~~MuCol~~ HFM – WP2.6 Muon Collider Solenoids and other magnets[1,2]

L. Bottura, B. Bordini, S. Fabbri, F. Boattini (CERN),
B. Caiffi, S. Mariotto, M. Statera (INFN)

HFM Annual Meeting – 12 February 2025

(1) MuCol is a EU study coordinated by CERN in support of the activities of the International Muon Collider Collaboration (IMCC)
(2) IMCC “muons magnets Working Group” and MuCol “WP7 – Magnets” practically overlap

Outline

- The Muon Collider magnets and their challenges
- Achievements within the scope of HFM WP2.6
- Plans for R&D
- Summary and perspective

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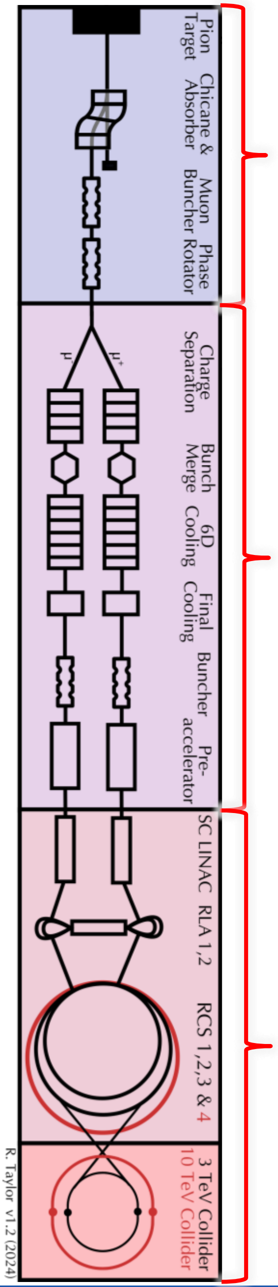
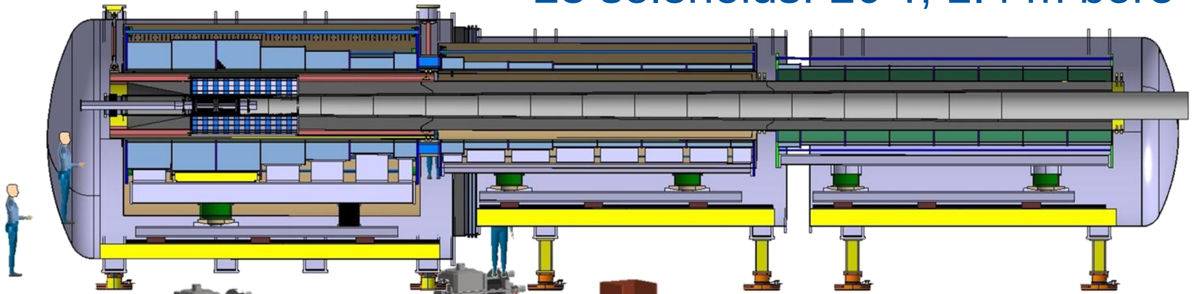
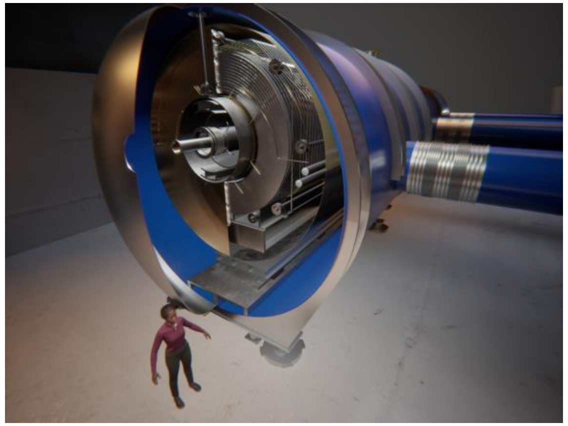


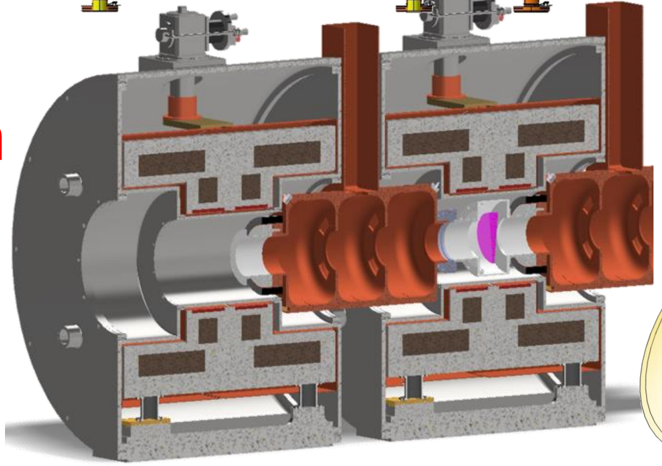
Target and capture solenoid

23 solenoids: 20 T, 1.4 m bore

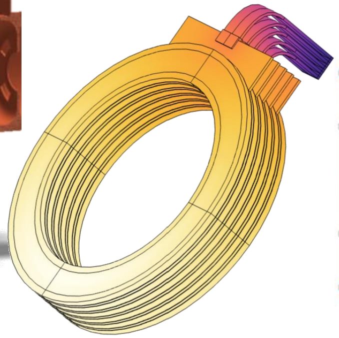


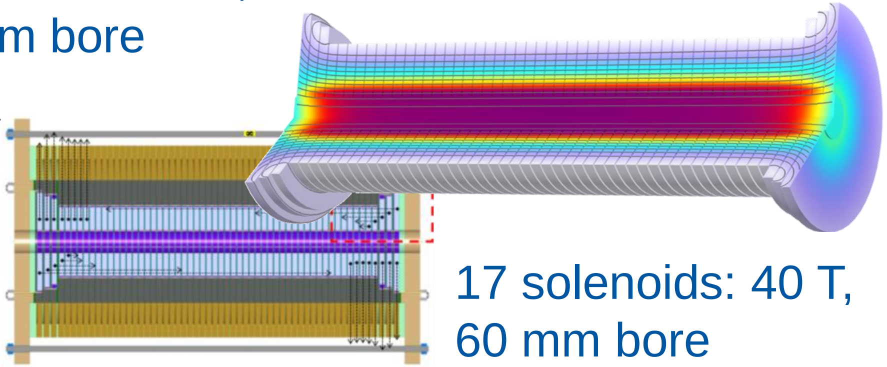


Muon beam cooling solenoids



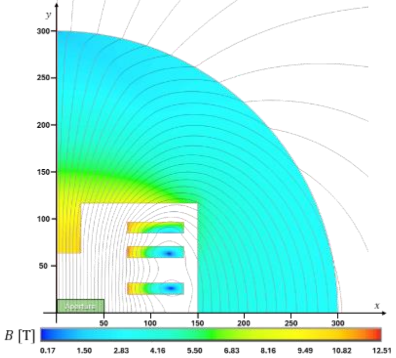
3000 solenoids: 2 to 14 T, 90 mm to 1.5 m bore

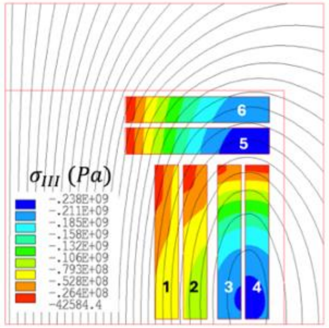


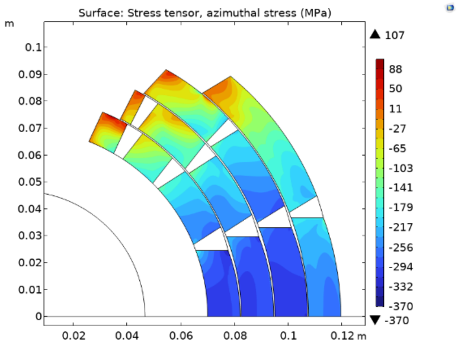


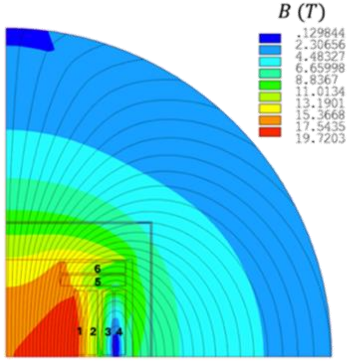
17 solenoids: 40 T, 60 mm bore

Accelerator and collider magnets









5 km: 10 T, 30(V) x 100 mm (H) dipoles

10 km 14 T, 140 mm bore dipoles

Focus on superconducting magnets only !

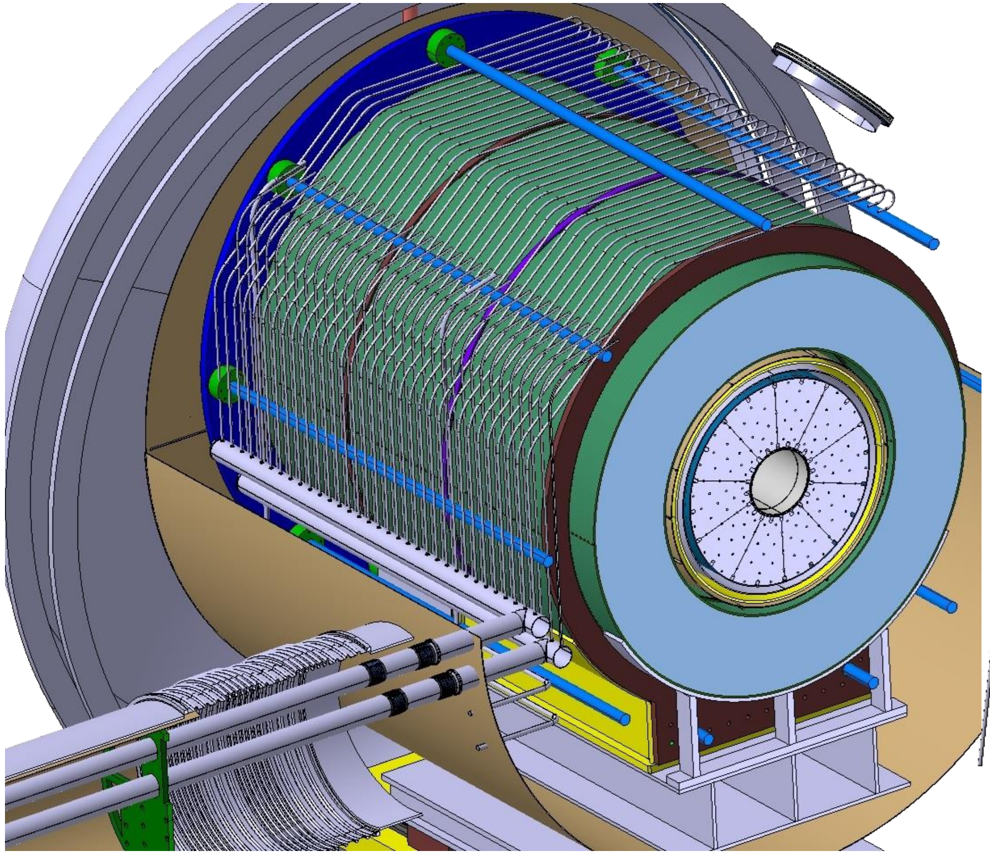
Overview of magnet development targets

Complex	Magnet	Conductor	Aperture (mm)	Length (m)	Bore Field (T)/(T/m)	Stored energy (MJ)	Ramp-rate (T/s)	Heat load (W/m)	Radiation dose (MGy)	Temperature (K)	TRL range (-)	
Target, decay and capture	Solenoid (HTS)	REBCO	1400	19	20	300	SS	2	80	20	5	6
6D cooling	Solenoid (HTS)	REBCO	90…1500	0.08…0.5	2…14	100	SS			4.5…20	3	4
Final cooling	Solenoid (HTS)	REBCO	50	0.5…1	> 40	10	SS			4.5	3	4
Rapid cycling synchrotron	NC Dipole	Cu	30x100	5	± 1.8	0.05	500…4200	5		300	7	8
	SC Dipole (HTS)	REBCO	30x100	1.5	10	10	SS	5		20	3	4
Collider (3 TeV)	Dipole (NbTi)	Nb-Ti	160	4…6	5	5	SS	5	30	4.5	7	8
	Dipole (Nb_3Sn)	Nb_3Sn	160	4…6	11	20	SS	5	30	4.5	6	7
Collider (10 TeV)	Dipole (HTS)	REBCO	140	4…6	14	40	SS	5	30	20	3	4
	IR Quadrupole (HTS)	REBCO	140	TBD	300	40	SS	5	30	4.5…20	3	4

Strong accent is put on HTS as technology enabler for a high-performance Muon Collider, because…

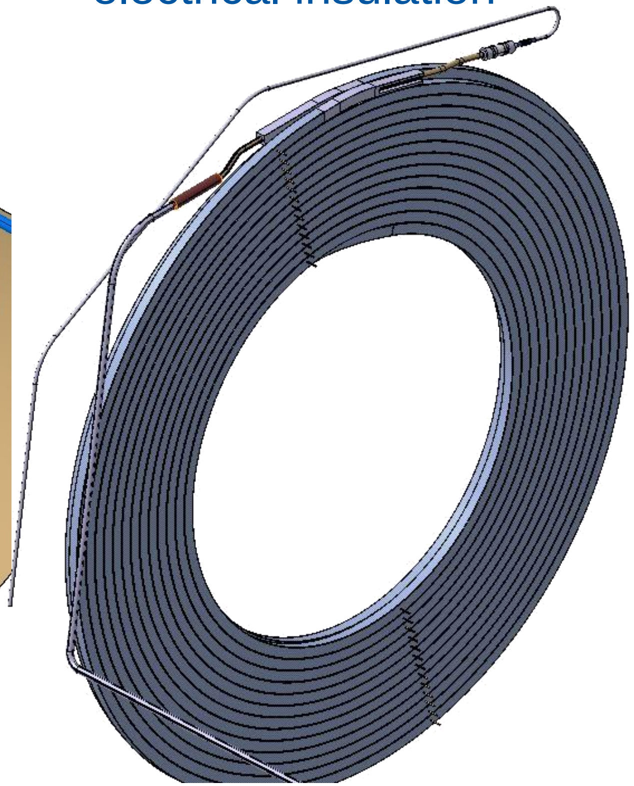
1. **Solenoids are critical** for the production and cooling of a high-intensity muon beam
2. High-field HTS accelerator magnets operated at 20 K **reduce CAPEX+OPEX**

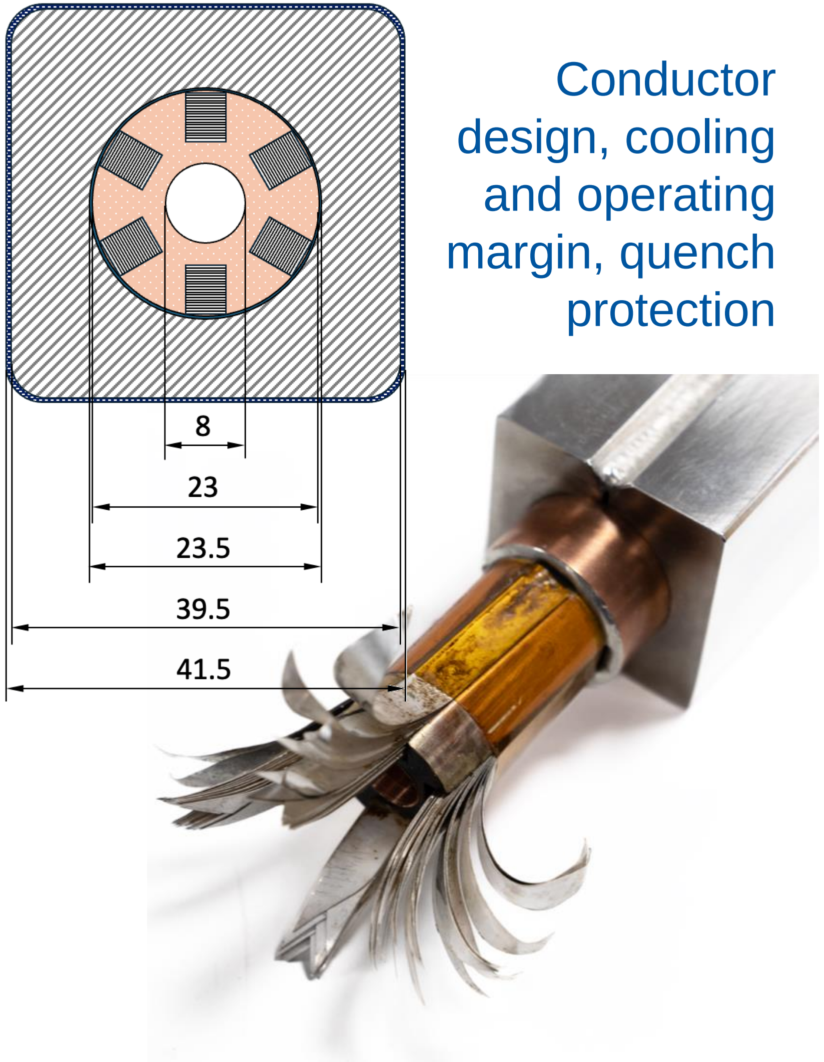
Target and capture solenoid



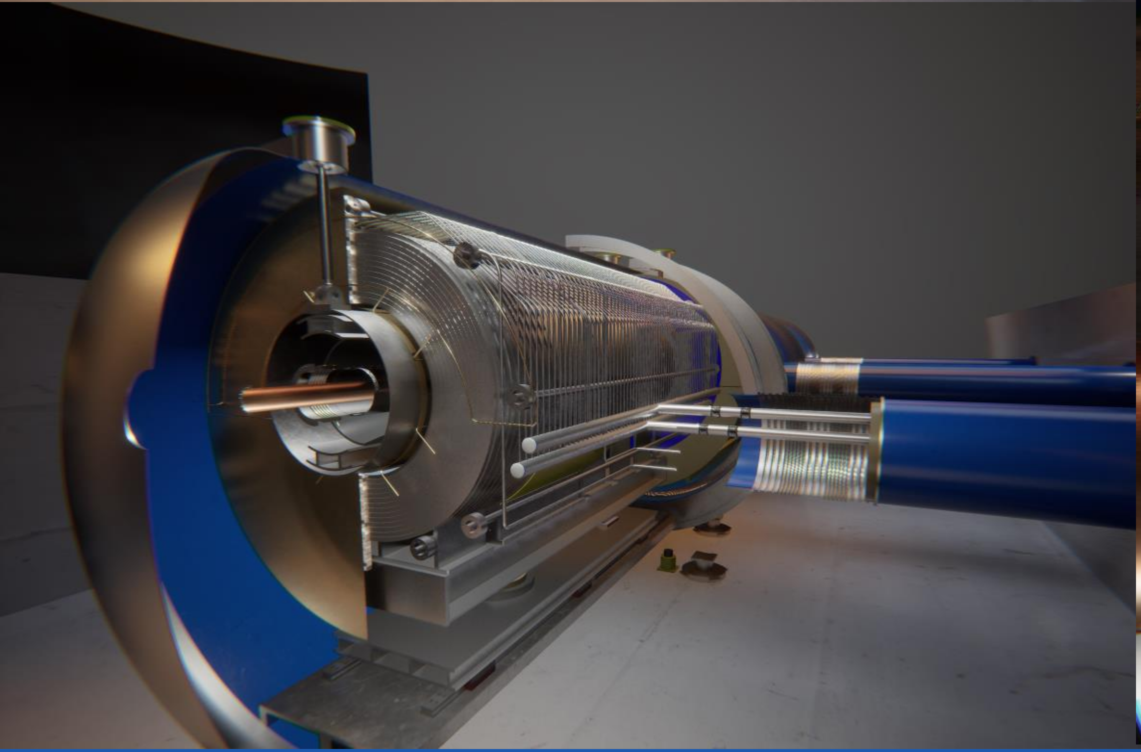
Coil assembly, helium cooling layout, busbars

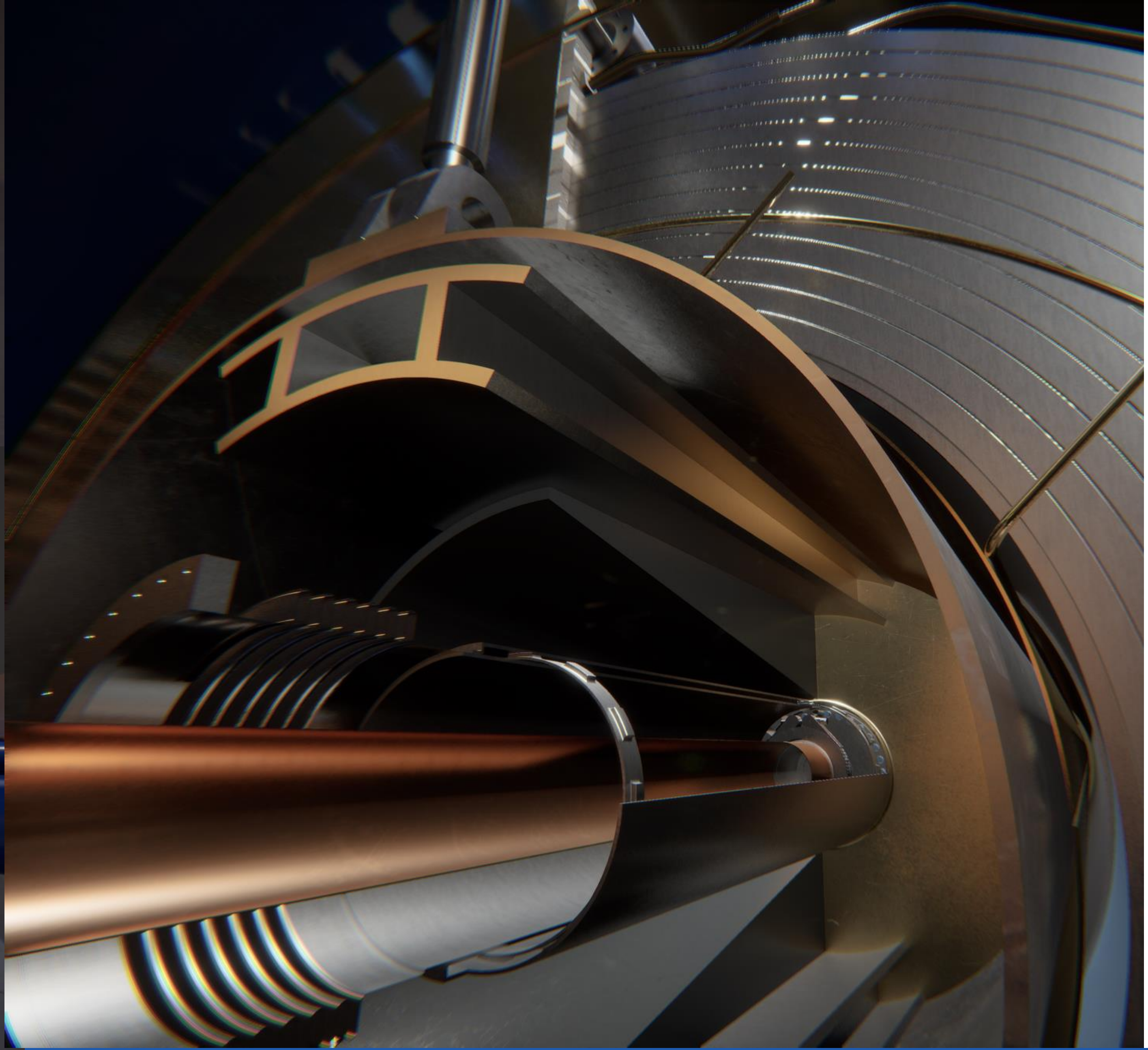
Double pancake winding, joints and terminations, electrical insulation





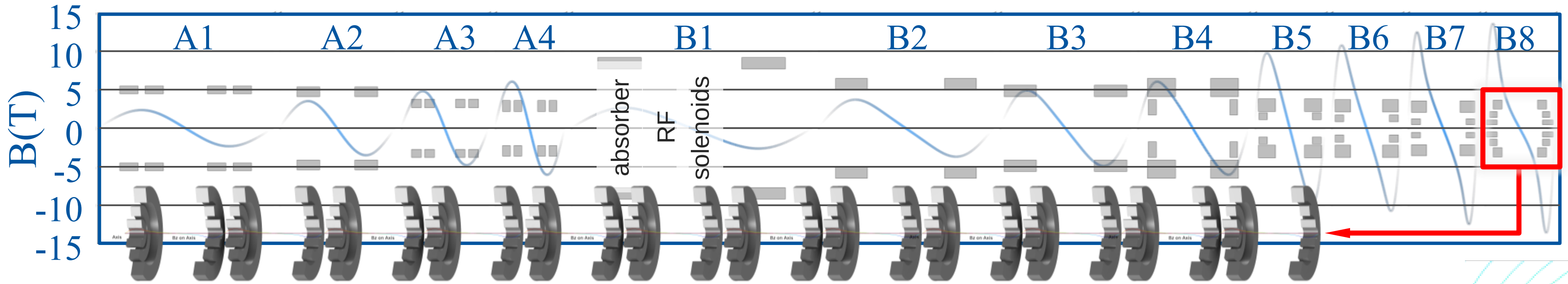
Conductor design, cooling and operating margin, quench protection



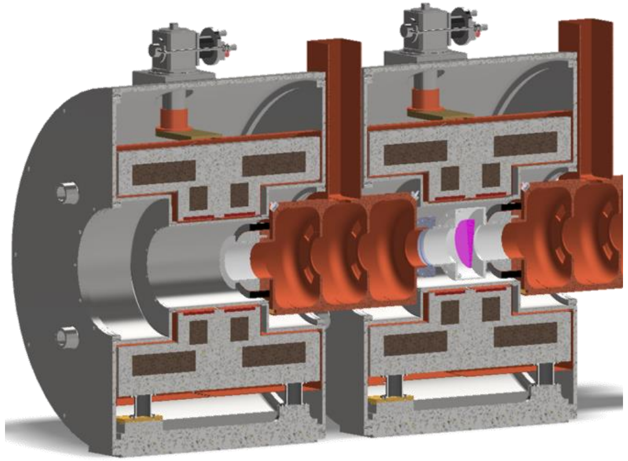


Courtesy of M. Brice (CERN) and CERN visuals

6D cooling solenoids

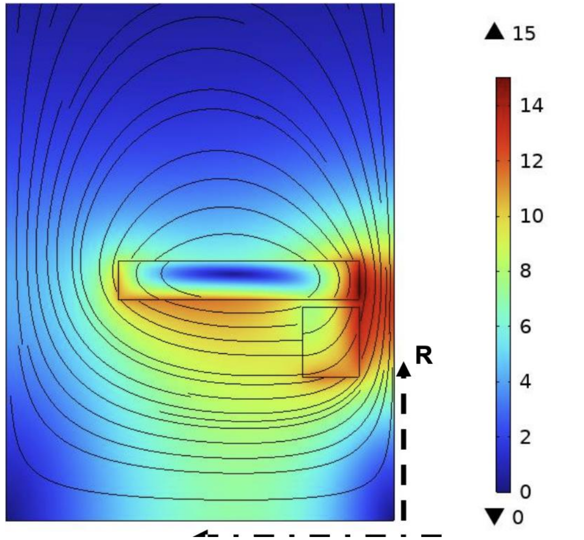


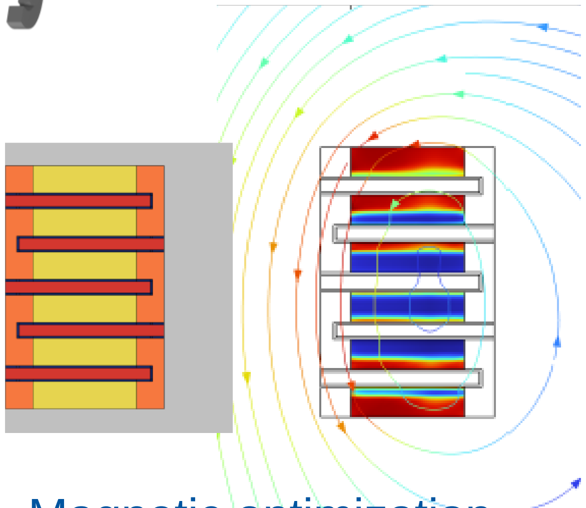
Cooling cells, ≈ 1 km length channel
About 3000 solenoids, axis field ≈ 2.6…17.9 T
Free bore diameter from 50 mm to 800 mm



Cell integration (large forces !)

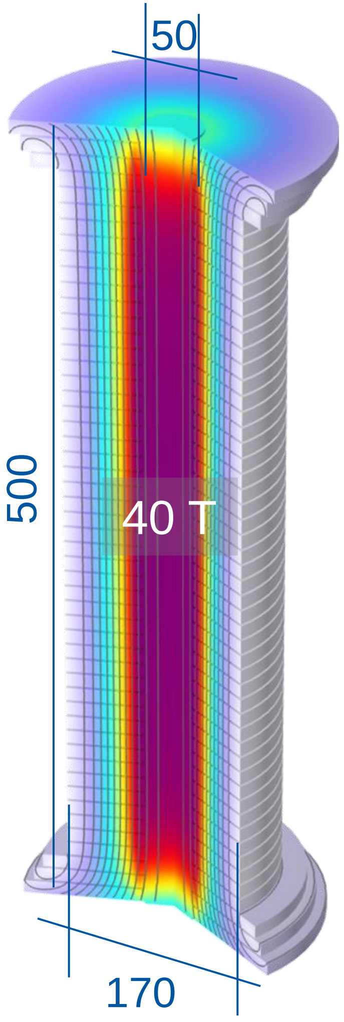
NI winding



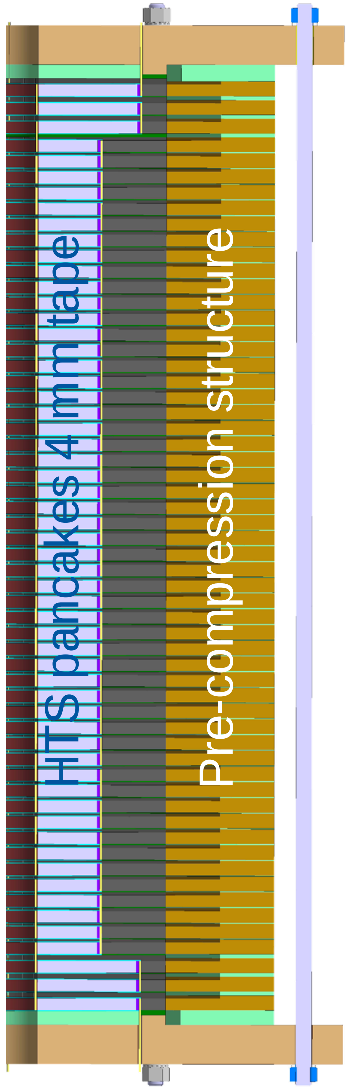


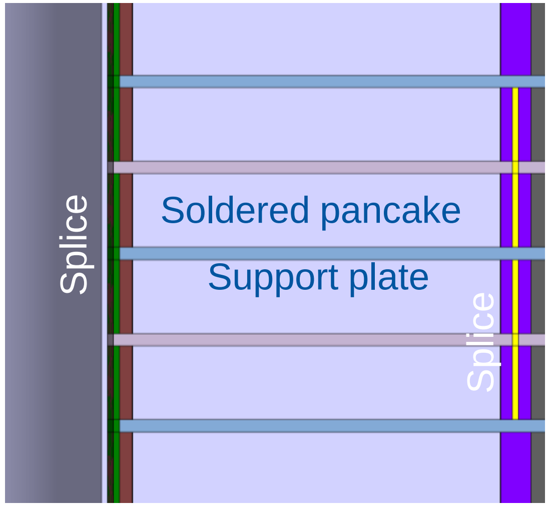
Magnetic optimization
Mechanical design
Thermal modeling
Magnetization and margin
Multiphysics studies (B, dB/dt, T)

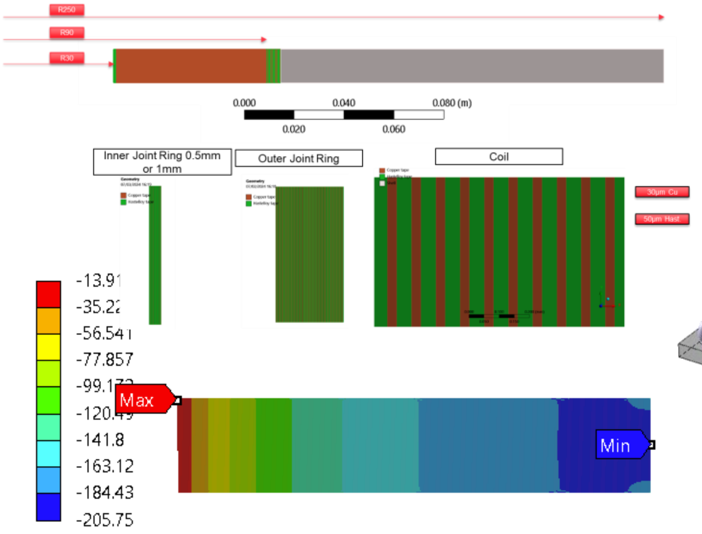
Final cooling solenoids



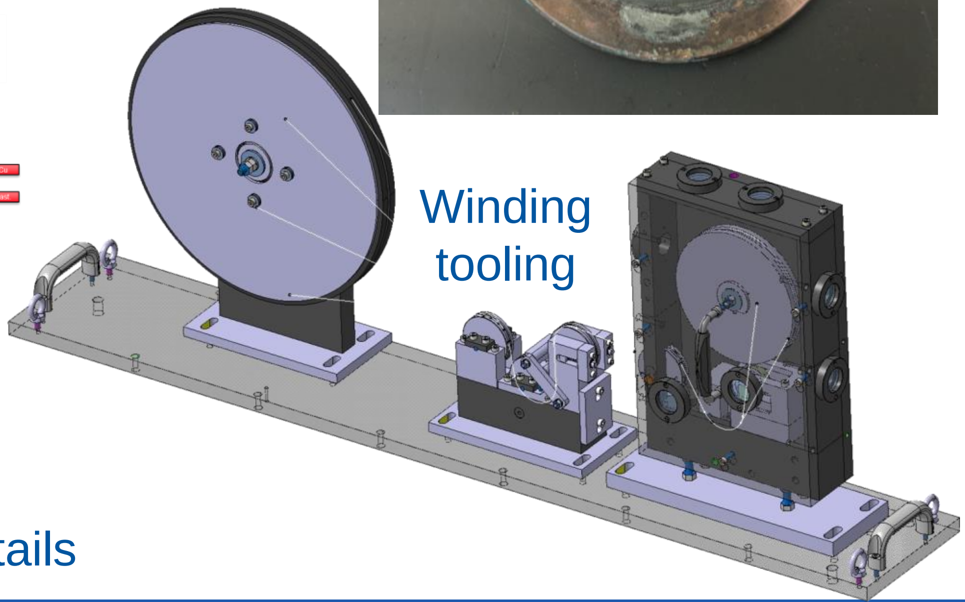
Magnet concept







Mechanics and assembly details



Winding tooling

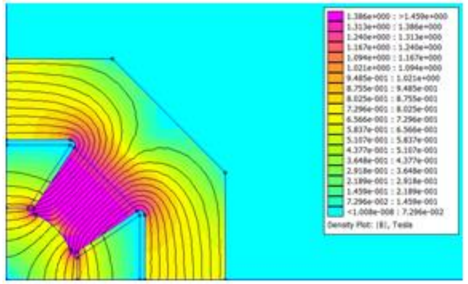
B. Bordini, A. Dudarev, M. Hafiz, C. Accettura, A. Bertarelli, A. Kolehmainen, F. Sanda

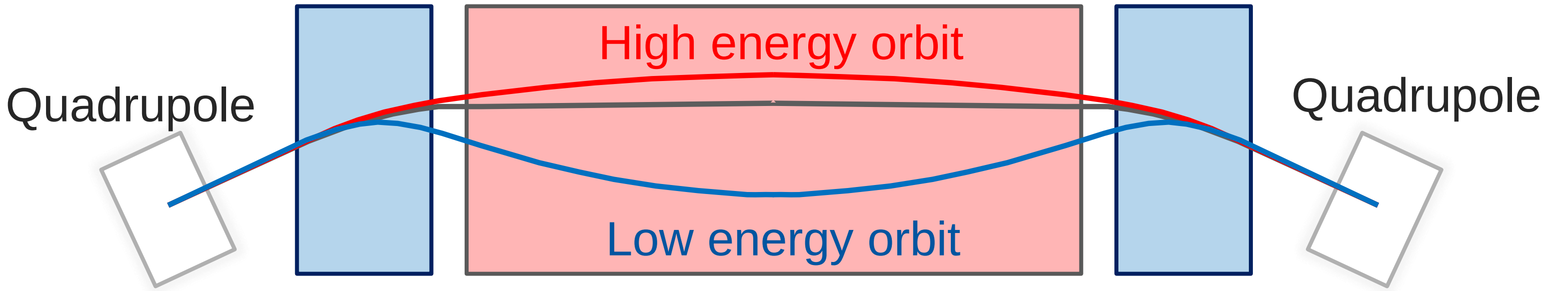
Accelerator magnets

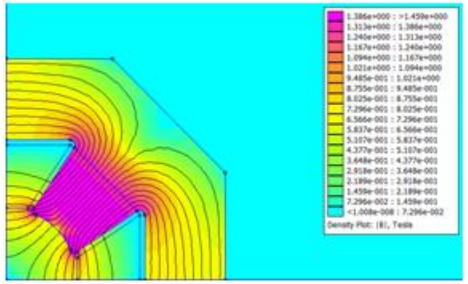
Steady state
SC 10 T dipole

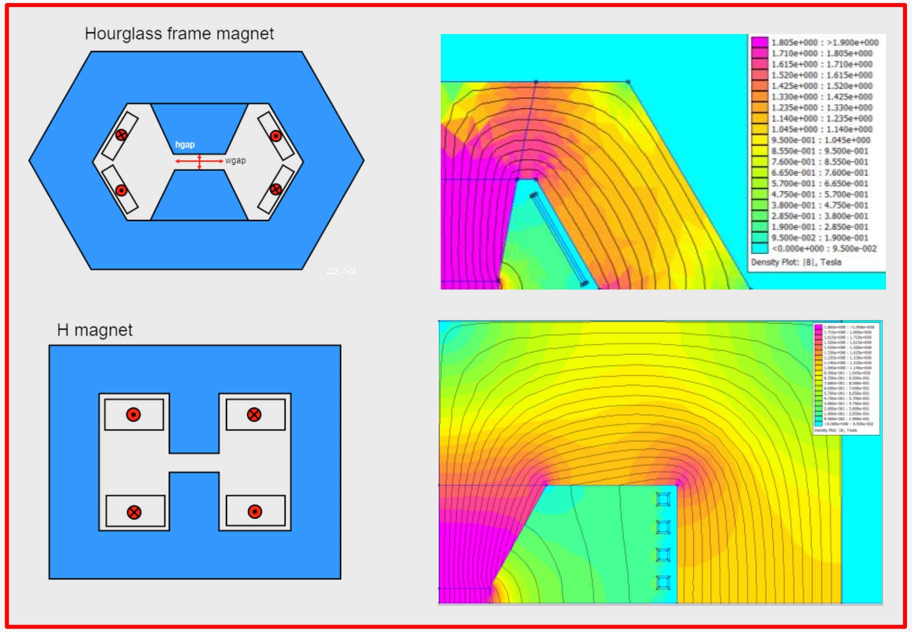
Pulsed
NC 1.8 T dipole

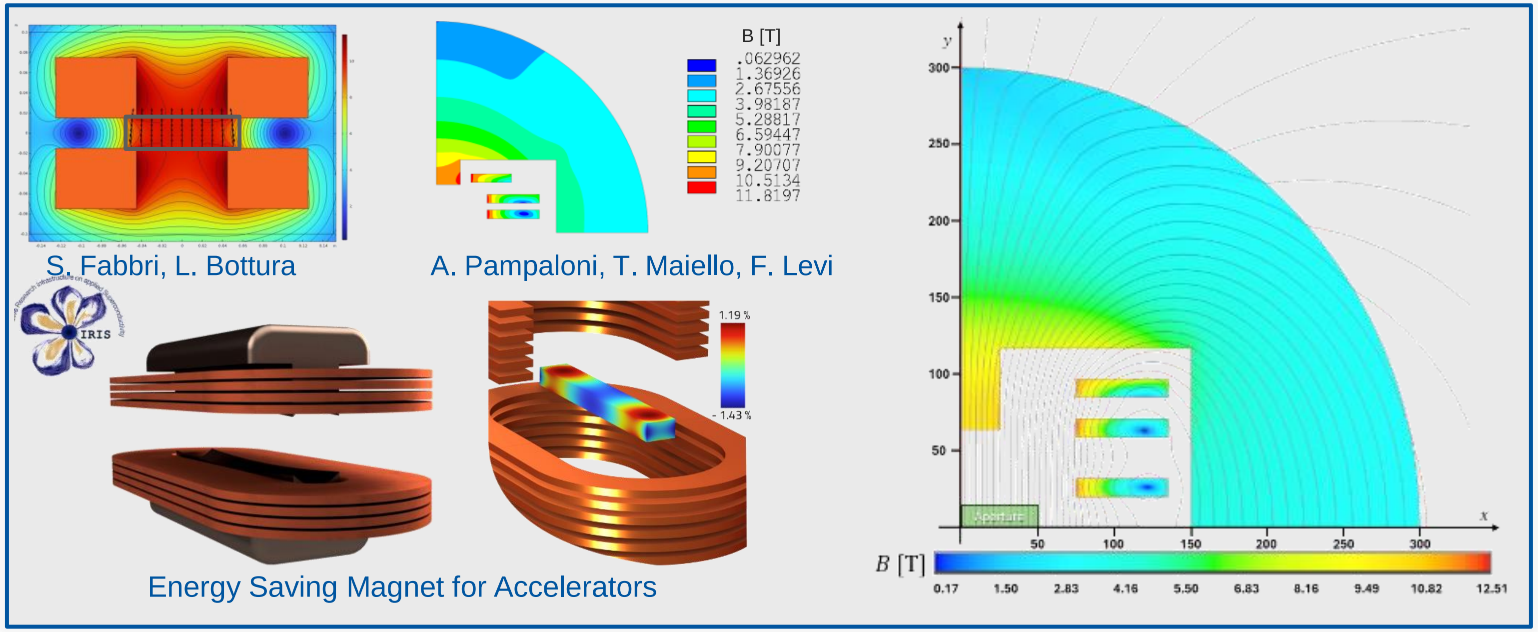
Steady state
SC 10 T dipole









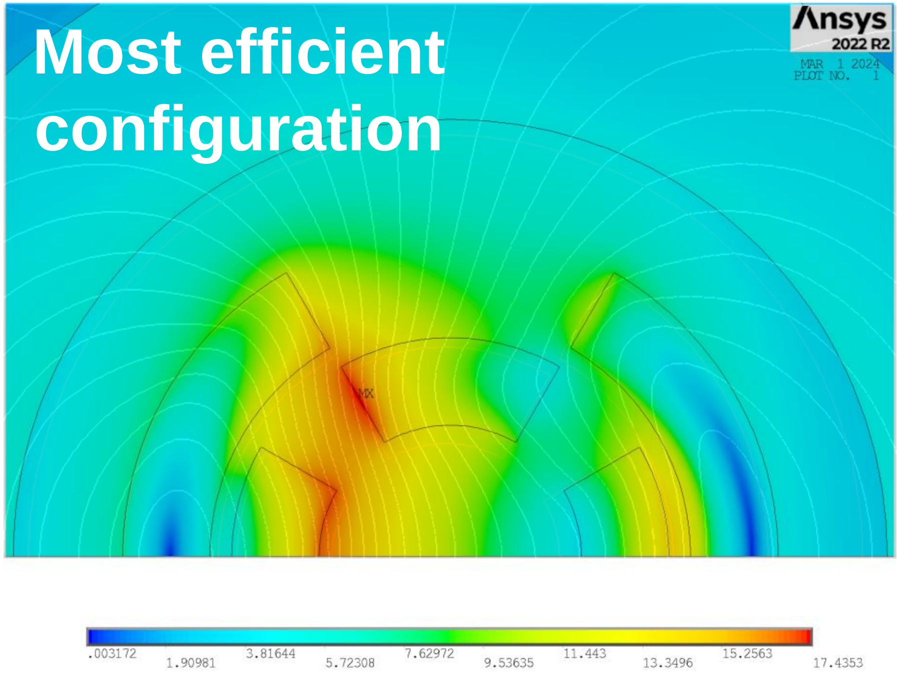


F. Boattini, M. Breschi, P.L. Ribani, S. Fabbri, A. Pampaloni, T. Maiello, F. Levi, S. Mariotto

Collider magnets

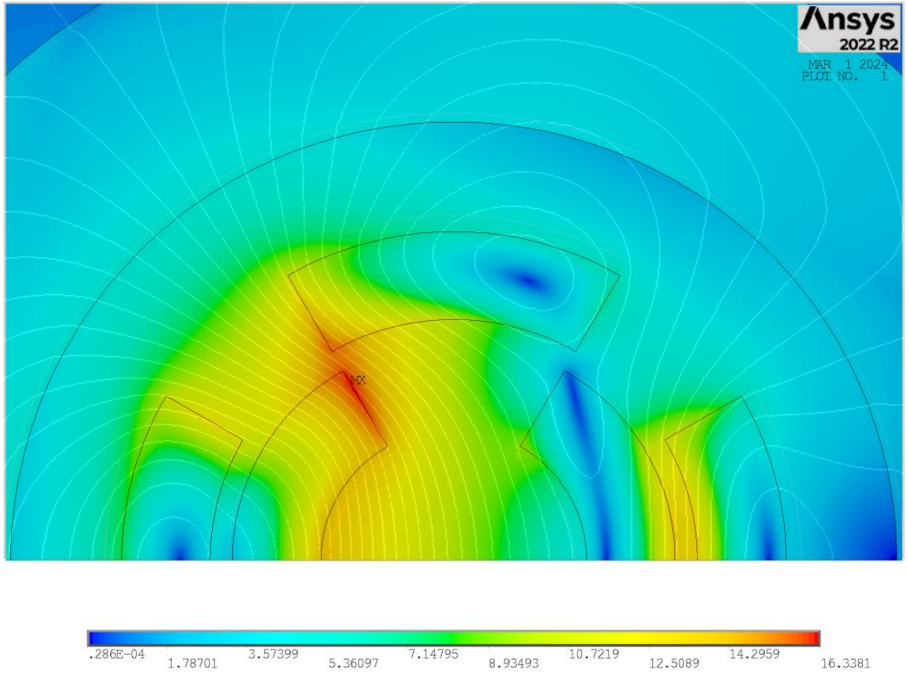
Quad into dipole
REBCO at 20 K
B = 11.7 T, G=143.3 T/m

Most efficient configuration

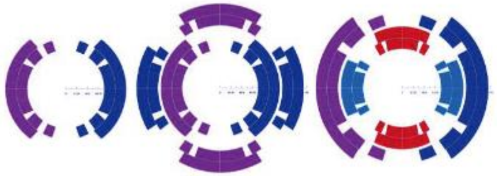


Combined function magnets (B1+B2)

Dipole into quadrupole
ReBCO at 20 K
B = 12.4 T, G=90.4 T/m

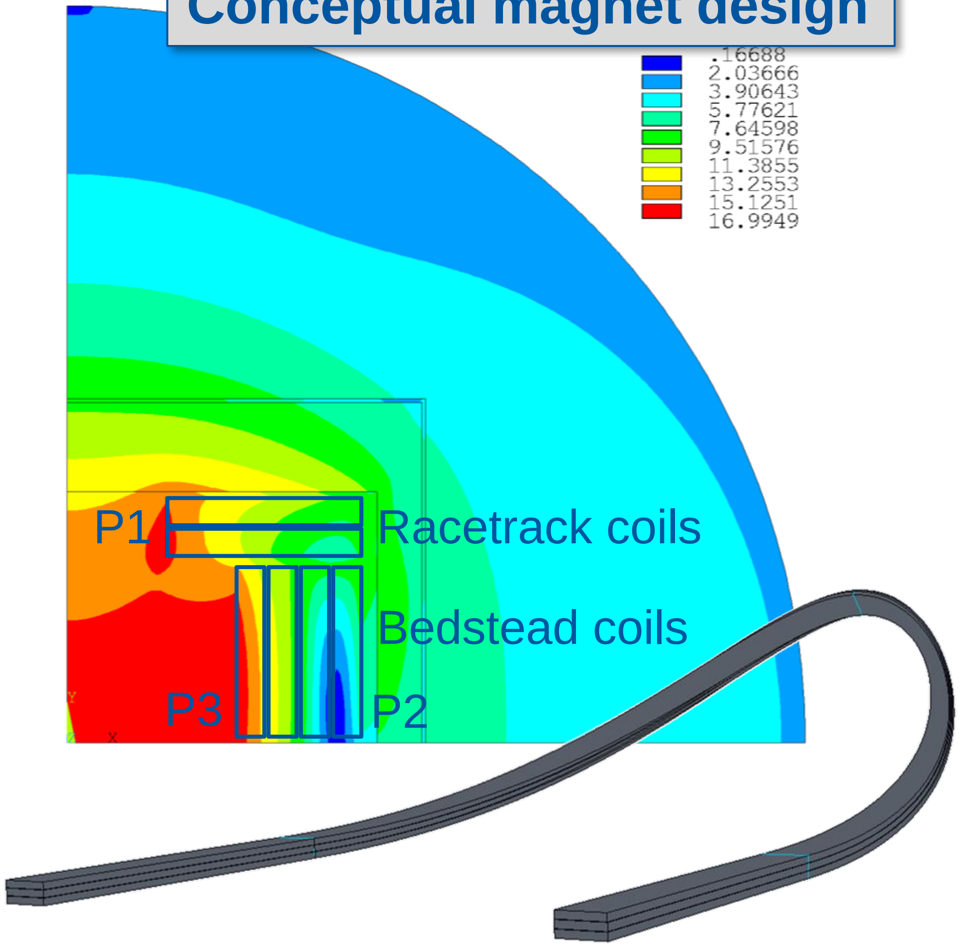


Findings consistent with: V. Kashikin, et al. "*High-Field Combined Function Magnets for a 1.5×1.5 TeV Muon Collider Storage Ring*", THPPD036, Proc. IPAC-2012, https://accelconf.web.cern.ch/IPAC2012/papers/thppd036.pdf

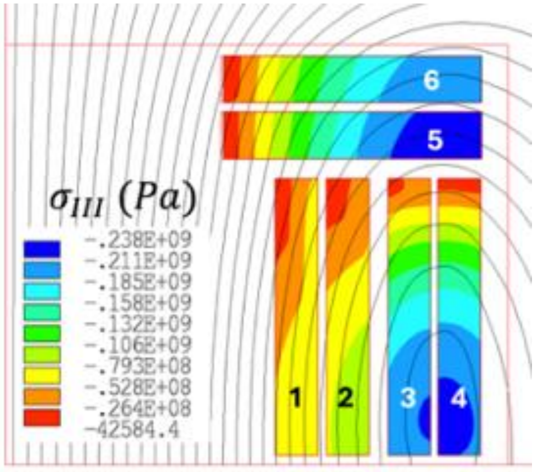


Collider magnets

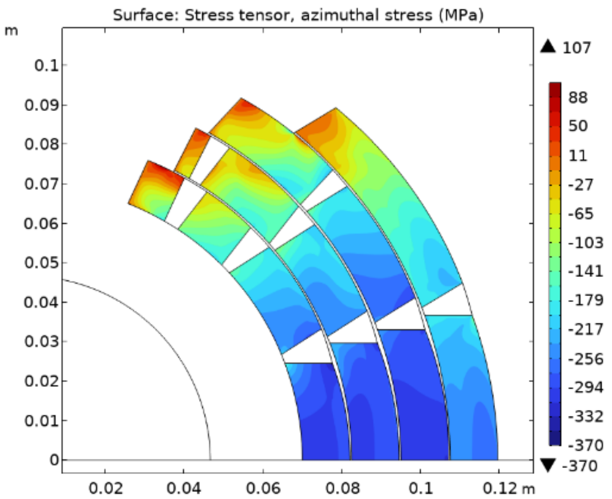
Conceptual magnet design



- HTS tape stack conductor (20 tapes) with 2.5 K operating margin
- Double pancake coils, encased in a supporting structure to manage the electromagnetic forces
- Minimal (no) hard-way bend for HTS tape winding
- Winding insulation technology (NI or other) yet TBD
- **Bore field: 15.7 T**
- **Magnet cost < 400 kEUR/m**



Block
vs.
Cos(theta)
…
What else ?



L. Alfonso, D. Novelli, F. Mariani, S. Mariotto, B. Caiffi, A. Bersani

Outline

- The Muon Collider magnets and their challenges
- Achievements within the scope of HFM WP2.6
- Plans for R&D
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CERN

Conductor procurement and characterization

European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

EDMS No. 2960999

DO-33893/ATS
Group Code: ATS

Price Enquiry

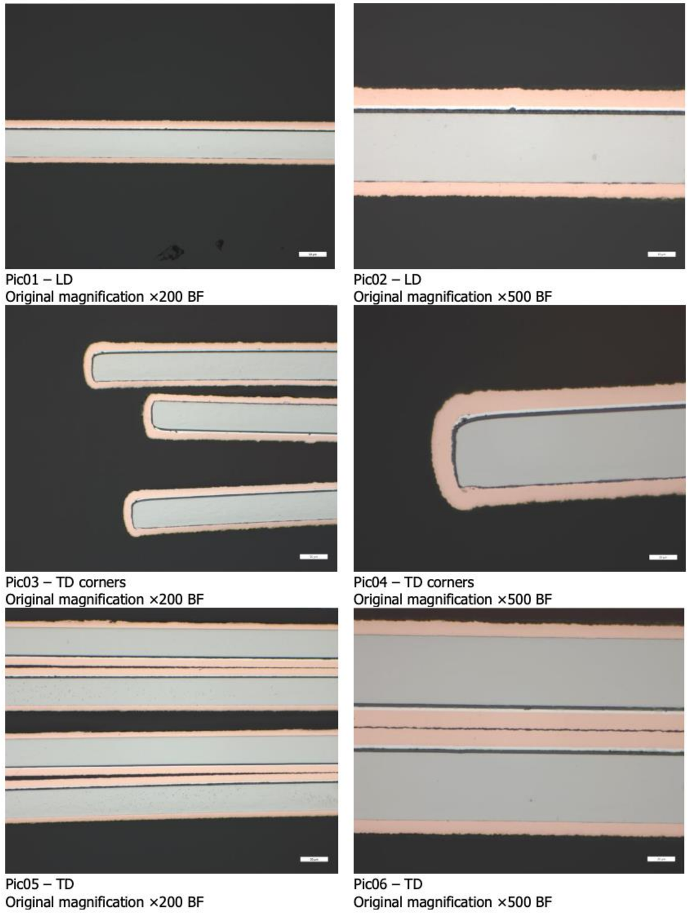
Technical Specification

Supply of REBCO Coated Conductor
for
Muon Collider Solenoids R&D

Abstract

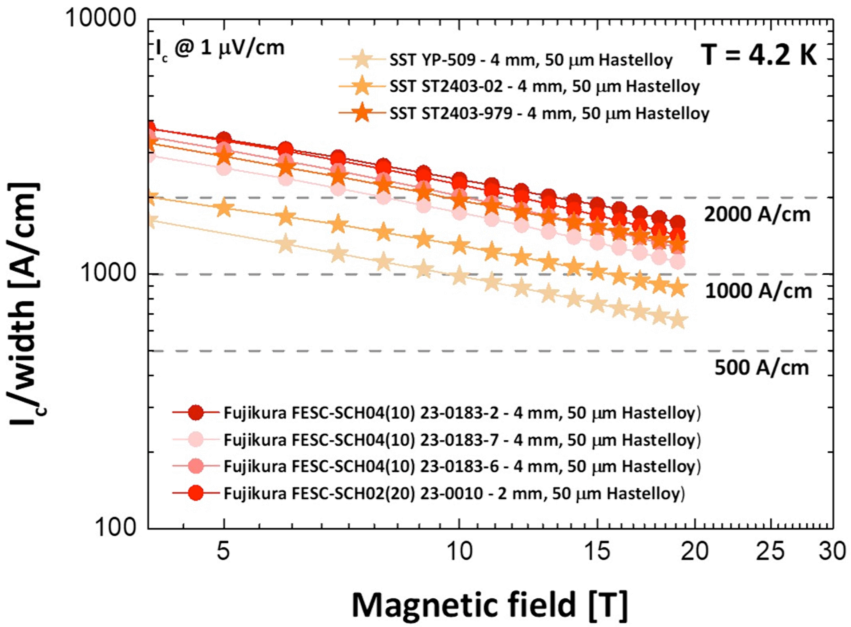
This Technical Specification concerns the supply of up to 9 000 m of REBCO coated conductor, to be quoted and delivered in batches of 3 000 m. Delivery completion is foreseen over seven months from notification of the Contract.

Procurement of 4 mm tape for R&D windings at FFJ, SST, Fujikura
Total 11 km of REBCO tape in house from 5 worldwide producers



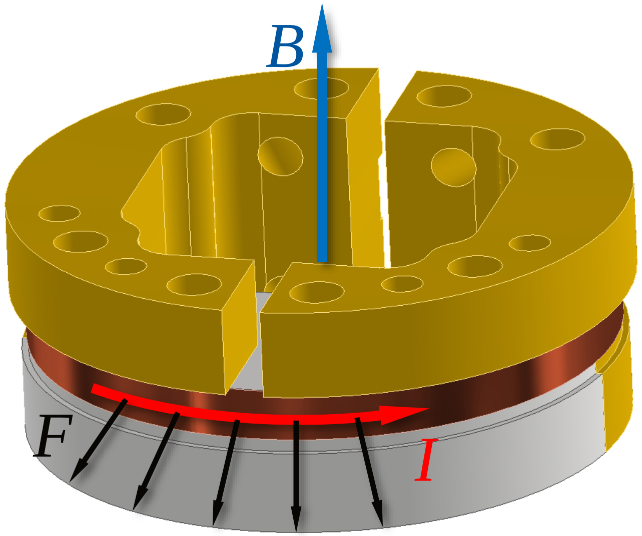
Metallographic inspections and surface analysis

J_E > 2000 A/mm^2
at 20 T, 4.2 K

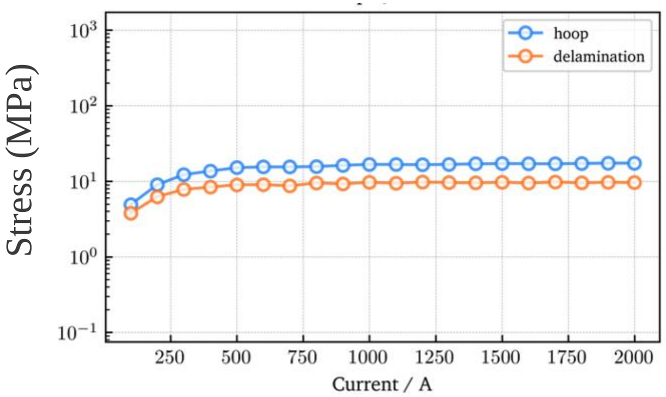


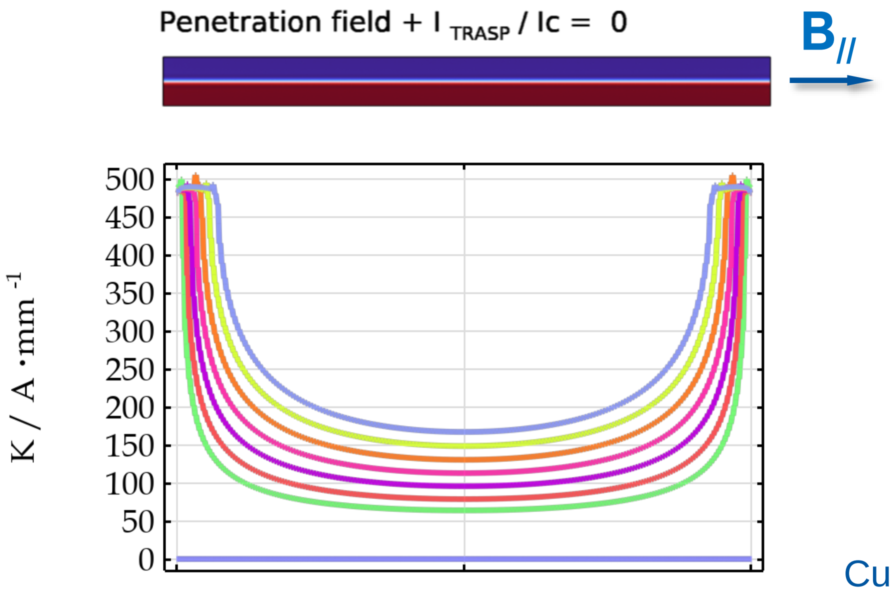
Critical current measurement in high field demonstrates electrical performance well above target specification for UHF applications
C. Senatore, HFM Annual Meeting 2025

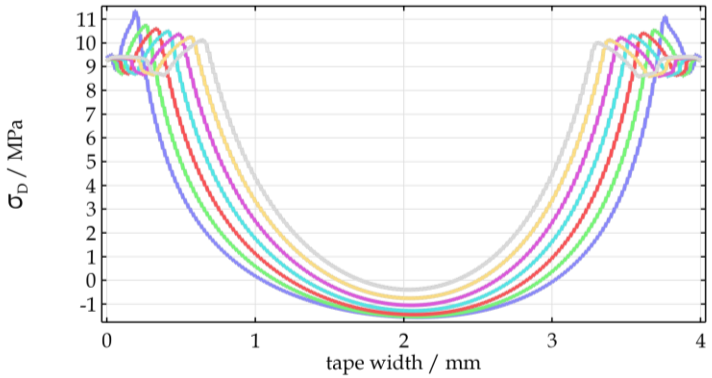
In-field stress test

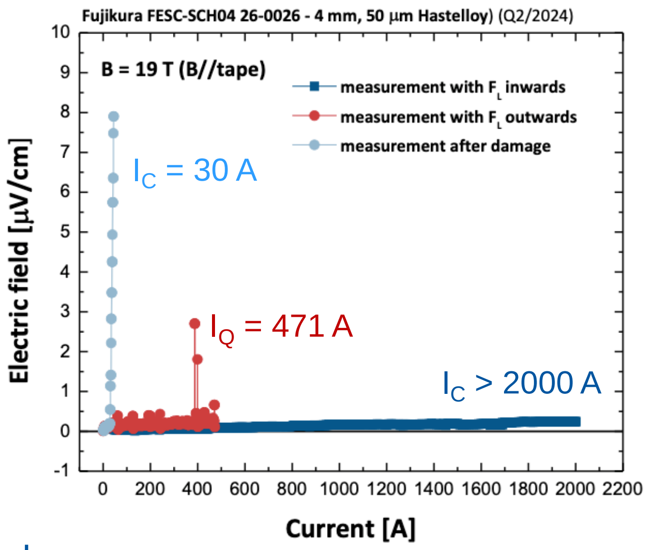


New experiment at University of Geneva allows in-field measurement of *delamination strength*



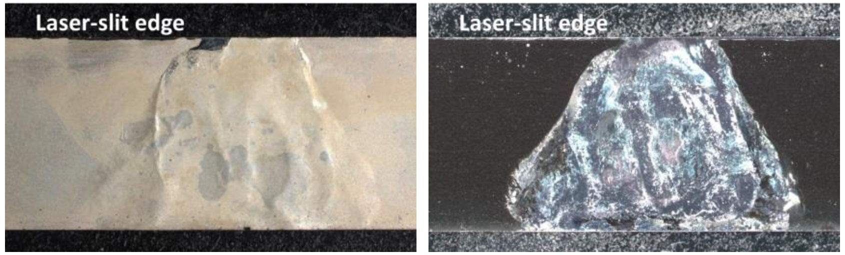






Cu etched

Ag etched



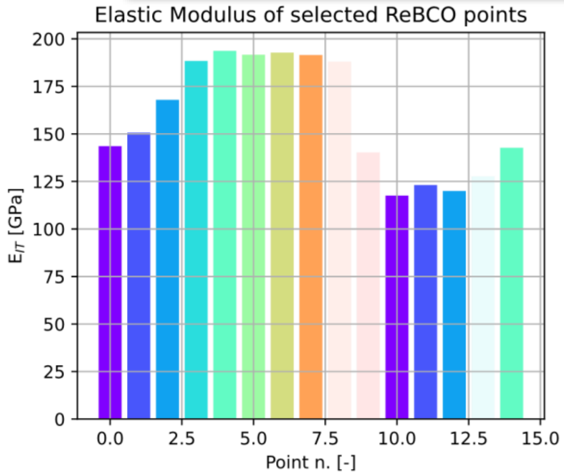
Interpreting values as delamination strength implies that **tapes cannot go in internal tensile stress** under any condition

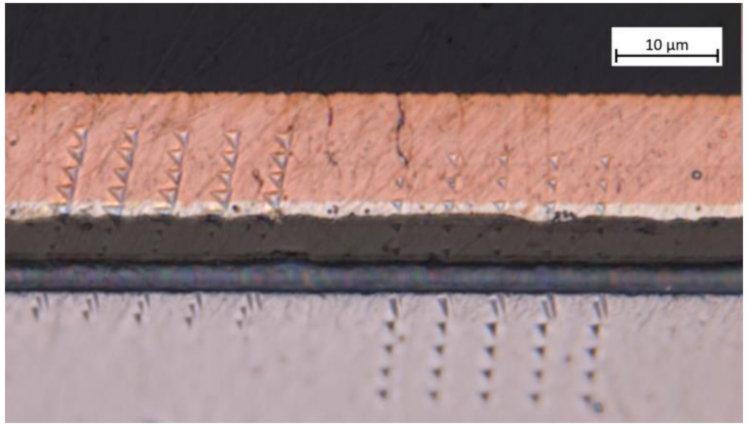
C. Senatore, M. Bonura, R. Babouche, C. Lucas, G. Vernassa, B. Bordini, H. Felice

Material science

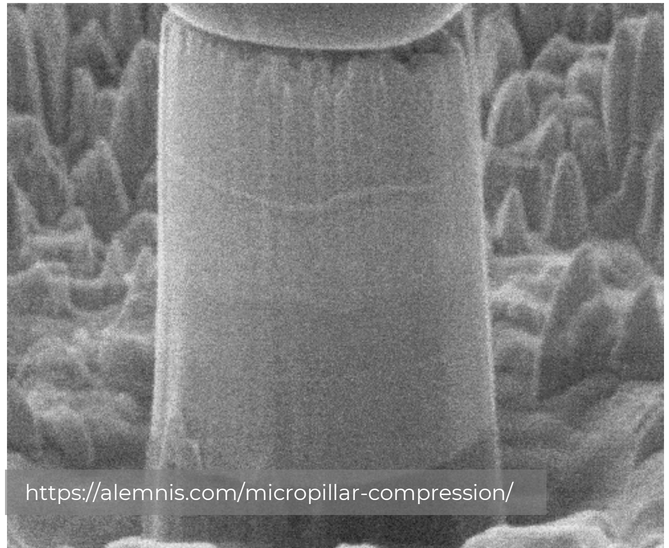
Mechanics will limit performance of high-field HTS magnets: establish mechanical and thermo-physical properties of industrial REBCO tapes and soldered stacks

Nano-indentation for the derivation of elastic properties

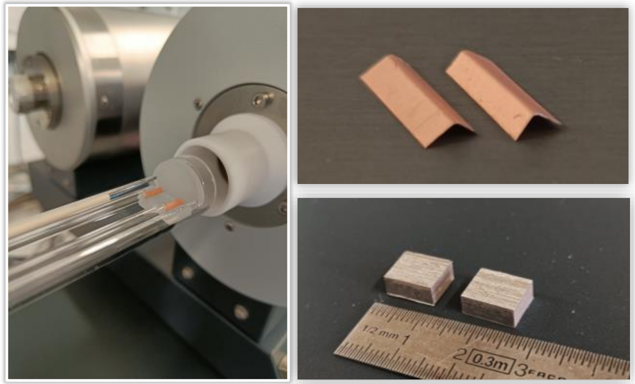


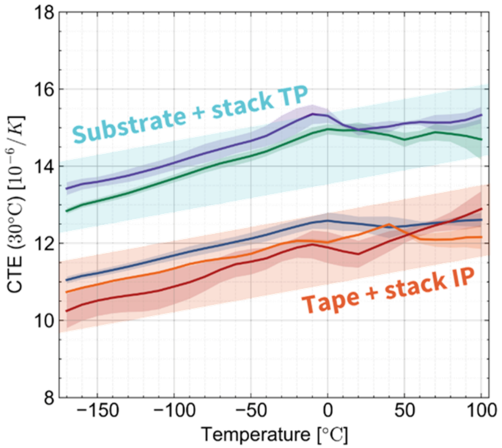


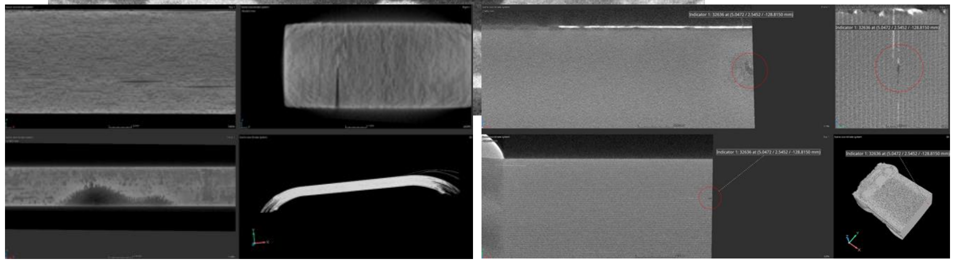
Micro-pillars stress-strain curves



Thermal expansion coefficients of tapes and soldered stacks





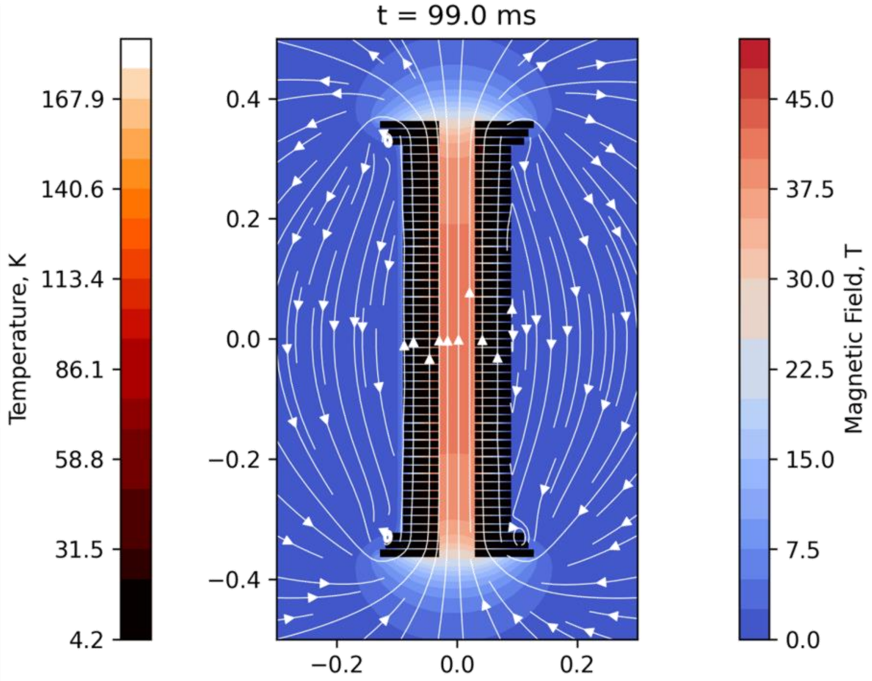


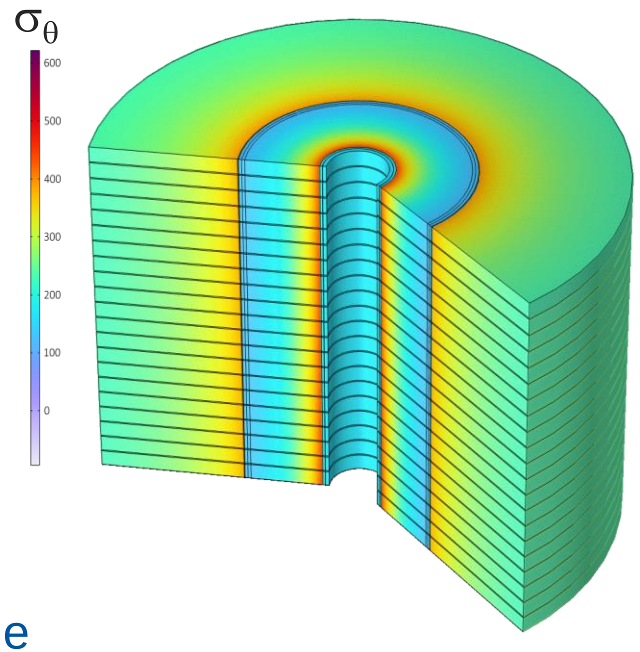
Porosity measurement in stacks and process optimization

G. Vernassa, B. Bordini, O. Sacristan, S. Hoell, M. Celuch, G. Kermouche, J.M. Bergheau, H. Felice

Multi-physics

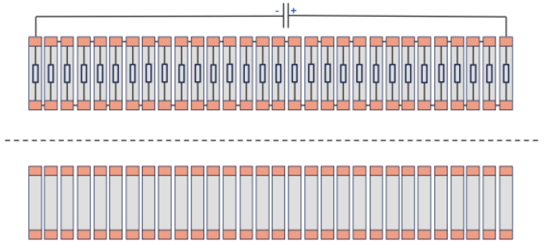
Natural quench evolution

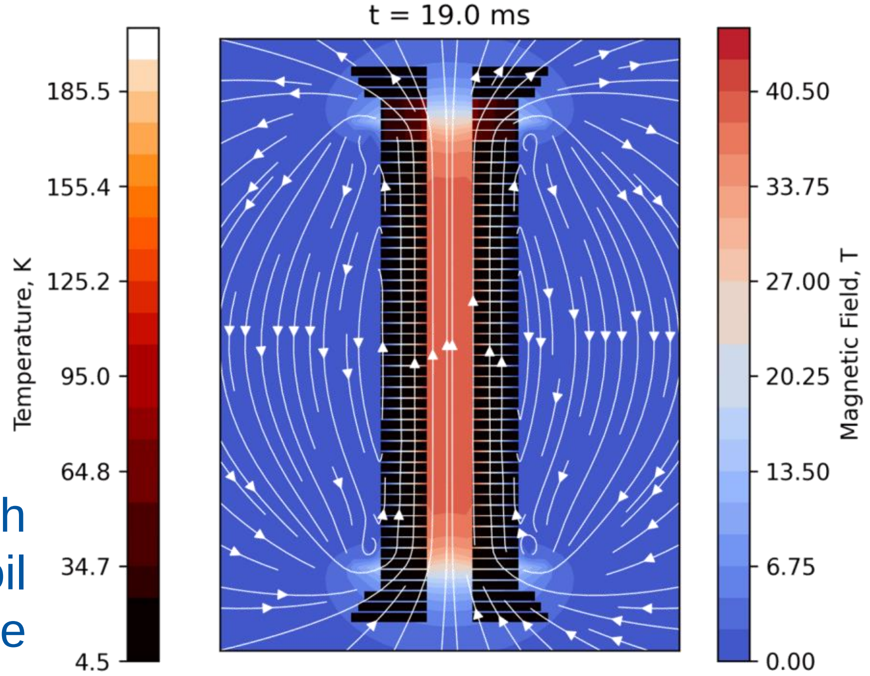




A propagating *quench wave* traverses the solenoid generating significant forces and stress

Forced quench evolution





Capacitor discharge triggered at quench detection forces a quench (transverse resistance heating) on larger percentage of the coil volume and mitigates the force and stress issue

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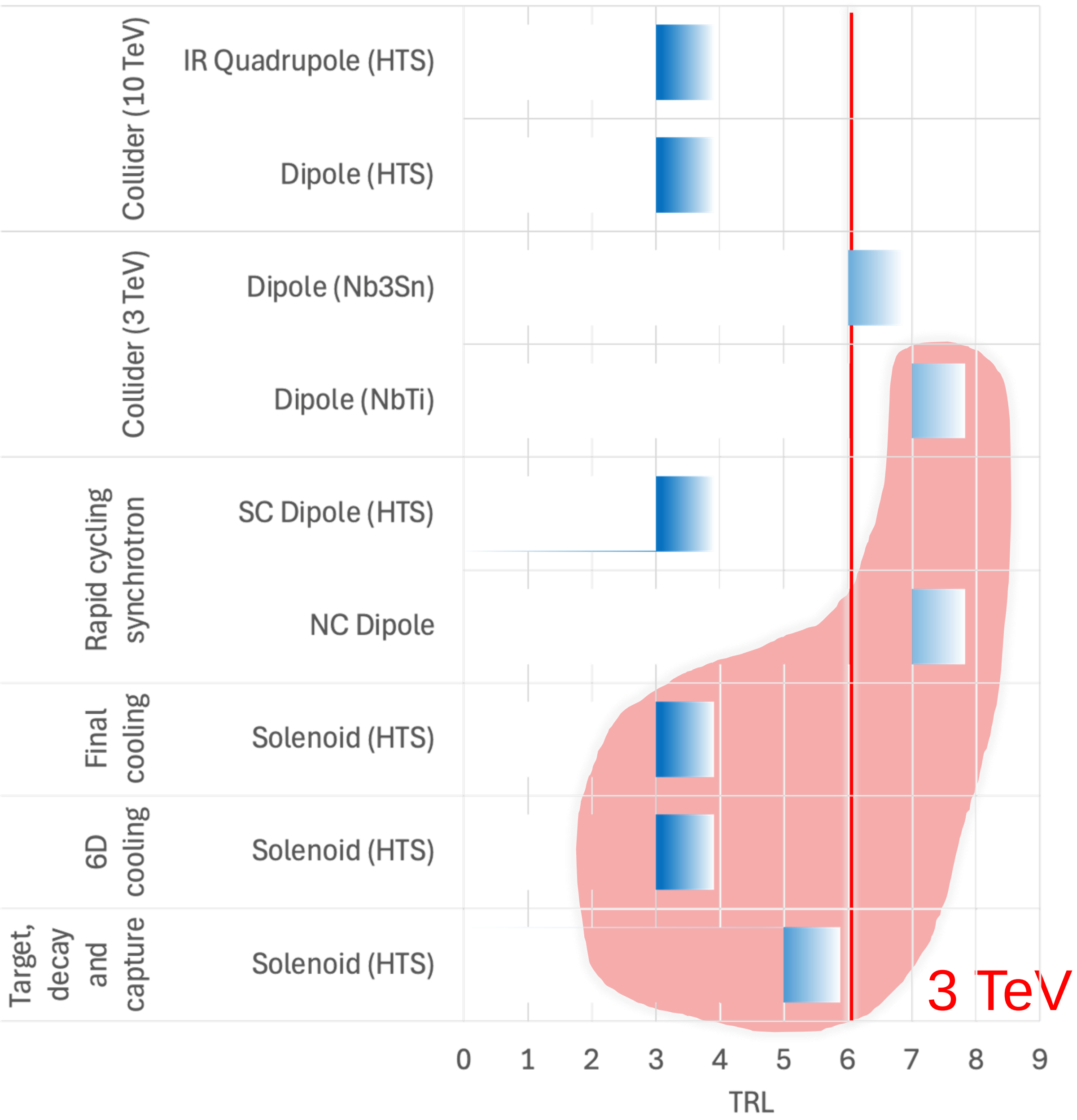
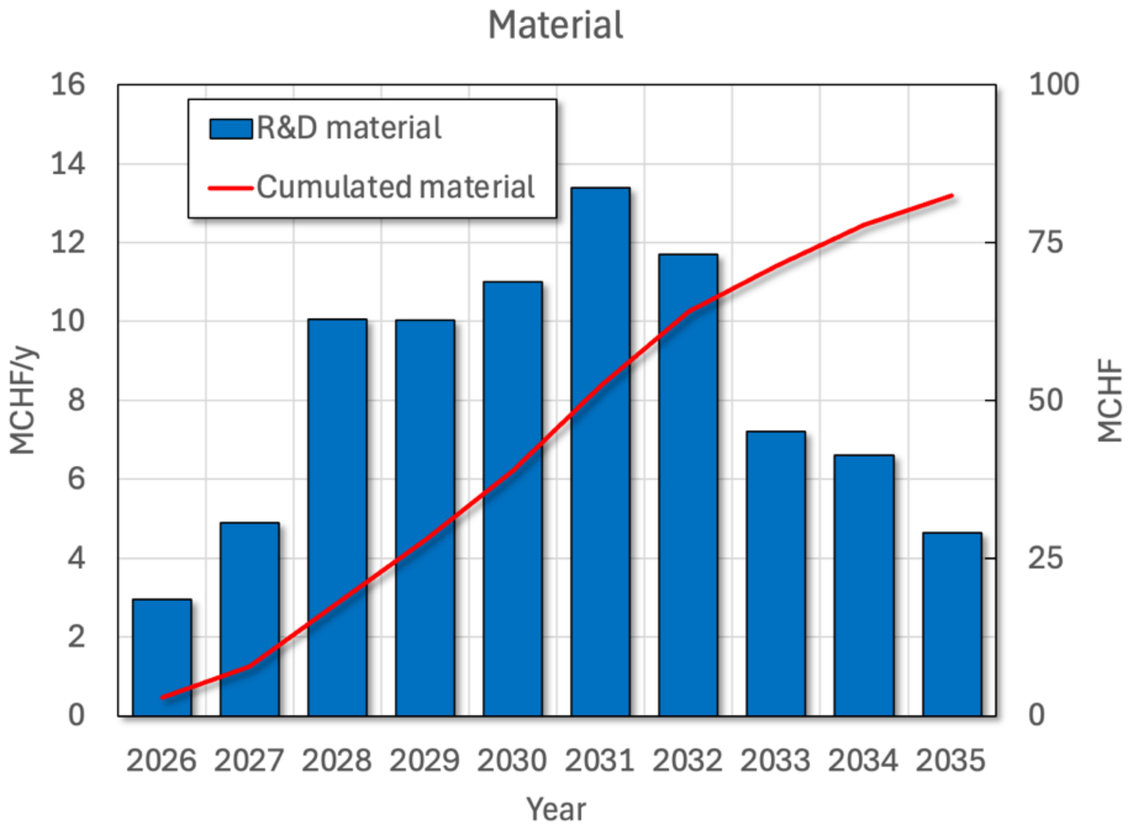
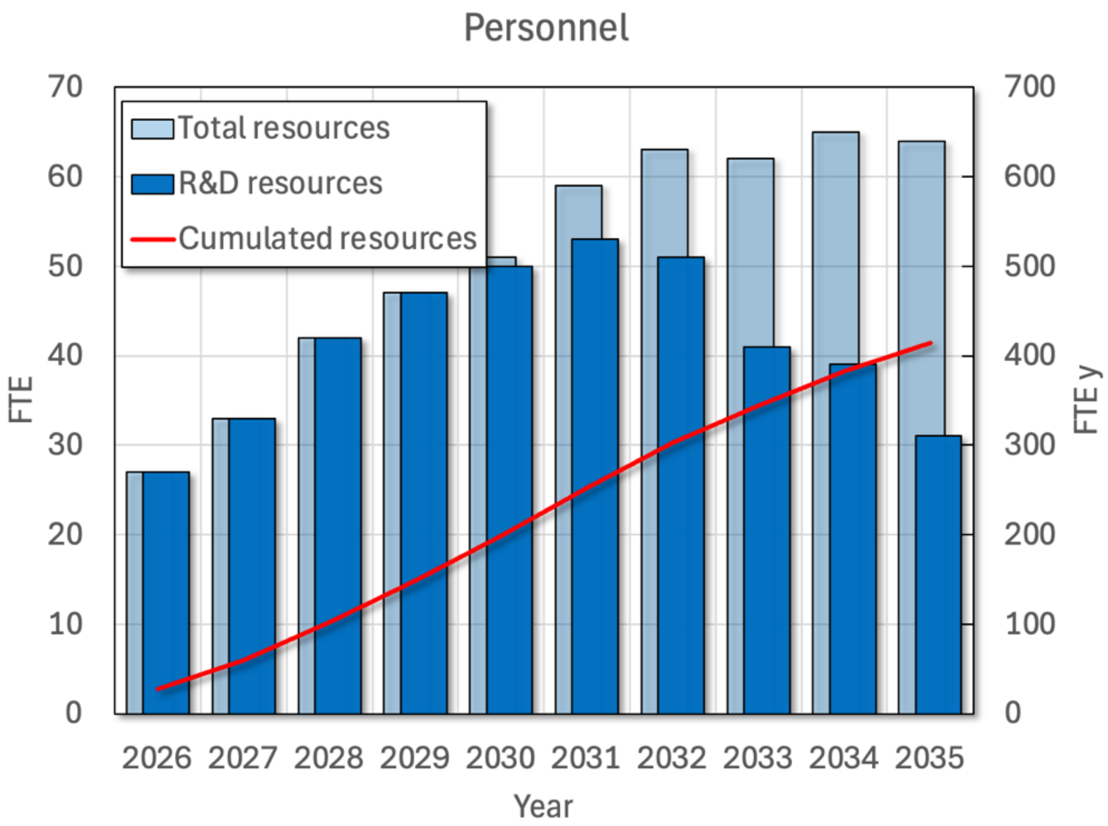
TRL driven R&D

- The medium-term R&D proposal (10 years) aims at:
  - Increasing TRL of critical magnet systems to a level sufficient for a go/no-go decision (TRL 6)
  - Demonstrating engineering readiness of high-TRL magnets towards the first stage of the Muon Collider (3 TeV)



R&D M+P proposal





- The proposal is presently at the level of “blue-sky thinking”, for discussion and evaluation. M+P is intended as the required resources to achieve targets (i.e. not only CERN)

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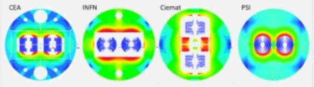
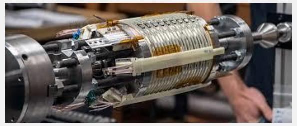
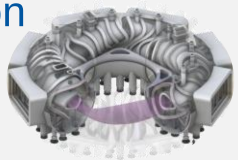
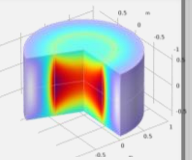
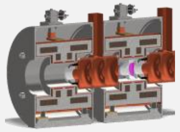
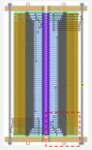
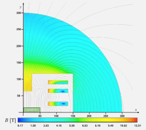
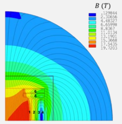
- Plans for R&D
- Summary and perspective

	HEP and NP 	High-field science 	NMR 	MRI	Fusion 	Motors/generators 
TM1 20@20 		**High field, low consumption**			**High-field, large bore and large stored energy**	
TM2 SOLID 		**High field, low consumption**		**High-field large bore, cryo-free technology**		
TM3 UHF-DEMO 	**FCC-ee, CLIC (e+ source)**	**Ultra-high-field**	**Ultra-high-field**			**High-field, compact windings**
TM4 RCS-String		**High pulsed power and energy recovery**			**High pulsed power and energy recovery**	
TM5 MBHY	**FCC-hh, SppC**					
TM6 MBHTS 	**FCC-hh, SppC**					**3D, compact pole winding**
TM7 MBHTSY 	**FCC-hh, SppC**					**3D, compact pole winding**
TM8 MQHTSY	**FCC-hh, SppC**					**3D, compact pole winding**

Magnet R&D for the Muon Collider has an exceptional impact potential

Summary – Technology advances

- Design concepts are consolidated, we move to **probing the limits of technology**
  - **High-field solenoid (20 T), large bore (1.4 m)**: proposal of a model coil achieving 20 T at 20 K
  - **Split solenoid (7 T on axis), large longitudinal gradient (15 T/m), large bore (570 mm), subjected to exceptional electromechanical forces and stresses (up to 15 MN)**: build and test coils (5 T to 7 T), including thermo-mechanical integration and optimization studies (cooling demonstrator)
  - **Ultra-high-field solenoid (40 T), small bore (60 mm)**: test pancakes, target fields 5 T (single pancake) to 25 T (stack)
  - Electrical, mechanical and thermo-physical material properties are **crucial ingredients** and will require sustained effort, with new areas such as radiation effects in spectra other than nuclear reactors
- This development connects directly to the HTS R&D in the scope of HFM
  - Shared technology challenges and advances, profiting from capabilities within RD2 (e.g. KC4)
  - The technology developed for solenoids is also relevant for accelerator magnets, probing and characterizing performance limits with limited use of conductor, and fast turn-around
  - Effective means to uncover complex interactions that may limit field reach, e.g. stress induced by screening currents or quench propagation in NI windings

Summary – Strategic

- Priority in HTS solenoids is crucial for a 3 TeV Muon Collider stage. It is a grand challenge, but we are not alone:
  - Developments in fusion towards high field/large bore HTS magnets
  - Developments in high-field science and NMR towards 40 T solenoids
- **Personal opinion**: the next step collider at the frontier of high energy demanded by physics will arguably need HTS magnets(1)
  - CAPEX: compact windings, high J_E, lower unit material cost(2)
  - OPEX: operation at 20 K, helium inventory

(1) Nb_3Sn has taught us "*the importance of remaining honest and humble*". The focus on HTS is **no reason to ditch any of the knowledge and experience** that has been and is being developed in LTS.

(2) The price of a superconductor depends on the existence of a **sizeable and sustained market** that justifies investment in infrastructure and process optimization. Relevant market size is several thousands tons/year (see Nb-Ti). Whether Nb_3Sn or HTS will ever reach and sustain such size is **a discussion of high strategic interest**.

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Scope of the work package

MC.HFM High-field magnet technologies

The goal is to develop realistic targets for the high-field magnet specifications and to develop an R&D programme to demonstrate them, where they are beyond the state of the art. The emphasis is on high-field solenoids in the muon production and cooling complex since they are unique for colliders. In particular:

- Assessment of realistic target parameters for the superconducting collider ring magnets. This contains theoretical studies that translate the progress of the High-field Magnet programme into the specific case of the muon collider.
- Assessment of realistic target parameters for the superconducting final muon cooling solenoids, aiming well beyond 30 T and ideally for 50 T. The solenoids have small apertures and the luminosity will be roughly proportional to their field. This includes theoretical studies using input from the High-Field Magnet programme and other developments.
- Assessment of realistic target parameters for the 6D muon cooling solenoids, which form the main part of the system. The goal is to use HTS solenoids instead of Nb_3Sn technology for field strength of 20 to 25 T, well above the level in the MAP study. This may allow a shorter system and improve both the muon survival rate and the emittance. (*MIN*)
- Assessment of realistic target parameters for the solenoid system around the target in order to understand the strong constraints arising from the large aperture and the high-radiation environment. Higher field corresponds to a higher capture rate of muons. (*MIN*)
- Testing and characterisation of cables and potentially the design and construction of models for the target solenoid at lower fields (around 30 T) to improve the understanding of the technology and to prepare the development of prototypes. (*MIN*)
- Testing and characterisation of cables and potentially the construction of models for the 6D solenoid. The closer packing, larger aperture but lower field places different demands on the technology than for the final solenoids. (*ASP*)
- Design of the solenoid for the test module in **MC.MOD**. This might use less ambitious specifications and technologies than the 6D cooling solenoid models. (*ASP*)
- Conceptual design of the target solenoid. (*ASP*)

Bright Muon Beams, European Strategy for Particle Physics - Accelerator R&D Roadmap, 2022, ISBN: 9789290836216

- Support efforts of the solenoid R&D for a Muon Collider performed in the scope of IMCC, and specifically:
  - *“Assessment of realistic target parameters […] well beyond 30 T […] This includes theoretical studies using input from the High-Field Magnet programme”*
  - *“Assessment of realistic target parameters for the 6D muon cooling solenoids […] The goal is to use HTS solenoids”*
- Integrate technology advances in HTS magnet technology from and to other work packages:
  - *The development of […] magnets for a muon collider […] will be addressed by targeted studies, but the (HFM) R&D […] will be highly relevant in developing suitable solutions*

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Plan - overview

WP2.6-T1	**UHF solenoids - General study work**	01/01/23	01/06/27	
WP2.6-T1.1	Review and define conductor requirements for UHF compact solenoids	01/01/23	30/05/23	Completed
WP2.6-T1.2	Review and define performance specifications for UHF solenoids	01/01/23	30/09/23	Completed
	Define reference geometries and estimate material needs for technology R&D	01/01/23	30/04/23	Completed
WP2.6-T1.3	Review material options for HF and UHF HTS solenoids (REBCO, Bi-2212, Bi-2223, IBS)	01/01/23	30/03/24	Delayed because the MuCol collaborator (University of Southampton) did not have enough resources to provide input material. Move this task by 18 months
WP2.6-T1.4	Cost and power estimate	01/01/23	01/06/27	First cost estimate available
WP2.6-T2	**UHF solenoids - Conductor procurement and characterization**	01/01/23	01/05/27	
WP2.6-T2-D1	Short samples for initial screening	01/01/23	01/05/27	Completed, material in measurement
WP2.6-T2-D2	Procurement of 9+3 km 4 mm tape for UHF solenoids R&D - phase I	01/05/23	30/06/24	Material in house and being qualified. One of the producers has to replace the present delivery because of a quality issue discovered after delivery
WP2.6-T2-D3	CERN - Procurement of 5 km 12 mm tape for UHF solenoids R&D - phase II	01/09/25	30/03/26	Delayed by 6 months (start in September 2025) and material reference to 12 mm tapes, same budget as from previous plan
WP2.6-T2-D4	CERN - Procurement of 15 km 12 mm tape for UHF solenoids R&D - phase III	01/01/29	30/06/29	NEW: Follow-up to complement needs for material into prototyping phase
	UNIGE - Technology Performance Limits experiment (delamination) at University of Geneva	01/01/25	31/12/26	NEW: Follow-up of MuCol activities of tailored testing of HTS electro-mechanical limits (delamination) and extended characterization (angles and temperature)
	TWENTE - Mechanical and electro-mechanical properties and degradation limits	01/01/25	31/12/26	NEW: Follow-up of MuCol activities of tailored testing of HTS electro-mechanical limits (stress and strain)
WP2.6-T3	**UHF solenoids - Engineering study and performance validation**	Sun 01/01/23	Tue 31/12/24	
WP2.6-T3-D1	CERN - engineering design of UHF final cooling solenoid	Sun 01/01/23	Tue 31/12/24	Approaching completion for small coils and first release of full-size UHF final cooling solenoid
WP2.6-T3-D2	CERN - study of large bore 6D cooling solenoid	01/01/25	30/6/26	NEW: Engineering study of 6D cooling solenoids for the accelerator - note that the demonstration and prototyping (RFMFTF) is done by INFN within the scope oif MuCol
WP2.6-T3-D3	CERN - components and tooling for UHF final cooling	01/01/25	31/12/26	NEW: Complement to MuCol small-scale coil construction and test. Additional components for UHF final cooling solenoid

Plan – General study work

WP2.6-T1.1	Review and define conductor requirements for UHF compact solenoids	01/01/23	30/05/23	Completed
WP2.6-T1.2	Review and define performance specifications for UHF solenoids	01/01/23	30/09/23	Completed
	Define reference geometries and estimate material needs for technology R&D	01/01/23	30/04/23	Completed
WP2.6-T1.3	Review material options for HF and UHF HTS solenoids (REBCO, Bi-2212, Bi-2223, IBS)	01/01/23	30/03/24	Delayed because the MuCol collaborator (University of Southampton) did not have enough resources to provide input material. Move this task by 18 months
WP2.6-T1.4	Cost and power estimate	01/01/23	01/06/27	First cost estimate available

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Plan – Conductor procurement and characterization

WP2.6-T2-D1	Short samples for initial screening	01/01/23	01/05/27	Completed, material in measurement
WP2.6-T2-D2	Procurement of 9+3 km 4 mm tape for UHF solenoids R&D - phase I	01/05/23	30/06/24	Material in house and being qualified. One of the producers has to replace the present delivery because of a quality issue discovered after delivery
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	TWENTE - Technology Performance Limits experiment - mechanical and electro-mechanical properties and degradation limits	01/01/25	31/12/26	NEW: Follow-up of MuCol activities of tailored testing of HTS electro-mechanical limits (stress and strain), was proposed in November 2023

NOTE: Work in collaboration could be part of existing agreements

Plan – Engineering study and performance validation

WP2.6-T3-D1	CERN - engineering design of UHF final cooling solenoid	01/01/23	31/12/24	Approaching completion for small coils and first release of full-size UHF final cooling solenoid
WP2.6-T3-D2	CERN - study of large bore 6D cooling solenoid	01/01/25	30/6/26	NEW: Engineering study of 6D cooling solenoids for the accelerator - note that the demonstration and prototyping (RFMFTF) is done by INFN within the scope of MuCol
WP2.6-T3-D3	CERN - components and tooling for UHF final cooling	01/01/25	31/12/26	NEW: Complement to MuCol small-scale coil construction and test. Additional components for UHF final cooling solenoid

NOTE: We expect test results on first pancake coils by end 2024, experimental activity to pick-up in 2025, to produce the planned deliverables for MuCol, IMCC and in support of the ESPPU cycle

NOTE: Components and tooling activities for UHF final cooling are likely to continue and expand after 31/12/26 moving towards a reduced-scale prototype, and eventually a full-scale prototype (2029-2030)

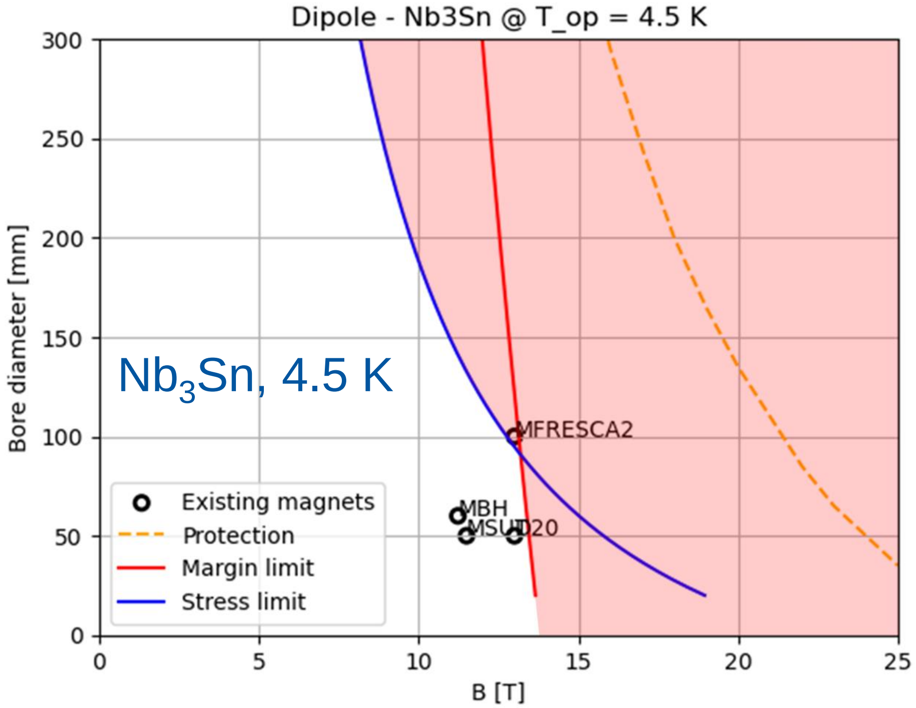
Risk register and mitigation (the plan)

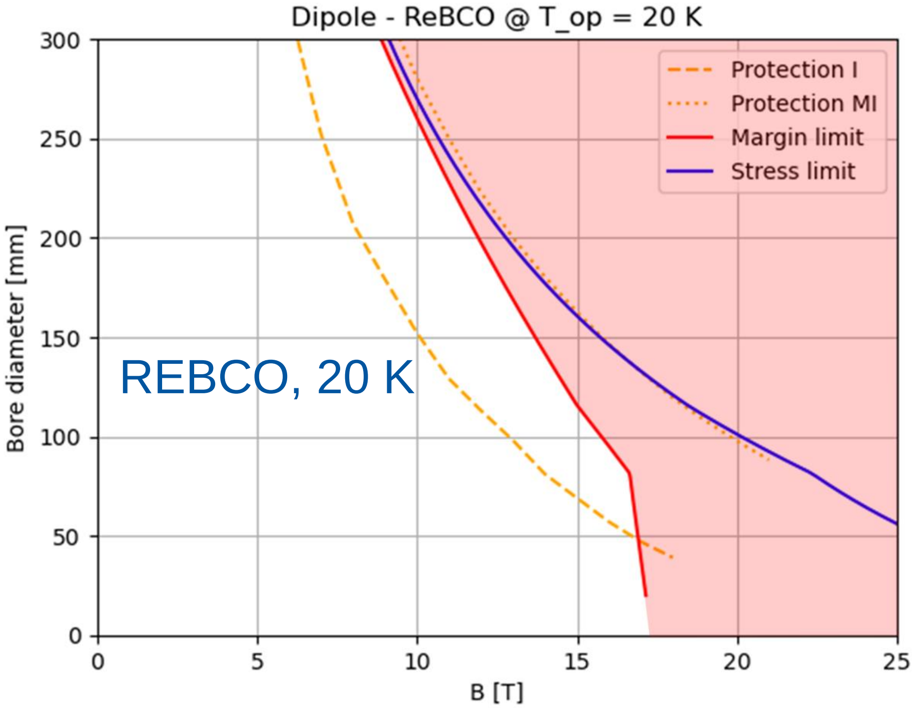
Risk	Mitigation action (program)	Tests (tape length)
Reaching field/sub-optimal performance	Use pancakes to test performance (force and thermal cycles) and compare to expected performance from characterized tapes (NOTE: need of complete Ic(B,T,angle) scaling)	10 sub-size (500) 5 full-size (1250)
Tape degradation during coil manufacturing	Test performance before/after winding at 77 K, partly covered by previous item. Dedicated tests to be performed for: soldering or potting, double pancakes and transitions, joints	10 sub-size (500)
Coil internal mechanics and mechanical properties	Instrumented stacks and dummy pancakes to verify stress components and distributions. Reinforcements and bonding of turns	20 stacks (200) 10 dummy (500) 10 sub-size loading (500)
Coil external mechanics and pre-load	Pre-loading structure development and tests	5 dummy (250) 5 sub-size loading (250) 5 full-size loading (1250)
Inter-turn resistance control and variants	Produce baseline windings (e.g. soldered, no insulation control) and variants introducing intrinsic and extrinsic resistance control	15 sub-size (750)
Joints resistance and stability	Produce test configuration for pancake joints and unit electrical/mechanical test. Integrate joints in pancakes and test resistance and stability (force and thermal cycles)	20 single joints (200) 10 sub-size (500) 2 full-size (500)
Quench detection	Introduce and test diagnostics in above tests. Select baseline (voltage ?) for comparison	Use above pancakes for dedicated tests
Quench protection	Test energy release and temperature increase in provoked and spontaneous quenches	Use above pancakes for dedicated tests
Coil dynamic forces	Test mini-coil stacks of pancakes	12 full-size (3000)

Total approximately 10 km of 4 mm tape

Collider magnets

A-B plots



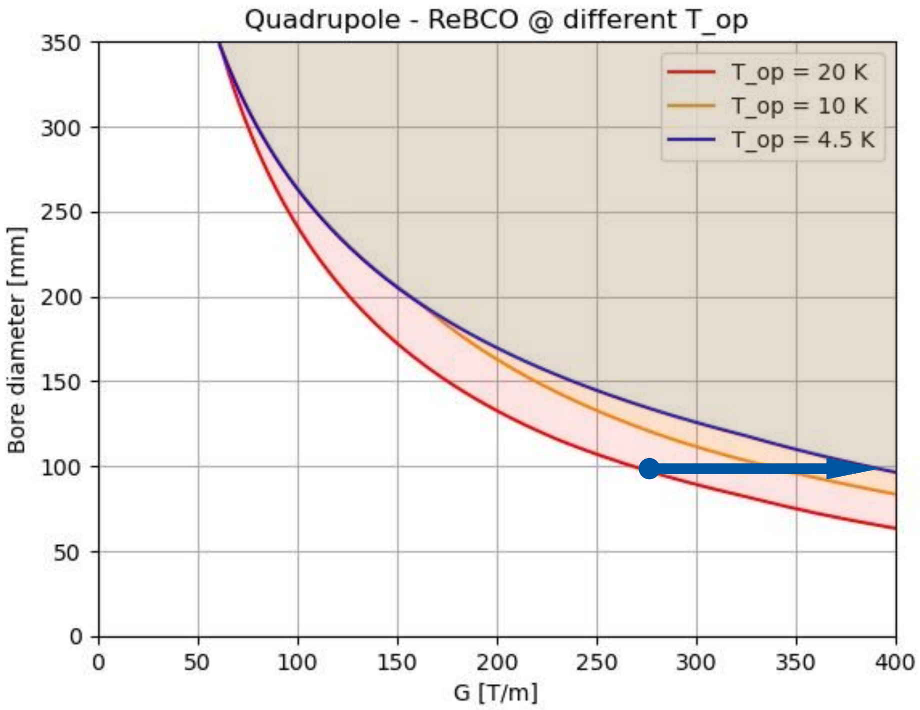


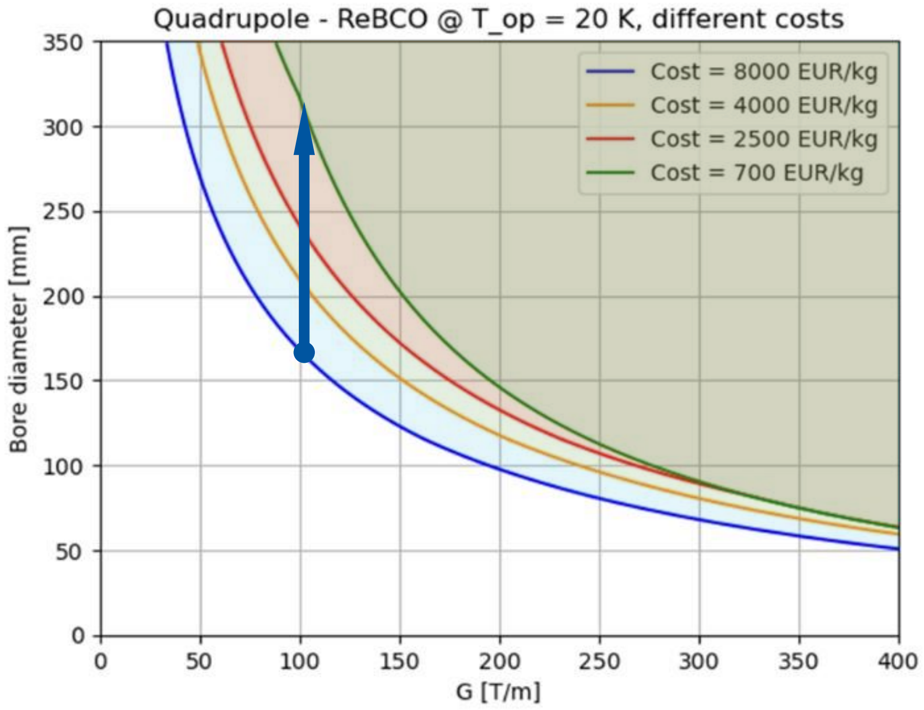
Nb_3Sn performance at 4.5 K is limited by **operating margin** and **peak stress**. There is not much we can do to break these limits

REBCO performance is limited by **quench protection**, NI winding may give the solution, **provided we master it in engineered accelerator magnets**

Collider magnets

A-B plots Understand main drivers and identify R&D needs





High J_c gives access to **larger quadrupole gradients**, and can be achieved lowering the operating temperature (e.g. only the IR)

Accepting higher cost, allowing for larger material amounts, relaxes stress and protection limits and results in **larger apertures**

HTS tape specifications – 1/2

Geometry and composition parameters		Specified	Comments
Nominal coated conductor width	(mm)	4.0 ± 0.050	After copper coating
Substrate material		High-strength alloy	Non-magnetic alloy such as Hastelloy C-276
Substrate thickness	(µm)	40 to 60	Acceptable range, must remain constant through production
Copper residual resistivity ratio	(-)	-	Expected range is 30 to 100
Total copper coating thickness	(µm)	20 (2x10)	This thickness is intended as total, i.e. twice the thickness of a homogeneous coating on both faces of the coated conductor
Coated conductor thickness	(µm)	60 to 100	Acceptable range, must remain constant through production
Coated conductor thickness tolerance and homogeneity	(µm)	± 5	There must be no dog-boning and bulges after copper coating

HTS tape specifications – 2/2

		Specification	Target
Minimum I_c (4.2 K, 20 T)	(A)	240	480
Minimum benchmark I_c (4.2 K, 5 T)	(A)	577	
Minimum n value at 1 μV/cm	(-)	15	
Maximum standard deviation $\sigma(I_c(4.2\ K, 20\ T))$	(%)	-	5
Minimum $J_{Cnon\text{-}Cu}$ (4.2 K, 20 T)	(A/mm²)	-	3000
Minimum $J_{Cnon\text{-}Cu}$ (20 K, 20 T)	(A/mm²)	-	1200
Minimum unit length	(m)	200	1000
Minimum bending radius	(mm)	10	5
Allowable non-Cu $\sigma_{longitudinal\ non\text{-}Cu}$ (4.2 K)	(MPa)	800	1000
Allowable compressive $\sigma_{transverse}$ (4.2 K)	(MPa)	300	600
Allowable tensile $\sigma_{transverse}$ (4.2 K)	(MPa)	> 5	50
Allowable shear $\tau_{transverse}$ (4.2 K)	(MPa)	> 5	50
Range of allowable $\varepsilon_{longitudinal}$	(%)	-0.1…0.4	-0.1…0.5
Internal specific resistance $\rho_{transverse}$ (77 K)	(nΩ cm²)	-	20

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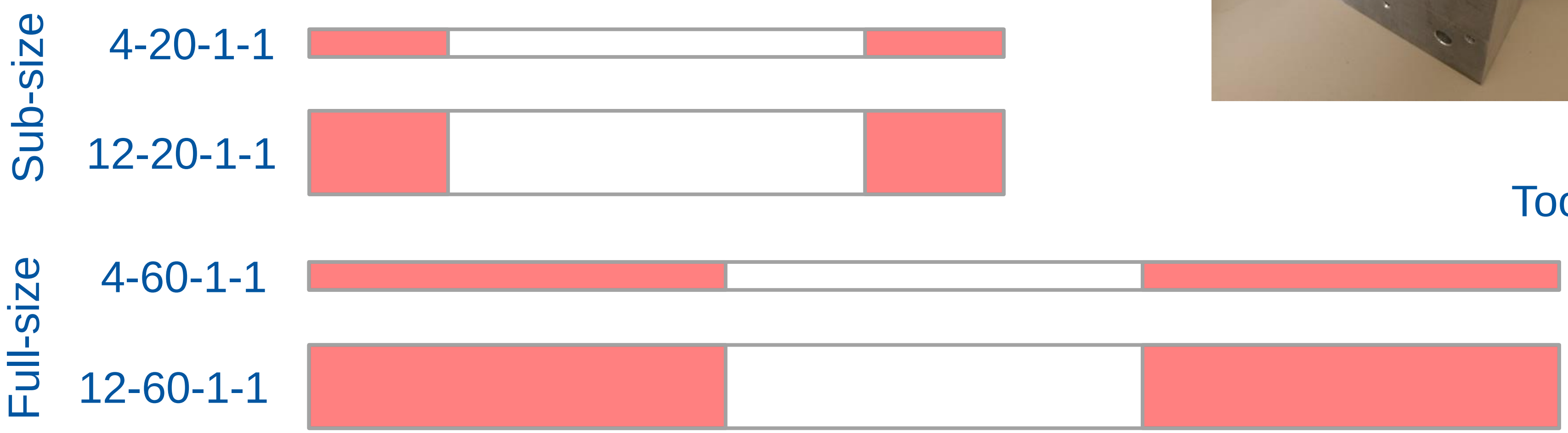
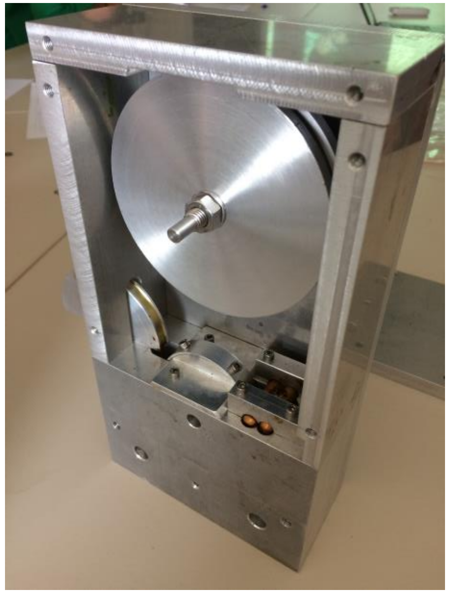
R&D Pancakes

Singe and stacked pancake tests planned to validate the concept and identify issues/solutions towards assessing the performance limits.

- 60 mm inner diameter
- 20 mm and 60 mm thickness
- 4 mm and 12 mm tape width
- Single and double pancakes winding
- One- and two-in-hand winding

Field reach: 15…25 T



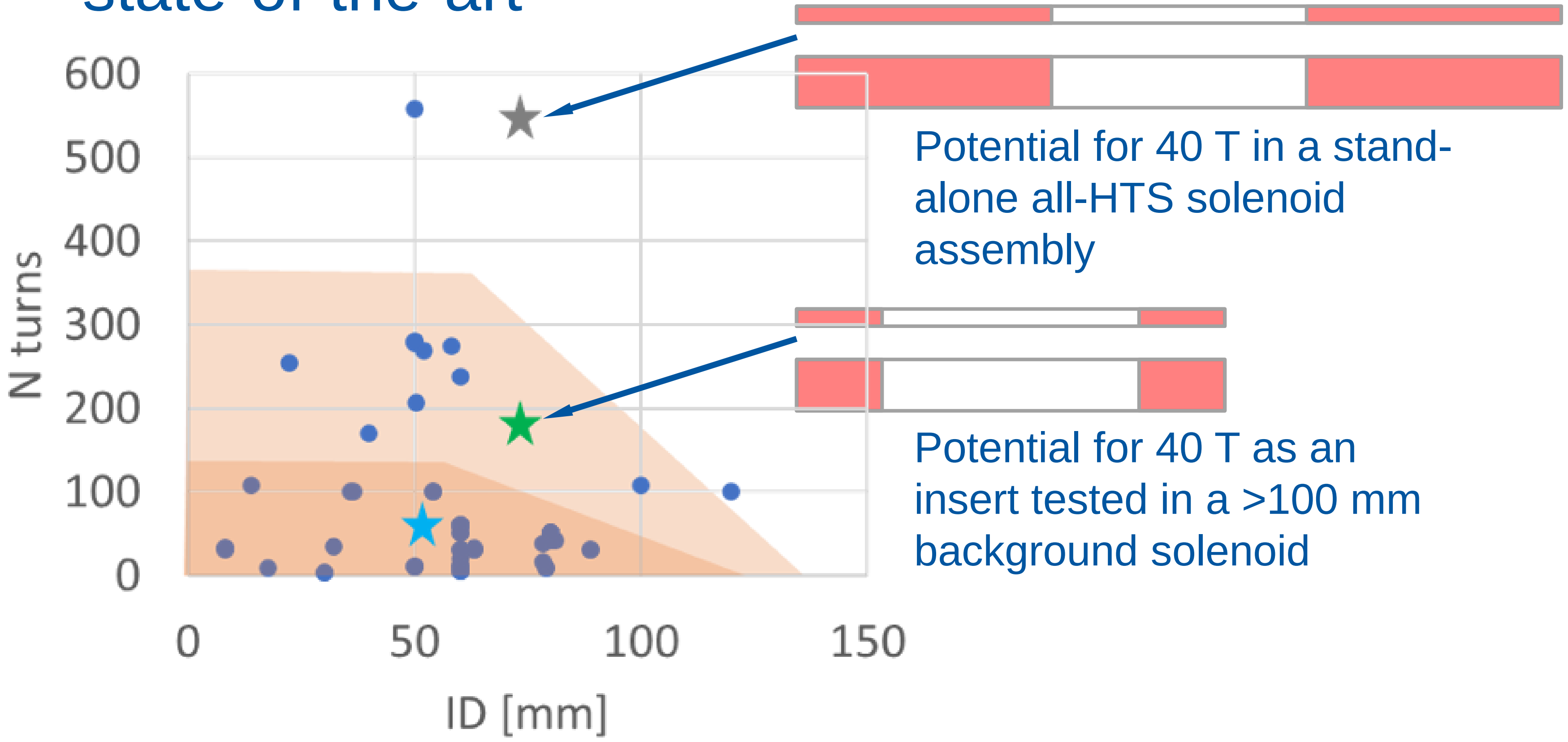


Winding trials EP-ADO
Tooling and material test EN-MME

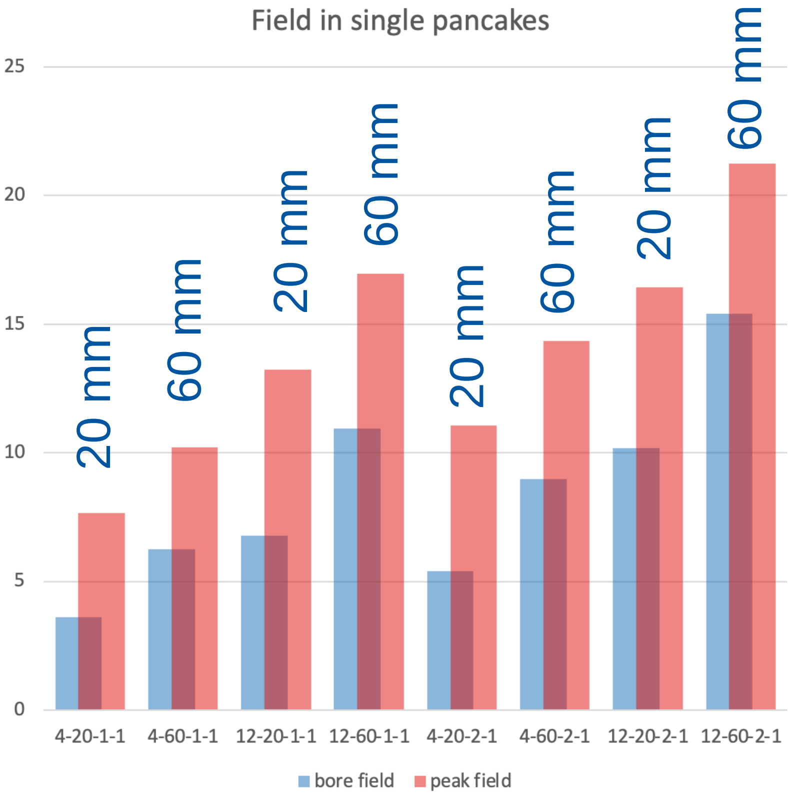
Funding: IMCC+MuCol

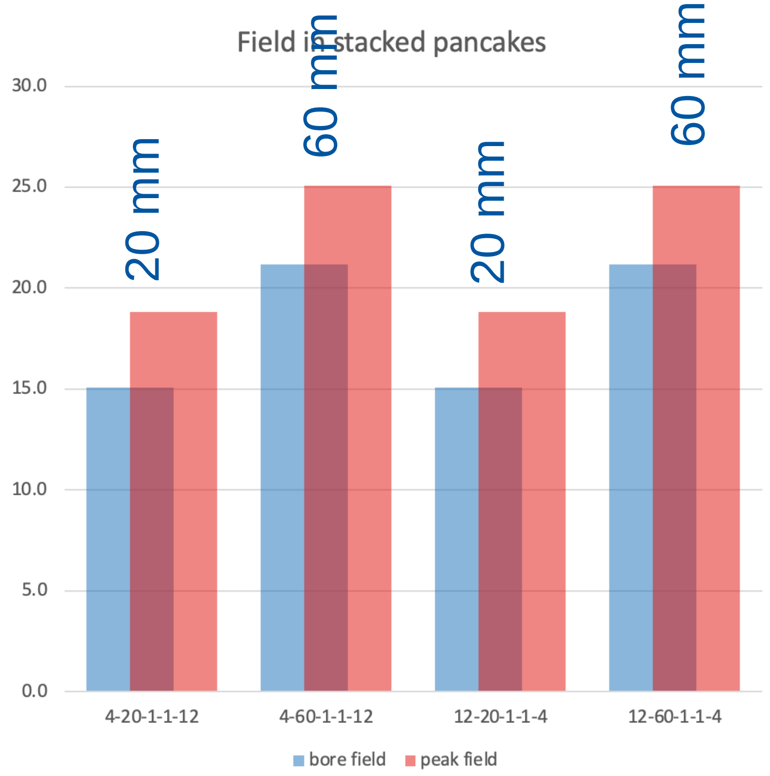
R&D Pancakes – 2/2

- The R&D pancakes will probe geometry and operating conditions well beyond the present state-of-the-art



Magnetic field reach





4 mm tape | 12 mm tape | 4 mm tape | 12 mm tape

Single pancakes | Double pancakes

4 mm tape | 12 mm tape

Stacked pancakes

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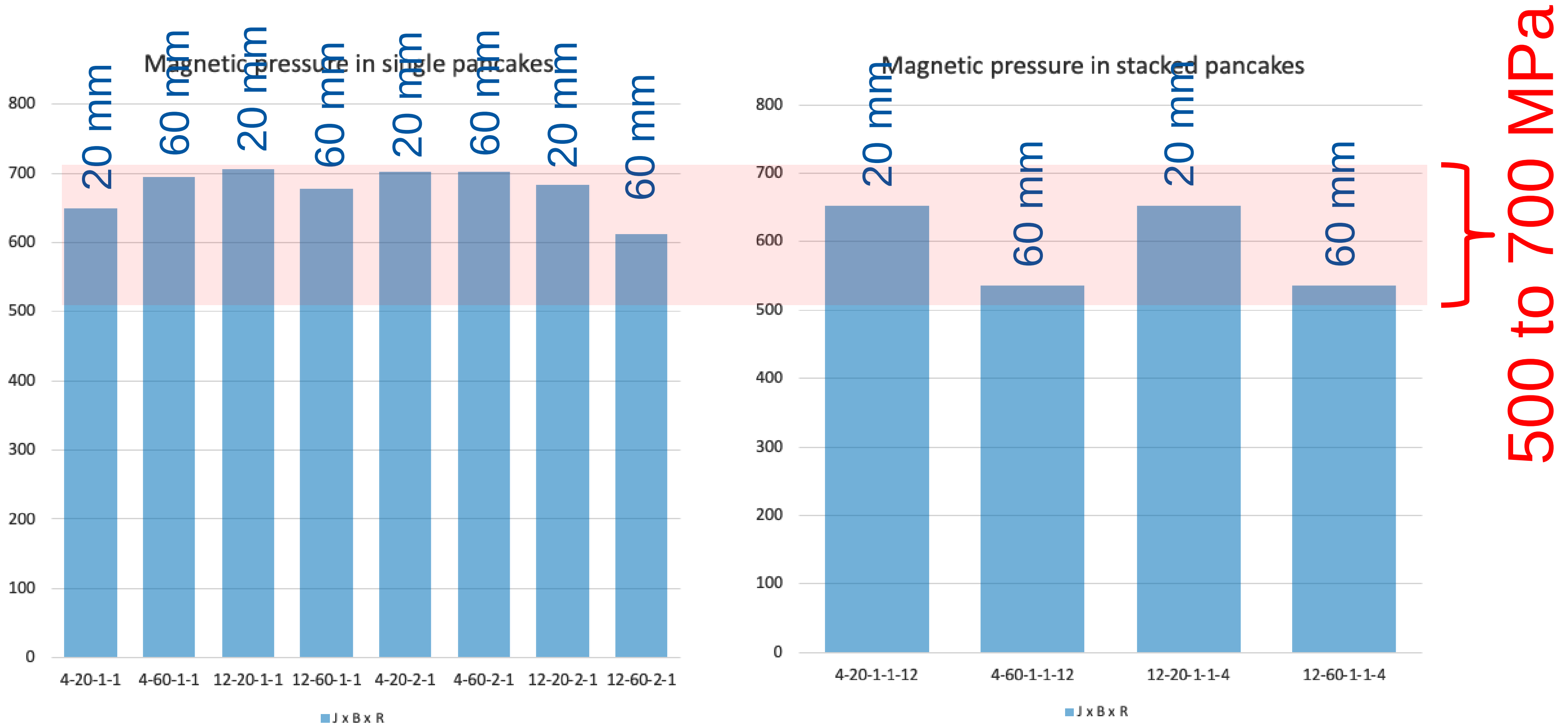
Magnetic pressure

MuC final cooling 40 T: 700 MPa



4 mm tape | 12 mm tape | 4 mm tape | 12 mm tape | 4 mm tape | 12 mm tape

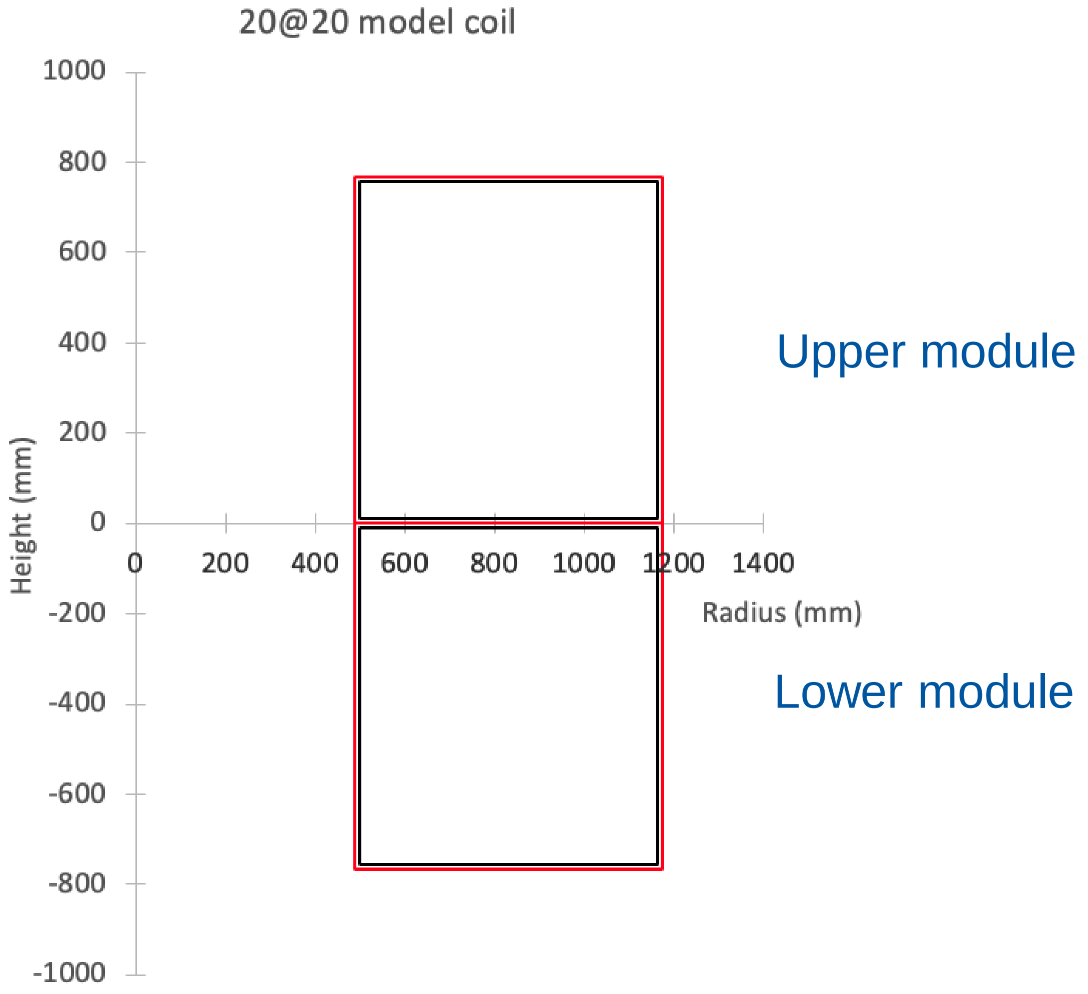
Single pancakes | Double pancakes | Stacked pancakes

Are solenoids relevant ?

- Solenoid model coils built with modest conductor lengths and size (few km) can probe performance limits at extreme values:
  - Field (20 T…40 T) – high and ultra-high field characterization of the critical surface $J_C(B,T,\alpha)$
  - Force and stress (500 MPa…700 Mpa) – engineering test at levels relevant and beyond full-size accelerator magnets
  - Current density (600 A/mm^2…900 A/mm^2) and energy density (300 MJ/m^3) – quench detection and protection in a new regime, where present technical solutions may not work (detection time would be too short, quench heater power would be too high)
- “Simple” engineering, fast turnaround samples

R&D proposal for the target solenoid

- A model coil using the full-size conductor to demonstrate:
- Performance (20 T),
- Cooling with high-pressure gaseous helium (20 K, 20 bar)
- Quench detection and protection (300 MJ stored energy)
- Manufacturing methods (double pancake winding, GE/resin insulation)



Benefits of technological innovation driven by magnet R&D for the muon collider

- High Energy Physics - Advances in HTS magnet technology benefit directly all future circular colliders at the energy frontier (MC, FCC-hh, SppC).
- Materials and life science - Higher field reach will enhance the capability to study materials under extreme conditions, and augment the diagnostic power of NMR in structural and functional inorganic and organic chemistry.
- Healthcare - Enhanced NMR and MRI technology made possible by HTS magnets will improve imaging, reducing healthcare expenses and facilitating market penetration. Cryo-free energy efficient HTS magnets can reduce the size of particle therapy accelerators and gantries, facilitating diffusion of particle-based cancer therapy.
- Energy and Power - Widespread introduction of HTS materials can lead to simpler and more efficient fusion plants, lightweight aeolic generators and motors with high power density, and reduced electricity distribution losses, thus enhancing energy efficiency.
- Cryogenics at 20K - Operating above liquid helium temperatures improves energy efficiency and reduces the complexity and costs of cryogenics systems, enabling broader scientific, societal and industrial applications.
- Economic and Societal Impact - A novel HTS magnet technology creates opportunities for spin-offs, novel industrial applications, job creation. Promotion of an innovation ecosystems is crucial to drive high-tech economic growth and sustainability initiatives.