U.S. MAGNET DEVELOPMENT PROGRAM

REBCO work at LBL

X. Wang

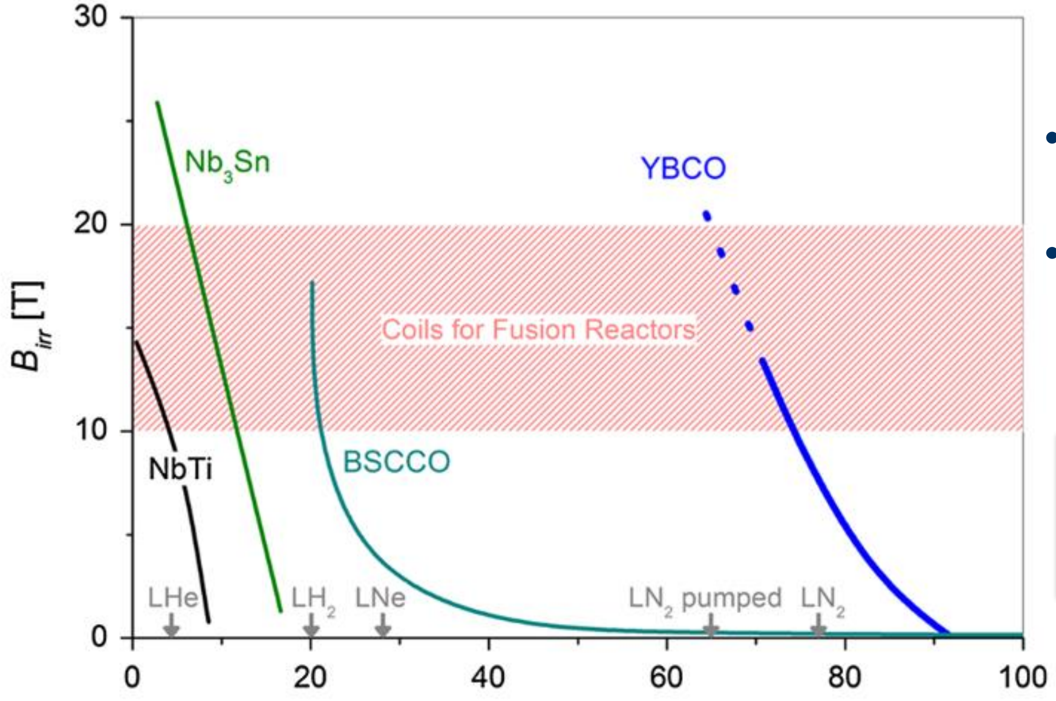
REBCO Round Table, Fermilab, 11/2/2023

Acknowledgments

- U.S. Magnet Development Program, DOE Office of HEP
- SBIR programs, DOE Office of HEP
- DOE Office of FES

- Colleagues at LBL, ASC/FSU, BNL and FNAL

REBCO can be the dream magnet technology for future circular colliders



Whyte16, Larbalestier01

- 20 T dipole field at 20 K with LH_2
- Presently the only conductor with a dozen vendors and a potential market [Vlad's talk]

A capable, affordable and sustainable collider

Today REBCO is a curious nightmare

- Least advanced magnet technology
  - 4.5 T maximum dipole field so far (EuCARD2 Feather2 magnet)
- We know little about it
  - Lots of open questions

We try to address a few selected driving questions

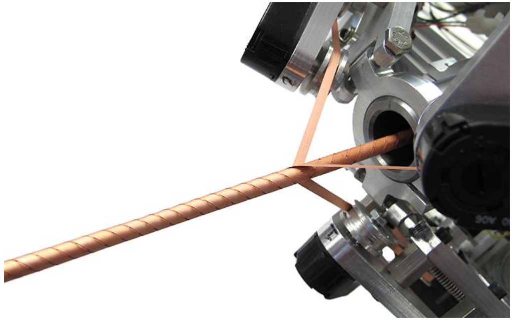
- How to make magnets using REBCO conductors?
- What kind of conductor works?
- What's the maximum field we can generate?
- What's the magnet performance? What are the performance-limiting factors? How do they fail?

So what?

We focus on round wires with industry partners

SBIR programs enabling effective collaboration

CORC® wire



https://www.advancedconductor.com/

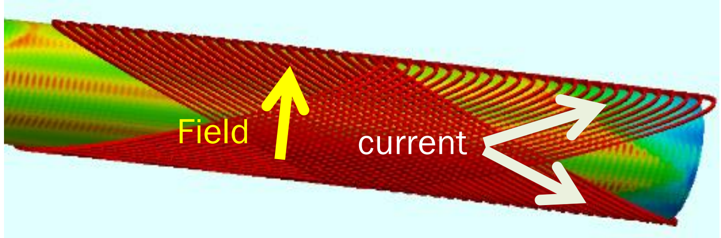
STAR® wire

http://www.ampeers-llc.com/

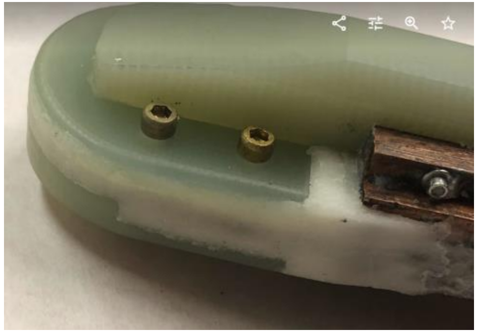
CCT is the main design for the baby magnets

- Canted cosθ design is attractive for high-field magnets
  - Reduce conductor stress
  - Provide good geometric field quality
  - Cancelled solenoid field lowers efficiency

- Leverage the effective development for Nb_3Sn CCT
  - Wax-impregnation for STAR® wires by José Luis and Diego



Meyer+Flasck70, Arbelaez22



We are making tools to build magnets

Reproducible winding

- REBCO is brittle and sensitive to handling

Magnet mandrel

Conductor spool

Human interface

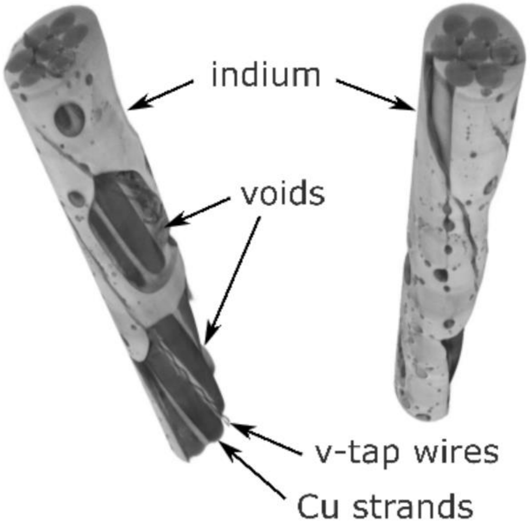
Master

We are making tools to build magnets

Low-resistance termination

- < 50 nOhm up to 12 kA at 4.2 K

A first prototype one on a 6-around-1 STAR® cable



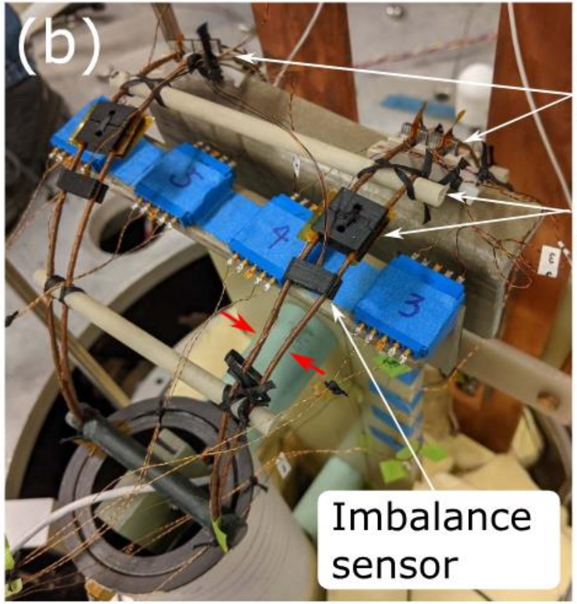
Micro-CT image from U. Houston

We are making tools to understand magnets

Diagnostic instrumentation for insight into magnet behavior

- Acoustic sensing
- Magnetic sensing
- Fiber-optic sensing

Magnetic sensing, more from Reed's talk



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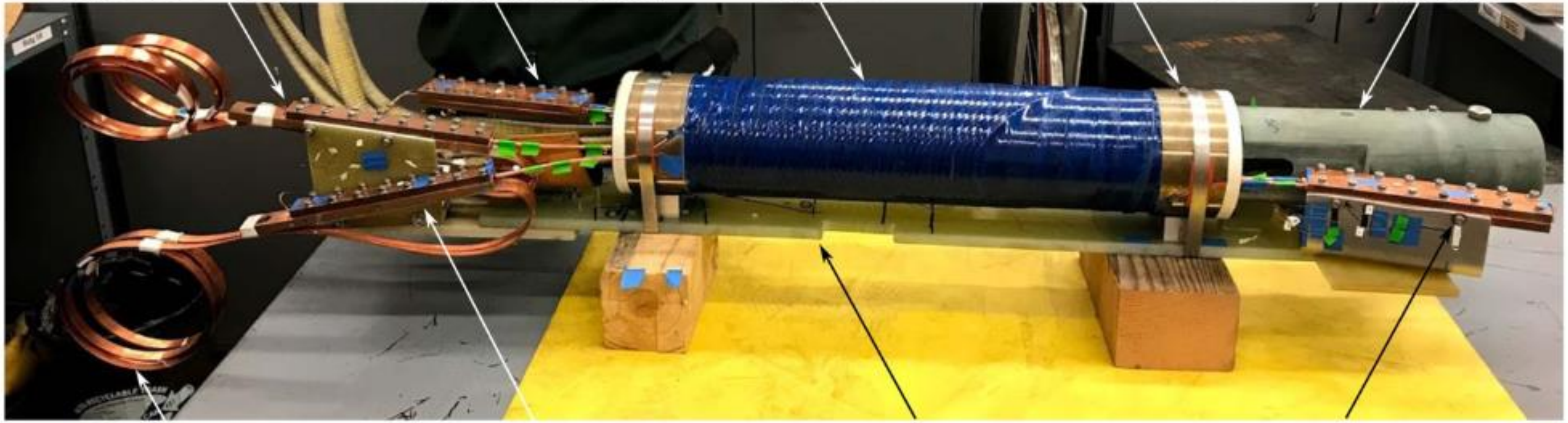
C2 with CORC®
generated 2.9 T dipole field at 4.2 K



C2

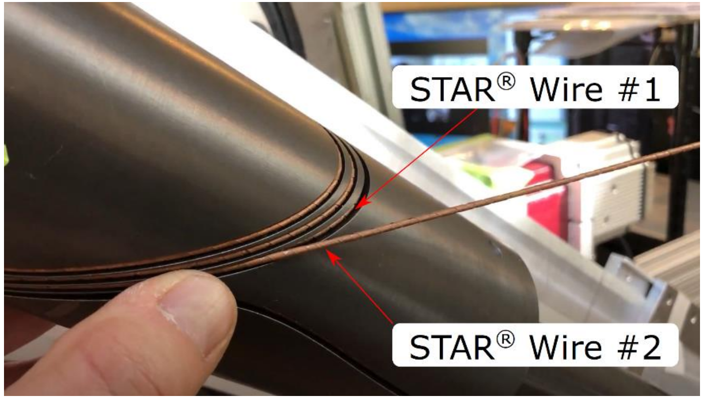
C3 with CORC®
aims at 5 T dipole field at 4.2 K

- Test the subscale version by December
- Test the full version in 12 months

Subscale C3

s1 with STAR® wires aim at 2.9 T stand-alone, 1.2 T @ 8 T background field

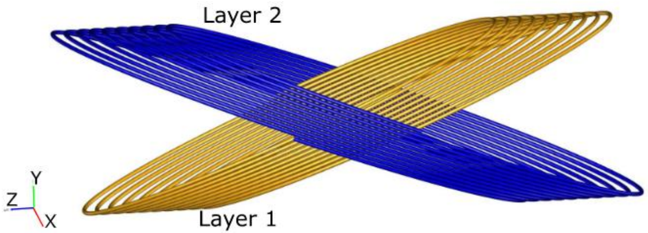
s0 with STAR® wires



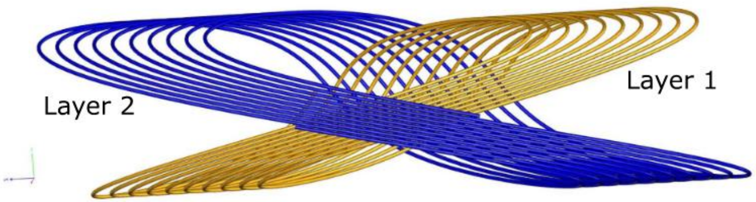
Little solenoid wound using transposed STAR® cable

150-mm aperture design: dipole and combined-function for muon collider. Pushing the field!

CCT dipole



Dipole-quad combined function



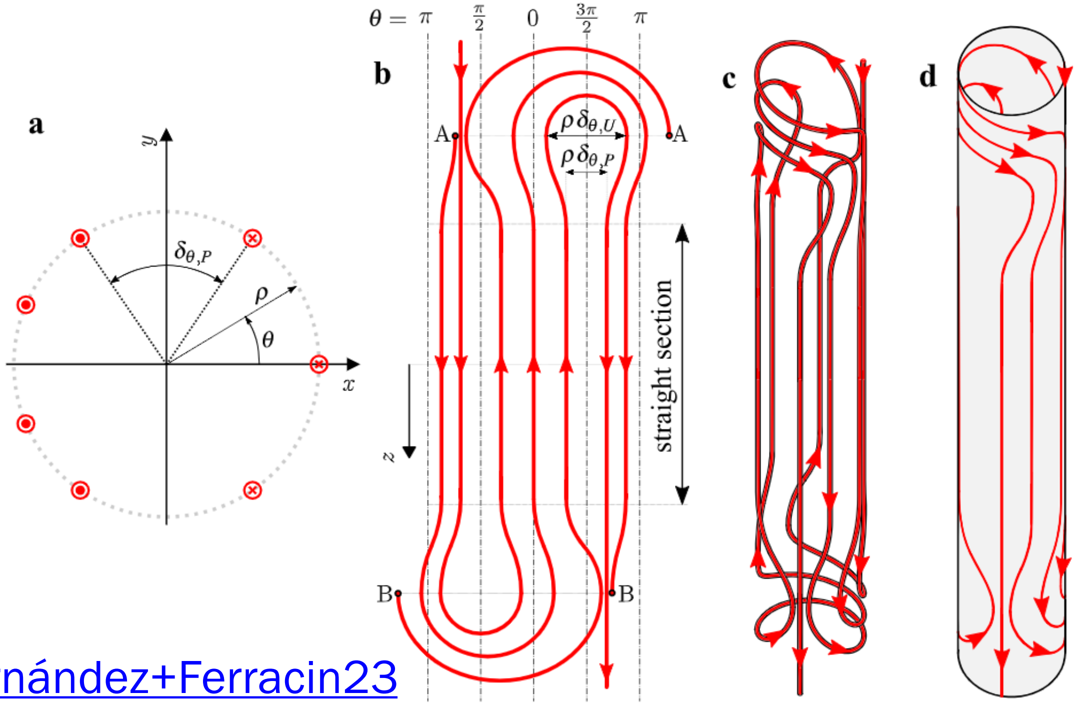
Number of layers		4			6		
Number of wires per layer		1	2	3	1	2	3
TF	T kA^{-1}	0.52	0.51	0.51	0.79	0.78	0.77
$B_p/B_1 - 1$	%	5	2.4	0.5	2.2	0.4	0.2
L	mH m^{-1}	11	12	13	30	34	40
R_{min}	mm	30					
OD	mm	229	262	294	270	319	368
B_1(4.2 K)	T	5.6	8.3	10.5	7.2	10.6	13.2
I_{total}(4.2 K)	kA	10.7	16.1	20.5	9.0	13.6	17.2
E(4.2 K)	MJ m^{-1}	0.6	1.6	2.8	1.2	3.1	5.8
B_1(20 K)	T	3.8	5.6	7.1	4.8	7.2	8.9
I_{total}(20 K)	kA	7.2	10.9	13.9	6.1	9.2	11.6
E(20 K)	MJ m^{-1}	0.3	0.7	1.3	0.6	1.4	2.6
l_{wire}	km m^{-1}	0.4	0.9	1.4	0.7	1.4	2.3
l_{tape}	km m^{-1}	23	51	80	40	80	131

An initial look

Explore new magnet designs for higher fields

Uni-layer design

- Addressing bend radius and efficiency issues of other designs



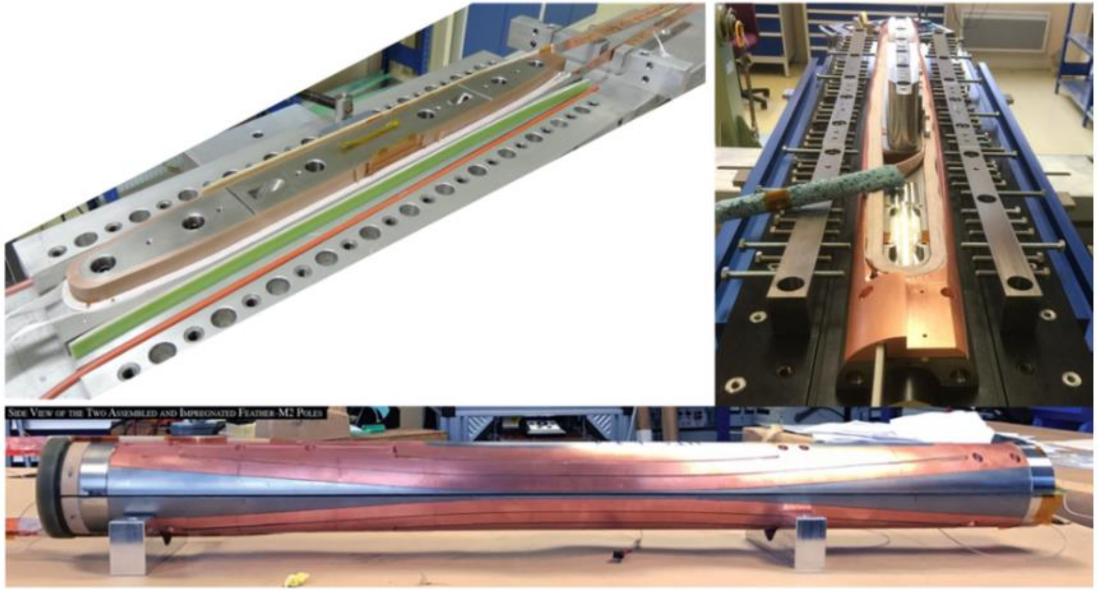
[Rudeiros Fernández+Ferracin23]

U.S. MAGNET DEVELOPMENT PROGRAM

Copy & paste impressions of the European activities from the ongoing HFM meeting

EU has led the development of REBCO magnet technology

Successfully demonstrated REBCO dipole magnets using Roebel cable, generating 4.5 T at 4.2 K



Rossi+Senatore21

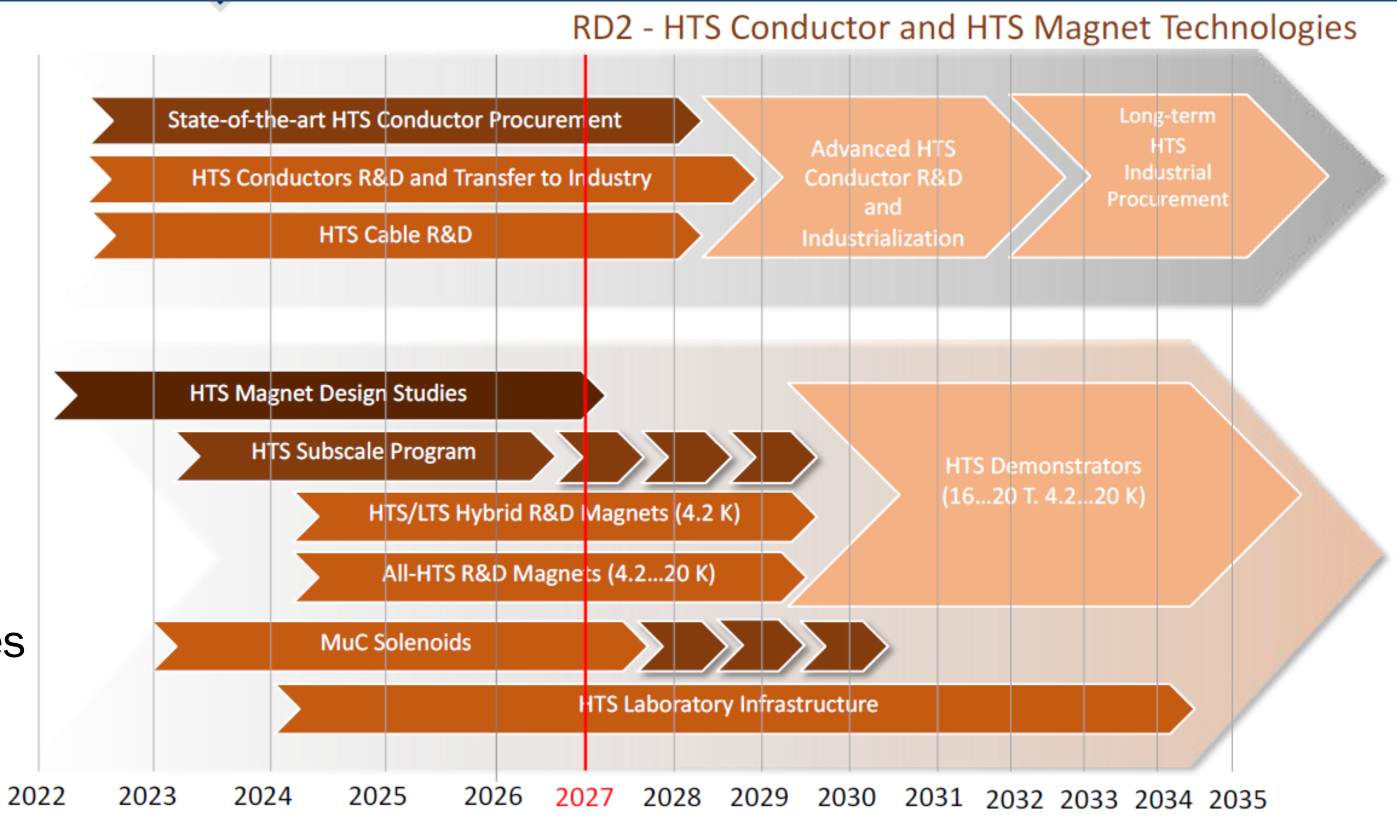
U.S. MAGNET DEVELOPMENT PROGRAM

Demonstration the suitability of HTS is one of three objectives of the new High Field Magnet Program

Conductor R&D

Magnet R&D

Multiple institutes



indico link

Stacked-tape cable is a focus for HFM – CERN

Overview of CERN activities REBCO Coils

- **Short Model Coil HTS Program** to test novel cables in a coil configuration: windibility, quench protection,
  - Target: **5 T - 8 T** at up to **10 K** in a **background field or 12 T-15 T**
- **Racetracks**
  - Full HTS
  - Hybrid (HTS in Nb_3Sn background field). Synergy with RD4 and with the extensive SMC Nb_3Sn program carried out at CERN
- Pancake **solenoids**

indico link

CERN is also studying round wires

Superconducting cables

- Designed, built and operated - as from mid 2022 – a **cabling machine** for making round, flexible and insulated **REBCO cables** Work done in the framework of HL-LHC Cold Powering: **up to 18 kA @ 60 K** and 0.7 T. About 1 km needed, in ULs of 2-4 m. No degradation of conductor after cabling
- Studied **different cable layouts** (core, number of layers, Φ,…)
- Implementing a **reel-to-reel system** for cabling long unit lengths
- We will use of these cables in **coils**

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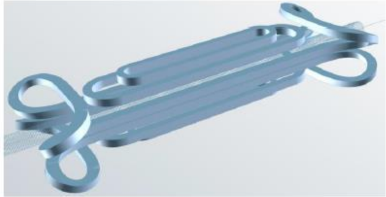
Stacked-tape cable is a focus for HFM – CEA

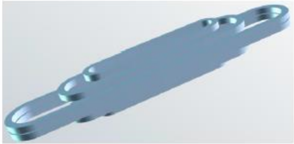
1. Program roadmap: Development main phases

Demonstrator of the metal-insulated REBCO high field magnet coils - CEA

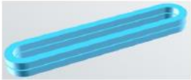
Phase 3 :
MI
16 T+ dipole magnet



Phase 2 :
MI 16 T+ dipole field
« EuCARD1 V2 »



Phase 1 **2023-2025**:
Racetrack MI



KE5647

Start: 01/04/2023
End: 31/03/2025

HFM Annual meeting Oct. 31th, 2023 - Demonstrator of the metal-insulated REBCO high field magnet coils- Thibault Lécrevisse 31/10/2023 4

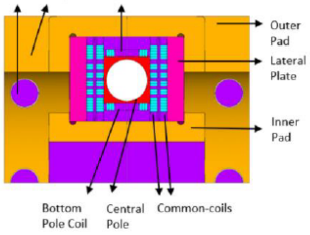
[indico link]

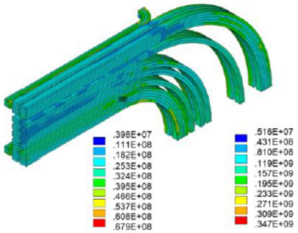
Stacked-tape cable is a focus for HFM – PSI

PAUL SCHERRER INSTITUT

Subscaling

ReBCO racetracks chosen for pole coils in upcoming Hybrid common-coil (LTS/HTS) magnet at 4.2 K (design by D. M. Araujo and CHART team).

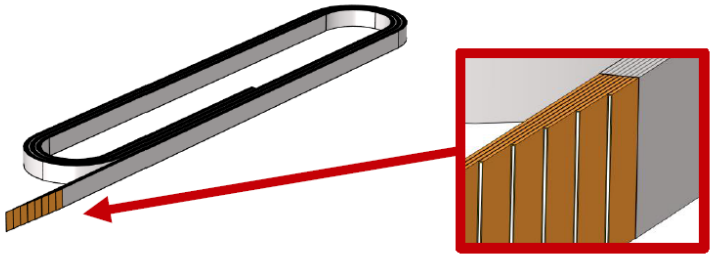




Pictures taken from pending paper of Douglas Martins Araujo

Based on current design of Hybrid magnet, we have the following requirements for ReBCO racetrack :

- **4-mm** tape **width**
- **8 tapes** in soldered **stack**
- **7.5 mm** – minimal bending **radius**



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Insulated solder-stack block coil 16-T benchmark

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Stacked-tape cable is a focus for HFM – INFN

Summary

INFN LASA

- Ongoing R&D to increase TRL of HTS magnets
- Started a program for small HTS coils production and test
- INFN is building and testing HTS magnets in next two years
- Update the test stations for variable temperature
- Several synergies in developing HTS magnets have yet to be fully exploited
- HF and UHF HTS solenoids will be one of the leading themes in an upcoming INFRA-TECH EU call
- Dedicated R&D for MgB_2 conductor for new magnets, refurbished ones and sustainability (see IRIS by L. Rossi on Thursday)

HFM High Field Magnets

iFAST

International MUON Collider Collaboration

IRIS – Innovative Research Infrastructure on applied Superconductivity

Italiadomani – Piano Nazionale di Ripresa e Resilienza

Finanziato dall'Unione europea NextGenerationEU

Marco Statera   HFM annual meeting 2023, CERN   16

[indico link]

IMCC is exploring REBCO magnet technology

Magnet development targets

Complex	Magnet	Aperture (mm)	Length (m)	Field (T)	Ramp rate (T/s)	Temperature (K)
Target, decay and capture channel	Solenoid	1200	19	20	SS	20
6D cooling channel	Solenoid	90…1500	0.08…0.5	4…15	SS	4.2…20
Final cooling channel	Solenoid	50	0.5	> 40	SS	4.2
Rapid cycling synchrotron	NC Dipole	30x100	5	± 1.8	4200	300
Rapid cycling synchrotron	SC Dipole	30x100	1.5	10	SS	4.2…20
Collider ring	Dipole	160…100	4…6	11…16	SS	4.2…20

CERN 5

- Focus is high-field solenoids for cooling
- More information in the backup slides of Luca's presentation

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How can we more effectively develop the REBCO technology?

- REBCO holds the promise of highest fields and lowest cost
  - If true, critical for next circular colliders

- What results in 3 years can most effectively help with a muon collider on the U.S. soil?