High Temperature Superconductor Harness for use in Cryogenic Applications

Contract No. 4000133578/21/NL/FE

Final Presentation

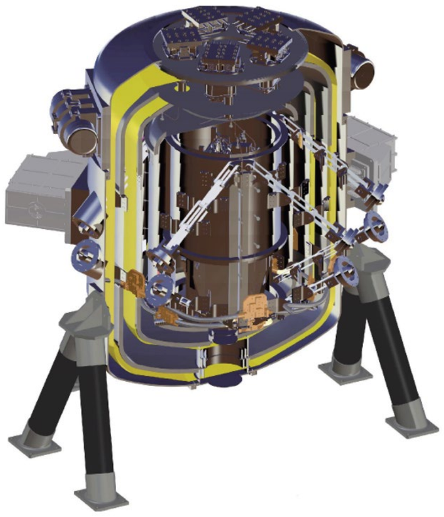
NEUTRON STAR SYSTEMS UG

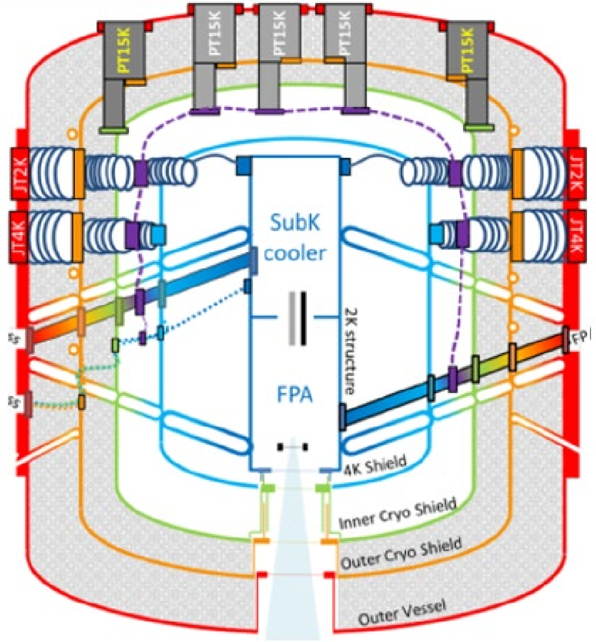
KARLSRUHE INSTITUTE FÜR TECHNOLOGIE

COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES

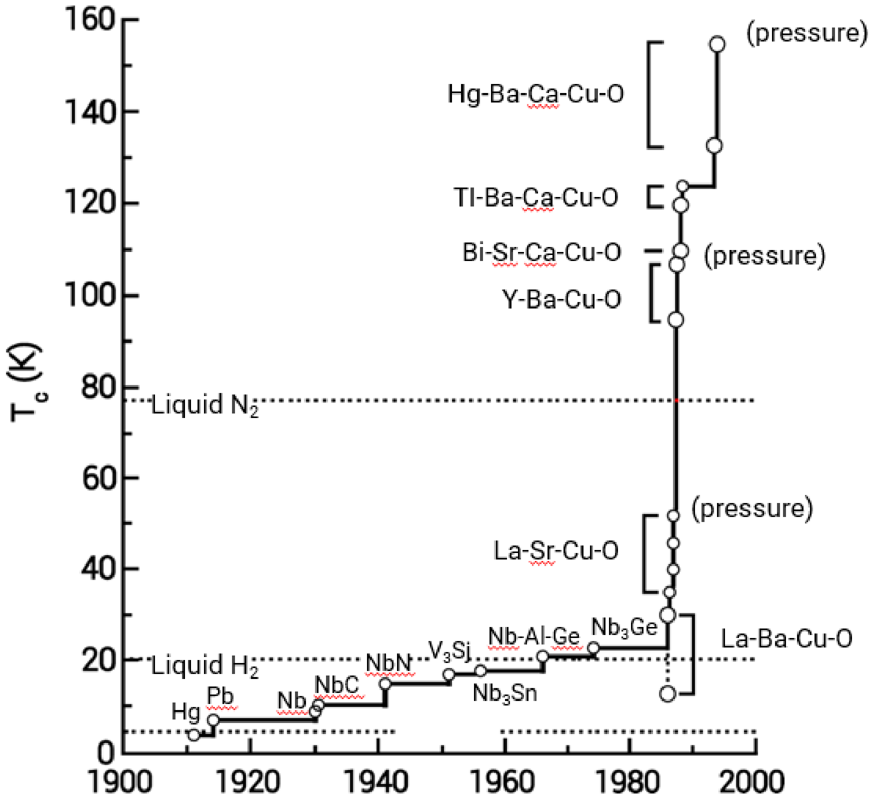
Project Context

- Some spacecraft instruments for scientific missions require extremely low temperatures to operate, even on the order of Millikelvin.
- These temperatures are provided by a complex chain of several cryocoolers, the last of which is an ADR cooler requiring 2A of electrical current.
- Every additional source of heat increases the demands and power required from the cryocoolers. Routing 2A through conventional conductors generates significant ohmic heating.
- High-Temperature Superconductors could provide this current with a significantly reduced heat load.

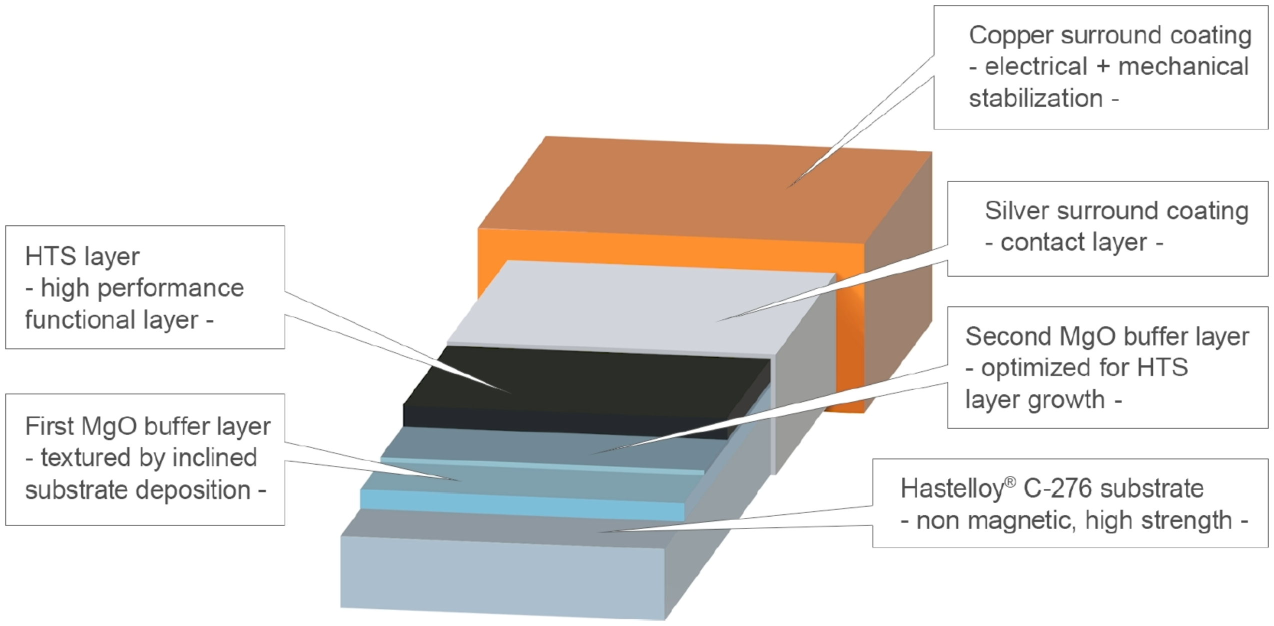




High-Temperature Superconductors



The highest known critical temperature over the past century



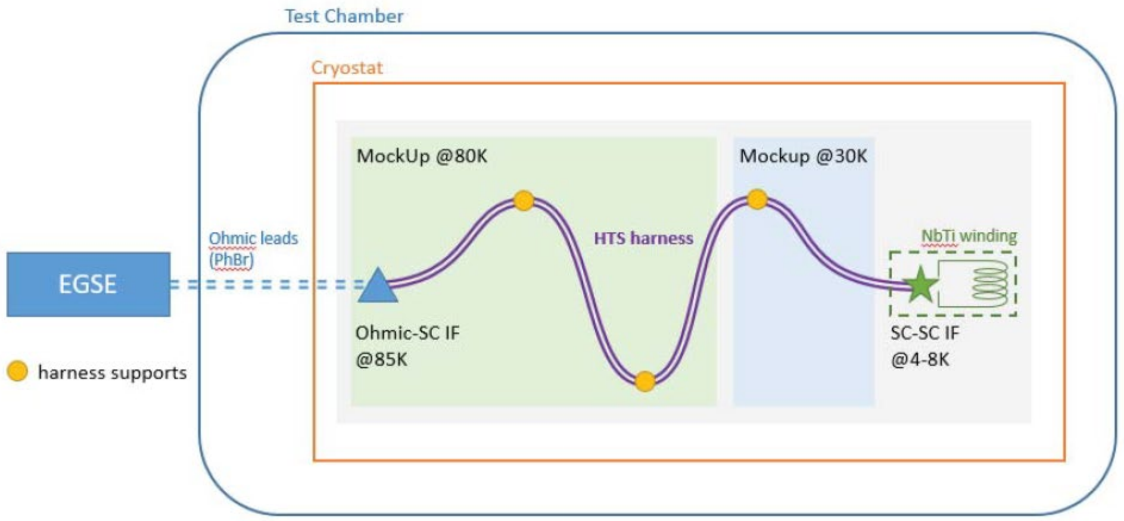
Source: Thomas Frey, M. Kleber, H. Kinder, R. Gross Oxidation behavior of RE123 superconductors with time and place resolution. Published on August 2004 at the Technical University of Munich submitted and accepted by the Faculty of Physics on January 2005

Source: THEVA Pro-Line Products, https://www.theva.com/products

Project Overview

Main Objectives

- Reduce the heat load arriving to the ADR cooler by using HTS wires with a higher T_c than currently used MgB_2 (~30K)
- Design a solution making use of commercially available HTS tapes with suitable encapsulation and electrical connection techniques.
- Maximise thermal anchoring performance
  - Sufficient heat evacuation at Joule-SC interface to keep $T_{op} < T_c$
  - Minimisation of heat dissipation at SC-SC interface to ensure $T_{op} << T_c$ (LTS)
- Validate design suitability through testing
- Ensure a reliable, repeatable, and accessible design for ESA use on future missions.



Project Overview

Tasks

- Task 1: Technology Review and Selection
  - Review commercial and technological options for the components of the harness.
  - Generate a first concept of the cable-jacket-connection combination to be pursued.
  - Review and finalise the requirements specification.
- Task 2: Design
  - Procurement of cables/materials.
  - Thermal and mechanical design of harness mockup and EM.
  - Preparation of drawings, test plans, and processes.
- Task 3: Manufacture and Testing
  - Production of cable, support structures, and GSE.
  - Assembly, integration, and testing of EM.
- Task 4: Final Review, Assessment and Outlook
  - Review of all project activities; Assessment of lessons learned; Articulation of future development roadmap
- Task 5: Management
  - Regular monitoring of project budget and schedule; Ensuring all deliverables and tasks are executed properly

Task 1: Technology Review and Selection

Overview

- Review commercial landscape of HTS suppliers and tapes.
  - High T_c (>85K)
  - Export and availability considerations.
- Assess alternative approaches
  - With in-house capabilities?
- Identify and develop a suitable encapsulation concept
  - Assessment of cable materials already used for space applications.
  - Assessment of space suitability of HTS jacket materials used in terrestrial applications.
- Review candidate connection technologies
  - Minimisation of heat loads and mass.
  - Maximisation of thermal anchoring efficiency and reliability.
  - Consideration of ease of use for testing activities.
- Define HTS Harness concept
- Review and finalise technical requirements baseline

Task 1 – HTS Cables

- Driving Requirements:
  - T_c > 85K
  - Minimise thermal conductivity
  - Availability
  - Easily modifiable
- MgB_2 considered but discarded
- Main selection: REBCO vs BSSCO
- BSSCO have higher T_c but also several drawbacks:
  - Limited suppliers
  - High percentage of thermally conductive Ag
  - Can't be modified due to presence of filaments
  - Poor mechanical characteristics.

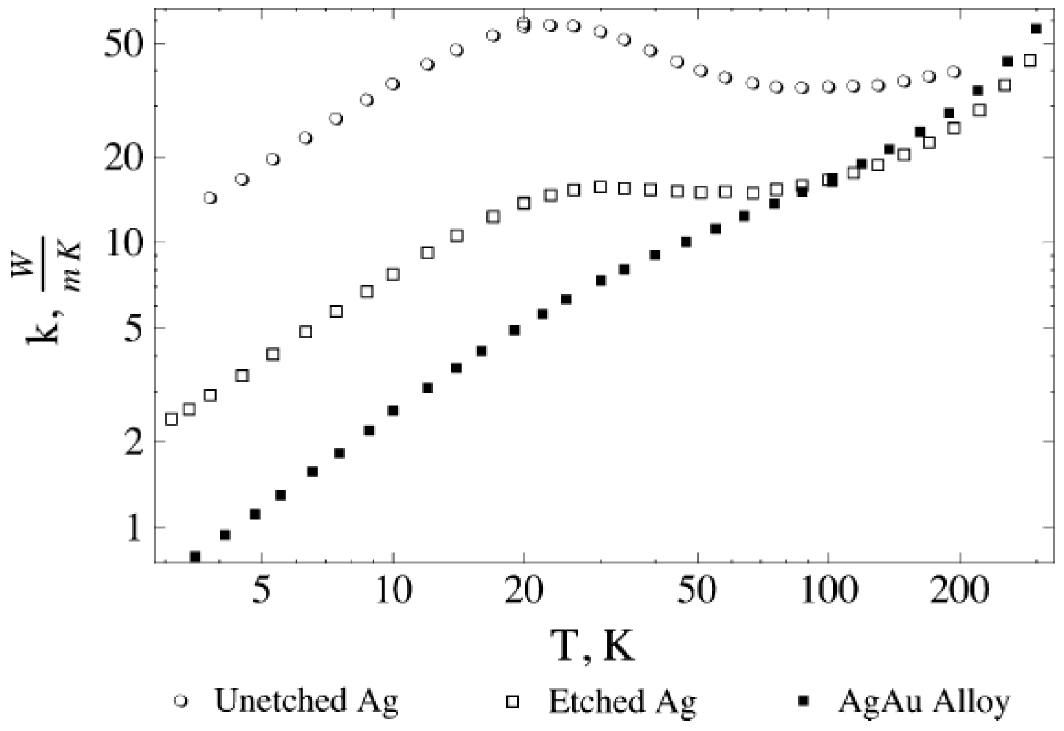
Review Criteria

	Bi2212: twisted, filamentary wire	Bi2223: non-twisted, filamentary tape	REBCO: monofilament tape
Fraction in the cross section of:			
Superconducting ceramic	20%–35%	30%–40%	<5%
Ag or Ag alloy	65%–80%	60%–70%	<1%
Matrix	—	—	50%–98% (Hastelloy)
Cu	—	—	0%–50%
Engineering current density (A mm^{-2} at 4.2 K, 15 T)	500–1000	350–500[b]	400–1500[a,b]
Non-Cu current density (A mm^{-2} at 4.2 K, 15 T)	—	—	800–4000[b,c]
Critical longitudinal tensile stress (at cryogenic temperature)	100–150 MPa (bare); 250MPa (reinforced)	30 MPa (bare); 270–450MPa (reinforced)	400–800 MPa
Reversible longitudinal strain range	0% to 0.3%–0.6%	−0.1%–0.25% (bare), 0.55% (reinforced)	−1.2% to 0.4%–1.0%
Critical transverse compressive stress (at cryogenic temperature)	Not available on modern wires	~50 MPa (bare); ~150MPa (reinforced)	300–750 MPa
Industrial manufacturers	Bruker-OST	Sumitomo	>10 companies
Typical piece length	>500 m	>500 m	<300 m

[a] Including 50 μm thick copper.
[b] Perpendicular to the wide face of the tape.
[c] 30 μm substrate.

REBCO Tapes

- Suppliers located in USA, Germany, China, Japan, South Korea, Russia
- All standard REBCO variations have T_c > 85K
- Factors affecting thermal conductivity:
  - Cap layer material
    - AgAu preferred.
  - Substrate Thickness
    - Thinner substrates preferred
- Artificial Pinning to be avoided (poor radiation resistance and reduction of I_c near T_c)



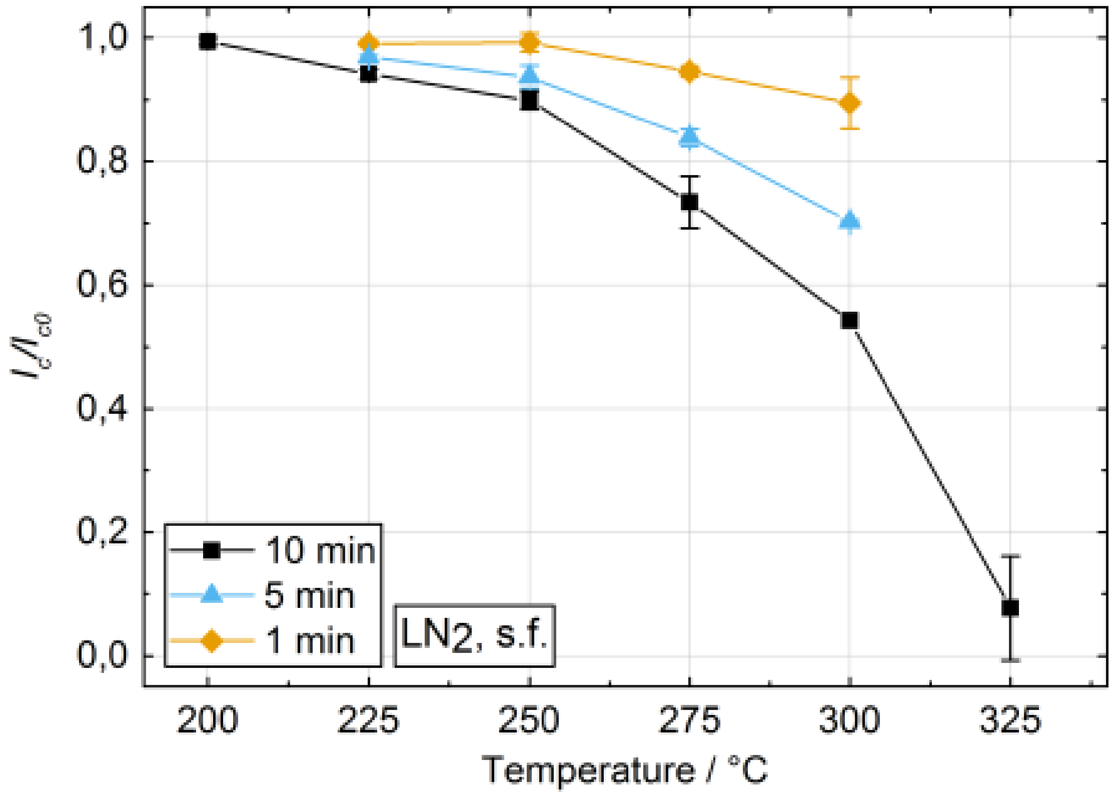
Task 1 – HTS Cables

Pre-Selection

	Pros	Cons
SuperPower SF12050-AP	• AgAu Cap Layer – low thermal conductivity • 12mm width to allow cutting of different shapes	• Artificial Pinning • Relatively low I_c • Lower T_c
Super-Ox (43 microns)	• Thinnest substrate available – low thermal conductivity • High I_c and T_c • 12 mm width	• Only Ag cap layer • Potential higher risk for future export control

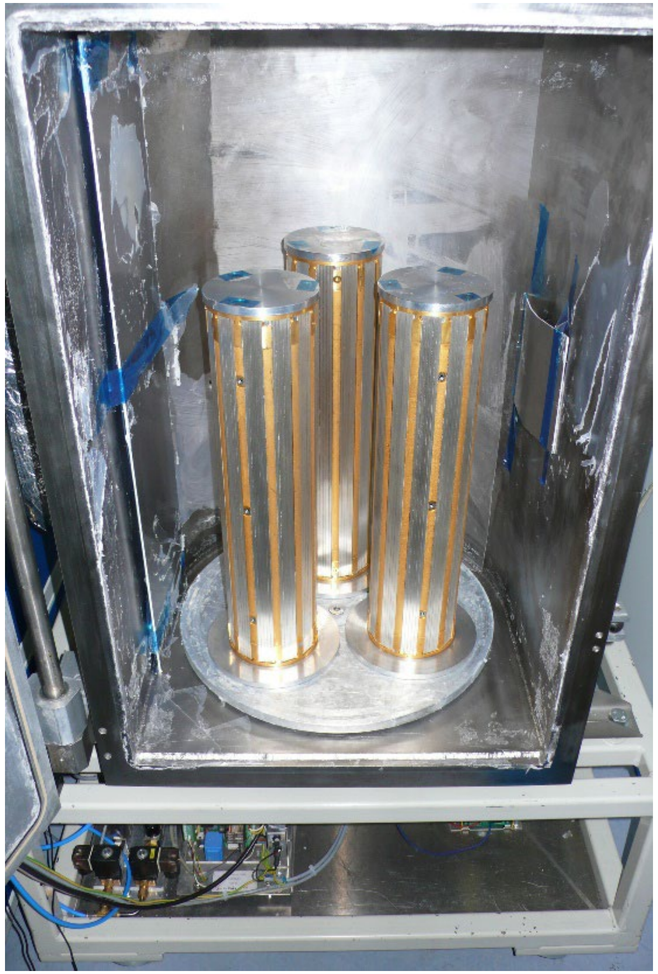
Review Criteria

- Driving Requirements:
  - Cryogenic Heritage
  - Space Heritage
  - Export Restrictions
  - Application Temperatures
- Two-part jacket concept considered
  - A material layer to seal the HTS tape and protect from humidity and hence I_c degradation
  - An outer layer to provide mechanical support



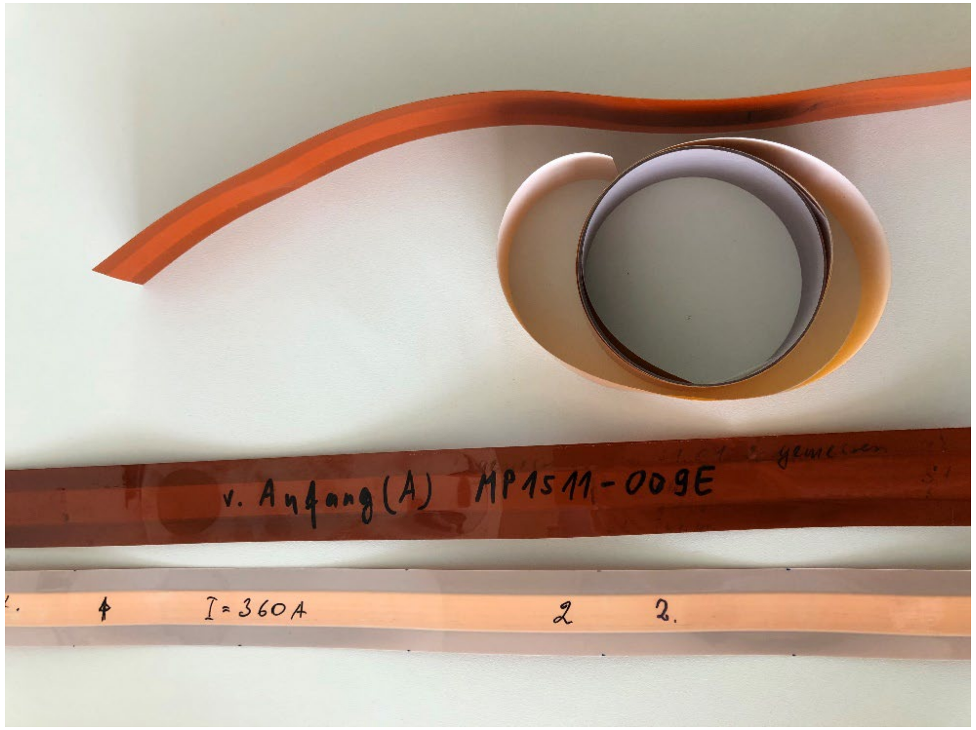
Sealing Material

- Parylene-C identified as most desirable option.
    - Excellent sealing properties due to vacuum evaporation process
    - Application at < 200°C is acceptable
    - High dielectric strength
    - Low water vapour transmission rate
    - Previous heritage in space applications including ISS and Deep Space 1
    - Previous experience using Parylene-C with local suppliers for fusion magnet applications.



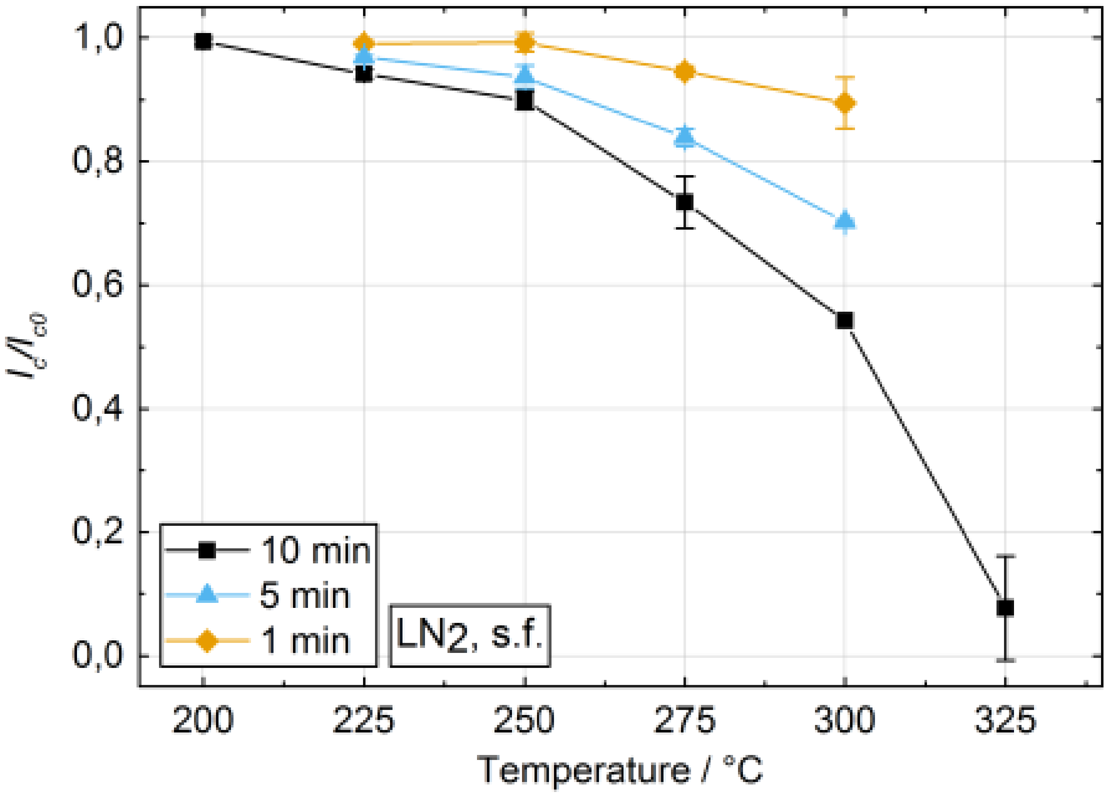
Outer Material

- Kapton preferred due to:
  - Space heritage
  - HTS heritage
  - High radiation resistance
  - Application temperature of only 120^{o}C
  - Significant internal experience using Kapton



Review Criteria

- Driving Requirements:
    - Dis-Connectable connections to ease testing activities.
    - Minimisation of electrical resistance.
    - Avoid high-temperature application (>200 °C)
    - Avoid connections involving the application of large mechanical forces
    - Avoid techniques which need specialised tools or facilities
- Joints involving superconductors:
    - Soldering
        - Numerous solders available with different resistivities and temperatures
    - Pressing (with Indium)
        - Easily affected by thermal cycles



Task 1 – Connection Techniques

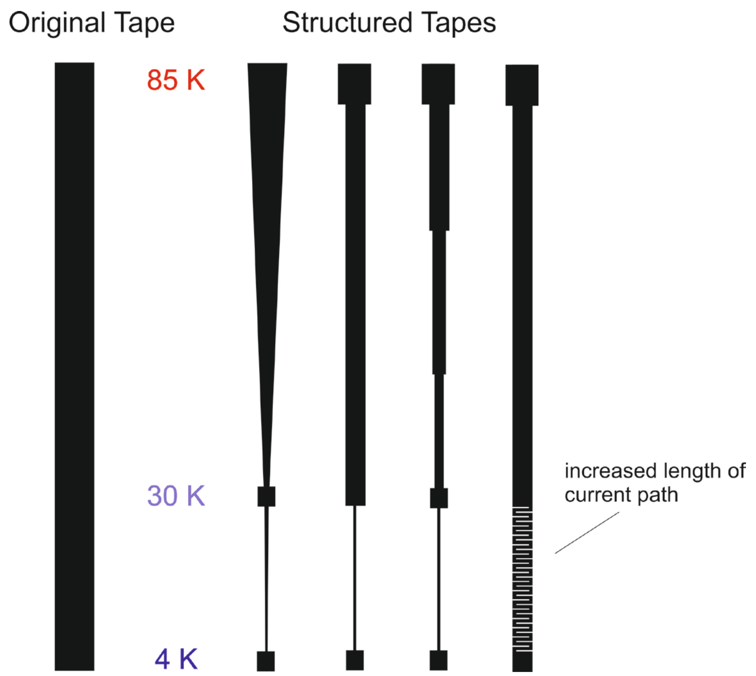
Dis-connectable Options

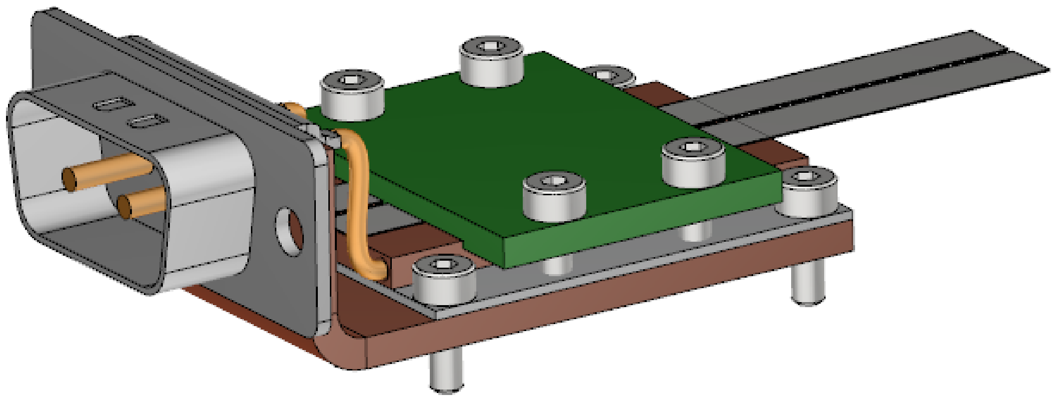
- Screw Connectors
  - Low ohmic loads
  - Gold-plating reduces resistivity
  - Can operate at lower temperatures
  - Custom design needed.
- Commercial connectors
  - Mechanically robust
  - COTS and space qualified
  - Higher ohmic loads
  - Concerns of CTE mismatch at very low temperatures (4K)
- Heat load evacuation at warm end necessitates heat sinking solution
  - Stycast heat-sinking wire canal
  - Aluminium Nitride (AlN) interface plate

	Connectors electrical resistance (mohms)	Max. rated current (A)	Minimum gauge number (and wire size in mm)	Space compatibility	Cryogenics compatibility
Micro-D	8	2.5	#24 (0.51 mm) #26 (0.404 mm)	Flight proven	Specified to -65°C Used at 4 K on Herschel
Sub-D	TBC	8	#20 (0.81 mm)	Flight proven	Specified to -65°C Usable at cryogenics TBC
Hiper-D (#20 pins)	TBC	7.5	#20 (0.81 mm)	Flight proven	Specified to -65°C Usable at cryogenics TBC
Hiper-D (#8 pins)	TBC	40	#8 (3.26 mm)	Flight proven	Specified to -65°C Usable at cryogenics TBC

Task 1 – Proposed Concept

- HTS Cable: SuperOx GdBCO (43 Micron thickness) OR SuperPower SF12050-AP
  - Proposed to procure both and decide based on tests
  - Customised geometry
- Jacket Insulation: Parylene
- Jacket Outer Coating and Mechanical Support: Kapton
- Cold End Connection Technique
  - Screw Connection (Copper with gold plating)
  - Soldered joints between REBCO-Cu and Cu-NbTi
- Warm End Connection Technique
  - Commercial Connector (GlenAir Microstrip) with AlN heat sinking.
  - Soldered joints between PhBr-Connector and Connector-REBCO



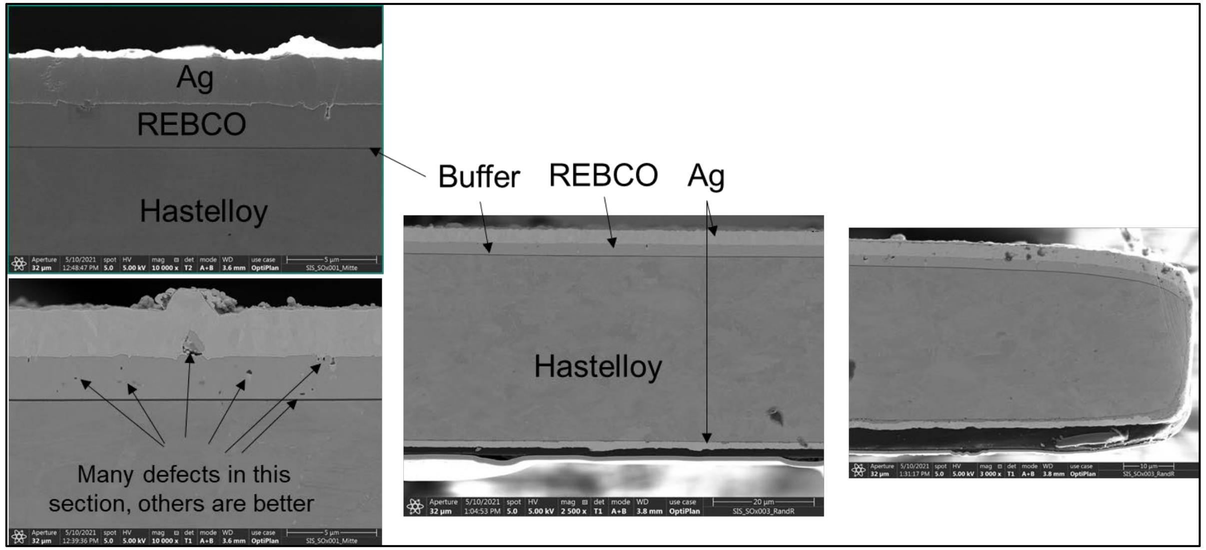


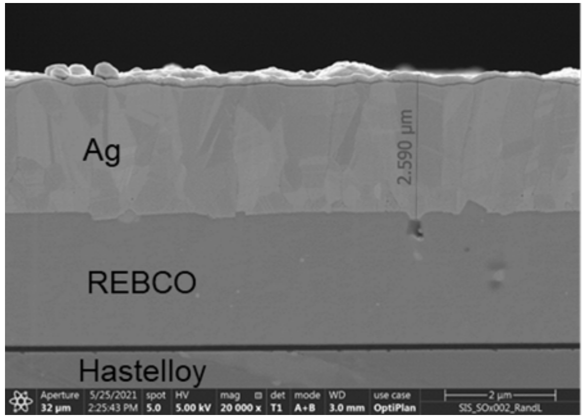
Task 2: Design

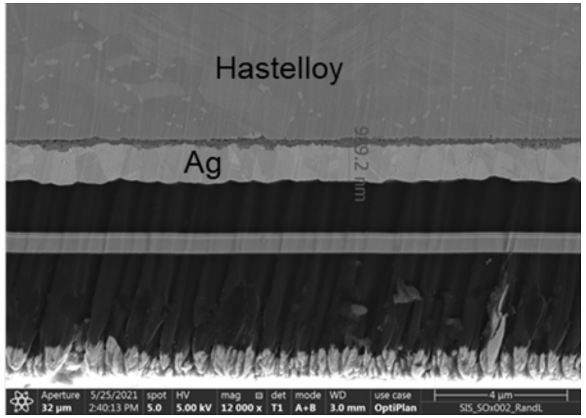
Task 2 – HTS Tape Characterisation

SEM Imaging

- Assessment of tape quality
- Measurement of layer geometry -> accurate assessment of contributions to thermal and structural behaviour



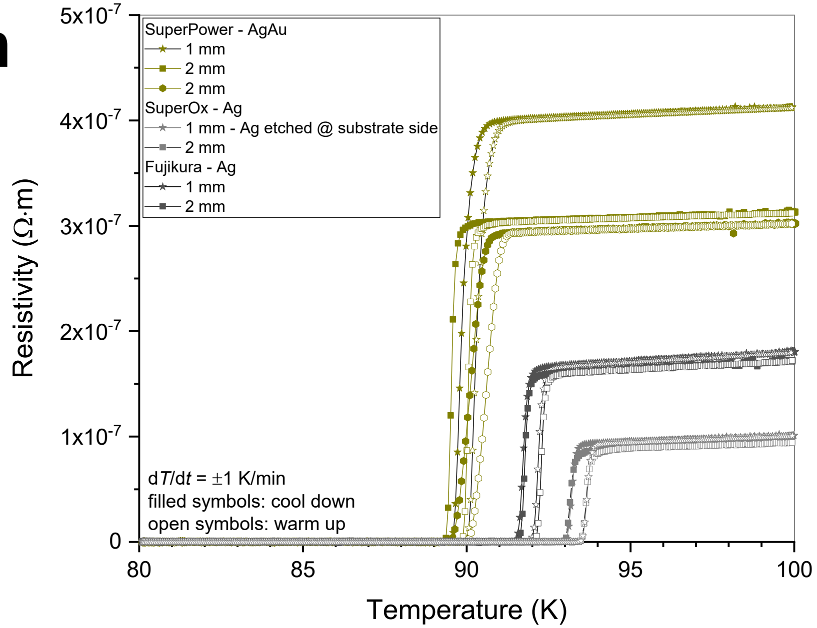


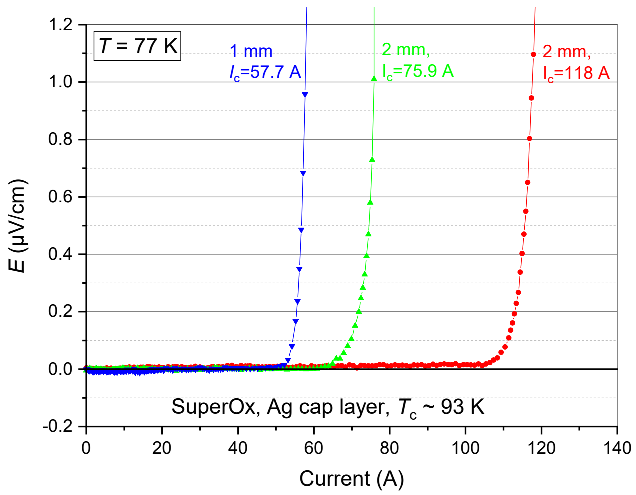


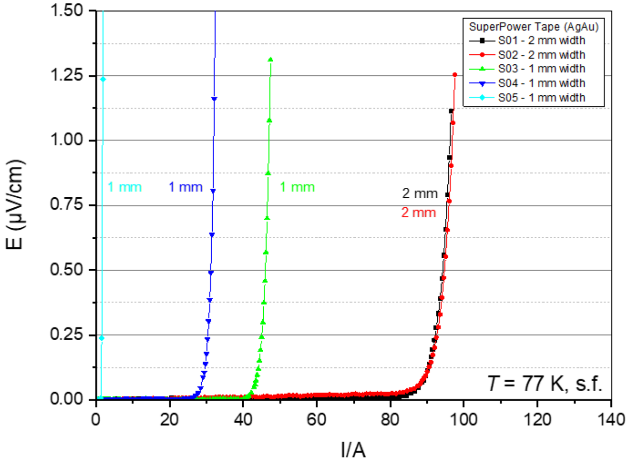
Task 2 – HTS Tape Characterisation

T_c and I_c characterisation

- T_c measurements made for the procured 12mm-wide tape -> values as expected.
- Tapes cut to 1mm and 2mm widths and measured again.
  - I_c performance not consistent in terms of I_c / unit width
  - Differences can be explained by the inhomogeneity of the tape

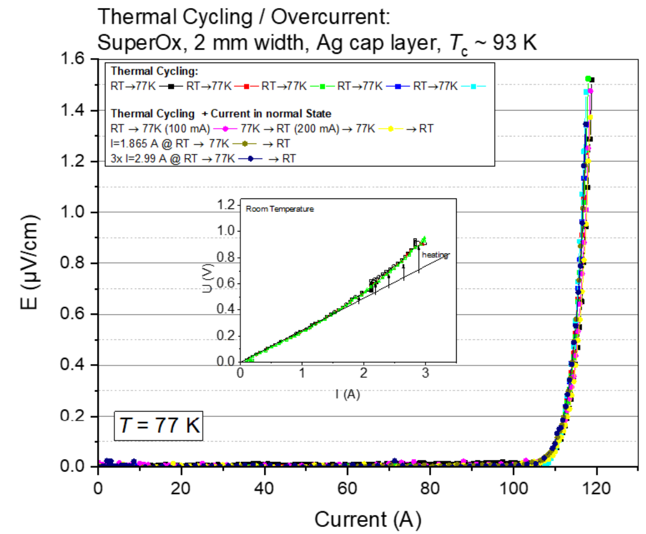


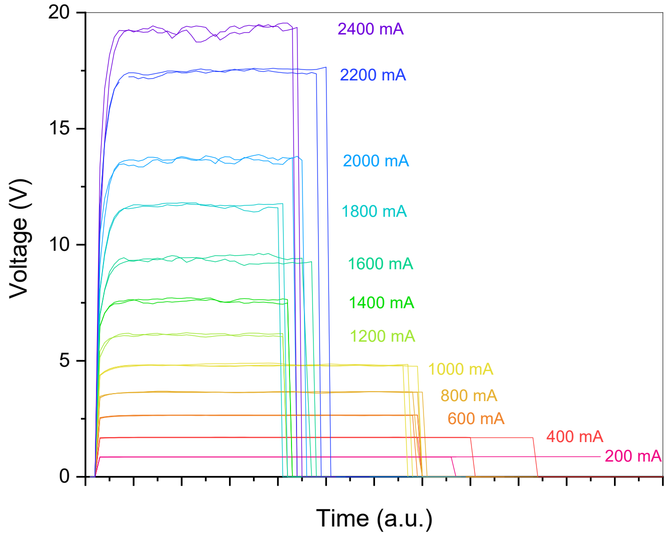


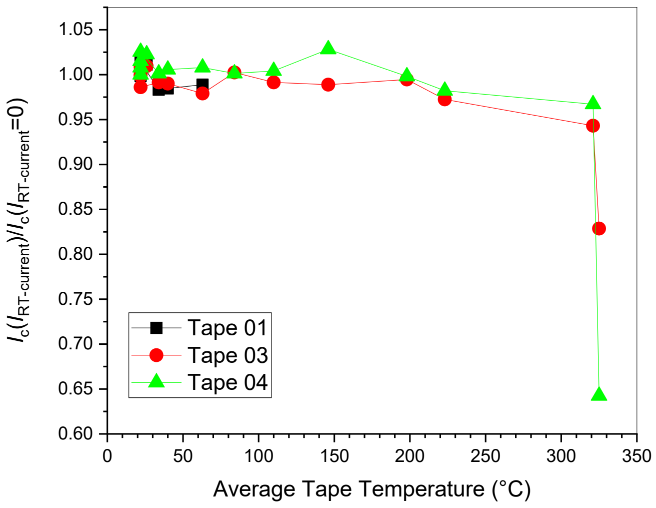


Overcurrent Tests

- The tapes were exposed to gradually increasing overcurrents at room temperature, up to 3A in their non-superconducting state.
  - No change in I_c was observed.
- Further overcurrent tests were performed up to 2.4 A with the temperature measured
  - Above 300 °C, degradation of the I_c is observed.







Task 2 – HTS Tape Characterisation

Temperature dependence of I_c

- Required current carrying capability: **5 A @ 85 K**

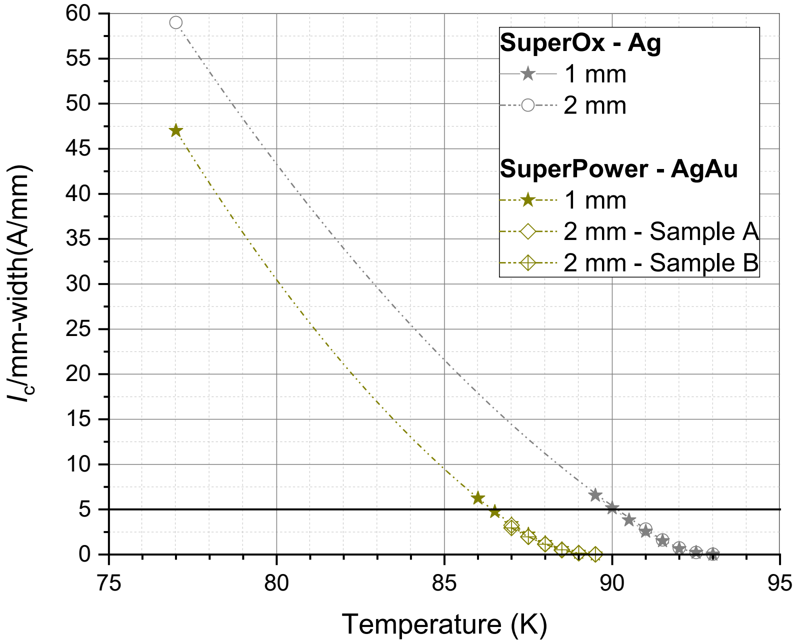
SuperOx:

GdBCO: Tc ~ 93 K -> 5 A/mm @ ~ **90 K**

SuperPower:

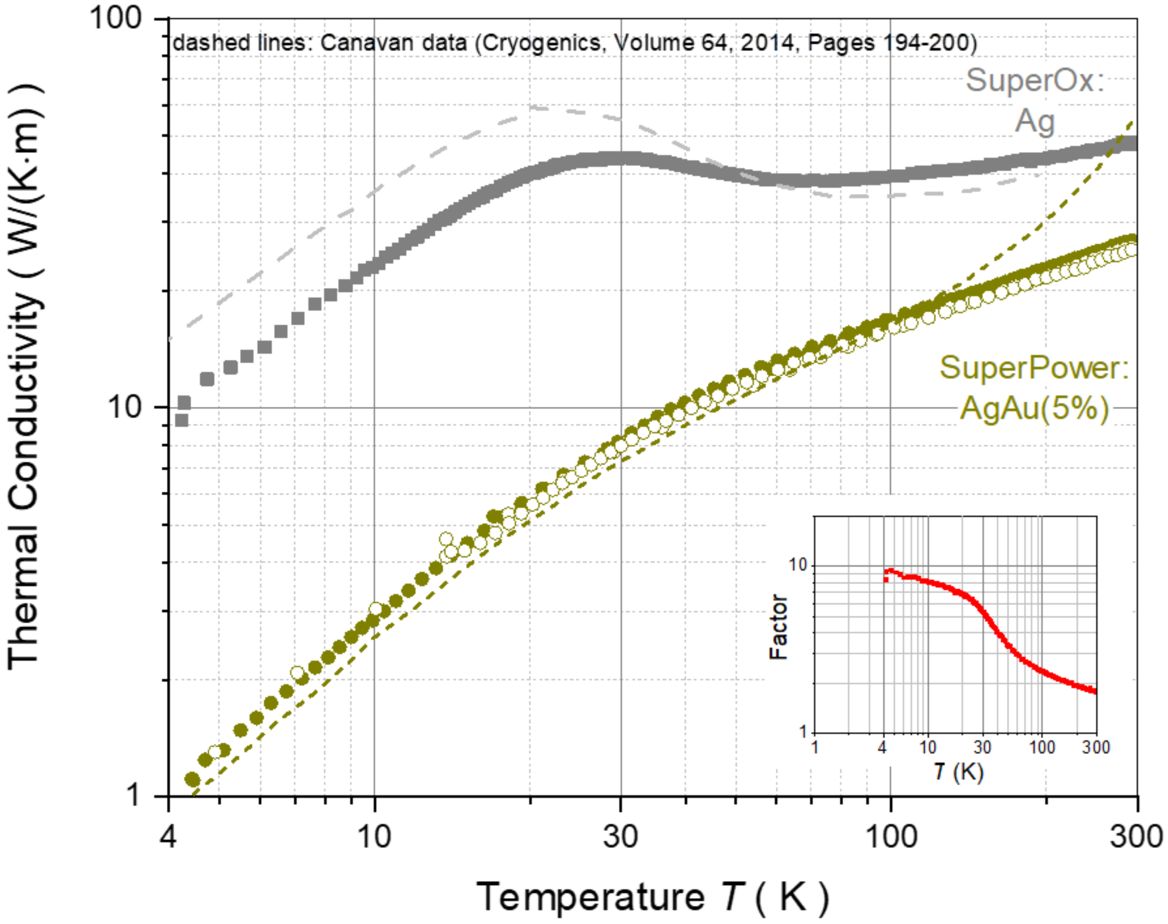
Advanced pinning (BZO doped) -> 5 A/mm @ ~ **86 K**

- SuperOx offers a higher safety margin for the same width



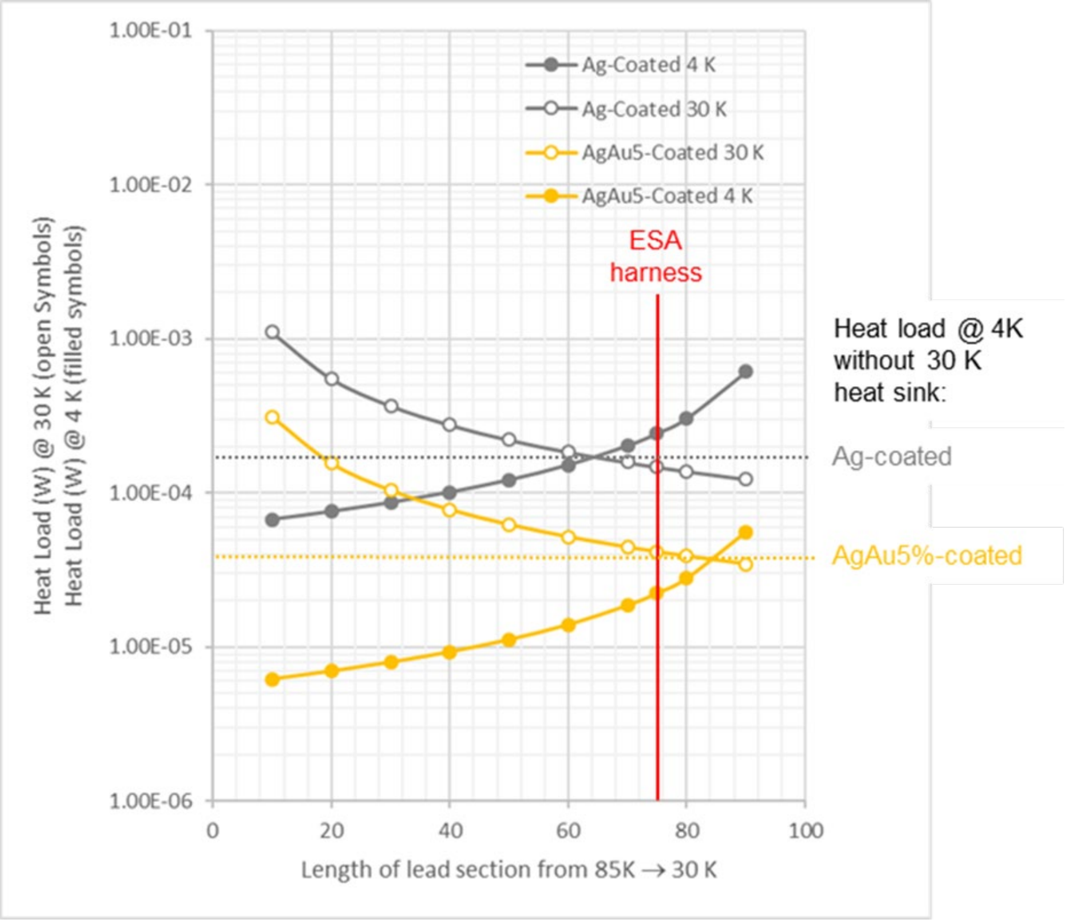
Temperature dependence of Thermal Conductivity

- As expected, AgAu-coated SuperPower tape had a lower thermal conductivity than the Ag-coated SuperOx tape.
  - ~1.75x lower @ 300K
  - ~ 10x lower @ 4K



Cap Layer Impact on 30K I/F

- Heat flow at 30K and 4K I/Fs was estimated depending on:
  - Cap Layer Material
  - Distance between 85K and 30K I/Fs
- Moving the 30K I/F further from the 85K I/F decreases the 30K heat load, but increases the 4K heat load.
- The intersection of the lines shows the heat loads without “artificial” heat sinking at 30K.
- The estimation indicated that heat sinking should be used only if the SuperOx tape was selected.



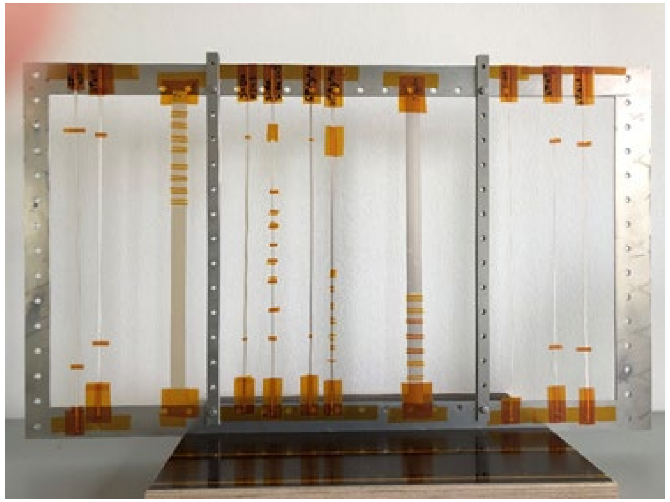
Tape Selection

- SuperOx tape was selected due to:
  - I_c of 1 mm wide SuperOx tape @ 85 K ~ 20 A, 4 times higher than the required max. Current of 5 A.
  - Higher T_c of 93 K provided high safety margin in the case of temperature rise with Ic > 5 A up to ~ 90 K.
  - Same tape width along harness --> simple geometry.
  - Ag-coated REBCO tapes with similar composition as SuperOx tape are available from as standard products.

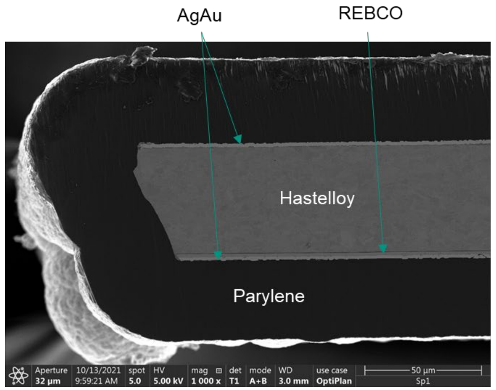
Tape	Cap-layer	Hastelloy Substrate	T_c	Ic @ 77 K Structured	Thermal Cycling	Overcurrent
SuperOx #243_323m-348m	Ag 2.5 µm + 1.3 µm	43 µm	93K	118 A @ 2 mm 57 A @ 1 mm	Yes, okay	3 A (@ 2mm, RT) okay
SuperPower	AgAu5%	50 µm	89K	47 A @ 1 mm	Yes, okay	Not performed
Fujikura	Ag ~ 3 µm	75 µm	93K	Not performed	Not performed	Not performed

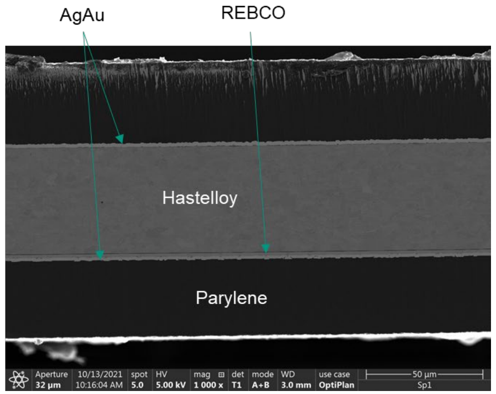
Task 2 – Jacket

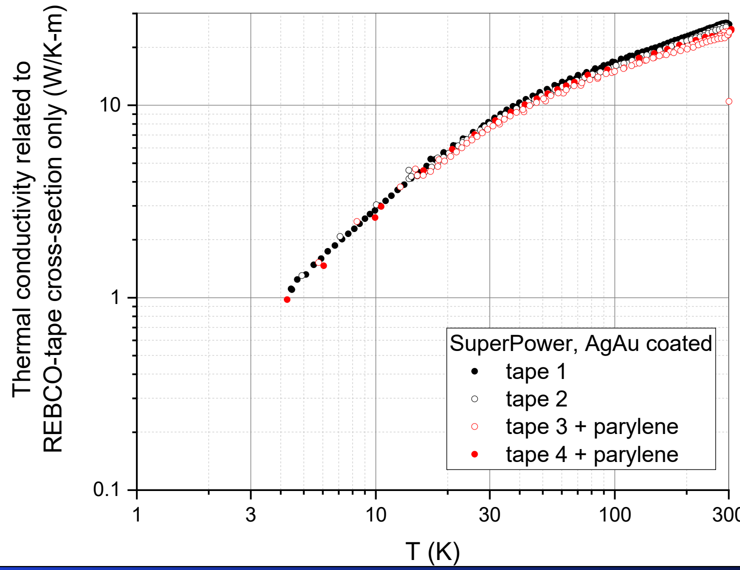
Parylene Coating Investigation



- REBCO tape samples sent for Parylene coating at Plasma Parylene Systems GmbH (PPS).
    - Kapton tape used to cover sections of the REBCO and prevent Parylene coating
- SEM analysis indicated a consistent coating thickness with no voids.
- The coating did not impact the thermal conductivity of the REBCO

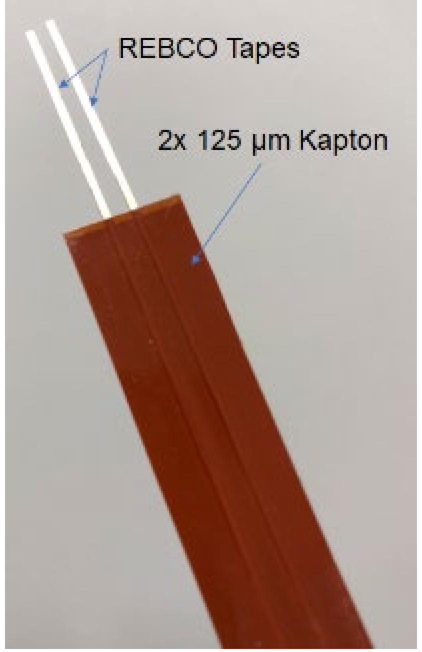


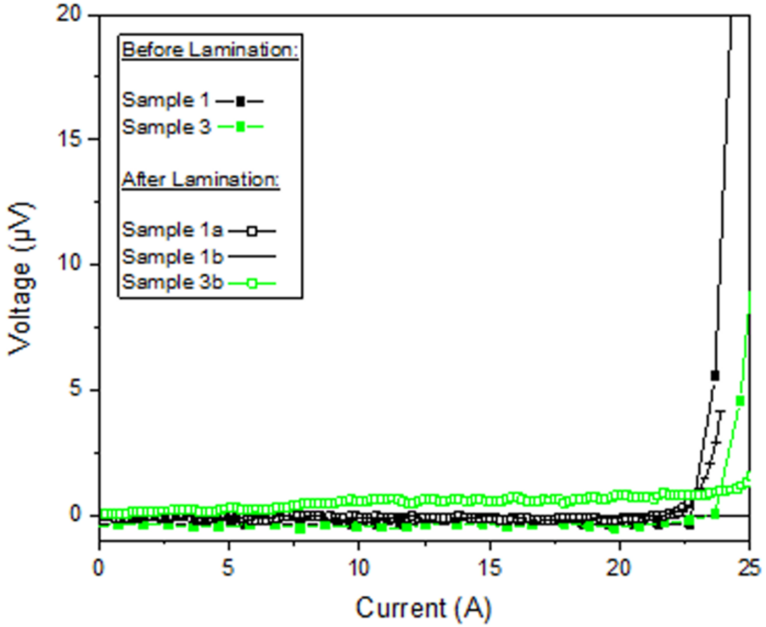


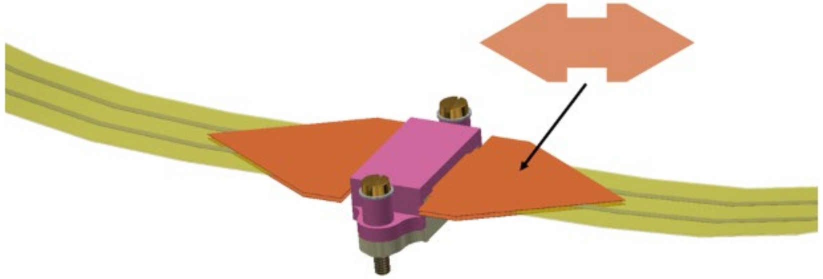


Kapton Laminate Investigation

- 1mm-wide REBCO tapes were laminated between Kapton foils to provide:
    - Electrical insulation
    - Radiation protection
    - Mechanical support
- The laminated tapes were subjected to thermal cycling between RT and 77K. No bubbles were seen, and the laminate remained tightly applied.
- The lamination process did not impact the I_c of the REBCO
- Kapton “reinforcement triangles” were designed to provide additional robustness at the mechanical supports and I/Fs

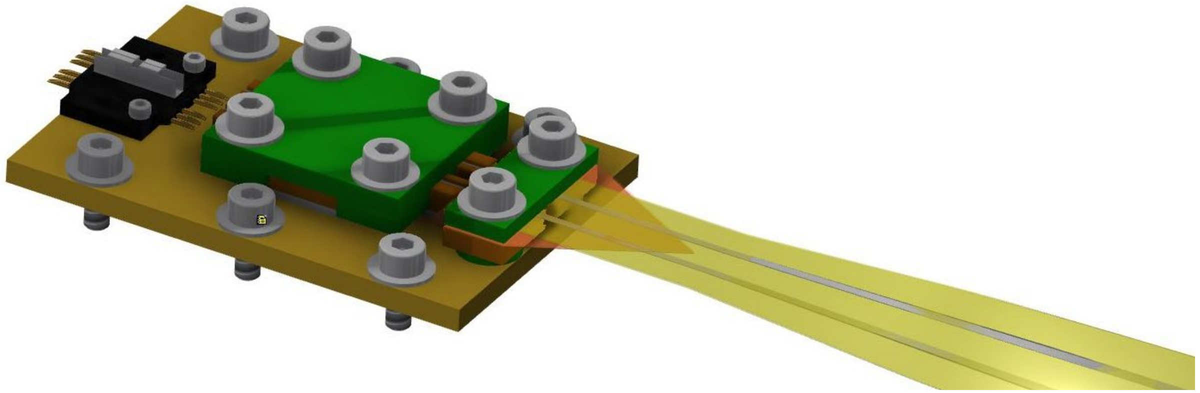


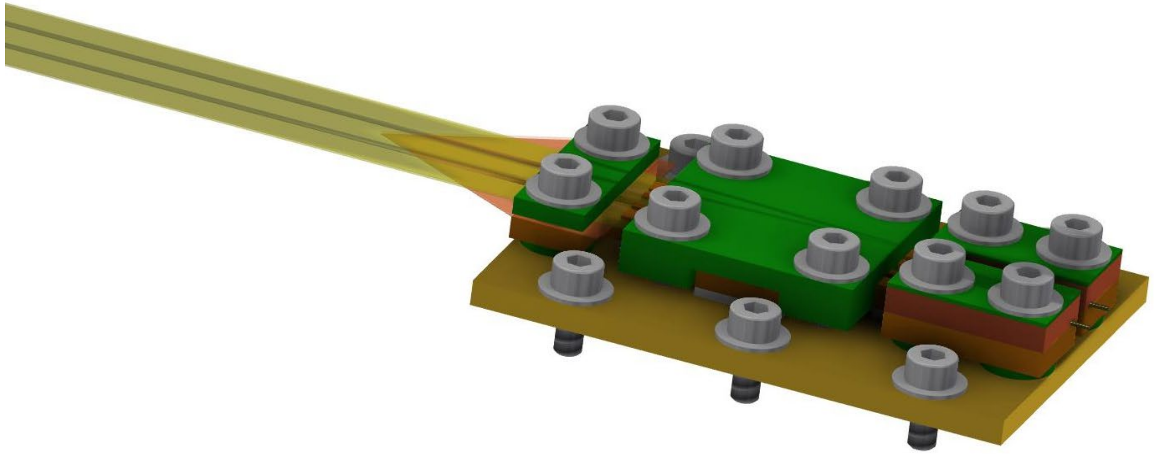




I/F Design

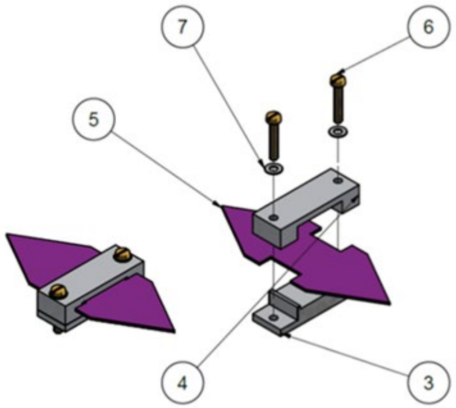
- Same basic design for both warm and cold I/F brackets.
  - Two copper blocks screwed together.
  - AlN intermediate plate with Indium foil provides electrical insulation / thermal sinking.
  - G10 plates and bushings utilised to electrically insulate the screws.
  - Kapton jacket strain relief implemented.
  - Warm I/F:
    - PhBr soldered to Microstrip connector
    - Cu soldered to Microstrip connector and copper block
    - REBCO soldered to copper block
  - Cold I/F:
    - NbTi soldered to copper block
    - REBCO soldered to copper block



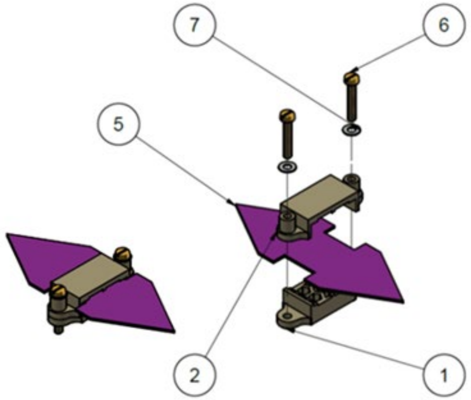


Mechanical Support Design

- Two part design which clamps the cable.
- Large surface area to spread the clamping force over the cable and minimise the load on the REBCO.
- 30K mechanical support is made of Aluminium to increase thermal sinking to the 30K I/F.
- 80K mechanical support is made of PEEK and utilises a "grid" design to minimise the thermal connection to the 80K I/F.



30 K Mechanical Support (Al)



80 K Mechanical Support (PEEK)

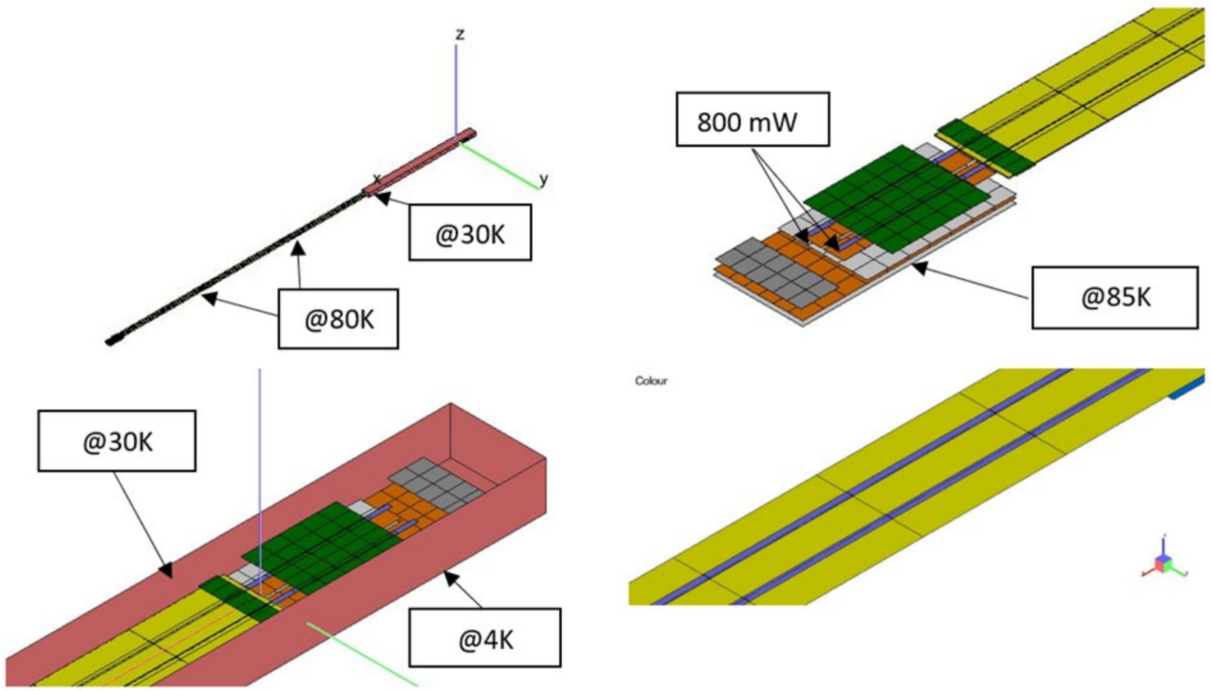
EM Summary

The EM consists of the following components:

- 2 x Ag-coated SuperOx REBCO tapes, 43 μm substrate, laser-cut to 1mm width throughout the harness.
- A Parylene C coating to provide humidity protection and electrical insulation.
- A Kapton laminate coating to provide further electrical insulation, radiation protection, and mechanical support.
- Screwed electrical I/F connections utilising copper plates for reduced resistivity, and Aluminium Nitride plates for effective thermal sinking.
- Soldered electrical connections between the REBCO tapes and the copper plates at the I/Fs.
- 3D printed PEEK mechanical support structures, to minimise thermal conductivity.
- An aluminium mechanical support structure at the 30K I/F, to maximise heat sinking at this point.

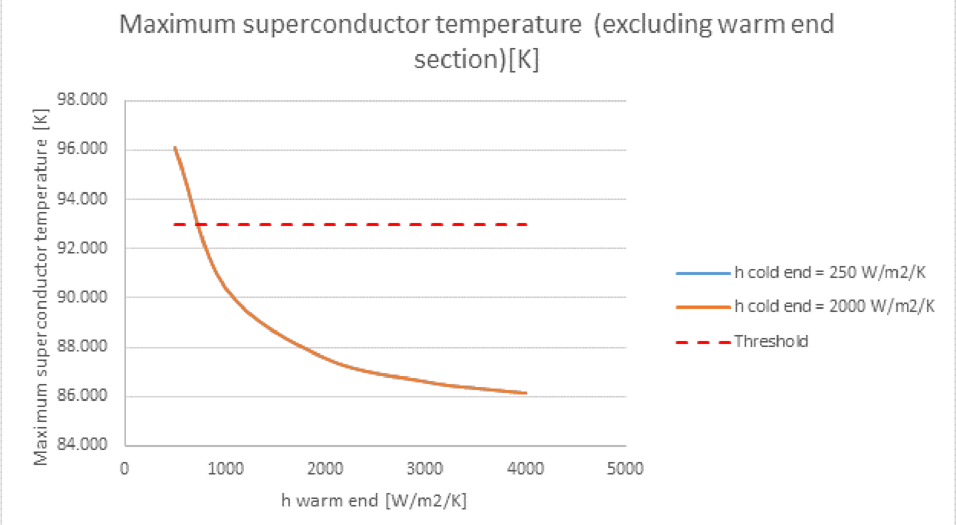
Thermal Analysis Setup

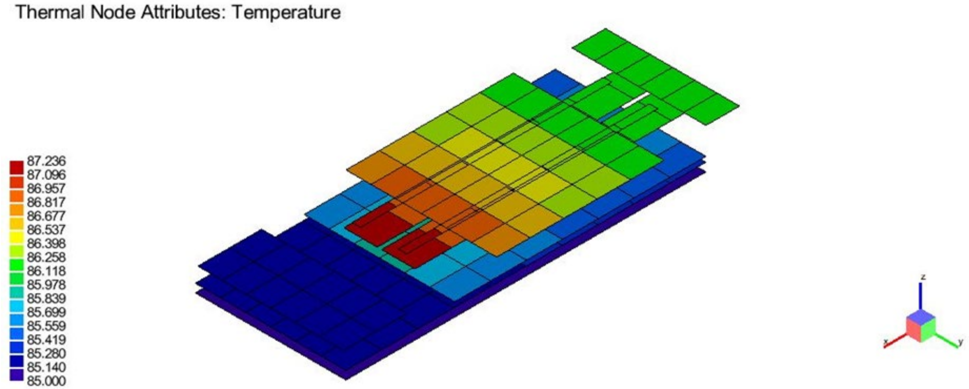
- Thermal model constructed in ESATAN with following boundary conditions:
  - Warm end mechanical I/F temperature set @85K
  - Mechanical Support Structure I/F set @80K (x2) and @30K (x1)
  - Heat injection of 800mW at warm end
  - Radiative environment set:
    - @80K for the section of the cable between the warm end and the 30K I/F
    - @30K for the section of the cable between the 30K I/F and the cold end
  - Cold end mechanical I/F temperature set @4K

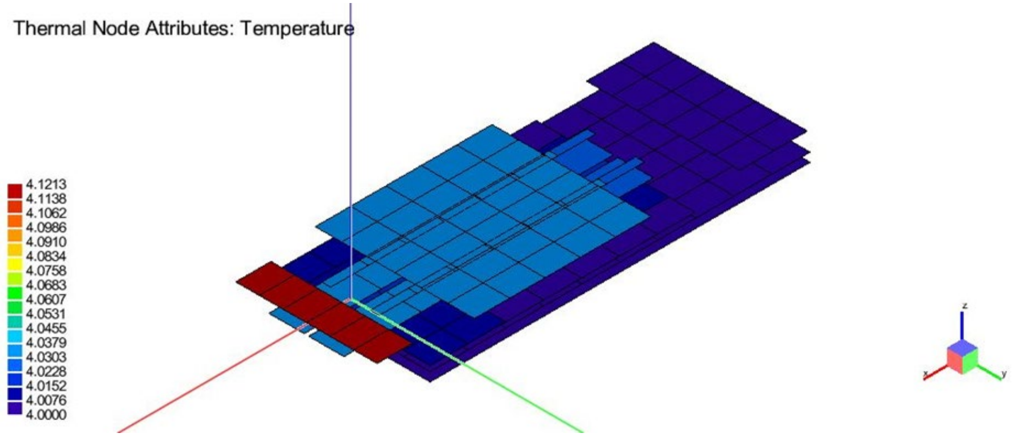


Thermal Analysis Results

- Sensitivity analyses performed regarding the thermal contact at the I/Fs and the conductive links at the support structures.
- Cable temperature < 90K if 1500W/m²/K thermal contact could be achieved at warm end.



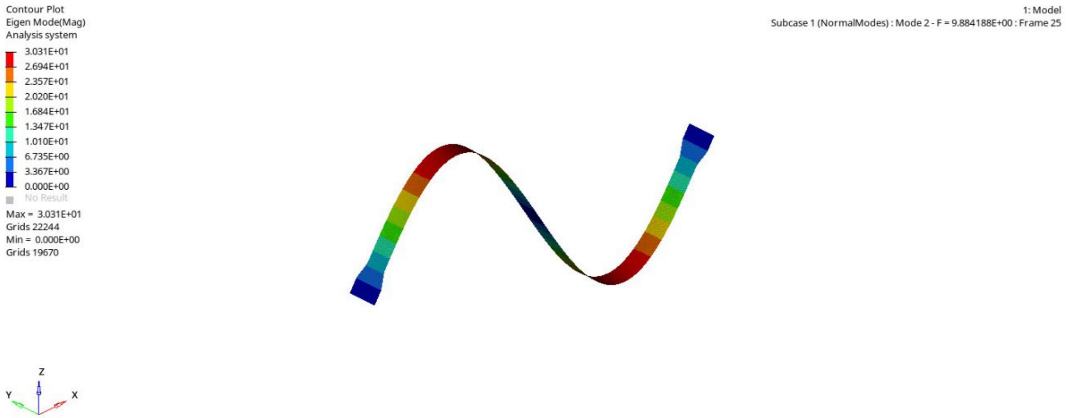




Task 2 – EM Design

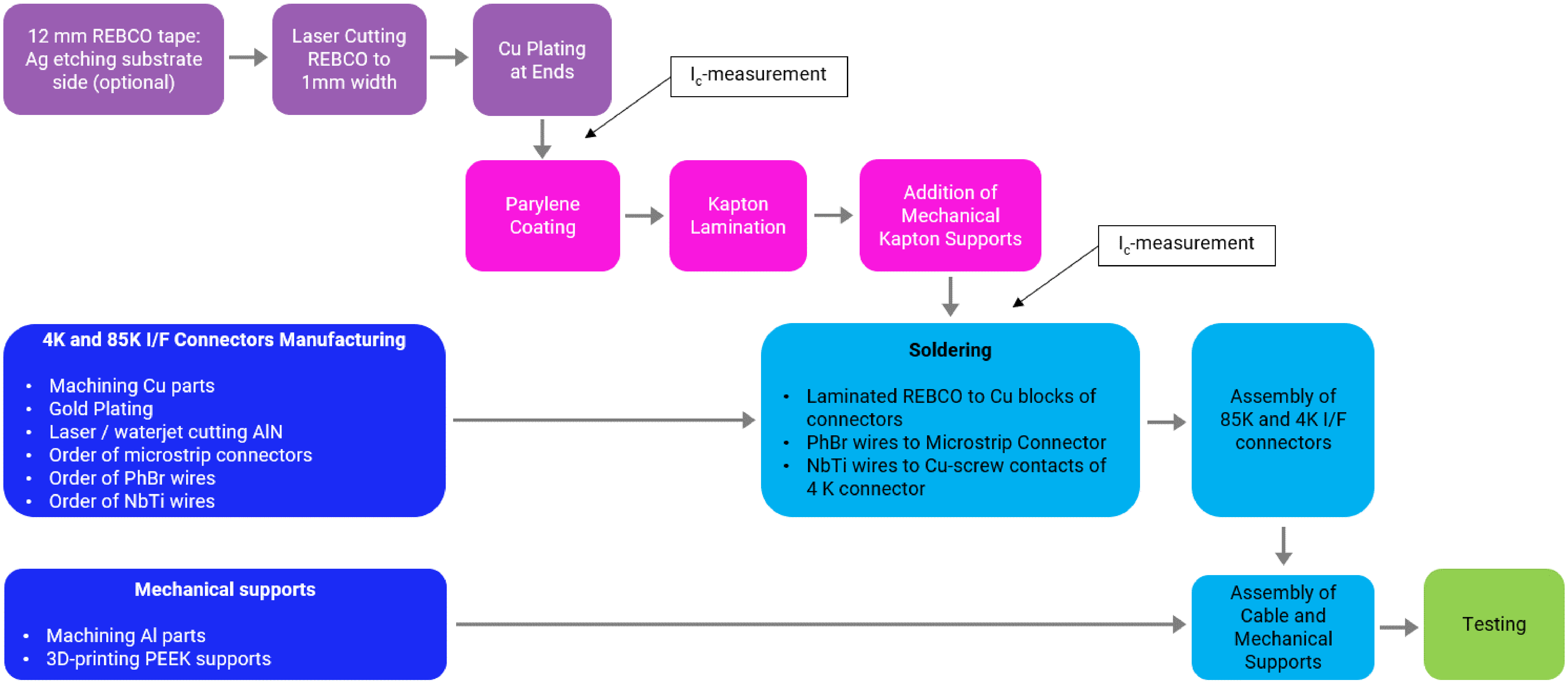
Structural Analysis

- Structural model setup in Hypermesh / Optistruct focusing on the cable length between I/Fs / support structures.
- Various configurations tested:
  - With and without CFRP strips.
  - 25cm vs 30cm span lengths
  - Simple supports and clamped supports.
- Margin of Safety > 9 for Kapton in the worst-case scenario (QSL and Random Loads)
  - > 38 for the REBCO tapes
- Inclusion of CFRP showed minimal benefits.
- No correlation between stress and span length
- Sine and shock loads could not be simulated due to non-linear behaviour of the cable.
  - Mechanical sample to be manufactured to de-risk the mechanical testing.



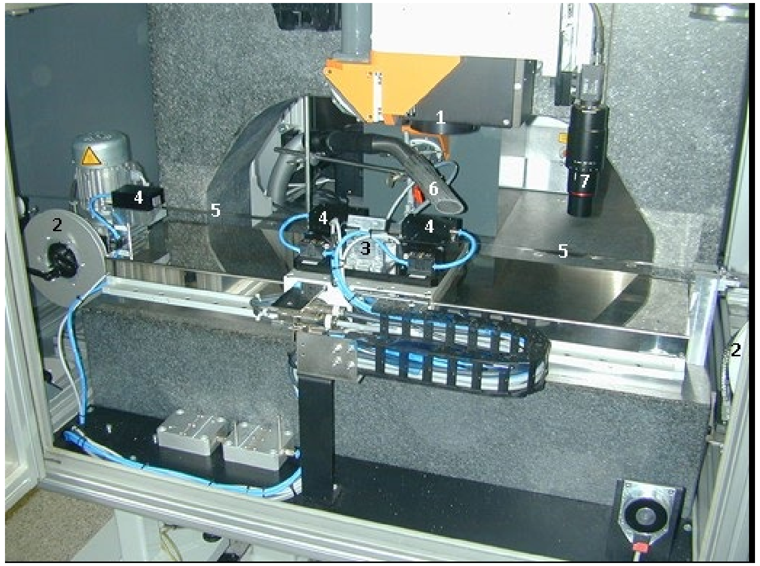
Task 3: Manufacture & Design

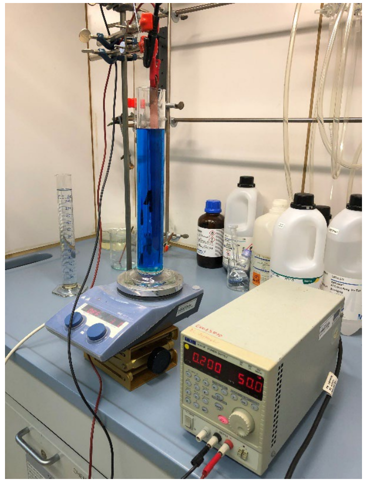
Task 3 – Manufacturing Plan

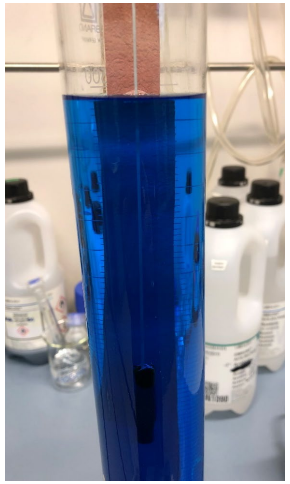


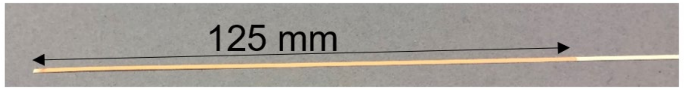
Laser Cutting & Electroplating

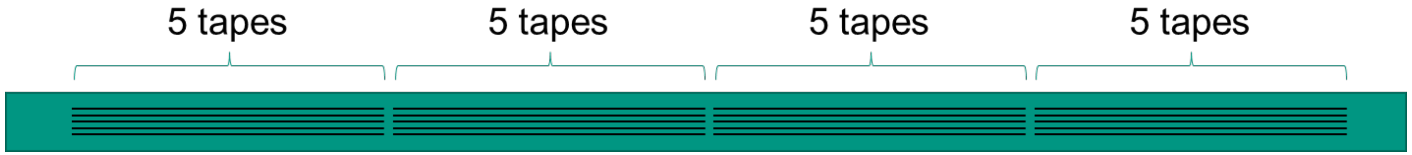
- Tapes cut using an infrared Nd:YAG laser.
    - 5 x 1mm-wide tapes cut from a 12mm-wide tape.
    - 1250mm length tapes cut to allow for electroplating.
- Electroplating performed in an electrolytic bath.







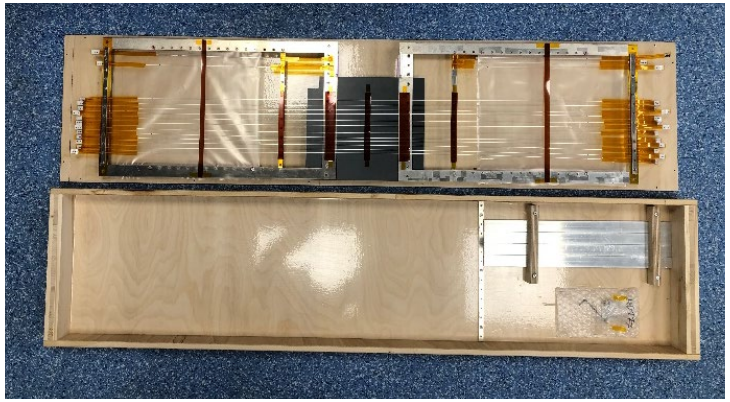


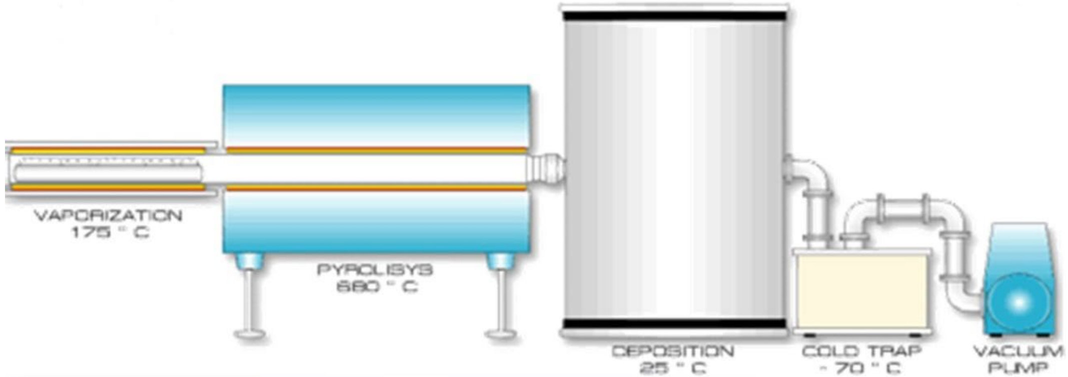


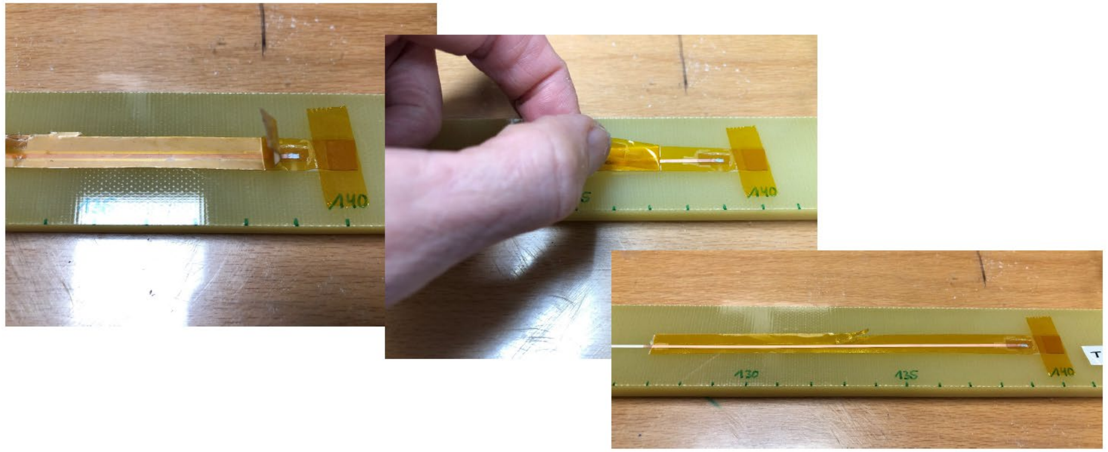
Task 3 – HTS

Parylene Coating

- REBCO surfaces must be free to be coated, while the coating chamber has a limited size.
    - Solution: Hang the tapes from a frame.
    - Frame designed to be collapsed for transportation without the need to dismount the tapes
- Kapton used to cover the REBCO where coating is not desired i.e., at tape ends. This is removed by hand after the process.

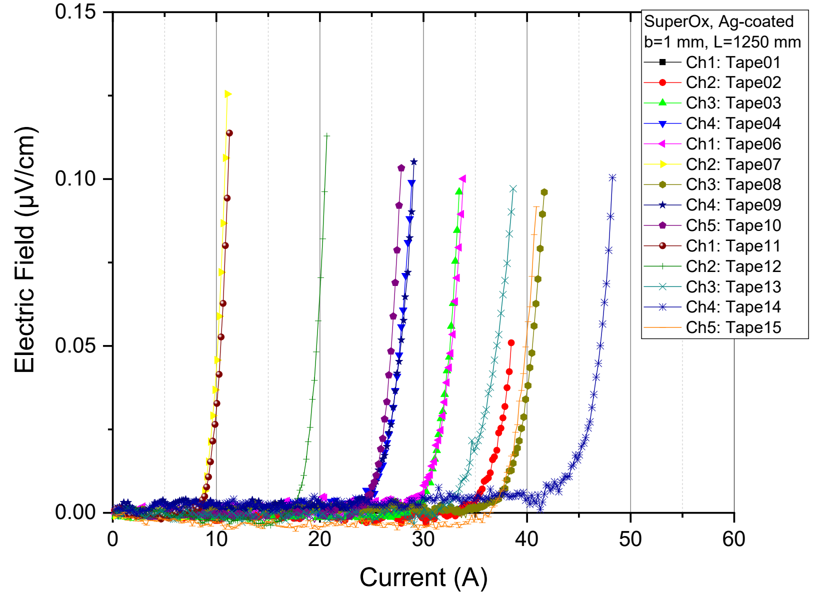


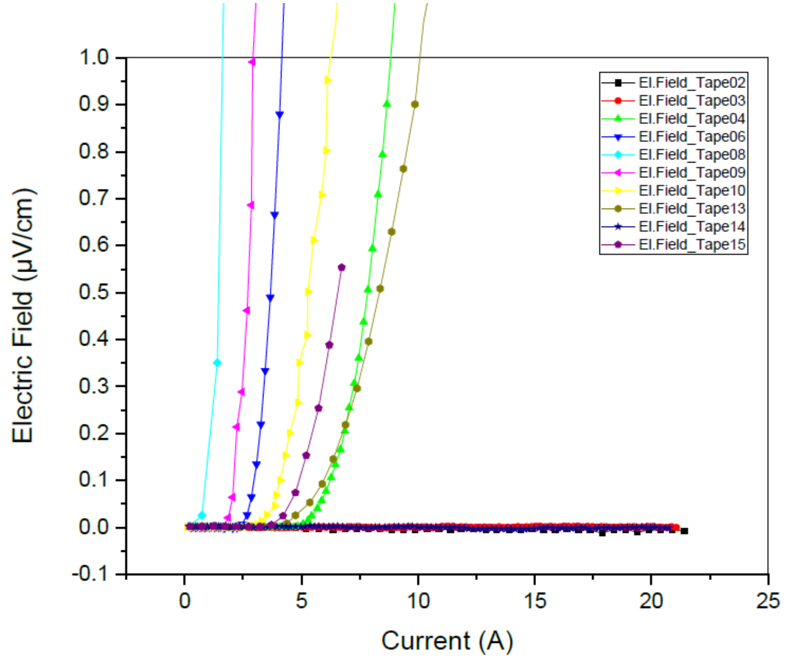


Task 3 – HTS

Batch 1 Tapes



Parylene Coating →



<u>Before Coating</u>

- 15 tapes produced | 2 tapes damaged | 3 tapes with low I_c < 20A | 10 usable tapes > 20A

<u>After Coating</u>

- 3 Tapes with I_c > 20A | all other tapes significantly degraded

Batch 1 Tapes – Cause of Failure

Step	Step Description	Damage Possible?
1	I_c measurement after laser cutting and electroplating	Tapes showed sufficient I_c **Damage unlikely**
2	Application of Kapton foil to Cu-plated ends	The tapes were not subject to unusual stress. **Damage unlikely**
3	Mounting of tapes within transportation frame	Potential bending of the box **Damage possible**
4	Transportation of tapes to PPS	Unknown handling conditions and loads **Damage possible**
5	Disassembly of frame from transportation box and vertical assembly	Disassembly performed by 3rd party **Damage possible**
6	Executing of Parylene coating	Test samples coated in task 2 without issue **Damage unlikely**
7	Disassembly of frame and re-mounting within transportation box	Disassembly performed by 3rd party **Damage possible**
8	Transportation of tapes to KIT	Unknown handling conditions and loads **Damage possible**
9	Dismounting of HTS tapes from frame	Dismounting performed by KIT persons **Damage unlikely**
10	Removal of Kapton from tapes	Removal was difficult and required the use of tools **Damage possible**

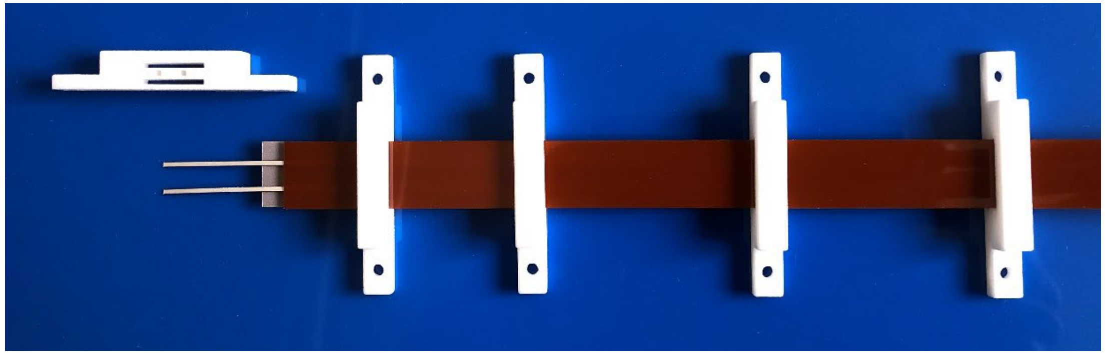
Batch 2 Tapes

- First batch of tapes discarded due to uncertainty of functionality.
  - Some tapes used for mechanical test sample
- Second batch of tapes produced (overall 40 tapes).
  - Several tapes damaged during electroplating -> new clamps implemented.
- 17 tapes selected for second round of Parylene coating
  - New transportation frame developed to increase robustness.
  - Transportation and coating process overseen personally by Dr. Schlachter from KIT
  - 8 tapes with I_c > 40A
  - 9 tapes with I_c > 23A

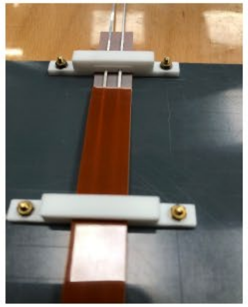
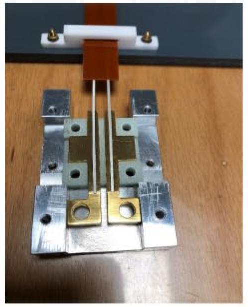
Task 3 – Kapton

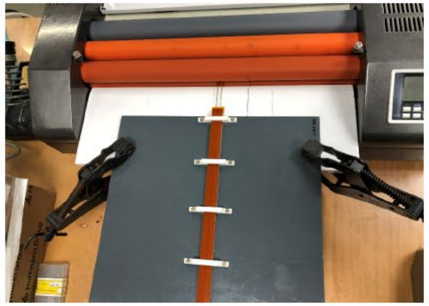
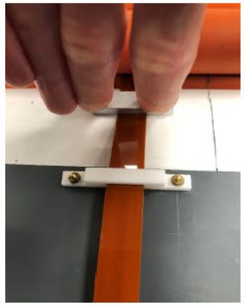
Lamination Process

- Kapton foil cut to correct size with paper guillotine.
- Lamination aids 3D printed to ensure correct alignment of REBCO and Kapton laminate.

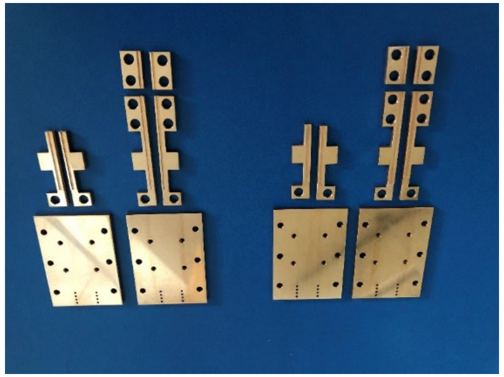


reels

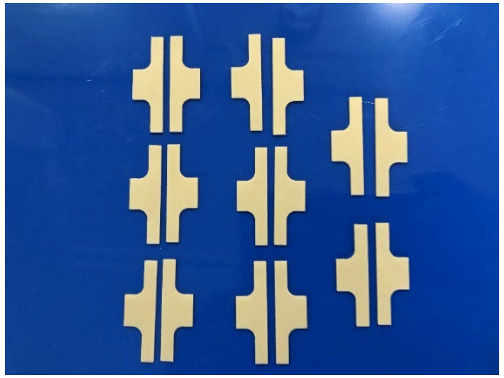



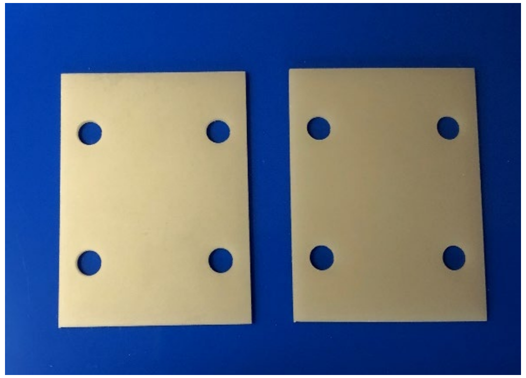
Component Manufacture



Copper Parts

- Standard machining.
- Gold plating
- 3 sets produced



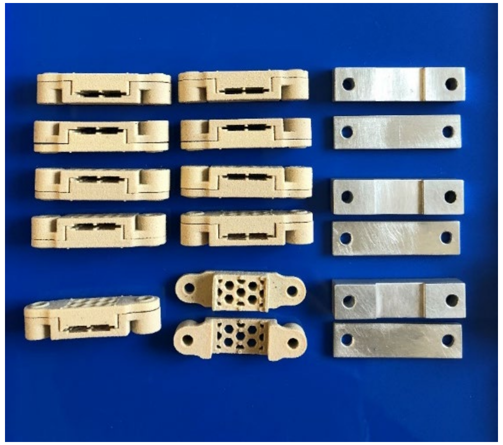


Aluminium Nitride Parts

- Waterjet Cut.
- Redesign during Task 2 to have one single plate rather than 2 separate ones -> simpler assembly, reduced arcing risk.

G10 Parts

- Standard milling, drilling, and turning.
- Waterjet Cut

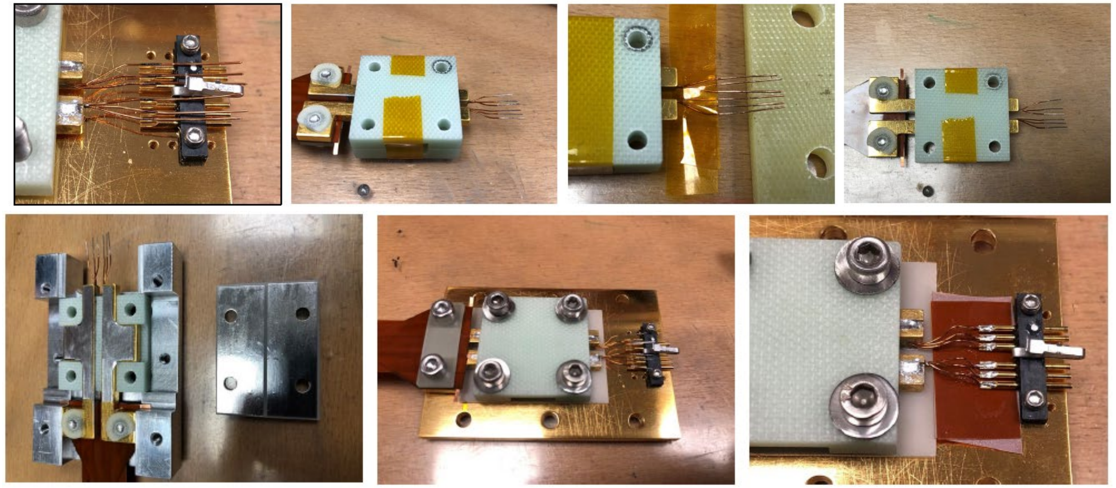


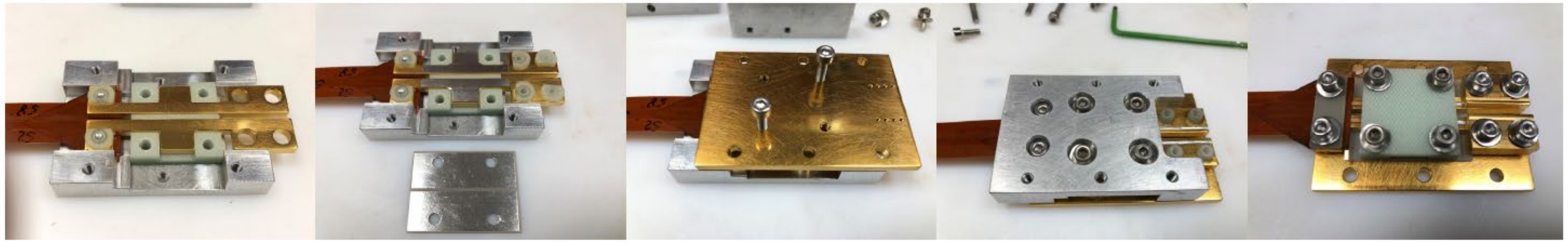
Support Structures

- PEEK: 3D Printed (Selective Laser Sintering
- Aluminium: Standard Machining

Task 3 – EM Assembly

- 2 EMs assembled:
  - Test EM: Preliminary thermal characterization.
  - Qualification EM: Full testing campaign.
- Cable assembled first with cut REBCO tapes and Kapton lamination incl. triangles.
- Copper wires soldered to I/F copper blocks.
- REBCO cable soldered to I/F copper blocks.
- I/Fs then assembled using guidance GSE.
- Similar process for mechanical sample





Task 3 – Testing

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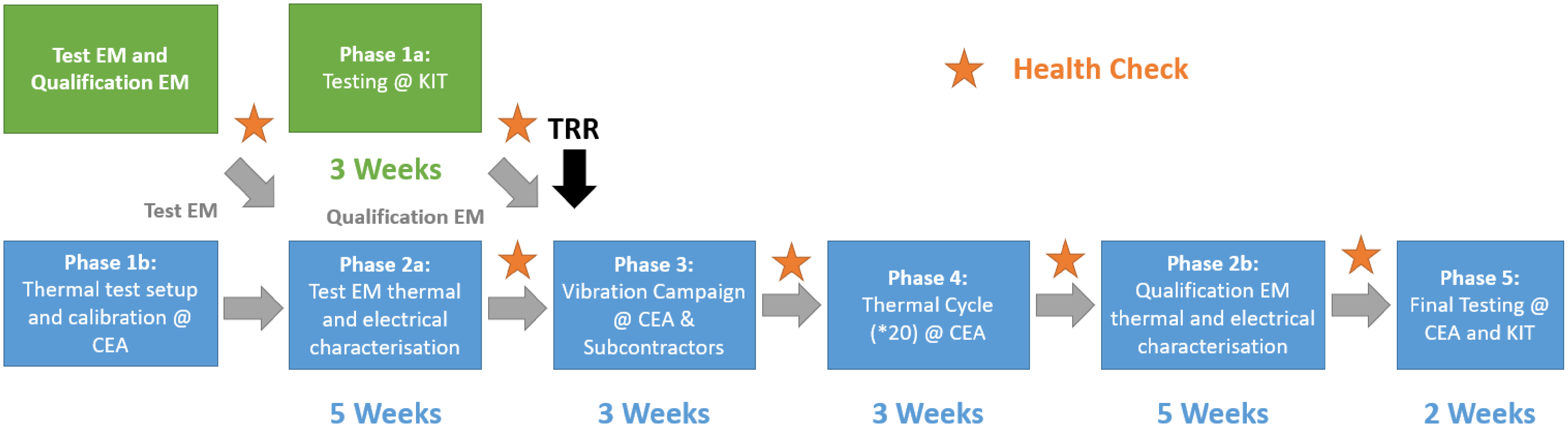
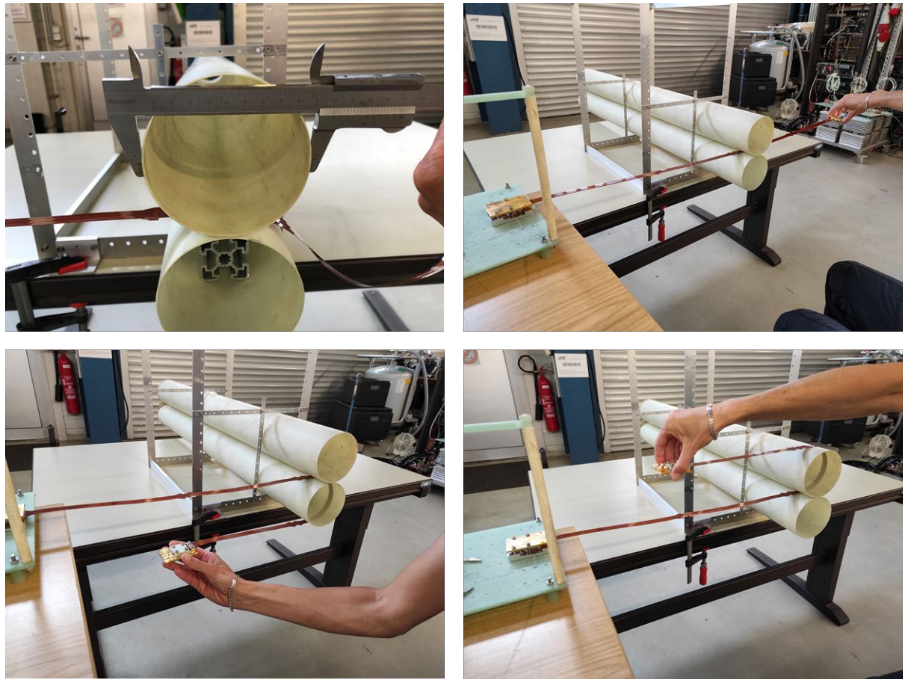
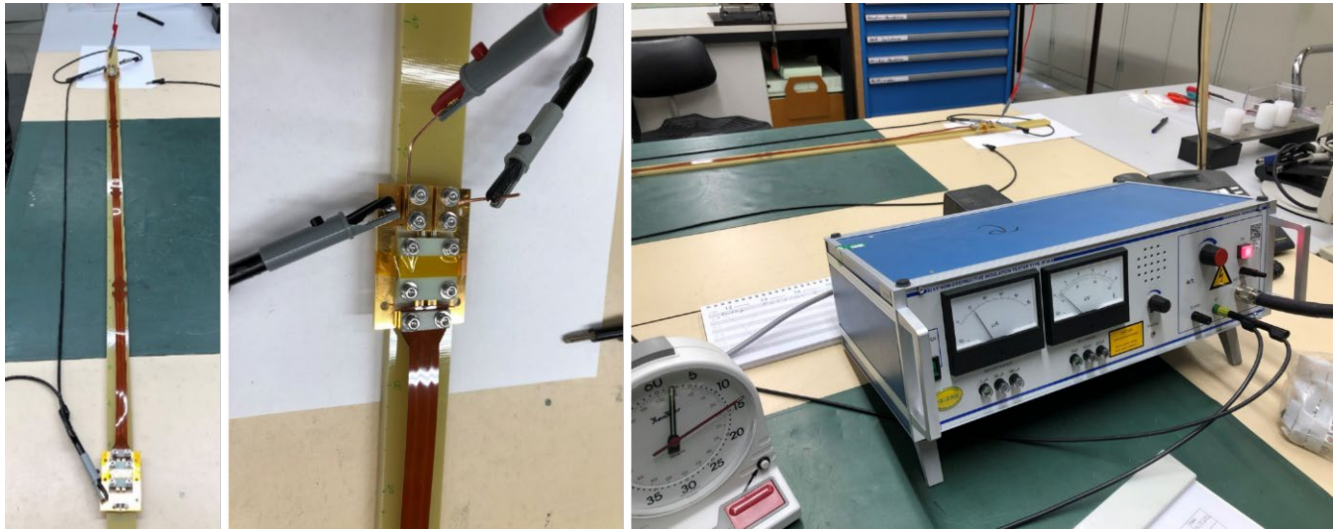
Test Logic



Task 3 – Testing

Phase 1a





Bending Tests

- 1000 bends performed manually.
- No I_c degradation

High Voltage Tests

- 200 V applied between the REBCO tapes, and between the REBCO and I/F
- All resistances measured above 800MΩ
- No I_c degradation

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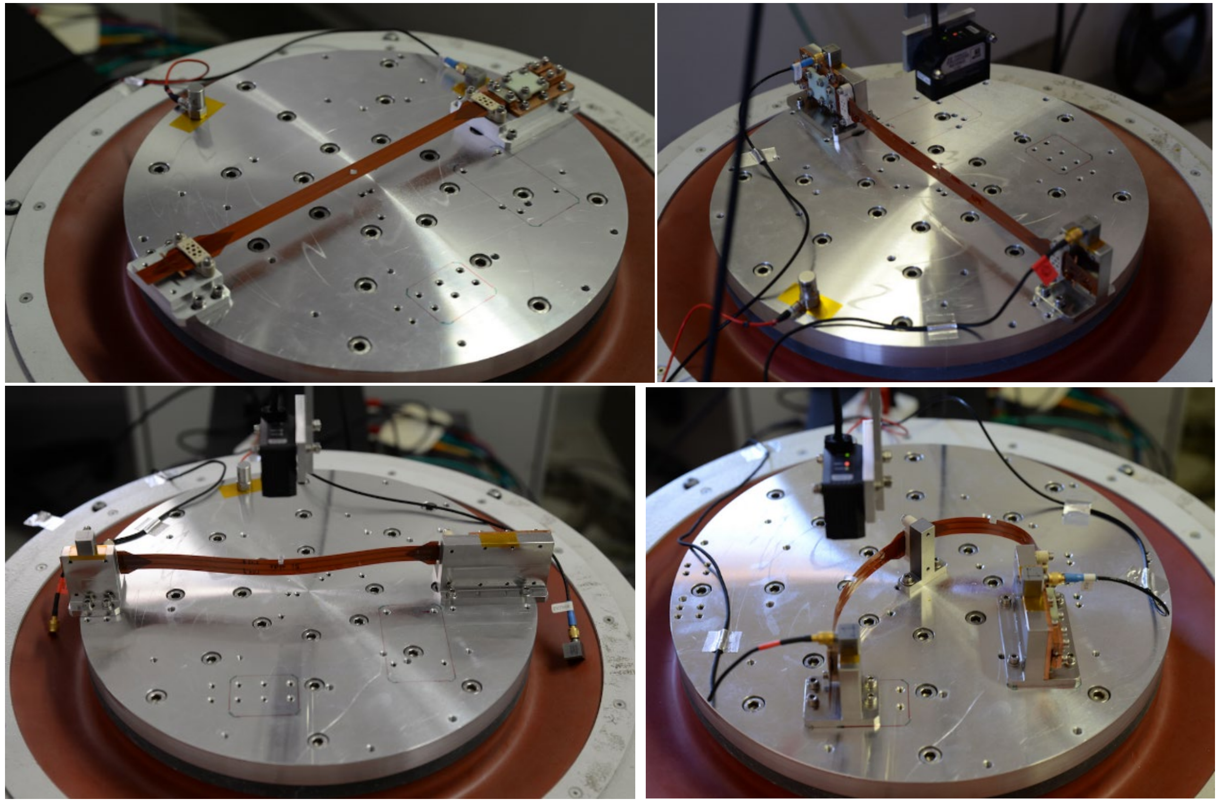
Phase 1b

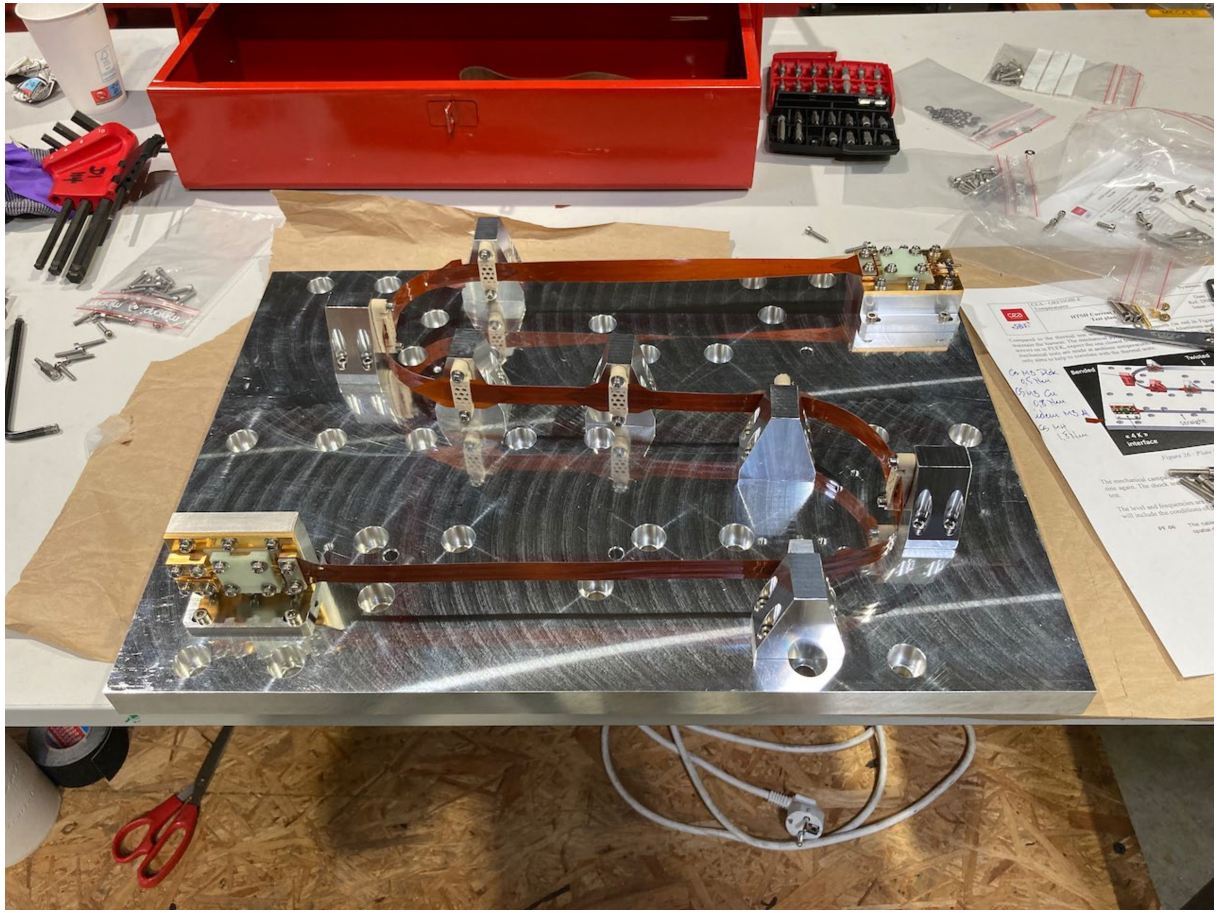
- Thermal test setup validated by measuring the thermal conductivity and power dissipation measurements of the various supports.
- Mechanical sample subjected to low sinus and random loads in various configurations (straight, bent, taut, with slack).
  - No visible degradation of the sample.
  - No I_c degradation
- Laser measurement system implemented to measure displacement and validate mechanical simulations.
  - Resonant frequency in the shaker test table made direct comparisons difficult.

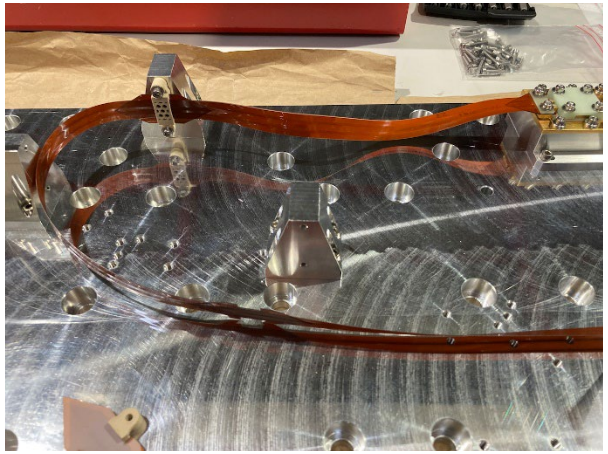


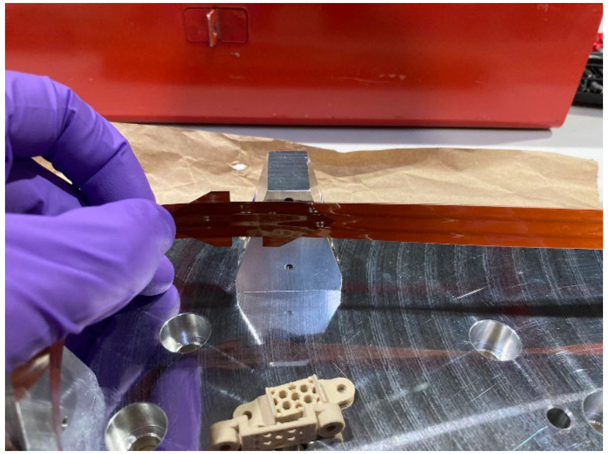
Task 3 – Testing

Phase 3

- Full mechanical test at subcontractor premises.
- Cable spans did not match the shaker plate!
    - Kapton triangles had to be cut away to allow mounting of the tape.
    - Aluminium tape added to prevent lateral movement.
- Despite the reduced mechanical robustness, the cable showed no visible signs of degradation, and no I_c degradation.

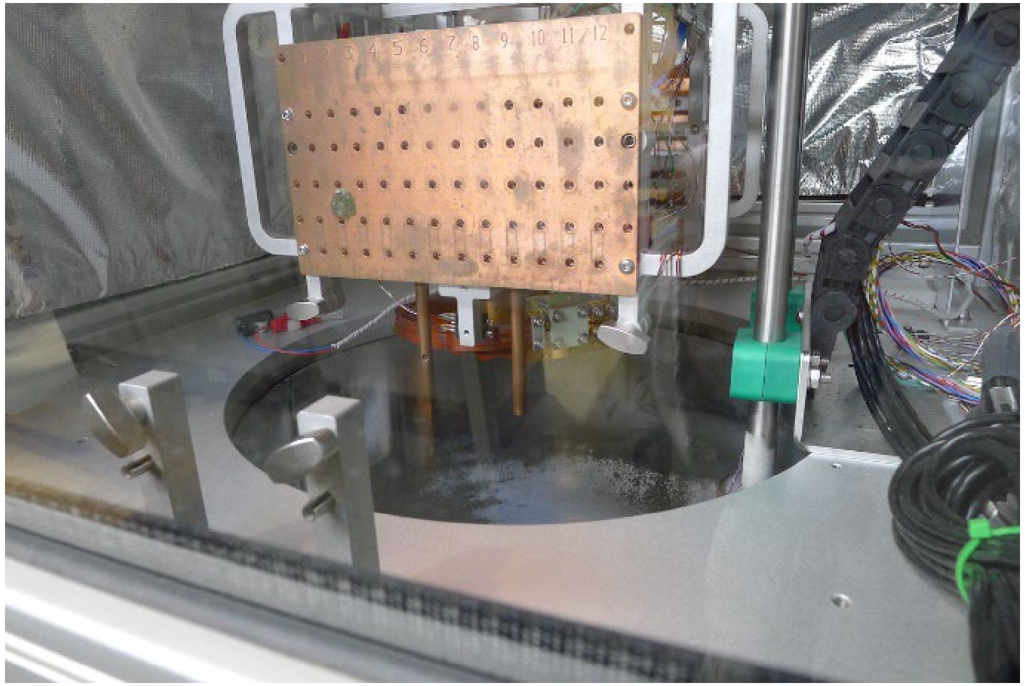






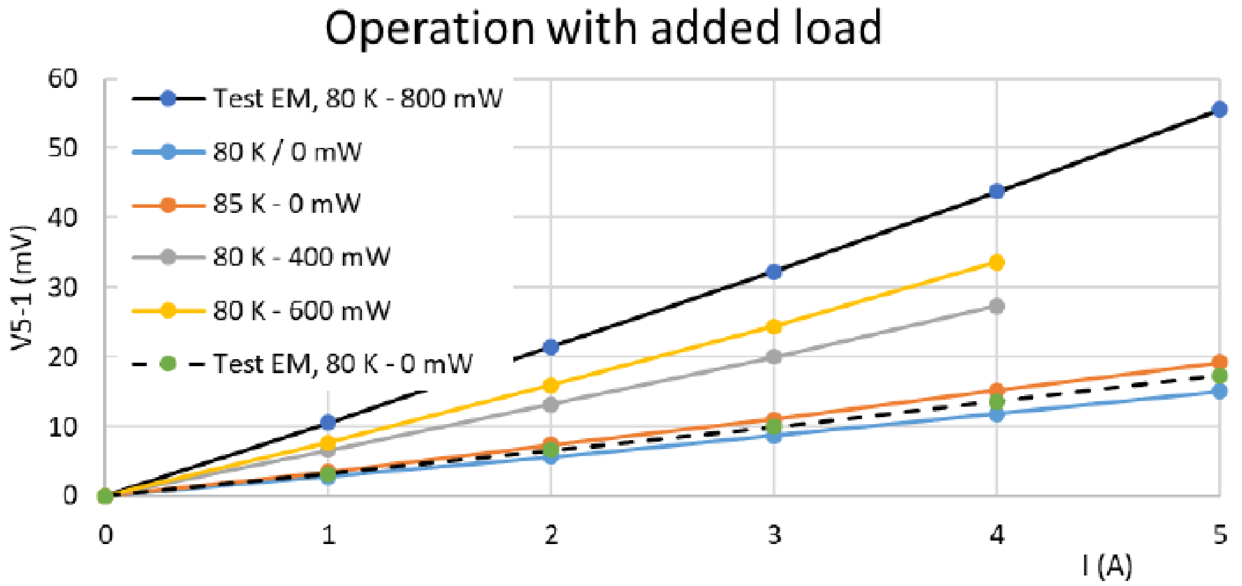
Phase 4

- Thermal cycling of the EM between RT and 77K – 20 cycles performed.
- Automated test setup implemented to improve schedule.
- No I_c degradation



Phase 2b

- Full thermal and electrical characterisation performed on the qualification EM.
- Conductive and radiative heat load contributions were validated to match simulations.
- Ohmic heating was 2 orders of magnitude higher than expected, resulting in 1.6mW @ 4K
  - This was due to low torque in the screw connection due to the G10 bushing.
  - Unit tests after phase 2b indicated that higher torques with stainless steel washers achieved the 1mW requirement.
- Dissipation at 30K I/F was validated vs simulations.
- Combinations of all three extreme requirements at the warm end I/F (i.e., 5A current, 85K temperature, 800mW heat load) could not be implemented without overheating of the cable. In particular, the 800mW was considered too high as this even precluded the use of the PhBr wires.



Task 4: Final Review, Assessment and Outlook

Task 4 – Requirements Compliance

Compliance Matrix

RQ ID	Compliant?	RQ ID	Compliant?	RQ ID	Compliant?
GE-01	C	PF-04	PC	JA-01	C
GE-02	C	PF-05	C	JA-02	PC
GE-03	C	PF-06	C	IF-01	PC
GE-04	PC	PF-07	C	IF-02	C
GE-05	C	PF-08	NC	IF-03	C
GE-06	C	PF-09	C	IF-04	C
GE-07	C	PF-10	C	IF-05	C
GE-08	C	EN-01	C	IF-06	C
GE-09	C	EN-02	C	IF-07	C
GE-10	C	EN-03	C	IF-08	C
PF-01	C	EN-04	C	IF-09	C
PF-02	C	EN-05	PC	IF-10	C
PF-03a	C	EN-06	C	IF-11	C
PF-03b	C	EN-07	C	IF-12	C
PF-03c	C	EN-08	C	IF-13	C

Task 4 – Requirements Compliance

Partial Compliance

- **GE-04: Outgassing**
  - The Kapton tape exhibits outgassing above 120 ^{o}C, whereas ESCC standards specify 125 ^{o}C for outgassing tests. Considering the upper qualification temperature of 40 ^{o}C, this partial compliance is not an issue.
- **EN-06: Thermal Cycling**
  - The requirement specified thermal cycling between the qualification temperature limits (down to 4K), whereas cycling was only performed down to 77K due to schedule limits. Negative effects of thermal cycling are expected to occur by this point and hence, this partial compliance is considered acceptable.
- **JA-02: Jacket Compliance**
  - Full compliance is not possible due to the unique nature of the HTS tapes.
- **IF-01 & PF-04: Warm End I/F Temperature**
  - Compliance to this requirement depends on the operational configuration. E.g.., at 2A this requirement is compliant, but at 5A and including the 800mW, it is not.

Non-Compliance

- **PF-08: Heat Load**
  - Operation with 800mW heat load was only possible at 80K interface temperature, hence the requirement is non-compliant. This requirement could be relaxed with optimised current leads.

Task 4 – Improvements for future designs

- **HTS Cable Handling**
  - Handling of the 1mm-wide tapes was difficult (commercial tapes are usually provided in 4, 8, or 12mm widths), and damage could be easily caused if proper care was not taken. It is recommended that people familiar with HTS handle the raw tapes before Kapton lamination. After this, the cable is much more robust.
- **Power Supply**
  - Additional specifications for the power supply are needed to prevent quenching of the REBCO, not only in operation, but also during integration and testing. A current and voltage limited supply is recommended with an automatic shut off in case a specified current (5A) or temperature limit (85K) is crossed.
- **85K Interface Temperature**
  - This temperature provided very little margin for the harness operation. In combination with the 800mW heat load, the requirements were too ambitious for the produced design. This could be improved by 1) using Stycast instead of AlN for better thermal sinking, 2) decreasing the 85K value, or 3) optimise the
- **I/F design improvements**
  - Use of G10 blocks to double insulate enamelled copper wires soldered to the Microstrip connector.
  - Addition of an external insulating housing to the I/F brackets.
  - Improvement of the assembly process to minimise solder degradation risk.
  - Use of countersunk stainless-steel fasteners and washers to enable high fastening torque.

Task 4 – Roadmap and mission applicability

Roadmap

- **TRL 5 -> TRL 6 (1 year)**
  - Updated requirements specification | Evaluation of alternative HTS tape supplier | New EM production incorporating identified design improvements | Update and approval of assembly and process documentation.
- **TRL 6 -> TRL 7 (1.5 years)**
  - Manufacture of a full, flight-representative harness assembly, using flight-grade hardware where possible.
  - The full system, including relevant interfaces and electronics, should be exposed to the environmental profile of the mission, including longer duration testing and exposure to additional failure modes.
- **TRL 7 -> TRL 8 (1.5 years)**
  - A flight model needs to be produced which will be subjected to the full qualification program, including significant margin on the extent of the environmental conditions.

Mission Applicability

- ATHENA and the X-IFU remain the main target mission for this harness. Future developments may reduce the warm end temperature to improve margin, whereas other design options, such as the use of 5 ADRs and hence 5 harnesses, are also possible.

Conclusions

- 8 out of 11 sub-objectives were fully achieved, 2 were partially achieved, and 1 was surpassed thanks to the production of 2 EMs and the mechanical sample.
- Although not all requirements were fully compliant, the performance against the specification was generally good, with only the most extreme and ambitious of the requirements posing problems.
- Many of the more significant challenges encountered during the project, such as the HTS cable processing and the mechanical design of the harness, have been successfully overcome, overall indicating a robust core design which can be easily adapted and scaled for future needs.
- **A key component, which is critical for the execution of future scientific missions, has been successfully developed and demonstrated.**

Acknowledgements to the Project Team

KIT: Sonja Schlachter, Antje Drechsler, Nadezda Bagrets, Manuela Erbe, Rainer Nast, Bernd Ringsdorf, Bernhard Holzapfel
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ESA: Robert Kroll, Moritz Branco, Martin Linder, Adrian Graham, Alexandru Vargalui
NSS: David Hindley, Manuel La Rosa Betancourt, Kapish Aggarwal, Feroz Khan, Elias Bögel, Jaime Martin Lozano

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