Leveraging fusion superconducting magnet R&D for an HTS-based Mu2E target solenoid

Zach Hartwig | MIT

Mu2e Collaboration meeting

28 Mar 22

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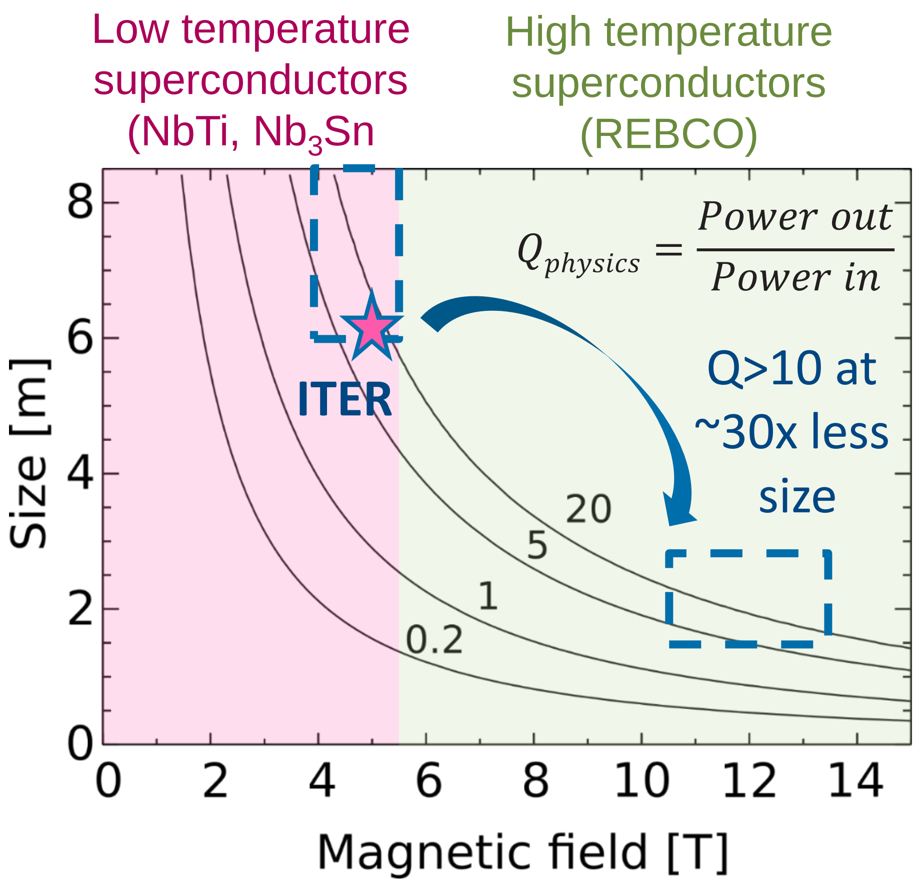
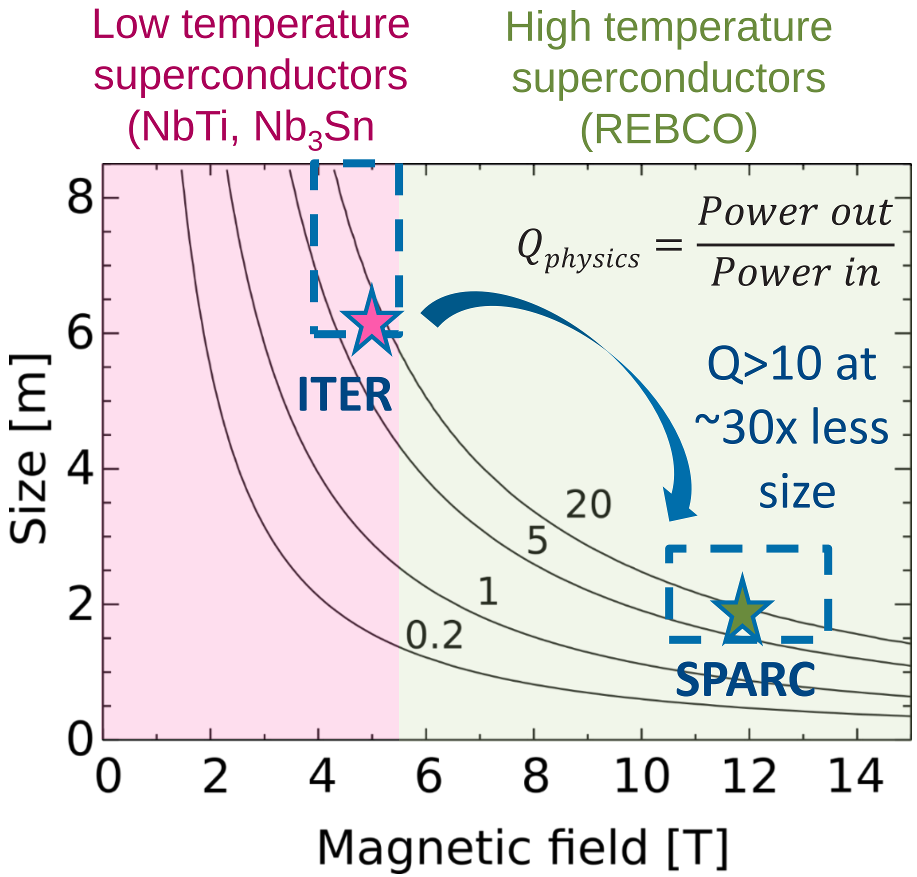
Thank you to Kevin Lynch, Rob Carey, Jim Miller, Lee Roberts

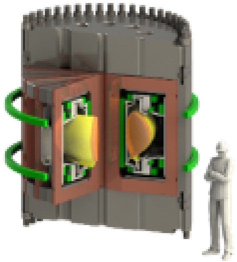
High magnetic fields offer an attractive path to net fusion energy



High magnetic fields offer an attractive path to net fusion energy



High-field fusion science → **Phase 1: Technology R&D** → **Phase 2: Demonstration**



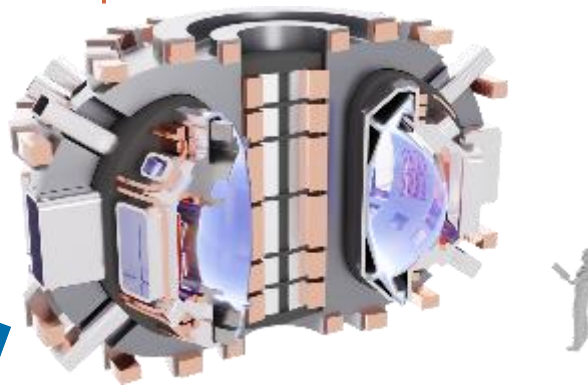
Alcator C-Mod

REBCO CICC cable concepts

No-insulation REBCO concepts

?

Commonwealth Fusion Systems



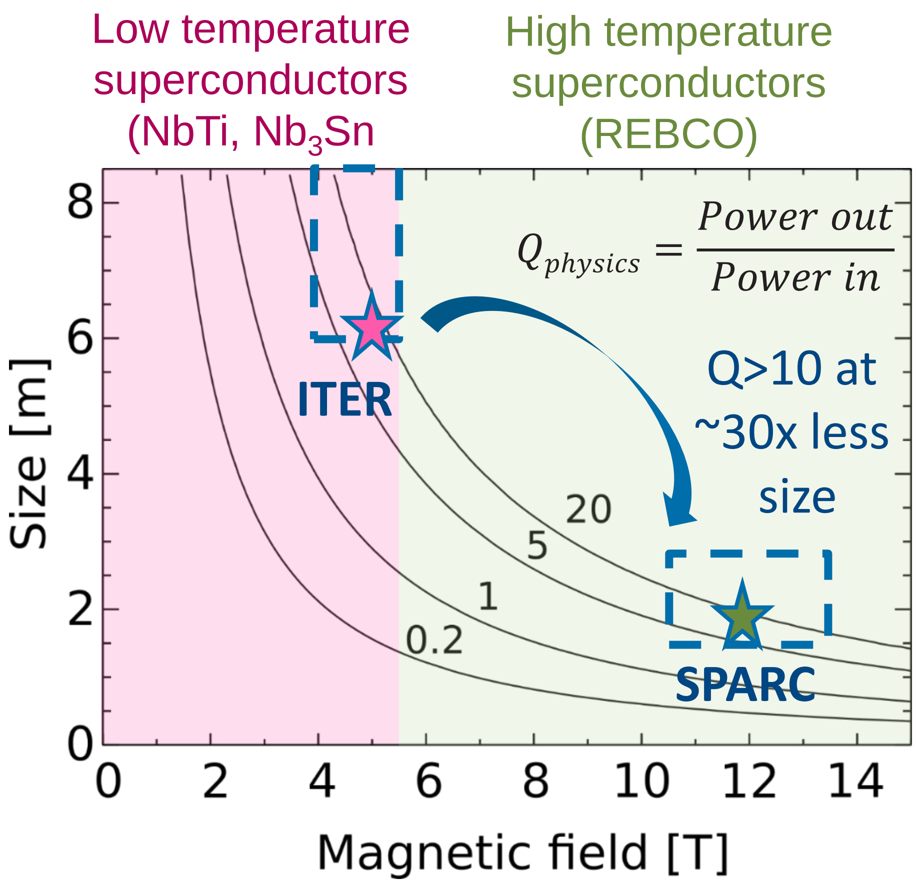
SPARC

Q>2

P > 100 MW

2016 **2021** **2025+**

High magnetic fields offer an attractive path to net fusion energy



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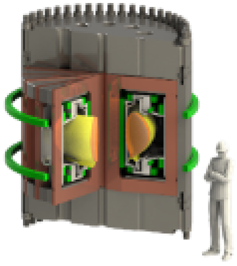

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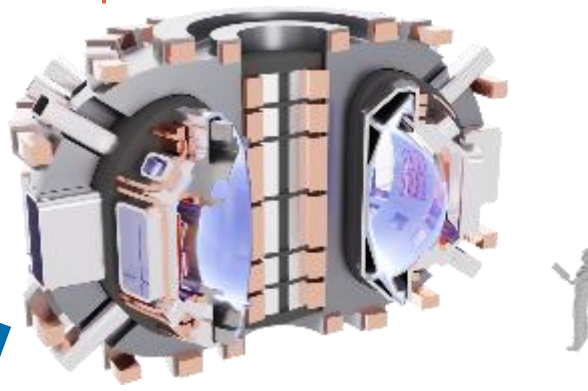

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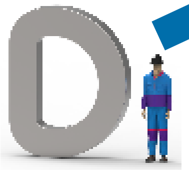
REBCO CICC cable concepts

No-insulation REBCO concepts

REBCO magnet R&D (2017-2019)



TF model coil (2019-2021)

The TFMC Project (MIT, CFS)

2016 **2021** **2025+**

REBCO: What is it? What are the positives and negatives?

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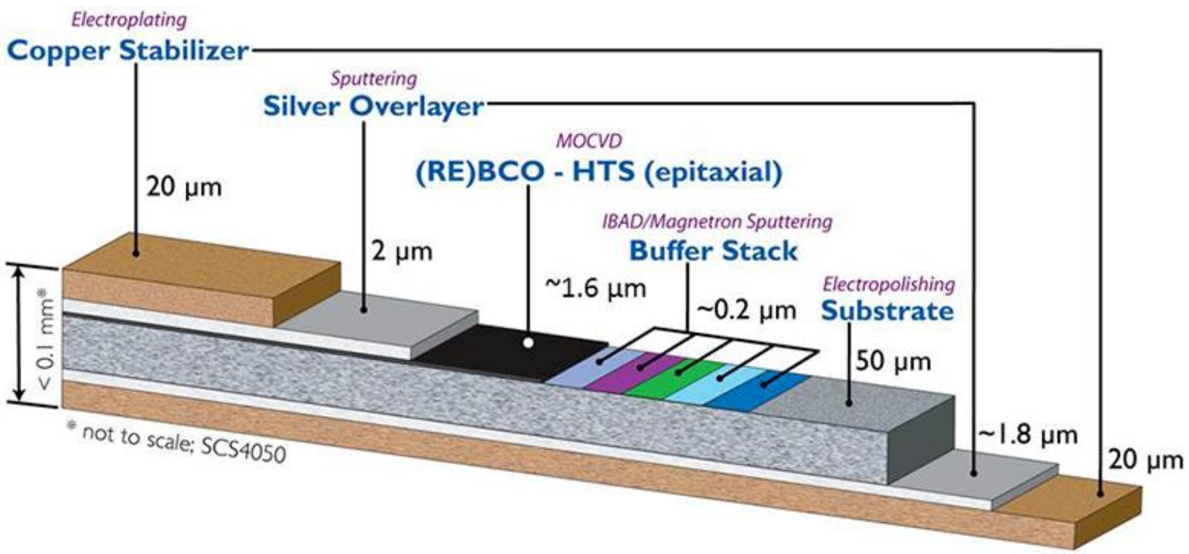
Rare-earth Barium Copper Oxide (REBCO)



Aside: There are other high temperature superconductor (HTS) materials, notably:

- Bi-2212 (not ready for prime time)
- MgB2 (primarily low-field applications)

Fusion energy (esp. private industry) is almost exclusively focused on REBCO for its future

+ High field operation (>16 T)
  - ➢ Magnets that can't be built otherwise
+ High temp operation (< 80 K practically)
  - ➢ Liquid-free or helium-free cooling
  - ➢ Cryostable (hard to quench)
  - ➢ Favorable engineering away from sub-4.2 K
+ High performance: >700 A/mm^2 (20 T, 20 K)
  - ➢ Use a little REBCO to do a lot in a small space
+ Industrialized, ~10 vendors worldwide
  - ➢ Increasing volume, decreasing costs

– More expensive than NbTi, Nb3Sn
  - – REBCO really wins when it has clear non-$ advantages over traditional SCs

– Quench detection is more difficult
  - – Magnet protection still an R&D project

Objective: Make REBCO progress feel real

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What I want to do today		Strategy for how to do it: "Show not tell!"
1. Convey the state-of-the-art in large-scale REBCO technology (caveat: MIT perspective!)	→	Provide a short overview of: • VIPER high current cables • TFMC no-insulation magnet • 50 kA feeder system
2. Translate what our progress in REBCO technology means for the Mu2e collaboration	→	Summarize key lessons-learned from our experience that have relevance for Mu2e
3. Convince you that a REBCO-based target solenoid is worth considering	→	Build and analyze a REBCO-based Mu2e target solenoid

Objectives and overview of the talk

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Design overview of the VIPER REBCO cable

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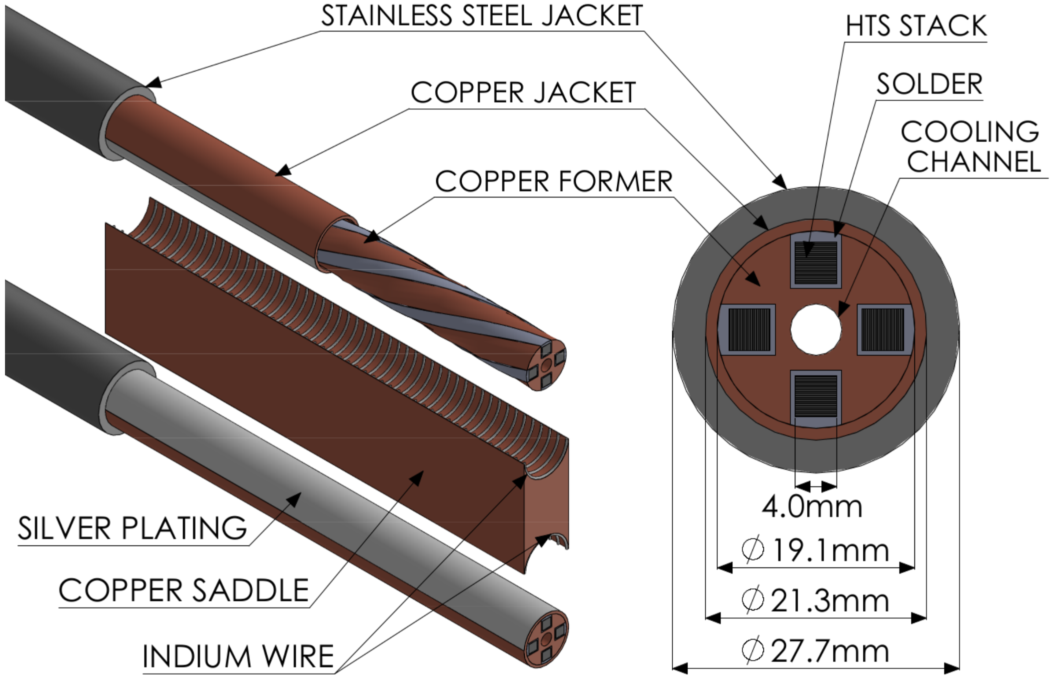
- High-current (25 – 100 kA class) REBCO cable AC and DC magnets [1,2}
- Extruded central copper former with REBCO channels on perimeter and central cooling channel
- Copper jacket compacted to provide electrical connectivity
- Optional steel jacket compacted to provide mechanical strength (round or square)
- Design is highly customizable for specific end-user applications



[1] Z. Hartwig *et al.*, SuST, **33** (2021) 11LT01
[2] M. Takayasu *et al.*, IEEE TAS, **21** (2011) 2340

VPI solder process enables VIPER cable performance

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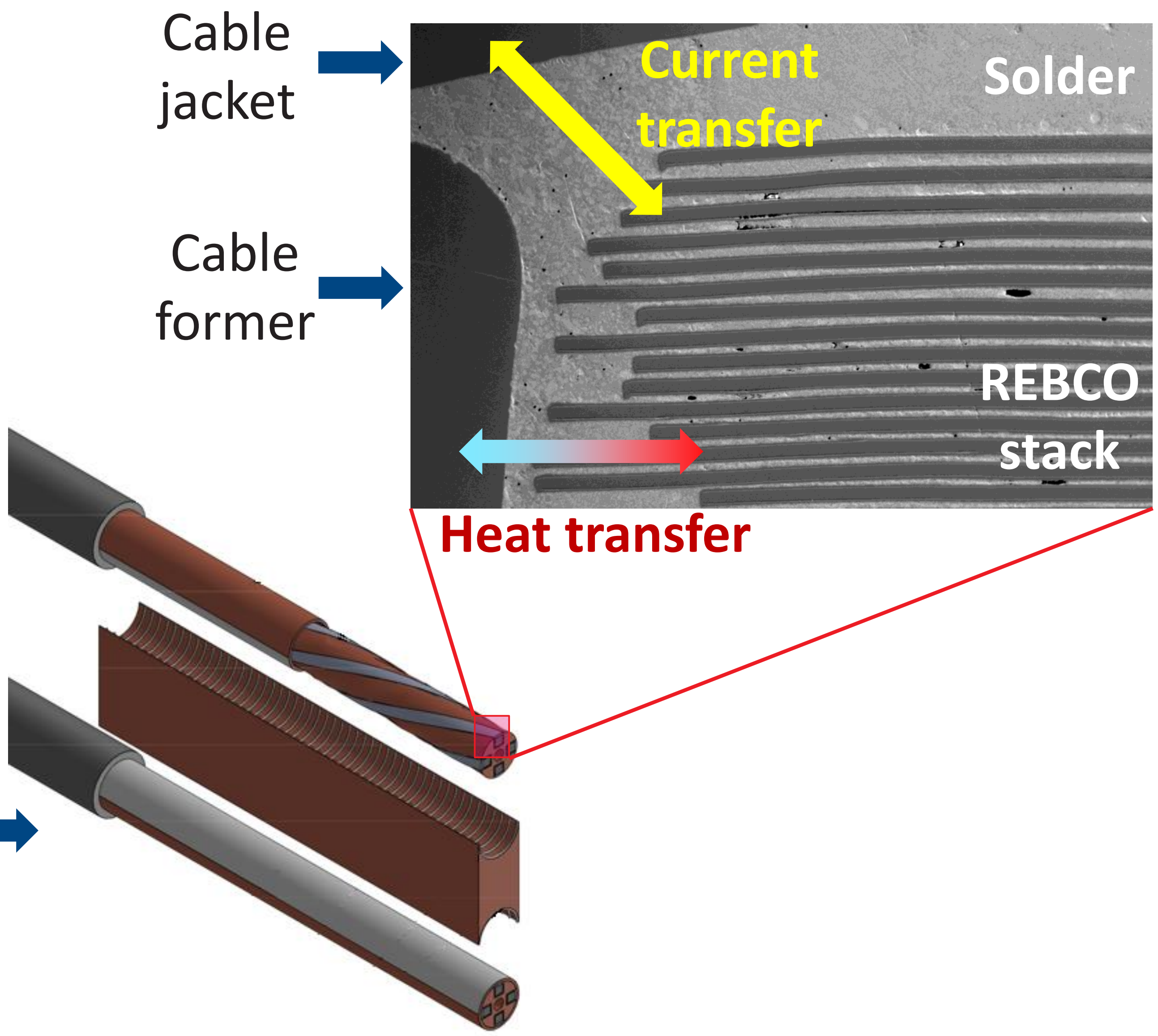
- Vacuum-pressure impregnation (VPI) solder process of the REBCO stacks to the copper former is the key design feature:
  - Mechanical strength as IxB body loads are transferred from REBCO -> copper -> steel
  - Thermal stability as internal heat easily and rapidly flows to central cooling channel
  - Electrical connectivity throughout the cable mitigates quench and manufacturing defects

- Soldering has two important impacts on REBCO:
  - All RECBO stacks are mechanically isolated. Thus, **IxB per REBCO stack** is the key figure of merit
  - VPI soldering occurs after cable fabrication and forming leading to strain-minimized REBCO

- REBCO soldering also enables simple, robust, and low resistance joints (~nΩ @ self-field, 5K) that require minimal preparation
  - Require no special processing other than joining cables-to-cable with copper saddle
  - Joints are demountable and reusable



VIPER cable R&D has focused on retiring the critical risks towards large-scale, high-field REBCO magnets

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	RISK	
✓	**Fabrication**	Scalable to >100 m cable manufacturing for large-scale magnets
✓	**Joints**	Simple, robust, low-resistance, demountable electrical joints
✓	**IxB**	Handle IxB loading + cycling equivalent to those found in >20 T magnets
✓	**Strain**	Handle axial strains on the HTS above ~0.3% equivalent to >20 T magnets
Active R&D	**Quench**	Incorporate viable quench detection with high cryostability

The SPARC Toroidal Field Model Coil Project: 1 picture

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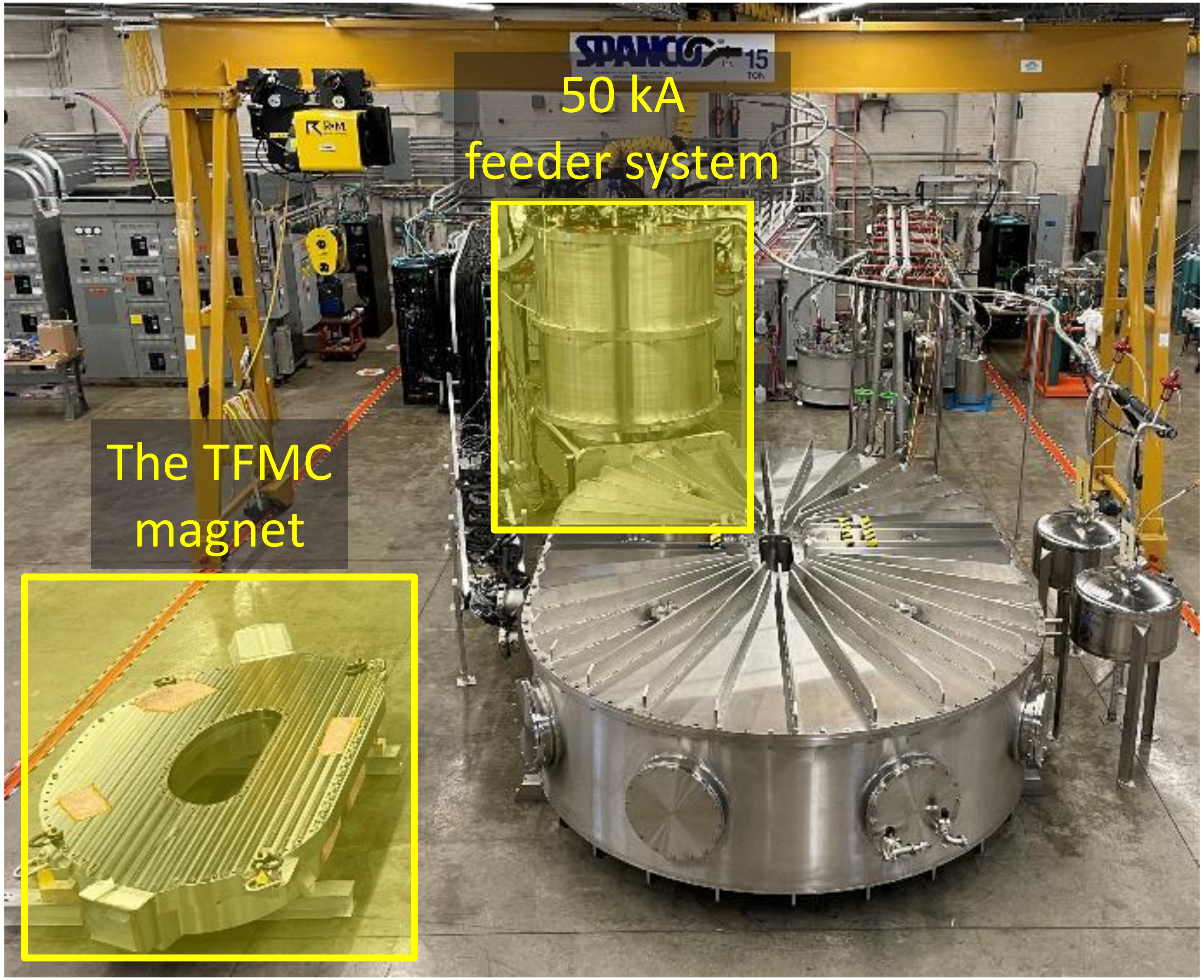

The TFMC at a glance

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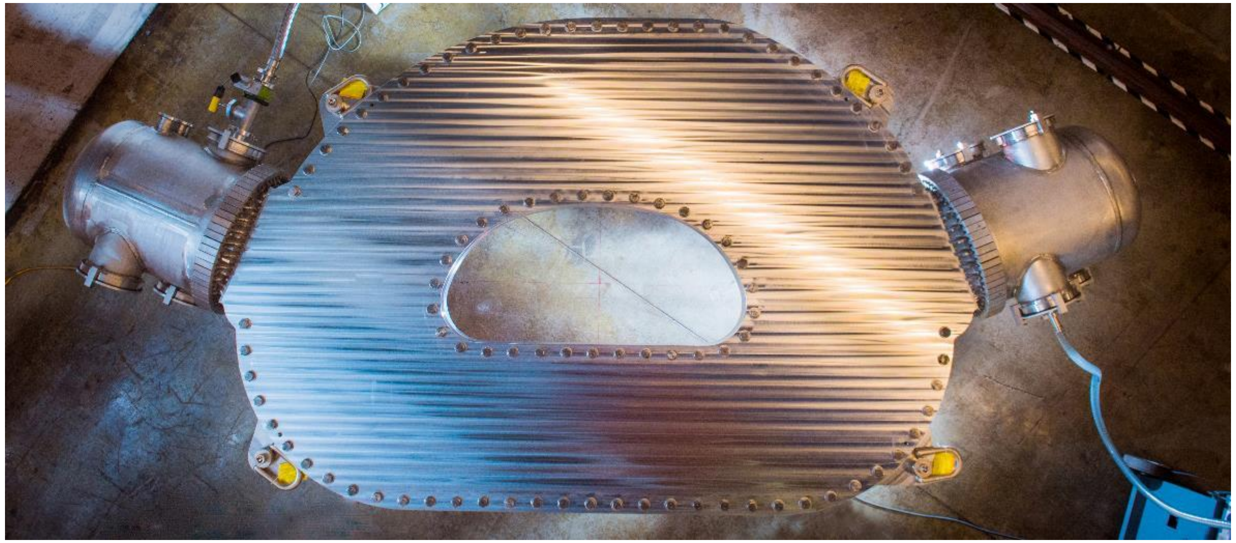

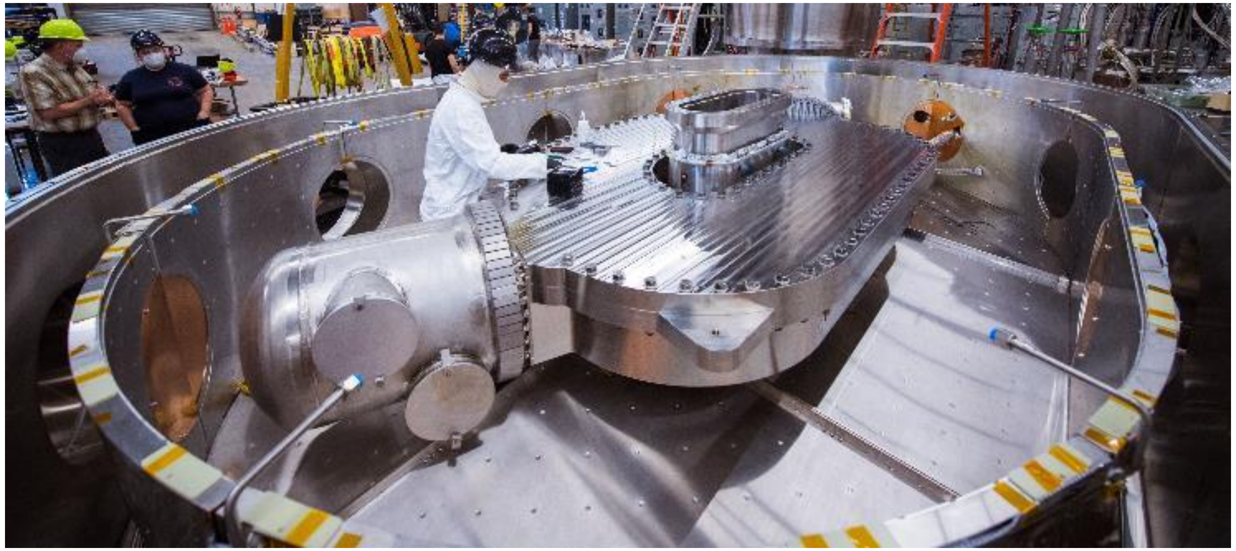

Nominal Design Parameter	Value
Number of pancakes	16
Total turns	256
Total REBCO tape	270 km
Operating temperature	20 K
Coolant type	Supercrit. He
Operating coolant pressure	20 bar (max)
Operating terminal current	40 kA
Peak magnetic field	20 T
Peak IxB force on REBCO	800 kN/m
Inductance	0.14 H
Magnetic stored energy	110 MJ
WP mass	5,113 kg
WP current density	153 A/mm^2
WP + case mass	10,058 kg
WP + case linear size	2.9 x 1.9 m

Binary 50 kA LN_2-cooled REBCO current leads demonstrated

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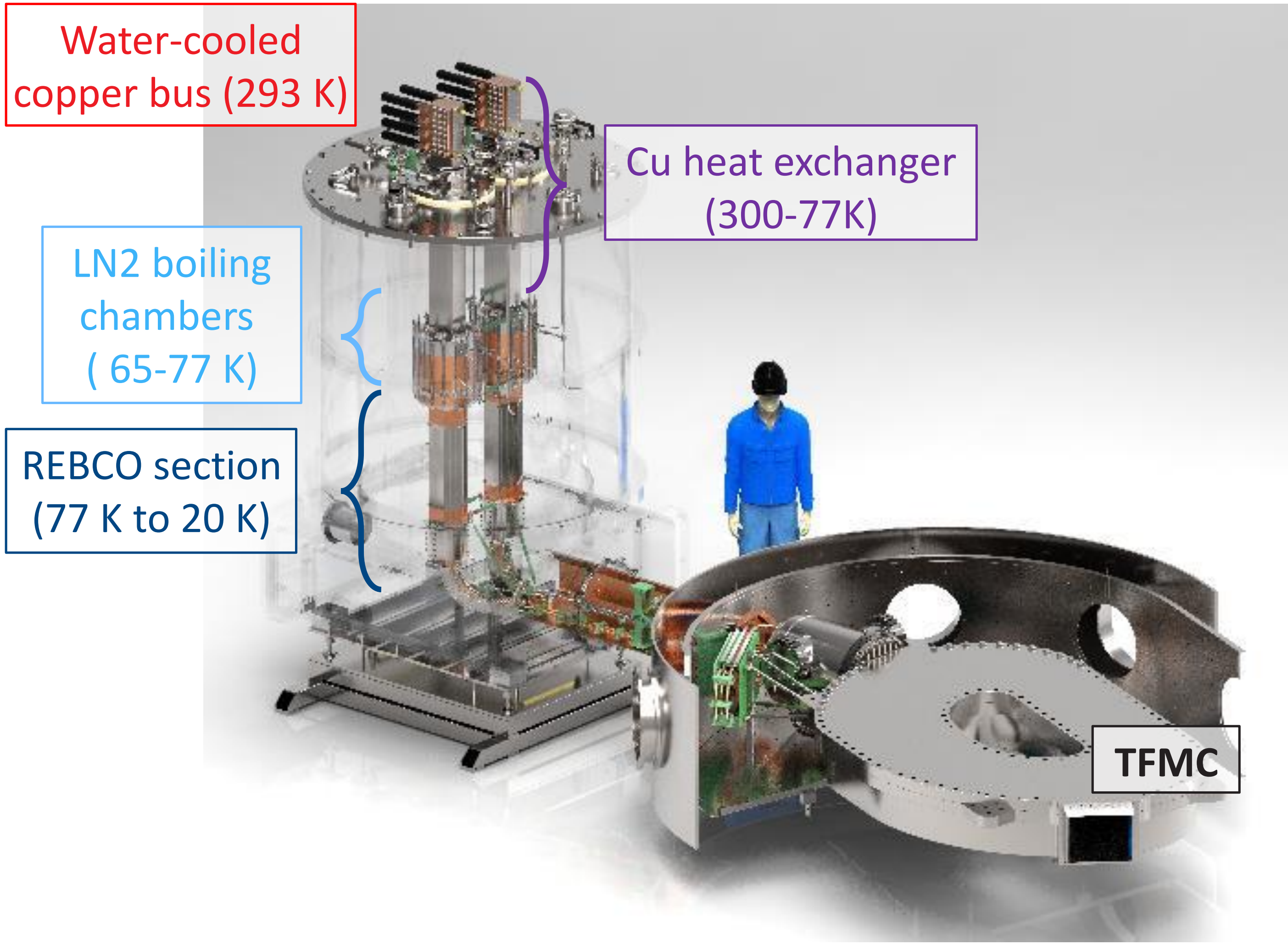
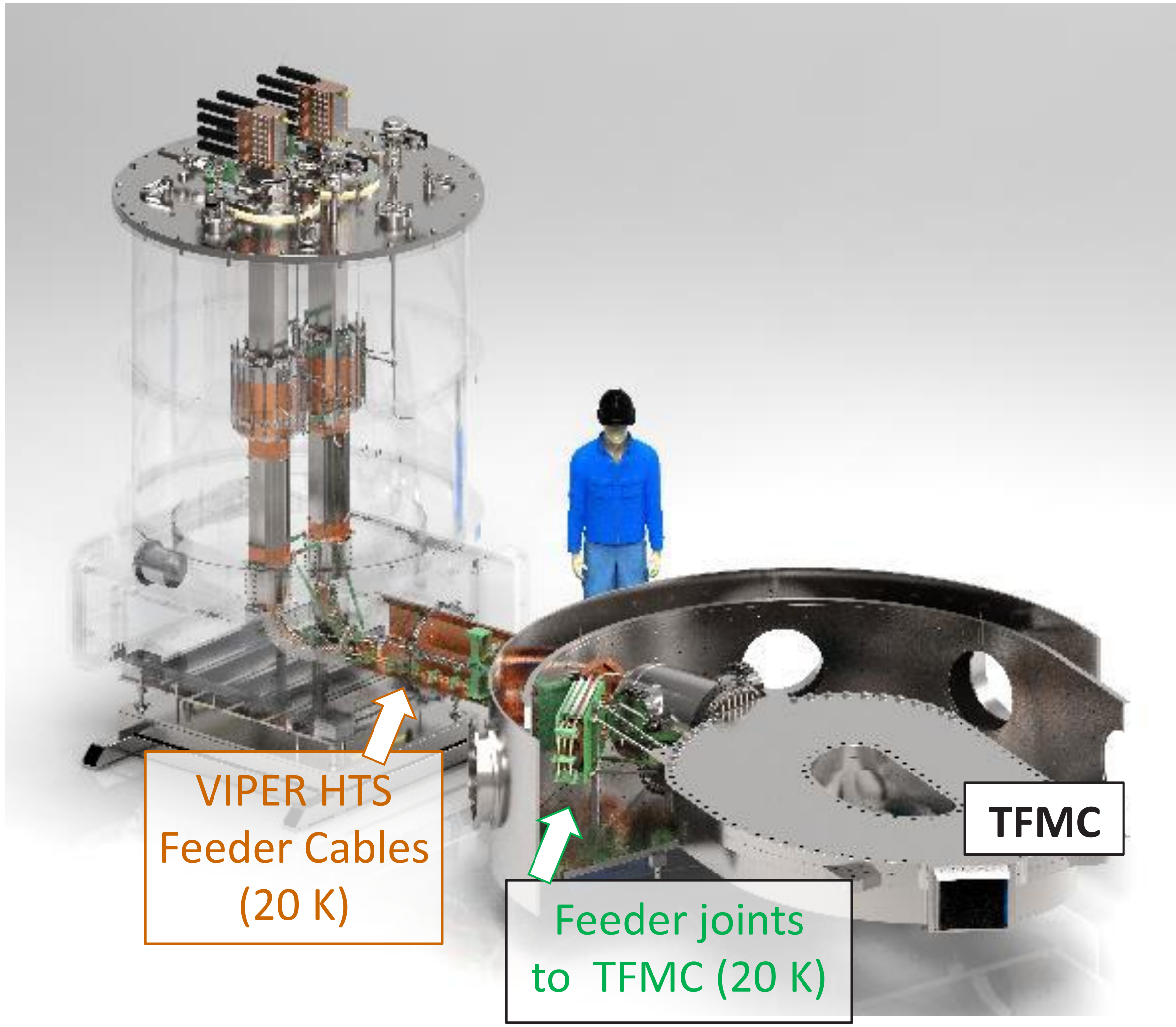
- REBCO current leads were designed, fabricated, and commissioned in-house
  - Designed to supply up to 50 kA for low voltage DC magnets
  - LN_2 (sub-cooled if desired) and SHe cooled
  - In-house development required to meet performance and schedule requirements



Binary 50 kA LN_2-cooled REBCO current leads demonstrated

MIT PSFC

- Binary HTS current leads were designed, fabricated, and commissioned in-house
  - Designed to supply up to 50 kA for low voltage DC magnets
  - LN2 section can be sub-cooled to enable high current performance
  - In-house development required to meet performance and schedule requirements
- Feeder system to magnet composed of 3 sets of VIPER REBCO cables
  - Complex shape to mitigate thermally induced differential strain due to cooldown
  - 3 sets of joints to simplify assembly
  - Unique high-pressure feedthrough to enable connection to TFMC magnet
- Leads and feeder system commissioned
  - Tested to 50 kA (25% above requirements)
  - All joints with 1.5 – 2.0 nOhm performance



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LL #1: REBCO is ready for large-scale, high-field magnets; high-volume, low-cost manufacturing now ramping up

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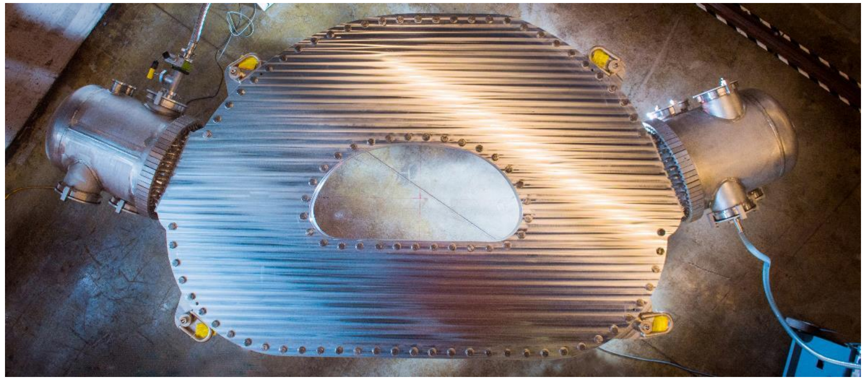
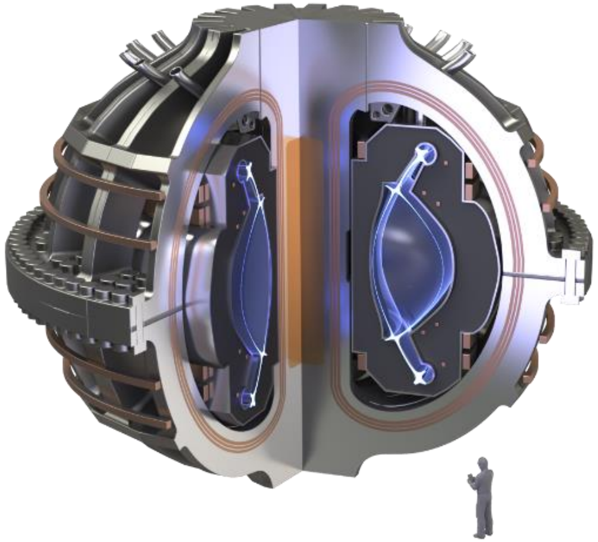
- TFMC has demonstrated that REBCO can enable fusion-scale large-bore >20 T SC magnets
  - TFMC checks the “REBCO performance in magnets” box
  - Post-TFMC will require O(100x) increase in volume just for a tokamak (e.g SPARC); $/kA-m is a critical quantity
  - Making REBCO accessible to other markets beyond fusion require significant volume and cost reduction not continued Ic increase in bespoke pieces, small volume



High-strength alloy required for stresses approaching 1 GPa at full field operation

- Unlike LTS, REBCO is no longer the critical constraint limiting magnetic field in fusion tokamaks
  - Mechanical limits of structural materials
  - Optimum on-axis field for tokamak plasma physics
  - Heat exhaust to materials in compact tokamaks
  - Competition for “real estate” in a tokamak power plant



Plasma physics and integrated optimization in tokamak power plants further limit the highest fields that are useful

Mu2e Lesson: Fusion energy is driving the REBCO market hard, dramatically increasing volume and reducing cost, creating opportunity for new users and critical new markets for REBCO suppliers.

LL #2: REBCO has proven impressively resilient to complex mechanical fabrication processes and forms

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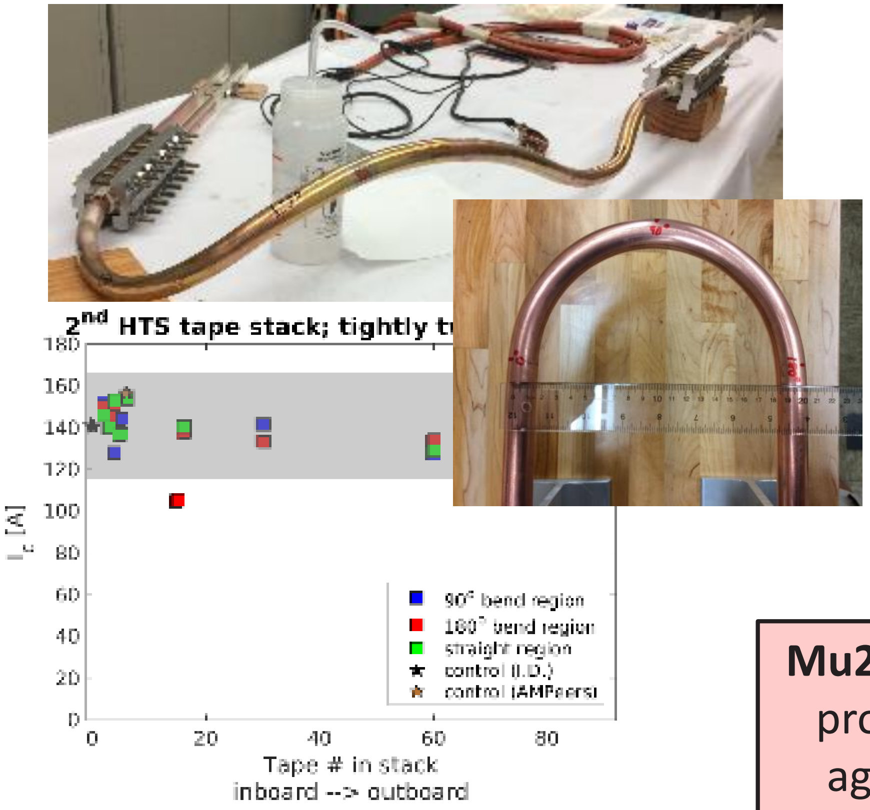
VIPER cables for non-planar coils

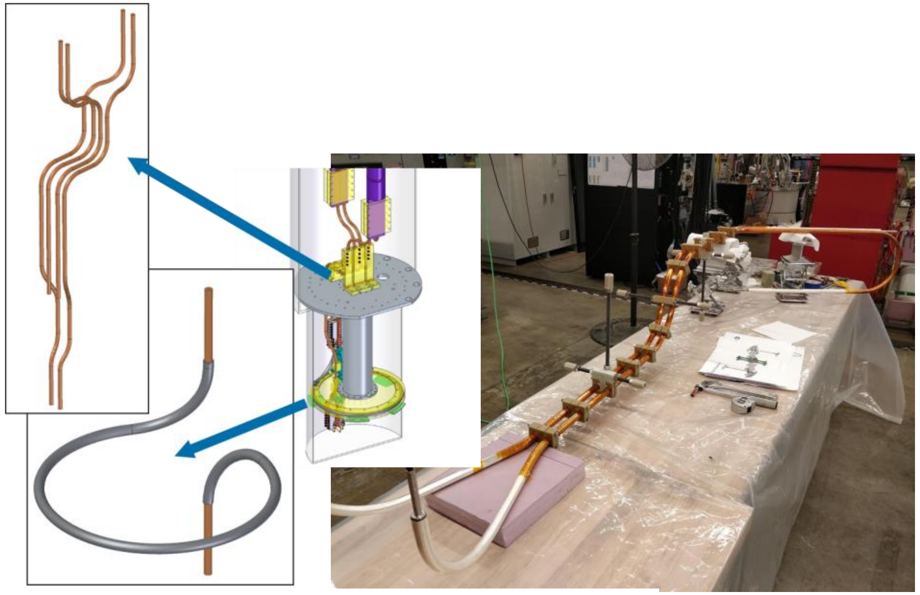
Twisted stacks in compound bends with 10 cm radii with 3D bending machines

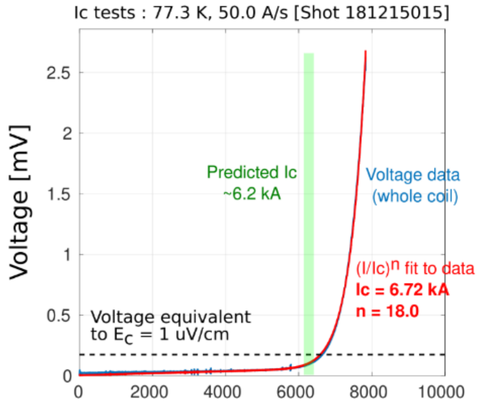


VIPER cables for pancake coils

VIPER Cables for 3D TFMC feeder:

>200 tape multiple twisted stacks in complex geometries for < 65 kA @ 20K





Mu2e Lesson: REBCO cable fabrication processes proven sufficient in more aggressive shapes than a potential Mu2e solenoid

LL #3: VPI solder-stabilized REBCO has survived high IxB loading, relevant axial strain, and thermal cycling

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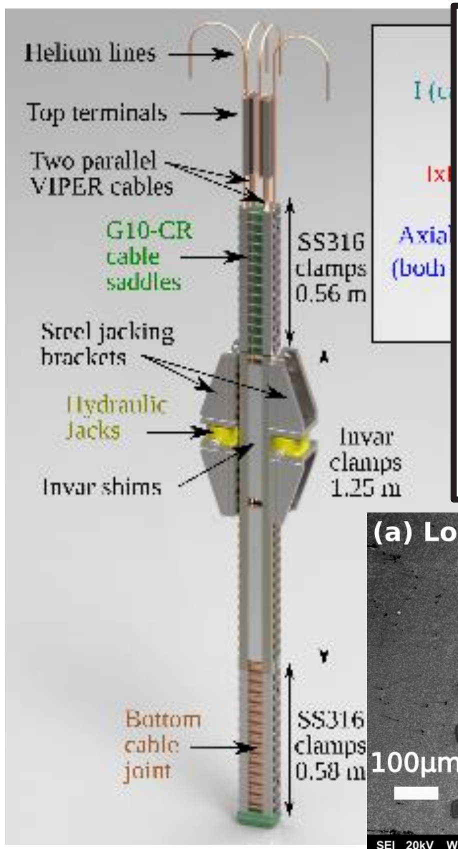
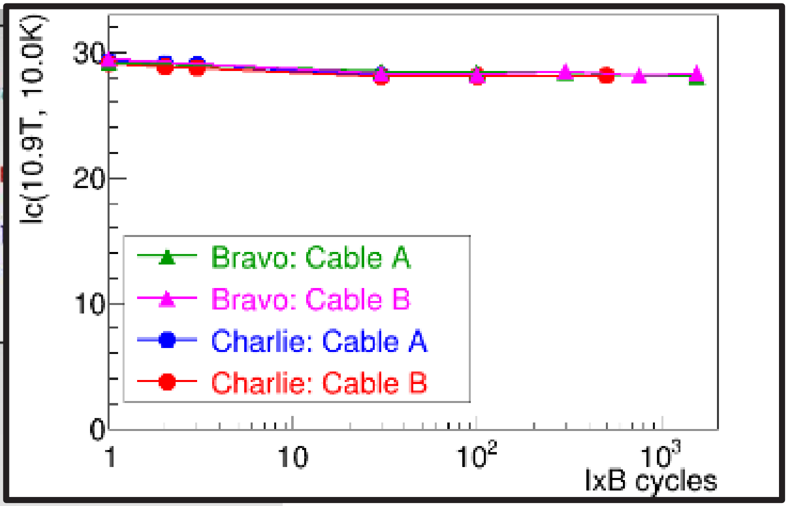
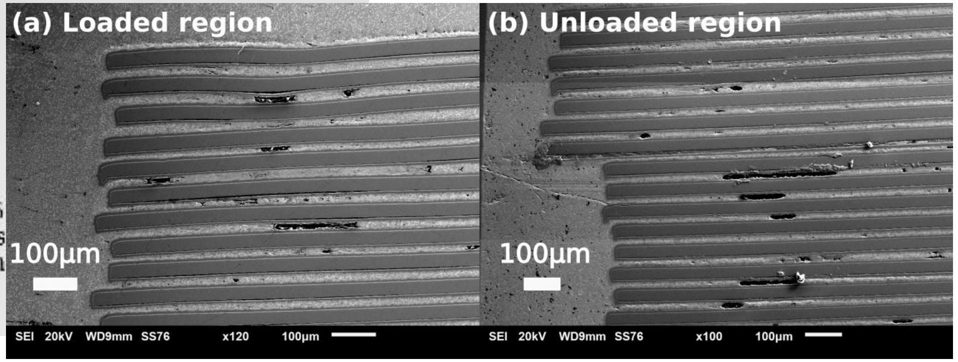
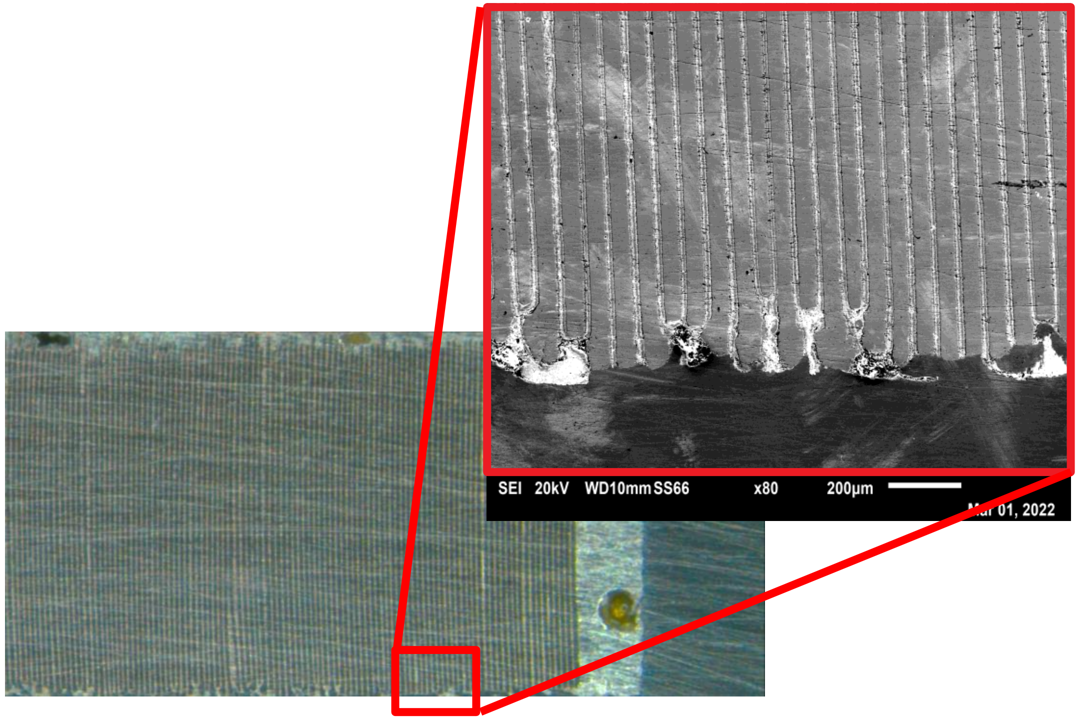
VIPER Cables: Consistent, stable Ic (<5% Ic degradation) after 1500 IxB cycles at 382 kN/m loading (all angles with ~0.3% axial strain and O(1) thermal cycles [1,2]

TFMC: Negligible Ic degradation after fabrication and several IxB cycles at >800 kN/m (perp. to REBCO plane) (small, isolated damage in low-frequency solder voids)









Mu2e Lesson: REBCO mechanical performance under EM load + cycling proven under much more extreme conditions than a Mu2e solenoid

[1] Z. Hartwig *et al.*, SuST, **33** (2021) 11LT01
[2] V. Fry *et al.*, SuST, **35** (2022) 075007

LL #4: REBCO's proven ability to deliver high-field @ 20 K and high-current @ 77 K enabled innovative ancillary technologies

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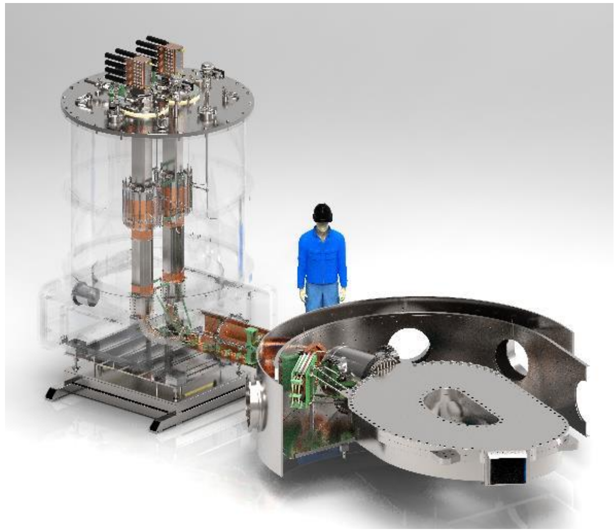
Liquid-free cryogenic system for large-scale magnets

- SHe down to 15 K and up to 25 barA (~60 g/s) with a total cooling capacity of 600 W @ 20 K
- Significantly reduced the schedule, cost, complexity and footprint of the TFMC test facility
- Insulated TFMC from helium shortages and enabled on-schedule, low operational cost tests

LN_2 cooled binary current leads

- Capable of providing 50 kA of current (or more … tests upcoming) w/ no consumption of helium
- Lower REBCO section built to achieve Ic = 59 kA @ 77 K (even higher with sub-cooled capability)
- Further reduces reliance on large, expensive, and difficult to supply liquid helium systems



Mu2e Lesson: In a helium scarce world, REBCO enables Mu2e to build large-scale magnets with benefits of lower cost, faster schedules, smaller and simpler facilities, and less schedule disruptions.

LL #5: Maximizing defect tolerance in REBCO cables and magnets is advantageous to magnet builders and REBCO suppliers

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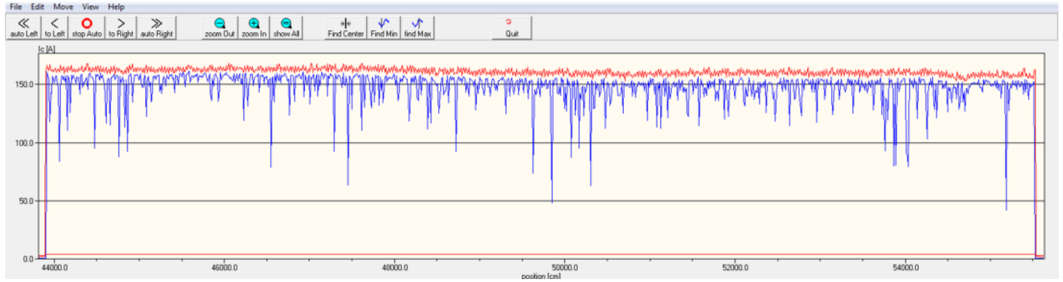
How do we use this (or worse!) REBCO tape?



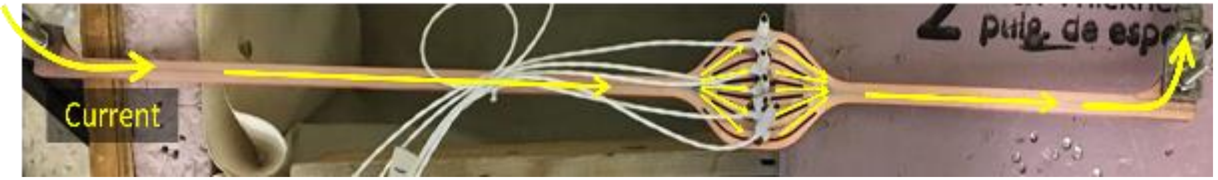
Defect-tolerant REBCO magnets have significant upside:

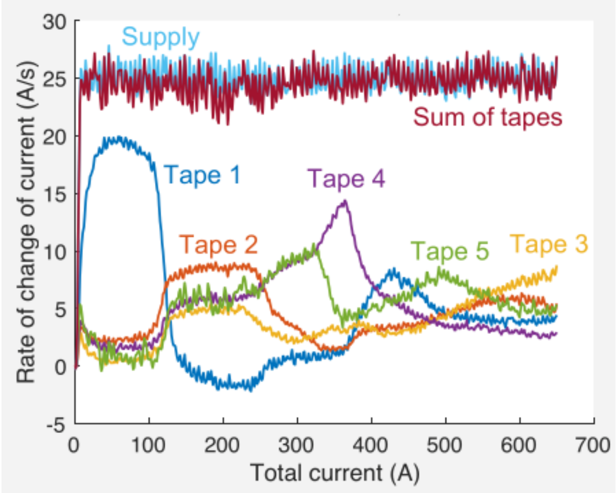
- Increase REBCO manufacturers' usable yield
- Reduce resource-intensive QA/QC processes
- Relax tight constraints on fabrication processes
- Improve robustness of magnets in operation

We are presently conducting R&D to maximize the defect-tolerance of REBCO cables and magnets

- MIT/CFS has tested "dropout cables" with high degree of mechanically imposed REBCO damage
- TFMC included REBCO with some defects with no issues
- MIT research into fundamental physics impact of defect behavior leading to predictive foundation for optimizing designs towards maximum use of "cutting room floor tape"

Defect-induced current redistribution measurements





Mu2e Lesson: Unlike NbTi/Nb3Sn, REBCO cables can tolerate significant defects, improving manufactureability, operational robustness, cost, and demountable joints.

LL #6: Understanding REBCO performance under high fidelity irradiation conditions is progressing rapidly

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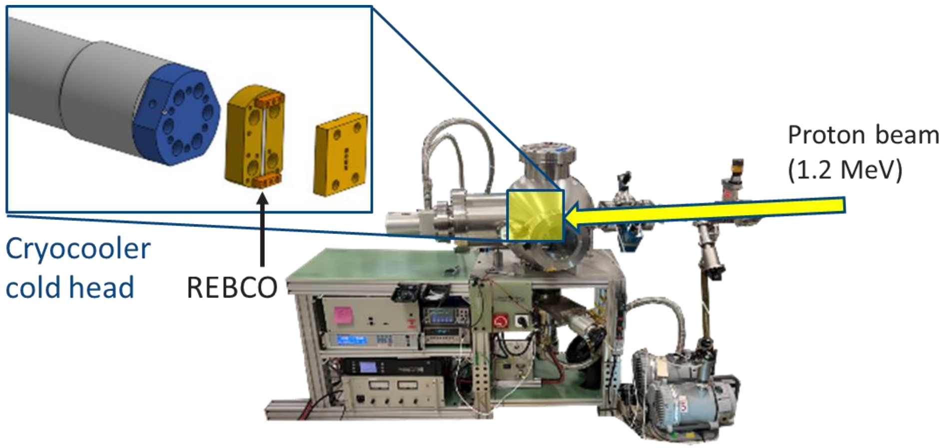


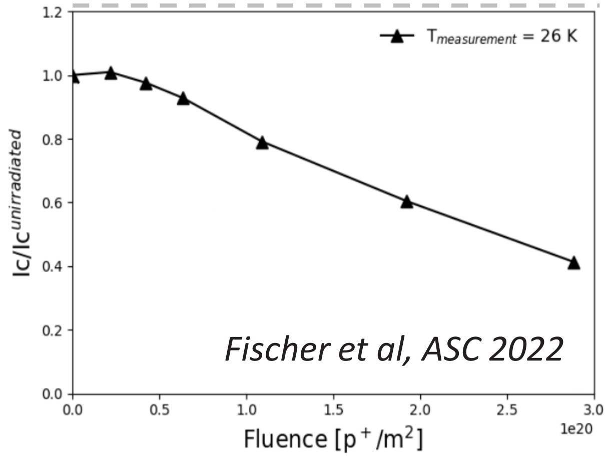
REBCO magnets (in fusion, HENP, medical cyclotrons, etc.) will experience radiation damage <u>under operating conditions</u>

MIT (collaborators in US, Austria, and Italy) are deploying new experimental and computational tools to study cryogenic, in-operando REBCO irradiation for fusion and HEP magnets

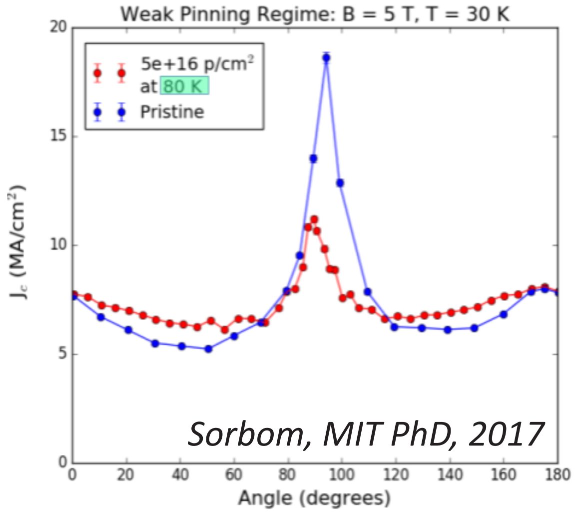
- Understanding REBCO degradation in **operating conditions**
- Connect microstructural evolution to macroscopic changes in critical current to enable Ic preduction under arbitrary radiation loads

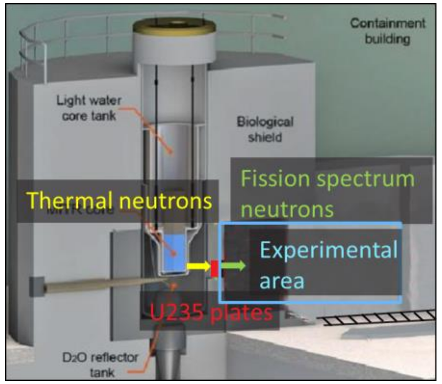
Mu2e Lesson: Opportunity to collaborate and leverage advances in high-fidelity REBCO irradiation understanding and resilience from fusion energy

Proton irradiation at 20 K



Ic(θ) dependence for proton irradiation at 80 K





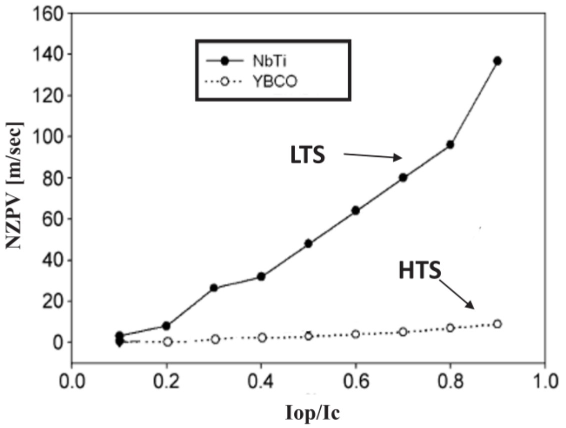
New cryogenic irradiation capabilities at MIT
12 MeV protons (left); fast fission neutrons (right)

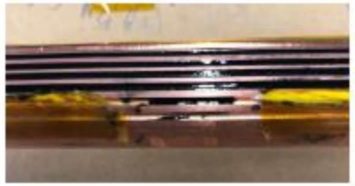
LL #7: Significant progress on quench detection and mitigation, but this remains a key technical risk to retire in full magnets

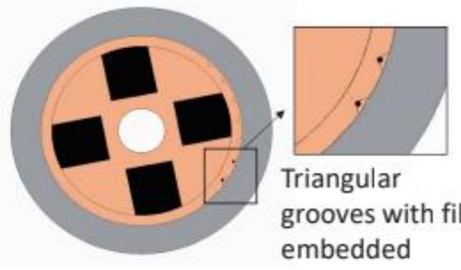
MIT PSFC

Quench detection and mitigation remains a key R&D area especially on large-scale coils.

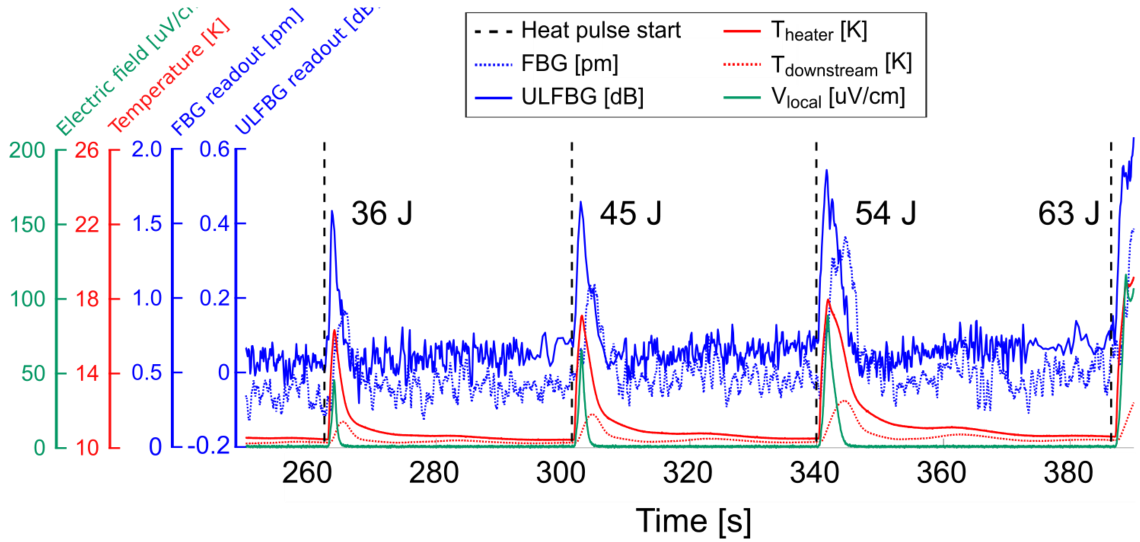
- Voltage tap-based methods promising for DC coils
- Alternative technologies being developed for more challenging AC fast-ramp coils in fusion energy
  - Multiple fiber optic quench detection systems
  - Active and passive acoustic sensors







Multiple fiber optic and acoustic quench technologies are being developed for VIPER cables [1,2,3]



Mu2e Lesson: Opportunity to collaborate and leverage advances in high-fidelity REBCO irradiation understanding and resilience from fusion energy. Mu2e DC solenoid quench detection challenges much easier than fusion AC pulsed magnets!

[1] Z. S. Hartwig *et al.*, SuST, **33** (2021) 11LT01
[2] E. S. Salazar *et al.*, SuST, **34** (2021) 035027
[4] G. S. Lee *et al.* IEEE Sensors, **22** (2022) 21846.

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Scoping a possible Mu2e-relevant VIPER REBCO cable

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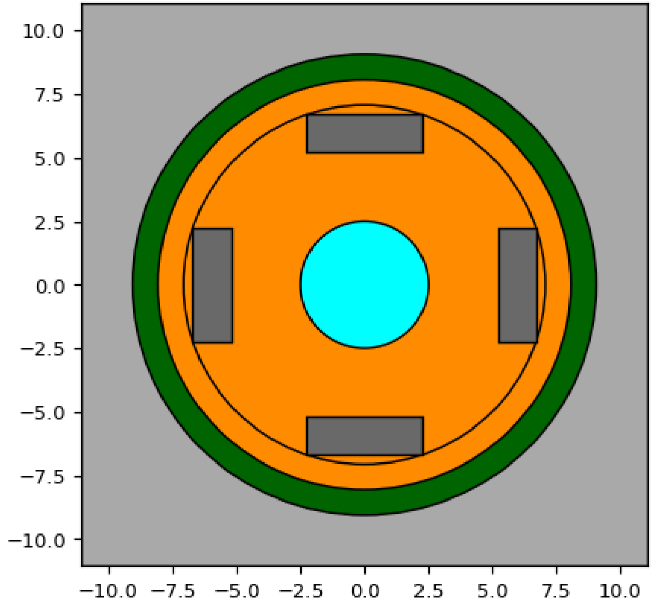
VIPER Cable Parameter	
Number of REBCO stacks	4
REBCO tapes per stack	18
REBCO eng. crit. current (20K, 20T)	700 A/mm^2
Helium coolant channel diameter	5 mm
Cable cross section	22 x 22 mm
Cable critical current (I_c)	32.8 kA
Cable operating current (I_{op})	25.5 kA
Op. critical current fraction (I_{op}/I_c)	0.77
Current density (cable)	52.0 A/mm^2
Current density (copper only)	162 A/mm^2

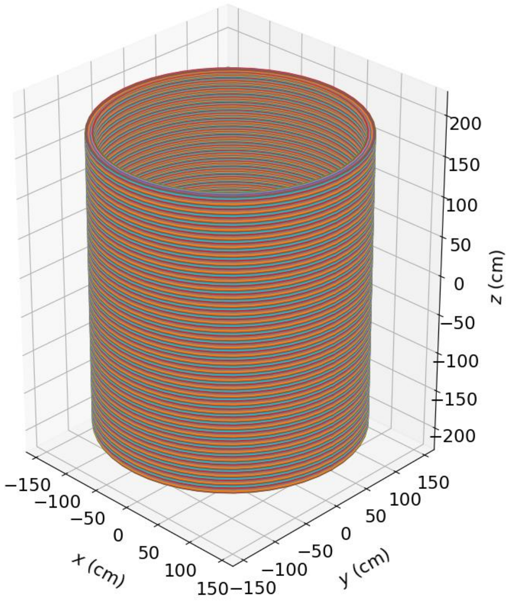


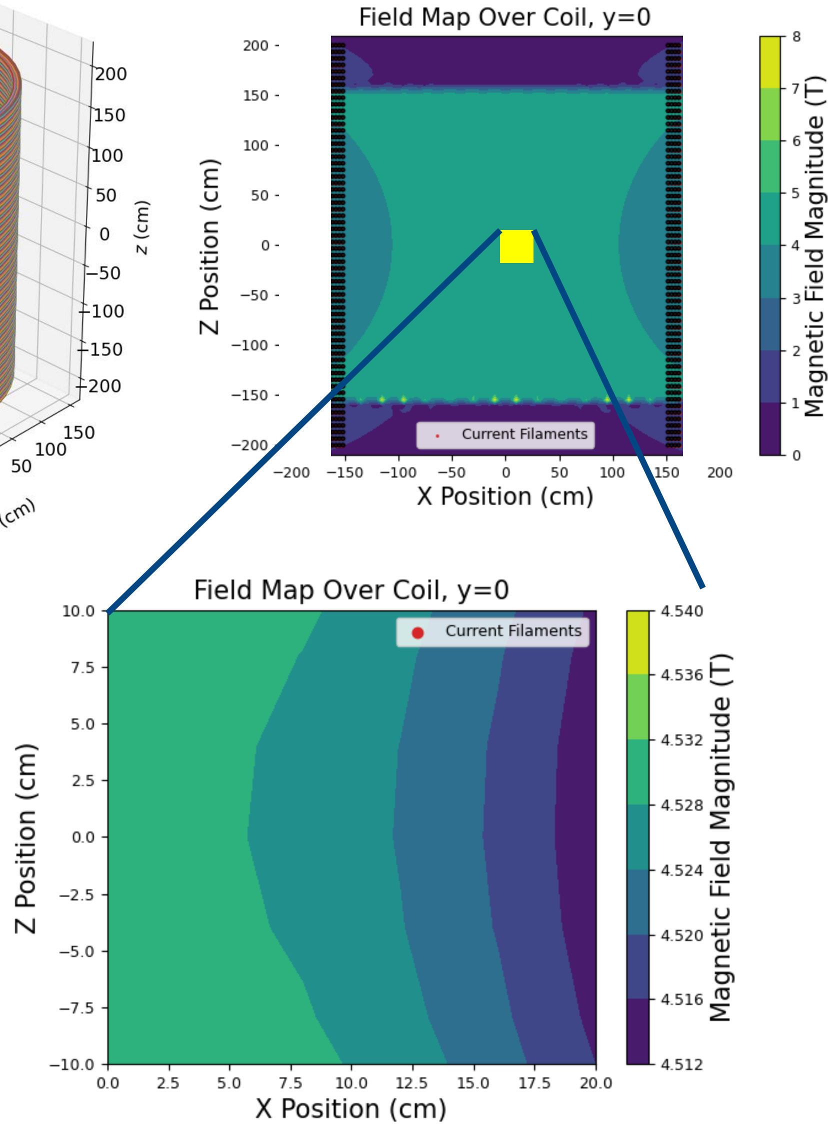
Key point: Preliminary and unvalidated!
Thanks to D. Korsun (PhD student)

Scoping a possible Mu2e-relevant VIPER target solenoid

MIT PSFC

Mu2e Target Solenoid	
Inner radius	150 cm
Outer radius	159 cm
Length	400 cm
Number of turns per pancake	4
Number of pancakes	181
Magnetic field on axis	4.5 T
Total cable length	1758 m
Total REBCO length	126.6 km
Total REBCO cost (assuming $40/m)	$5.0M





Mu2e can leverage advanced in fusion REBCO magnets

MIT PSFC

- Fusion has brought REBCO magnets from benchtop R&D to large-scale magnets
  - Increasing REBCO performance and volume, decreasing cost, providing market pull
  - Building Mu2e-relevant scale cables, magnets, and current leads
  - Actively pursuing remaining technical risks (e.g. quench detection)

- Considerations for using REBCO for Mu2e: What might be the key advantages?
  - Reduced cryogenic demand at 20 – 30 K operation. Liquid-free helium cooling options.
  - Ability to handle very large nuclear heating in magnet cold mass.
  - High cryostability to significantly reduce likelihood of quench.
  - Characterization of radiation damage issues, possibly superior radiation robustness.
  - High current density + structural robustness for compact magnet windings.
  - Use of jointed cables for simpler fabrication and assembly, possible easy repair.

- Myself and team at MIT are open to further discussions and collaboration!