# IFAST

Innovation Fostering in Accelerator Science and Technology

Horizon 2020 Research Infrastructures GA n° 101004730

# MILESTONE REPORT

# Test of mock-up coil with dummy cable (HTS CCT prototype)

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## ABSTRACT

In order to verify the developed technologies, tools and techniques for the manufacturing of the high-temperature superconductor canted cosine theta magnet prototype, a mock-up coil with only 6 turns was wound. This document presents the developed infrastructure and techniques, and the manufacturing/winding of the mock-up coil. The document also gives a brief overview of the tests which have led to the presented solution.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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## Delivery Slip

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| **Authored by** | D. Barna, P. Sári, E. De Matteis | Wigner RCP<br>LASA/INFN | 09/07/24 |
| **Edited by** | D. Barna, P. Sári, E. De Matteis | Wigner RCP<br>LASA/INFN | 09/07/24 |
| **Reviewed by** | A. Echeandia, J. Lucas | ELYTT | 03/09/24 |
| **Approved by** | M. Vretenar [on behalf of the Steering Committee] | | 03/09/24 |

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## *Executive summary*

*All techniques, tools, and the entire manufacturing process to construct the HTS canted cosine theta magnet prototype were developed and tested, and the necessary infrastructure was constructed. As a demonstration of the methods, a short mock-up coil with 6 turns was wound. These efforts are summarized in this document. The major steps of this process are as follows.*

*A short test former with realistic dimensions, and a rib thickness varying between 0.5 and 0.9 mm was designed to evaluate manufacturability. A partner company (hsm.as) was identified capable of manufacturing the formers of the final prototype. The short test former was manufactured, and no problems were identified with the design and parameters.*

*The components of the composite conductor (2 Cu tapes + 2 HTS tapes insulated by kapton) need to be soldered to provide good electrical and thermal contact, for an efficient stabilization.* $In_{52}Sn_{48}$ *solder was chosen as this has a low enough melting point of 118 °C to avoid* $I_c$ *degradation. Individual tapes will be solder-coated by a machine developed and built for this purpose and heat-treated after winding.*

*A custom winding machine was designed, constructed, and tested which creates the composite, insulated cable on-the-fly and rotates the former in the plane of the winding turns to avoid the difficult handling of the tape conductors.*

*The mock-up coil was wound with dummy copper tapes replacing the HTS tapes. No showstopper was observed during this process.*

*A simple wax impregnation test demonstrated that wax can penetrate in between and into the cables at their ends and penetrate along their length, properly filling even the capillary volumes.*

*The results of cabling and splicing tests on the performance of 4 mm HTS REBCO tape under various conditions highlighted no degradation during the cabling procedure, while also emphasizing the need for further studies on splice procedure reproducibility and the impact of self-field effects on tape performance.*

# 1. Introduction

One of the two deliverables of Work Package 8 (Innovative Superconducting Magnets) of the I.FAST project is a canted cosine theta (CCT) magnet prototype using high-temperature superconductor (HTS) cables. HTS conductors are available in the form of tape, that can only be bent in the direction of its normal vector ("easy way bend"). This makes both the coil design and the winding process rather difficult. While NbTi-based CCT magnets are routinely made by several institutes today, the number of CCT magnets using HTS conductors is quite limited. In fact, to our knowledge, HTS CCT magnet prototypes have only been made so far with CORC cables[1,2], which restores the isotropy of the conductor to overcome the difficulties associated with the tape geometry.

An earlier work [3] laid down the basic concepts and parameters of the prototype magnet. This document is a milestone report to the funding agency and presents the development of the manufacturing methods and techniques, demonstrating the achieved status: the construction of the composite conductor, the soldering and winding process, and impregnation. The milestone associated with this document is the construction of a mock-up coil which demonstrates the efficiency of the developed methods. The associated design, simulation and optimization work will be described separately in a scientific paper.

# 2. Manufacturing technologies and tools

## 2.1 SOLDER COATING

### CHOICE OF THE SOLDERING PROCESS AND THE SOLDER MATERIAL

The composite cable consists of two HTS tapes sandwiched between two high-RRR copper tapes of thickness 0.2 mm, for stabilization purposes. A good electrical and thermal contact between the tapes is necessary to efficiently share the current and take away heat in case of a quench, which can be realized by soldering. Soldering can be done in three different ways: (i) soldering the 4 tapes together before winding, (ii) soldering the 4 tapes on-the-fly during winding, and (iii) soldering in-situ. In the case of option (i) the soldered cable needs to be first spooled, and then unspooled and wound onto the former. While early tests indicated that bending a soldered stack of tapes is possible without problems, straightening (during unspooling) of a bent, soldered stack causes detachment between the tapes (or eventually delamination of the HTS tapes layers). Option (ii) is excluded because on-the-fly soldering would require steady processing conditions, which can not be guaranteed during the winding of an entire cable. Option (iii) would be realized by first coating the individual tapes with an appropriate solder material, then assembling the tapes into an insulated, stacked cable, winding this cable onto the former, and then heating the winding to a proper temperature. Since the winding represents a huge thermal inertia (the mass is about 250 kg), a fast thermal cycle is excluded, the winding will spend a long time (of the order of hours) at the treatment temperature.

Exposure to elevated temperatures can cause significant degradation of the critical current of HTS tapes, see [4,5,6] and references therein. Exposure above a threshold as low as 150 $^{o}$C can already have an effect. Above 200 $^{o}$C, already few-minute-long exposures can cause $I_c$ degradation. Standard Sn-Pb based solders have melting points above 180 $^{o}$C, which - taking into account a temperature margin - are too high for hours-long exposures. The presence of bismuth decreases the melting temperature significantly but causes cracks during cool-down. $In_{52}Sn_{48}$ was finally chosen, based on its favorable properties:

Properties of $In_{52}Sn_{48}$

| | |
|---|---|
| Melting point | 118 $^{o}$C |
| Eutectic | yes |
| Toxic | no |
| Mech. properties @ cold | good malleability, compensation of different thermal expansion of joined pieces |

## Coating

Tests performed with $In_{52}Sn_{48}$ indicated that proper bonding requires no exposure to oxygen while the solder material is hot/molten, and flux is necessary to treat the tape before coating it with solder. A coating machine was constructed (Figure 1) which pulls the tape first through a liquid flux pot (water solution of zinc-chloride and ammonium-chloride, or L-glutamic acid hydrochloride), and a hot solder pot. The big white arrows indicate the two moving parts that can be pushed downwards into the corresponding pots after lacing the tape into the machine. The pusher of the liquid flux pot includes two sets of silicone wiper blades that remove the liquid from the tape. The entire setup is mounted in a kapton/policarbonate box which can be filled with nitrogen or argon gas, to avoid the formation of an oxide layer on the surface of the hot solder bath, or on the coating.

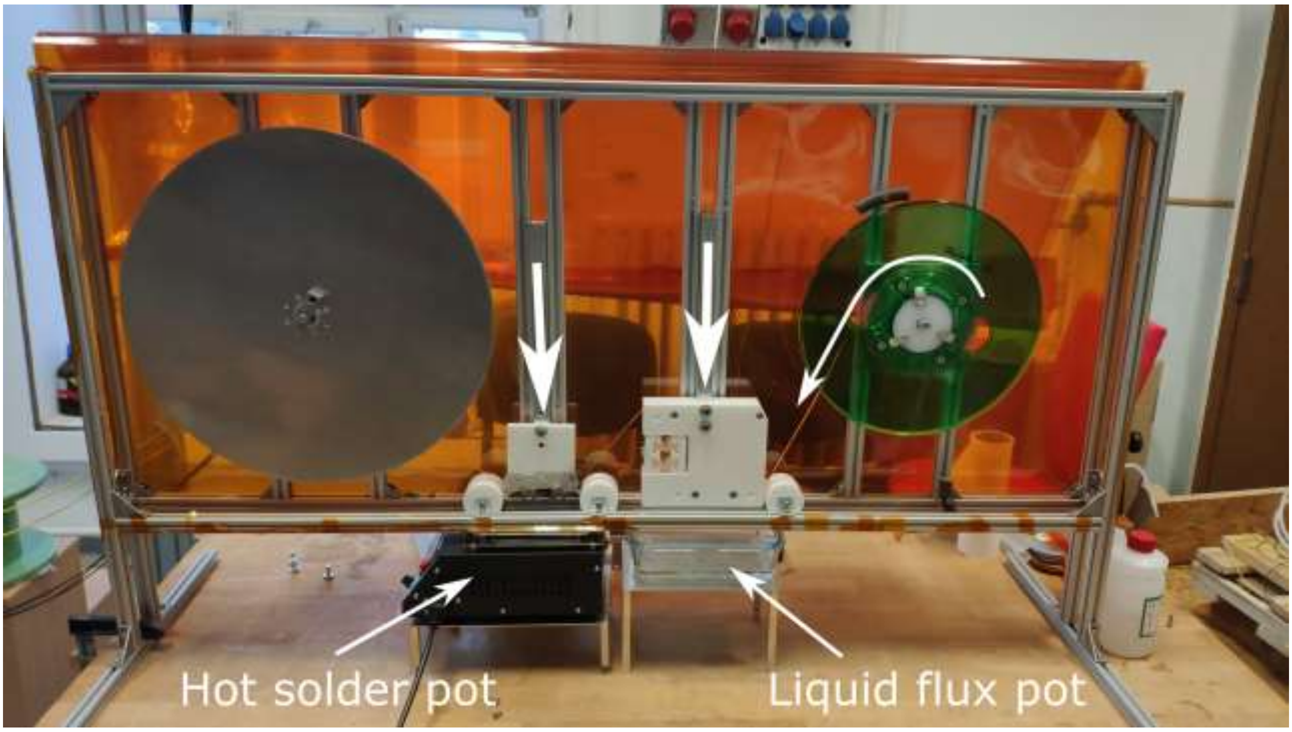


*Figure 1: Solder-coating machine*

The target spool is driven with a stepper motor controlled by a Raspberry PI computer. The control software takes into account the accumulated tapes on the spool to keep a constant speed of the tape.

Soldering tests indicated that for proper bonding a coating thickness of at least 40 microns is needed on both sides of the tapes. As a general trend, it was found that the coating thickness increases if the solder pot temperature is decreased, and/or the tape speed is increased. This was explained by assuming that the solder has less viscosity, or has more time to flow back down into the pot as the tape exits vertically from it, if the temperature is higher, or the tape speed is lower, respectively. If the tape proceeds quickly, more solder is driven by it up to the point where it freezes. A pot temperature of 140 °C, and a tape speed of 70 mm/s were found to give 40-50 micron thick layers. This temperature, and especially the exposure time are considered safe from the point of view of $I_c$ degradation.

There are some indications that long-time operation of the coating setup without replacing the $In_{52}Sn_{48}$ solder can lead to the accumulation of residues of the liquid flux in the solder pot, and in turn to a pitted surface of the coating. A small amount of liquid flux is presumably carried over into the solder pot by the tape, despite the silicone wiper blades. A different arrangement using resin-based flux paste is being currently tested to avoid this problem.

## 2.2 CABLE AND INSULATION

Even though insulation wrapping techniques are easily available as commercial services today, these technologies are optimized for long batches. The nature of the R&D process of a novel prototype magnet with plenty of challenges requires frequent quick tests with different parameters. Collaboration with a commercial company in this respect was considered a showstopper. An insulation wrapping technique was therefore developed in-house.

Two different configurations were considered: (i) helical wrap, and (ii) longitudinal folding of a kapton tape. After some initial trials, it was concluded that helical wrapping is difficult due to the transverse force exerted by the tensioned kapton tape to the HTS/Cu tapes, which were too weak to support this force.

Self-adhesive commercial kapton tape of width 12 mm was wrapped around a stack of 4 Cu tapes. Since the kapton tape was sticking to both external Cu tapes and prohibited their relative movement, bending the insulated stack, and the associated slipping of the Cu tapes caused the inner tape to buckle and break the kapton layer (see Figure 2). Free slipping of the tapes within the kapton sleeve must therefore be ensured.

*Figure 2: Behaviour of a Cu tape stack insulated by a commercial self-adhesive kapton tape*

A 13 mm wide, 50 µm thick kapton tape, coated with CMC 15581 acrylic adhesive over a width of 4 mm, aligned with one edge of the tape, was ordered from cmc.de. This adhesive proved to withstand exposures to 160 °C for longer periods, and few-10 °C higher temperatures for shorter periods, optionally submerged in liquid wax. The company's other recommended adhesive (CMC 15240 silicone), which had an even higher temperature rating (200 °C for longer periods), failed during the tests: it instantly released and sprung into a string when submerged in liquid wax at 124 °C. A 3D printed plastic tool (Figure 3) was designed, that - similarly to the hemming foot of a sewing machine - folds first the un-coated side of the kapton tape onto the Cu/HTS tape stack, then the adhesive-coated side of the kapton tape, so that it sticks to itself, forming a flat sleeve around the conductor.

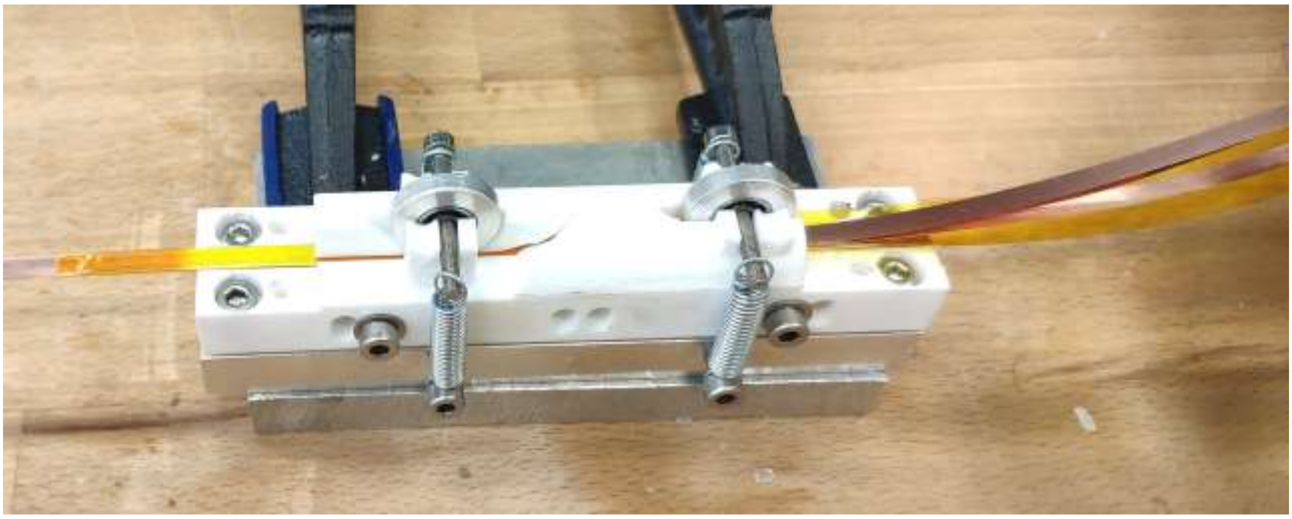


*Figure 3: Kapton insulation folding tool*

## 2.3 WINDING

The format of the HTS conductor (0.1 mm thick, 4 mm wide tape) requires special efforts both in the design of the winding and during the winding process. In contrast to the isotropic NbTi conductors which can be bent in any direction, tapes do not tolerate "hard-way bends". Consequences of this constraint on the design are beyond the scope of this document and are being summarised in a scientific journal article. The winding machine developed for this project had to cope with the following challenges:

- Assemble the stacked, composite cable (2 HTS tapes sandwiched between 2 Cu tapes, insulated by a kapton layer) on the fly, ensuring the relative slipping of the tapes within the stack. Assembling the cable over its entire length in a separate process is not possible since the different developed lengths of the component tapes can not be assured.
- The composite cable must not suffer any hard-way bending during the winding process; the cable must enter the grooves tangentially.

A dedicated machine was designed and built for this purpose, see Fig. 4. The former is mounted onto a shaft, which is suspended at 30° (the tilt angle of the winding) between two large rotating wheels driven by two stepper motors. The HTS, the copper tape and the kapton insulation spools are mounted on a frame that can translate in all directions, driven by 3 stepper motors and ball screws. This movement is necessary to follow the wandering movement of the groove's contour (being approximately an ellipse) when non-central turns are wound, and to keep the cable tension that is provided by the friction between the kapton insulation and the insulation folding tool. This friction can be adjusted by replacing the springs that hold down the two rollers of the kapton folding tool. The two HTS tapes go through a pocket that is filled with flux paste. On one hand, this paste acts as a lubricant to ensure differential slipping of the tapes during winding (clean InSn surfaces are sticking to each other under the slightest force). On the other hand, the flux paste ensures proper bonding of the solder-coated surfaces during heat treatment. Flux paste application can be extended to the two Cu tapes as well in a similar way.

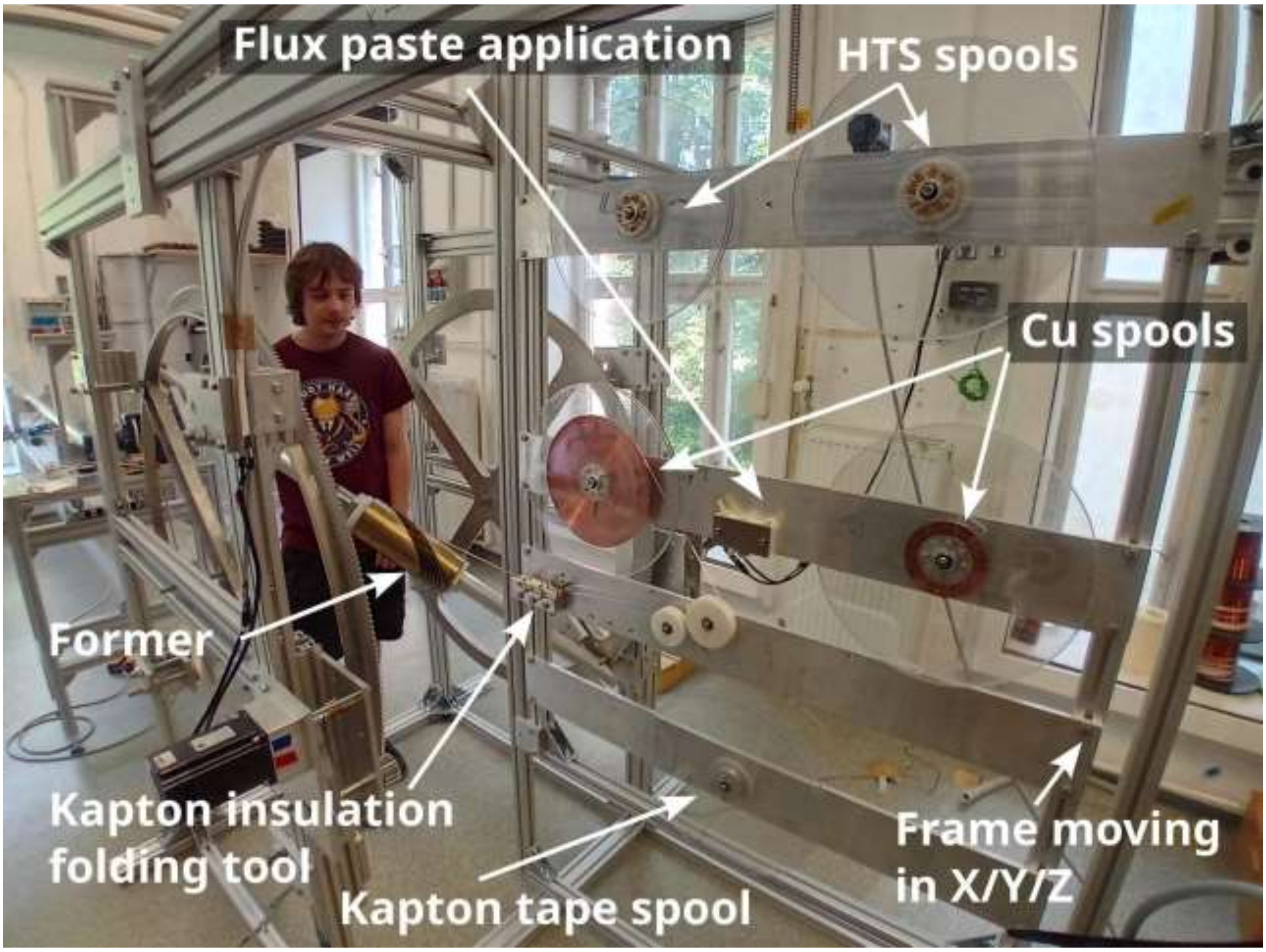


*Figure 4: The winding machine. Note that the HTS and kapton tape spools are empty*

The 5 stepper motors of the system are driven by a Raspberry PI computer. The control software has an intuitive graphical user interface to set up the system initially, adjust the position of the individual motors during winding if necessary, and track the process. The weight of the formers (150 kg for the outer layer), and the weight of the moving frame with all spools mounted are sufficient to back-drive the corresponding stepper motors in case of a power outage and cause damage to the system. As a quick solution, the machine is therefore operated via a UPS unit.

### 2.4 WAX IMPREGNATION

Based on the positive experience with the SuShi septum magnet [7] (training and quench-free operation) it was decided that the winding would be impregnated with paraffin wax, following the procedure developed earlier for that prototype magnet. In this procedure, the magnet is positioned vertically and constitutes a closed, sealed volume for wax. A local wax reservoir is hermetically mounted to its top. The magnet is wrapped with a heater tape and insulation jacket. The magnet is pumped at the top, through the reservoir. Liquid wax is injected into the magnet at its bottom from an external pot via a heated hose. When the reservoir is filled, the transfer of wax is stopped, and the pumping line is replaced by a pressurized nitrogen hose at the top. The bore of the magnet is cooled from the bottom, while the heating is kept. This ensures simultaneous vertical and radial temperature gradient within the mass of the magnet, required to create a void-free result.

## 3. Manufacturing of the mock-up coil and associated tests

### 3.1 DESIGN AND MANUFACTURING OF THE FORMER

The manufacturing of the former is a technical challenge. Due to the tilted grooves, a 5-axis machine (X,Y,Z,A,B) is required. In contrast to LTS CCT magnet formers where the grooves are everywhere normal to the cylindrical surface, and the rib thickness reaches its minimum only at the midplane, for an HTS CCT magnet former the rib thickness (around 0.5 mm) is constant along the entire turn. The aspect ratio of the groove dimensions (depth >= 5 x width) is unfavorable. These issues pose several problems, like vibrations, breakage of the tool, or the thin rib. In order to gain experience and assess achievable parameters, a test former was designed with 6 turns, and a variable rib thickness changing between 0.5 and 0.9 mm. The groove depth (20.2 mm) was slightly less than that for the final former (26.45 mm for 23 cables). The groove width was 4.5 mm. The oscillating tilt of the spindle around the B axis requires a significant extra stroke along the X axis. Our strategy was to manufacture the short test former at a company having the capability to manufacture the final former as well. This surprisingly narrowed down the available choices. Based on CERN’s recommendation, the Norwegian company “High Speed Machining” (https://hsm.as) was identified as the best candidate.

The test former was manufactured from aluminium-bronze (CuAl10Fe5Ni5), see Figures 5 and 6. No showstoppers were identified, the smallest rib thickness could be achieved without any damage.

*Figure 5: Manufacturing of the test former at [https://hsm.as](https://hsm.as)*

*Figure 6: The test former*

## 3.2 WINDING THE MOCK-UP COIL

The mock-up coil was planned to be wound with 20 cables, with the two HTS tapes (thickness of 0.1 mm) replaced by a single Cu tape (0.2 mm thickness), each being pre-coated with $In_{52}Sn_{48}$ solder. Unfortunately, $In_{52}Sn_{48}$ remaining after preceding tests was no longer sufficient to coat all of the tapes. In total, the tapes within 7 of the wound cables were coated, namely the first three, two in the middle (cable 11 and 12) and the two outermost ones. Upon reaching cable 14, we also ran out of the 13 mm kapton insulation and had to switch to a fully adhesive, commercial 12 mm wide tape as a replacement. In order to avoid the problem with this tape described above, the two external Cu tapes were flux-paste-coated during the winding to avoid sticking of the kapton tape to the Cu tapes.

As more and more cables were wound, the grooved filled up on the flat side considerably faster than on the poles, filling it up completely by cable #15. That is, due to the smaller curvature of the groove in the midplane of the magnet, the compressing forces were lower, and the stack of composite cables - acting as a spring - were compressed less. The stack of cables could easily be compressed manually without resulting in significant excess length of the cables. For subsequent cables, a tool was used to push the tapes down at the flat side already during the winding process, which allowed all layers to fit the groove. Upon placing the 20th cable the remaining depth of the groove was measured to be approximately 3 mm at the poles and below 1 mm at the flat side.

*Figure 7: The wound test former*

The composite cable for the final magnet has a thickness of 1.07mm, during the mock-up winding however, the cable used contained three copper tapes instead, which reduced the theoretical thickness to 0.99 mm with and 0.75 mm without solder coating. In practice and without compression, the cable, however was 1.3 mm thick, requiring compression to reach the theoretical value. Measurements after the winding show that at the pole the tapes are close to this theoretical thickness, but at the flat sides there was a 15% increase.

## 3.3 IN-SITU SOLDERING

While several in-situ soldering tests demonstrated proper bonding, the soldering of the mock-up coil produced unsatisfactory results. The interface surfaces were only bonded partially. This is attributed to the thinner solder layer (about 20 microns) on the tapes, due to the dropping solder level in the bath. The winding and soldering of the mock-up coil with at least a few cables will therefore be repeated, after the delivery of a new $In_{52}Sn_{48}$ package.

## 3.4 HIGH-VOLTAGE TESTING

Unfortunately, the edges of the grooves were not rounded during manufacturing. Some manual smoothing was carried out by abrasive tools, but this was not as efficient as rounding during manufacturing. The sharp edges – especially at the locations indicated by red arrows in Fig. 6 – could easily damage the insulation during winding. Eventually, protective kapton foils can be used to cover these edges. Cables that were not damaged were high-voltage tested and withstood 1 kV applied between the cable and the former.

## 3.5 TILT OF THE CABLES WITHIN THE GROOVE

Strictly speaking, a hard-way-bend-free tape geometry can only be achieved for an infinitely thin tape. In a finite-thickness tape, or in a parallel stack of cables, the layers that are off from the reference layer will in general have a hard-way bend, even if the reference layer was designed to be hard-way-bend-free, except in a few special cases.  In practice, this means that independent cables within a groove can not all be aligned such that their normal coincides with the groove's direction. In the current design, the bottom cable has the largest relative tilt with respect to the groove, which was numerically evaluated to be everywhere below 5 degrees. This means that the tensions within the cable are not homogeneous during winding, and subsequent cables would exert an unpleasant twisting force on lower-lying cables. Eventual adverse effects of this were tested using an analogous setup. A dismountable, cylindrical mandrel with a slightly conical bottom of the groove (5 degrees) was wound on the same machine, with the same composite cable, under the same conditions. Critical current tests carried out in liquid nitrogen indicated no change in the critical current density of the central HTS tapes.

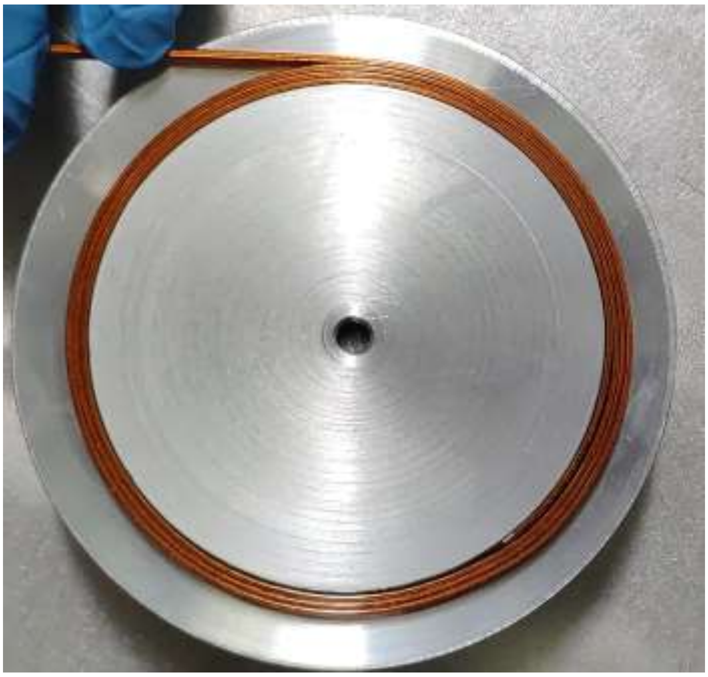


*Figure 8: Tilted-bottom winding mandrel, without the removable disk*

## 3.6 WAX IMPREGNATION

Wax impregnation of the mock-up coil, wound with only 2 layers of cable, was demonstrated in the frame of a visit to Wigner Research Centre by researchers/technicians from Elytt Energy and INFN/LASA. Despite improper conditions (partial impregnation, too fast and uncontrolled cool-down due to time constraints, and no overpressure applied during cooldown), the wax volume within the grooves was solid (Figure 9). Even though the cables have a tight fit within the groove, the capillary volumes between and below the cables were properly filled with wax. In fact, the interior volume of the cables within the kapton insulation was also filled with wax over the entire length of the cables (Figure 10). Since the kapton insulation did not open up during the wax impregnation, wax must have penetrated at the cable ends, and propagate along the entire length. Although the final prototype magnet will have 50 turns (in contrast to the present 6 turns), it is believed that if the magnet is properly evacuated before impregnation, wax will fill the insulation of the cables in the prototype magnet as well. This is considered an advantage as voids are to be avoided. If for any reason the penetration of wax into the cables is blocked, the applied isostatic overpressure of liquid wax (a few bars) will compress the kapton sleeve onto the cables.

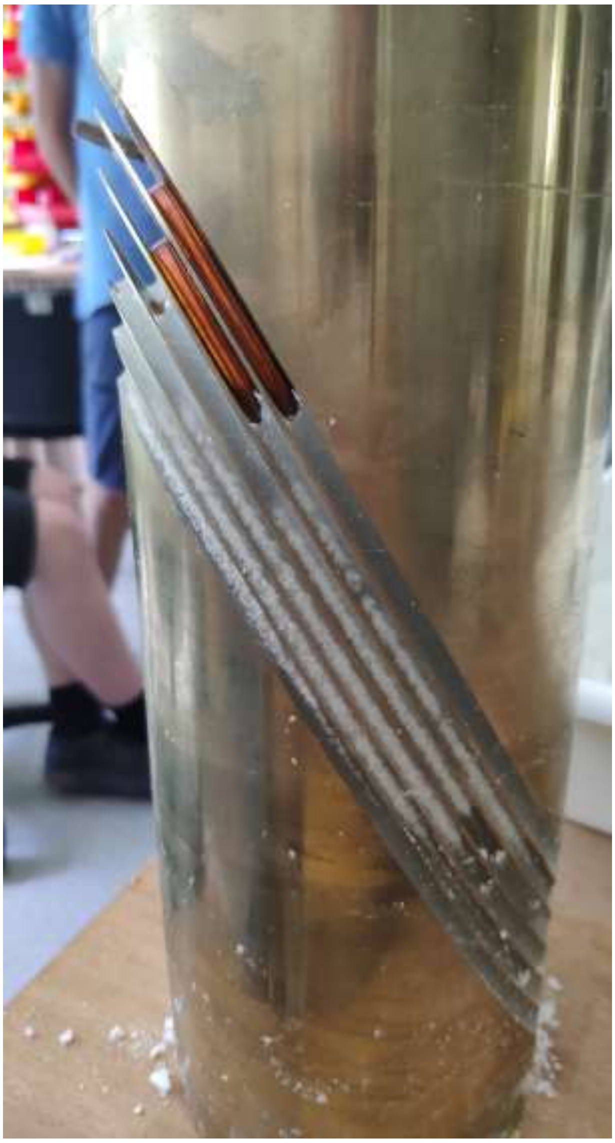


*Figure 9: Wax-impregnated former after removing the glass-fiber tape, and excess wax. Snow-flake like features are located only close to the surface*

*Figure 10: Wax observed inside the kapton insulation after opening it up*

## 3.7 CABLING AND SPLICING TESTS

This section presents the detailed methodologies and results of the cabling and splicing tests conducted on the HTS (High-Temperature Superconducting) CCT (Canted Cosine Theta) magnet as part of the I.FAST (Innovation Fostering in Accelerator Science and Technology) project. The primary focus is on evaluating the performance of 4 mm HTS Faraday Factory Japan YBCO tape under various conditions, including self-field measurements in liquid nitrogen (LN2). The tests could be divided into two sets: cabling and splicing tests. The following subsections will elaborate on the testing procedures, data analysis, and performance evaluation of these diverse samples, highlighting their implications for the HTS CCT magnet development within the I.FAST project.

### Cabling Tests

The tests were performed in liquid nitrogen (77 K) and each sample underwent a series of current ramps at a constant ramp rate, powered by a battery supply (2500 A / 4 V). Samples were received from Wigner RCP, encompassing a range of conditions and treatments. The variations include virgin samples, coated samples with Indium-Tin alloy (pulled through a 140 $^{o}$C solder bath at a speed of 70 mm/s), conductors wound and treated with Mob39, both cooked and uncooked, and samples with different turn configurations (four turns and three turns). Additionally, some conductors were wound uncooked with the start and end out. The first campaign samples tested are shown in Figure 11, mounted on dedicated holders. The thin red and white wires are voltage tap wires soldered at a distance of 50 mm from each other.

The standard short sample power law for inner voltage taps is:

$$V = V_{th} \cdot \left(\frac{I}{I_c}\right)^n$$

The criterion used is the Ic100 ($E_{th} = 1\ \mu V$/cm), corresponding to a $V_{th} \sim 5\ \mu V$. In Fig. 12 a typical voltage transition during the test ramp to evaluate the Ic transition is shown. Table 1 shows the results of the tests conducted on the REBCO tape in its virgin, coated, and extracted forms. The measurements highlight high compatibility, indicating no degradation in tape performance in terms of critical current due to the coating, cabling, and winding procedures. Table 2 presents the results of tests on cable samples: unwound-soldered (straight cable in situ-soldered) and wound-soldered (cable in situ-soldered on a test mandrel), showing compatible results between these two methods. However, there is a significant discrepancy of about 12% compared to the ideal case of having a cable with 2 (virgin) tapes. This discrepancy is justified by the self-field effect of the two tapes soldered together in the cable, as even a minimal magnetic field can significantly degrade the performance of the HTS cable/tape, as illustrated in Figure 13. This aspect requires further detailed studies and tests.

It can be concluded, that the winding process (even in a groove with a tilted bottom surface), or the heat treatments (solder coating, or in-situ soldering for XXX hours) do not cause a performance degradation of the conductor.

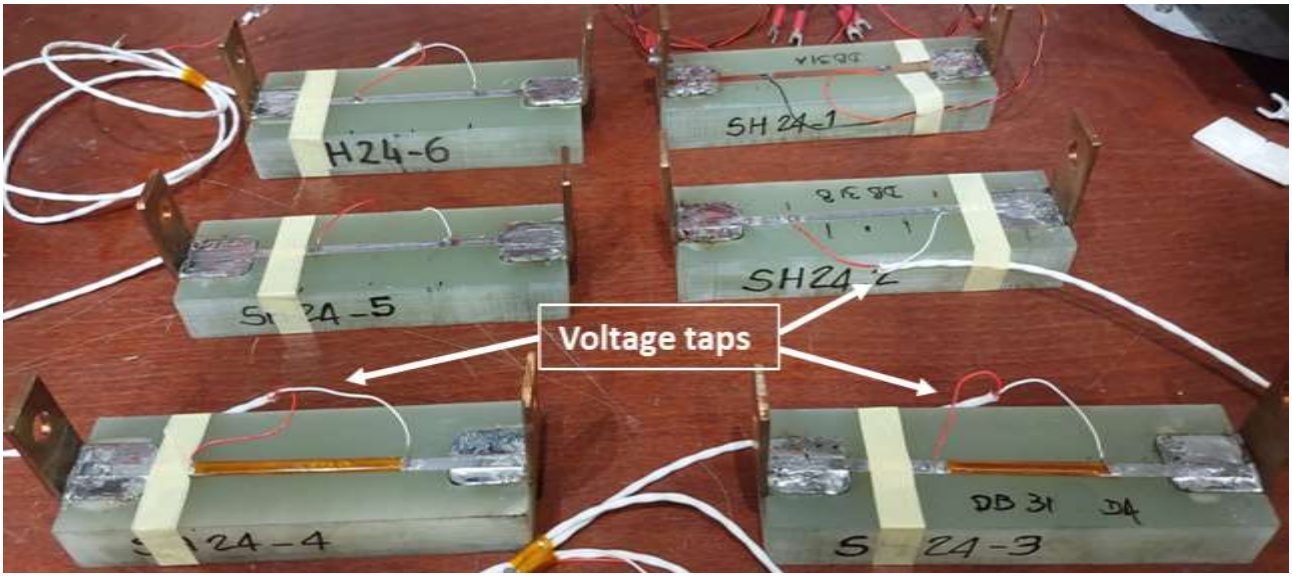


*Figure 11: Samples mounted on the holders and tested in the first campaign of cold tests in liquid nitrogen (red and white wires are voltage tap wires)*

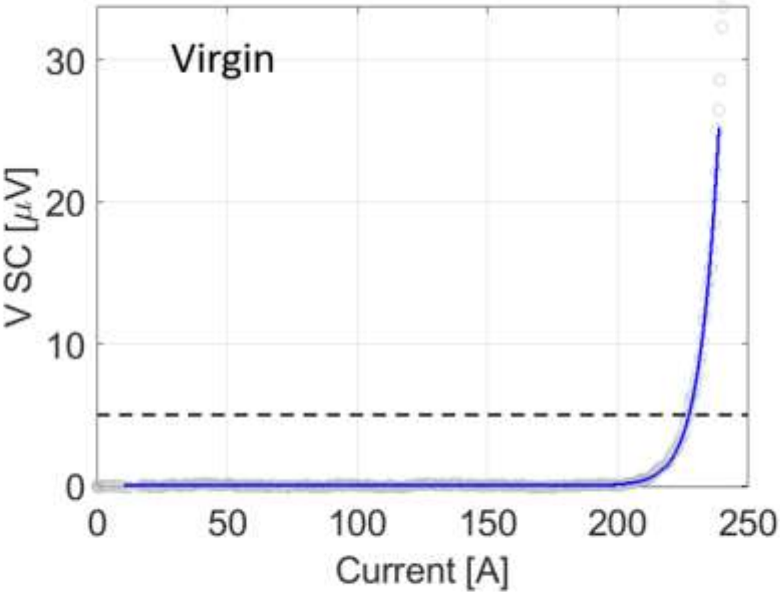


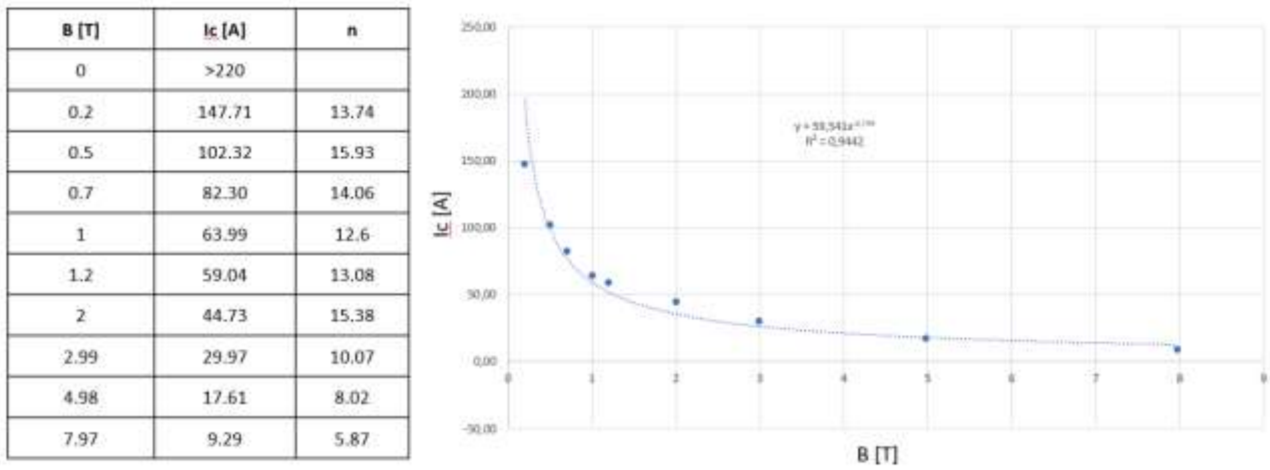
*Figure 12: Voltage signal of the virgin tape sample during the Ic measurements. The dashed line represents the 5 μV threshold of the Ic100 criterion*

*Table 1: Critical current measurement results of the cold test done on the tape samples (Ic100 criterion): critical current measurements, n-value, and uncertainty of the critical current meurements.*

| **Tape sample** | **critical current meas. Ic [A]** | **n - value** | **uncertainty δ(Ic) [A]** |
|---|---|---|---|
| virgin | 227 | 33 | ±2 |
| coated | 227 | 32 | ±2 |
| uncooked - extracted | 225 | 30 | ±2 |

*Table 2: Critical current measurement results of the cold test done on the cable samples (Ic100 criterion): critical current measurements, n-value, and uncertainty of the critical current meurements.*

| **Cable sample** | **critical current meas. Ic [A]** | **n - value** | **σ (Ic) [A]** |
|---|---|---|---|
| 2 x virgin tape | 454 | - | ±4 |
| unwound-soldered | 400 | 36 | ±4 |
| wound-soldered | 396 | 38 | ±4 |



| B [T] | Ic [A] | n |
|---|---|---|
| 0 | >220 | |
| 0.2 | 147.71 | 13.74 |
| 0.5 | 102.32 | 15.93 |
| 0.7 | 82.30 | 14.06 |
| 1 | 63.99 | 12.6 |
| 1.2 | 59.04 | 13.08 |
| 2 | 44.73 | 15.38 |
| 2.99 | 29.97 | 10.07 |
| 4.98 | 17.61 | 8.02 |
| 7.97 | 9.29 | 5.87 |

*Figure 13: Table and graph of the critical current measurements of a single HTS tape exposed to magnetic field*

## Splicing Tests

Another critical point is the splice procedure and its definition to reduce fault probability and the heat losses generated, which significantly contribute to the heat balance for the cooling system. The splicing procedure involves a "shaking hands" configuration, where each tape of one cable intersects with the corresponding tape of the other cable (a figure may be needed for clarity). Tests were conducted with different joint lengths to verify the reproducibility of the procedure and establish an extrapolation law for the splice resistance. Once the splice length is determined, the joint is created by heating the area to 140°C and applying a pressure of approximately 0.8 MPa. The samples were tested using the same setup as the cabling tests (Figure 14). Preliminary cold test results, shown in Table 3, highlight still poor reproducibility. Additional tests are ongoing to define the final procedure.

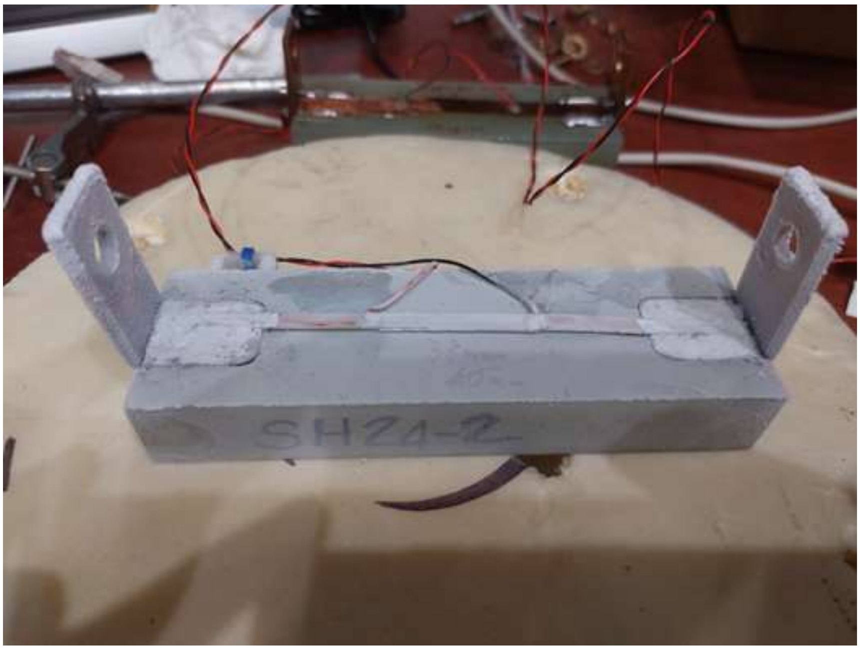


*Figure 14: Splice sample mounted on the holder, just after a cold test in liquid nitrogen*

*Table 3: Critical current measurement results of the cold test done on the splice samples (Ic100 criterion): critical current measurements, n-value, and uncertainty of the critical current meurements*

| Splice length [mm] | critical current meas. Ic [A] | n - value | Resistance [μΩ] |
|---|---|---|---|
| 38 | 376 | 12 | 0.096 |
| 48 | 434 | 45 | 0.140 |

# 4. Summary

All manufacturing techniques and tools have been developed to construct the HTS CCT prototype magnet. Their performance was demonstrated by winding, soldering and impregnating a mock-up coil. In-situ soldering produced improper bonding, which is attributed to the too thin coating layer, caused by running-out solder. Preceding soldering tests produced satisfactory results. Nevertheless, this manufacturing step will be repeated on the mock-up coil. All other manufacturing steps produced satisfactory results, directly applicable for the manufacturing of the final prototype magnet. The cabling and splicing tests for 4 mm HTS REBCO tape under various conditions found no degradation during the cabling procedure, but identified the need for further studies on splice procedure reproducibility and the impact of self-field effects on tape performance.

# 5. References

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# 1. Annex: Glossary

| **Acronym** | **Definition** |
|---|---|
| CCT | Canted Cosine Theta |
| HTS | high-temperature superconductor |
| CORC | conductor on round core |
| RRR | residual resistivity ratio |