Swiss Accelerator Research and Technology

# CHART Scientific Report (Final Report for Phase 2)

# FCC-ee High-Temperature-Superconducting Short Straight Sections

# (FCCee HTS4)

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## 1. Introduction / Original goals of this project

This project studies the possibility of replacing the normal-conducting short straight sections (SSSs) of the arcs of the FCC-ee main storage ring with superconducting ones. Such an approach has significant performance advantages over the baseline solution as well as very important savings in power consumption.

## 2. Progress

We are in the second year of this three-year project. Although some delays have accumulated due to difficulties in recruiting, good progress has been made in both collaborating labs, CERN and PSI.

### Activities (mainly) at PSI

At PSI, the efforts towards demonstrating the advantages of introducing HTS in the FCC-ee tunnel were focused on the following topics

- Identification of requirements
  In collaboration with the group of Tatiana Pieloni (EPFL), CHART project FCC-ee Beam Dynamics Studies and developments.

It became clear that nesting the dipole, sextupole and quadrupole main magnets has significant advantages. The energy savings relative to the normal conducting baseline can be as large as 20-30% of the total FCC-ee energy consumption. There is a need for individual control of the different multipoles, and relative polarities of short straight section (SSS) magnets are not the same in every operating mode. This makes combined function magnets, and therefore also superferric magnets, less attractive than the nested solutions with independent multipoles that we are pursuing at FCCee-HTS4. The HTS4 baseline as it stands does not include nested dipole magnets, which results in only about half the savings possible with a fully nested system. But the advantages are important enough so as to consider this option at a later stage.

- Coil geometry & demonstrator
  We looked at the cosine-theta (CT) geometry to identify how the required field quality can be achieved with the simplest coil layout. The ReBCO conductor, which dislikes hard-way bending, needs to be wound in a stress-free way. For this, a 3D geometry was designed, and a short demonstrator will be built in the second half of 2024, to be tested in PSI's cryogen-free test stand at 40 K. The superconductor for this demonstrator has been procured, and winding trials have started.

- Coating station
  A coating line was developed. It can coat bare (uninsulated) tape with a self-bonding adhesive doped with micron-sized silver powder. In this way we hope to achieve both bonding and a well-defined turn-to-turn resistance between turns. This paves the way towards partially insulated cabling.

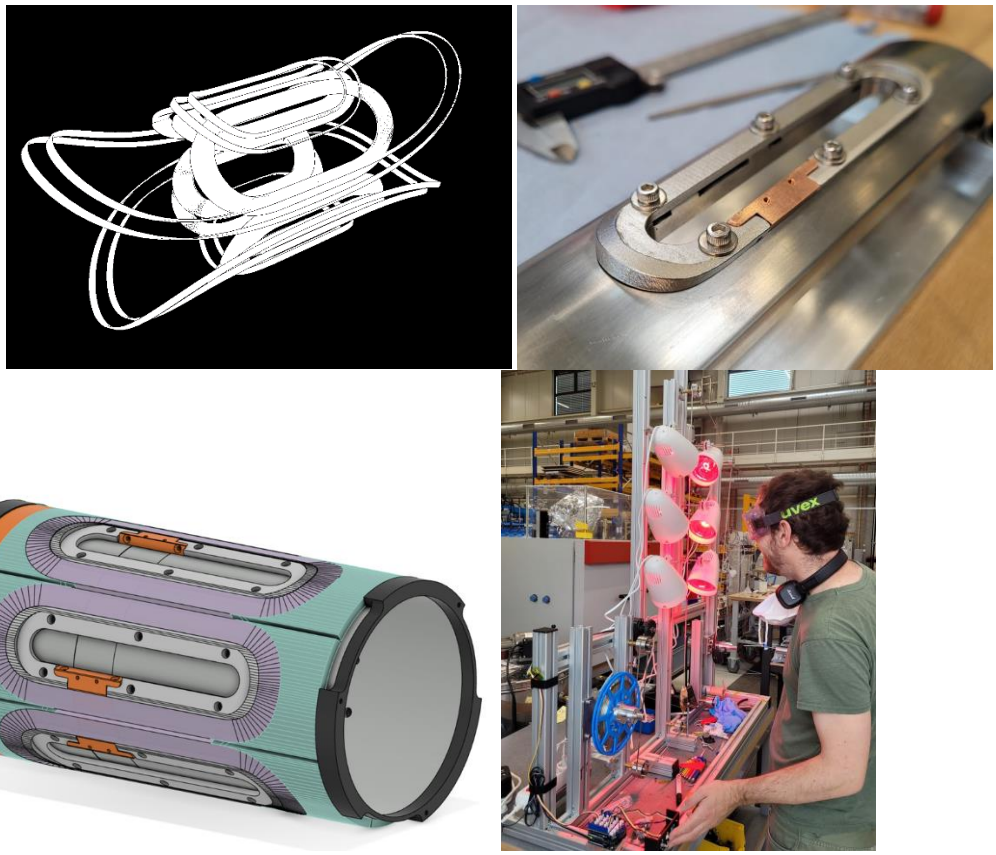


Figure 1. Clockwise from top left: 1) Example of a nested configuration consisting of, from outside-in, a dipole, quadrupole, sextupole. 2) Metal-printed pole piece for winding trials. 3) Reel-to-reel coating line. 4) CAD of sextupole demonstrator.

- Operating temperature
  An algorithm was developed to estimate the ideal operating temperature of the HTS magnets. Here the amount of conductor (which favours lower temperature) is balanced with the cost of cooling (with increases with decreasing temperature).

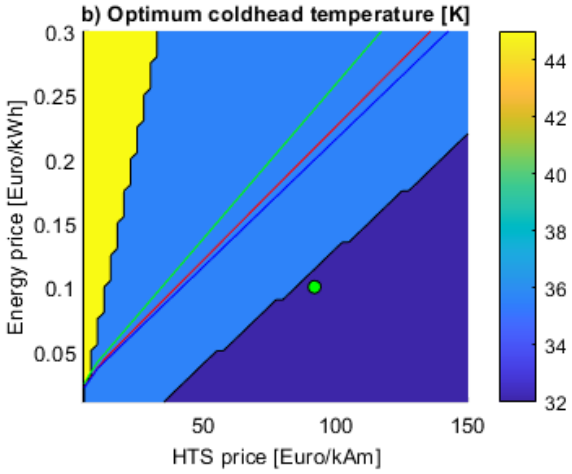


*Figure 2. The optimum operating temperature can be derived based on the operational costs (depending on energy costing) and HTS conductor price.*

- Cooling
  The feasibility of cooling the 2900 magnets required for HTS-based FCC-ee operation by a cryocooler based scheme has been investigated. This cooling strategy will be augmented by centralized cooling options in the future.

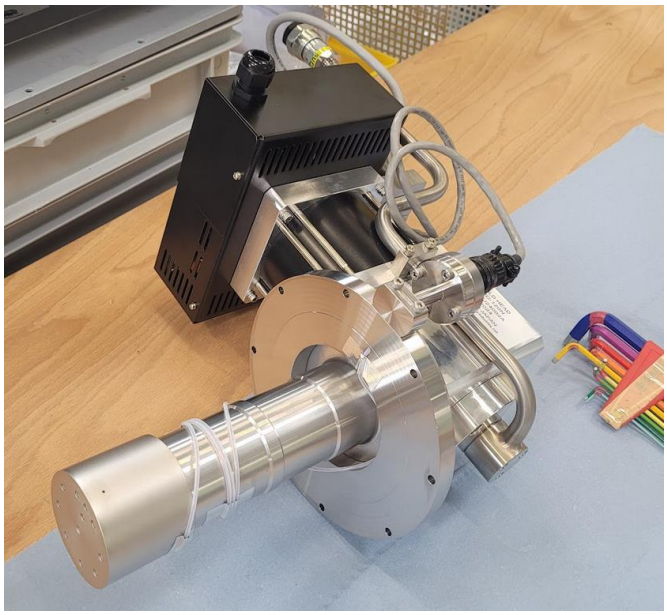

*Figure 3. Photo of high-reliability coldhead. We will be the first to adapt this device for the application of superconducting magnets.*

By basic reliability calculations, it was found that if one is selective in the type of cryocooler and adds some redundancy, it is possible to cool the 2900 SSSs with a high overall reliability. The required yearly preventive maintenance, estimated at 300 FTE-days, is deemed to be

acceptable. The only remaining open point is the possible effect of radiation on the coldheads and/or compressors.

A novel high-reliability compressor/cryocooler combination has been procured from Sumitomo Cryogenics. This combination has arrived at PSI and will serve as the cooling method for the prototype that will be the final hardware deliverable of the project.

| | | Working coolers $i$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Installed coolers $n$ | 1 | 0.0880 | | | | | |
| | 2 | 0.9980 | 0.0077 | | | | |
| | 3 | 1.0000 | 0.9939 | 0.0007 | | | |
| | 4 | 1.0000 | 1.0000 | 0.9879 | 0.0001 | | |
| | 5 | 1.0000 | 1.0000 | 1.0000 | 0.9799 | 0 | |
| | 6 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.9700 | 0 |

*Figure 4. Example of system reliability calculations, towards a credible cooling option for HTS.*

- Superconducting switch for magnet protection

The magnets in this project are expected to operate using a cryogenic dc/dc converter (CHART project FCCee-CPES, ETHZ), to avoid the heat load associated with traditional high-current leads. To be able to protect the coils in case of a quench, and at the same time limit the voltage seen by the converter, we investigated the possibly of a fast HTS-based switch. A demonstrator switch (made by an intern, T. Garg, with testing support from M. Duda) resulted in a 200 ms response time. A design now exists for a 50 ms switch, and the required material has been procured.

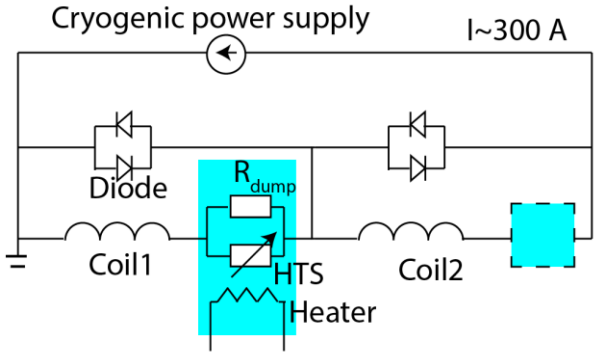


*Figure 5. Simplified schematic of HTS4 circuit including protection.*

**Activities (mainly) at CERN**

During this period at CERN we concentrated with the design and manufacture of a sextupole demonstrator using CCT technology (WP1). CCT magnets are relatively easy to manufacture but the use of HTS tape, as in the case of CT magnets, provides a formidable challenge which can be appreciated by the fact that no CCT magnets have been constructed to date using HTS tape anywhere in the world. We are using a proprietary technology and have managed to design, fabricate and wind such a magnet.

- Sextupole demonstrator

The following steps have been performed:

a) Design completed
b) Manufacturing done at CERN main workshop. Request sent June 2023 hardware received February 2024

c) Quality control done (March to June 2024)
d) Winding rig finished
e) Winding done
f) Impregnation rig built and tested

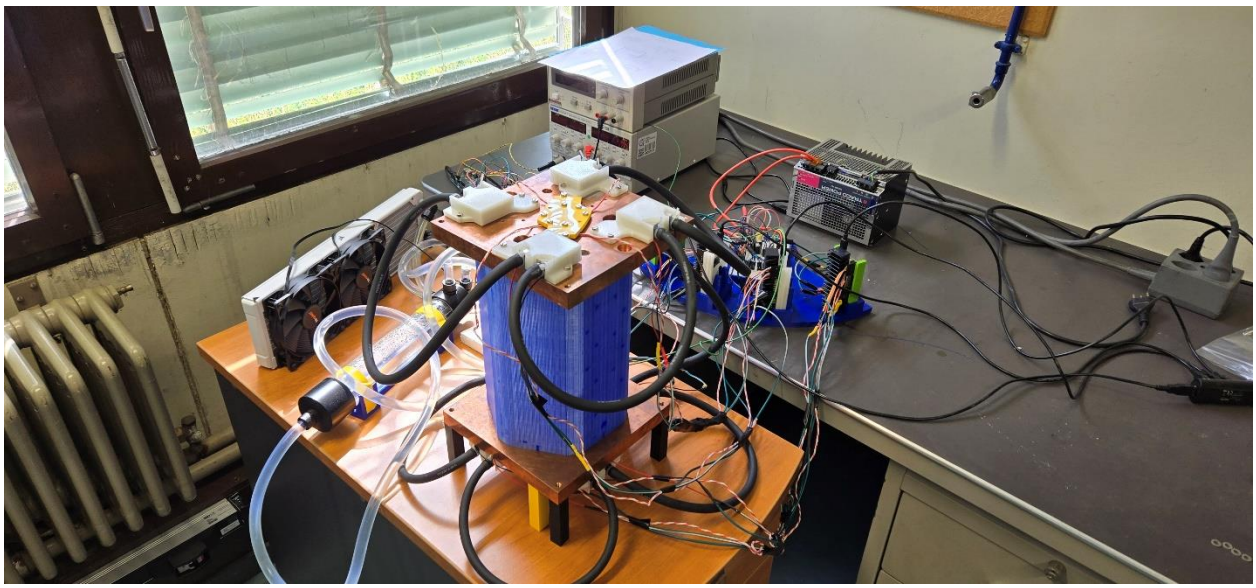

*Figure 6: Impregnation rig with associated electronics and water cooling parts*

g) Winding rig completed
h) Splice tool designed and manufactured

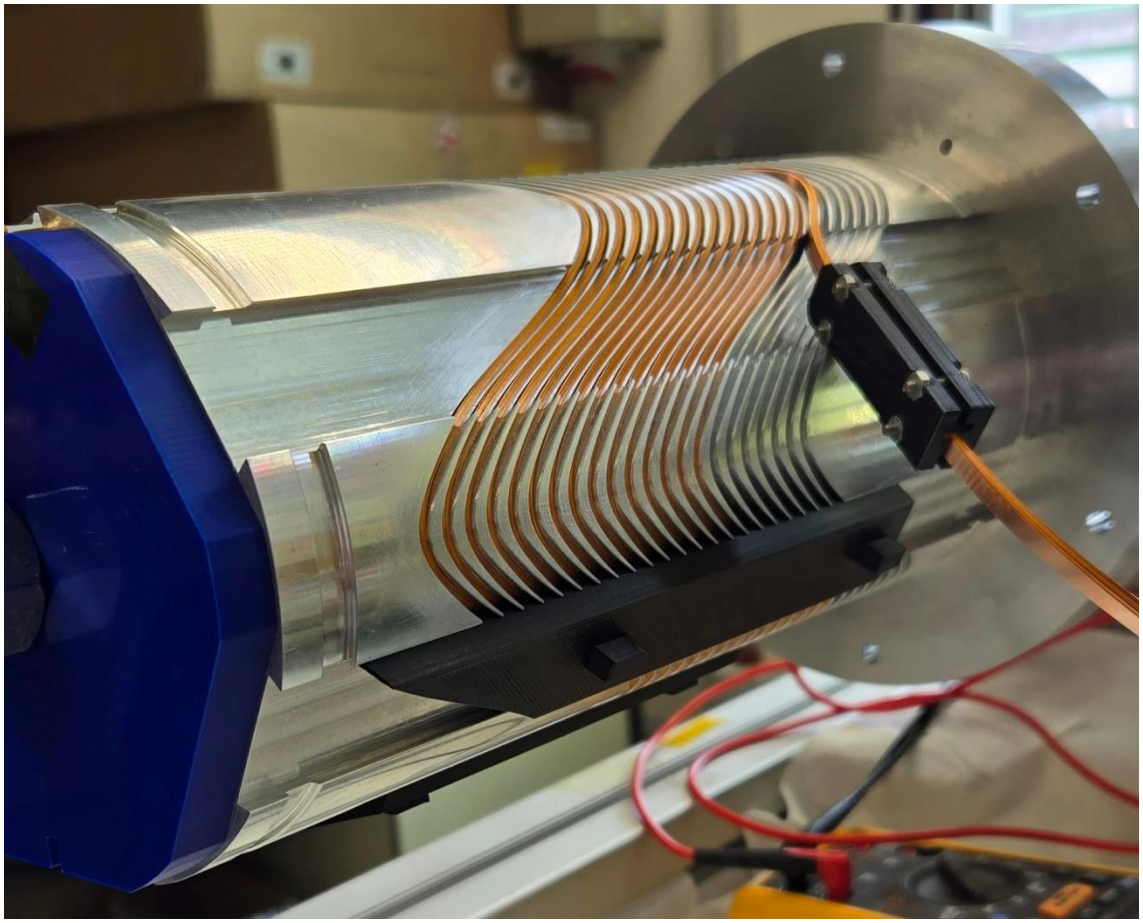

*Figure 7: picture of demonstrator during the winding of the inner layer*

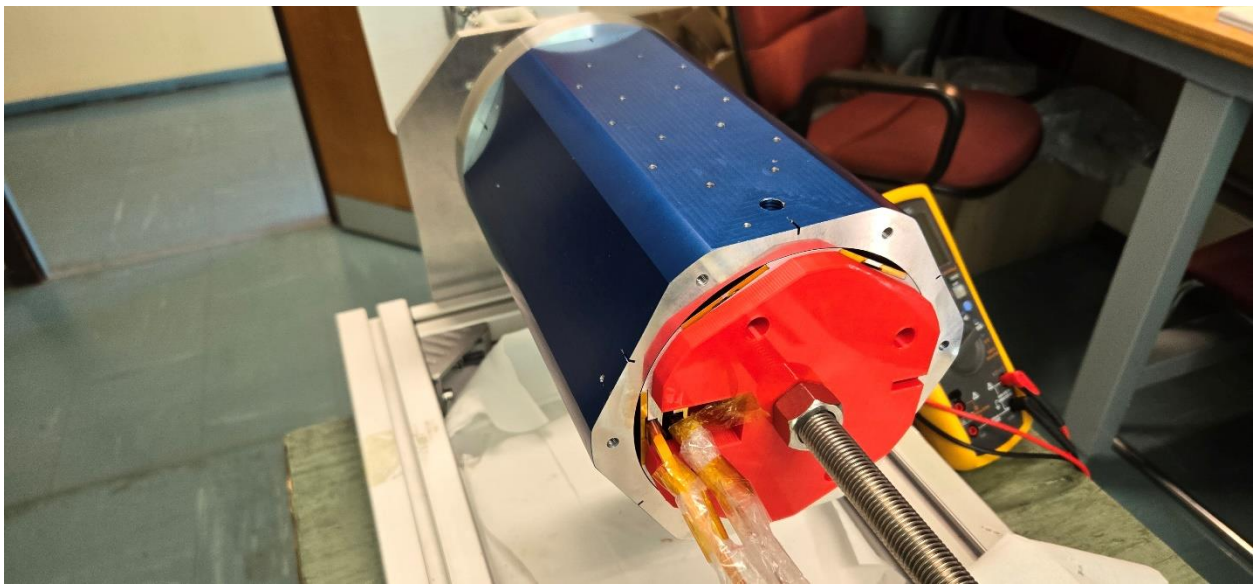

*Figure 8: picture of demonstrator with winding completed*

- Wax impregnation

Wax impregnation (as opposed to epoxy resin impregnation) has the potential of much better performance regarding superconducting magnet training. Since wax impregnation is our method of choice for the HTS4 magnets, we got a unique opportunity to test our ideas by impregnating a (previously non-impregnated) NbTi magnet, the FCCee final focus quadrupole prototype.

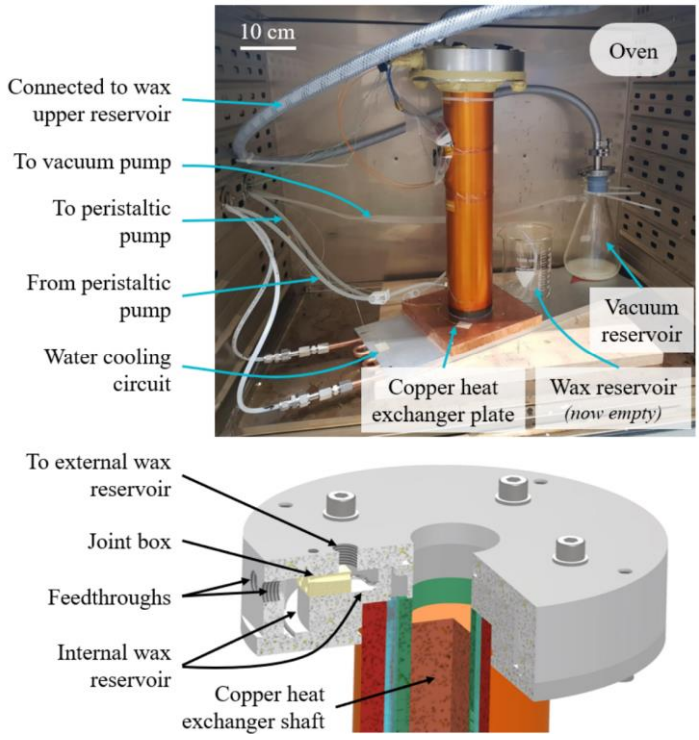


*Figure 9: Wax impregnation station inside an oven (top); Cross-section view of the top part of the magnet mounted within the setup (bottom)*

Impregnation was performed at PSI and the lessons learned will be used for future impregnations of HTS4 magnets. Impregnation was a resounding success as the final focus quadrupole when tested exhibited zero training quenches before reaching short-sample performance.

- Integration

HTS4 represents a large enough deviation from the baseline FCC solutions, that careful integration studies should be performed and are part of the HTS4 project (WP2)

a) Radiation in the tunnel: analysis has been performed for a system that shields radiation in the tunnel much more efficiently than the baseline. We are currently collaborating with the radiation task force of FCC on a common analysis.
b) Impedance calculations: there are subtle differences in the beam pipe of the HTS4 SSSs. We are collaborating with the FCC impedance group to calculate its effects and to compare it with the baseline.

## 3. Results / Conclusions / Deliverables

HTS4 is progressing well, with various specialized hardware being constructed, as well as many in-depth analysis of critical issues. Hardware demonstrators will be ready for testing during the second half od 2024.

## 4. Publications and Outreach

- Presentation at MT28 conference, on reliability (2023)
- Conference paper published in IEEE TAS, on reliability. http://dx.doi.org/10.1109/TASC.2023.3346847 (2023)
- Draft paper prepared for optimum operating temperature (2024)
- FCC week 2024: HTS4 presentation https://indico.cern.ch/event/1298458/contributions/5997286/
- Poster and paper on the impregnation and test results of the final focus FCC quadrupole: https://inspirehep.net/literature/2791808
- HTS4 in the press:
    - HTS4 project explores superconducting options for the FCC-ee https://acceleratingnews.eu/news/issue-44/future-circular-collider-fcc/hts4-project-explores-superconducting-options-fcc-ee
    - Another piece of hardware sees the light of day at FCC: https://acceleratingnews.eu/news/issue-47/future-circular-collider-fcc/another-piece-hardware-sees-light-day-fcc
    - HTS main arc magnets https://cerncourier.com/a/advancing-hardware/
    - FCC-ee designers turn up the heat: https://cerncourier.com/a/fcc-ee-designers-turn-up-the-heat/
    - Best poster award at the FCC week 2023: https://chart.ch/2023/08/14/best-poster-award-at-the-fcc-week-2023/

This final report is only a very brief summary of all activities. More detailed scientific reports are published at https://chart.ch/reports/