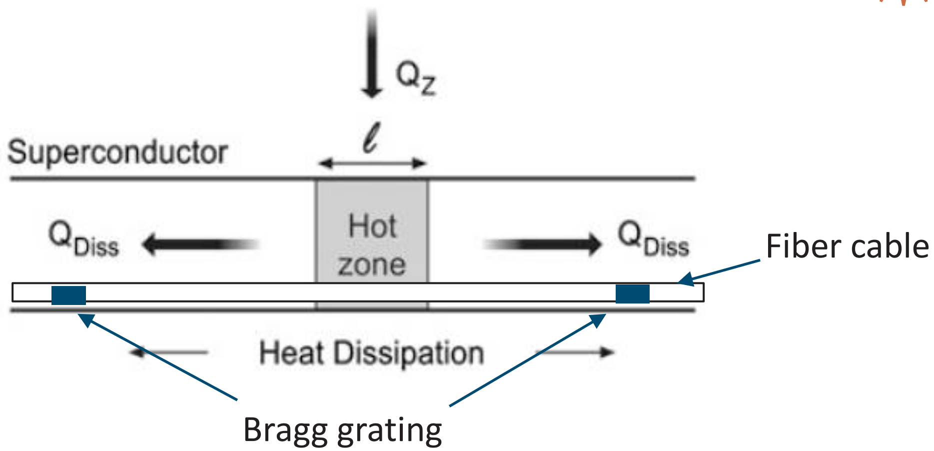
Alternative quench detection methods worth considering!

Alternative: Temperature-based method

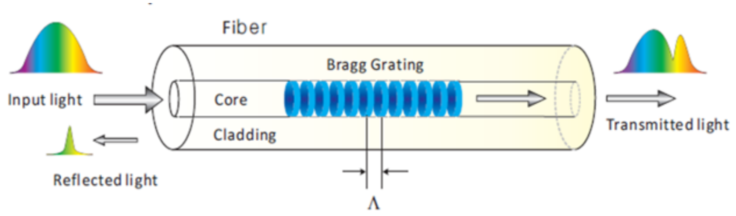
- Not a lot of large-scale magnet testing with fiber
- Fibers are fragile

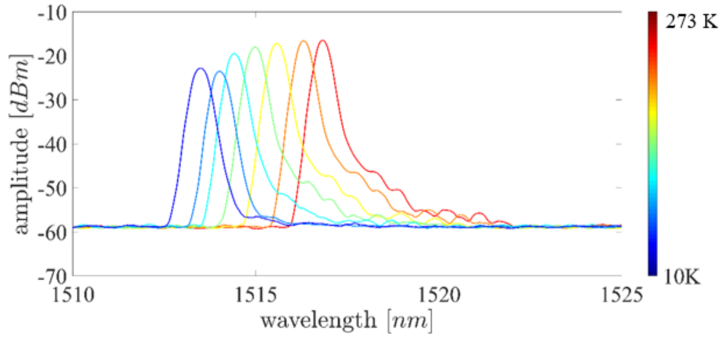
New VIPER cable design and testing opportunity can answer these questions!





Working principle of fiber Bragg grating technology

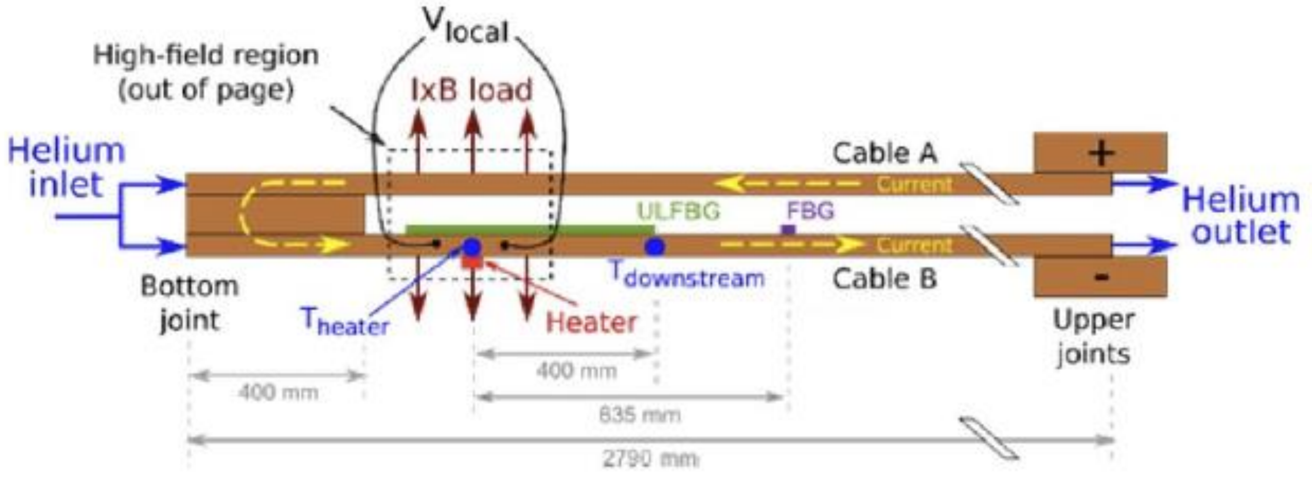


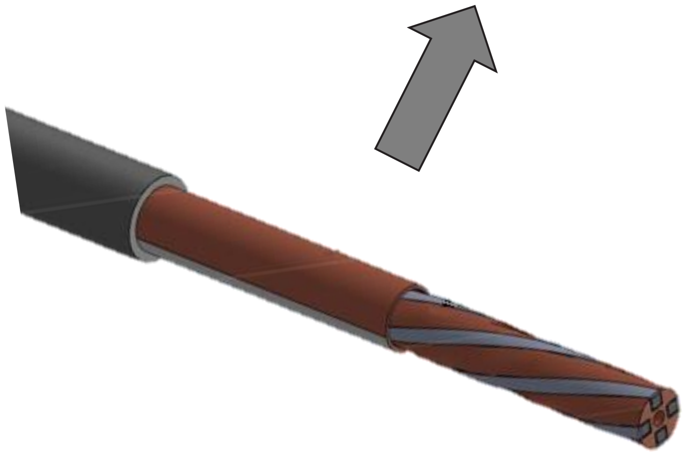


Delta: High-fidelity quench test and fiber optic validation

Instrumentation suite installed to measure and induce a quench:

- Resistive surface heaters installed on copper jacket to induce a quench
- Voltage taps were installed to measure quench propagation velocity
- Cernox sensors installed along cable to measure temperature propagation and compare to fiber measurements
- Two different fiber technologies were integrated into the copper former
  - Fiber Bragg Grating (FBG) from CERN
  - Ultra-Long FBG (ULFBG) from RRI





E. Salazar et al, submitted to SUST, 2020

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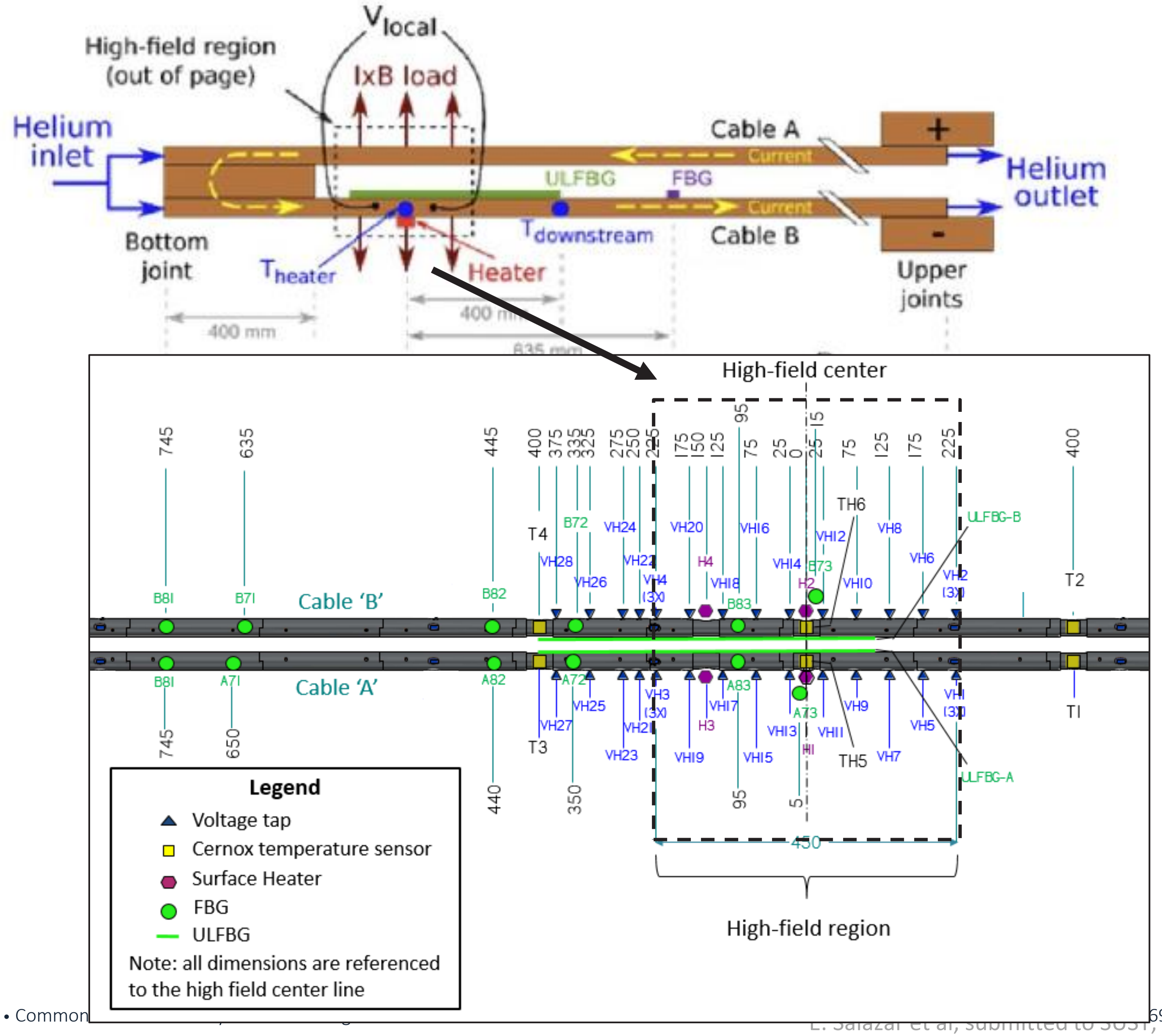

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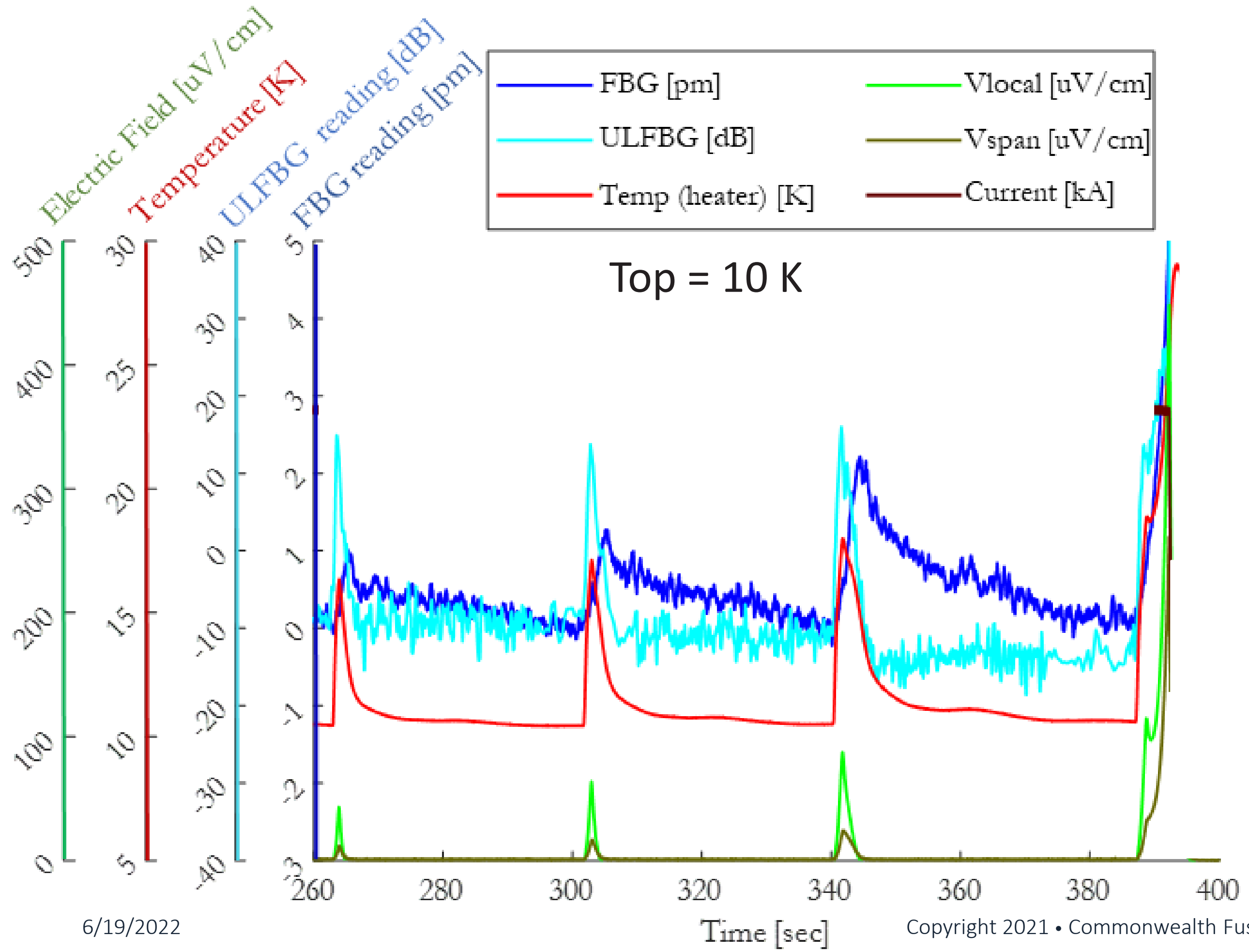
Delta: Both FBG and ULFBG fibers rapidly detect quench initiation

- Both fibers able to detect temperature deviation as small as 2-3 K
- Fiber signal response either before or at similar time as voltage measurement



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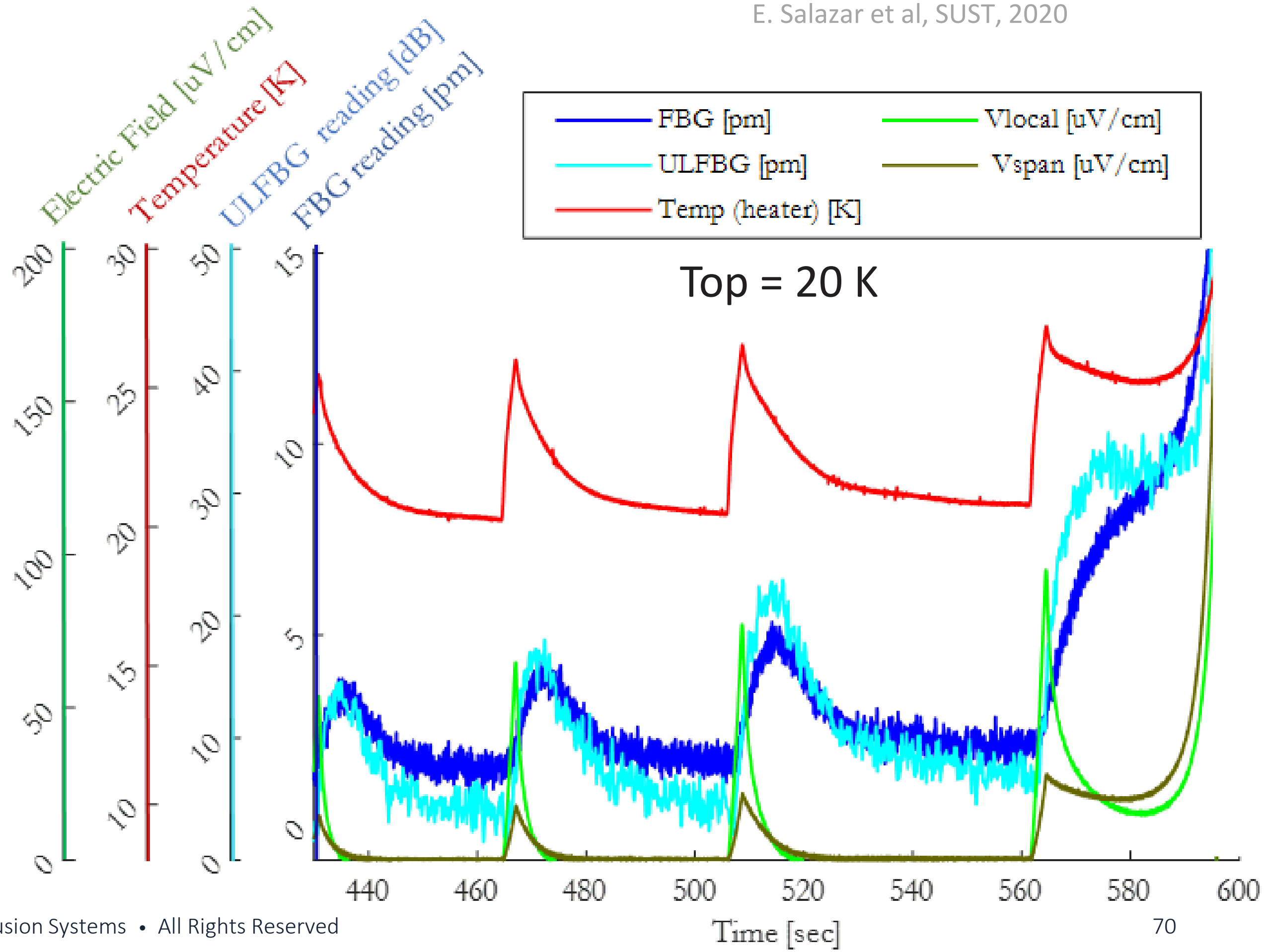

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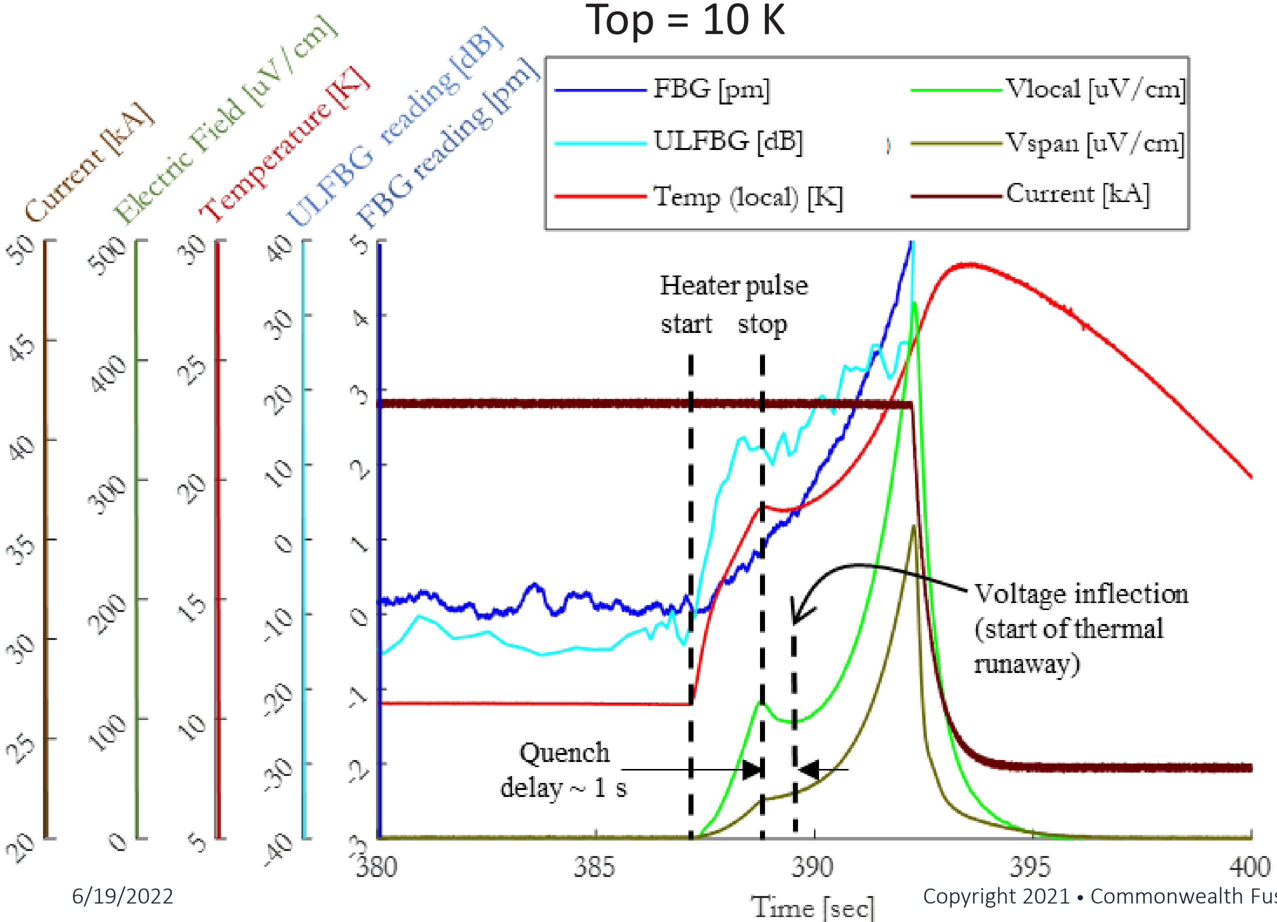
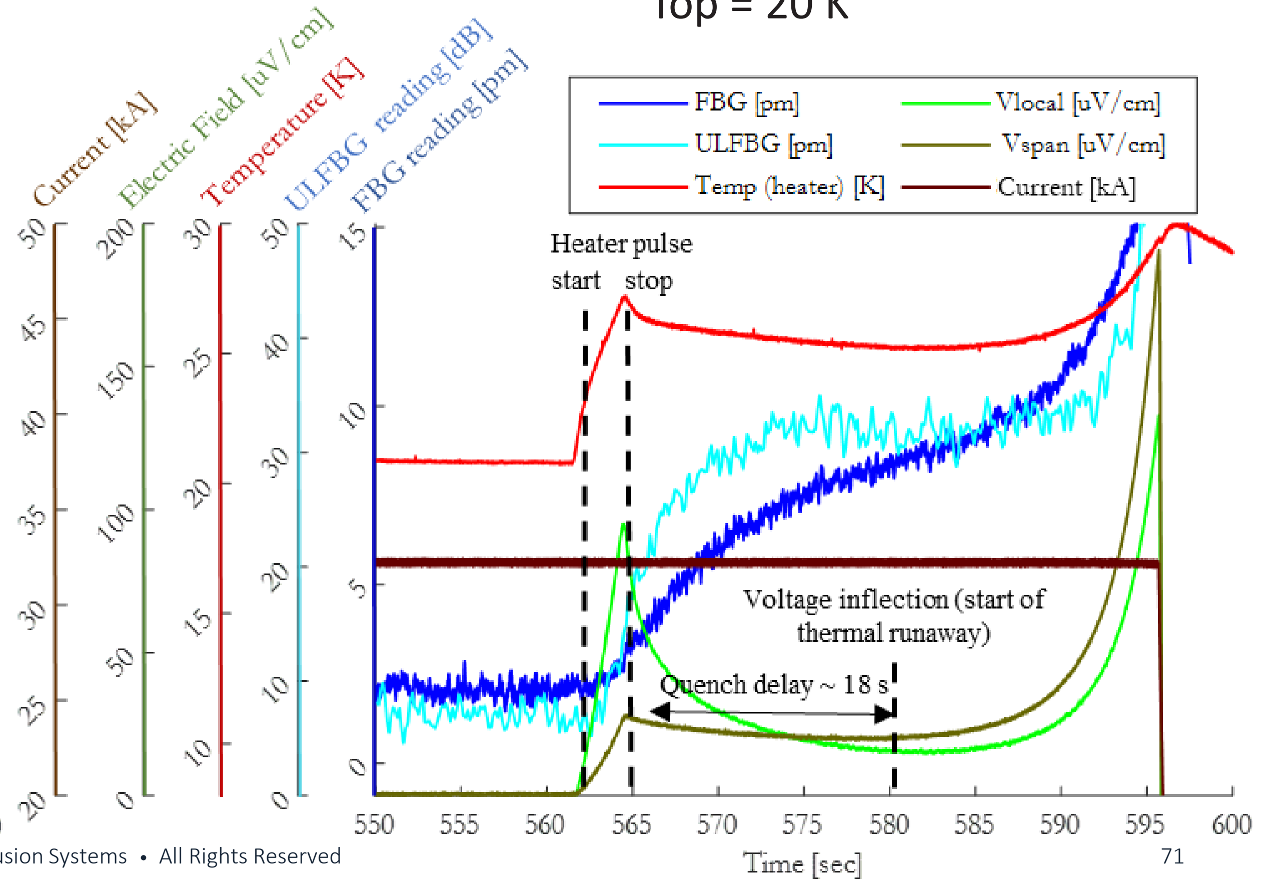
- Both fibers able to detect temperature deviation as small as 2-3 K
- ULFBG and nearest FBG (A72) exhibit rise in signal either before or at similar time as voltage measurement

E. Salazar et al, SUST, 2020

Top = 10 K

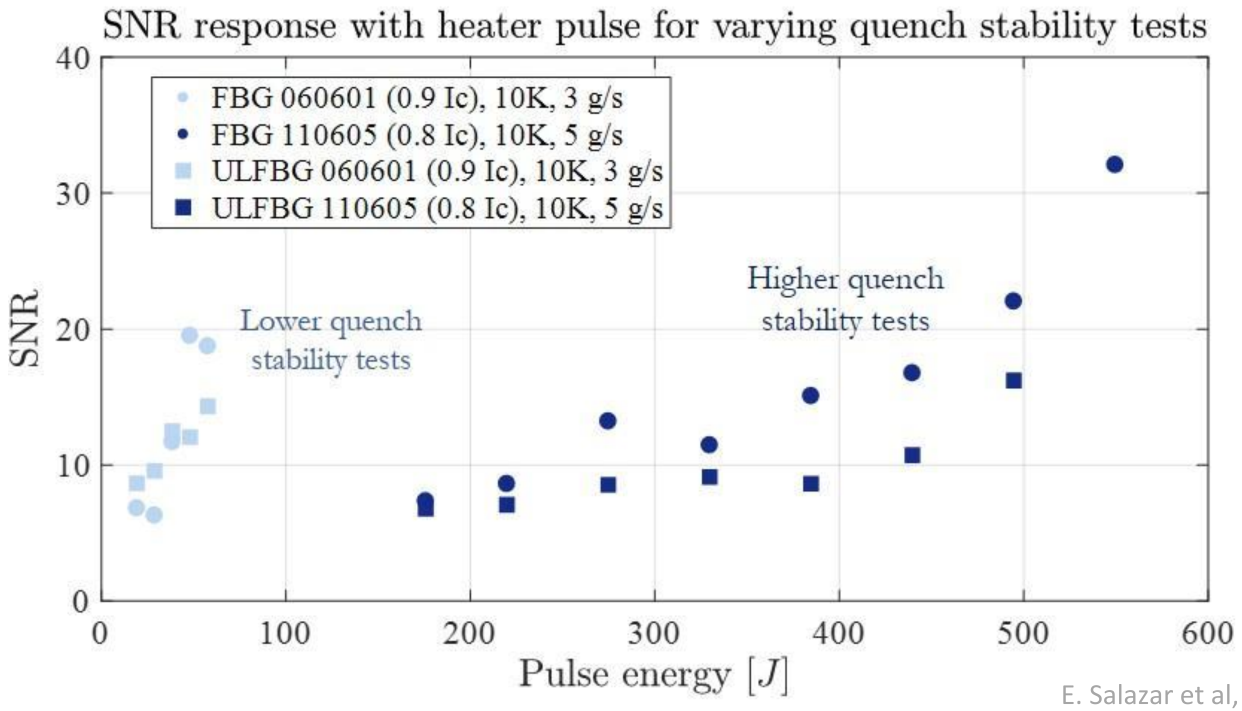


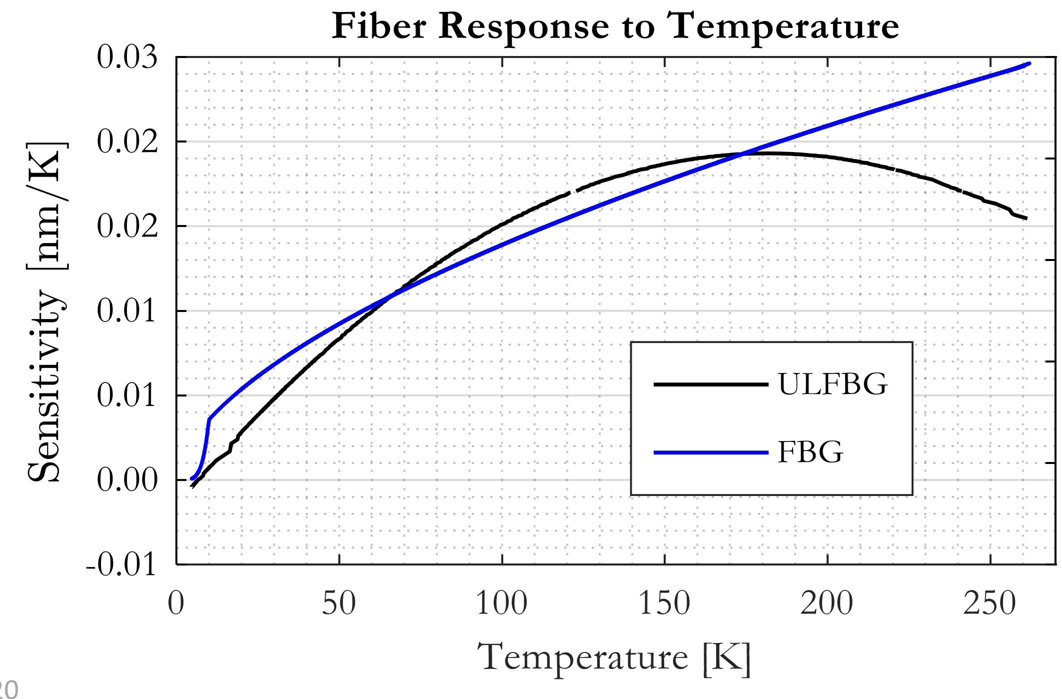
Top = 20 K



Delta: Both FBG and ULFBG fibers rapidly detect quench initiation

- Both fibers detect temperature deviation as small as 2-3 K
- ULFBG and nearest FBG show signal response either before or at similar time as voltage measurement
- Fibers show high sensitivity to mechanically induced strain → specialized coatings will reduce
- The fiber signal-to-noise ratio (SNR) increase as the quench energy increases
- **→ FBG and ULFBG's are a promising quench detection technology!**





E. Salazar et al, SUST, 2020

Roadmap to de-risking HTS Cables for Fusion

New Technology (HTS) → New Scientific Challenges → **De-risking: Testing + Modeling**

✓ IXB loads per stack up to 382 kN/m, with max ~4% Ic degradation
→ **high confidence to operate HTS with high loads**

✓ Fiber optic technology shows ability to detect slow propagating quench
→ **increased confidence in developing QD tech**

✓ Fabricated complex 3D bends (20 cm bend radius), scaled up lengths to 12m
→ **high confidence in manufacturability**

HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → **New Scientific Challenges** → De-risking: Testing + Modeling

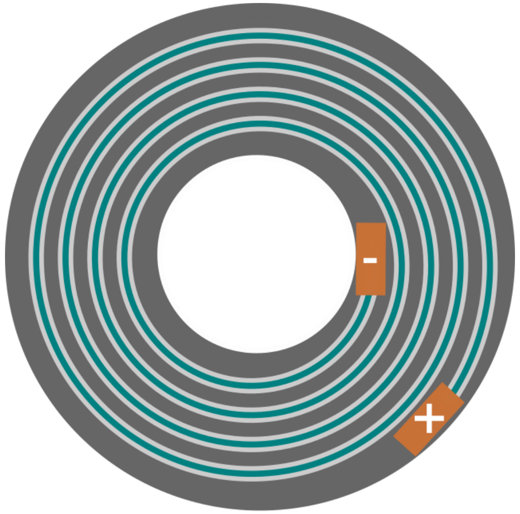
VIPER HTS CABLE

Developed for *multiple* SPARC applications:

- High current feeder cables
- AC magnets: SPARC CS, PF (w/ modifications)
- DC magnets: back-up for SPARC TF

Z. Hartwig et al, *SUST*, 2020

No Insulation No Twist (NINT) Coils



Z. Hartwig, MT27, 2021

Developed for a *specific* SPARC application:

- DC magnet: SPARC TF magnet -> The TFMC

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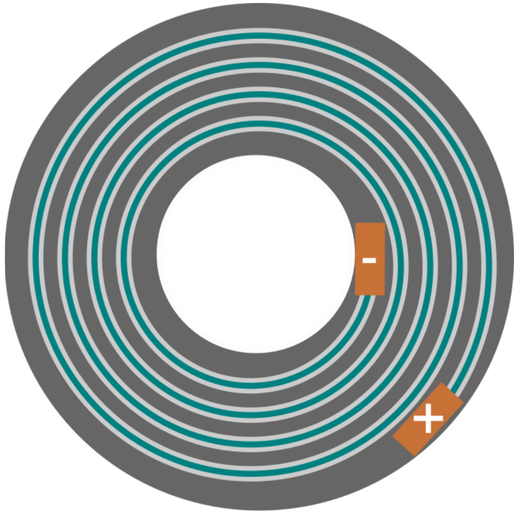

Z. Hartwig, MT27, 2021

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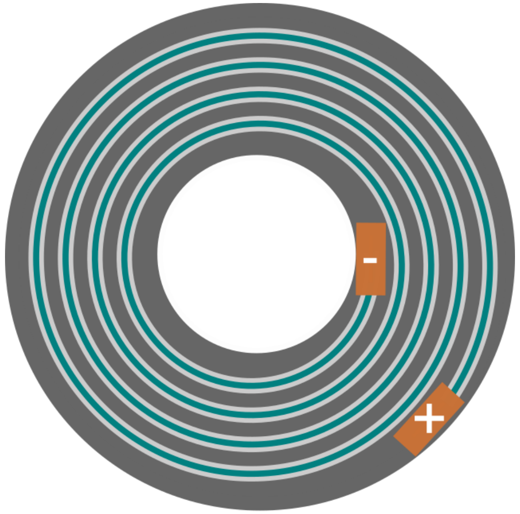
HTS provides superior performance for fusion, but brings new challenges

New Technology (HTS) → New Scientific Challenges → **De-risking: Testing + Modeling**

No Insulation No Twist (NINT) Coils

- Specialized magnet testing facilities not available for large scale magnets
- De-risk manufacturing and operation of innovative designs

New innovative design
→ in-house testing!



Z. Hartwig, MT27, 2021

Developed for a *specific* SPARC application:

- DC magnet: SPARC TF magnet -> The TFMC

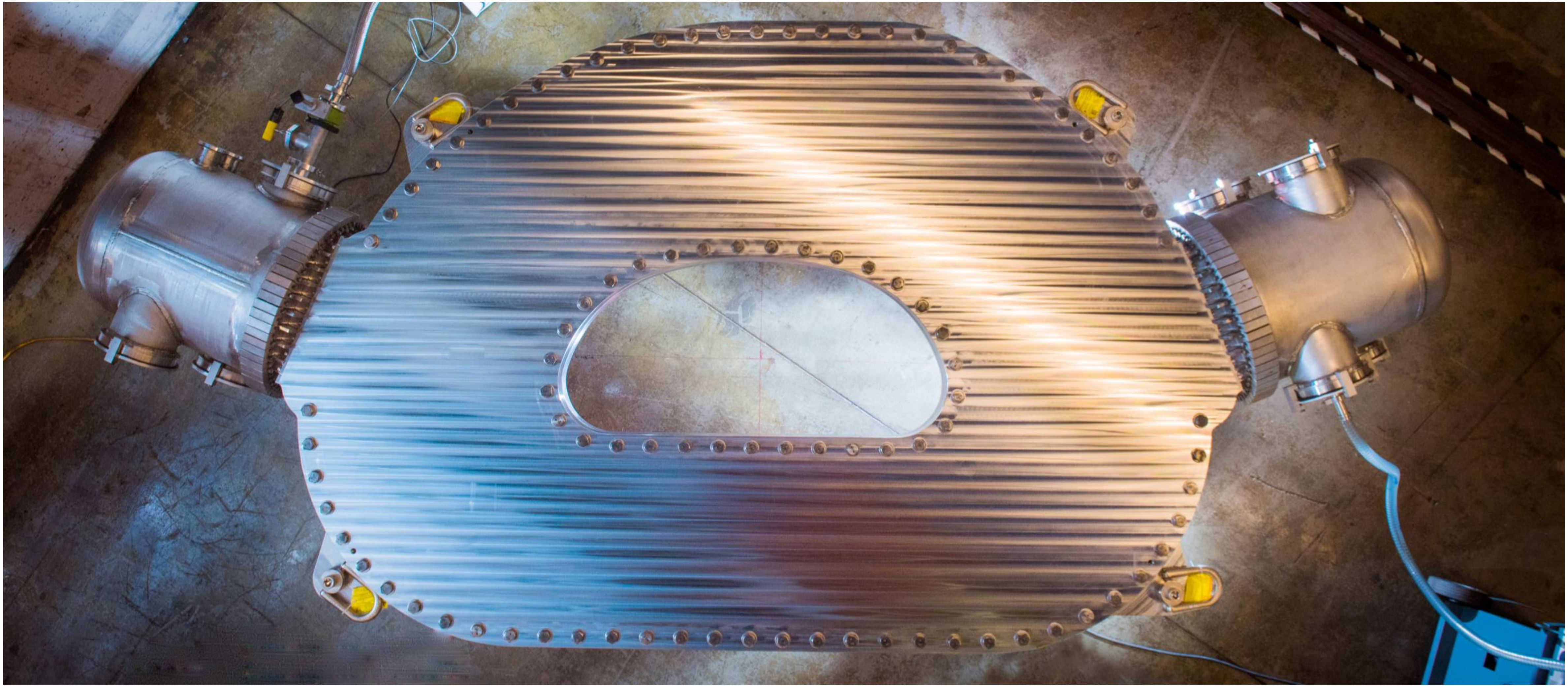
A new magnet test facility has been established at MIT

Facility provides substantial test capabilities for the TFMC and future magnet R&D

Courtesy of MIT-PSFC

The TFMC is the first NI large-scale high-field fusion magnet

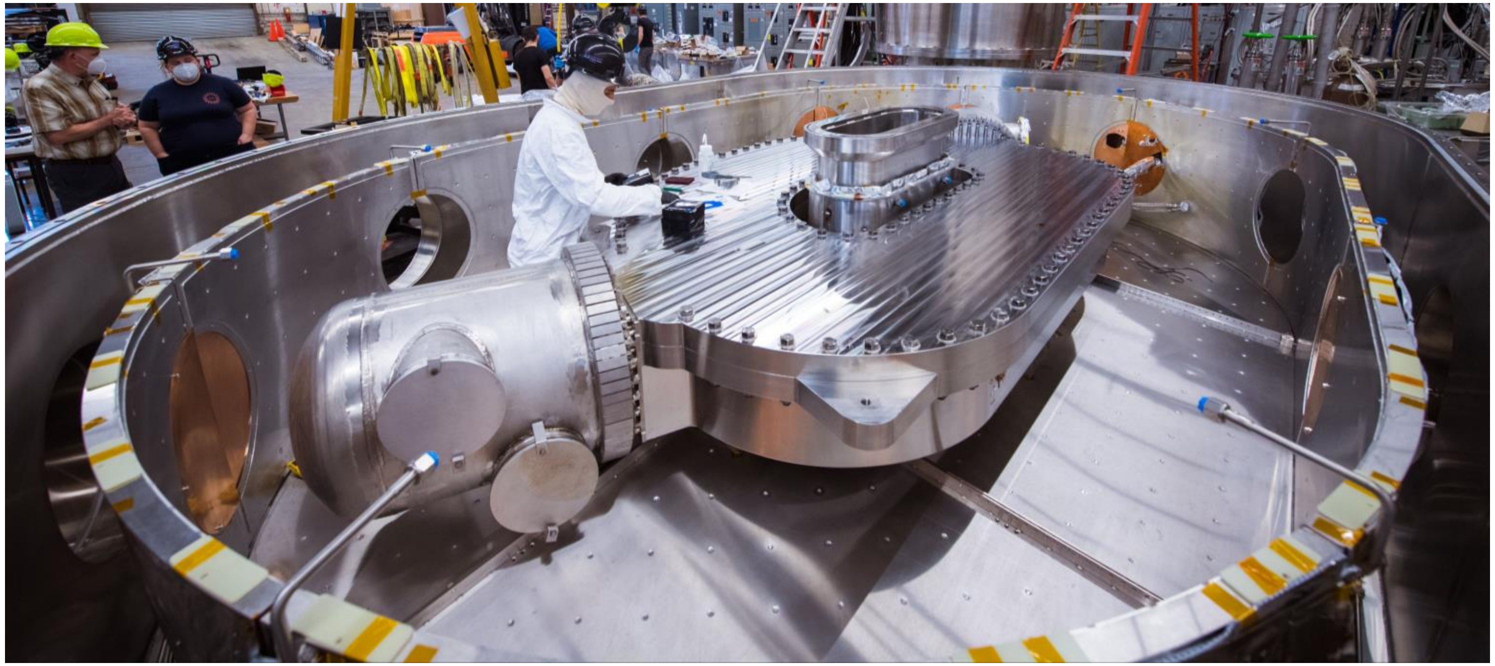
Targeting peak fields >20 T with simple manufacturing, novel cooling, passive quench handling

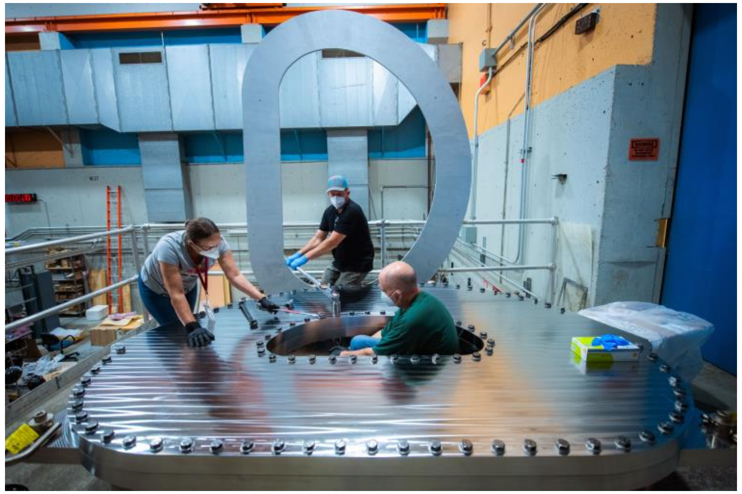


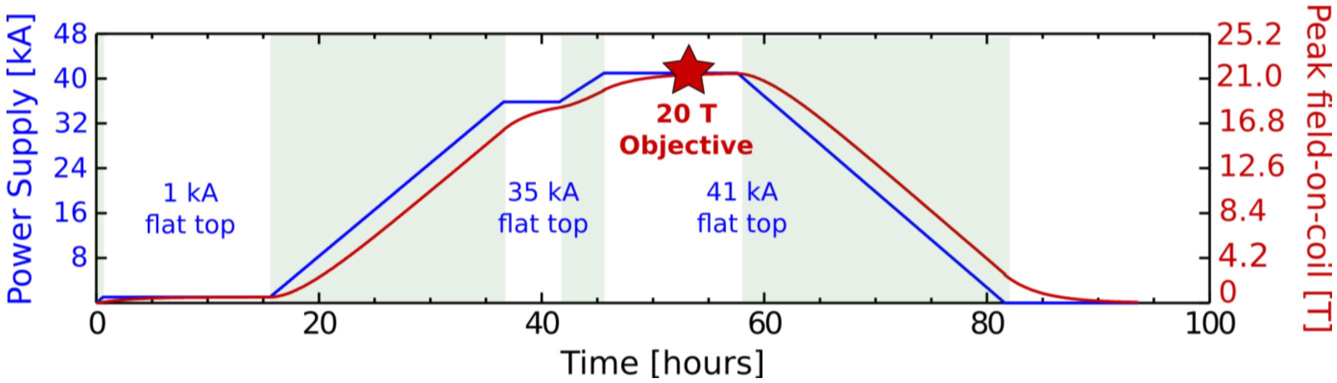
1.9 meters

2.9 meters

The TFMC has established a solid foundation to design and operate large-scale, large-bore HTS magnets exceeding 20 tesla







World's strongest HTS magnet demonstrated

The Boston Globe

Cambridge startup takes big step toward clean fusion power

By Hiawatha Bray Globe Staff, Updated September 8, 2021, 1:50 p.m.

A team of engineers and scientists from CFS and MIT's PSFC lower the superconducting magnet into the test stand in which the magnet was cooled and powered to produce a magnetic field of 20 tesla. COMMONWEALTH FUSION SYSTEMS

The scientists from MIT and Commonwealth Fusion Systems said they may have a device ready for everyday use in the early 2030s.

"This was designed to be commercial," said MIT Vice President Maria Zuber, a prominent physicist. "This was not designed to be a science experiment."

CNBC

Fusion gets closer with successful test of new kind of magnet at MIT start-up backed by Bill Gates

ars TECHNICA BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTUR

IT'S ALIVE —

Fusion startup builds 10-foot-high, 20-tesla superconducting magnet

Calculations indicate the magnet should allow fusion to break even, energy-wise.

"Because we've been able to go to very high magnetic field, we've relieved a lot of the constraints that push all those other aspects up against some really tough technical challenges," Mumgaard said. "We really pushed hard on the magnet side so that we could get some relief on these other types of issues."

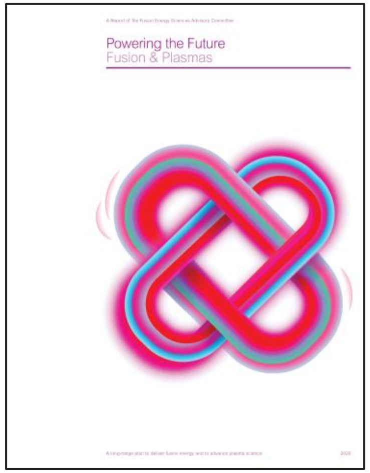
U.S.News & WORLD REPORT **Los Angeles Times**

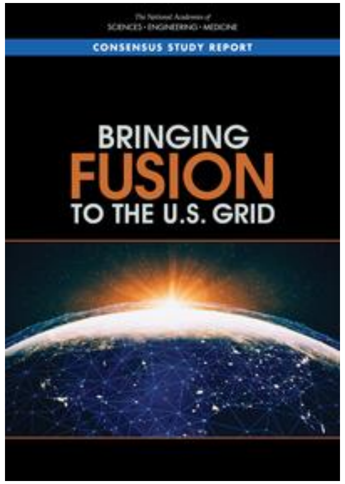
Magnet milestones move dream of nuclear fusion closer

AP The high temperature superconducting magnet demonstrated on Sunday will be used in CFS and MIT's test fusion device, called SPARC, which is already under construction in Devens, Mass., and is and on track to demonstrate net energy from fusion by 2025, the teams said.

Importance of HTS magnets for fusion is well established

- 2020 DOE FESAC Report on Fusion
  - “Important technological breakthroughs include high-temperature superconductors (HTS) that enable the advances in magnet technology required to achieve that confinement.” – Page 2





- 2021 National Academies of Science Report on Fusion
  - “… the higher magnetic field made possible by the development of demountable high temperature superconducting magnets was identified as a key enabling technology that provides a potential path, when combined with advanced operating scenarios, to a compact fusion pilot plant with high fusion power density.” – Page 59

Outline

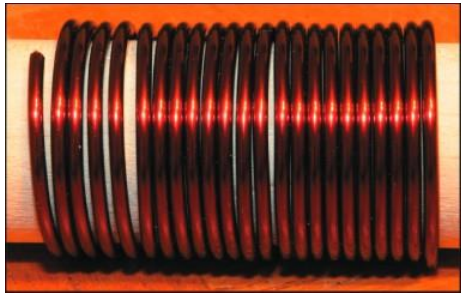
1. Our Motivation: Rapid Global Warming Requires Rapid Solutions
2. The Future of Fusion with High Temperature Superconductors (HTS)
3. The Design Challenges of Using HTS
4. De-risking the Challenges and Proving Technical Feasibility
5. **Marching towards a SPARC era**

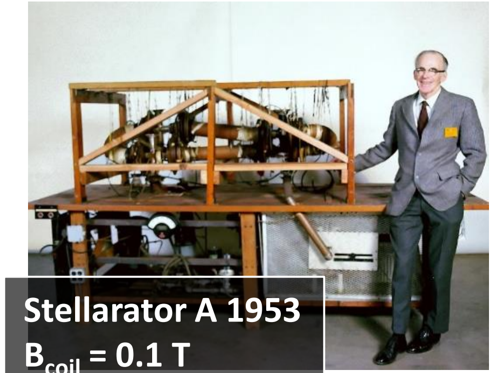
Fusion continues to push the limits of magnets!

1950-1960s:

Copper wire

The pioneers



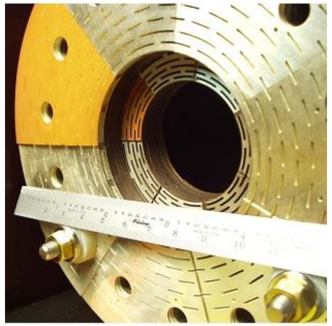


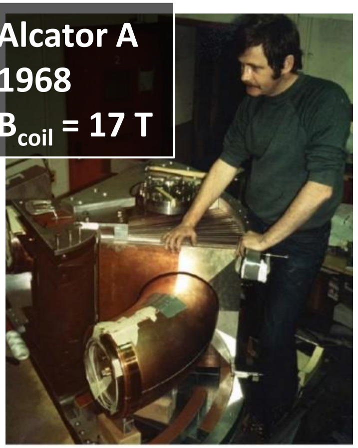
Stellarator A 1953
B_{coil} = 0.1 T

1960-1980s:

Cryogenic Bitter plates

The Alcators at MIT



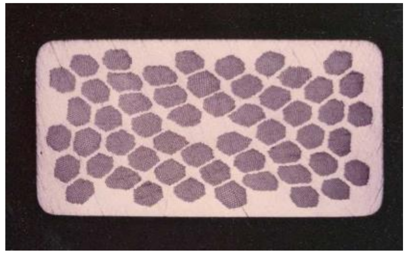


Alcator A
1968
B_{coil} = 17 T

1980-2000s:

NbTi superconductors

First SC fusion devices



Tore Supra 1988
B_{coil} = 9 T

1990s-2010s:

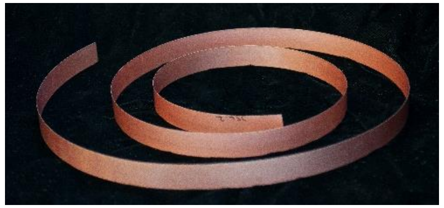
Nb_3Sn for higher field

Reactor-class devices

ITER 2015
B_{coil} = 13 T

2010-2020s:

REBCO: very high magnetic fields



MIT/CFS
B_{coil} > 20 T

High field path to commercial fusion energy

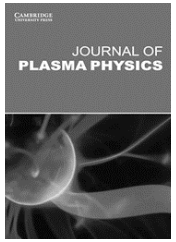
COMPLETED
Proven science
Alcator C-Mod

COMPLETED
October 2020
Published peer-reviewed SPARC physics basis in Journal of Plasma Physics

COMPLETED
September 2021
Demonstrate groundbreaking magnets

CONSTRUCTION UNDERWAY
Operation in 2025
Achieve net energy from fusion

Early 2030s
Fusion power on the grid $P_{electric}$~200MW



HTS Magnets

SPARC Q>10

ARC

Domestic burning plasma by 2025

- **Acquired land:** Spring 2021
- **Total size**: 47 acres
- **Location:** Devens, MA
- **Initial magnet manufacturing facility:** 160,000 sf
- **Manufacturing operations:** 2022
- **SPARC operations:** 2025

Construction is underway

Acknowledgements

This work was sponsored by Commonwealth Fusion Systems. Thank you for your sponsorship and support!

I also thank the CFS and MIT personnel for their efforts on designing and manufacturing the VIPER cable.

Thanks to our fiber collaborators: Robinson Research Institute (ULFBG) and CERN (FBG).

The implementation of the SULTAN tests would not be possible without the hard work and efforts of the SULTAN team at PSI.

And last but not least…

All credit to the exceptional team that delivered the TFMC Project

- *Project Head*: Zach Hartwig
- *Chief Engineer*: Rui Vieira
- *Group leaders*: Brian LaBombard (E&M), Chris Lammi (Analysis), Joy Dunn (Manufacturing), Ted Golfinopoulos and Phil Michael (Test)
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All work funded by Commonwealth Fusion Systems

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CFS path to commercial fusion energy

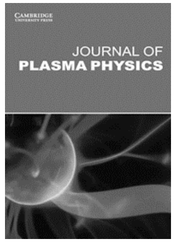
COMPLETED
Proven science
Alcator C-Mod

COMPLETED
October 2020
Published peer-reviewed SPARC physics basis in Journal of Plasma Physics

COMPLETED
September 2021
Demonstrate groundbreaking magnets

CONSTRUCTION UNDERWAY
Operation in 2025
Achieve net energy from fusion

Early 2030s
Fusion power on the grid $P_{electric}$~200MW



HTS Magnets

SPARC

ARC