# HFM – WP2.6
# Solenoids for the Muon Collider(*)

Presented by L. Bottura, CERN

TE-HFM workshop – 19 September 2024

(*) proposal to rename the WP

HFM
High Field Magnets

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# Outline

- Scope of the work package
- Recent advances
- Plans, milestones and deliverables

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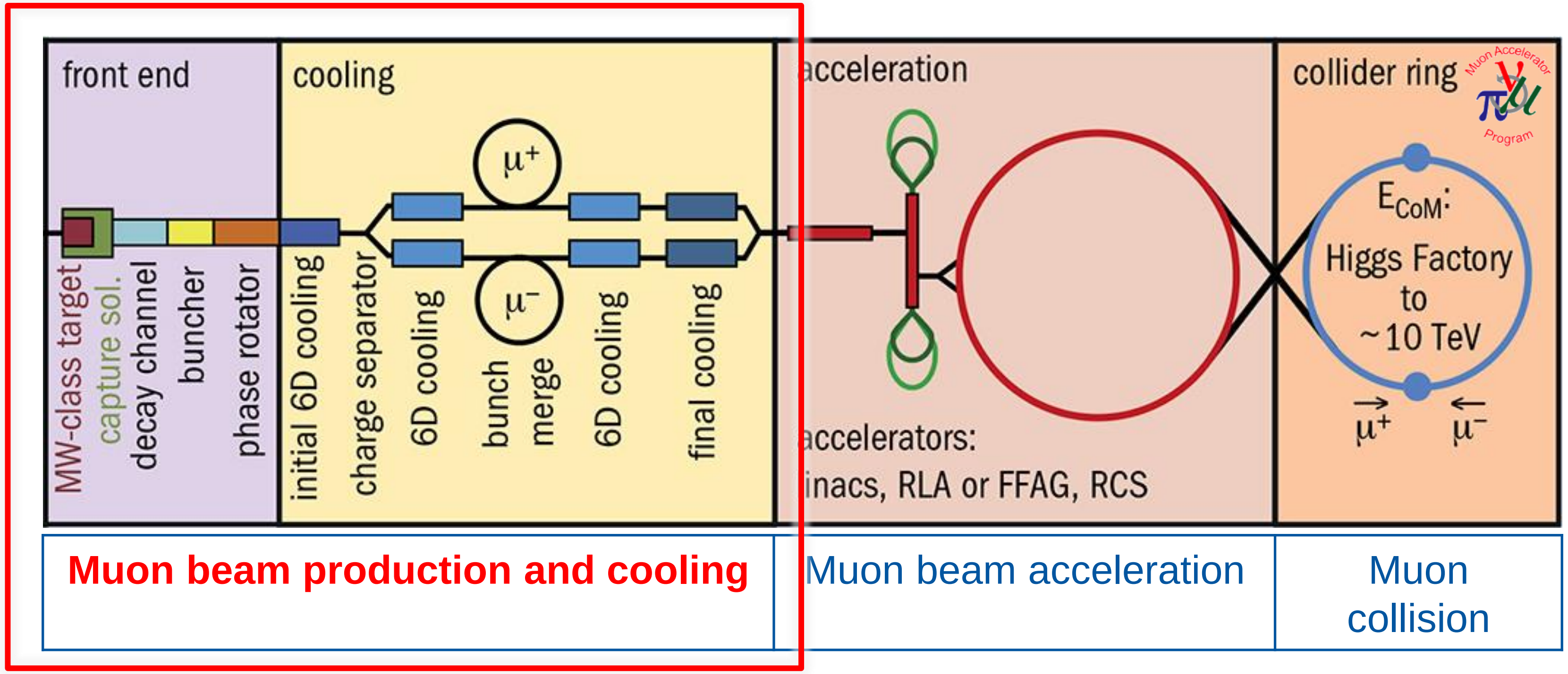
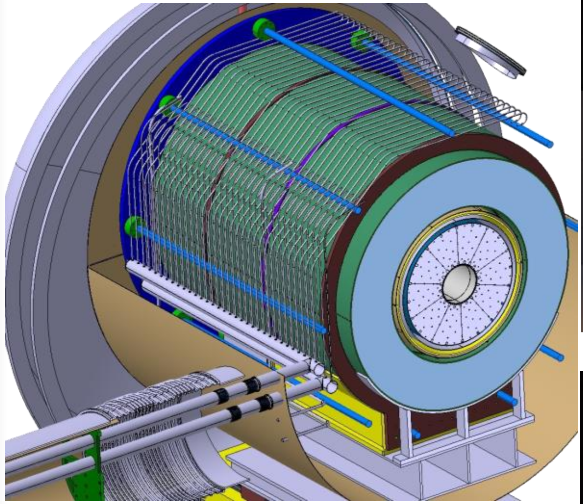


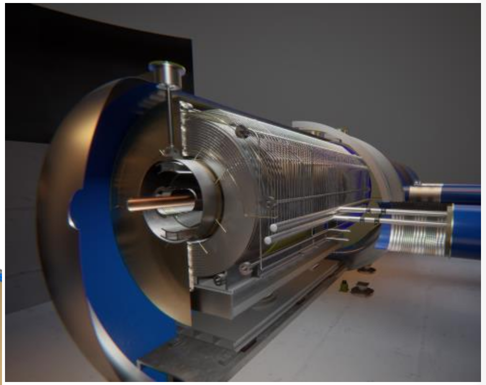

International MUON Collider Collaboration

MuCol

# The solenoids

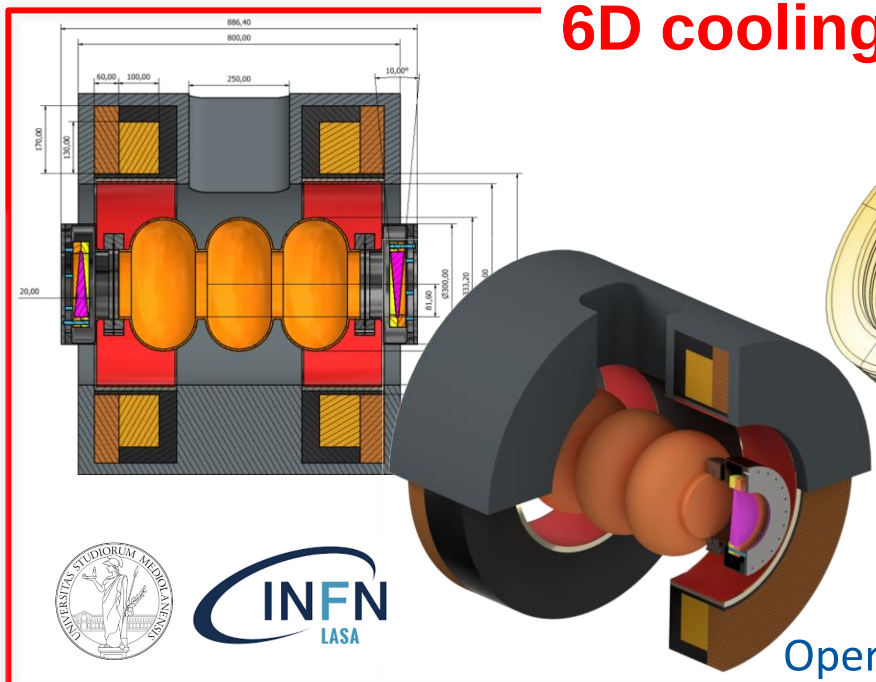
## Target, decay and capture

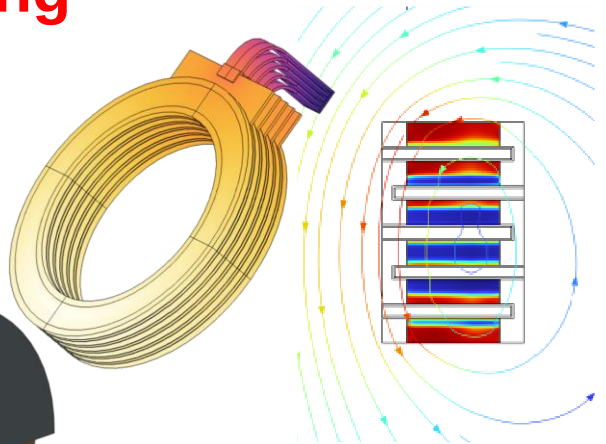




Operating field: 20 T
Magnet bore: 1.4 m
Operating temperature: 20 K

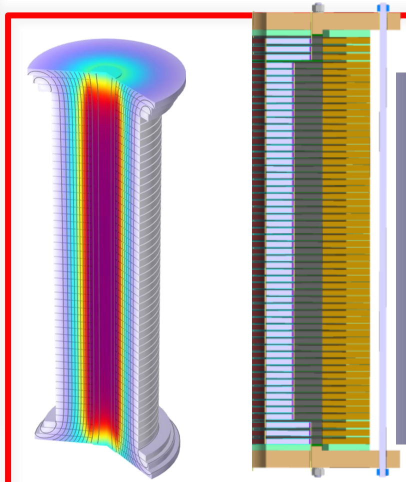
## 6D cooling

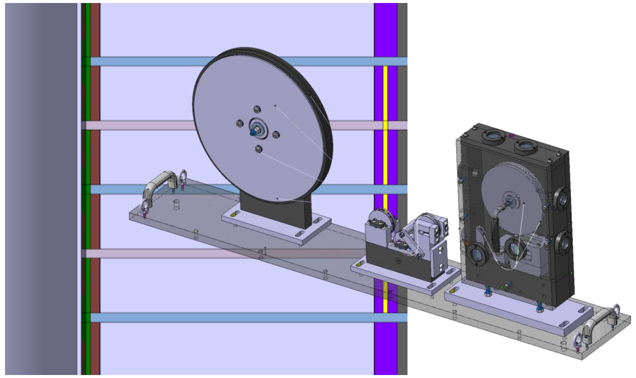




Operating field: 2…14 T
Magnet bore: 90 mm…1.5 m
Operating temperature: 4.2…20 K

## Final cooling





Operating field: 40 T
Magnet bore: 50 mm
Operating temperature: 4.2…20 K

# 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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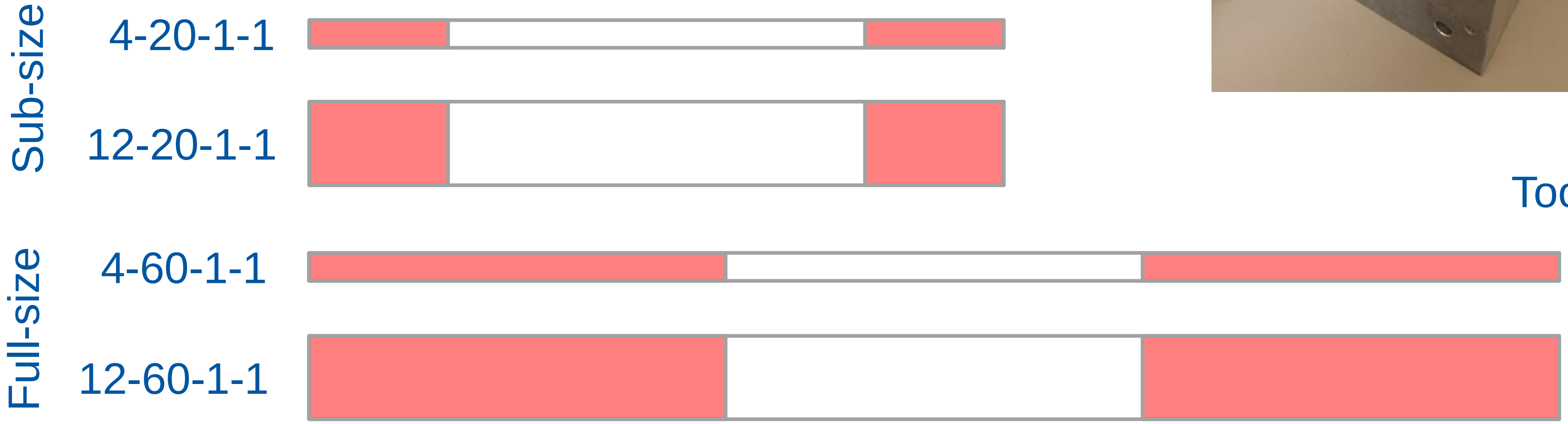
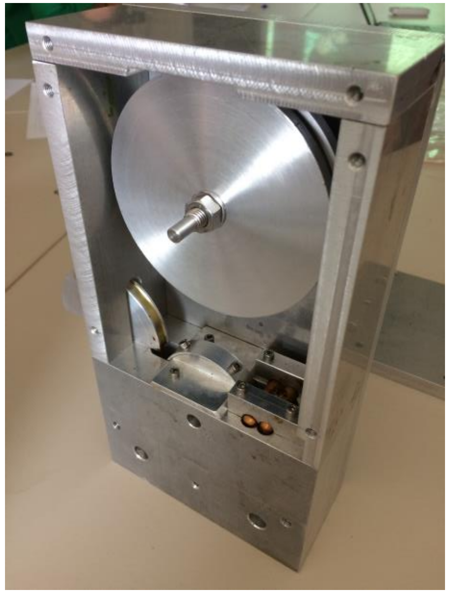
# R&D Pancakes

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

# 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

# Outline

- Scope of the work package
- Recent advances
- Plans, milestones and deliverables

# Recent advances – tapes

European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

EDMS No. 2960999

**Price Enquiry**

**Technical Specification**

**Supply of REBCO Coated Conductor for Muon Collider Solenoids R&I**

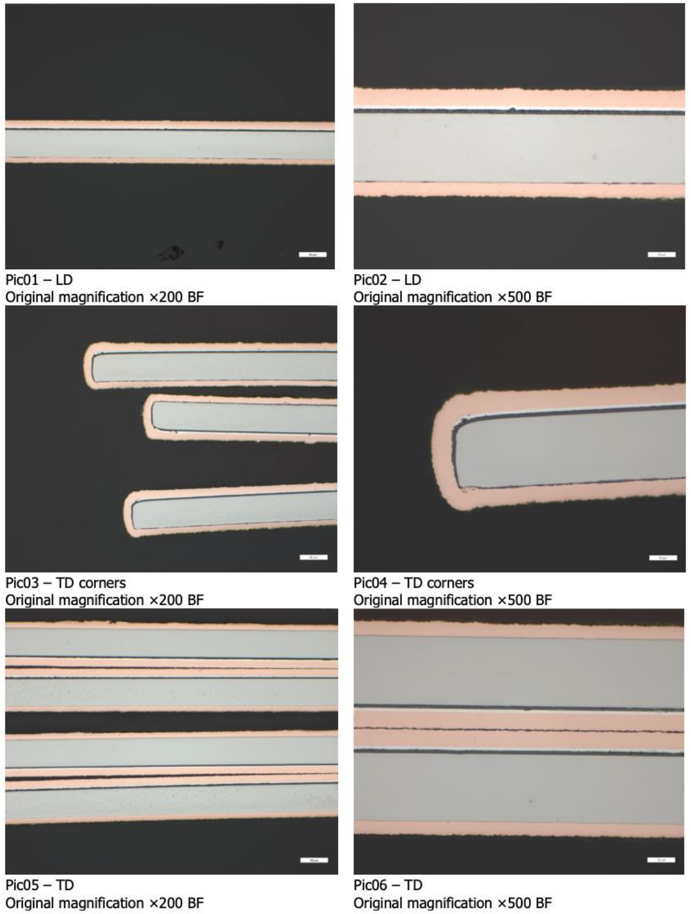
**Abstract**

This Technical Specification concerns the supply of up to 9 0… REBCO coated conductor, to be quoted and delivered in batc… Delivery completion is foreseen over seven months from noti… Contract.

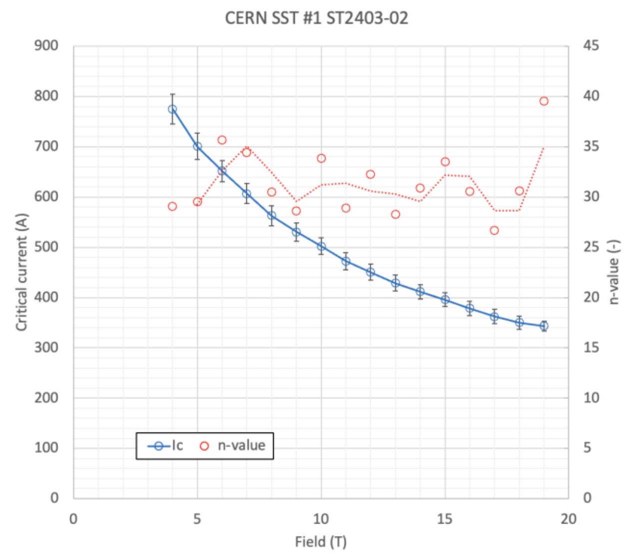
| Geometry and composition parameters | | Specified |
|---|---|---|
| Nominal coated conductor width | (mm) | 4.0 ± 0.050 |
| Substrate material | | High-strength alloy |
| Substrate thickness | (µm) | 40 to 60 |
| Copper residual resistivity ratio | (-) | - |
| Total copper coating thickness | (µm) | 20 (2x10) |
| Coated conductor thickness | (µm) | 60 to 100 |
| Coated conductor thickness tolerance and homogeneity | (µm) | ± 5 |

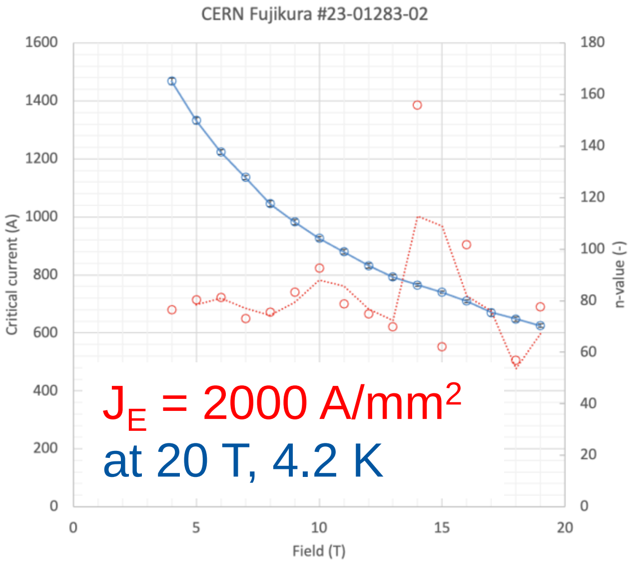
| | |
|---|---|
| Minimum $I_c$ (4.2 K, 20 T) | (A) |
| Minimum benchmark $I_c$ (4.2 K, 5 T) | (A) |
| Minimum n value at 1µV/cm | (-) |
| Maximum standard deviation σ($I_c$(4.2 K, 20 T)) | (%) |
| Minimum $J_{Cnon\text{-}Cu}$ (4.2 K, 20 T) | (A/mm |
| Minimum $J_{Cnon\text{-}Cu}$ (20 K, 20 T) | (A/mm |
| Minimum unit length | (m) |
| Minimum bending radius | (mm |
| Allowable non-Cu … Cu (4.2 K) | (MPa |
| … (4.2 K) | (MPa |
| … K) | (MPa |
| … ) | (MPa |
| | (%) |
| …verse (77 K) | (nΩ cm |

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

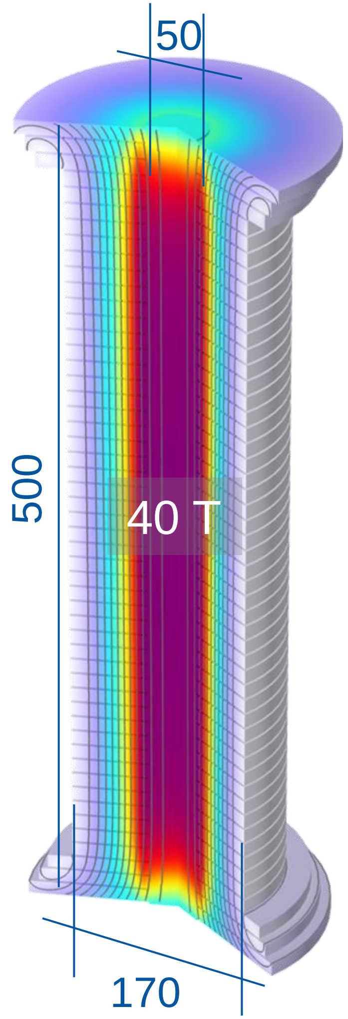


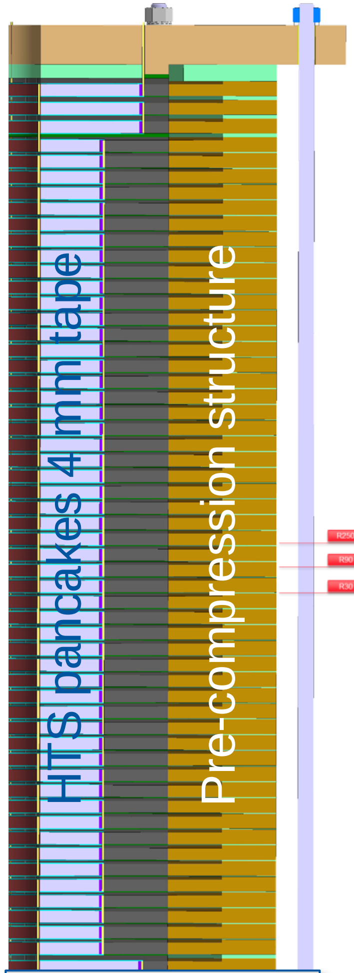

$J_E$ = 2000 A/mm$^2$ at 20 T, 4.2 K

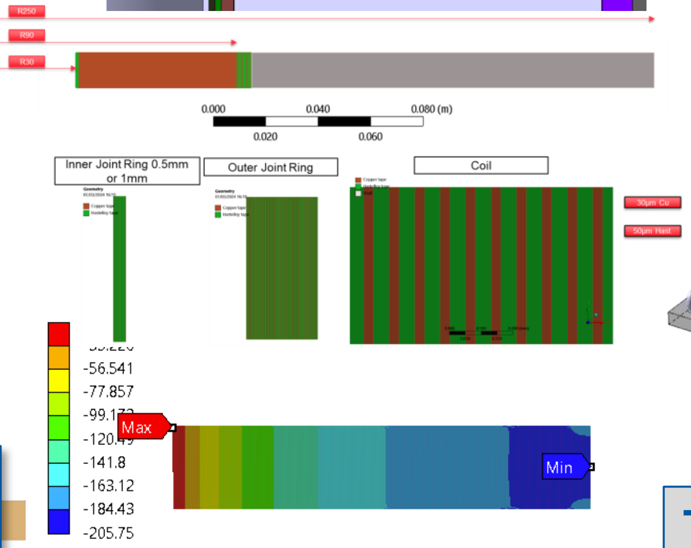
Critical current measurement

# Recent advances – engineering

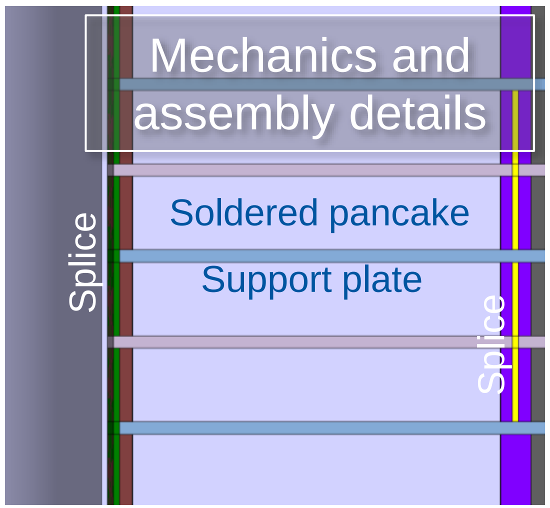


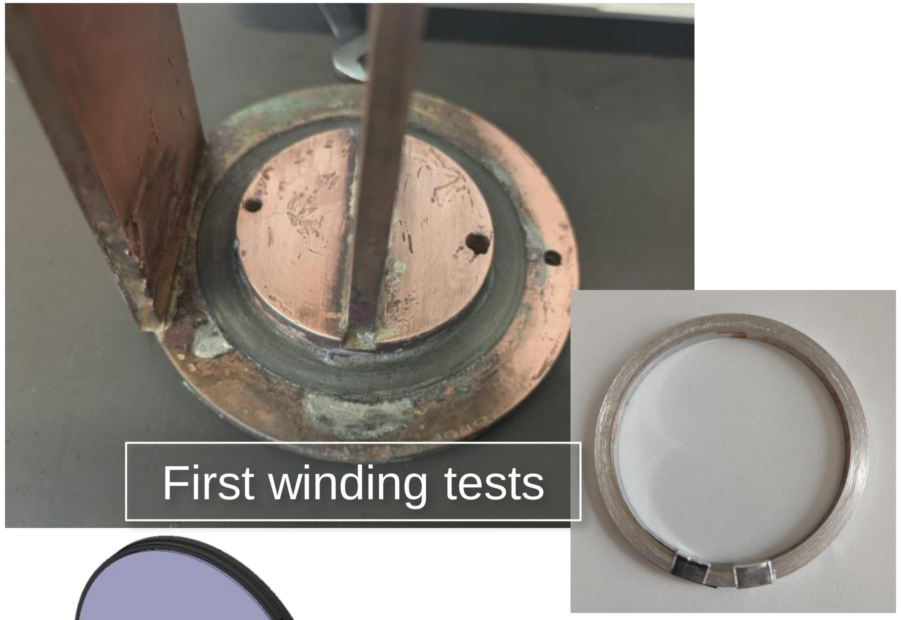

Magnet concept



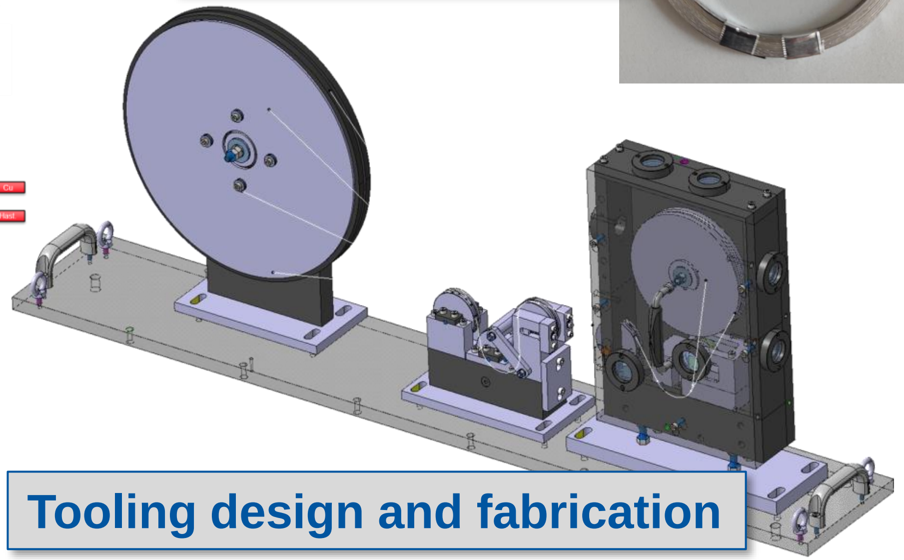




Mechanical design



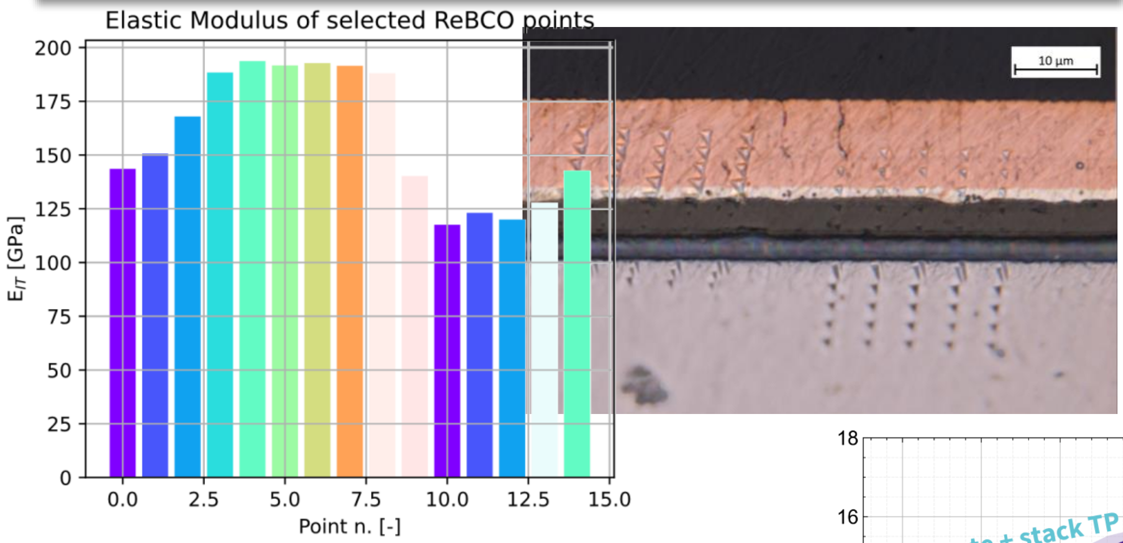
First winding tests

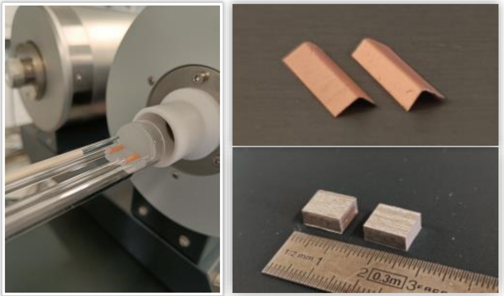


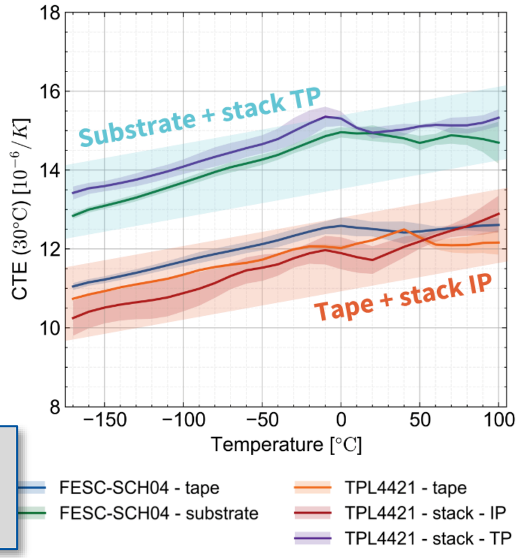
Tooling design and fabrication

# Recent advances – material tests

Nano-indentation for the derivation of elastic properties

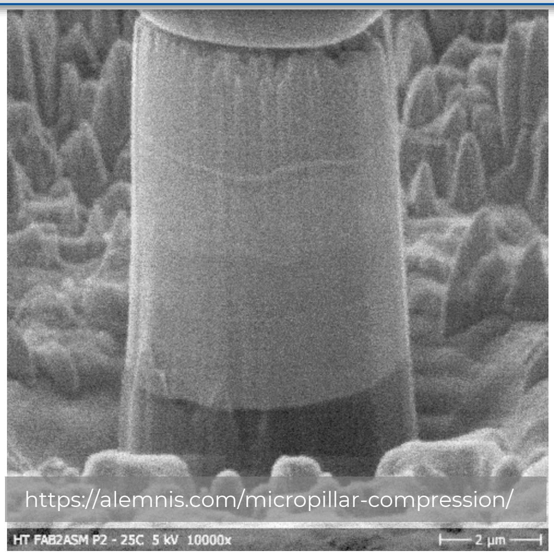


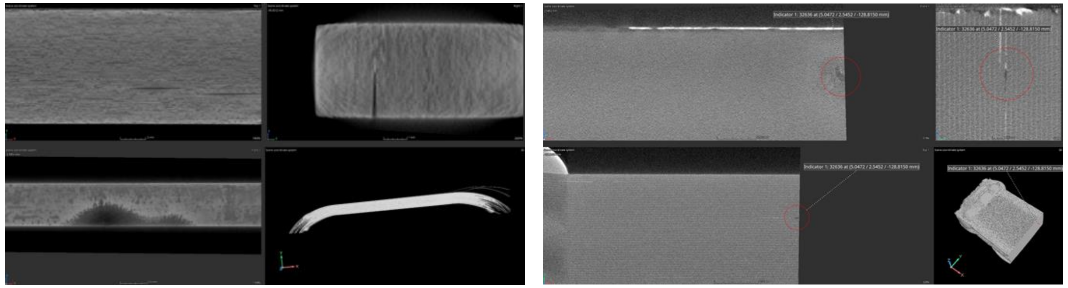






Thermal expansion coefficients of tapes and soldered stacks

Micro-pillars stress-strain curves



Porosity measurement in stacks and process optimization

# Outline

- Scope of the work package
- Recent advances
- Plans, milestones and deliverables

# 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 |

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# 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 |

# 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 |
| 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 - 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)

# Summary and perspective

- The magnet activities in the scope of the International Muon Collider Collaboration (IMCC) and the EU design study MuCol have a strong focus on HF and UHF HTS solenoids
  - We wish to probe the limits of present technology, and define the R&D required to achieve such performance (MuCol and ESPP deliverable)
  - This work is instrumental to achieving the muon collider luminosity targets (i.e. performance beyond US-MAP)
- This technology development connects directly to the R&D in the scope of HFM
  - Share technology challenges and advances, and profit from capabilities within RD2 (e.g. KC4)
  - Recall that the technology developed is also relevant for other magnets, such as arc dipoles and IR quadrupoles for the Muon Collider (steady state)
- Proposal – initiate “code sharing”, calling common meetings of mmWG and RD2.6

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# 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)<br>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)<br>10 dummy (500)<br>10 sub-size loading (500) |
| Coil external mechanics and pre-load | Pre-loading structure development and tests | 5 dummy (250)<br>5 sub-size loading (250)<br>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)<br>10 sub-size (500)<br>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

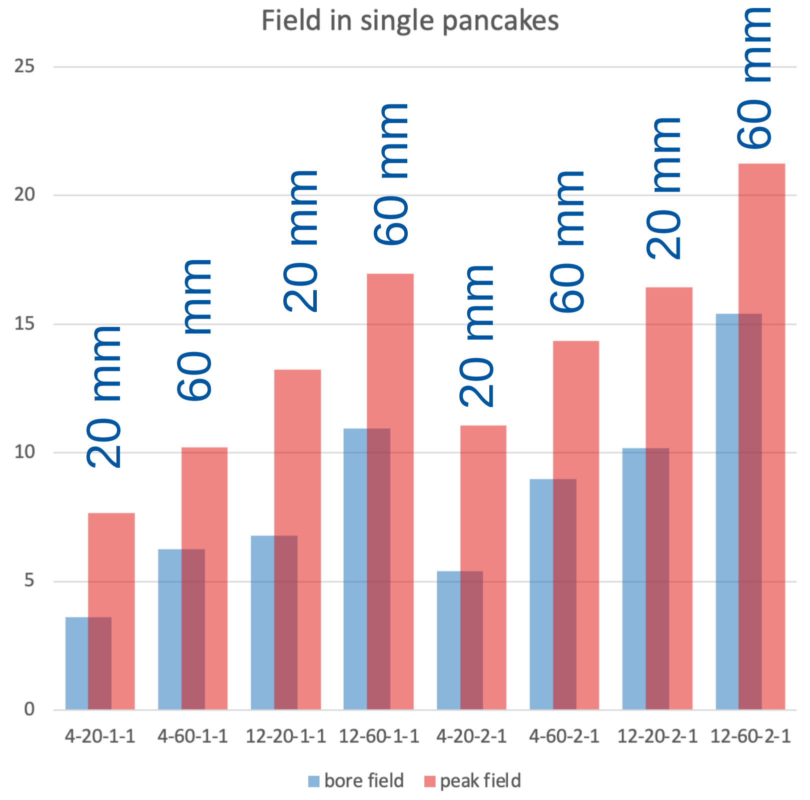
# HTS tape specifications – 1/2

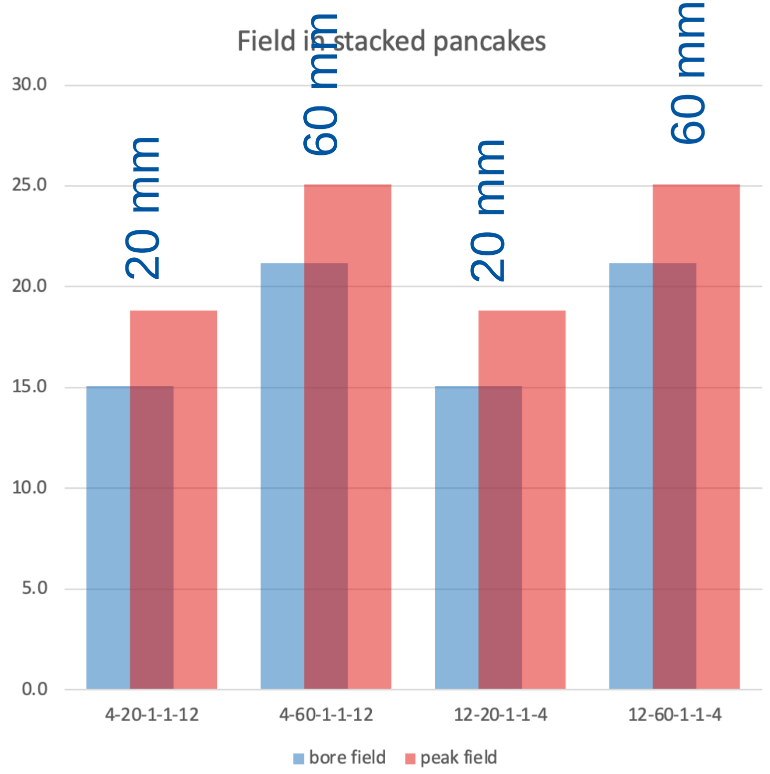
| Geometry and composition parameters | | Specified | Comments |
|---|---|---|---|
| Nominal coated conductor width | (mm) | 4.0 ± 0.050 | After copper coating |
| Substrate material | | High-strength alloy | Non-magnetic alloy such as Hastelloy C-276 |
| Substrate thickness | (µm) | 40 to 60 | Acceptable 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) | ($A/mm^2$) | - | 3000 |
| Minimum $J_{Cnon\text{-}Cu}$ (20 K, 20 T) | ($A/mm^2$) | - | 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) | ($n\Omega\ cm^2$) | - | 20 |

# Magnetic field reach




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

Single pancakes | Double pancakes | Stacked pancakes

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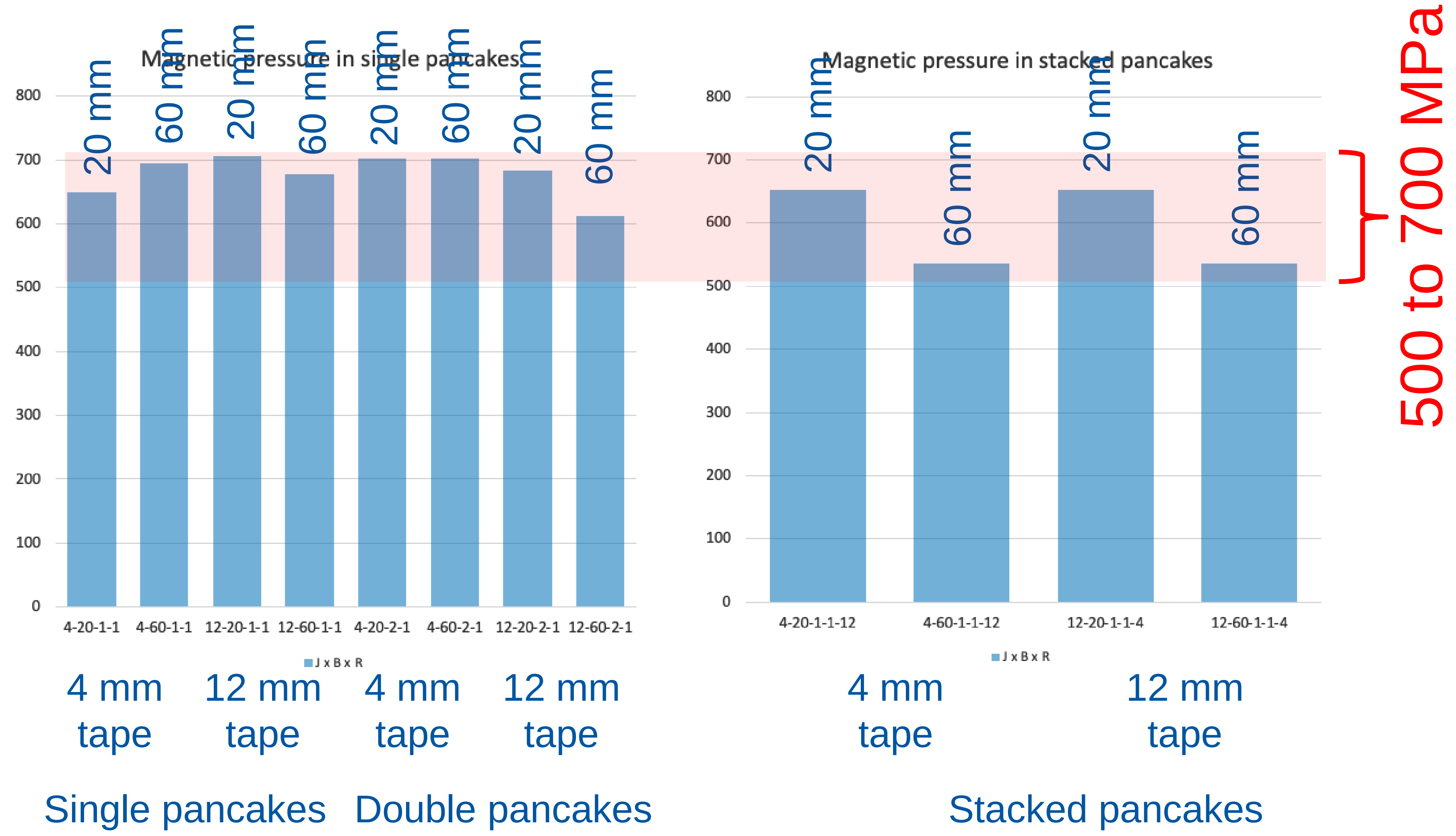
# Magnetic pressure

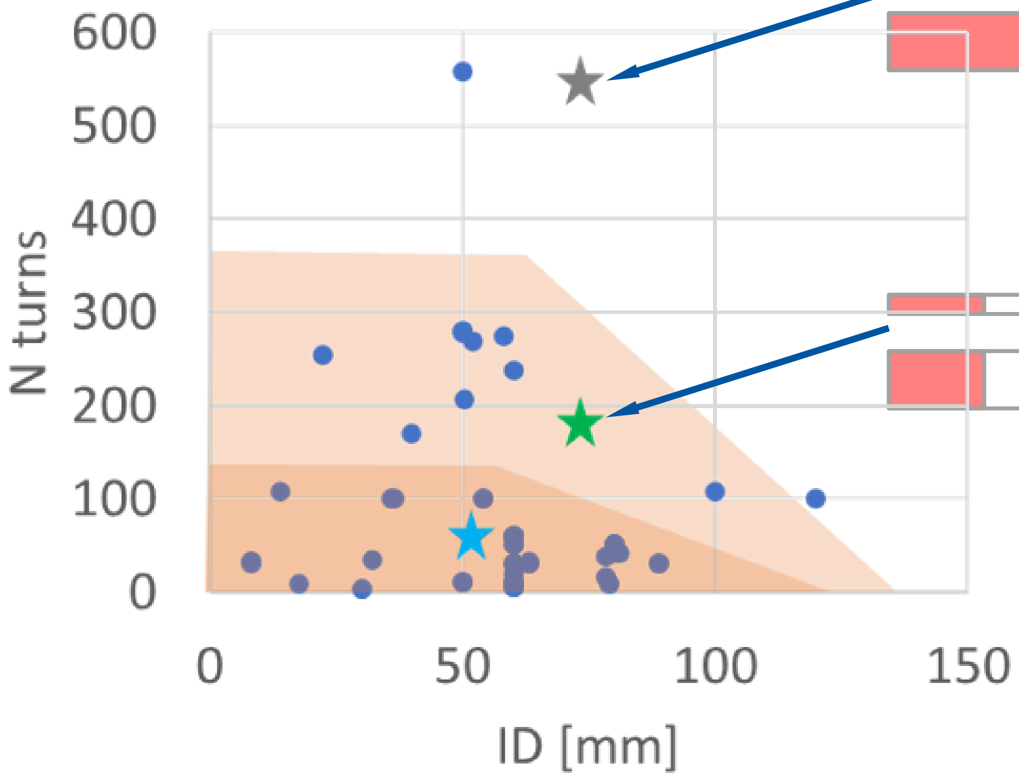
MuC final cooling 40 T: 700 MPa



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




Potential for 40 T in a stand-alone all-HTS solenoid assembly

Potential for 40 T as an insert tested in a >100 mm background solenoid