HFM

High Field Magnets Programme

FCC-hh cryo magnet system and integration

SAC Meeting
B. Auchmann, E. Todesco for the HFM Programme
November 20, 2024

HFM
High Field Magnets
Programme

Contents

- Update on HFM Programme deliverables LTS and HTS
- Status cryo studies 4.5 K
- Spotlight on transient-effect studies in HTS magnets

Contents

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- Status cryo studies 4.5 K
- Spotlight on transient-effect studies in HTS magnets

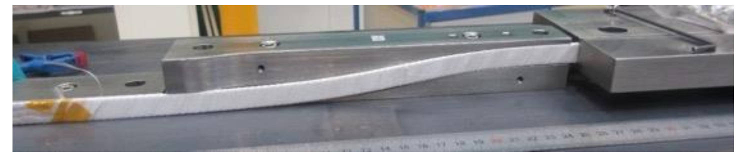
CEA LTS Program

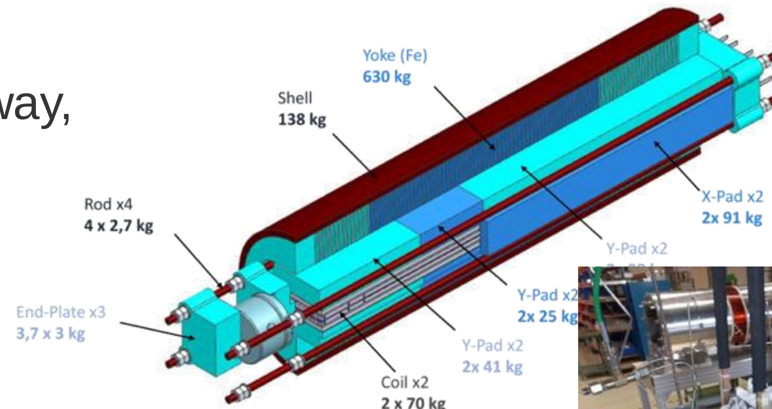
KE3782

- 2024
  - R2D2 coil fabrication under way:
    - **1st coil with weak electrical insulation,**
    - **2nd coil wound,**
  - structure procurement under way, all components expected by November,
- 2025 R2D2 test in summer.

KE5655

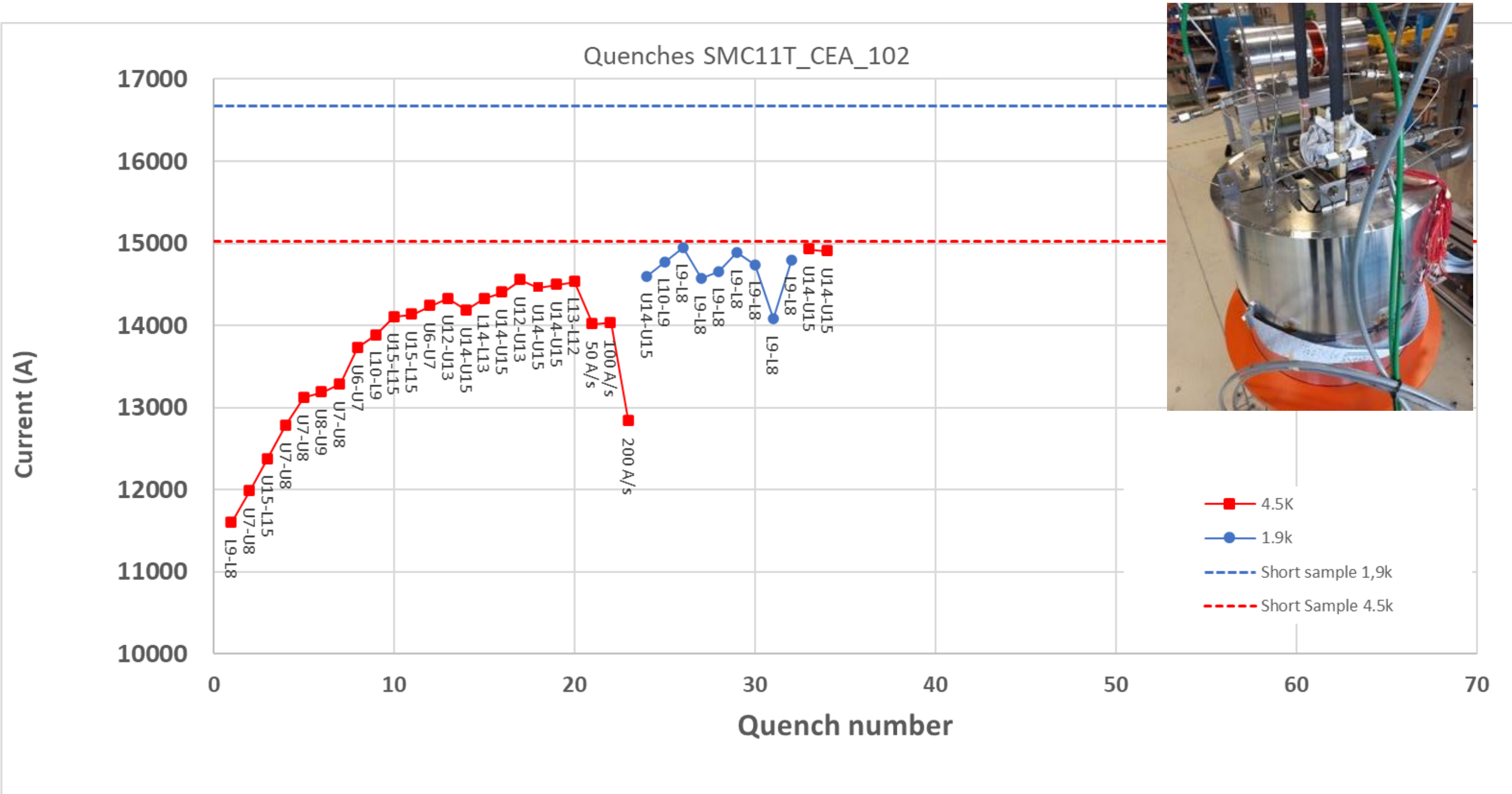
- 2024
  - **SMC v2 assembled and pre-loaded at CERN**
  - **First thermal cycle complete**
- 2025/26 ff. R2D2 v2, FD, F2D2





WPL: E. Rochepault

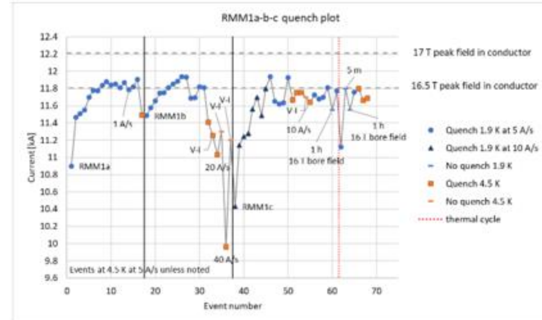
CEA LTS Program

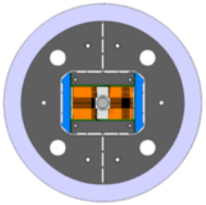


[Test data courtesy of G. Willering, CERN]

WPLs: J.-C. Perez, A. Foussat, A. Haziot

CERN LTS Program

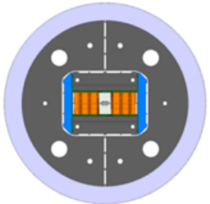




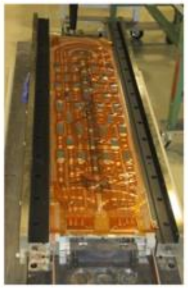
RMM

Magnet program:

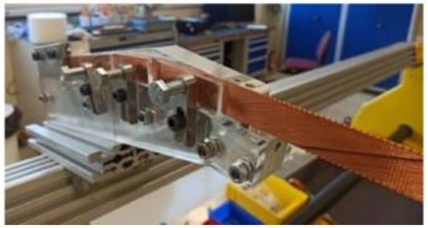
- **SMC test with novel ESC protection**
- RMM1 preload study:
  - **RMM1d powering test completed.**
- ERMC2:
  - 3 new coils in various stages of manufacturing
  - Test beginning 2025
- RMM2 test mid 2025



ERMC



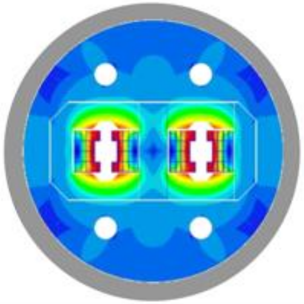
- 14 T 2-layer block-coil 2-in-1 configuration.
  - LBNL support for cable manufacturing.
  - **1-in-1 mechanical analysis ongoing** (G. Bellini)
  - **Winding test for flared ends** (E. Mora, et al.)
  - **Magnetic design of double aperture** (A. Haziot)
  - https://indico.cern.ch/category/16467/
- Test in 2026.



Conductor procurement: WPL: T. Boutboul

- Order with B-OST finalized.
- Delivery expected Q4/2026.

Description	Quantity [km]	Quantity [kg]
1.1 mm 162/169	74	605
0.7 mm 60/91	110	397
1 mm 150/169	20	136
1.1 mm 108/127	2	17
1.0 mm 108/127	2	14
0.85 mm 180/217 scale-up	non-recurring charges and one restack (up to 60 kg)	



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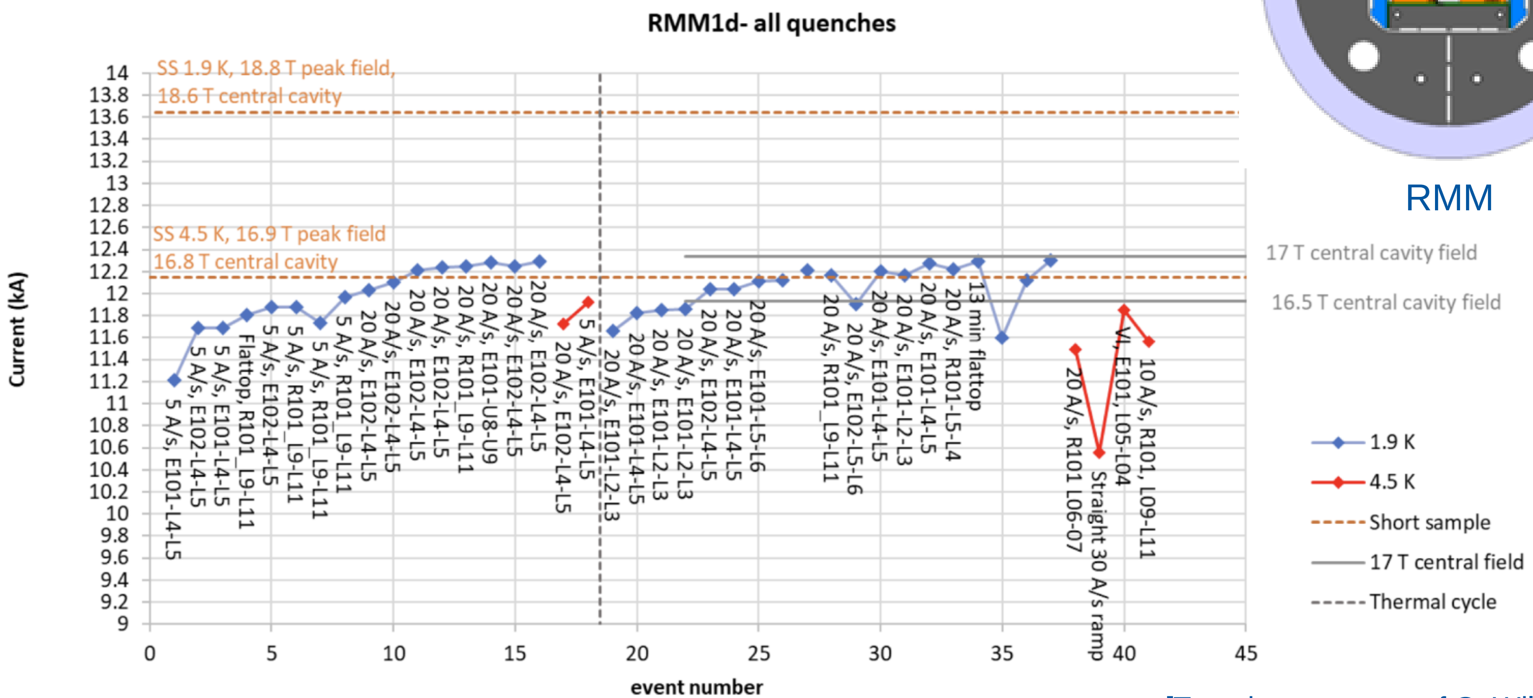

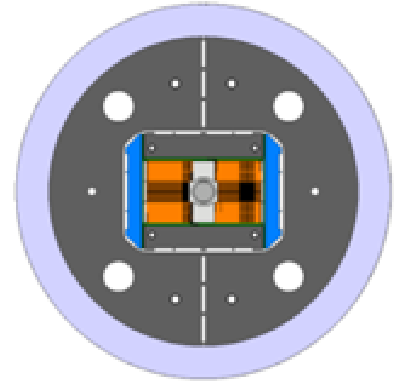

RMM

[Test data courtesy of G. Willering, CERN
https://indico.cern.ch/event/1464833/

1.9 K performance:

- Max. field of 16.9 T limited by instability in low-field region.
- Quenches on plateau at and above 11.81 kA.
- Stable plateau achieved at 15.75 T, or 84% of I_{ss}.

4.5 K performance

- Max. field of 16.5 T at 98% of I_{ss}. Stable-plateau not (yet) verified.

WPLs: J.-C. Perez, A. Foussat, A. Haziot

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CERN LTS Program

Energy-Shift with Coupling (ESC)

Dielectrically isolated close-coupled normalconducting coils.

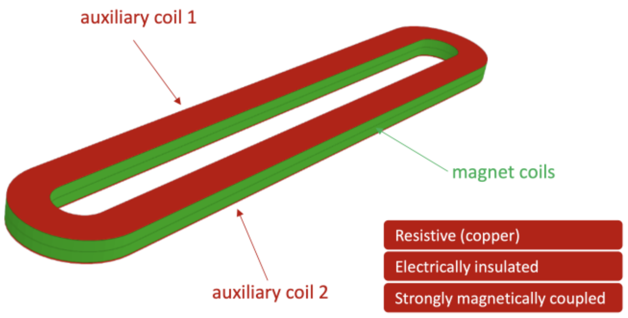
Current pulse induced with capacitive discharge.

Total linked flux stays ~constant, SC current drops. Field lines move quickly across SC coil and induce resistive transition in the whole coil.

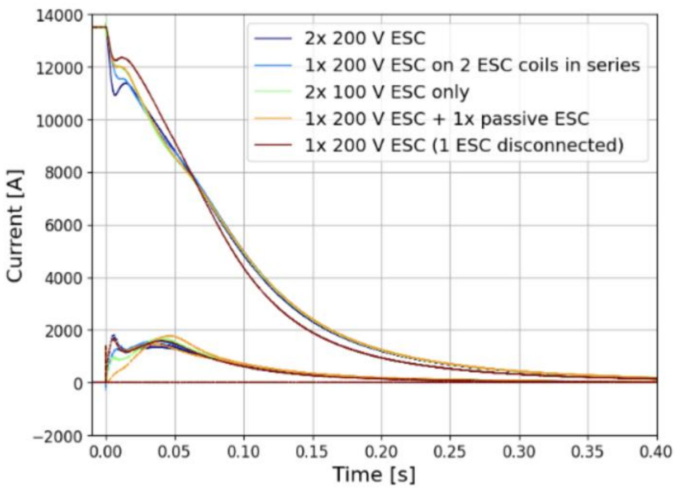
Large amounts of energy are dissipated in the copper auxiliary coils.

Needs to be foreseen at the earliest stages of magnet design!

Experimental validation on SMC flat racetrack coils **fully successful**.



[Pics courtesy of E. Ravaioli https://indico.cern.ch/event/1468340/]

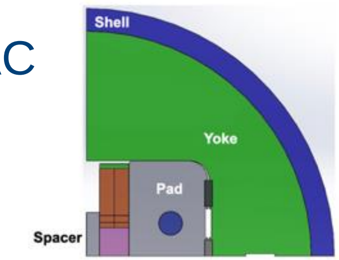


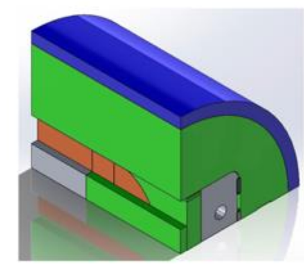
WPL: F. Toral

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CIEMAT LTS Program

ISAAC





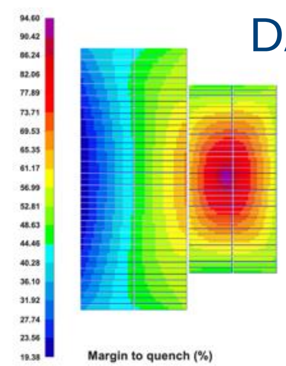
2023/24

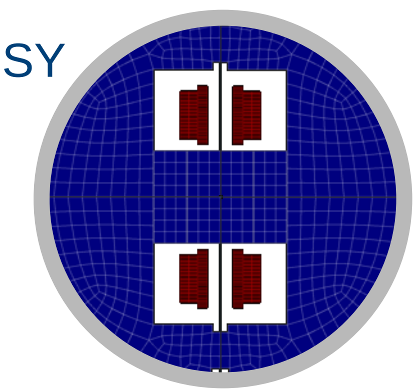
- Lab infrastructure build-up
  - Furnace and collaring press contract placed.
  - Furnace delivery expected before end of year —> commissioning

2024

- ISAAC common-coils assembly with ERMC coils
  - Learn about low-prestress common-coil structural design and assembly
  - **Mechanical structure design under way, 3D design ongoing**
  - Procurement started
  - Assembly at CERN in March; test April/May 2025
- DAISY 14 T design progressing:
  - Initial plan Nb_3Sn/Nb-Ti hybrid

DAISY





2025/26

- 14 T engineering design conceptual
- Procurement of tooling and parts
- Manufacturing
- Test planned for the end of 2026

INFN LTS Program

WPLs: S. Farinon, M. Sorbi

2024

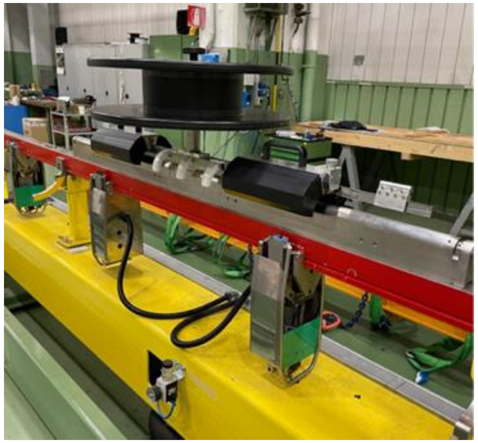
- Winding/curing tooling is at ASG.
- **Coil parts are arriving**
  - **Insulated wedges are expected from CERN in October.**
  - **3D printed spacers available, machined spacers delayed.**
- Manufacturing of Cu dummy coil
  - **Winding trials start as soon as wedges arrive.**
- Structure engineering design
- Engineering-design review

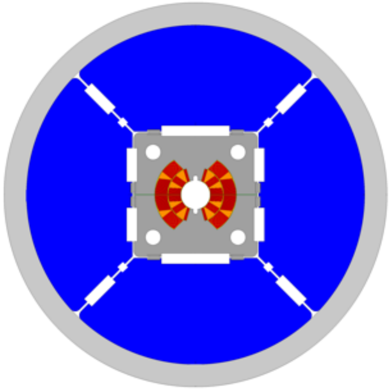
2025

- Completion of dummy coil
- 1-2 Nb_3Sn practice coils completed
- Structure tested with dummy load

2026

- Two to four production coils
- Assembly of accepted coils into structure
- Magnet test at INFN (before re-testing at 1.9 K at CERN)





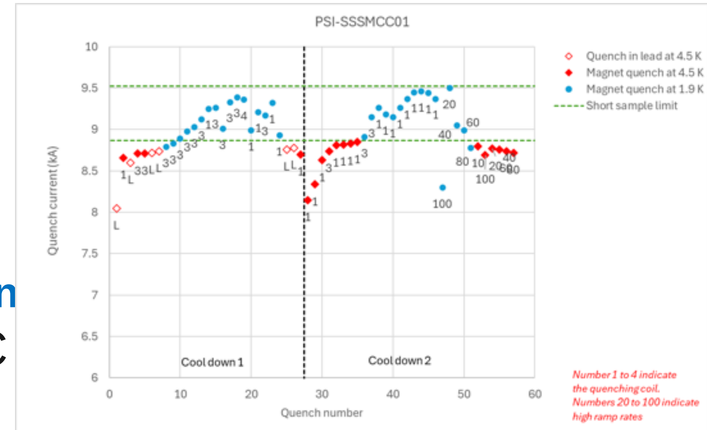
CHART/PSI LTS Program

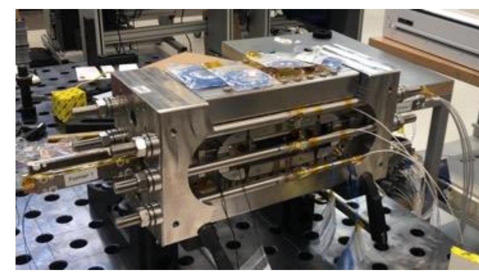
CHART Swiss Accelerator Research and Technology — PSI

WPL: D. M. Araujo

2024

- Subscale stress-managed common coil
  - **subSMCC1 tested at SM18**
  - 4.5 K 98% of Iss after minimal training
  - 1.9 K 95% of Iss after limited training
  - **subSMCC2 with ESC protection in autumn**
- SMACC Stress-Managed Asymmetric CC
  - Winding trials with HF cable successful
  - Coils engineering design started
  - November, conceptual design review



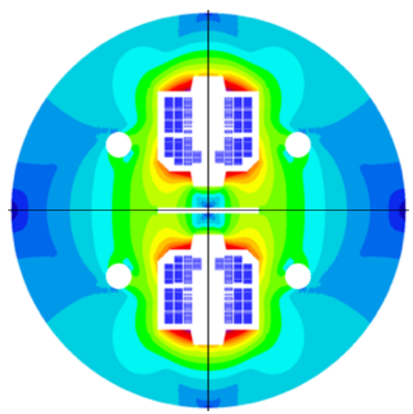


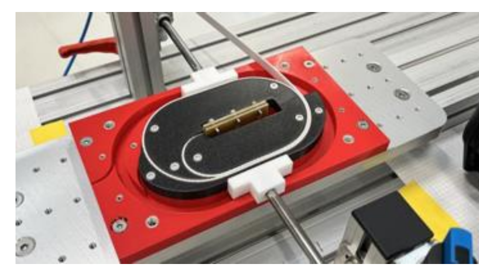
2025

- SMACC
  - Structure engineering design
  - Coil manufacturing

2026

- SMACC
  - Assembly and test by summer





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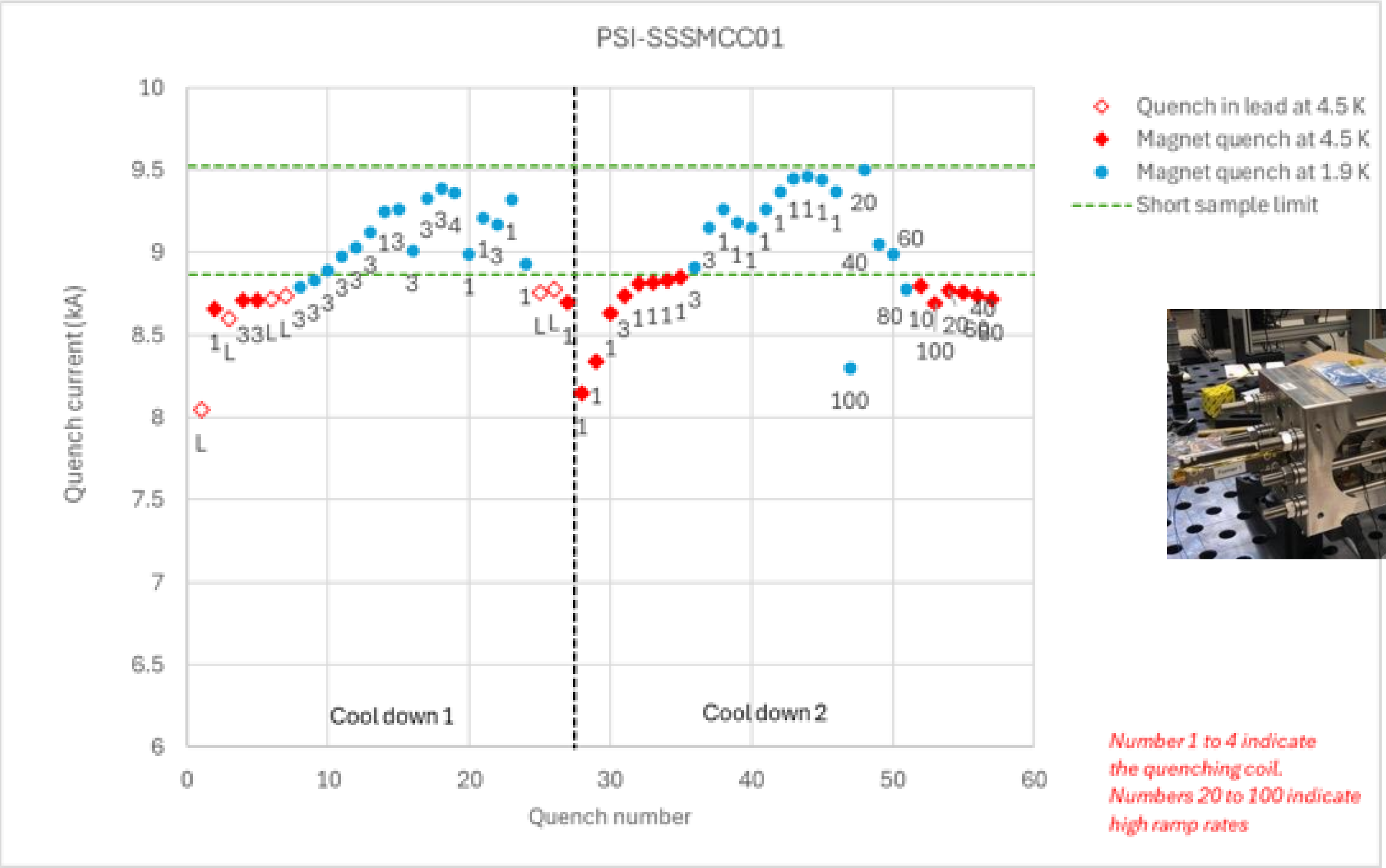
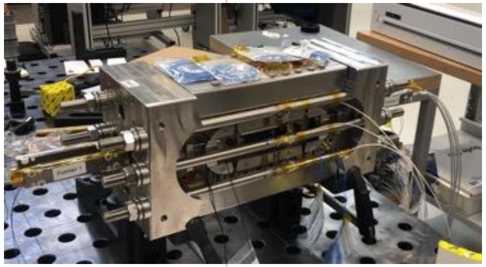
CHART/PSI LTS Program

WPL: D. M. Araujo





[Test data courtesy of G. Willering, CERN]

LTS Dipole Magnet Tests

Lab	Description	2024				2025				2026			
CEA	SMC v2 test				X								
	R2D2 v1 test						X						
	FDv1 test												X
CERN	MQXFS pre-load studies		X	X	X	X	X						
	ERMC test					X							
	RMM1 pre-load study		X	X	X								
	RMM2 test						X						
	12-T cos-theta test												X
	BOND 14-T block coil test												X
CIEMAT	ISAAC common coil assembly of ERMC coils test				X		X						
	DAISY 14-T demonstrator test												X
INFN	FalconD test												X
PSI	Subscale Common Coil		X		X								
	SMACC demonstrator test										X		

ISAAC test shifted due to re-design of vertical structural support.

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CEA HTS Program

WPL: T. Lecrevisse

MI (Metal Insulated) Racetrack program:

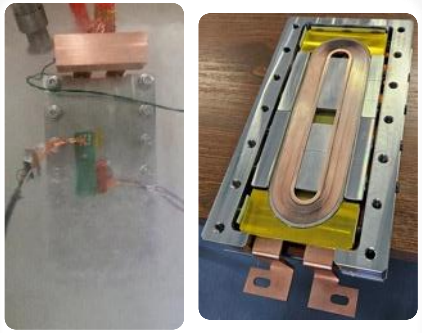
- Goals: validate design tools and manu-facturing processes for **600-mm-long coils, 5 T central field**.

2024

- **Low-grade 140 mm coils w & w/o artificial defect fabricated and tested in LN_2.**
- **Two high-grade coils wound, testing in LN_2 imminent. 4.2-K test in Q1/25.**
- 2-stack test in the pipeline.
- **600-mm racetrack engineering and tooling design well advanced.**
- 600-mm racetrack modelling well advanced
  - Transient EM and thermal model (PEEC-R) published.
  - EM and thermal FEM model (SALOME / CASTEM) published.
  - Mechanical model ongoing

2025

- Q1/Q2 600-mm racetrack winding and LN2 test
- Q2/Q3: 600-mm single- or double racetrack test below 50 K.

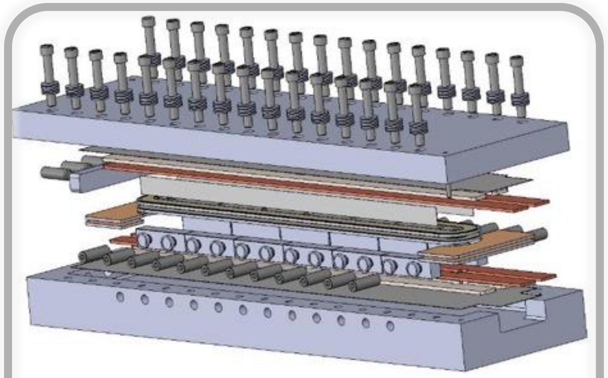


July 2024 : first prototype w/ and w/o local damage, 77 K test (Old CEA R&D tape)

MI simple Durnomag®, HFM SST REBCO tape

MI double Durnomag®, HFM SST REBCO tape

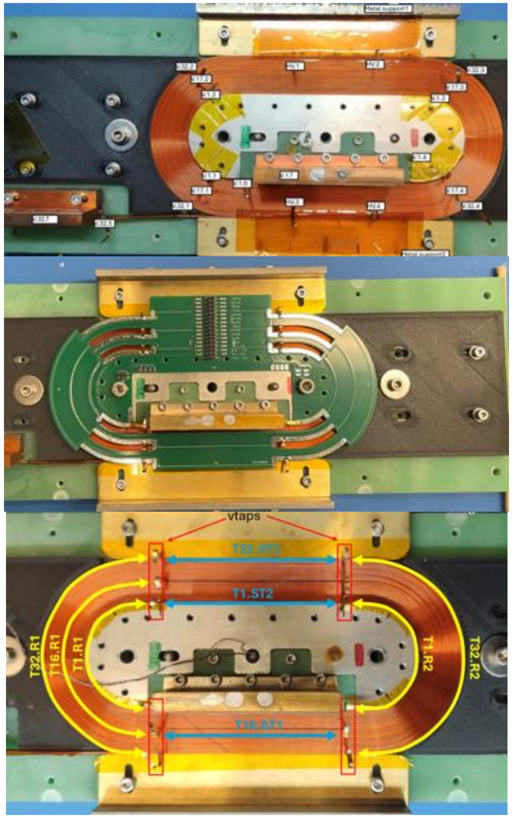
Sept. 2024 : First winding using SST HFM REBCO tape



Structure adaptation for 600 mm racetracks (under finalization)

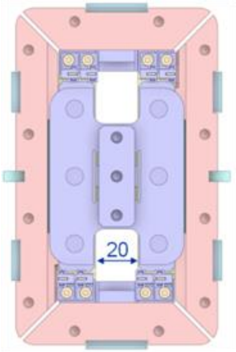
CERN HTS Program

WPL: A. Ballarino



2024

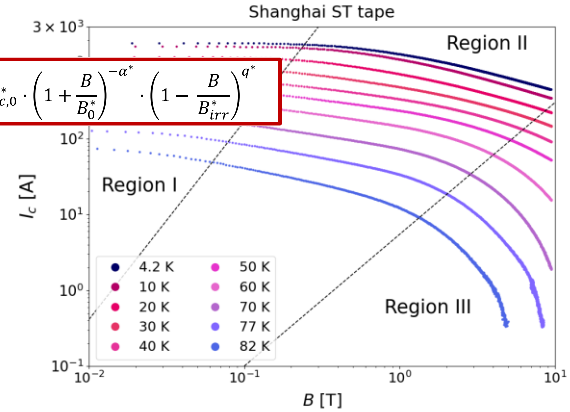
- Racetracks from insulated dry-tape-stack cable
  - **Three coils wound and tested; iterative improvements; Coil 3 successfully tested in LN_2**
  - Q3/4: Single and double racetrack tests in LHe and LN_2.
- Common coil design under way.
- Conductor characterization
  - Order for 11 km divided with multiple suppliers.
  - **100s of tape samples measured** and characterized.
  - Theva **TapeStar commissioned** for reel-to-reel for indirect Ic measurement being.
  - Hall-probe scanning for conductor defects.

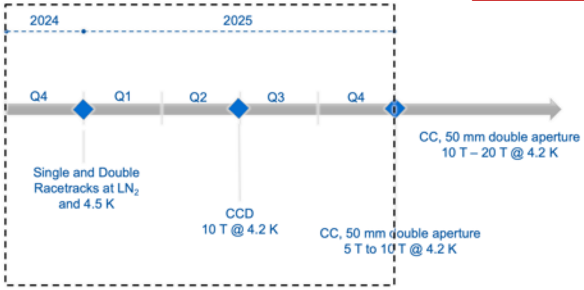


2025/26

- Common-coil roadmap gradually increasing aperture and field towards FCC-hh specs.

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





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PSI HTS Program

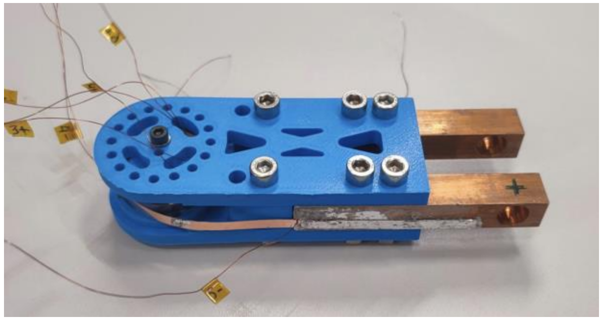
WPL: D. Araujo

2024

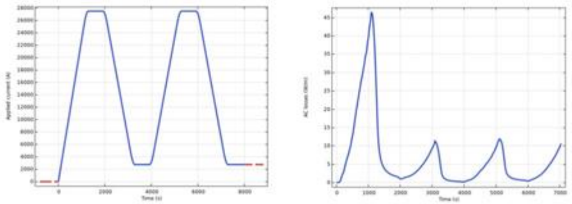
- **Numerical tool qualification**
  - Qualification of commercial solvers and numerical methods; in collaboration with HTS Modeling WG.
- **AC loss estimation for 2-in-1 14-T block-coil (cloverleaf ends) topology at 20 K.**
  - As benchmark case for HTS Modeling WG.
  - As input into cryo considerations for FCC FS report.
- Insulated soldered tape-stack cable development
  - Produce round pancake coils for validation of manufacturing processes and AC-loss measurement.
- HTS subSMCC tooling and engineering design

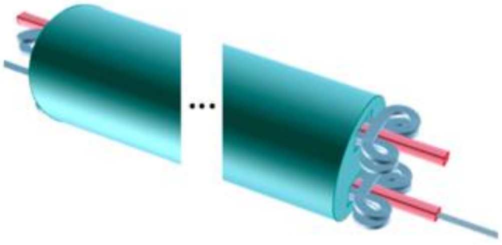
2025

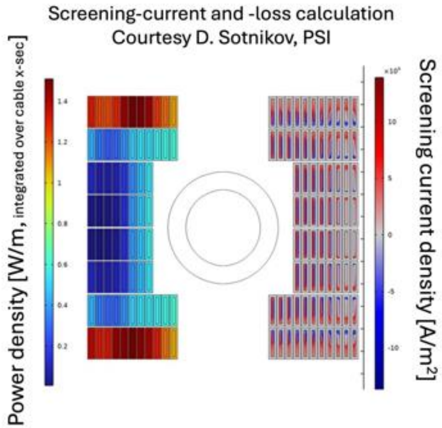
- HTS subSMCC manufacturing and testing
- 5-6 T field on conductor
- HTS roadmap deliberations with HFM.



[Courtesy D. Sotnikov]







HFM
High Field Magnets Programme

HTS Dipole Magnet/Coil Tests

Lab	Description	2024				2025				2026			
CEA	MI racetrack stack conceptual design MI short racetrack stack manufacturing and testing				X X								
	MI long racetrack manufacturing and testing						X						
CERN	Racetrack fabrication and testing				X								
	Common coils magnet						X						
	Round-cable coil?											X	
PSI	Small racetracks in common-coil background field						X						

No shifts in schedule since last SB.

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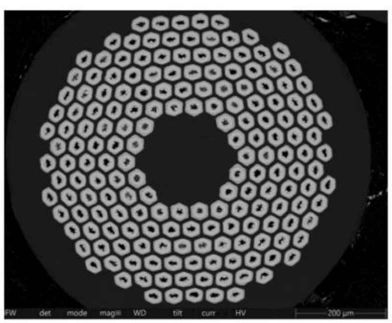
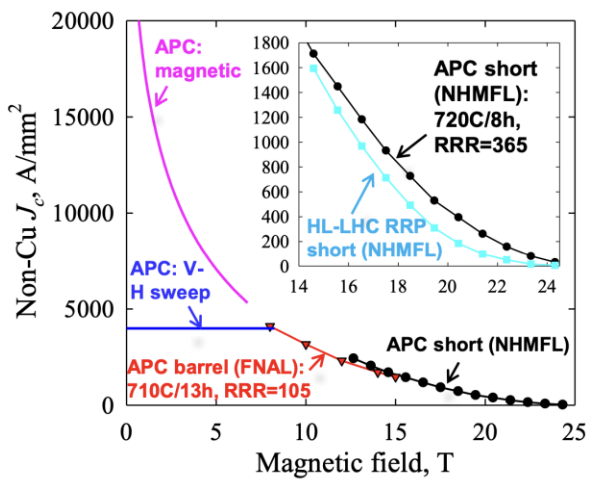
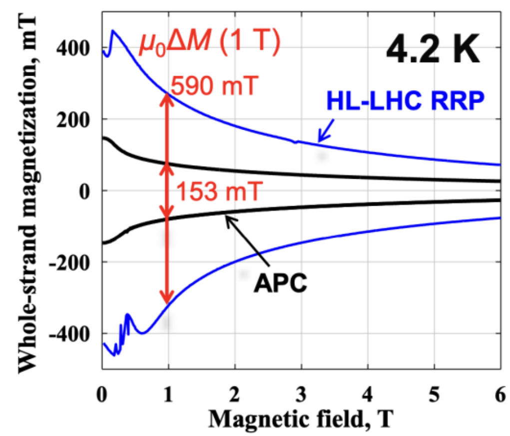
14-T LTS Magnet at 4.5 K: Ramp Losses

- Recall: CDR target for ramp losses:
  - Magnet chapter: 5 kJ/m.cycle
  - Cryo chapter: 10 kJ/m.cycle
  - Today's Nb_3Sn technology: closer to 20 kJ/m.cycle
  - Potential for Artificial-Pinning-Center (APC) technology to reduce the magnetization curve and reduce losses.
  - Agreed target for present study: 10 kJ/m.cycle







[Courtesy: X. Xu, https://indico.cern.ch/event/1454133/]

The Superconducting Super Collider (SSC)

Accelerator magnet cooling at around 4 K

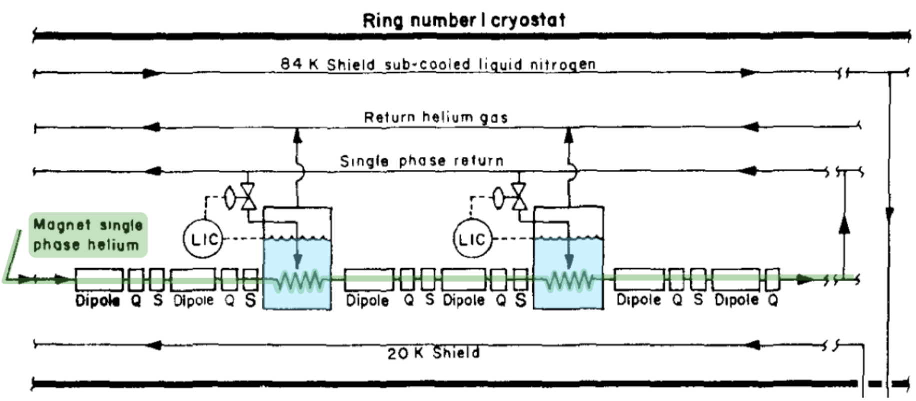


Figure 5.3-1. A conceptual representation of the SSC collider rings cryogenics system. In each of the two rings the collider magnets are cooled in series by a flow of single-phase helium. This stream is recooled at cell intervals by heat exchange with boiling helium. The cryostat of each ring contains cooled shields at 84 K and 20 K.

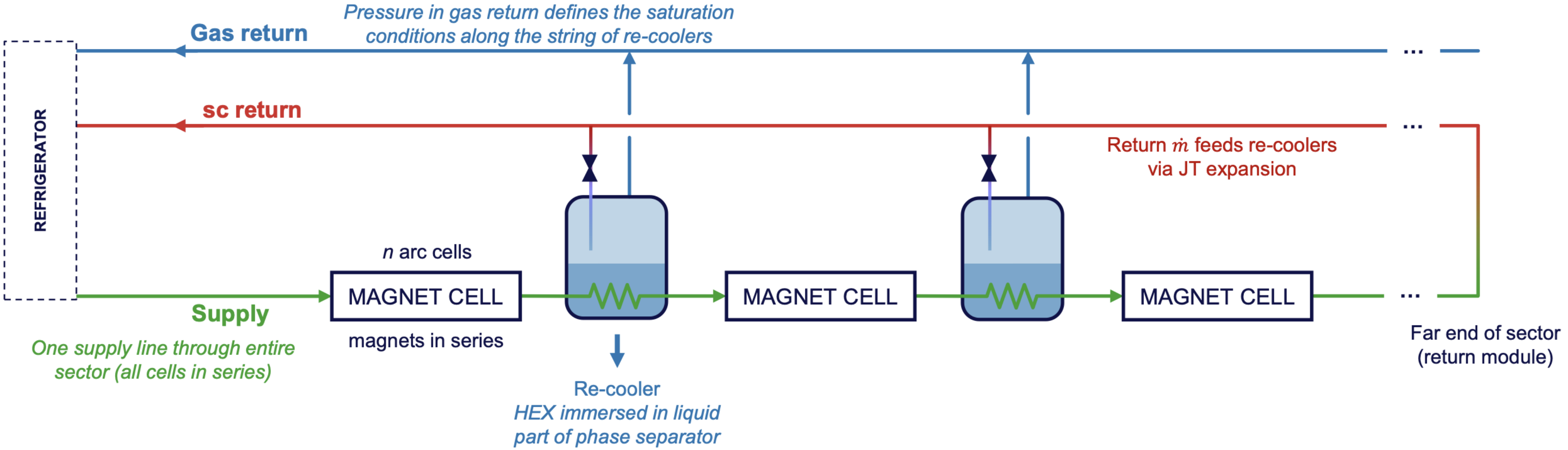
The basic concept of magnet cooling and refrigeration distribution is illustrated in Fig. 5.3-1. In this figure a refrigeration plant is on the left, providing and accepting flow. Single-phase helium at 4.15 K and 4 atmospheres is forced out into the magnet string of each ring upstream and downstream from the refrigerator for a distance of 4 km. It flows through the magnets in series and is recooled periodically to maintain the superconducting windings at or below the specified 4.35 K. At the end of the 4 km string, the flow is returned toward the refrigerator. This fluid is flowing at a pressure above its critical pressure, so in all parts of the circuit only a single phase is possible. Along this line small flows are withdrawn and expanded into pool-boiling recoolers spaced at intervals of one cell, 192 meters. The saturated gas from the recoolers is collected and returned to the refrigerator in a third line.

Tevatron → SSC → … FCC ?

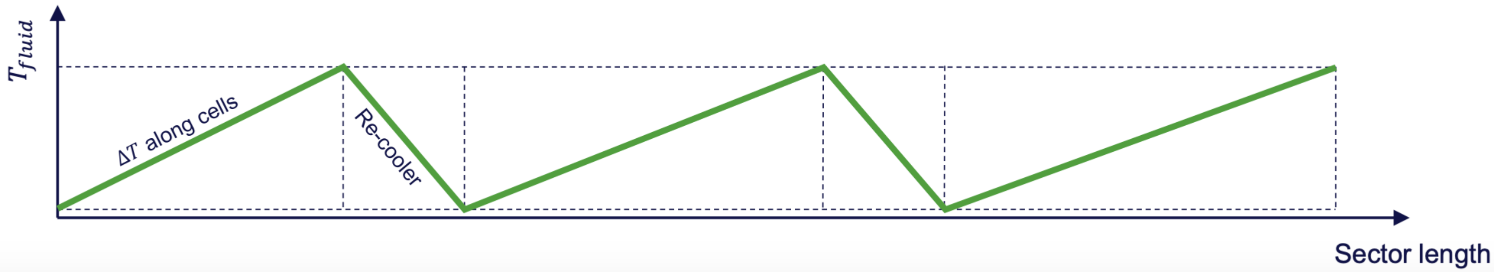
The ancestor of the SSC is, of course, the Tevatron, and this heredity is reflected in the cryogenic system requirements. The Tevatron has produced a body of successful superconducting magnet operating experience with beam and beam-loss heating. The Tevatron magnets are cooled by immersion in supercritical helium, the so-called single-phase flow, that is cooled in turn by heat exchange with boiling helium. Although other systems are possible and may have attractive features, any fundamental change in the single-phase cooling concept requires development and demonstration under realistic operating conditions. This is a complex and expensive task; unless some very strong reasons can be adduced for the superiority of some alternative system, the Tevatron model must be used for the SSC.

Conceptual Design of the Superconducting Super Collider, 1986

Proposed cooling scheme



- T_{min}?
- T_{max}?
- $\Delta T_{coil \rightarrow He}$?



Radial ΔT: estimates based on x-section

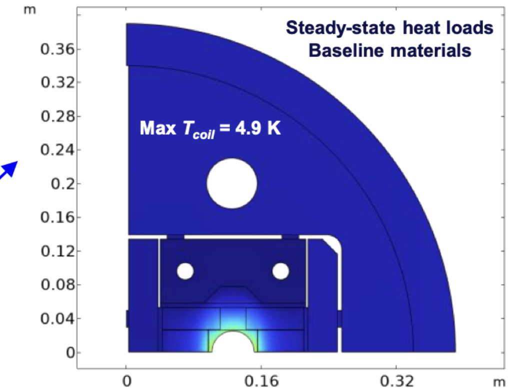
Courtesy X. Gallud Cidoncha

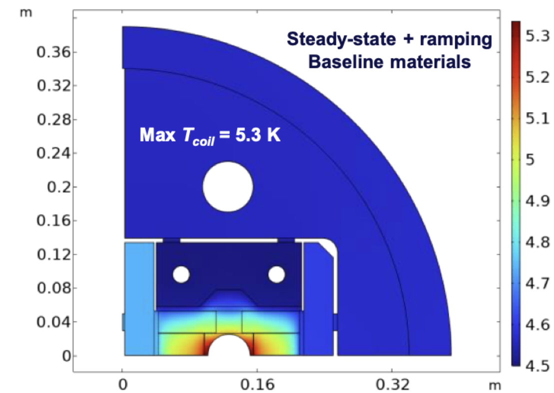
Using the magnet cross-section provided by A. Haziot, we estimated the **radial temperature gradient during steady-state operation and during the ramp down/up cycle**

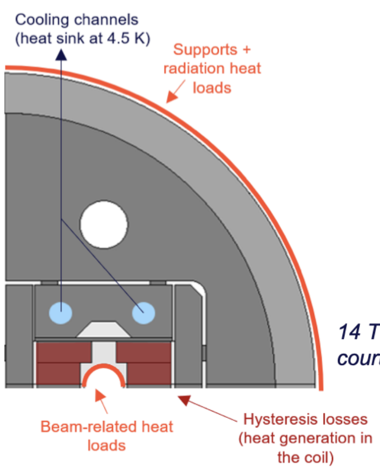
Reminder:
- Steady-state – 1.4 W/m
- Ramping – 3 W/m

*Calculated for He T = 4.5 K

	Pole material	Insulation scheme	Heat load case	Max. T in coil [K]	ΔT from He [K]
First design	Titanium alloy	G10	Steady state	4.92	0.42
			Steady-state + ramp	5.28	0.78







14 T block coil design, courtesy Ariel Haziot

NB: Effective thermal conductivity used for the coil blocks is taken from 11T experimental data, incl. impregnation and interlayer insulation where applicable (see EDMS 1871957)
NB II: Thermal properties of other solids from NIST data, no thermal contact resistance added

Discussion

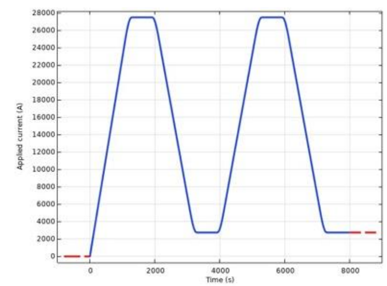
- Can reduced ramp rates compensate for increased ramp losses? We need a clear, quantified statement.
- What can magnet engineers do to reduce transverse temperature gradients in their magnets? Losses are highest where margin are lowest ..
- Concrete numbers on space requirements, power consumption, cryogen inventory for the 4.5 K cryo system option will be presented by Laurent Delprat (WPL) in the end-of-year Feasibility Study report.
- We need a 20 K study for the HTS option.

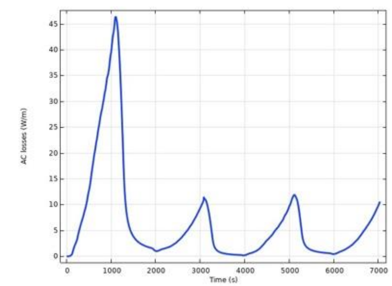
Contents

- Update on HFM Programme deliverables LTS and HTS
- Status cryo studies 4.5 K
- Spotlight on transient-effect studies in HTS magnets

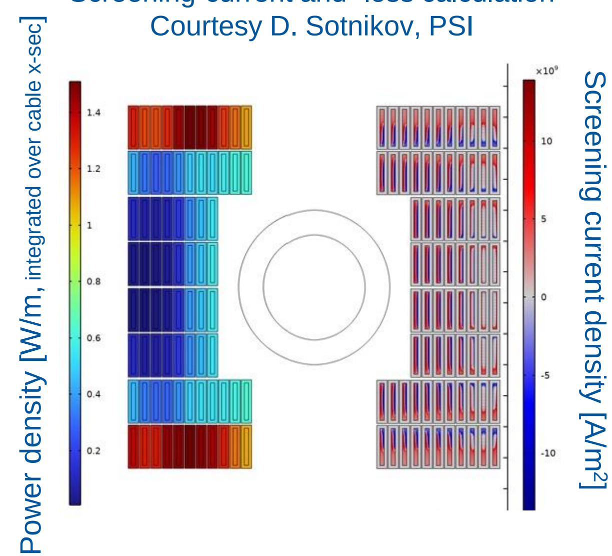
AC Losses in HTS Magnets?

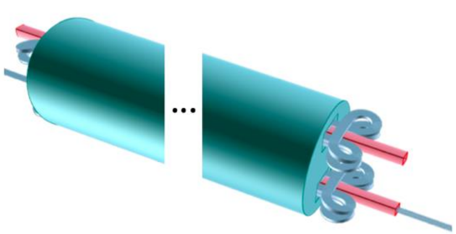
- Working our way into HTS technology for accelerator magnets.
- Benchmark case for cross-validation of numerical models and relative scaling studies.
  - Assumption: block-coil type HTS magnet with clover-leaf ends.
  - 5 K temperature margin.
  - Crude assumptions on protection.
  - No work on mechanics.
- Losses on order of 50 kJ/m.cycle.
- Benchmark under study by HFM HTS Modeling WG.
- Requires experimental validation!
- Starting point for actual magnet design.

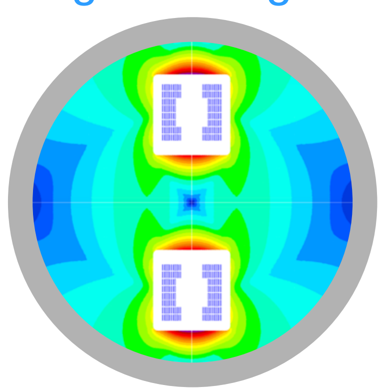




Screening-current and -loss calculation
Courtesy D. Sotnikov, PSI







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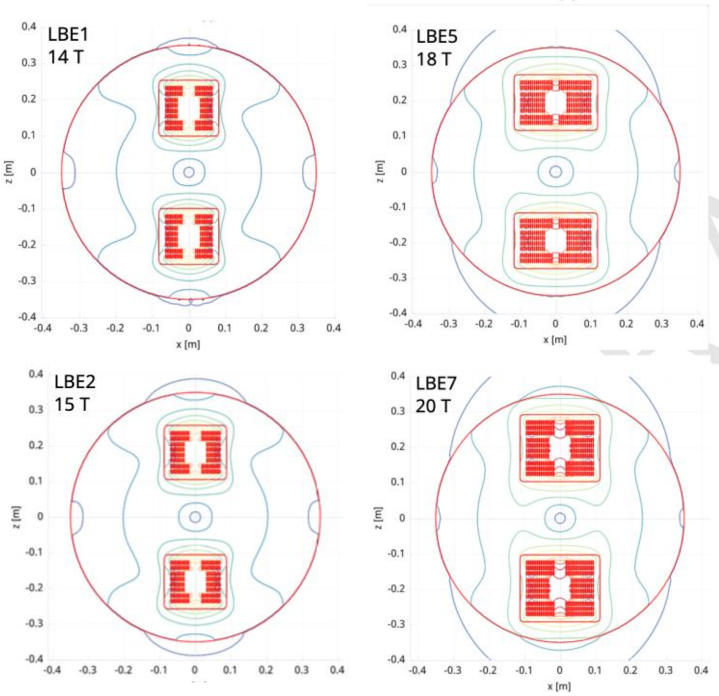
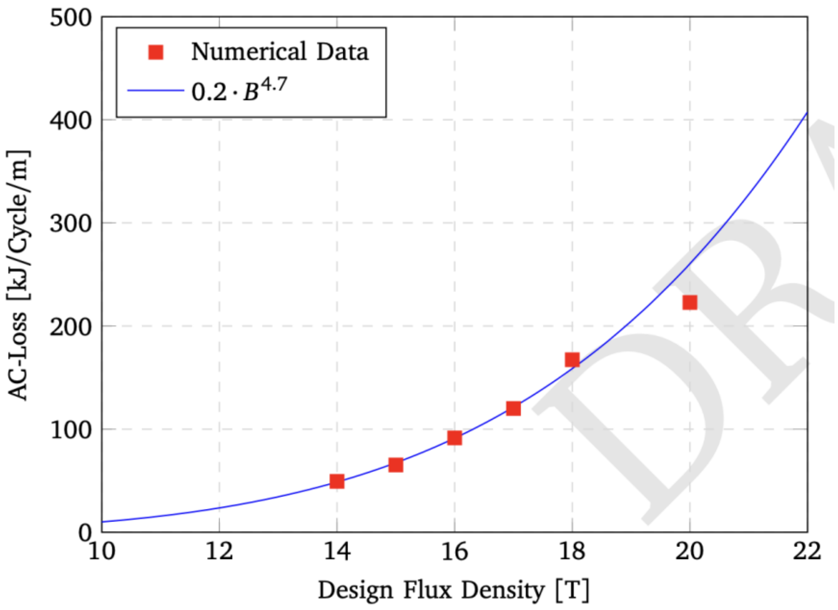
Scaling of AC Losses with Field

- As expected, AC losses grow non-linearly with field due to larger field sweep and growth in coil-size.
- In this study (for which all previous caveats and assumptions apply) AC losses increase 4-fold from 14 to 20 T.





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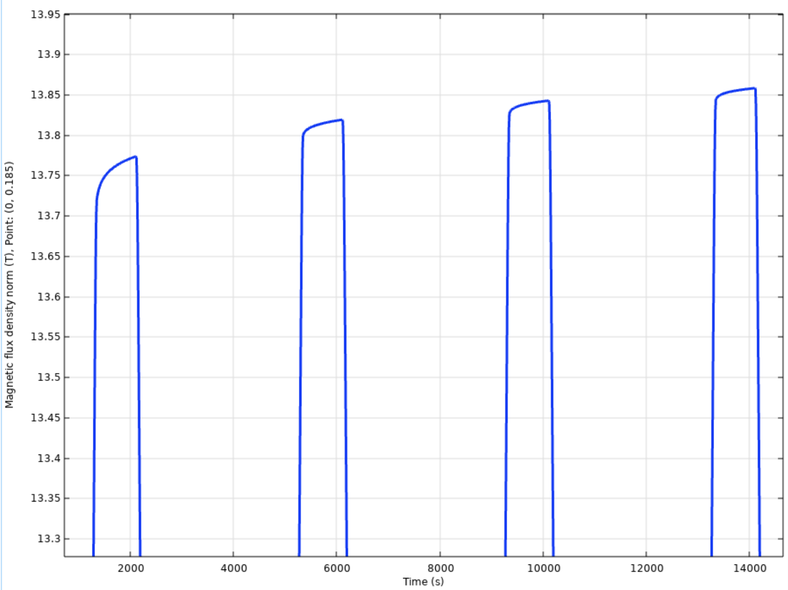
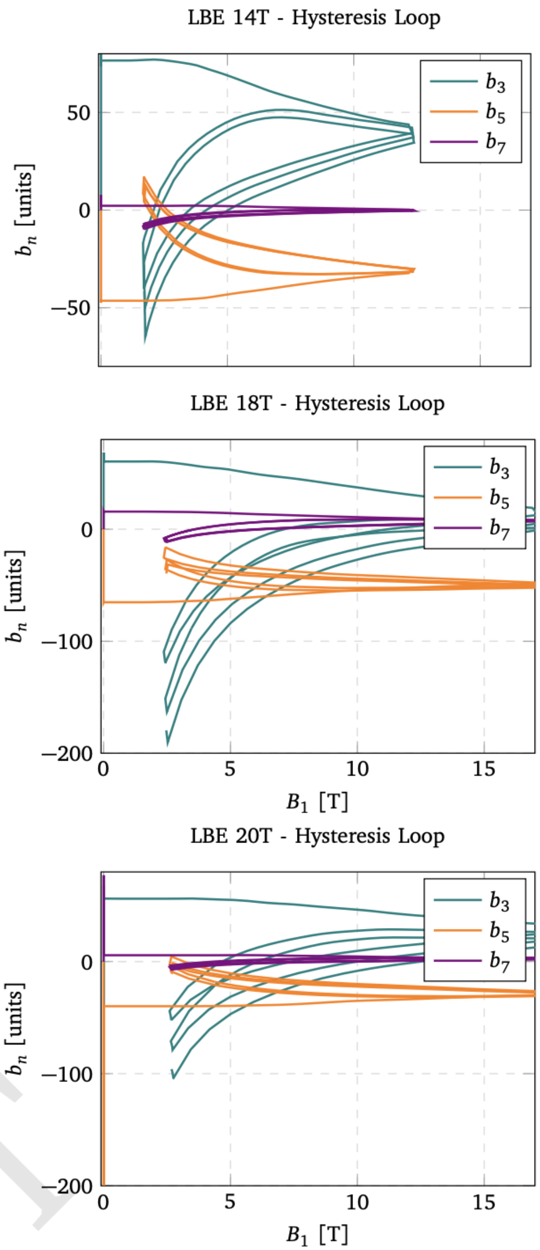
Field quality

- In this study, a strong screening effect is observed. Multiple cycles are needed to reach reproducible conditions.
- Experimental validation is of the essence.
- Local correction schemes will be required.
- How much can be achieved with beam-based feedback and possibly AI models?





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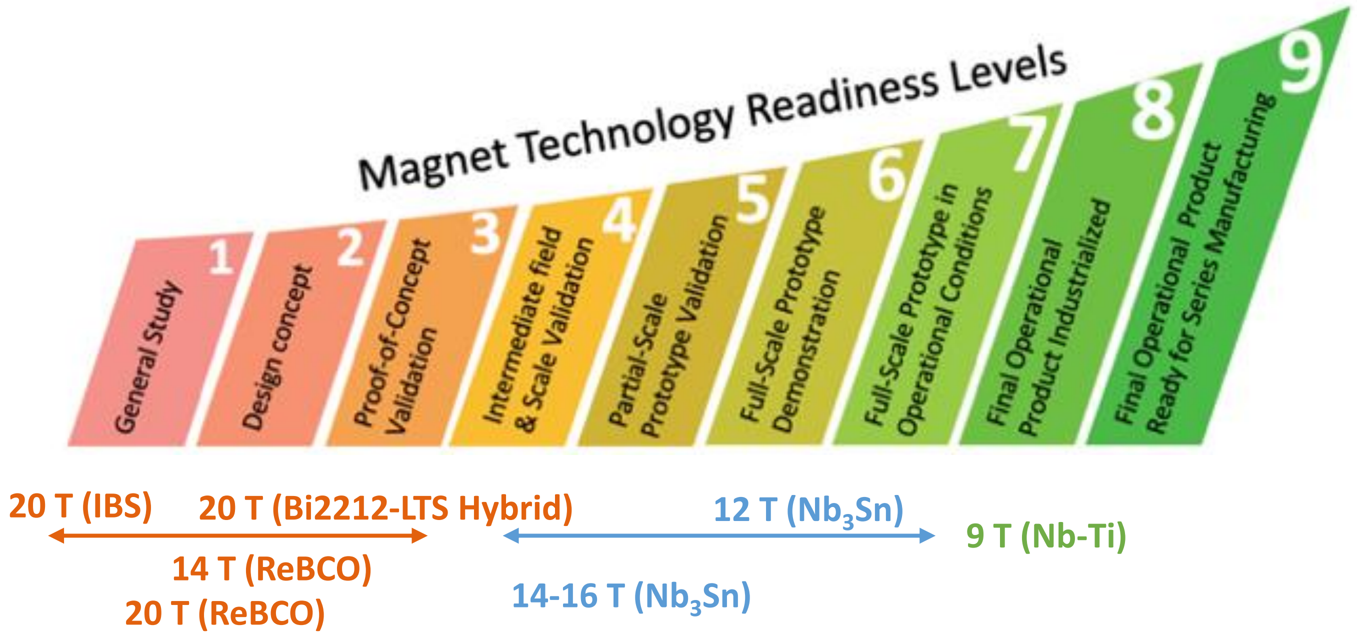
Towards an HTS Roadmap



- 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 year.
- We are entering uncharted territory. Breakthroughs and (temporary) setbacks will be encountered along the way.

Summary

- HFM LTS activities continue to build momentum towards a series of demonstrator tests in 2026.
- Cryogenics study for 4.5K proceeds steadily with results available for the FCC Feasibility Study report by the end of the year.
- HTS experimental activities will see first subscale magnet tests with AC-loss and FQ measurements throughout 2025.
- Numerical AC-loss studies provide preliminary input to cryo study. AC-loss study should extend to temperatures <20 K.
- Validated HTS numerical models will underpin innovation process towards a new HTS baseline technology.