



# Magnet Session Summary

Karie Badgley

Workshop on Future Muon Program at Fermilab

March 29, 2023

# Presenters

- Luca Bottura – CERN
  - Magnet Technology for the Muon Collider: Needs, opportunities, and challenges for HTS
- Zach Hartwig - MIT
  - Leveraging Fusion Superconducting Magnet R&D for an HTS-based Mu2e Target Solenoid
- Cole Kampa – Northwestern
  - Magnetic Field Calculation Tool for Alternative Mu2e-II PS Conductor





# Magnet technology for the muon collider

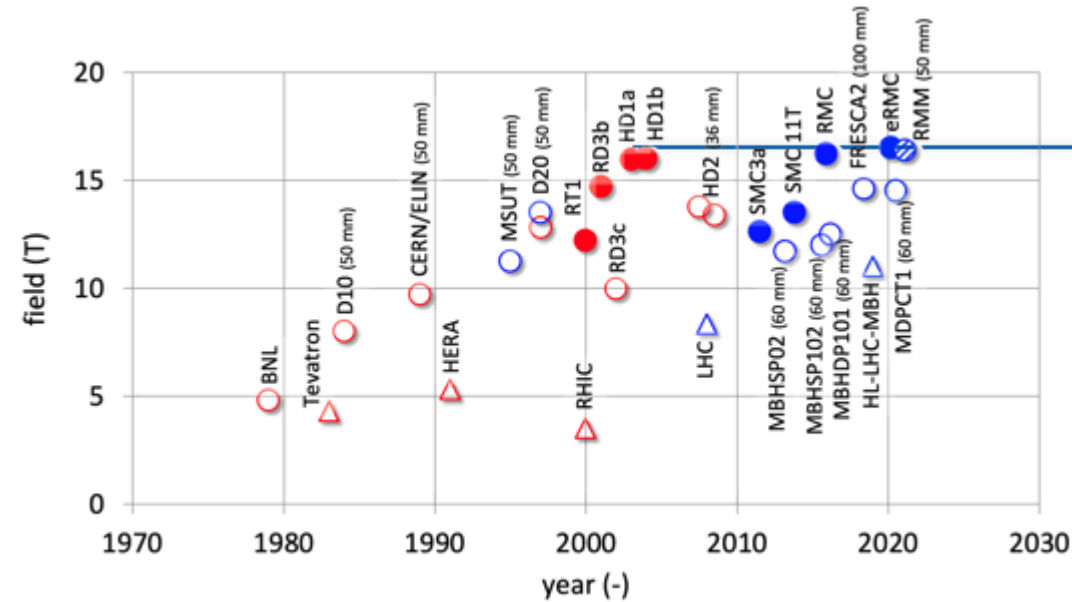
## Needs, opportunities and challenges for HTS

Presented by L. Bottura, CERN

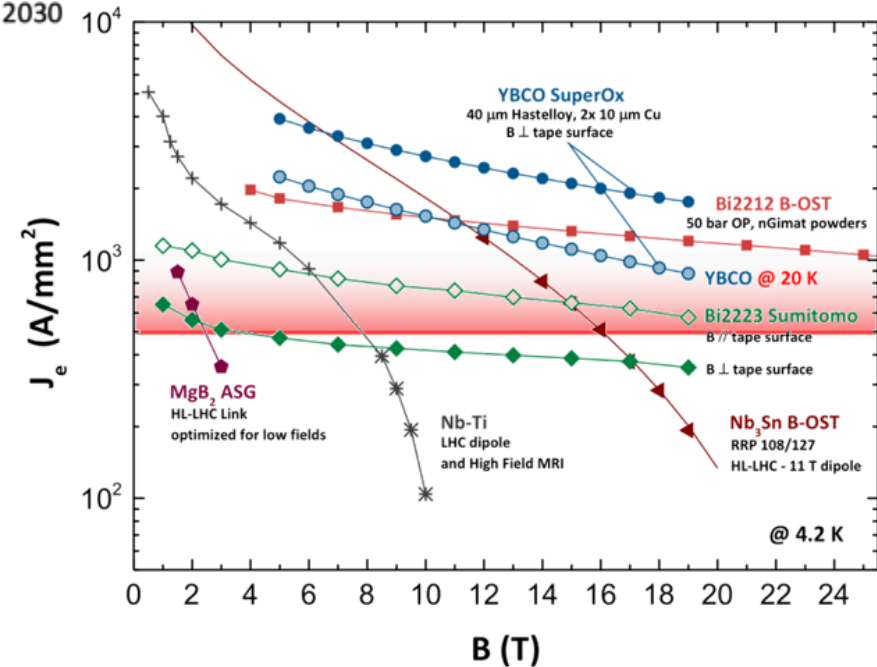


Workshop on Future muon program at Fermilab  
28 March 2023

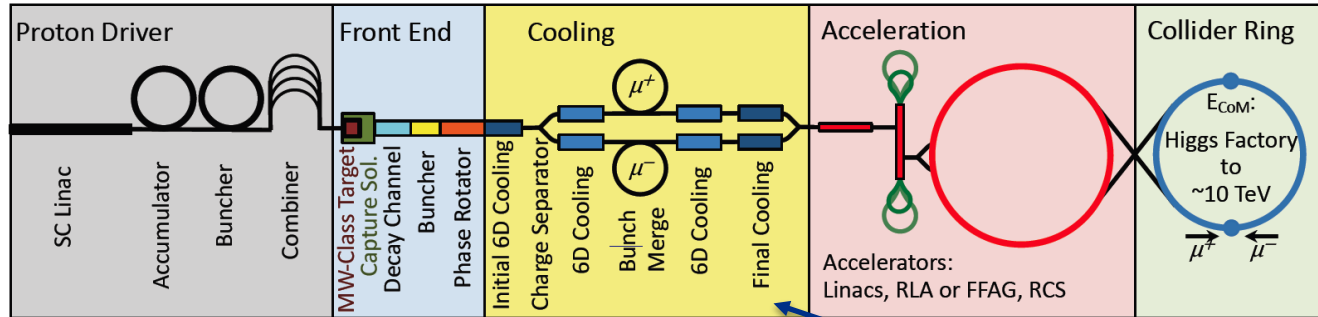
# Currently HTS is the only path beyond 16 T



	LTS				HTS		
	Nb-Ti	Nb <sub>3</sub> Sn	Nb <sub>3</sub> Al	MgB <sub>2</sub>	YBCO	BSCCO	IBS
T <sub>c</sub> (K)	1961	1954	1958	2001	1987	1988	2006
	9.2	18.2	19.1	39	≈93	95 <sup>(5)</sup> 108 <sup>(6)</sup>	16 <sup>(7)</sup> 38 <sup>(8)</sup> 55 <sup>(9)</sup>
B <sub>c</sub> (T)	14.5	≈30	33	18 <sup>(1)</sup> 36...74 <sup>(2)</sup>	≈120 <sup>(3)</sup> ≈250 <sup>(4)</sup>	≈200	40 <sup>(7)</sup> 80 <sup>(8)</sup> 100 <sup>(9)</sup>



# Magnet Challenges of Proton-driven Muon Collider Concept



## Target/capture solenoid

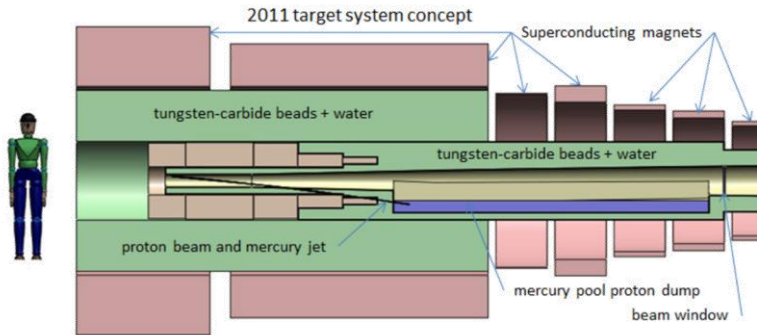
20 T, 200 mm

Radiation dose: 80 MGy damage  $\sim 10^{-2}$  DPA

Large stored E and cryogenic heat load

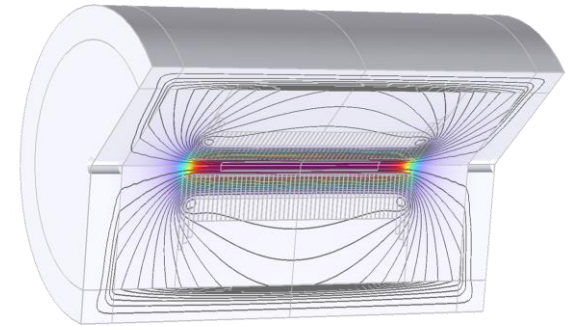
## Final Cooling UHF Solenoid

> 40 T, 60 mm



US-MAP **2011** design  
LTS (14 T) + NC (6 T)

H.G. Kirk, PAC 2011

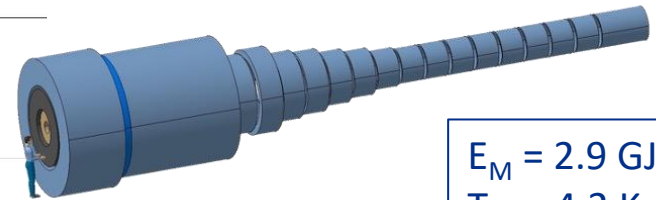
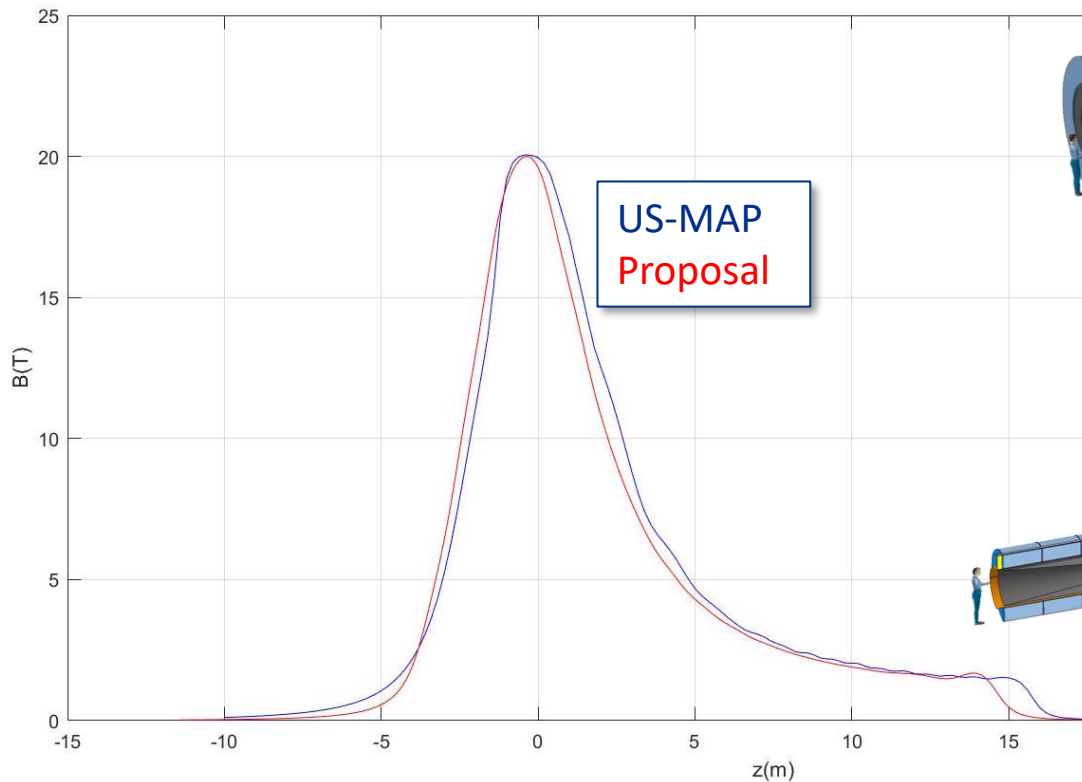
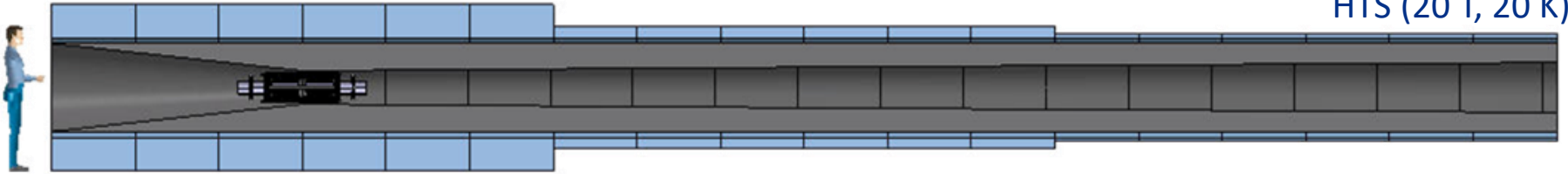


L. Bottura

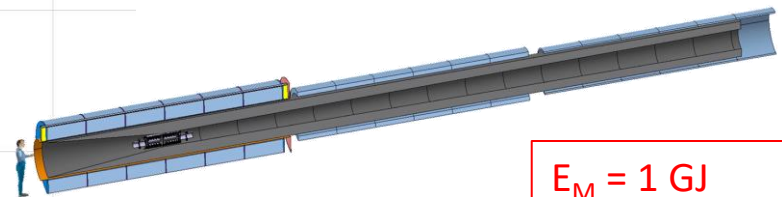
# HTS Target and Capture

Preliminary

MuCol **2022** design  
HTS (20 T, 20 K)



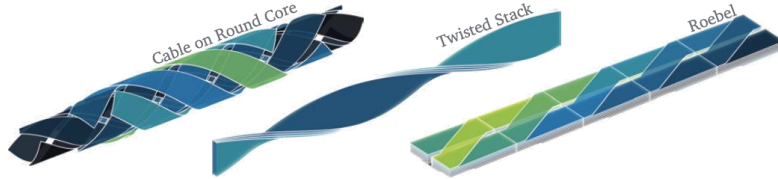
$E_M = 2.9$  GJ  
 $T_{op} = 4.2$  K  
 $M_{coils} = 200$  tons  
 $M_{shield} = 300$  tons  
 $P = 12$  MW



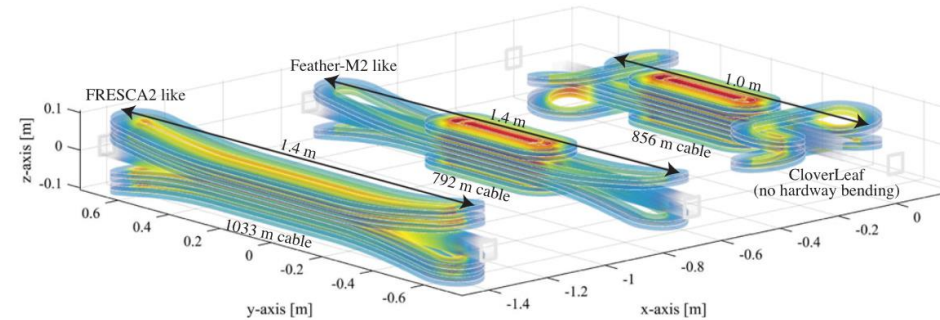
$E_M = 1$  GJ  
 $T_{op} = 10...20$  K  
 $M_{coils} = 110$  tons  
 $M_{shield} = 196$  tons  
 $P = 1$  MW

# HTS Issues

- How to wind



- How to support



Mechanical stresses producing irreversible critical current reduction

- Tensile stress in thickness direction: **10-100 MPa<sup>3</sup>**
- Shear stress > **19 MPa<sup>3</sup>**
- Cleavage/Peel stress<sup>3</sup> (tensile at tape extremities) < **1 MPa<sup>3</sup>**

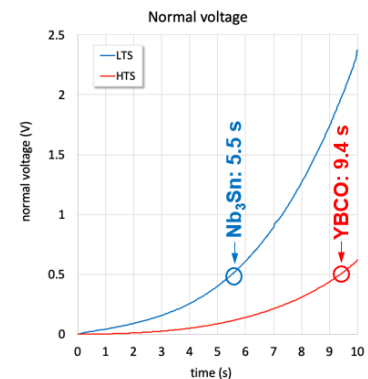
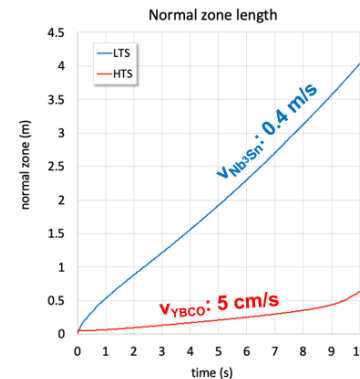
- How to protect

Slow quench velocity leads to localized heating

Non-insulated coils

- How to manage radiation damage

Radiation effects are not fully understood, still needs dedicated characterization

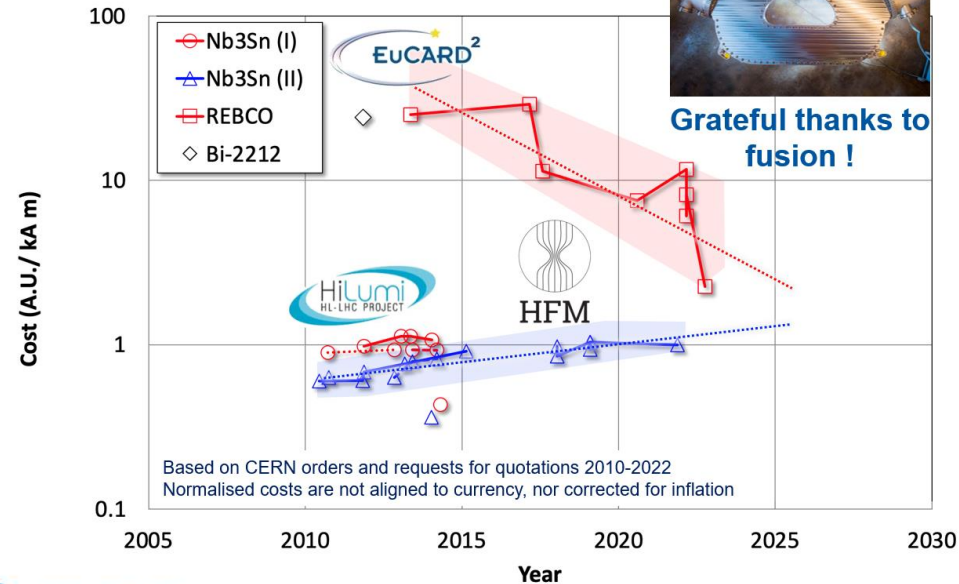


L. Bottura

# Cost

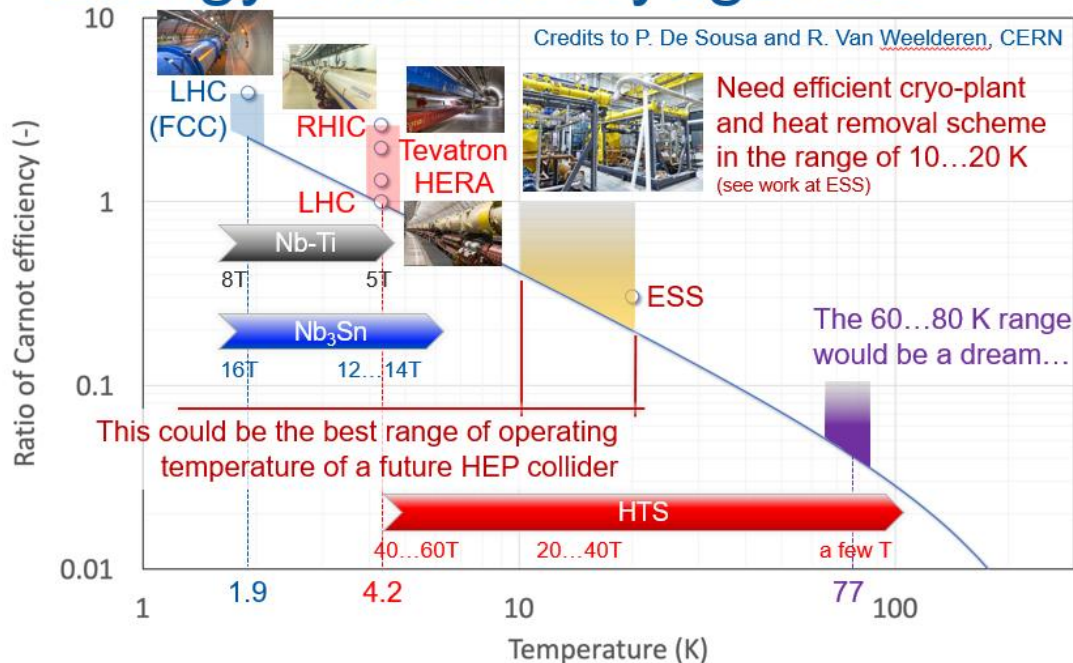
Thanks to advances from fusion, the cost of HTS is nearly the same as Nb3Sn

# Conductor cost



# Energy efficient cryogenics

$$W/Q = (T_h - T_c)/T_c$$



Higher operating T also reduces cryogenic costs

# Summary- Why HTS?

- High temperature superconductors **may be the best technology** (but not the only one!) to make a muon collider affordable and efficient
- HTS magnet technology R&D for a muon collider has **close and tight relation to the advances needed for other science and societal applications**
- We are just starting and many engineering challenges need to be solved, but given the potential of HTS **this R&D is definitely worth the effort !**



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

Zach Hartwig | MIT

Mu2e Collaboration meeting

28 Mar 22

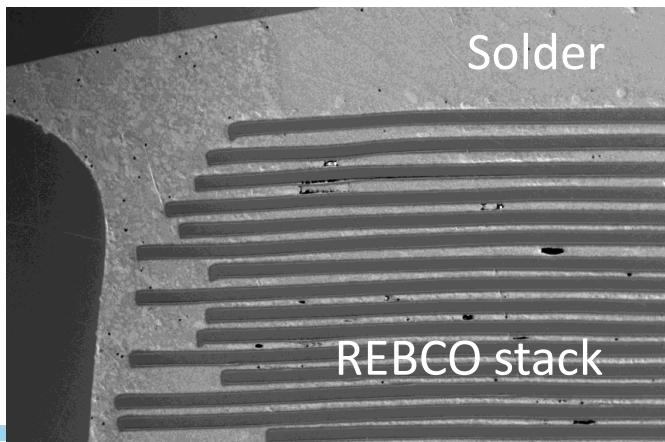


PSFC

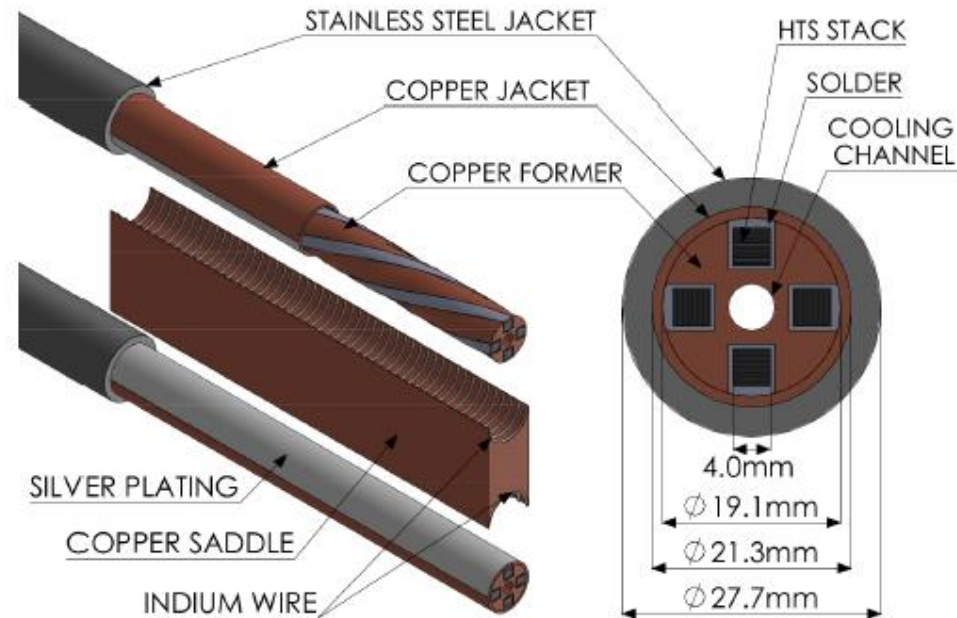
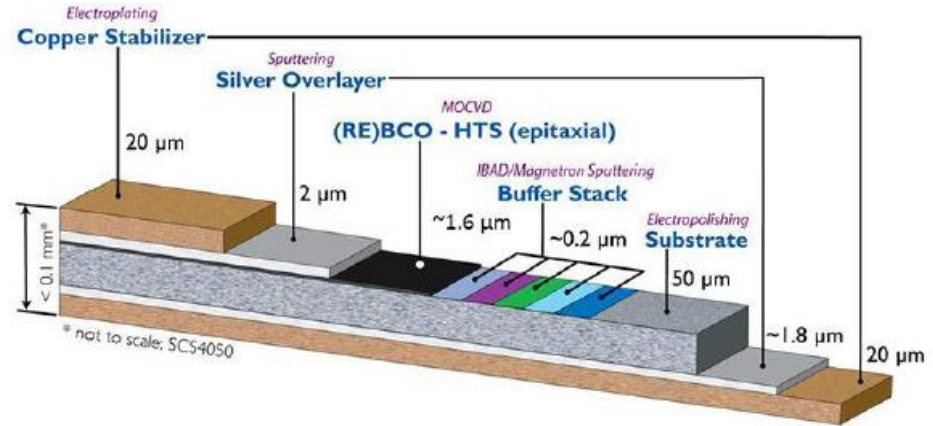
Thank you to Kevin Lynch, Rob Carey, Jim Miller, Lee Roberts

# VIPER REBCO Cable

- Extruded copper former with REBCO slots and cooling channel
- Copper compacted jacket
- VPI solder provides mechanical strength, thermal stability, electrical connectivity
- REBCO stacks are mechanically isolated
- Simple low resistive joints, demountable and reusable

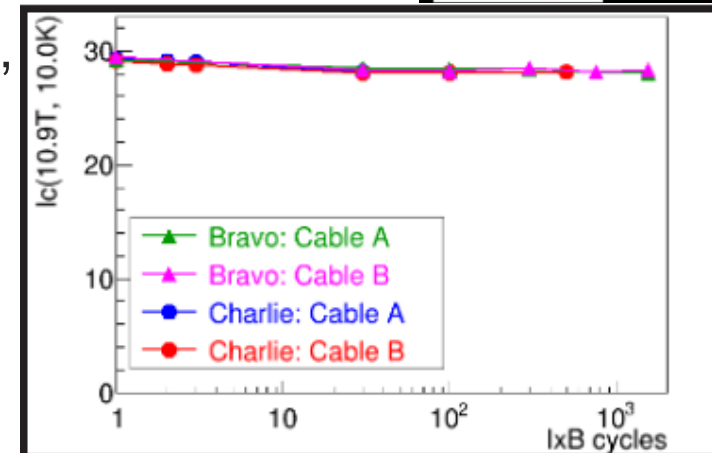
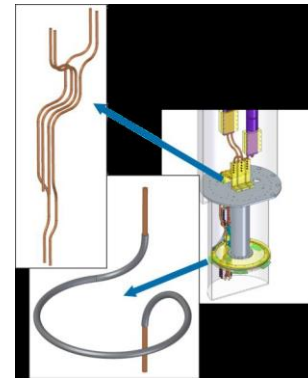


## Rare-earth Barium Copper Oxide (REBCO)



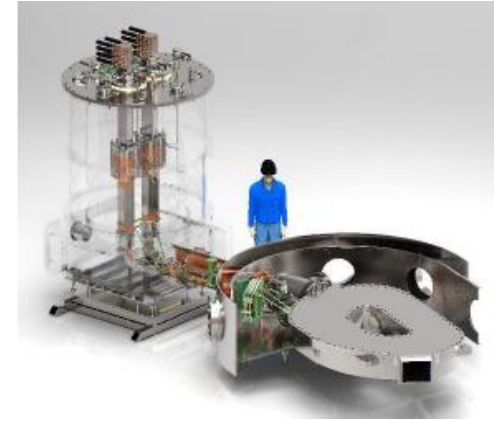
# REBCO Lessons for Mu2e

- Ready for large scale, high field magnets
  - Fusion is driving the REBCO market hard, increasing volume and reducing cost
- Impressively resilient to complex mechanical fabrication and forms
  - Cable proven sufficient in more aggressive shapes than potential Mu2e solenoid
- VPI solder stabilized survives high  $I \times B$  loading, relevant axial strain and thermal loading
  - Proven performance under loads more extreme than Mu2e solenoids

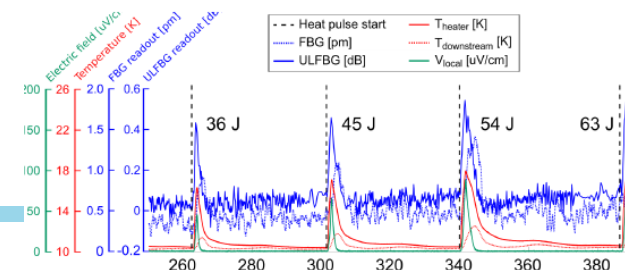
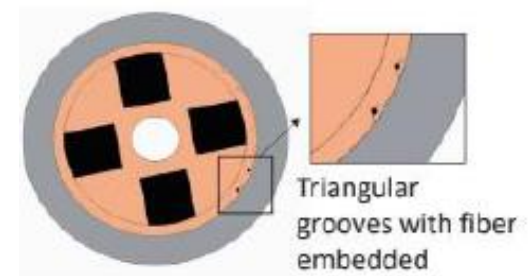


# REBCO Lessons for Mu2e

- Ability to deliver high field at 20K and high current at 77 K
  - In He scarce world, REBCO enables Mu2e to build large magnets with low cost and simpler cryo facilities
- Defect tolerant
  - Can tolerate significant defects, improving manufacturability, operational robustness, cost, and demountable joints
- Understanding radiation performance progressing rapidly
  - Opportunity to collaborate and leverage from fusion
- Progress on quench detection and mitigation, remains a risk to retire for full magnets
  - Opportunity to collaborate. Mu2e DC solenoid easier than AC fusion magnets



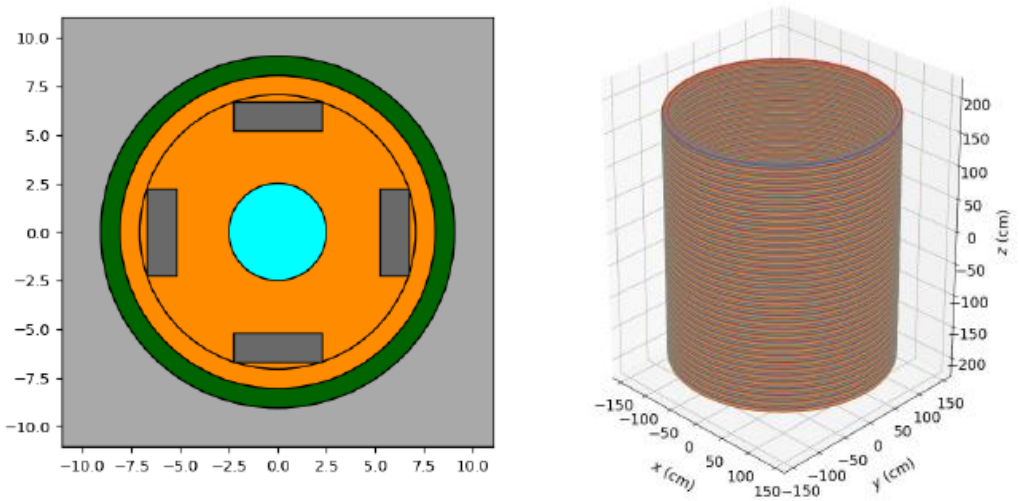
LN2 cooled 50 kA leads



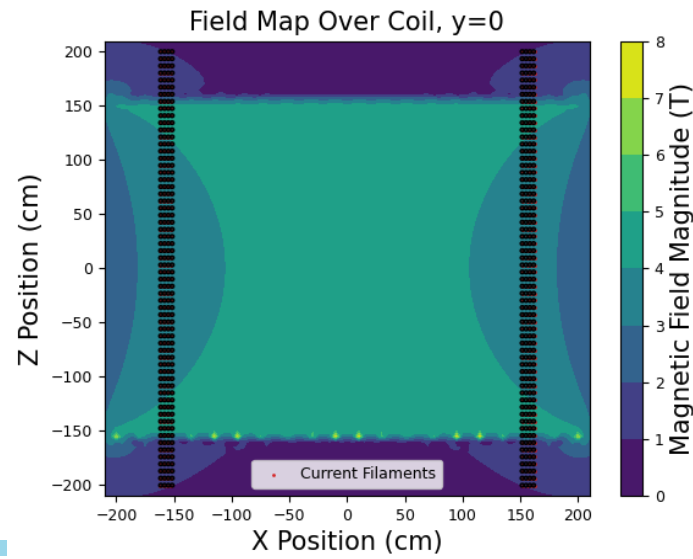
Viper Cable for Mu2e Solenoid

Preliminary and unvalidated  
Z. Hartwig and student D. Korsun

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



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



# Summary: Mu2e can leverage advances in fusion REBCO magnets

- 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!

# Magnetic Field Calculation Tool for Alternative Mu2e-II PS Conductor CalTech Workshop

**Cole Kampa, Michael Schmitt**

Northwestern University

March 28, 2023

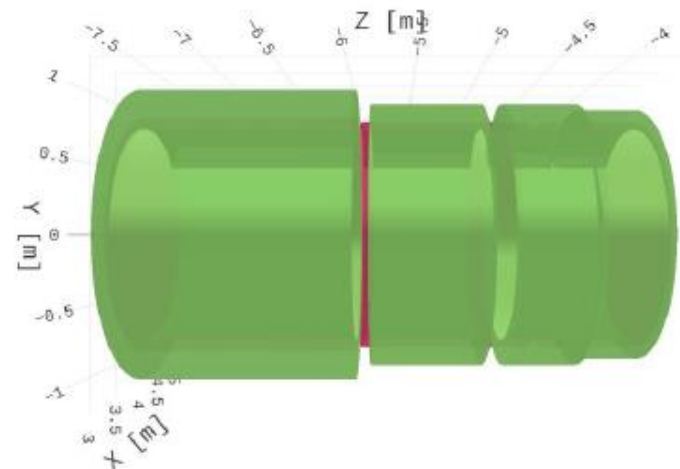
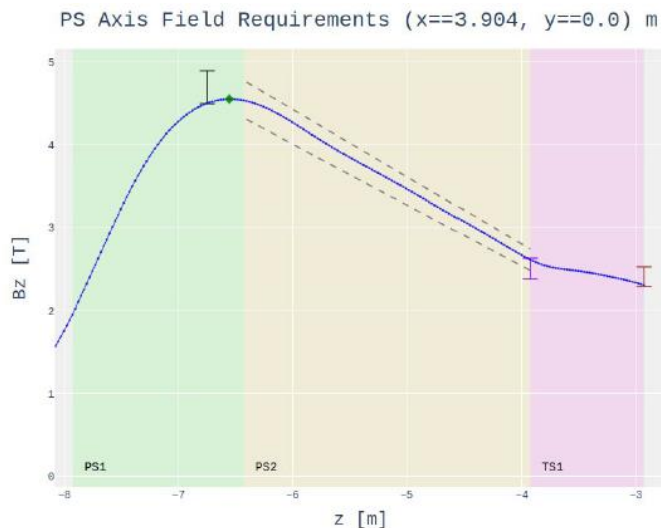
# SolCalc +GUI

Repo: [https://github.com/Mu2e/FMS\\_helicalc](https://github.com/Mu2e/FMS_helicalc)

GUI: [https://github.com/Mu2e/FMS\\_helicalc/tree/main/scripts/SolCalc\\_GUI](https://github.com/Mu2e/FMS_helicalc/tree/main/scripts/SolCalc_GUI)

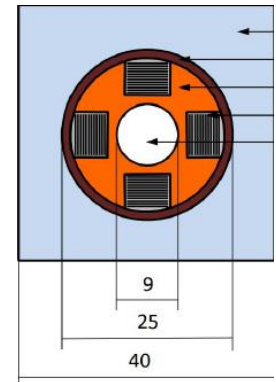
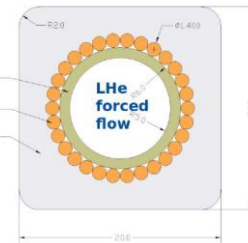
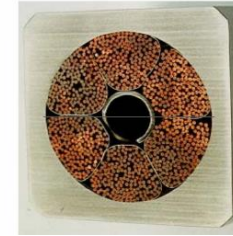
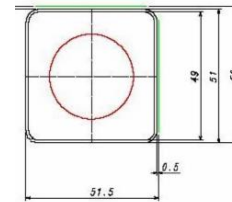
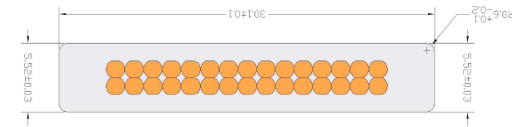
Commit: [6232a8a894405d7da44e8e75469e74fb6a9b24a7](https://github.com/Mu2e/FMS_helicalc/commit/6232a8a894405d7da44e8e75469e74fb6a9b24a7)

- SolCalc is built in to the helicalc Python package that Mu2e uses for magnetic field calculations
- Converted SolCalc from Matlab to Python and added a GUI
- Plots fields to determine if specs are met
- 3D plot of coil configuration
- Calculates cable length and resistive power for non-sc conductor
- Tunable coil and conductor parameters



# Conductor Options

1. Mu2e PS conductor (NbTi SC, Al stabilized)
2. Cable-in-conduit (CICC, SC)
3. Internally-cooled Al stabilized cable (ICASC, SC)
4. High-temperature superconductor (HTS, SC)
5. Water-cooled resistive coil (RC)
6. LN2-cooled resistive coil (RC)



# Conductor Options

## Lengths of Cable & Power Consumption

1. Mu2e PS (NbTi): 8.65 km
2. CICC (Nb<sub>3</sub>Sn): 2.18 km (4 coils, used 42,000 A instead of nominal 45,000 A)
  - a. ITER central solenoid: 5.94 km. Not sure the cost.
3. ICASC (NbTi): 9.81 km (used 8,900 A instead of nominal 9,200 A)
4. HTS (VIPER REBCO): 1.44 km (4 coils)
5. Water-cooled Cu: 112 km, 6.28 MW (far from spec)
6. LN<sub>2</sub>-cooled Cu: 13.5 km, 7.11 MW (5 coils; in spec; did not extend into HRS)

C. Kampa

# Summary

- Adapted the SolCalc ideal solenoid integrator to include a GUI for studying different conductor configurations for the Mu2e-II PS.
- Started exploring different proposed conductors to see if a field within spec seems plausible to construct
  - Cable-in-conduit conductor: Yes, but coldmass outer radius is larger than Mu2e.
  - Internally-cooled Al stabilized cable: Yes, but coldmass outer radius is larger than Mu2e.
  - HTS: Yes
  - Water-cooled resistive coil: Maybe, but needs serious tuning. Very large footprint.
  - LN2-cooled resistive coil: Yes, but needs tuning to decrease power consumption.

## Next Steps

- Fine tune parameters to get a field in-spec for each conductor type, if possible
- Generate a complete PS map and TSu map which can be used in simulations