Romanian participation at EUROfusion WPMAG, WPENS and complementary research / WPMAG-ENS-RO

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The report is divided in four specific contributions:

I. Optimization of CT Scanning for Oversized Samples.

Here, the main objective of the 2025 phase was the development and validation of an experimental setup, which included the acquisition of a custom support frame for high-precision translation and rotation axes, the experimental validation using reference specimens, the complete alignment of the setup and metrological calibration of system distances and geometry, as well as the optimization of the experimental configuration for testing CICC samples intended for the SULTAN facility—a line of work initiated in 2024.

The tomography frame was designed and developed in order to accommodate for oversized samples of up to 3 m long. The sample can be rotated 360 degrees in order to perform X-ray tomography on any area of the sample. The sample is mounted on a powerful rotation stage at one end and on a sample holder with bearings on the other end. It can be moved and aligned to the view area of the detector. The X-ray tube is mounted in front of the X-ray detector and this whole assembly can travel along the length of the sample to investigate various regions of interest.

The original project was improved and optimized and a new frame for the tomography system was envisioned having the following requirements:

- Length: 2150 mm, width: 1000 mm, in order to fit inside the X ray shielded cabinet
- Two possible horizontal tomography setups:

1) The classic setup (Figure 1 a) where the X ray tube and flat panel detector are placed along the length of the frame. They maintain a fixed position; the sample is placed in the vertical plane; it can be moved and rotated.

2) The setup for oversized samples (Figure 1 b) where the X ray tube and flat panel detector are placed along the width of the frame. The sample is placed in the horizontal plane; it maintains a fixed position and can be rotated. The X ray tube and detector assembly can travel along the length of the sample.

In both scenarios the samples need to be moved up / down and in the tube-detector direction, in order for the region of interest of the sample to be properly viewed on the detector. In the first setup the X ray tube and detector have three degrees of freedom (X / Y / Z) and the distance between the tube and detector can be modified. In the second setup they have only one degree of freedom (along the sample length), the distance between the tube and detector is fixed.

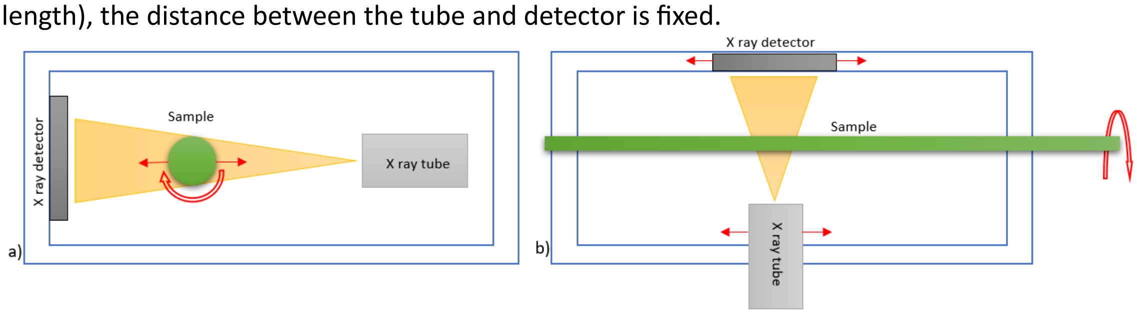


Figure 1. X ray tomography setup sketch: a) classic – “setup 1”; b) for oversized samples – “setup 2”.

The above requirements were taken into account and a frame was developed using a CAD (computer aided design) software (Figure 2). Multiple iterations were needed together with the manufacturing company in order to account for raw materials suitable for the frame and different parts, manufacturing limitations, correct and precise dimensioning of all components that need to fit together, ways of implementing various features and details.

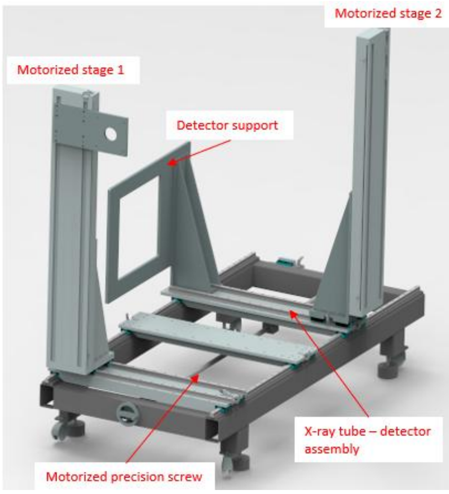


Figure 2. The CAD design of the frame – depicts the setup for oversized samples.

The final setup weas used in tomography measurements of 2.77 m long samples and 50 Kg weight (Figure 3).

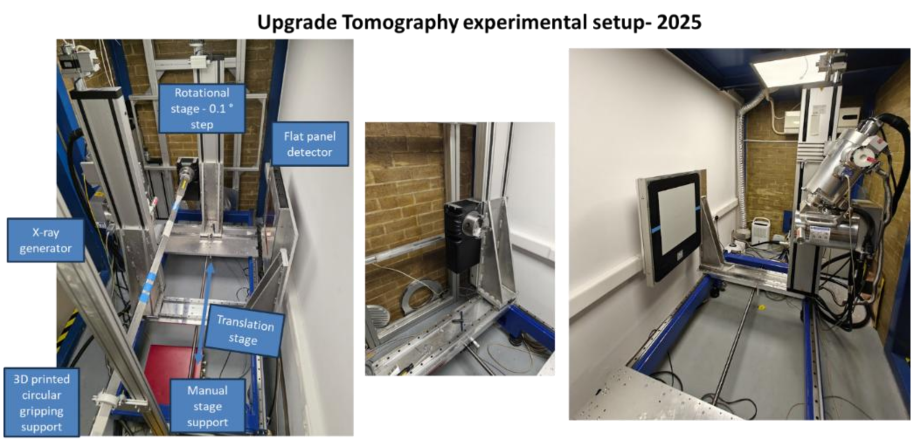


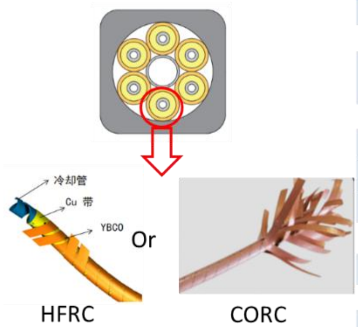
Figure 3. Different photographs with the 2025 upgrade 320 keV Tomography setup with linear motorized stage for automated scanning across the sample. The HTS CICC samples were fixed using custom 3D printed circular gripping support.

In this phase, the experimental configuration was successfully established and validated, demonstrating geometric stability, repeatability, and full compatibility with the requirements for testing CICC samples and reference standards. Customized alignment and calibration methods were developed and implemented, specifically tailored to the geometry of this setup, including dedicated metrological procedures for accurately determining system distances and correcting potential misalignments within the source–detector–specimen arrangement.

II. X-ray microtomography analysis of full-length HTS conductor prototype and electrical termination samples developed under the EU-China collaboration

Due to the large size of the samples (Figure 4), we need to raise the voltage of the X-ray generator to 300-310 kV to achieve sharper projections with high Signal to noise ratio (S/N). All CT acquisitions were conducted at a nominal voxel size of approximately 40 µm.

◆ **Conductor specimen configuration and specimens**

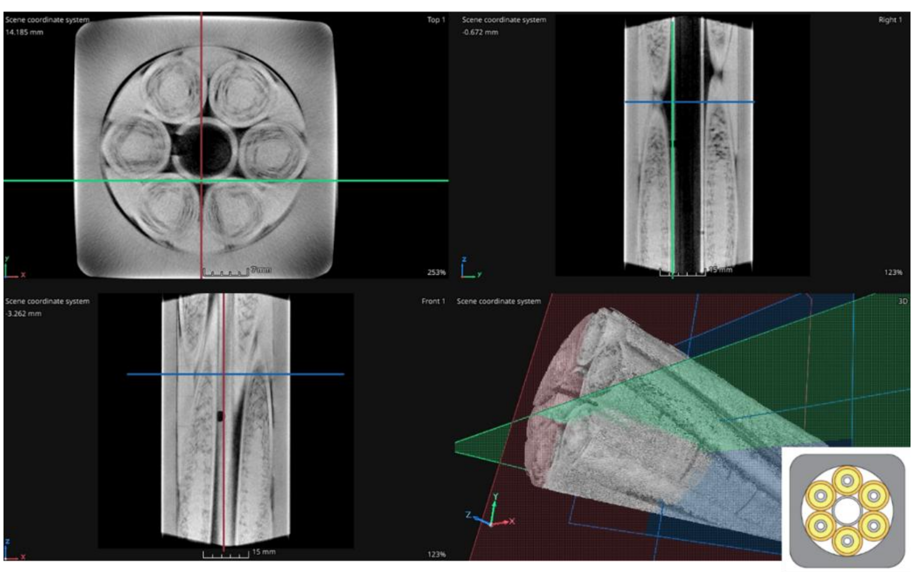


Item	Parameter
No. of sub-cable	6
Tape dimension	4 x 0.1 mm
Sub-cable configuration	SS –I: CORC SS-III: HFRC
Number of SC layer /sub-cable	40
Sub-cable OD without/with Cu tube	8.9 mm/10.9 mm
OD of CICC cable	~ 32.8 mm
OD of Jacket	~ 42.6 mm
Maximum dimension of Termination	64 mm x41 mm
Length of termination	330 mm
Length	~2.77m
Weight	~ 50 kg

Figure 4. The HTS-CICC samples received for CT investigations

XCT of HTS-CICC I – CORC sub-cable presented in Figure 5 showed no deformation or defects.

XCT HTS-CICC I – CORC sub-cable



Conductor section

Figure 5. XCT of HTS-CICC I – CORC sub-cable

Figure 6 presents the comparison between the 225 and 320 kV X-ray generator for HTS-CICC I – CORC sub-cable in the Conductor to Bottom Termination Section showing the increased quality of the CT data with the 320 kV X-ray generator.

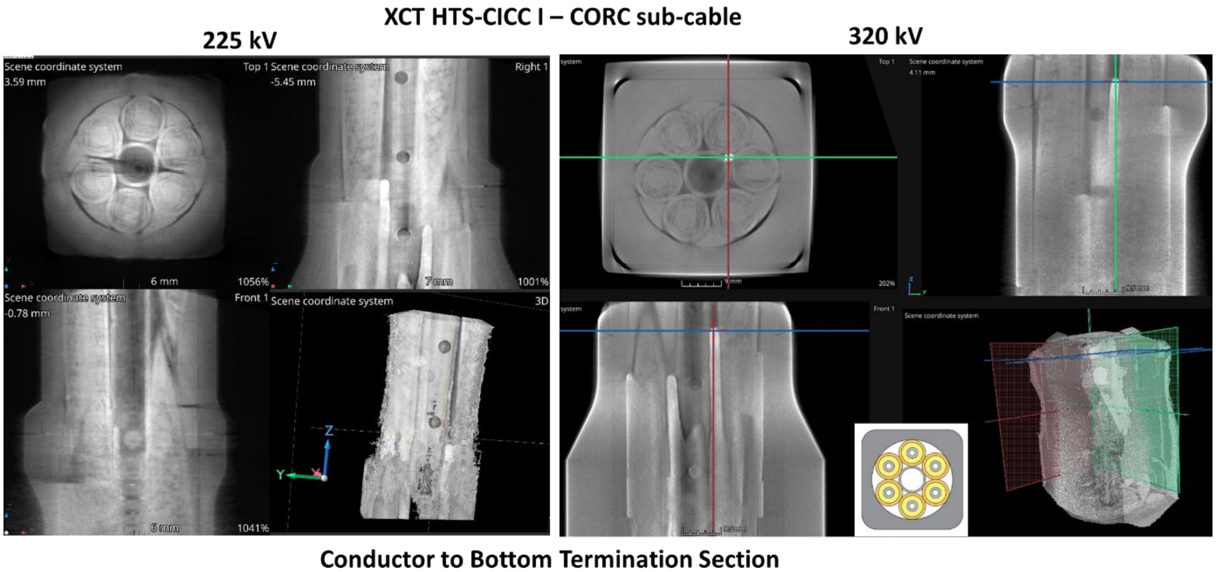


Figure 6. Comparison of XCT measures with 225 and 320 kV X-ray generator for HTS-CICC I – CORC sub-cable in the Conductor to Bottom Termination Section.

To address the limitations encountered in 2024 and improve the CT system performance, we employed a 320 kV X-ray generator within an upgraded experimental setup, allowing for greater sample penetration and enabling automated scans of larger specimens.

All conductor sections present the structure of the six component HFRC or CORC sub-cables with an empty tube for He cooling that has holes for homogenous He distribution across the superconductor. All sizes are confirmed in the CT reconstructions in accord with the design presented.

Bottom terminations present the inhomogeneous soldering filling and formed voids between the end of the superconductors and soldering filling. For even more in volume detection in the termination, the samples need to be mechanically adjusted.

III. Identification of non-destructive testing needs by X-ray imaging to evaluate the manufacturing technology of the High Flux Test Module (HFTM) irradiation capsule and components.

The foremost objective of the ENS work package 2021-27 is to complete the engineering design of a Demo Oriented NEutron Source (DONES) for irradiation testing of fusion material candidates for the construction of future nuclear fusion power plants. Several Test Modules, which are the devices where the samples to be irradiated are installed. The Test Modules supply all means (heating, cooling, etc) required for the irradiation conditions. In DONES, the irradiation of structural materials in the High Flux Test Module (HFTM). The material specimen stacks will be hermetically enclosed in Irradiation Capsule Assemblies. To achieve the temperature control of the specimen stacks, each capsule will be equipped with heaters and monitored by multi-scale resolution X-ray microtomography is considered a suitable technique for the

Quality Assurance (QA) of the Irradiation Capsule Assemblies. Based on our previous experience in the assessment of the structural integrity of a prototypical instrumented International Fusion Materials Irradiation Facility (IFMIF) high flux test module rig by fully 3D X-ray microtomography, we propose to establish a QA routine for the irradiation capsules that will be delivered to DONES for irradiation.

Based on the positive results of previous work, in 2021-2024, it is proposed to extend this kind of analysis to (Figure 7):
Object #1: A mockup of an IFMIF/EVEDA capsule made of solid steel (low alloy) with the characteristic knop pattern on its surfaces to define the stagnant gas gap width.
Object #2: A prototype of an IFMIF/EVEDA rig hull made of 1.4571 stainless steel, hollow rectangular profile with sheet with ribs on its surface to define the flowing helium gap width.
Object #3: A rig hull prototype already welded to its bottom reflector, which is an additional mass.
The capsule mockup (#1) shall be inserted into the rig hull prototype (#2).
These representative components were prepared by Karlsruhe Institute of Technology (KIT).

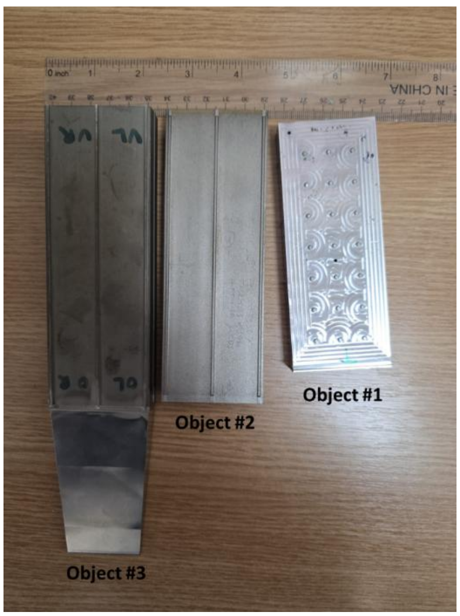


Figure 7. Photograph of the received samples: A mock-up of IFMIF/EVEDA capsule made of solid steel (low alloy) - **Object #1**; A prototype of an IFMIF/EVEDA rig hull - **Object #2**; and A rig hull prototype already welded to its bottom reflector - **Object #3.**
Figure 8 presents representative tomography cross sections for all investigated objects, the CT inspection produced good-quality images that will be taken as input for the metrology analysis.

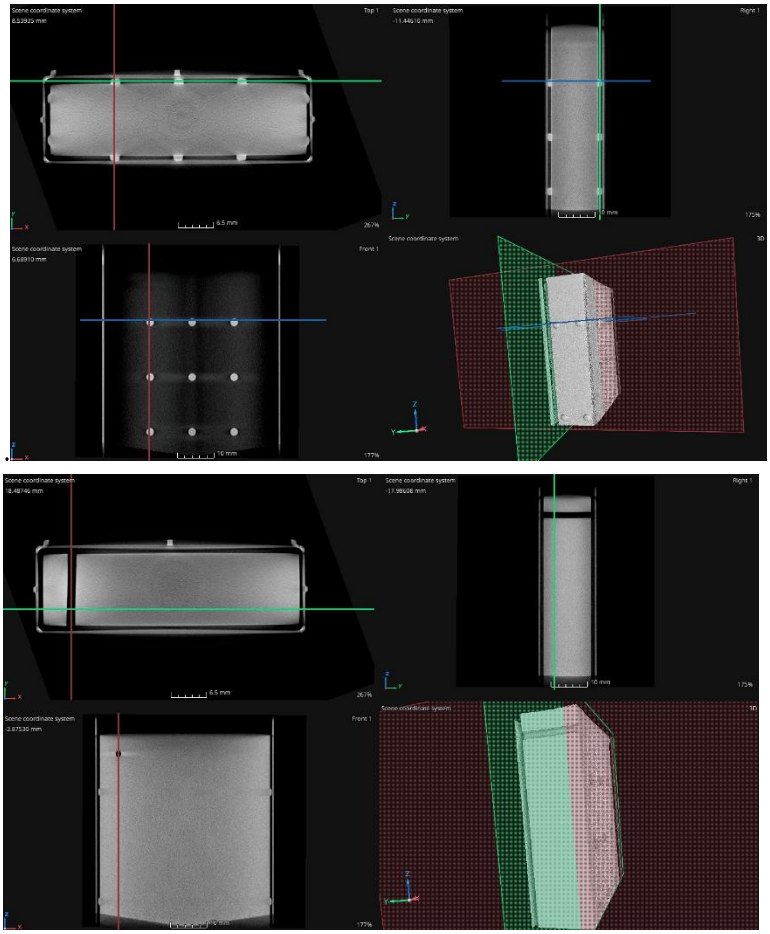


Figure 8. XCT of bottom part of Object #1 and #3 to assess the stagnant gas gap formed between the two objects.

IV. ENEA High-temperature superconducting (HTS) conductors XCT analysis

High-temperature superconducting (HTS) conductors play a crucial role in advancing magnet technology, particularly for fusion energy applications and high-field magnet designs. The ENEA HTS conductor tested at the SULTAN Facility features a well-defined tape arrangement within a structured aluminum-stainless steel double jacket, ensuring mechanical stability and optimal thermal management. In parallel, CEA-HTS conductors employ a different structural concept based on CORC-type sub-elements, requiring precise characterization methods to evaluate mechanical and electrical interfaces. Given the complexity of these conductors, advanced imaging techniques such as micro-CT are essential for assessing interface quality, contact areas, and soldering efficacy, ultimately contributing to the optimization of conductor performance and manufacturing processes.

X-ray microtomography analysis of short-length of HTS cables, conductors, and joints (IAP)

Objectives:

Obtaining high-quality CT images for HTS CICC and electrical terminations

Evaluation of soldering quality by CT analysis

Analysis of the soldering material distribution between tapes

Metrological measurements of the defects (approximation of the gaps between tapes represented by the missing soldering material)

The ENEA HTS conductor tested at the SULTAN Facility features a tape arrangement of 6 stacks × 13 HTS tapes, a total of 78 tapes. It has a 6-slot aluminum core with straight slots and straight stacks. The conductor follows a double jacket concept, consisting of an inner aluminum layer and an outer stainless steel (SS) layer, ensuring structural integrity and thermal stability (Figure 9).

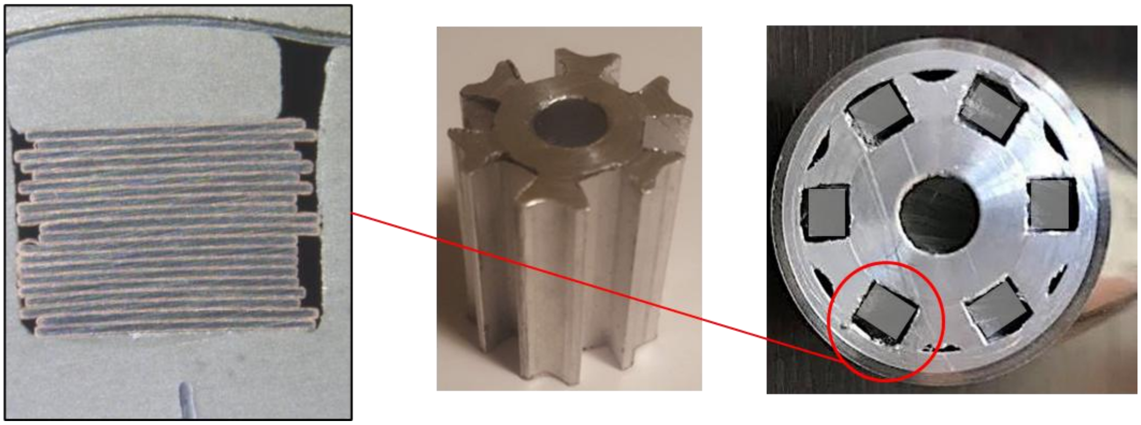


Figure 9. ENEA - HTS Conductors tested at the SULTAN Facility

The structural design of CEA-HTS conductors, based on short samples of CORC-type sub-elements. Given the complexity of these conductors, it is essential to develop a non-invasive evaluation method using micro-CT to accurately determine the contact areas between ReBCO and Cu, as well as between the HTS tapes and their supporting structures. Such an approach would provide valuable information regarding the quality of mechanical and electrical interfaces, helping to optimize fabrication processes and improve overall conductor performance.

Figure 10 presents a representative CT image highlighting key manufacturing features of the sample, specifically illustrating the transition zone between the soldering material and the copper element.

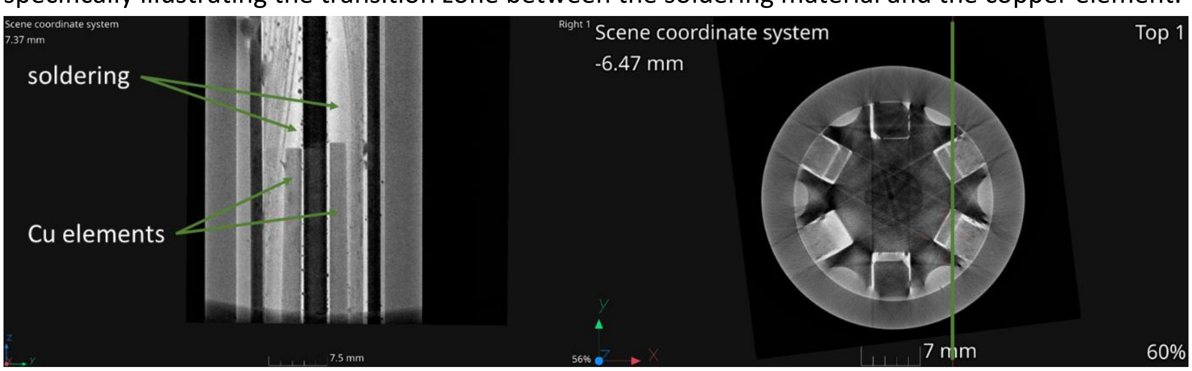


Figure 10. Computed tomography (CT) cross-sectional representation of the HTS sample, featuring a longitudinal view (left) and a corresponding axial top-down projection (right). The green line in the top view indicates the location of the cross-sectional slice depicted in the right-side view.

This study highlights the effectiveness of micro-CT imaging in assessing the structural integrity and interfacial properties of HTS conductors.

The micro-CT investigation successfully identified microstructural features relevant to the mechanical and electrical integrity of HTS conductors, including voids, soldering inconsistencies, and interfacial contact quality. The ability to resolve features down to ~20 µm/voxel provided critical insight into bonding deficiencies that are otherwise undetectable using conventional methods.

The analysis provides crucial insights into solder distribution uniformity, void formation, and mechanical interface quality. The results indicate that regions with incomplete or insufficient solder coverage led to increased electrical resistance and potential mechanical instabilities.

Future investigations should prioritize the optimization of the soldering process for CORC-like sub-elements, focusing on joint adhesion strength, defect characterization, and electrical performance.

Papers

Gorit, Q., Babouche, R., Dumitru, D., Lacroix, B., Louzguiti, A., Lungu, M., Nicollet, S., Tiseanu, I., Torre, A., Topin, F. and Zani, L., 2025. Effective thermal conductivity numerical estimations of CICC porous media using X-ray tomography images. Thermal Science and Engineering Progress, p.103789.

Conferences

Giuseppe Celentano, Gabriele Colombo, Valentina Corato, Gianluca De Marzi, Andrea Formichetti, Ferruccio Maierna, Marcello Marchetti, Andrea Masi, Lucio Merli, Luigi Muzzi, Alessandro Rufoloni, Angelo Vannozzi, Marco Breschi, Ion Tiseanu Analysis of the Quench Experiment on the Aluminum slotted-core HTS conductors 17th European Conference on Applied Superconductivity, 21-25 September 2025, Porto

Meetings

1. WPMAG Final Meeting, February 4-6, 2025, ENEA, Frascati
2. Virtual Technical Meeting 01 of 2025 of WPENS. Test Systems-OIM session, 10th of July 2025
3. Seminar on High-Temperature Superconducting Magnets within EU-CN Cooperation, Shanghai, China 06th- 07th NOV, 2025