HFM

High Field Magnets
Programme

HTS option for FCC-hh and the HFM program

FCC Week 2024, San Francisco

B. Auchmann, A. Ballarino, E. Todesco for the HFM Programme

June 13, 2024

CERN

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Overview

- HTS – the promise
- ReBCO for FCC-hh – the challenges
  - Notes on Bi-2212 and IBS
- HFM HTS activities
- FCC-hh requirements – priority topics
- Cooperation with US-MDP

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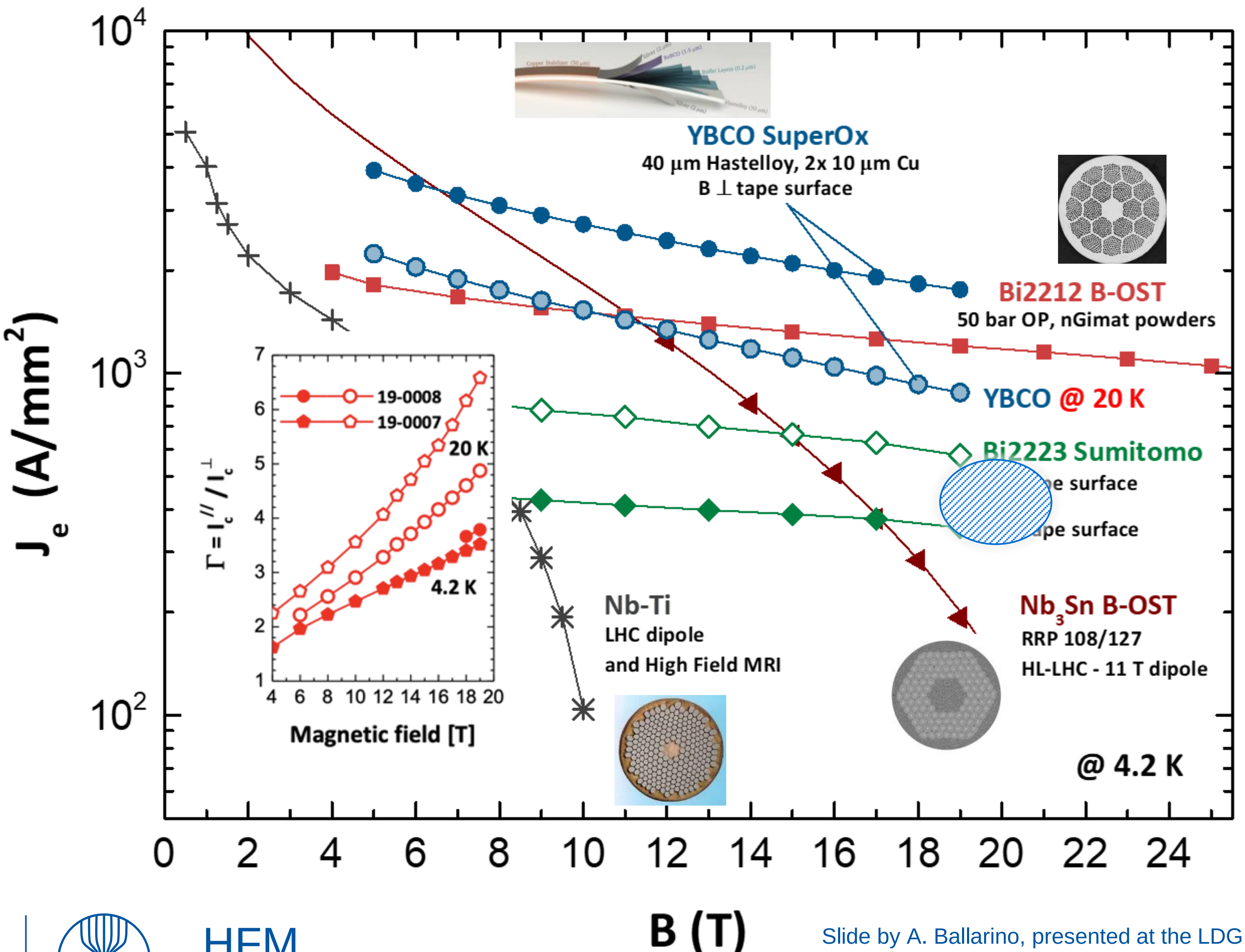
LTS and HTS Conductor Performance



IBS SotA:
Je > 400 A/mm^2
@ **20 T**, **10 K**

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Slide by A. Ballarino, presented at the LDG Mtg and Acc. R&D Workshop at BNL, June 5, 2024

HTS – The Promise(s)

HTS Conductors – whether ReBCO, Bi-2212, or IBS – enable higher operating field and/or higher operating temperatures than LTS conductors.

- Typically, 20 T and 20 K are mentioned as ultimate targets for HFM.
- Intuitively, this translates in to **increased physics reach** and **more sustainable operation**.

ReBCO conductor is becoming available at industrial scale, underpinning the magnetically-confined fusion startup boom, and possibly entering new market categories such as power transmission.

- This should mean a **lower conductor price** for FCC-hh R&D and production.

ReBCO features a deposited SC layer (no heat treatment is necessary), high resilience to transverse pressure, and high thermal stability.

- Coil **manufacturing could be simpler**, and **performance more resilient**.

Substantial investment in innovative magnet technology is necessary to create accelerator-grade HTS magnets. The capital investment in HTS for an HTS FCC-hh is important, even on the scale of a growing global market.

- An HTS FCC-hh unlocks a **sizeable and meaningful societal impact**.

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Challenges of ReBCO Conductor

Tape form factor

- Easy-way bending only – coil-end problem

Anisotropy

- 5x performance ratio B_{par}/B_{perp} at 20 K, 20 T
- Sharp peak requires good placement tolerances

Layered conductor

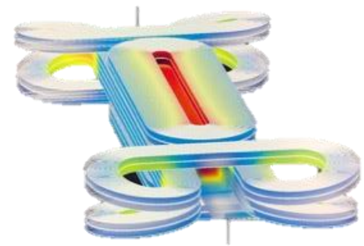
- Low **de-lamination** strength may be related to some examples of performance degradation in high-field solenoids.
- Large variation in internal layer2layer resistivity with implications to current sharing and jointing.

Local defects

- Limit filamentization (slicing)
- Imply high uncertainties on "lift factor" (ratio of 77 K self-field performance to low-temp in-field performance
- Introduce uncertainties on performance peak in angular distribution.

Screening currents

- Long time constants in screening-current effects.



[Courtesy G. Kirby, J. v. Nugteren, J. S. Murtomäki, et al.]

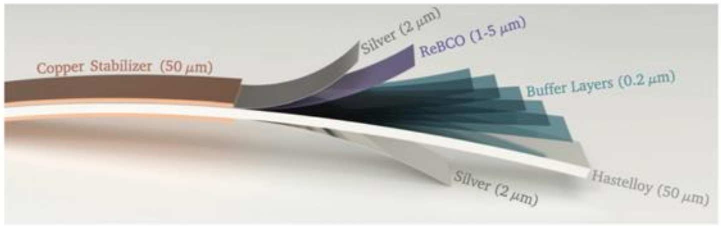


Figure 1.7. *Material composition of ReBCO coated conductor. For visual clearness the tape is cut in half along its length such that the inside becomes visible. In reality the copper and the silver layers fully surround the hastelloy substrate carrier.*

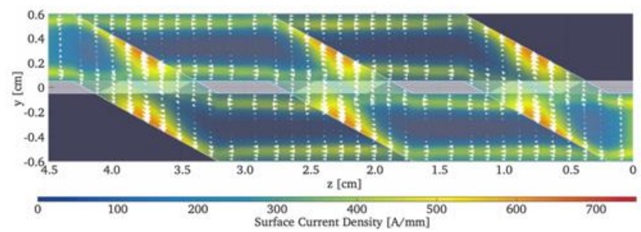


Figure 4.1. *Calculated vector field, which indicates the overall current direction for a Roebel cable, shown for an perpendicular uniform applied magnetic field of 0.7 T, which was ramped over the virgin curve using a frequency of 0.1 Hz. The operating temperature is set at 4.5 K. The engineering current density of the conductor is scaled to 527 A/mm² at 20 T ⊥ 4.5 K and 4.4 kA/mm² at 20 T ∥ 4.5 K in the 100 μm thick tape.*

Effective filament size: Nb-Ti 4-5 μm,
Nb3Sn 20-50 μm,
ReBCO **2-12 mm**

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[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]

ReBCO Magnet Engineering Challenges

Field quality

- Screening-current induced swings in field quality (FQ) during ramp.
- **Reproducibility** of FQ $B_n(I)$ and of FQ stability on flat-top to be determined (see cryo comments below).

Ramp-Induced Losses

- Cable and coil design determine losses.
- Technology choices impose requirements on the cryo system for stable operating margins and reproducible field quality.
- Increased ramp losses may partly (or fully) cancel out the improved cryogenic efficiency at 20 K.
- But the full picture is more complex and requires study to develop loss targets for ReBCO magnet R&D
    - main cryo load in FCC-hh is synchrotron radiation (SR) on the beam screen
    - beam screen temperature is determined by cryo efficiency, vacuum requirements, and technology choices for impedance optimization
    - SR scales $\propto B^4$

[L. Bortot, et al., https://arxiv.org/pdf/2005.09467]

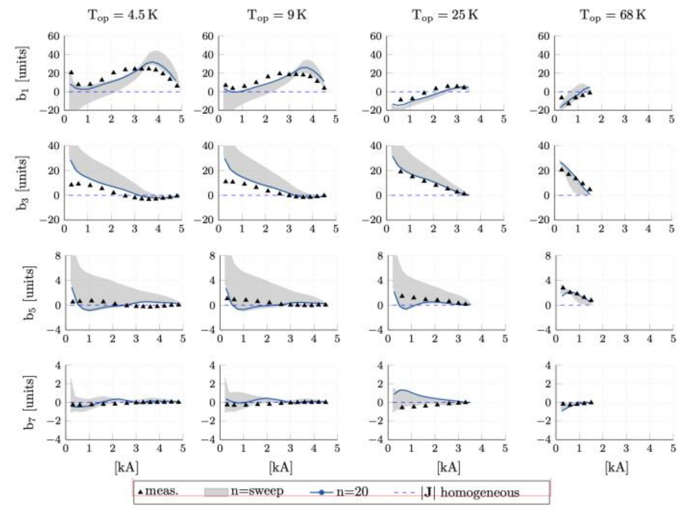
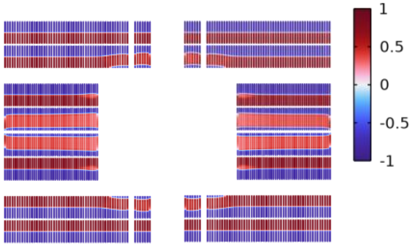


Figure 17. Screening currents-induced magnetic field contribution to the magnetic field quality, in units, as a function of the current in the magnet. Measurements are given by markers, whereas the shaded area corresponds to the envelope of the numerical solutions, obtained with the parametric sweep of the n-value as $4 \leq n \leq 30$. The solution for $n = 20$ is marked with a solid line. The dotted line is obtained by assuming a homogeneous current density distribution in the superconducting tapes. From left to right: results at 4.5, 9, 25, and 68 K. From top to bottom: results for the b_1, b_3, b_5, b_7 multipole coefficients.



[L. Bortot, priv. comm., April 2023]

Estimation of screening-current induced losses in 20 T block-coil at 4.2 K with 12-mm tape-stack cable: 650 kJ/m (CDR target: 10 kJ/m)

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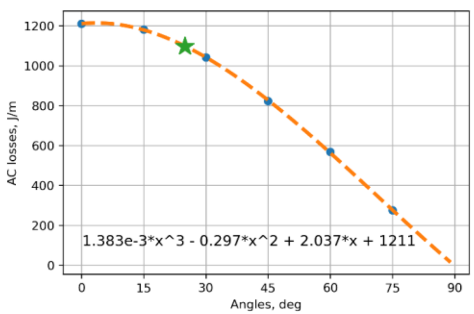
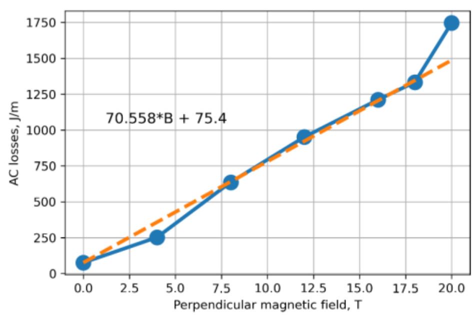
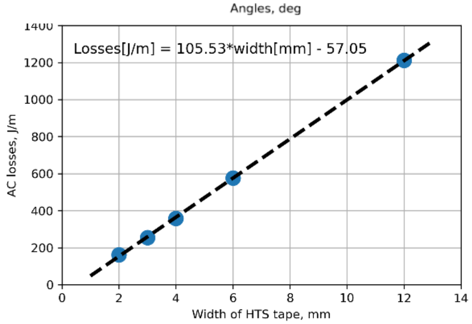
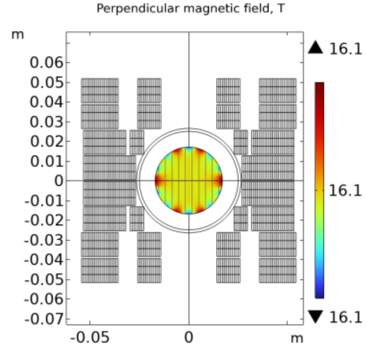


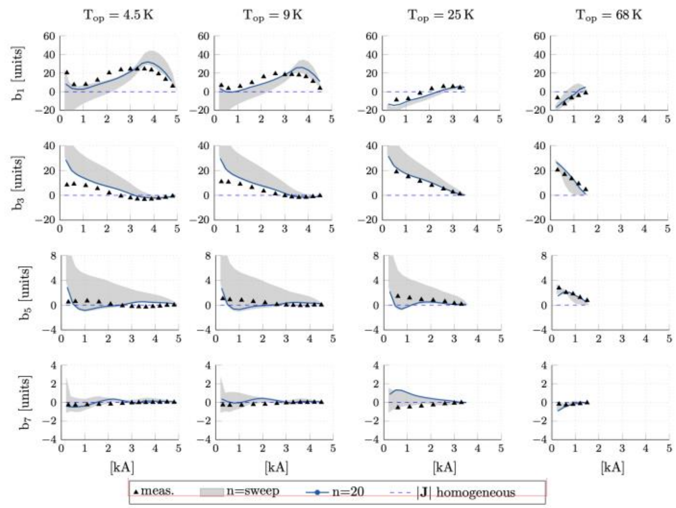






Courtesy [D. Sotnikov]

[L. Bortot, et al., https://arxiv.org/pdf/2005.09467]



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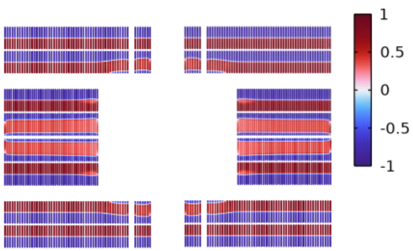

[L. Bortot, priv. comm., April 2023]

Estimation of screening-current induced losses in 20 T block-coil at 4.2 K with 12-mm tape-stack cable: 650 kJ/m (CDR target: 10 kJ/m)

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ReBCO Magnet Engineering Challenges

Protection/Detection

- Slow voltage rise due to "soft" SC/NC transition implies difficult detection.
- Increased temperature/enthalpy margins render it more difficult to quickly quench the entire coil.
- Cold energy extraction with or without close-coupled secondary may be an alternative to absorbing the magnetic energy in the coil itself.
- US-MDP is considering a non-protection paradigm, with a premium on margins and risk mitigation, e.g., in the event of sudden beam losses.

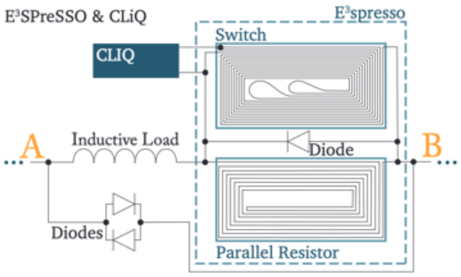

Fig. 4. Schematic showing the electrical connection of the E³SPreSSO unit to the CLIQ box, consisting of a quadrifilar switch and bifilar parallel resistor, and the main inductive load it is protecting.

J. v. Nugteren, et al., A Fast Quench Protection System for HTS Magnets, IEEE Trans. On Appl. SC, Vol 29, 2018.

Mechanics

- **Avoid shear and tension (delamination).**
- Pre-stress paradigms shifts away from full pre-stress for quench avoidance (no spontaneous quenches) to a **strain criterion on the superconductor**.
- Transverse and axial structures for up to 20 T magnets must stay compact for double-aperture in FCC tunnel.

[RMM axial loading at CERN; courtesy of J.-C. Perez]

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ReBCO Magnet Engineering Challenges

Cryogenics

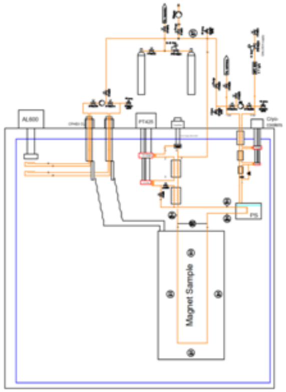
- Baseline for 20 K is high p high $\dot{m}$ He.
- What is the **achievable ΔT inlet/outlet** along cryogenic sector given ReBCO ramp losses?
- What are the implications on operating margins and field quality?
- Hydrogen as low ΔT inlet/outlet cooling option is studied in US-MDP.

Numerics

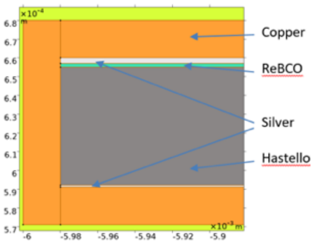
- Aspect-ratio of physically relevant layers in ReBCO make modeling and homogenization in all physical domains difficult:
- Coupled EM (screening currents)-thermal models under develop-ment; high-fidelity mechanical models need to be studied.
- Continuous experimental validation is needed.

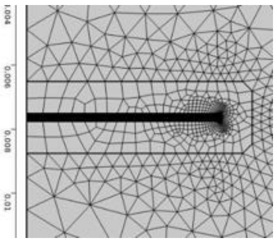
Systems perspective

- An HTS FCC-hh features **substantially stronger coupling among subsystems** and disciplines (magnets, protection, powering, cryogenics, vacuum, beam dynamics, integration, etc.).
- Systems thinking and systems engineering methods must develop apace.



[Courtesy Patricia Borges de Sousa, CERN]





[Courtesy D. Sotnikov, PSI]

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ReBCO technology for accelerator magnets is akin to Nb-Ti technology in the late 1970s

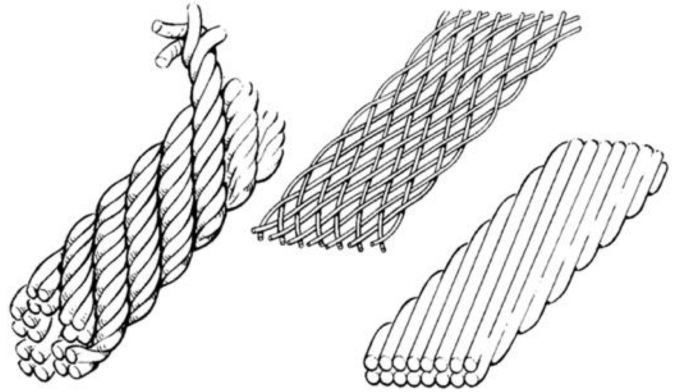
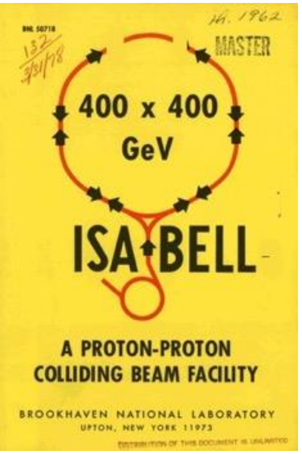


Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

Early options of cables for main dipoles in Isabelle accelerator at BNL.

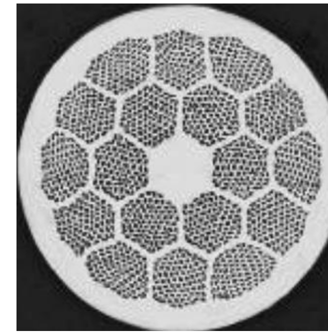
Braided cable failed in series manufacturing. Rutherford-cable development arrived too late, but underpins the LTS accelerator era: Tevatron (1983), Hera (1991), RHIC (2000), (SSC), LHC (2008), HL-LHC (2026)

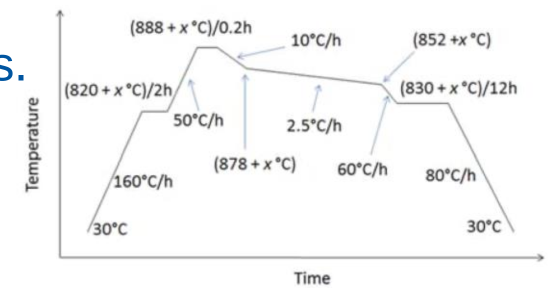


[M. Wilson, Pulsed Superconducting Magnets' CERN Academic Training May 2006]
[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]

Bi-2212 for High-Field Accelerator Magnets

- Bi-2212 is produced in wire form with twisted SC filaments.
- Expected ramp-losses and attainable field quality are in line with well-known LTS technology for accelerators.
- Like Nb_3Sn, Bi-2212 uses a wind&react manufacturing process, albeit with enhanced parameters: 50 bar oxygen-atmosphere, ~900ºC.
- Like Nb_3Sn, Bi-2212 is sensitive to transverse stress.
- Conductor cost today is substantially higher than Nb_3Sn and ReBCO, and raw-material cost is higher due to high Ag content.
- $I_c(B)$ performance, low-loss characteristics, and conductor cost today all justify hybrid Bi-2212/Nb_3Sn as a viable route.
- US-MDP explores Bi-2212 towards 20-T accelerator magnets with stress-management, for the time being as hybrid Bi-2212/Nb_3Sn system.





[J. Jianyi, https://doi.org/10.1109/TASC.2021.3055475]

Activity at CNR-SPIN:
IBS for High-Field Accelerator Magnets

Iron-Based Superconductors promise:

- improved cost (low raw material cost)
- higher mechanical resilience
- multi-filamentary and isotropic wires

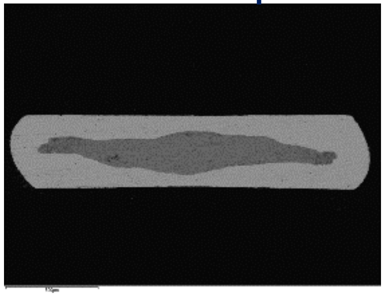
Today only China invests significantly in IBS for high filed applications.

HFM launched the CERN-SPIN (Genova, IT) collaboration on IBS in 2023/24, with the goals to

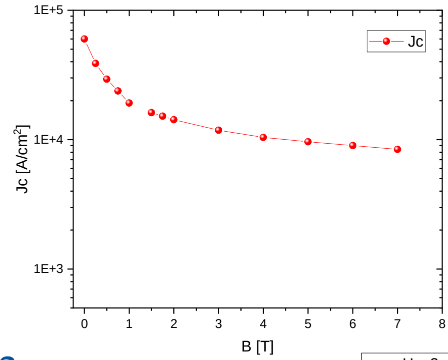
- develop powder-in-tube multifilamentary isotropic wire
- catch up in performance to Chinese results
- achieve scalability of powder- and wire production with
- low-pressure reaction process, in-line with standard (Nb3Sn, MgB2) wind&react coil-manufacturing

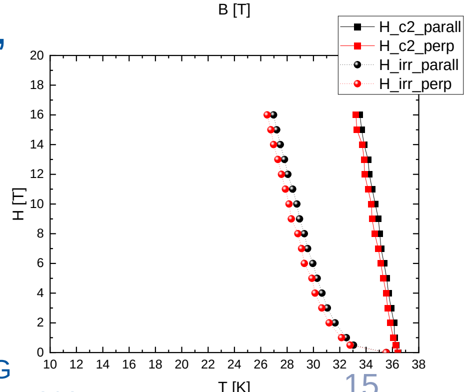
Laboratory at SPIN is set up, powder optimization is in progress, and first mono-filamentary tapes have been characterized.

Ba-122 tape



Width ~2 mm, Thickness ~0.4 mm
Short samples (~2 m long)





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Slides by A. Ballarino, presented at the LDG Mtg and Acc. R&D Workshop at BNL, June 5, 2024

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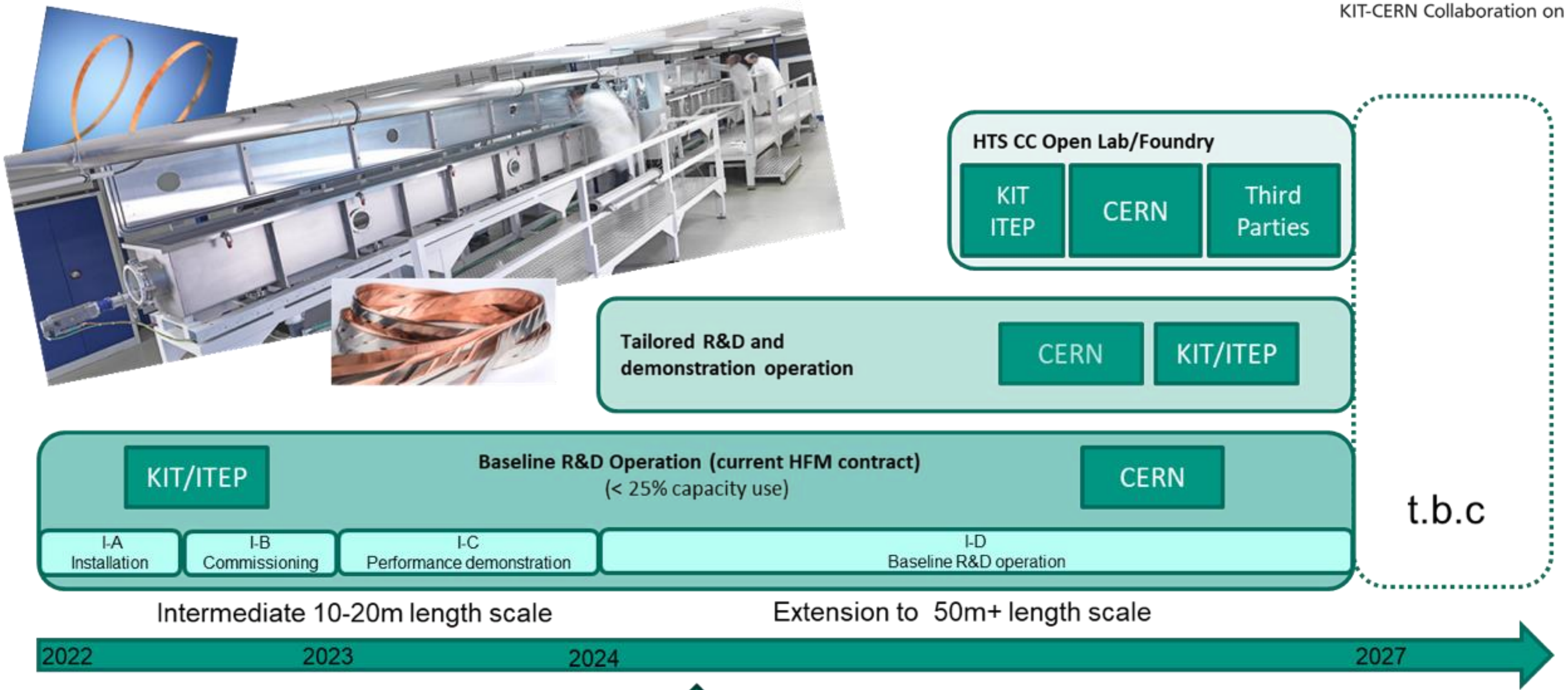
Activity at **KIT**:
ReBCO Conductor R&D

KIT-CERN Collaboration on Coated Conductors
Program and Timeline



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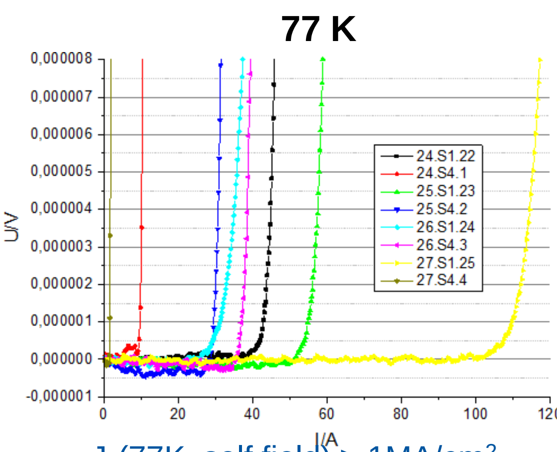
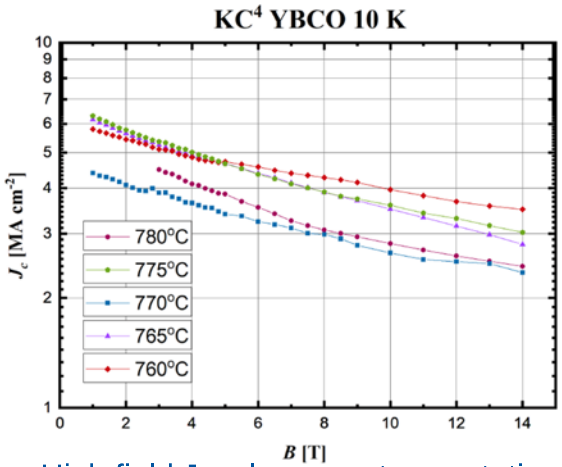
Activity at **KIT**:
ReBCO Conductor R&D

- KC4 Baseline R&D operation (10 m long samples) within the HFM program since March 2024
- So far 61 full deposition runs (each run inclides 1 day for PLD, 1 day for silver coating, 1 day for oxygenation)
- Launched tailored research program for understanding and improving internal resistance in tapes

KIT-CERN Collaboration on CC



J_c(77K, self field) > 1MA/cm^2
Good homogeneity demonstrated



High field J_c values meet expectations
More characterization needed

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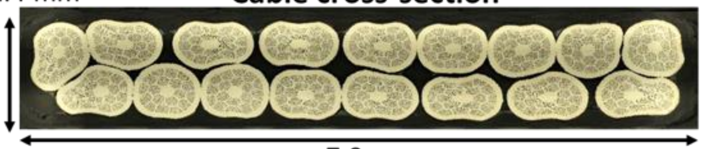
Karlsruhe Institute of Technology

Slides by A. Ballarino, presented at the LDG Mtg and Acc. R&D Workshop at BNL, June 5, 2024

Activity at **Twente University**:
Bi-2212 Cable Ic vs. Transverse Stress

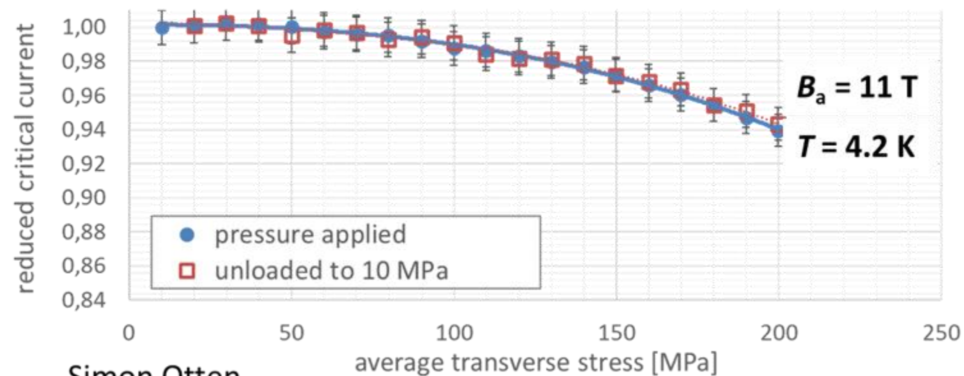
BSCCO-2212 Rutherford cable: critical current versus transverse stress



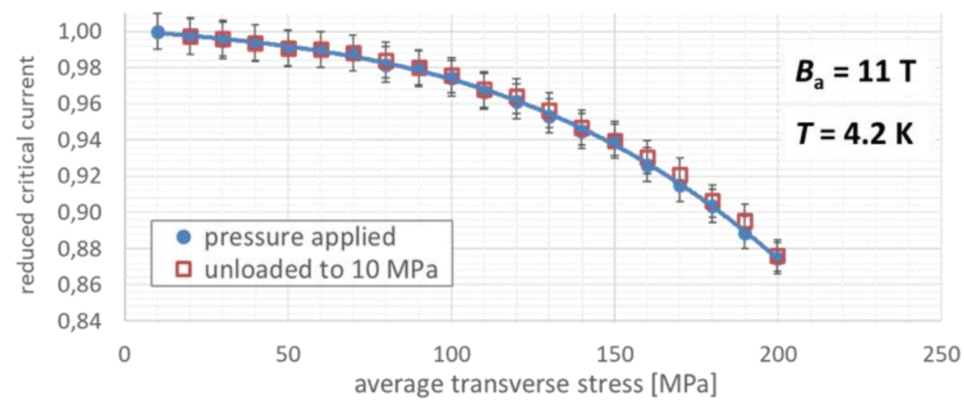
Applied magnetic field 11 T, normalized to initial I_c of 2.70 kA (sample 3), and 4.07 kA (sample 4)

- Measurement sequence:
  10, 20, 10, 30, 10, 40 MPa, etc.

- **5% <u>irreversible</u> degradation reached at:**
  170 - 200 MPa in sample 3 and
  120 - 150 MPa in sample 4



Simon Otten



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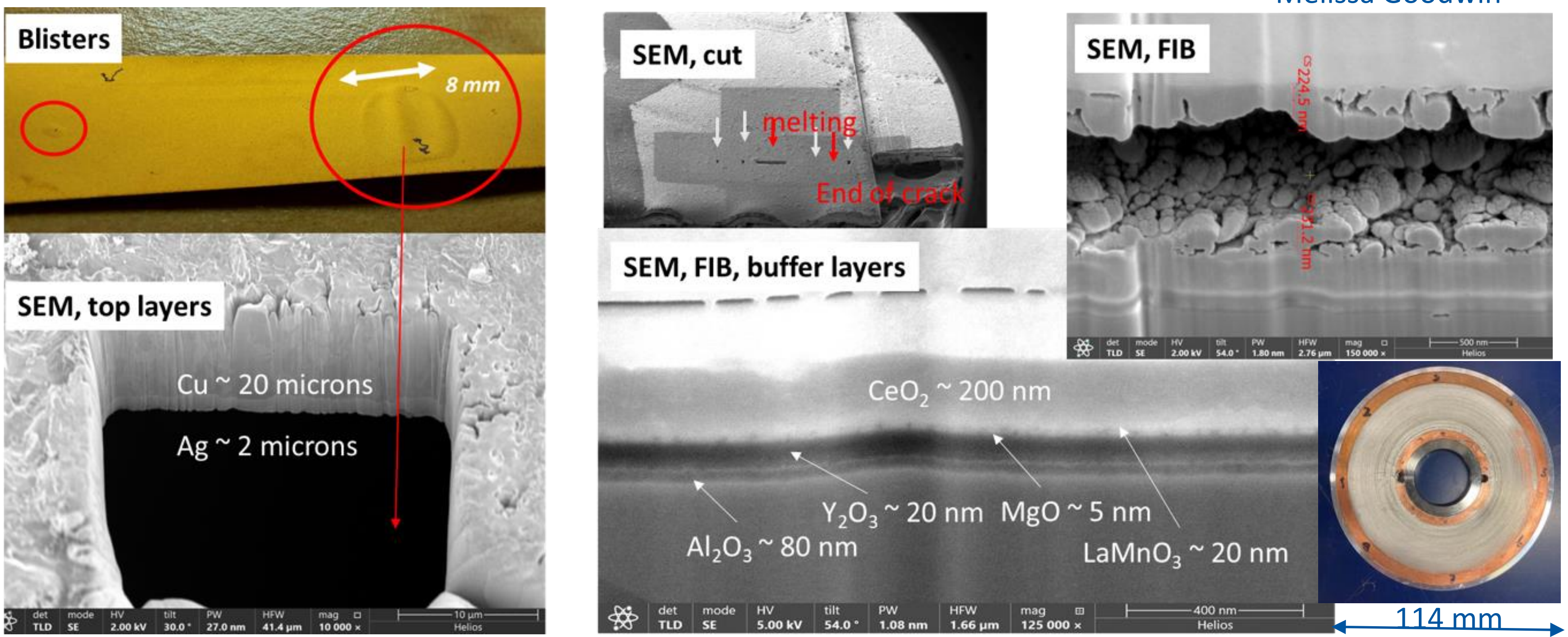
UNIVERSITY OF TWENTE.

Slides by A. Ballarino, presented at the LDG Mtg and Acc. R&D Workshop at BNL, June 5, 2024

Activity at Twente University:
Bi-2212 Cable Ic vs. Transverse Stress

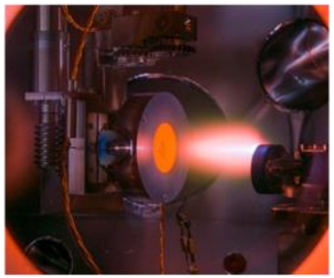
ReBCO pancake coils: NI dry double-tape coil degraded at LHe, postmortem analysis - Microstructure

Melissa Goodwin



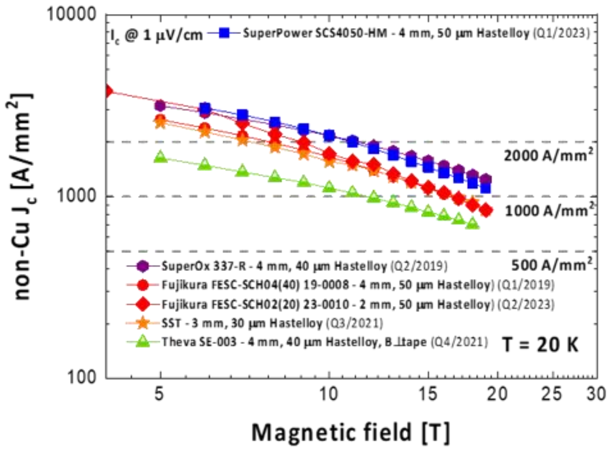
Irreversible degradation of the tape, most probably due to local defects inducing quench with temperatures reaching several hundreds Celsius

Activity at **University of Geneva**:
Multi-Physics ReBCO Conductor Characterization

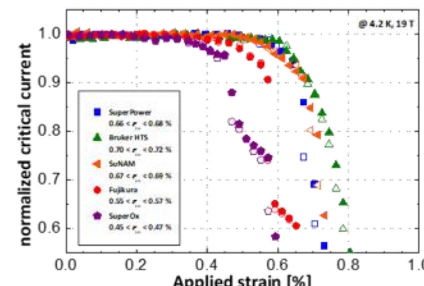


R&D on materials

HTS film deposition by physical and chemical routes

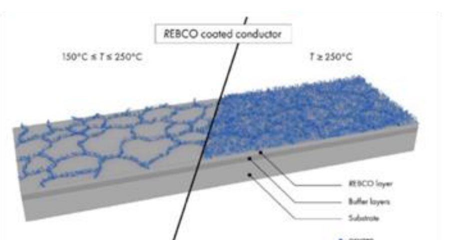


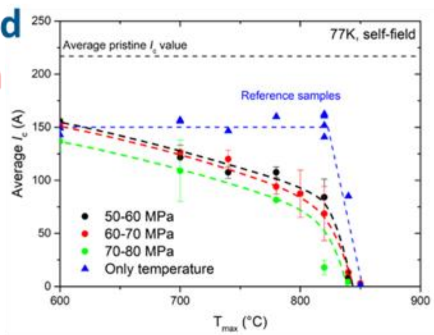
High-field/Low-temperature characterization of the critical current surface up to 20 T

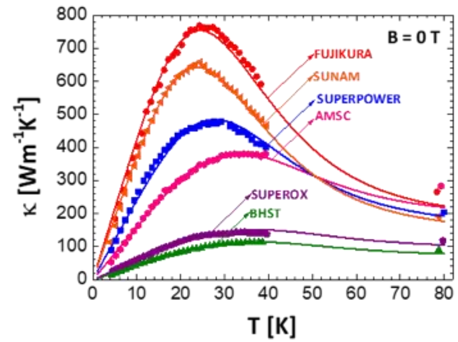


Thermo-mechanical studies

Heat and pressure induced performance degradation







Electromechanical and Thermophysical properties to support magnet design

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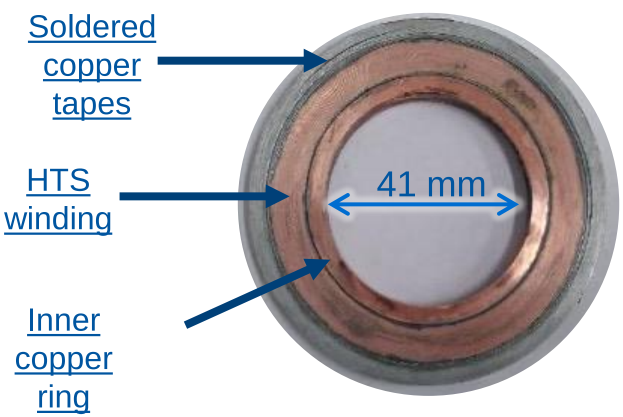
Activity at **CEA**:
Exploration of Metal-Insulation Coil Technology

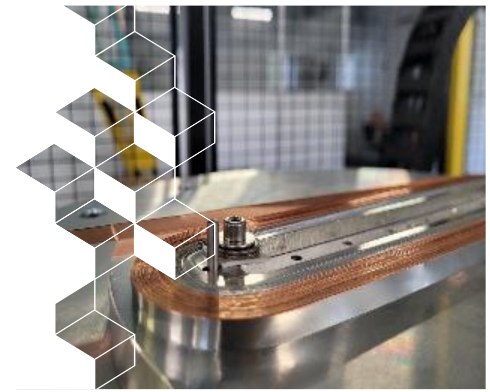
HTS Metal-Insulated technology development at CEA towards 20 T dipole magnets: pancakes and racetracks

First windings completed

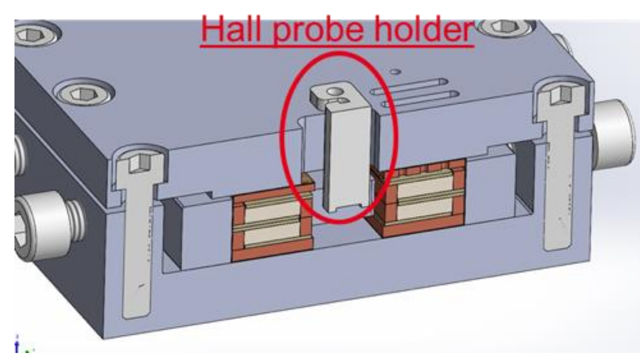
Inner ring : 3 mm thick, OD 41 mm
Outer ring : 3 mm thick (100 µm copper tape)
HTS Winding : 50 turns



Metal-insulated coils



Stacks of racetracks (up to 4)



Tests to be done in the next months

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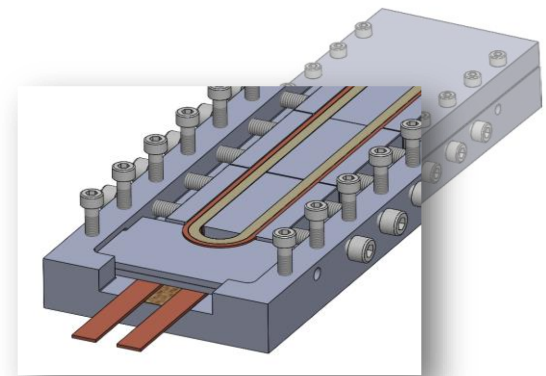
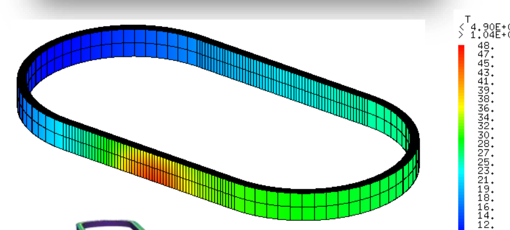
Slides by A. Ballarino, presented at the LDG Mtg and Acc. R&D Workshop at BNL, June 5, 2024

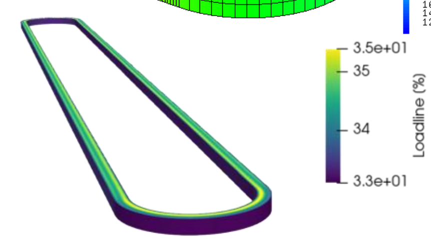
Activity at **CEA**:
Numerical Modeling of Metal-Insulation Coils

Numerical modelling

- PEEC — SALOME (python) — CAST3M
  - Mechanical
    - Forces
    - Stresses
  - Thermal
    - Conduction cooling dimensioning
    - Thermal stability
  - Magnetic
    - Static field
    - Loadline
    - Temperature margin





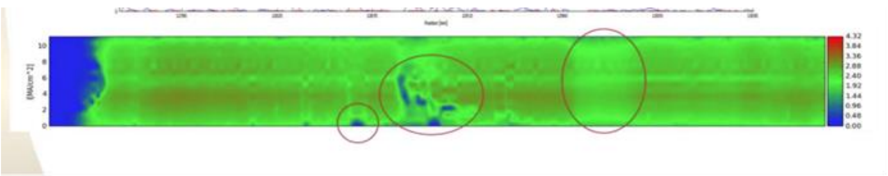


Activity at **CERN**:
ReBCO Conductor

- **Procurement of tape** (for CERN and for HFM collaborators)
  - IT with specific requirements and QA
  - Ic @ 20 T, 4.2 K and 20 K
  - Unit length ≥ 100 m
  - **33 km**, **width: 2-4-12 mm**, **four suppliers**, full quantity delivered in 2024

- Procured THEVA Tapestar™ XL-HF. High throughput (200 m/h). Reel-to-reel.

- Critical current and critical current homogeneity
- Identification and localization of defects



Defects and their location

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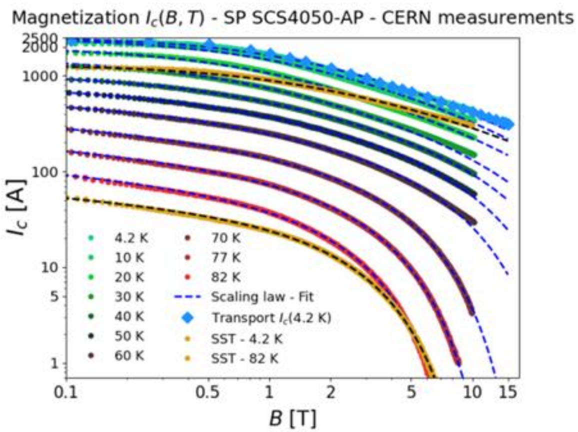
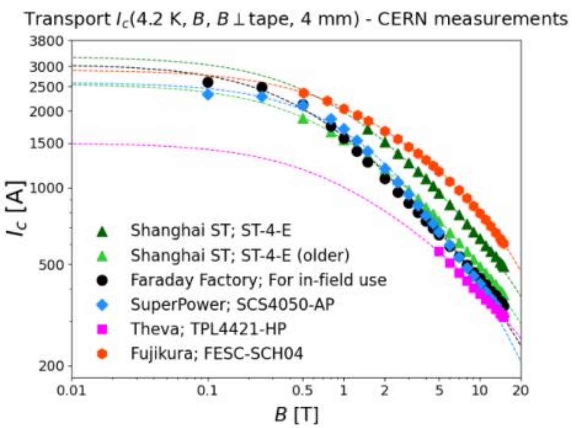
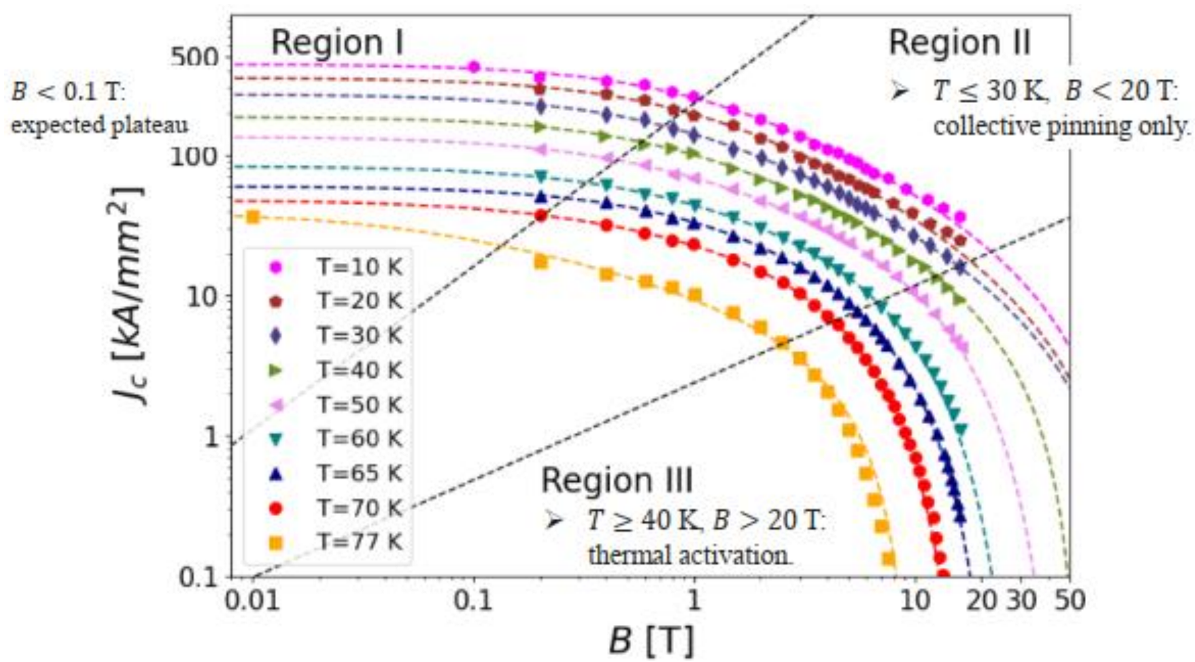
Activity at **CERN**:
ReBCO Conductor





From measurements to Scaling Laws

$$I_c(B, T = T^*, \theta = \theta^*) = I^*_{c,0} \cdot \left(1 + \frac{B}{B^*_0}\right)^{-\alpha^*} \cdot \left(1 - \frac{B}{B^*_{irr}}\right)^{q^*}$$



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Activity at **CERN**: ReBCO Coils

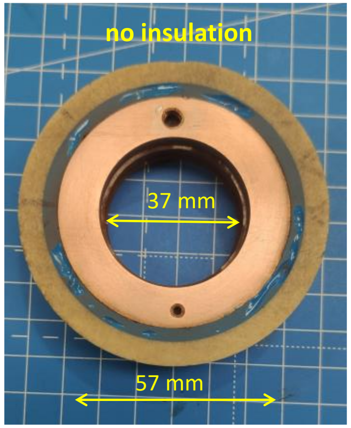
Racetrack coil program

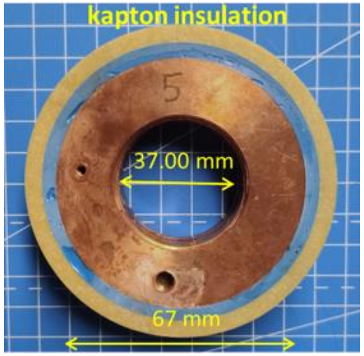
- **Racetrack coils** with straight section of about 10 cm
- Kapton® **insulated cable** in a stack of tapes configuration being used now. Other cables under development
- **Modular approach** allowing for intermediate milestones of 3 T and 5 T

Goal: 10 T @ 4.2 K (8.7 T @ 10 K, 7.2 T @ 20 K, 1.14 T @ 77)

Parameter	Value
HTS tape	4 mm wide from SST
Required I_c @ 12.5 T	> 550 A
Number of HTS tapes	4
Additional copper	2 x 100 µm
Insulation thickness	50 - 100 µm Kapton

Double pancakes
2x 7.35 meters of tape
3.93 T @ 4.2 K, 1500 A





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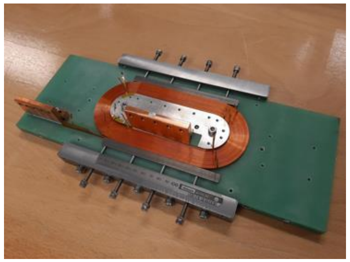
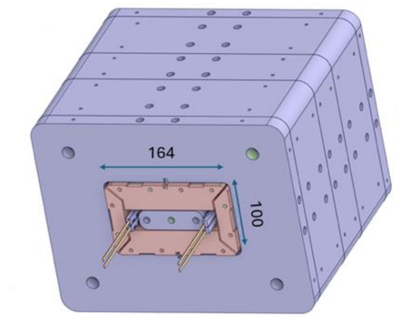
Activity at **CERN**:
ReBCO Coils and Modeling

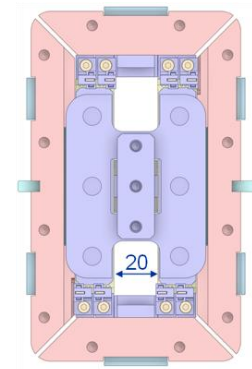


Stage 1: Single pancake

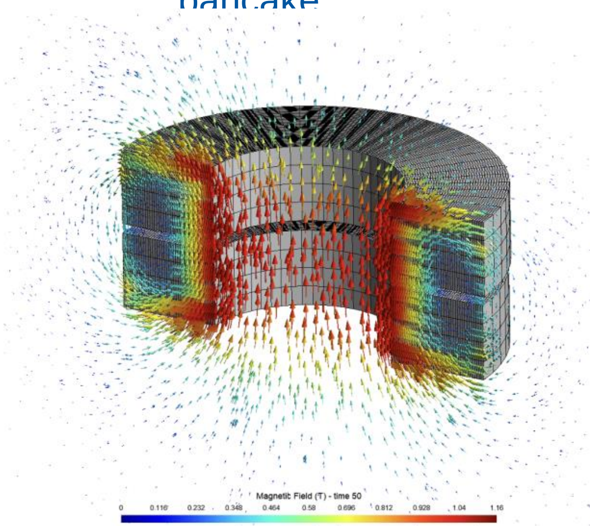


Stage 2: Four double pancakes (**5 T**)

Stage 3: Up to Six double pancakes (**10 T**)



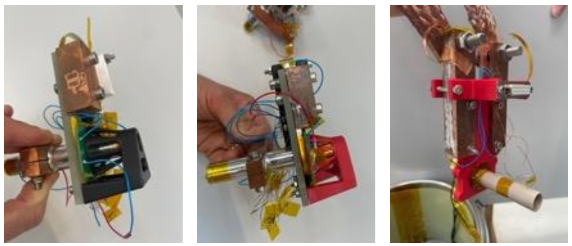
Stage 4: Common Coil double aperture **demonstrator**



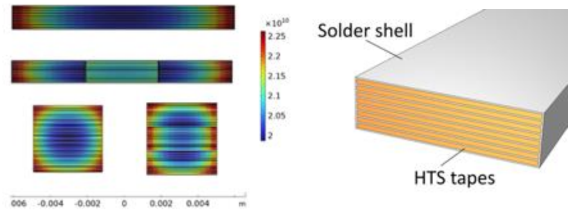
HTS Modeling activities for quench protection and transient analysis .

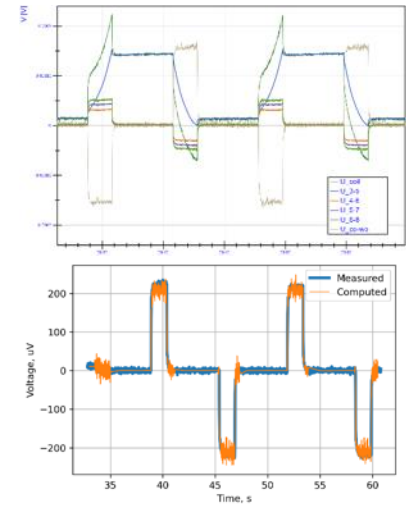
Activity at PSI:
ReBCO Coils and Magnets

Small-scale coils for model validation and cable testing



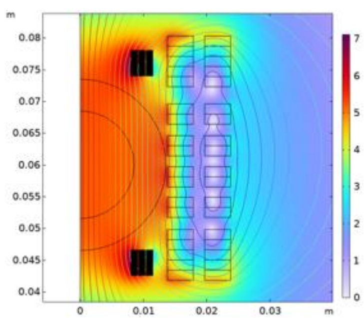
“Baby-HTS” Coils (1-3) with 2-stack single-pancake (1,2) and 1-stack double-pancake (3) geometry.

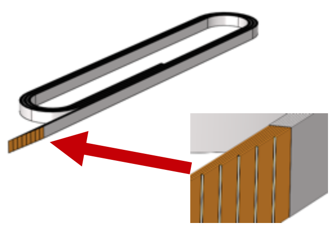


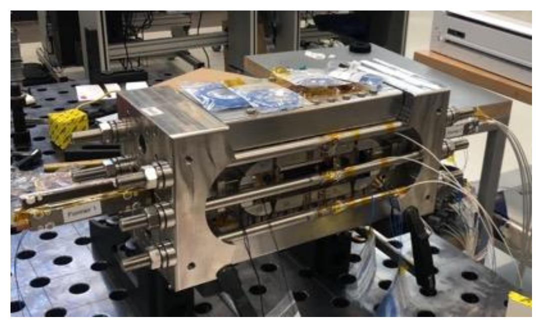


Measured signal from Coil 2

Design of Racetrack coils to operate in background field of Nb_3Sn 5-T subscale stress-managed common coil







Nb_3Sn subSMCC1

HFM High Field Magnets Programme

PSI

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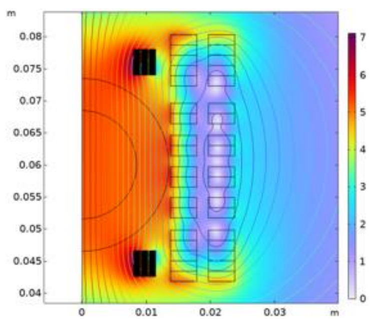
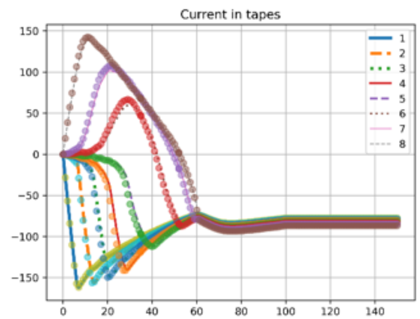
Activity at PSI:
Numerical Tools for ReBCO Magnets

Development of stable and performant 2D FEA models for magnet design

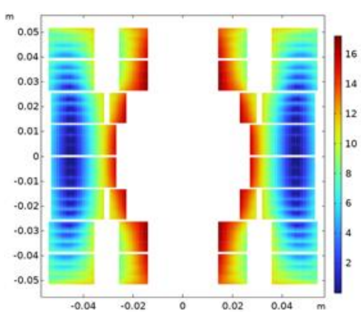




COMSOL MULTIPHYSICS® QUANSCIENT

Current sharing in 8-tape solder-stack cable.
Model comparison COMSOL (lines) vs. Quanscient (dots).

Design study for AC losses with different cable and coil layout
Prepare PSI R&D Roadmap



16-T coil, from 4-mm soldered tape-stack cable, operated at 20 K
Highly compact coil
(Protection not considered!)
224 kJ/m full-cycle ramp losses

COMSOL MULTIPHYSICS® QUANSCIENT Little Beast engineering

CERN | HFM High Field Magnets Programme PSI

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Overview

- HTS – the promise
- ReBCO for FCC-hh – the challenges
  - Notes on Bi-2212 and IBS
- HFM HTS activities
- FCC-hh requirements – priority topics
- Cooperation with US-MDP

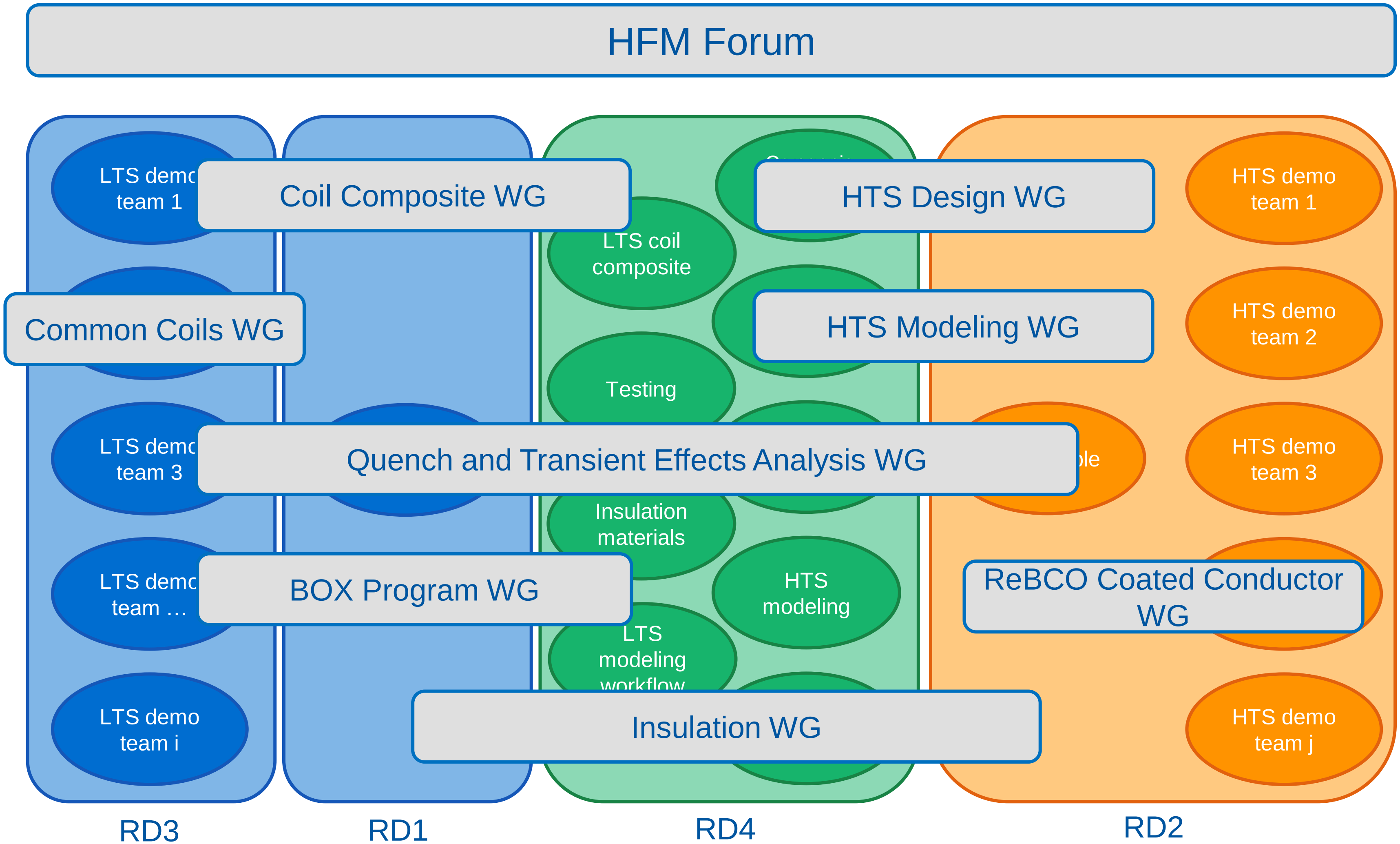
FCC-hh Priority Topics

From the CERN Scientific Policy Committee (SPC) recommendations following the FCC Feasibility Study midterm report, we derive the following three priority topics:

- Confirm the compatibility of the baseline FCC-ee tunnel with an HTS accelerator with up-to-20-T magnets.
- Adopt a more integrated system-wide approach to SC magnet and cryogenics development and discuss the full scope of FCC-hh sustainability including, among others, synchrotron radiation heat load.
- Provide benchmark roadmaps for target fields up to 20 T, with a conservative LTS option and an aggressive HTS/hybrid scenario.

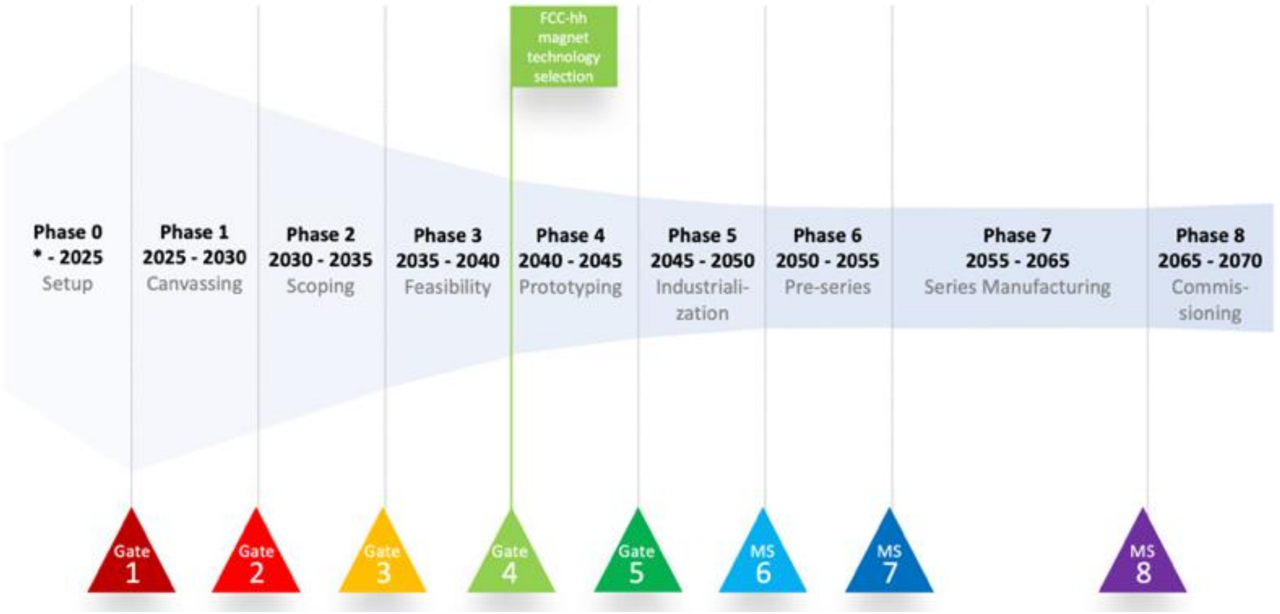
Statements on these topics should be delivered asap, preliminary answers are needed for the Feasibility Study final report by November 2024.

HFM Organization



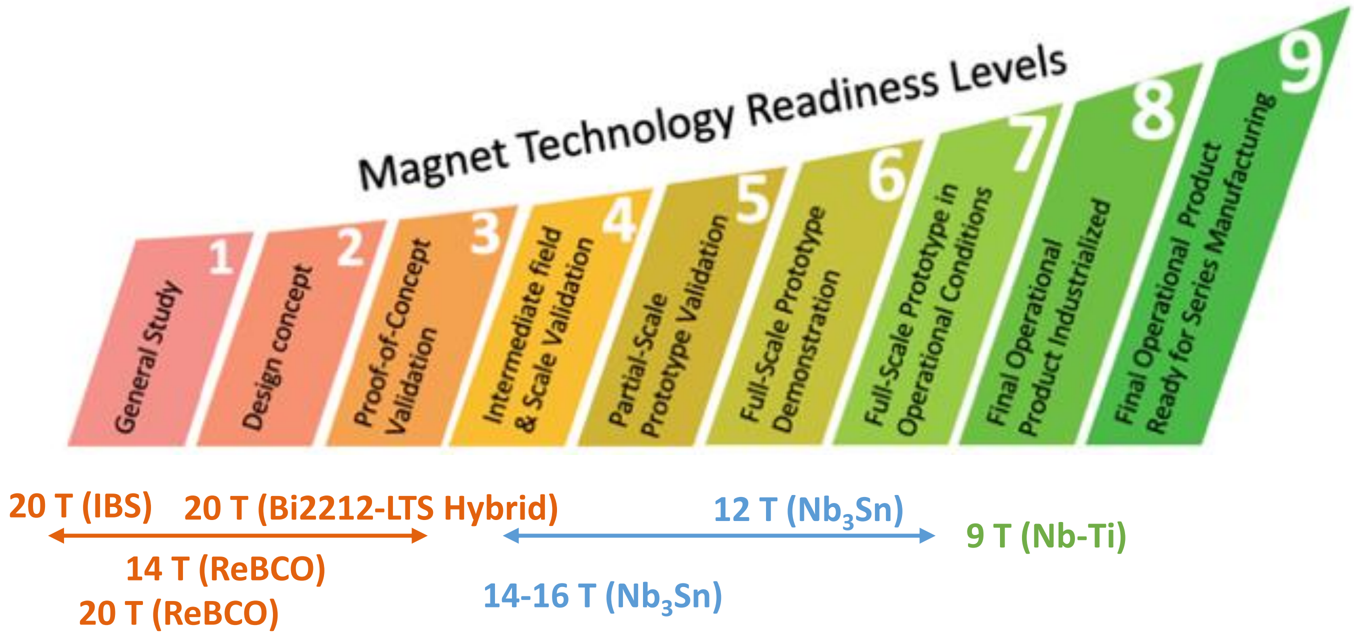
Towards an HTS Roadmap

Long-term strategic roadmap in the FCC Feasibility Study Midterm Report chapter on FCC-hh Magnets.



- 2023-2025 … **setup** of manufacturing facilities, hiring in concerned labs
- 2025-2030 … **canvassing** candidate technologies
- 2030-2035 … **scoping** to achieve accelerator quality and target field in short magnets
- 2035-2040 … **feasibility** of length scale-up

Towards an HTS Roadmap



[B. Auchmann, A. Ballarino, L. Bottura, S. Prestemon in FCC Feasibility Study Midterm Report]

- ReBCO magnet technology for (synchrotron) high-field accelerator magnets need to close the TRL gap to LTS: Key technology questions must be solved within the next 5-10 years.
- A technical roadmap based on initial canvassing results will be developed over the coming years.
- We are entering uncharted territory. Breakthroughs and/or roadblocks may be encountered along the way.

Overview

- HTS – the promise
- ReBCO for FCC-hh – the challenges
  - Notes on Bi-2212 and IBS
- HFM HTS activities
- FCC-hh requirements – priority topics
- Cooperation with US-MDP

Cooperation with US-MDP

Ongoing technical exchanges include the following topics:

- 20-T quench protection analysis,
- 20-T stress-managed common coils design,
- Stress-management material technologies,
- Bi-2212 cable characterization under transverse pressure,

Complementarity of approaches mitigates risk factors:

- Bi-2212 as well as CORC/Star ReBCO wires in US-MDP,
- ReBCO anisotropic cables and IBS in HFM,
- High-risk high-reward topics (no-protection, hydrogen) covered in US-MDP.

Increased cooperation FCC/US-MDP/HFM is desirable, for example:

- Shared technical seminars,
- Increased integration of each other's "working groups",
- Continued exchange on roadmaps and strategies, etfc.

Summary

- The promises and challenges of an HTS FCC-hh are formidable.
- The technological readiness of HTS for FCC-hh (synchrotron, small aperture, large industrial production) is many years behind that of LTS.
- ReBCO has a particularly interesting set of properties, but the layered nature of the conductor makes it hard to make optimal use and the expected ramp losses need to be studied.
- Alternative PIT-type HTS conductors Bi-2212 and IBS are also studied. Bi-2212 is more in line with LTS conductors. US-MDP research on Bi-2212 magnet technology provides a complementary approach.
- HFM is working through interdisciplinary working groups across institutes and with other sub-systems in the FCC on a technical roadmap for ReBCO high-field accelerator magnets.
- The prospect of highly relevant results and sizable societal impact are strong motivators for our teams!