CHART Scientific Report

Platform for Superconducting Magnet Design and Optimization. (MagNum2)

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15.03.2026

1. Introduction

Due to the steady increase in compactness and performance, the modeling of accelerator magnets increasingly relies on multi-scale analyses, where detailed models of conductors, cables, or cable stacks provide input for models of entire coils and magnets. At the same time, as the different physical domains (electromagnetic, thermal, and mechanical) become more strongly coupled, modeling and development activities are becoming more interconnected and may involve several teams across different institutes over extended periods (potentially several decades if the accelerator is built and operated). To address the challenge of keeping such developments tightly coupled, consistent, traceable, and repeatable, the MagNum project at ETHZ D-ITET developed a Model-Based Systems Engineering (MBSE) methodology. This approach is now being used in the CHART LTS magnet R&D program for accelerators, as well as in the MagNum2 project with ETHZ D-ITET, which focuses on multi-scale modeling in LTS and HTS magnets.

2. Realisation

To provide a clearer overview of the work carried out during the first two years of the project, we divide it into five categories: Characterization, Modelling, Validation, Platform, and Other Contributions.

Characterization**:** In collaboration with ETH Zurich (D-MATL), mechanical characterization of materials and composites (impregnated Nb_3Sn cable) was carried out at room temperature and at 77 K. This work was made possible through the synergies between the CHART MagComp project (https://chart.ch/chart-projects/), and the MagDev and MagNum initiatives. Cable-stack assemblies, representing the stress-managed magnet structure, were prepared at PSI. The preparation included tooling design and manufacturing, sample assembly, reaction, impregnation, post-cutting, and final sample preparation. Once these activities were completed, the samples were sent to ETH Zurich (D-MATL) for characterization. Additional samples, for example those consisting only of the impregnation system, were also prepared at PSI and measured at ETH Zurich (D-MATL).

Recently, the following paper was published with co-authors from both teams:

X. Kong, J. L. Van den Eijnden, A. Brem, D. Araujo, B. Auchmann, and T. A. Tervoort, “Light a candle for impregnation of superconducting magnets with wax: Thermo-mechanical behavior of an alumina-filled paraffin wax from ambient to cryogenic temperatures,” *Cryogenics*, vol. 157, p. 104326, May 2026, doi: 10.1016/j.cryogenics.2026.104326.

More broadly, comparisons of the characterization of epoxy-based 10-stack samples are being carried out by CEA, CERN, ETH Zurich, and PSI as part of the High-Field Programme hosted at CERN.

On the modelling front, we developed a predictive, experimentally validated multiscale modelling framework that combines mechanical and electromagnetic simulations for Nb_3Sn Rutherford cables. The workflow integrates Rutherford cabling simulations that capture strand deformation, automated FEM mesh generation, strand homogenization, and contact modelling, enabling accurate evaluation of stress and strain distributions in compacted Rutherford cable geometries.

Validation against cable stack measurements and the Compression BOX* experiment demonstrated that the model accurately reproduces both the mechanical stress–strain response of cable stacks and the measured reduction in I_c of Rutherford cables under and after transverse loading.

* A. Brem *et al.*, “From Hot to Cold: Advanced Materials and Processes for Nb3Sn Based Magnets,” *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY*, vol. 34, no. 5, 2024.

The tool, which will be made available in the form of a platform, supports the systematic evaluation of cable architecture, compaction, and material selection, enabling predictive design and optimization of Nb_3Sn cables and accelerator magnets. Its integration into a Model-Based Systems Engineering framework*, currently maintained by CERN and partly developed within the CHART MagNum1 project, will facilitate its application in magnet design across the high-field magnet community. As part of the simulations are carried out using the Ansys software LS-DYNA, the integration of this software into the platform is being developed in collaboration with CADFEM.

*M. Maciejewski, B. Auchmann, D. M. Araujo, G. Vallone, J. Leuthold, and J. Smajic, “Model-Based System Engineering Framework for Superconducting Accelerator Magnet Design,” *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1–5, Aug. 2023, doi: 10.1109/TASC.2023.3249647.

Other relevant contributions were made with respect to the Compression BOX experiment. As part of the modelling validation, the PhD candidate is using the existing models for this experiment. Based on his latest findings, we are planning to modify the experiment by adding additional mechanical instrumentation. Furthermore, the BigBOX experiment* will also be used as part of the validation of the modelling. In this context, the PhD candidate is using the existing models within the workflow to predict the coil performance.

*D. M. Araujo *et al.*, “Assessment of Training Performance, Degradation and Robustness of Paraffin-Wax Impregnated Nb3Sn Demonstrator Under High Magnetic Field,” *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–8, Aug. 2024, doi: 10.1109/TASC.2024.3368995.

3. Results

Thanks to the developments described in the previous section, the main result obtained is a predictive multiscale modelling framework, together with numerical tools supporting such a workflow, for Nb_3Sn Rutherford cables at the strand and cable scales, aimed at supporting the design of high-field magnets. This framework was experimentally validated and enables the simulation of stress and strain distributions, as well as the prediction of critical current reduction in such cables.

The parametric workflow used, and its integration into the pyMBSE platform currently under development, includes a cabling model that captures strand transposition and compaction-induced deformation during the cabling process. The workflow was validated against 10-stack Rutherford cable measurements at 77 K, showing accurate stress–strain response. The predicted critical current reduction under transverse stress was also validated against the Compression BOX experiment, which revealed that strands located at the cable edges dominate the reduction of critical current in these experiments.

The next expected results include the completion of the workflow integration into the pyMBSE platform, as well as the use of the full workflow to predict the $I_c$reduction of ongoing magnets and experiments in which PSI is involved, such as the BigBOX and SMACC1 magnets.

4. Publications and Outreach

In 2026, a paper was submitted to the journal *Superconductor Science and Technology*.

"A Multiscale Modeling Framework for Accelerator Magnets Accounting for Fabrication-Induced Deformation and Operational Strain in Nb3Sn Rutherford Cables", Joep L. Van den Eijnden et al., submitted to SUST in 2026.

This paper discloses the full cycle of tools and characterization, from the mechanical properties of impregnated Nb_3Sn Rutherford cables, measured under cryogenic conditions (77 K) and their modelling, to the experimental validation using the BOX experiment in collaboration with the University of Twente.

A second paper will be submitted to the journal *IEEE Transactions on Applied Superconductivity*, presenting the results from the Compression BOX experiment and providing the community with measurements of $I_c$reduction for different cable architectures tested under high-field magnet conditions (4.5 K and background magnetic field).

Preliminary title: "Compression BOX: Transverse Stress Sensitivity of Epoxy, Wax, and Filled Wax-Impregnated Nb3Sn Rutherford Cables"

The PhD candidate is also contributing to the simulations of a third experiment, BigBOX, carried out in collaboration with Brookhaven National Laboratory (USA). The second version of the experiment is planned to be tested in summer 2026. An abstract has been submitted to the ASC 2026 Conference.

The integration of the commercial software Ansys LS-DYNA into the platform currently under development, which is being co-developed with CADFEM, will be presented at the CADFEM World Conference in Darmstadt (DE) in October 2026.

MagNum2 Gannt Chart

Task	Q2 26	Q3 26	Q4 26	Q1 27	Q2 27	Q3 27	Q4 27	Q1 28
LTS[1] Platform Integration								
LTS PSI Cases								
HTS[2] Modelling								
HTS Platform Integration								
HTS PSI Cases								
Manuscript								

[1] Low-temperature superconductors

[2] High-temperature superconductors

Overview Time Schedule

CHART Project	Q2 Q3 24	25	26	27	Q1 28
MagNum2[3]					

[3] The project effectively started in Q3 2024.