CHART Scientific Report (Final Report for Phase 2)

Studies on the electrical insulation for the final cooling solenoid of the Muon collider

(Magmu)

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1. Introduction / Original goals of this project

In the context of feasibility studies for the Muon collider [1], the development of superconductor technology is needed. Indeed, for its luminosity target of 3-10 TeV, very high magnetic fields are requested especially in the final cooling section where a 40 T full-high-temperature-superconductor (HTS) solenoid with a 50 mm aperture would be required. The quench propagation velocity in HTS is typically 2 or 3 order of magnitude lower than in low temperature superconductors (LTS). Also, heat conductivity is low for cuprates (compared to intermetallic compounds used for LTS [2]). This makes protecting HTS magnets harder. In our work we investigate possibilities offered by novel insulation materials to allow the current to follow bypass paths in case of a quench.

We investigate "smart" materials that in cryogenic conditions have temperature dependent resistivity switch or non-linear IV curve. The goal is to combine the current-sharing capability, typical of non-insulated windings with the rapid charging time of insulated magnets. We study smart materials candidates for the electrical insulation of the 40 T magnet, select the most promising smart material according to simulations (FEM model) and build a small demonstrator of smart insulated pancake.

Figure 1: HTS demonstrator with tuned turn-to-turn contact resistance

2. Realisation

The project started with a literature review of the state-of-the-art on smart coatings and smart protection for ReBCO magnets. Various candidate for the smart coating were measured in cryogenic condition (down to 4 K, see Fig. 3). Samples include Pedot:Pss, positive thermocouple (PTC), varistor paste and amorphous materials.
A lever setup was built and used to measure the behaviour of the Metrosil Varistor paste at 77 K under a few MPa of applied pressure. A smaller set up to measure contact resistance at a fixed pressure of 0.3 MPa on a 8mm x 8mm cross section was also prepared.
The tuneability of turn-to-turn contact resistance for an HTS pancake, using thermoplastic based coating was investigated (see publications).
There is ongoing preparatory work to build a HTS ReBCO pancake with turn-to-turn insulation and a smart coating applied on the top and the bottom of coil faces.
On the numerical side: 2D axisymmetric electro thermal simulations for the 40 T final cooling solenoid are ongoing. The fit of the critical surface is currently being updated to reflect 40 T conditions. For the FEM the anisotropic resistivity tensor of Mataira [3] has been implemented in a full H-formulation approach. For rapid convergence H-phi formulation framework was explored for the anisotropic resistivity tensor and while field and inductance value seem to be predicted correctly current flow in the homogeneous winding doesn't seem to be compatible with this approach.

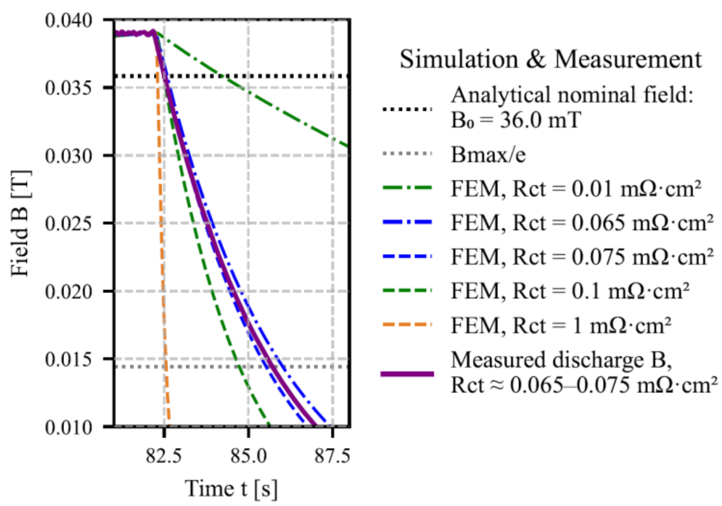

Figure 2: Measurement of field decay of an HTS winding against FEM model prediction

3. Results / Conclusions / Deliverables

Various smart samples curves have been measured, offering a range of resistive switch to feed to the simulations.
We studied the tuneability of turn-to-turn contact resistance down to 77 K and developed an easy to process coating. Its tuneability has been tested by building a small demonstrator (Fig. 1) and measuring its field decay. A FEM model that predicted the behaviour of the demonstrator was built and matches the measurement (Fig. 2).

Currently we are working on a winding to observe smart material behaviour not between turns but on top of a pancake.
The goal is to build a small demonstrator with a turn-to-turn smart insulation, study resilience to quench and behaviour in external field (~12 T) at the university of Geneva.

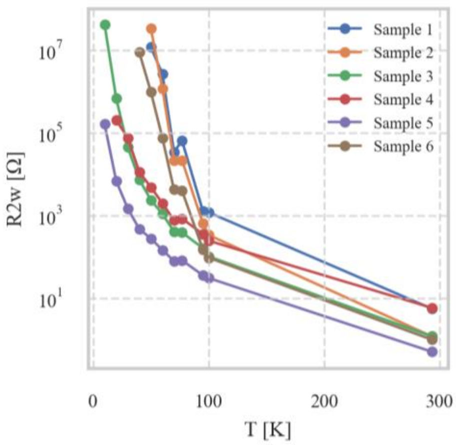

Figure 3: Smart material candidate (PTC) cryogenic behavior (dip in liquid Helium)

4. Publications and Outreach

- Slides for the Swiss Physical Society (SPS) 2025:

  https://drive.switch.ch/index.php/apps/files/?dir=/CHART/Publications/Presentations/2025_08_SPS_(SwissPhysicalSociety)&fileid=9123665157#pdfviewer

- Poster Eucas 2025:

  https://drive.switch.ch/index.php/apps/files/?dir=/CHART/Publications/Presentations/2025_09_EUCAS/Poster&fileid=9123615657#pdfviewer

- Conference paper (Eucas 2025): *Filled Thermoplastic Based Coating for Tailored Contact Resistance in HTS Coils*, DOI: 10.1109/TASC.2026.3656161

5. References

[1] Carlotta Accettura et al. “Towards a muon collider”. en. In: Eur. Phys. J. C 83.9 (Sept. 2023), p. 864. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052- 023- 11889- x. URL: https://doi.org/10.1140/epjc/s10052-023-11889-x (visited on 02/18/2026)

[2] Marchevsky, M. Quench Detection and Protection for High-Temperature Superconductor Accelerator Magnets. *Instruments* **2021**, *5*, 27. URL: https://doi.org/10.3390/instruments5030027 (visited on 03/13/2026)

[3] R C Mataira et al. “Finite-element modelling of no-insulation HTS coils using rotated anisotropic resistivity”. en. In: Supercond. Sci. Technol. 33.8 (June 2020). Publisher: IOP Publishing, 08LT01. ISSN: 0953-2048. DOI: 10.1088/1361-6668/ab9688. URL: https://doi.org/10.1088/1361-6668/ab9688 (visited on 02/18/2026)