The Technologies of the EuCARD2 HTS Accelerator Dipole Magnet Development

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Talk Overview

EuCARD2 magnet

Development of design tools

Philosophy for models

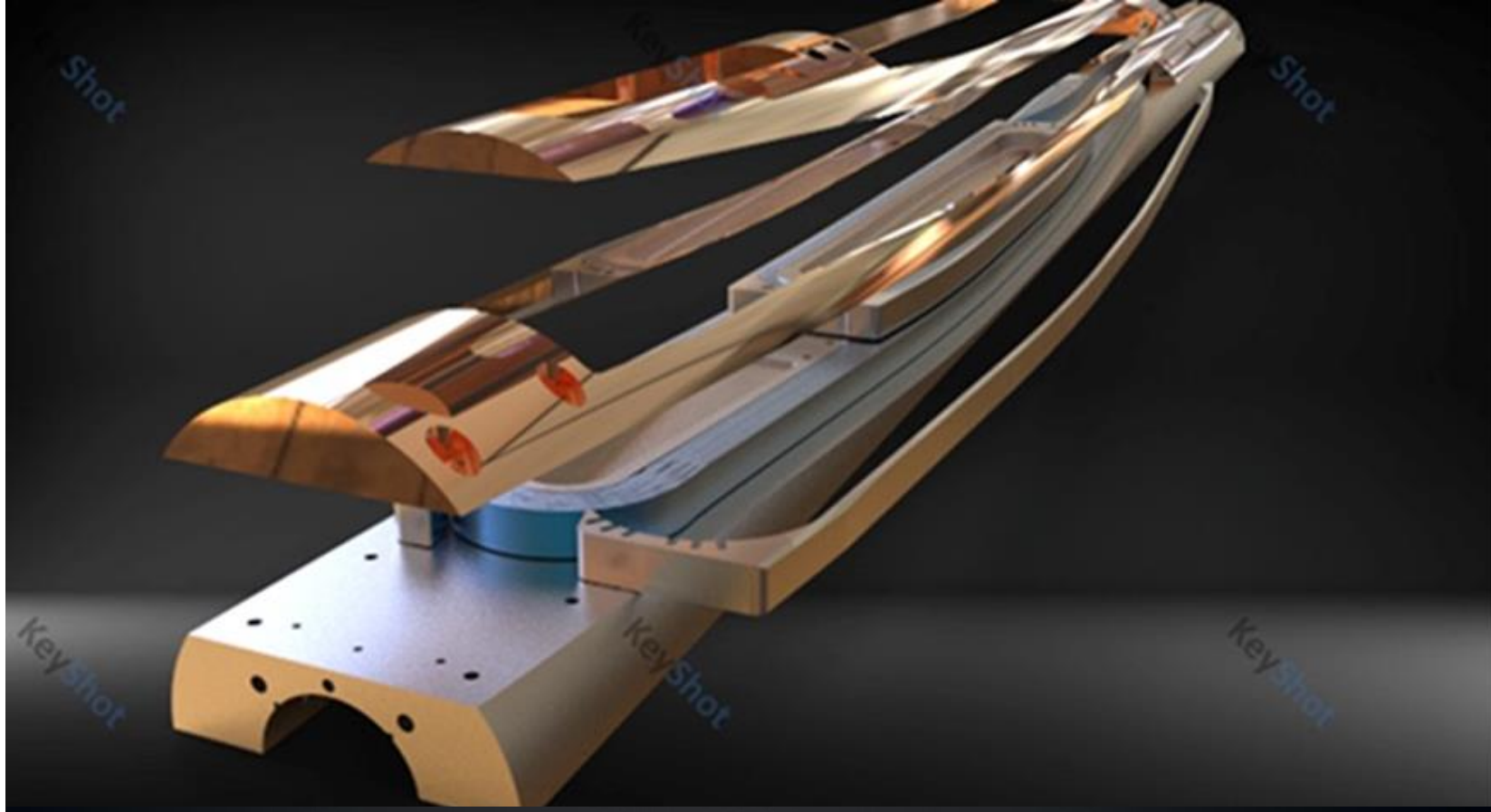
observations

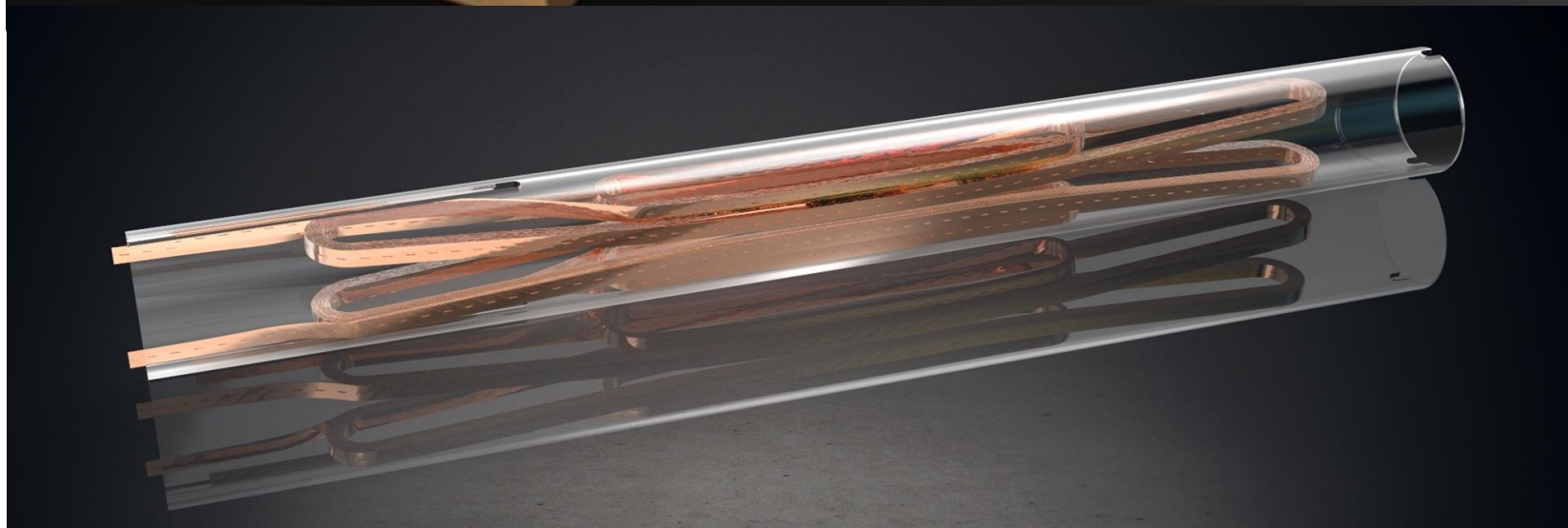
Magnet technology
- cable
- Winding
- Impregnation

Joint developments

Planning

Future stuff

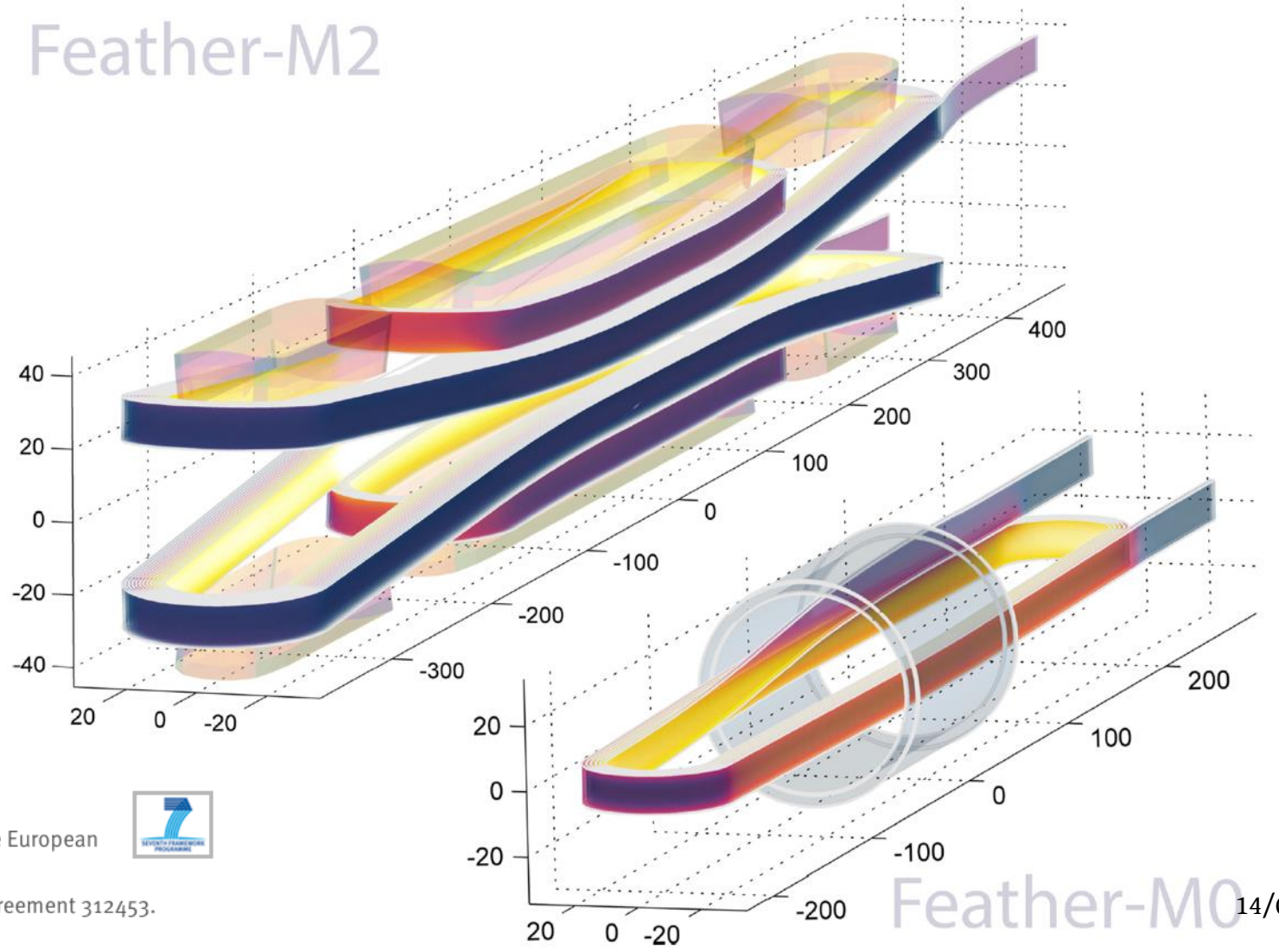




INTRODUCTION TO THE EUCARD2 WP 10 PROJECT

- 5 Tesla stand alone, (18 Tesla to 20+ Tesla in 13 Tesla background or other)
- 40 mm aperture
- 10 kA class cable
- Accelerator Field quality
- @ 4.5K

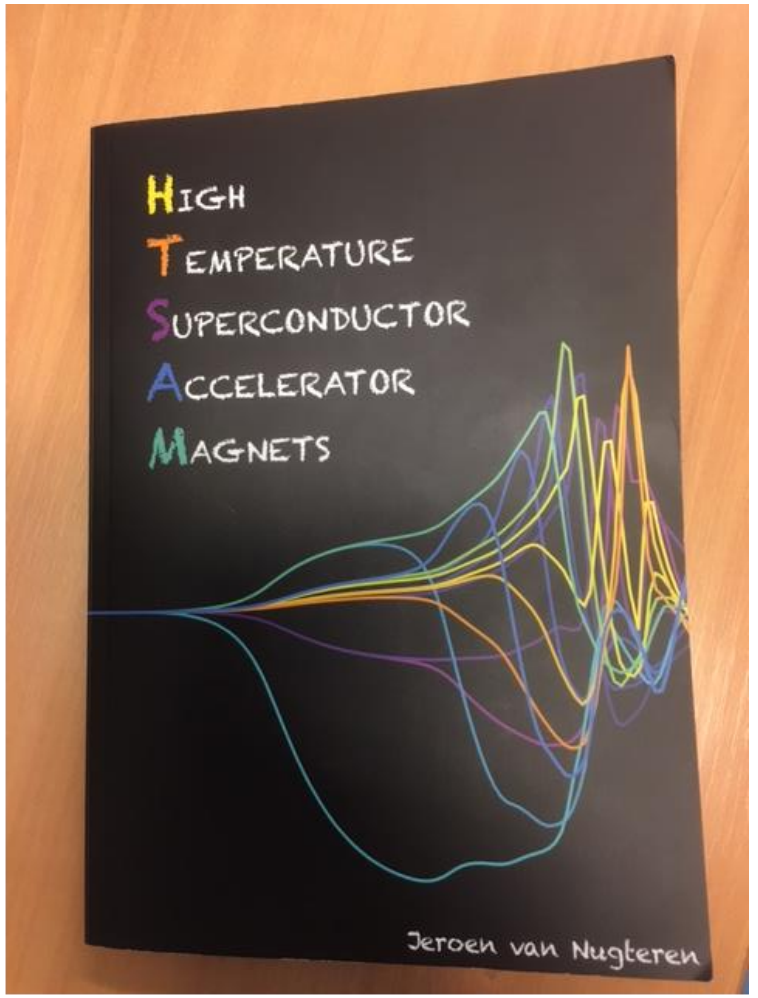
- WP 10 Magnets
  - 10.1 Communication
  - 10.2 Cable 10kA 20T
  - 10.3 Magnet
  - 10.4 Test



http://eucard2.web.cern.ch/

EuCARD-2 is co-funded by the partners and the European Commission
under Capacities 7th Framework Programme, Grant Agreement 312453.

Design tools

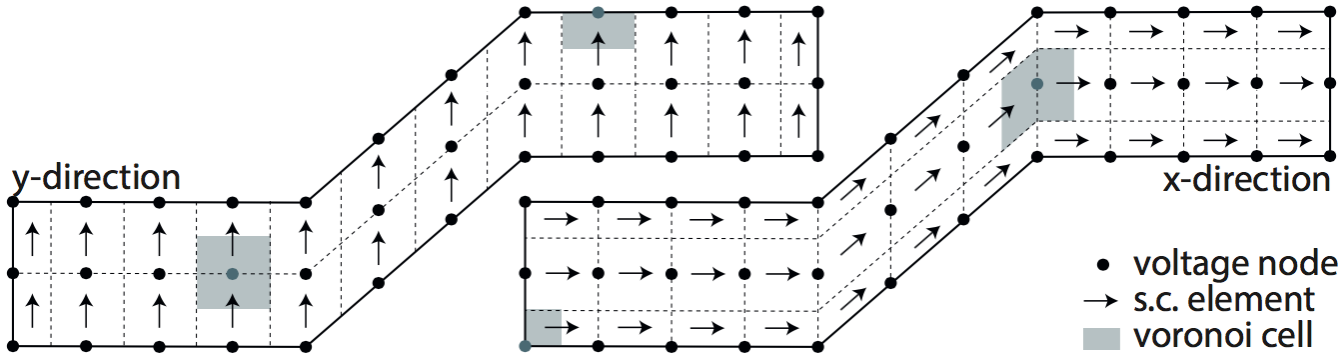


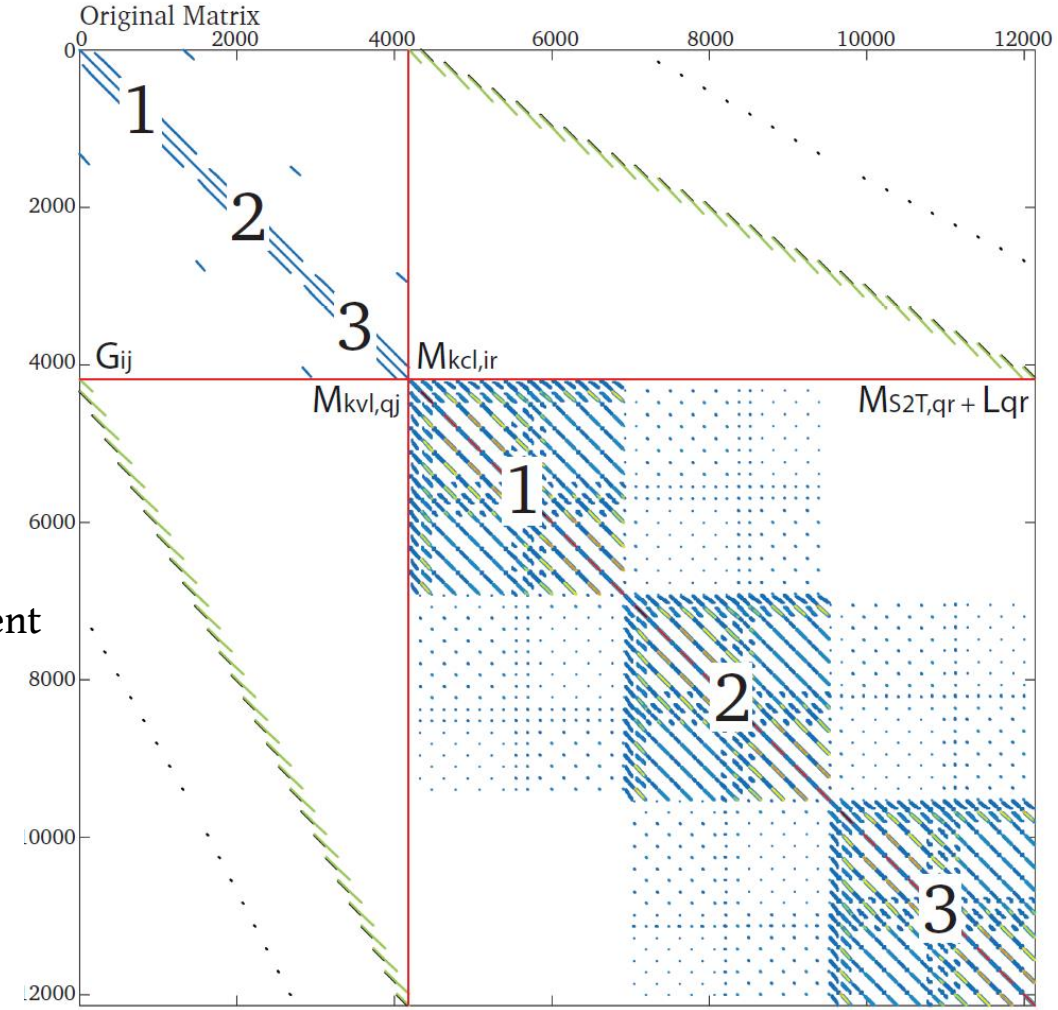
See Dr Jeroen Van Nugteren's PhD

Electro-Magnetic and Thermal Network Model

Network of Nodes and Elements

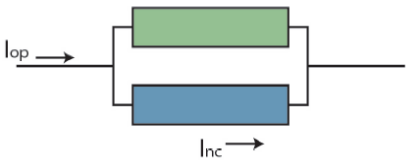
- To be able to model the screening currents the superconducting tapes are modeled as ribbon shaped meshes of elements (PEEC)





Current Sharing Equation

- Superconducting power law element in parallel with resistive (matrix) element (implicit equation)
- Non-linear superconducting elements provide macroscopic description of hysteresis

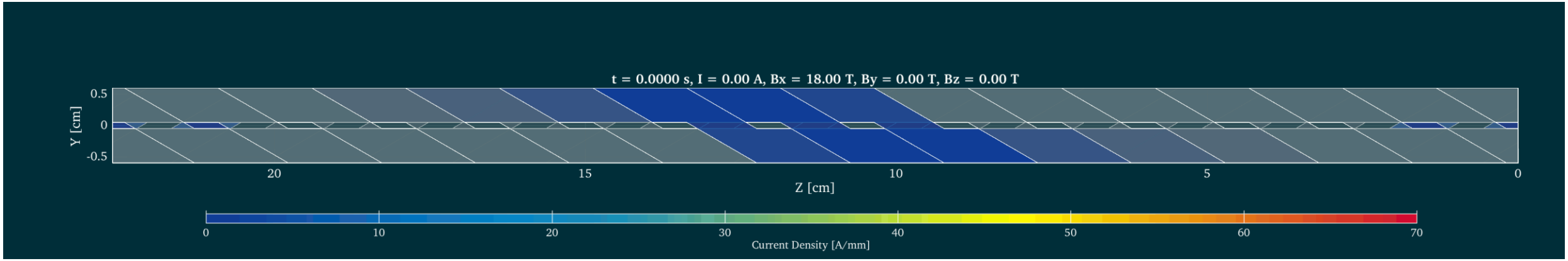


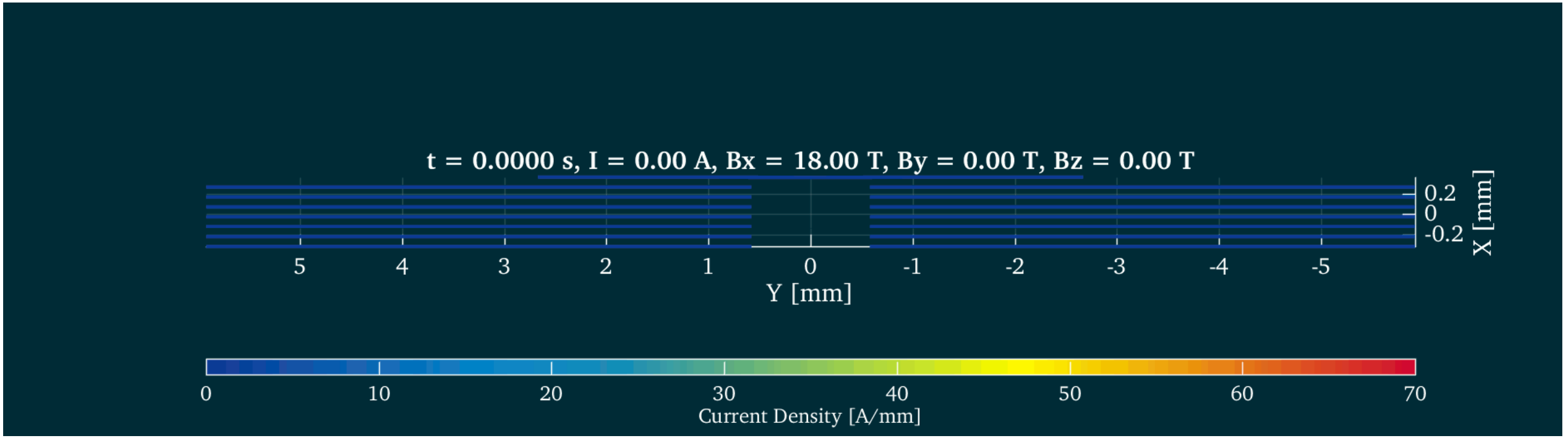
$$I_q - \overbrace{\frac{E_0}{\rho_{tq}\left(\left|B_q\right|, T_q\right)}\left[\frac{I_{sc,q}}{I_{c,q}\left(\left|B_q\right|, T_q, \alpha_q\right)}\right]^{N_{sc}}}^{\text{normal conducting current}} - I_{sc,q} = r \cong 0,$$

System of Equations

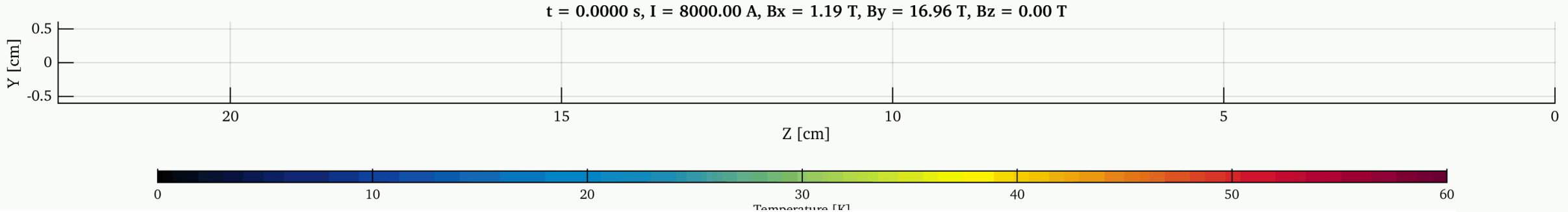
$$\overbrace{\begin{bmatrix} G_{ij} & M_{\mathrm{kcl},ir} & 0 \\ M_{\mathrm{kvl},qj} & R_{qr} & 0 \\ 0 & 0 & K_{sp} - K_{\mathrm{cool},sp} \end{bmatrix}\begin{bmatrix} V_j \\ I_r \\ T_p \end{bmatrix}}^{\text{time independent linear}} + \overbrace{\begin{bmatrix} 0 \\ V_{\mathrm{nl},q}\left(I_r, T_r, \left|\vec{B}_r\right|, \alpha_r\right) \\ P_{\mathrm{nl},s}\left(I_r, T_r, \left|\vec{B}_r\right|, \alpha_r\right) + P_{G,s}\left(V_j\right) + P_{R,s}\left(I_r\right) \end{bmatrix}}^{\text{time independent non-linear}} + \overbrace{\begin{bmatrix} I_{s,i} + I_{\mathrm{bg},i}\left(\frac{\partial \vec{B}}{\partial t}\right) \\ V_{s,q} + V_{\mathrm{bg},q}\left(\frac{\partial \vec{B}}{\partial t}\right) \\ P_{s,s} + K_{\mathrm{cool},ss} T_{\mathrm{bath}} \end{bmatrix}}^{\text{external sources}} + \overbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & L_{qr} + M_{\mathrm{S2T},qr} & 0 \\ 0 & 0 & -C_{p,sp} \end{bmatrix}\begin{bmatrix} \frac{\partial V_j}{\partial t} \\ \frac{\partial I_r}{\partial t} \\ \frac{\partial T_p}{\partial t} \end{bmatrix} + \begin{bmatrix} 0 \\ V_{\mathrm{mlfmm},q}\left(\frac{\partial I_r}{\partial t}\right) \\ 0 \end{bmatrix}}^{\text{time dependent linear}} = \overbrace{\begin{bmatrix} I_{\mathrm{res},i} \\ V_{\mathrm{res},q} \\ P_{\mathrm{res},s} \end{bmatrix}}^{\text{residual}} \cong \vec{0},$$

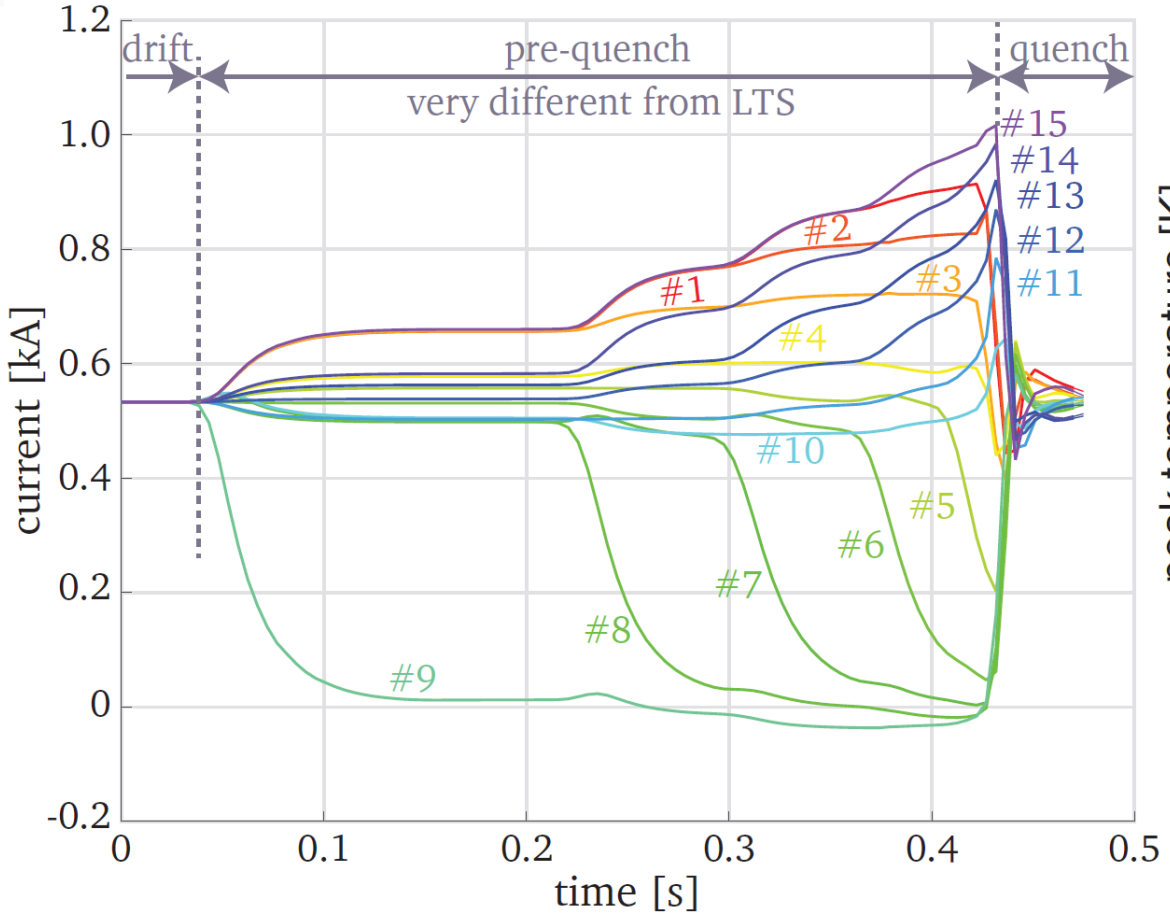
Current Distribution in cable and coil

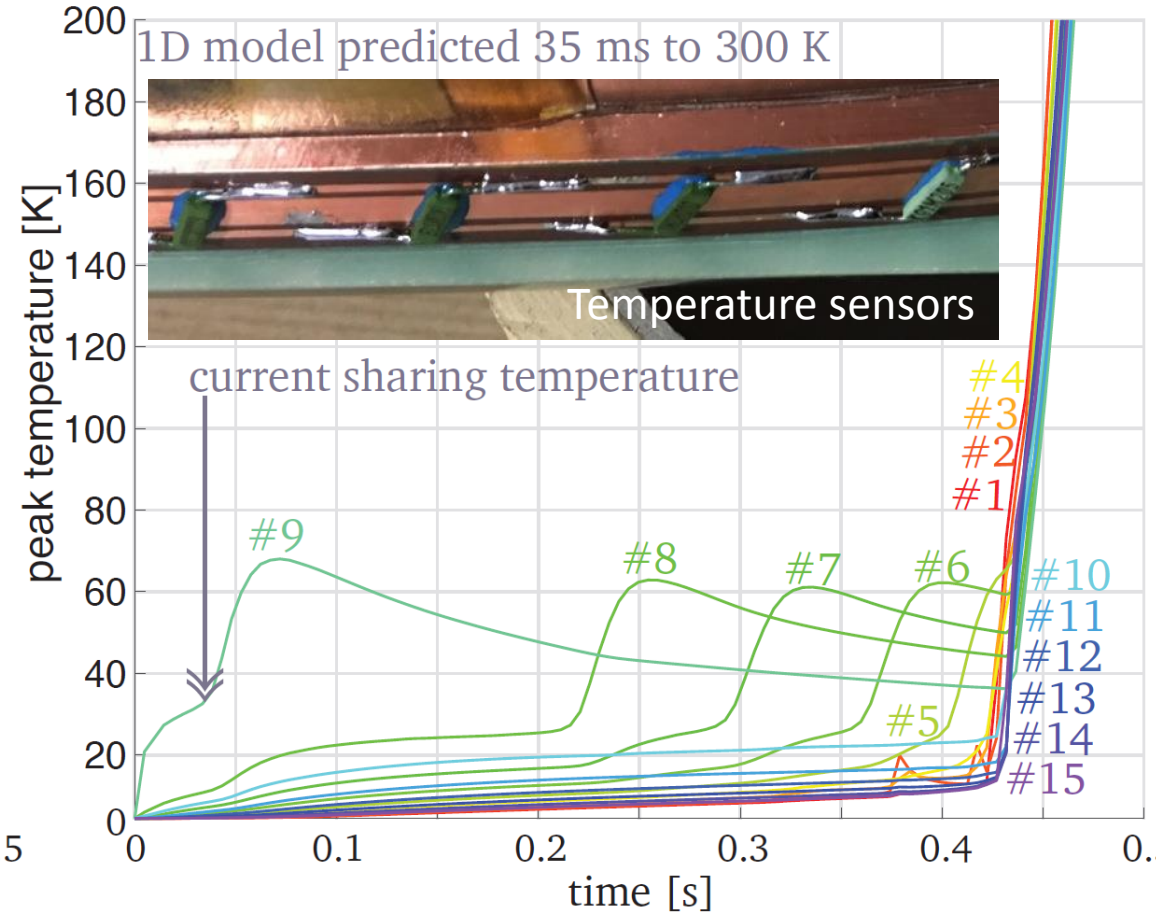




Quench Analysis

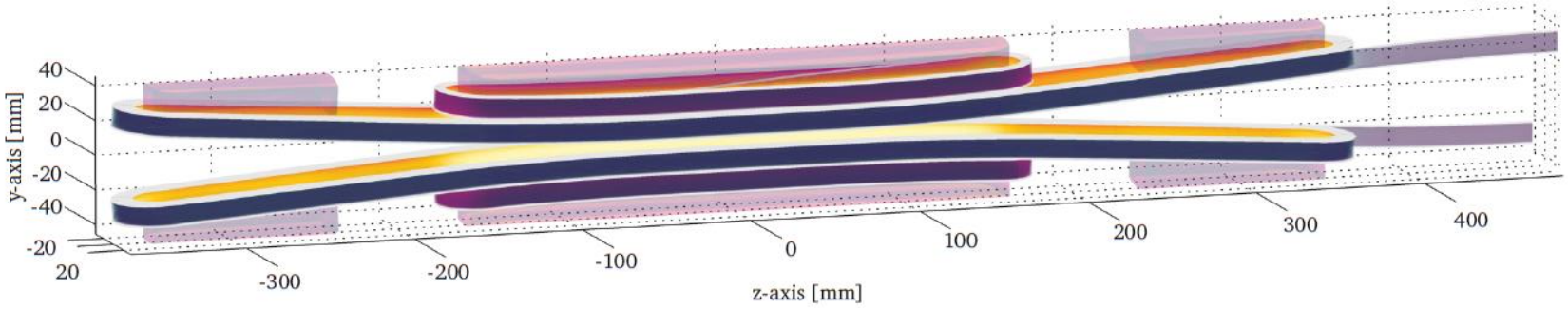


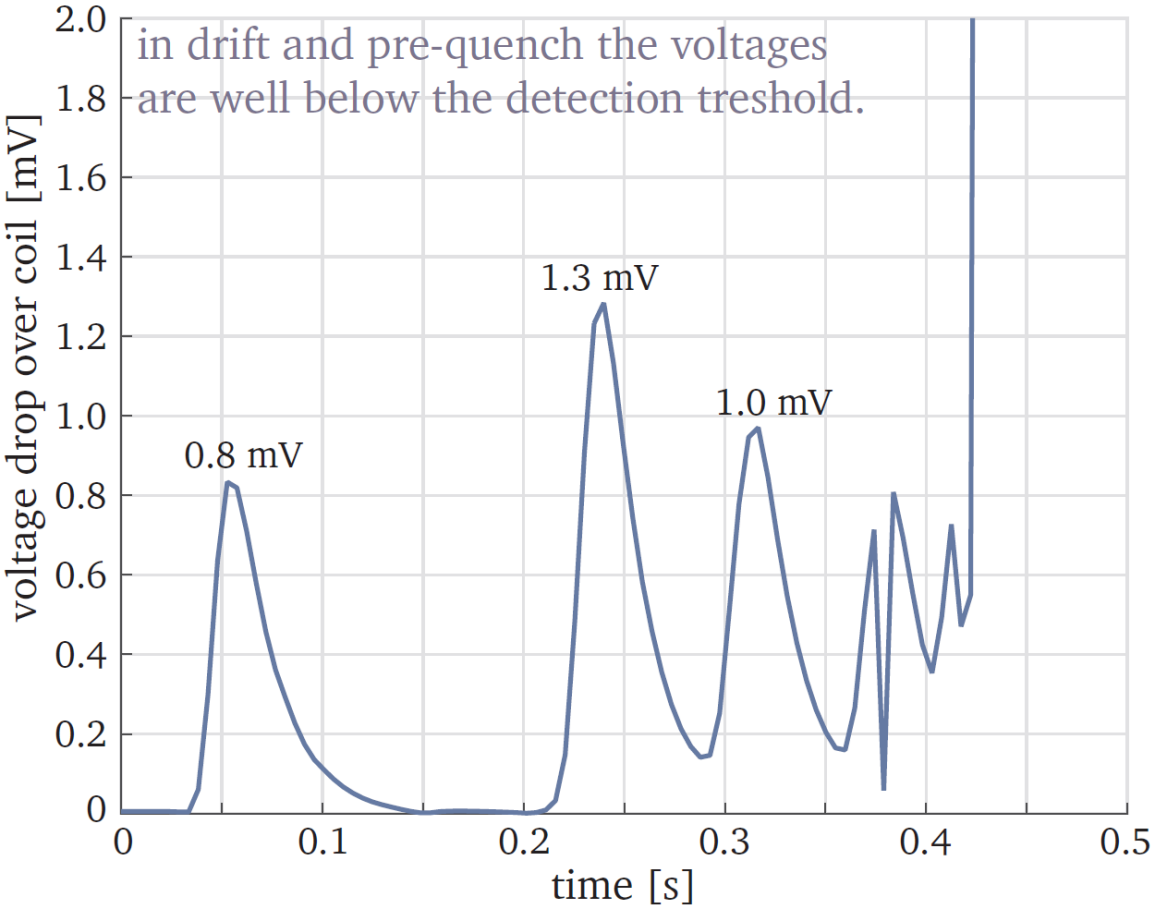


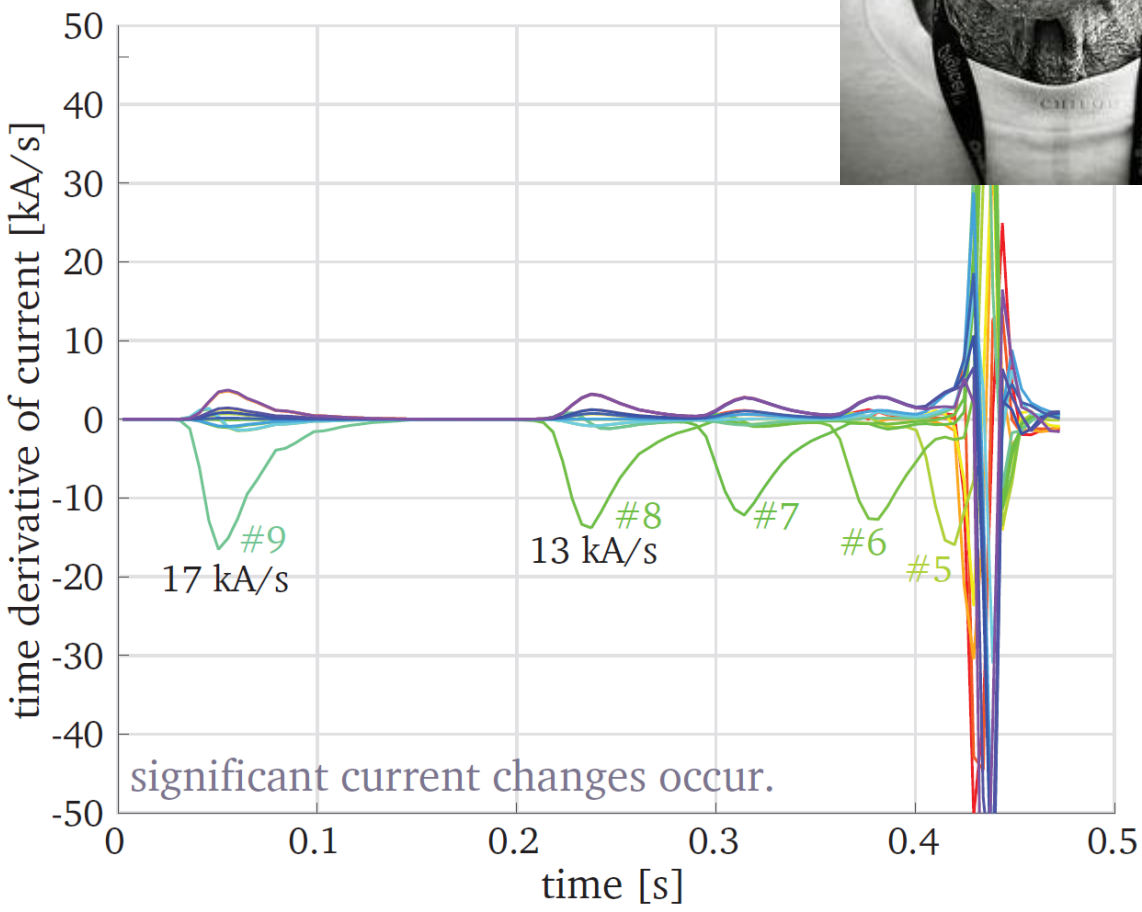


Coil Voltages

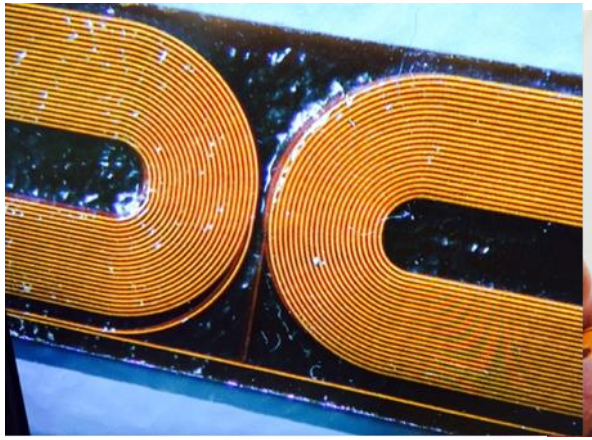
Mr. voltage tap

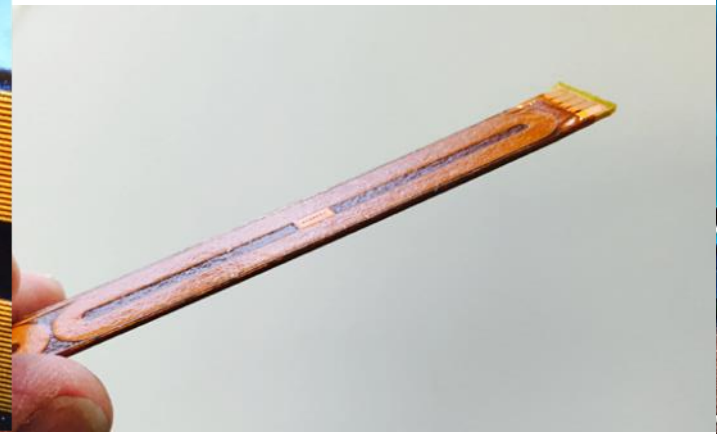


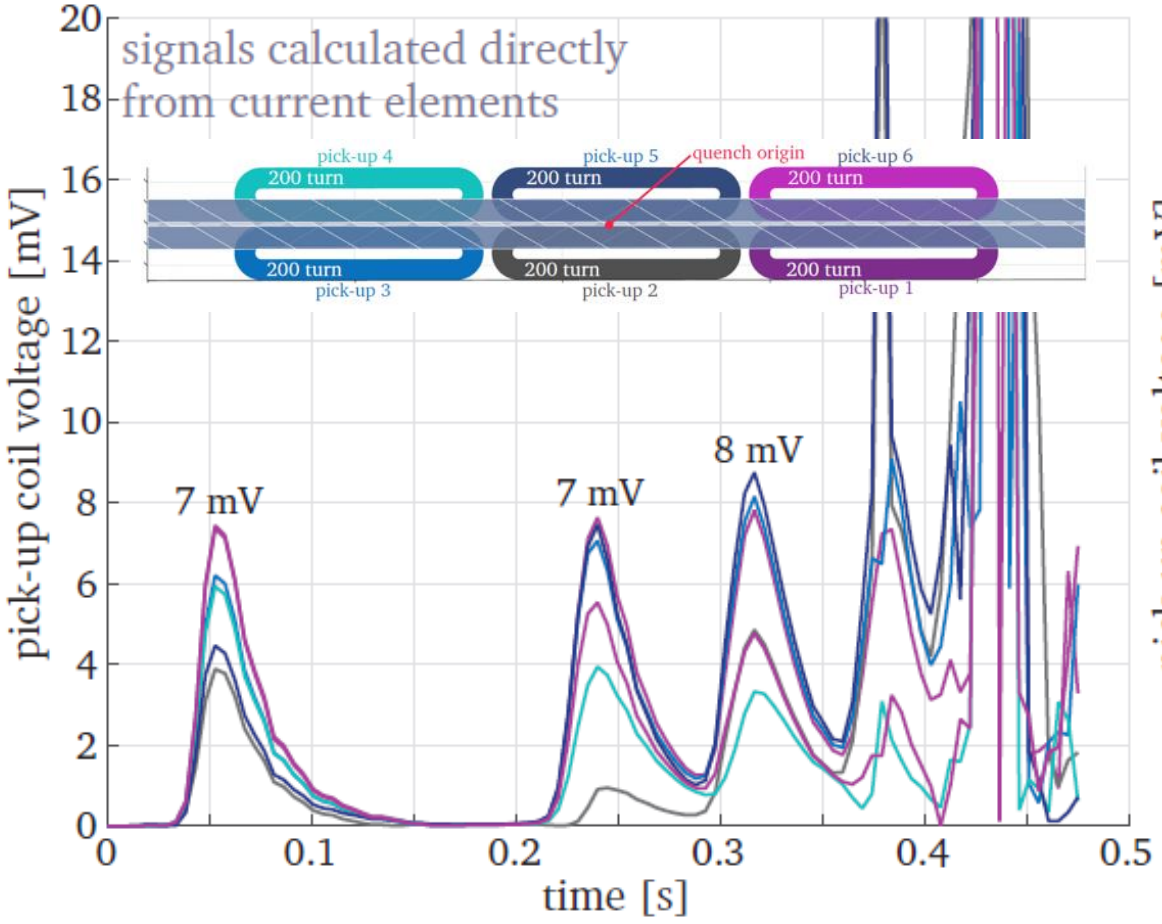


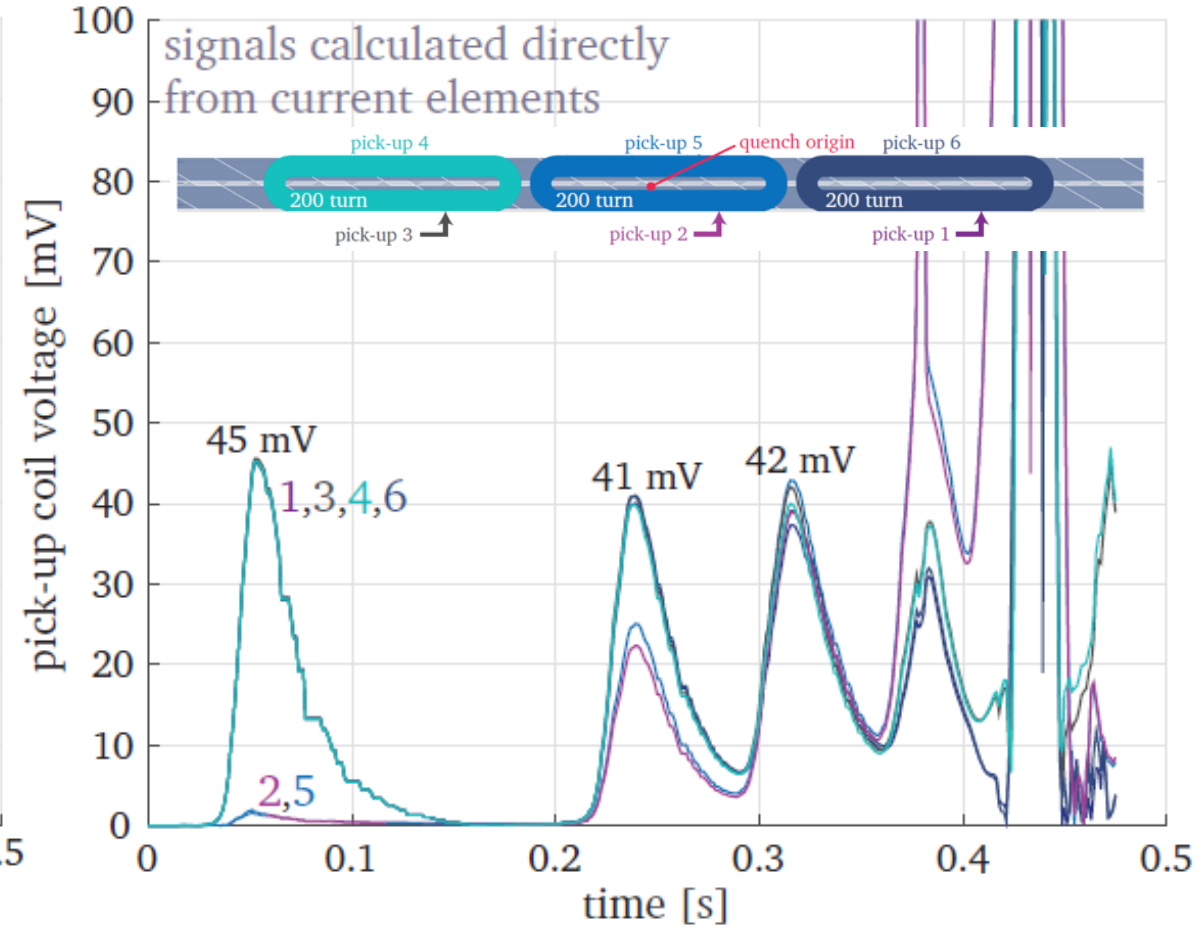


PICKUP COILS





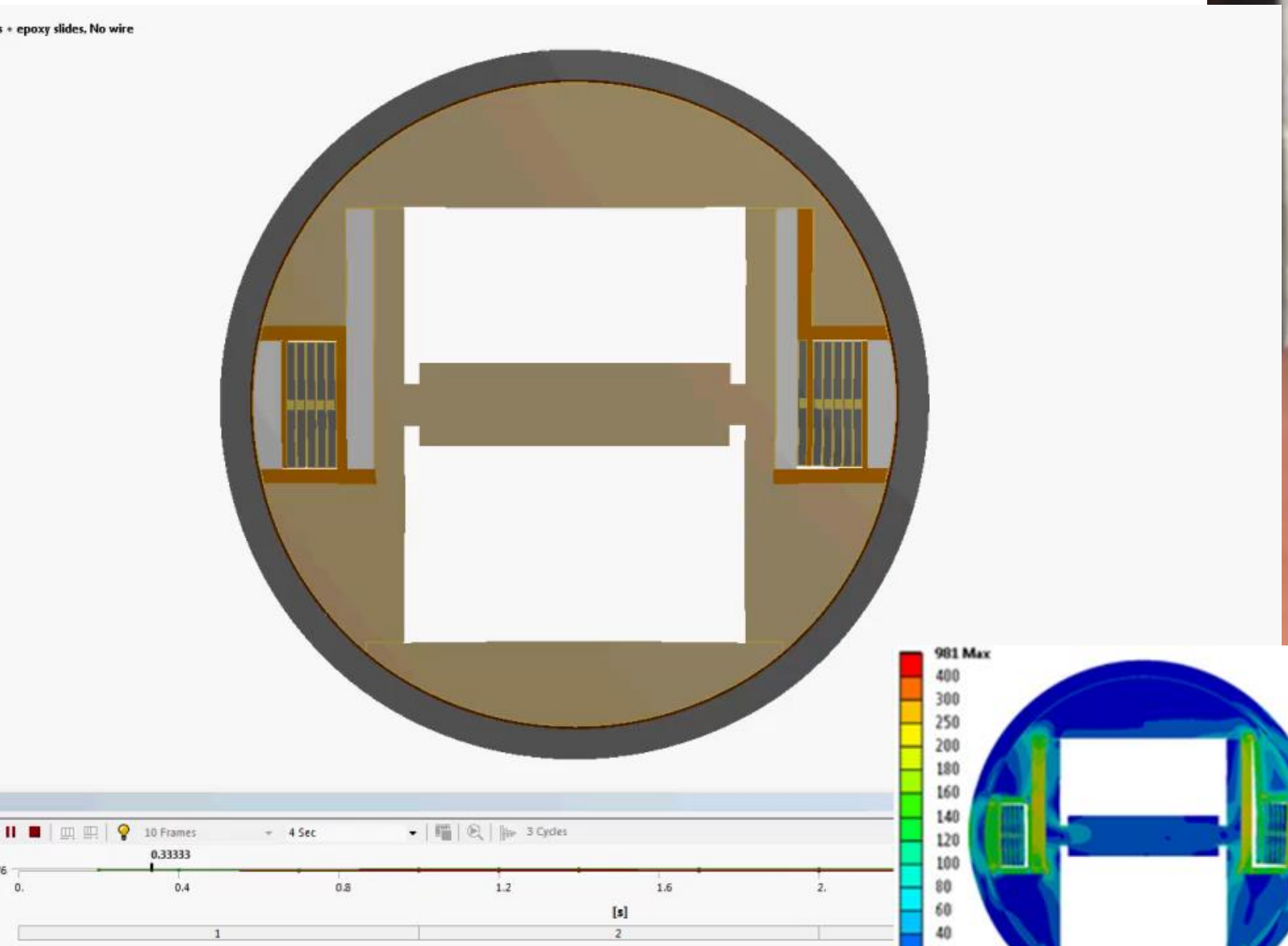


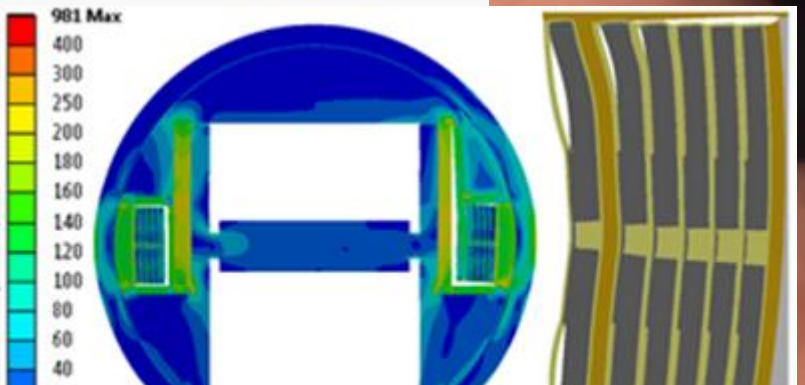


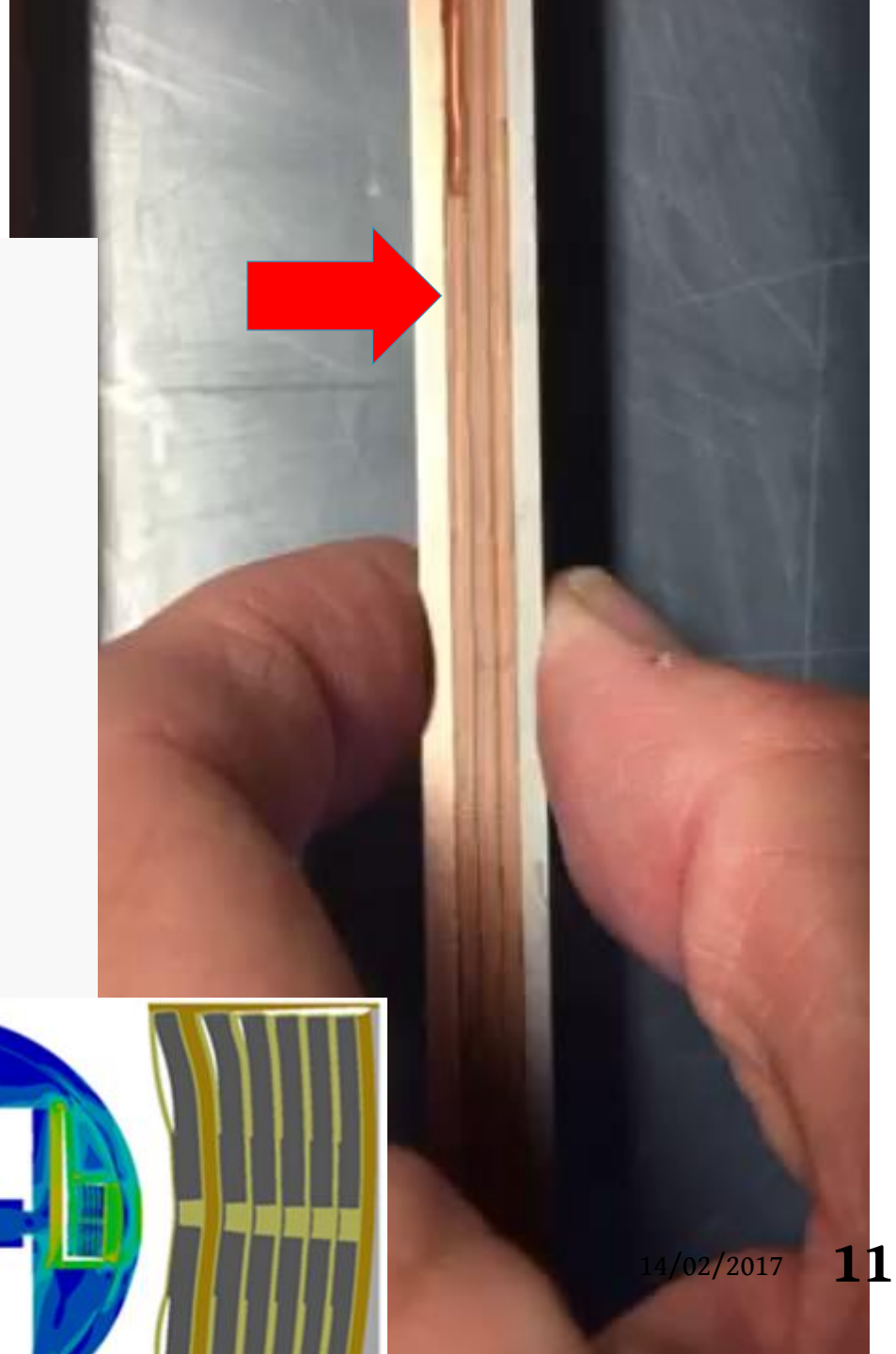
PHILOSOPHY

The direction of the force is important! The YBCO should push onto the steel backing.!!

Mould release on coil former

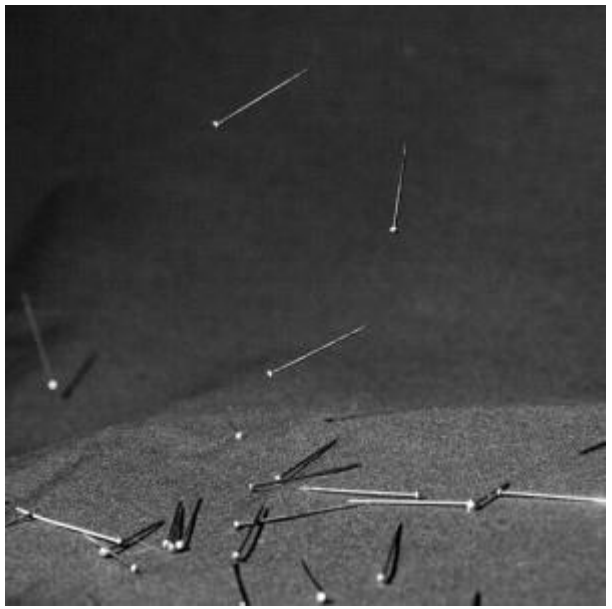






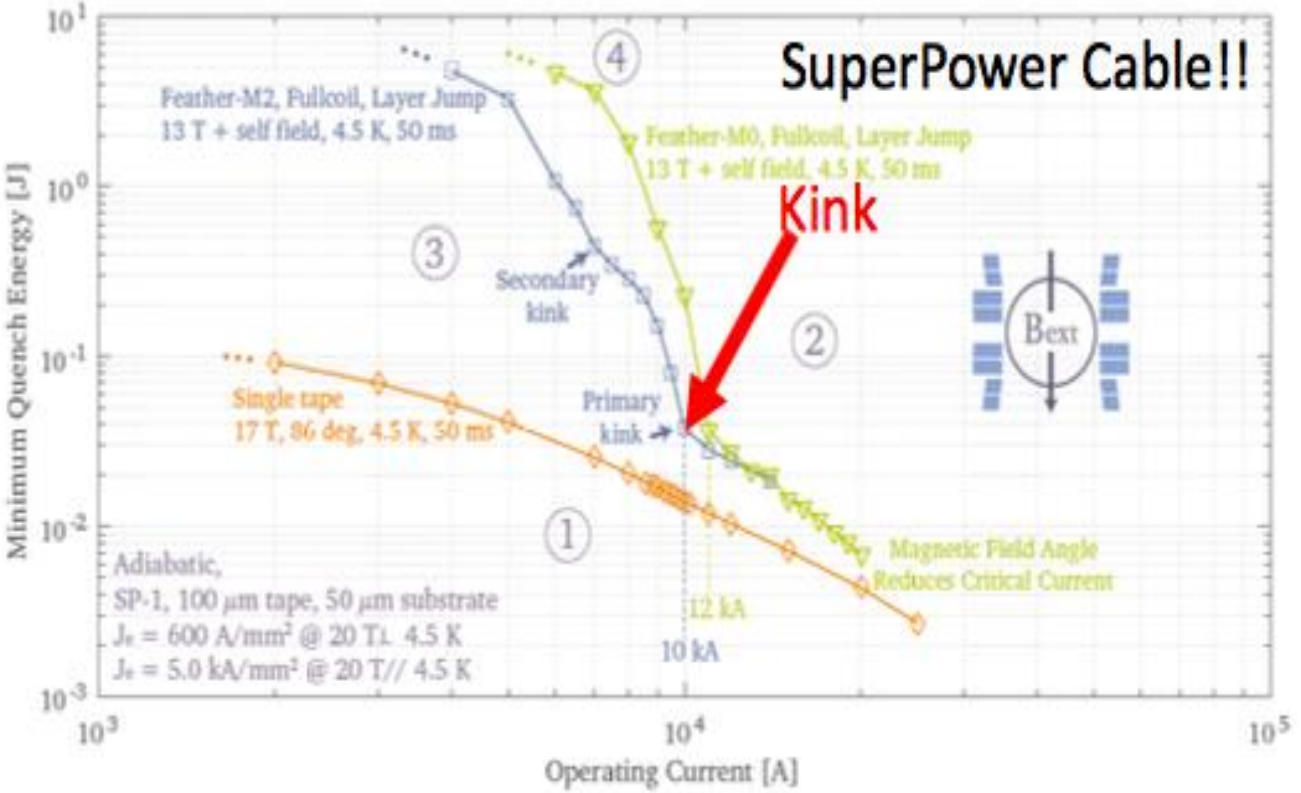
Minimum Quench Energy in HTS Cable (MQE)

- MQE for cables with 1,2,3,4,..... Tapes in cables.
- HTS MQE is **3 orders of magnitude** higher than low temperature superconductor
- What will induce a Quench ?



A drop Pin 1 cm LTS

5 Kg HTS



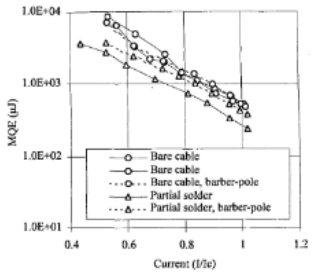
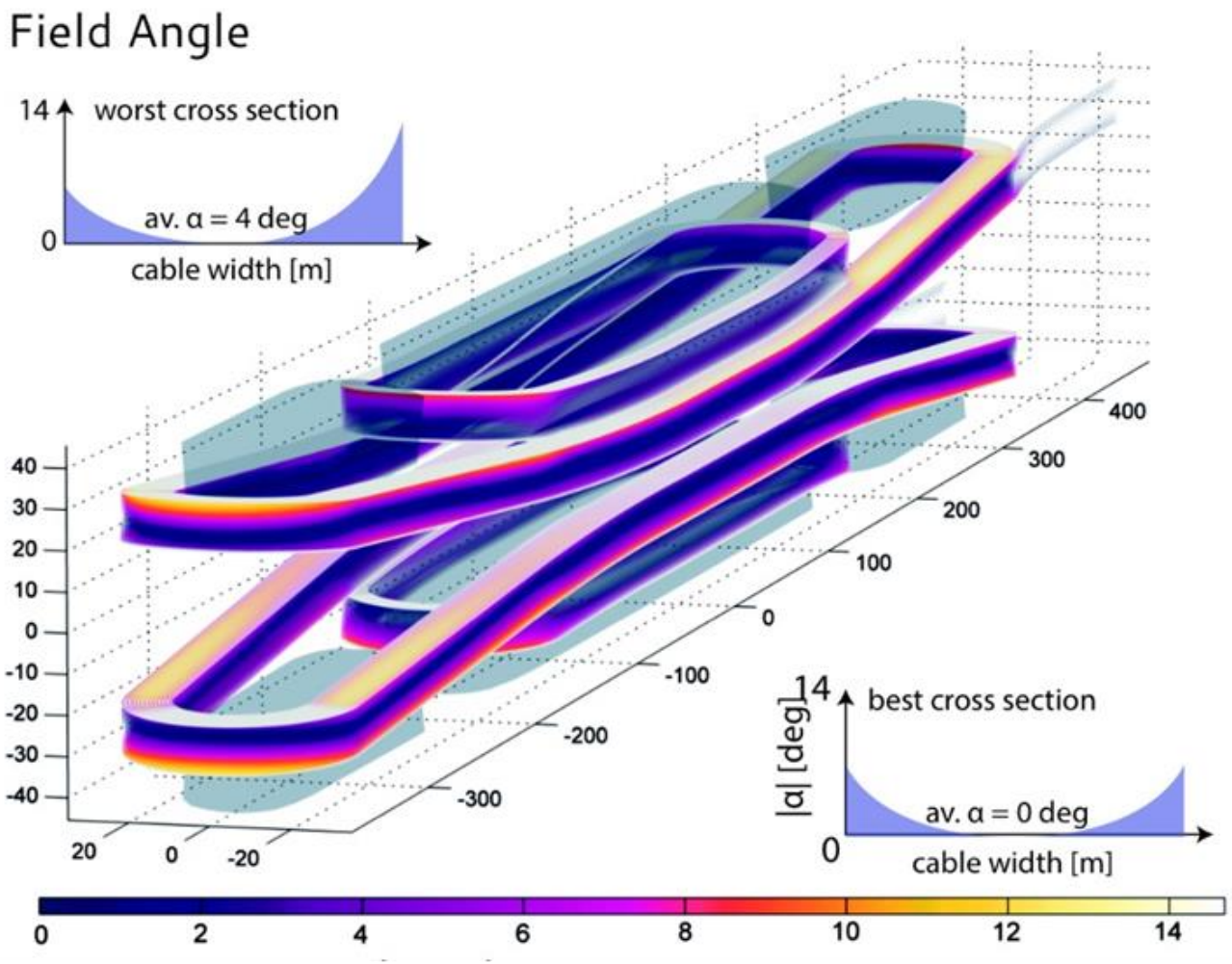
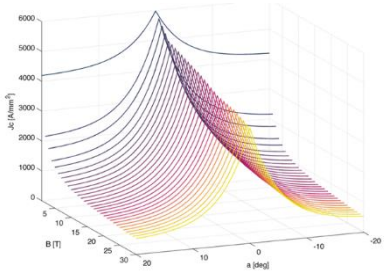


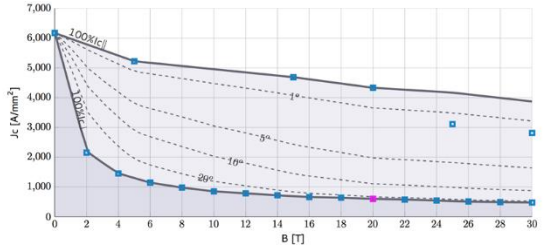
Fig. 2. Measured MQE's of the cable sample B. The bath temperature was 4.5K, and the magnetic field is 7T parallel.

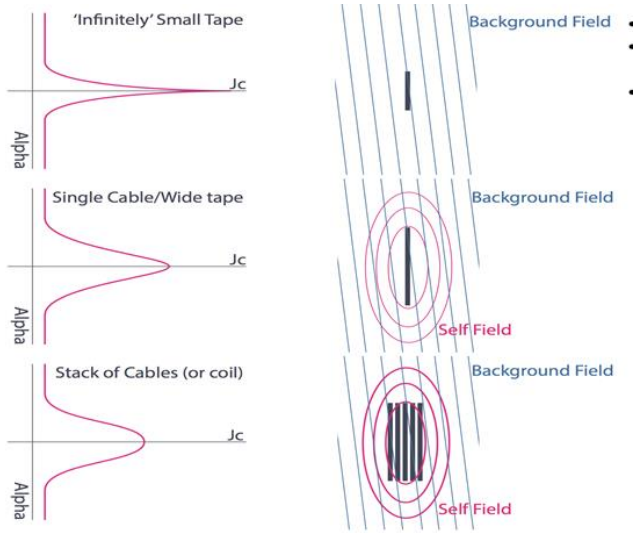
LHC LTS Nb-Ti

Design: 3D Analysis Field Angle in Freather-M2

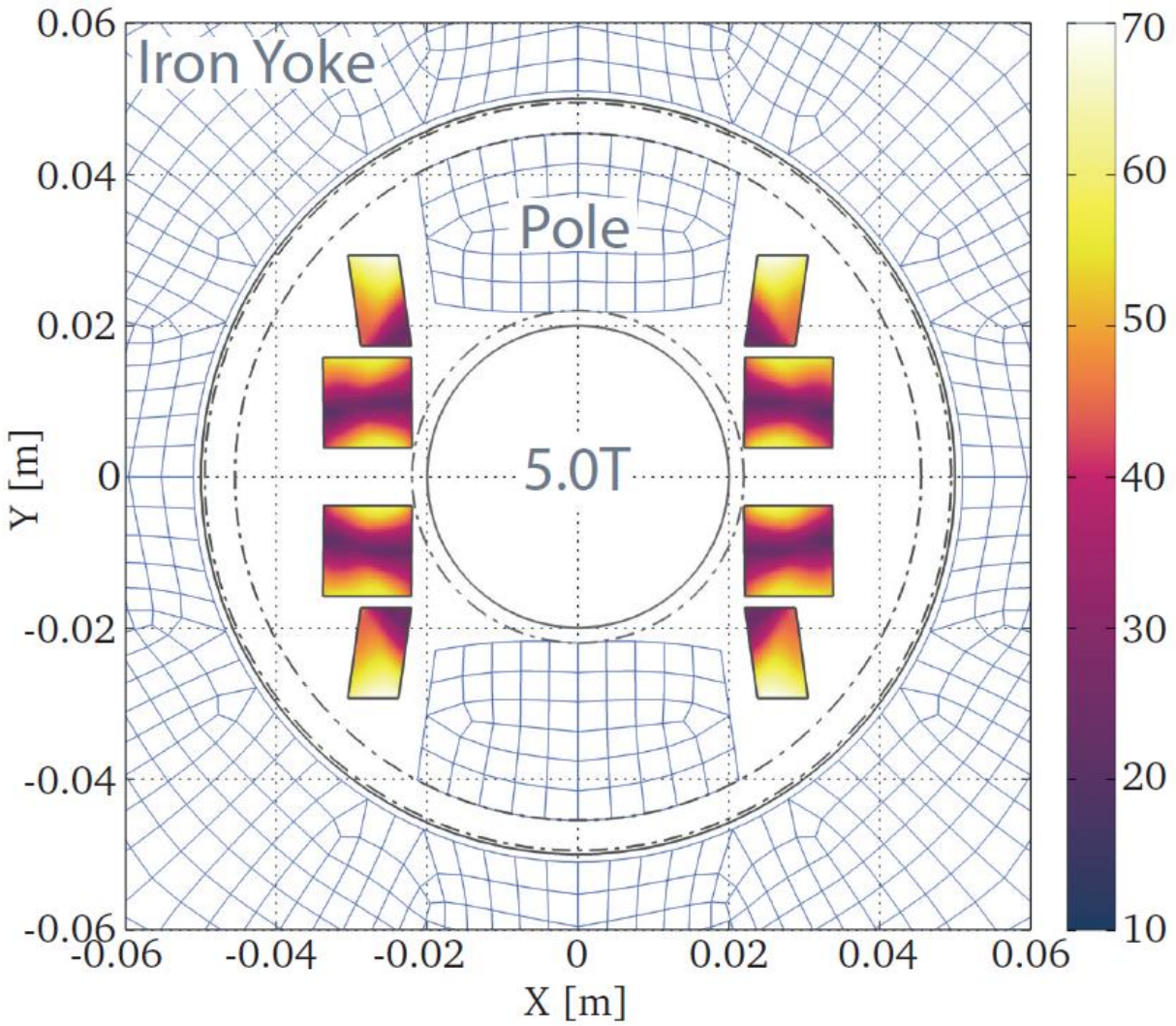


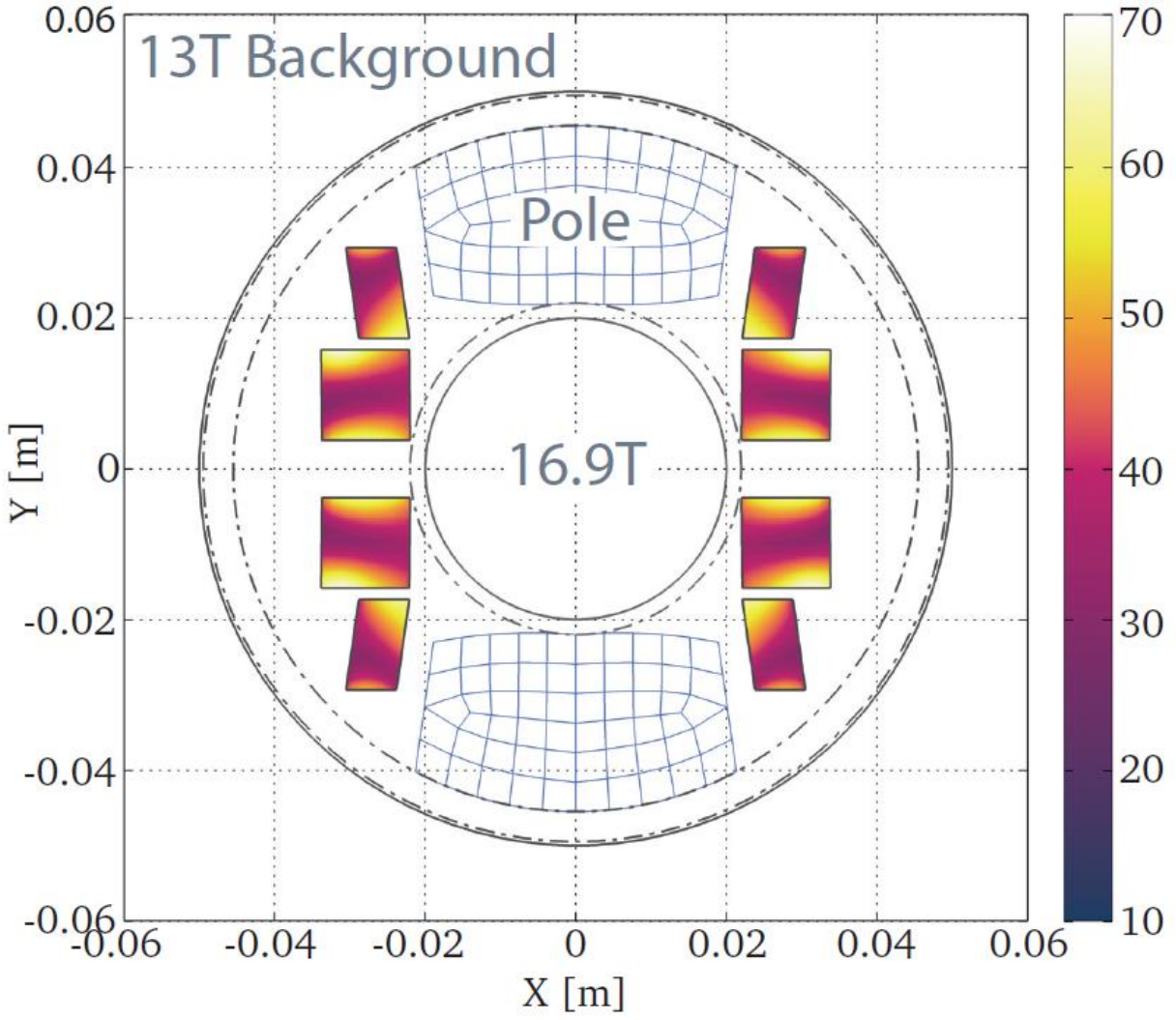






Percentage on the Load-line



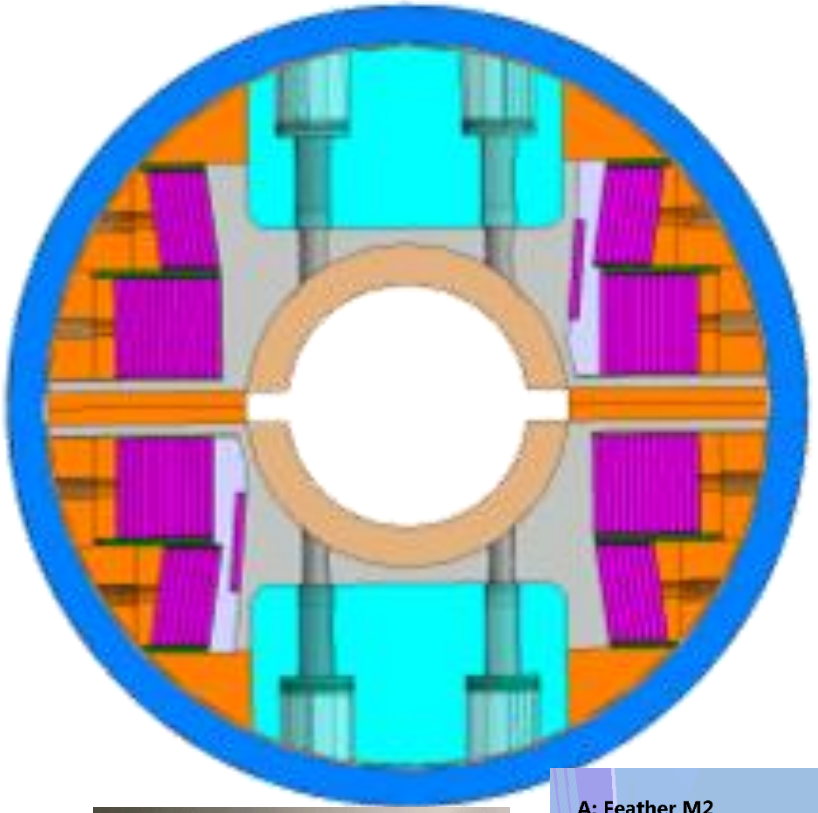


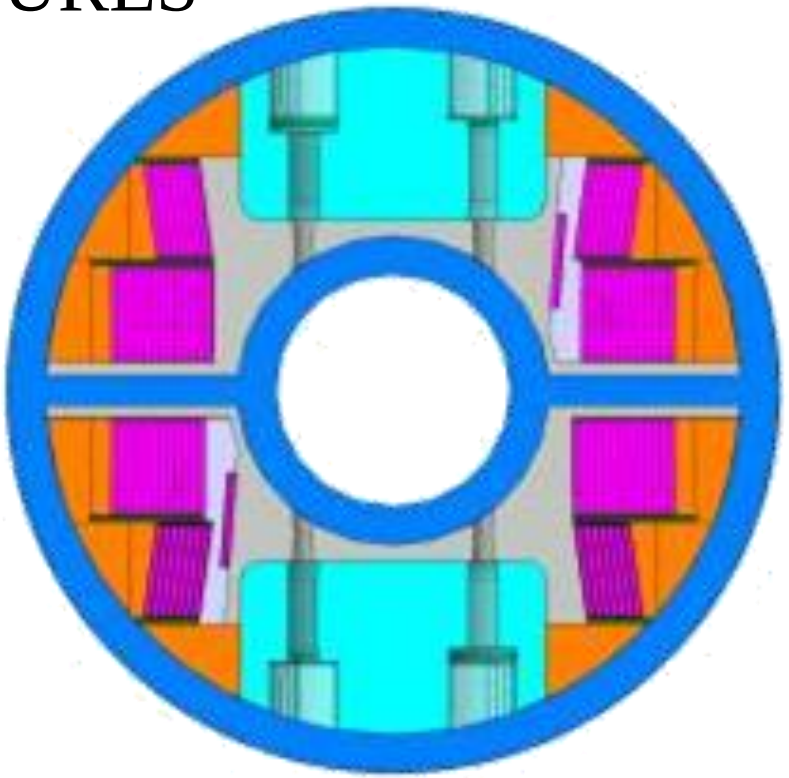
Angular dependence changes the picture may help with field quality?.

Assumed homogeneous current distribution

EuCARD2 5T & 17T

STRUCTURES

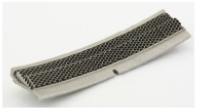




Material Specification

Nickel Alloy In718

Building Success Layer by Layer™ 3T®



Application: In718 is a nickel based heat resistant alloy. Its composition corresponds to UNS N07718, AMS 5662, AMS 5664, W.Nr 2.4668, DIN NiCr19Fe19NbMo3. This kind of precipitation-hardening nickel-chromium alloy is characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700°C. In718 alloy also has outstanding corrosion resistance in various corrosive environments.

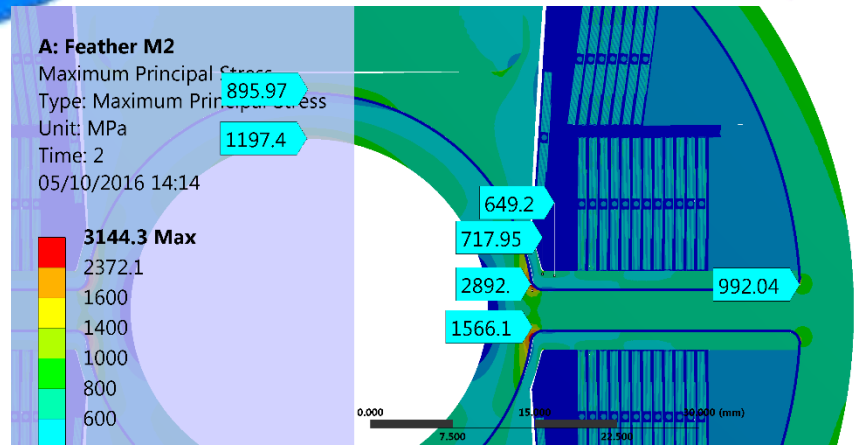
This material is ideal for many high temperature applications such as gas turbine parts, instrumentation parts, power and process industry parts etc. The material also possesses excellent cryogenic properties and potential for cryogenic applications.

Typical applications:

- Aero and land based turbine engine parts
- Rocket and space application components
- Chemical and process industry parts
- Oil well, petroleum and natural gas industry parts

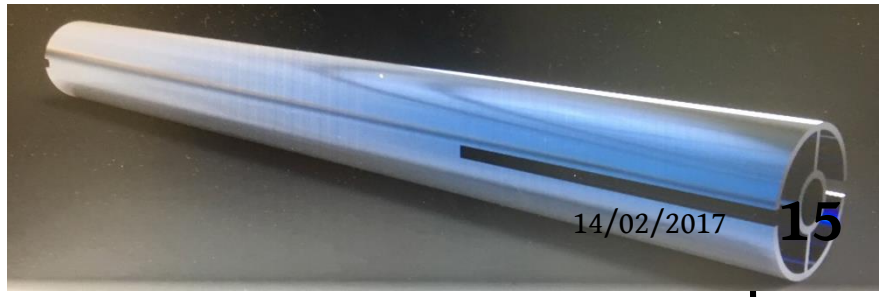
Physical and Chemical Properties:						
Relative Density with Standard Parameters	approx. 100% (min. 8.15 g/cm³)					
Material composition	Ni	50-55 wt%	Ti	0.65-1.15 wt%	C	≤ 0.08 wt%
	Cr	17-21 wt%	Al	0.20-0.80 wt%	Si, Mn	each ≤ 0.35 wt%
	Nb	4.75-5.5 wt%	Co	≤ 1.0 wt%	P, S	each ≤ 0.015 wt%
	Mo	2.8-3.3 wt%	Cu	≤ 0.3 wt%	B	≤ 0.006 wt%
					Fe	balance

Mechanical Properties:		After standard heat treatment cycle NI_In718_C
Tensile Strength	- horizontal direction (XY) - vertical direction (Z)	typ. 1400 MPa ± 100 MPa
Yield strength (Rp 0.2%)	- horizontal direction (XY) - vertical direction (Z)	typ. 1150 MPa ± 100 MPa
Elongation at break	- horizontal direction (XY) - vertical direction (Z)	typ. 15 ± 3%
Modulus of elasticity		typ. 170 GPa ± 20 GPa
Hardness		typ. 47 HRC
Thermal Properties:		
Coefficient of thermal expansion		over 25-200°C 12.5-13.0 x 10⁻⁶ m/m°C over 25-750°C 16.6-17.2 x 10⁻⁶ m/m°C
Maximum operating temperature for parts under load		approx. 650°C
Oxidation resistance up to (according to literature)		approx. 980°C

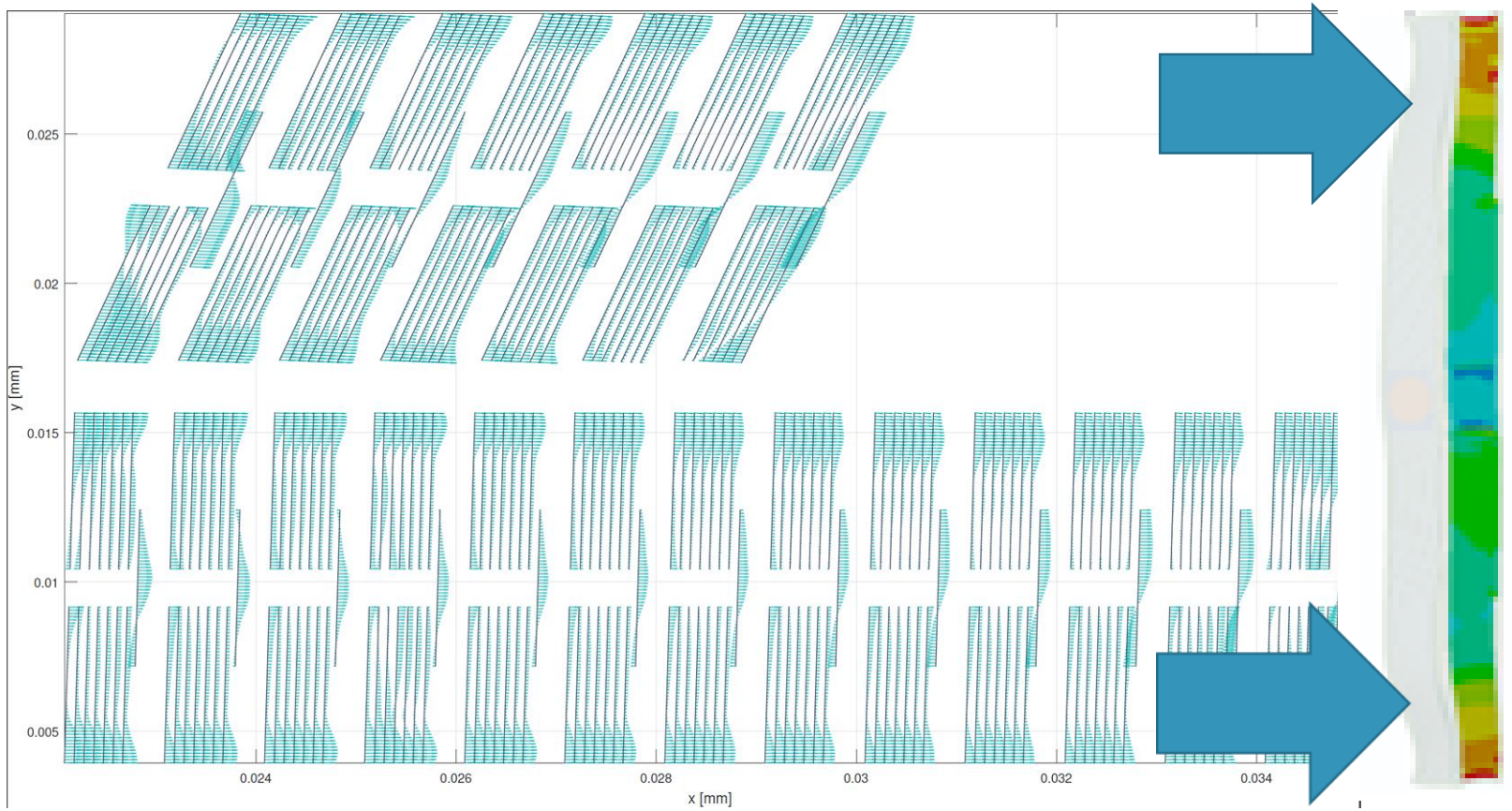


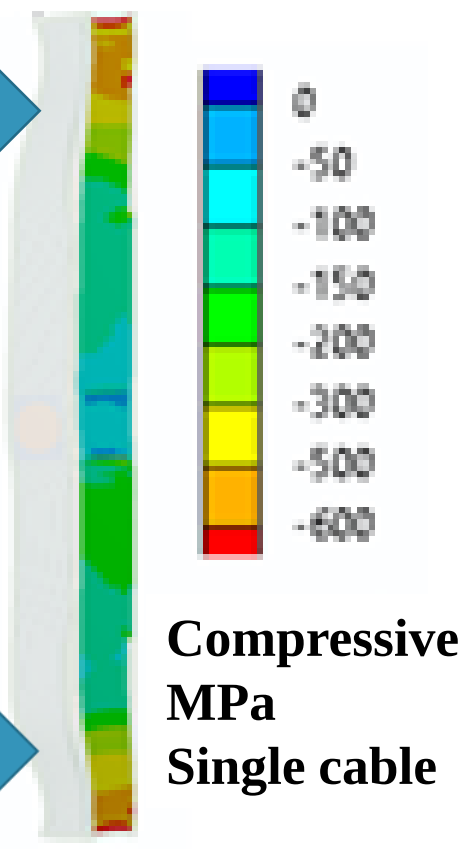
Yield stress 1150 Mpa

Tensile 1400 MPa



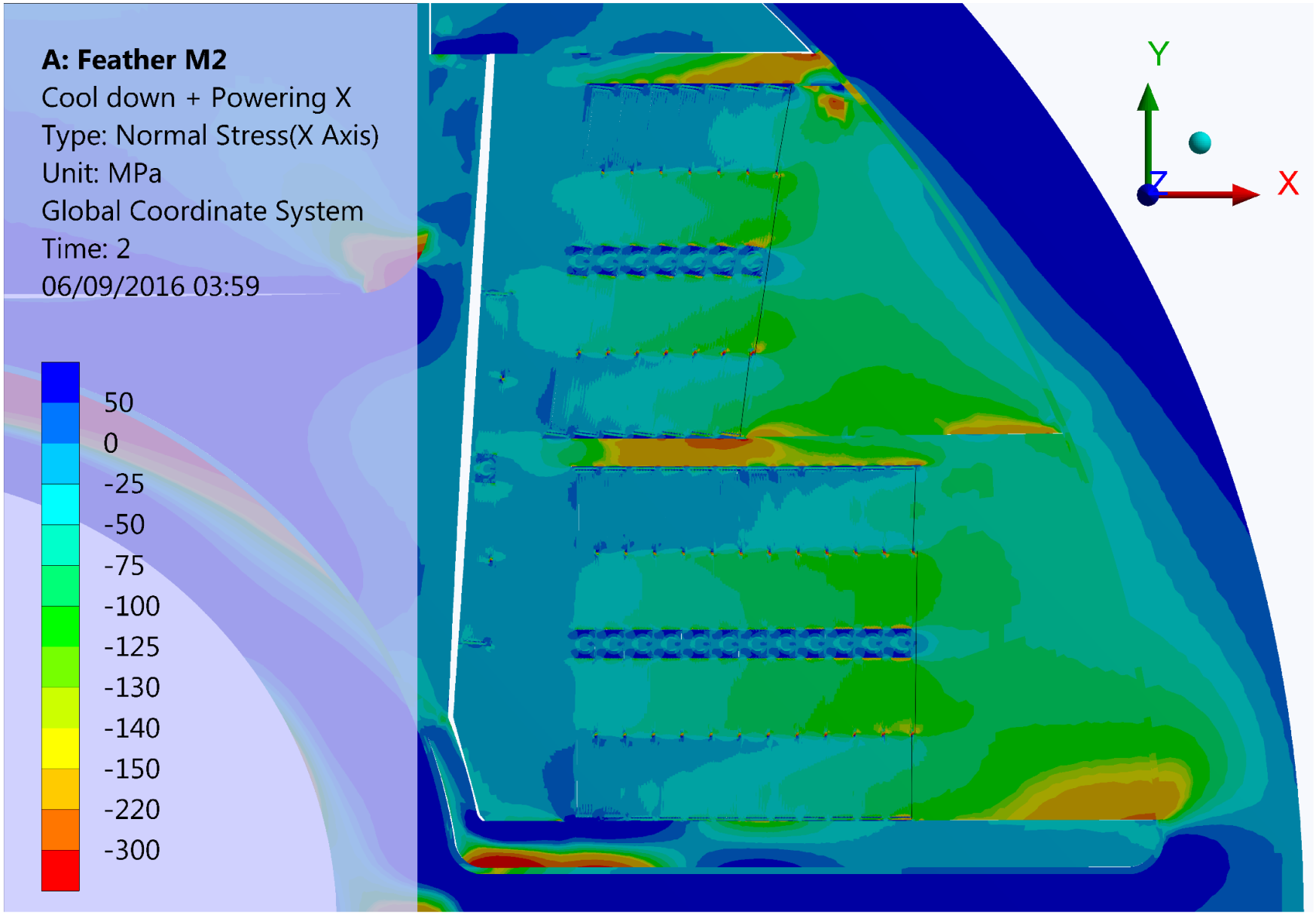
CURRENT FORCE AT EDGE OF TAPES





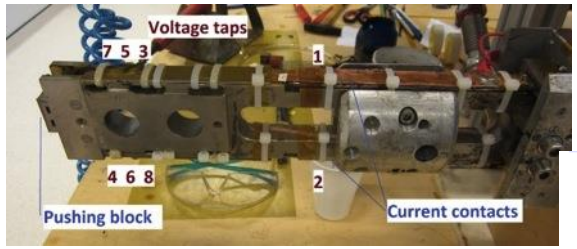
Compressive
MPa
Single cable

Mechanical Analysis 17T (by Jaakko Murtomaki)

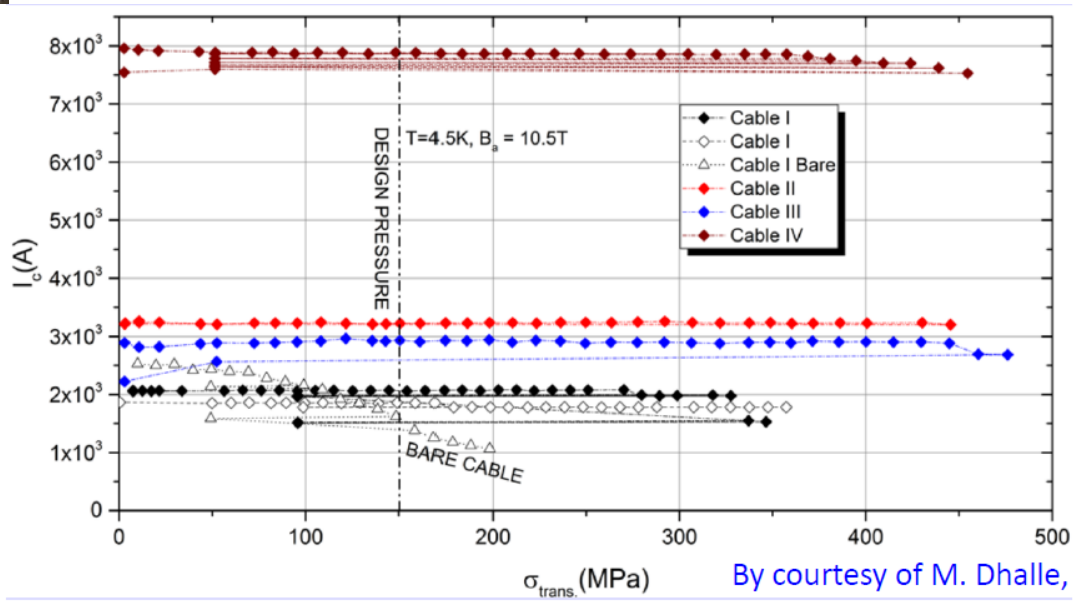


IMPREGNATION

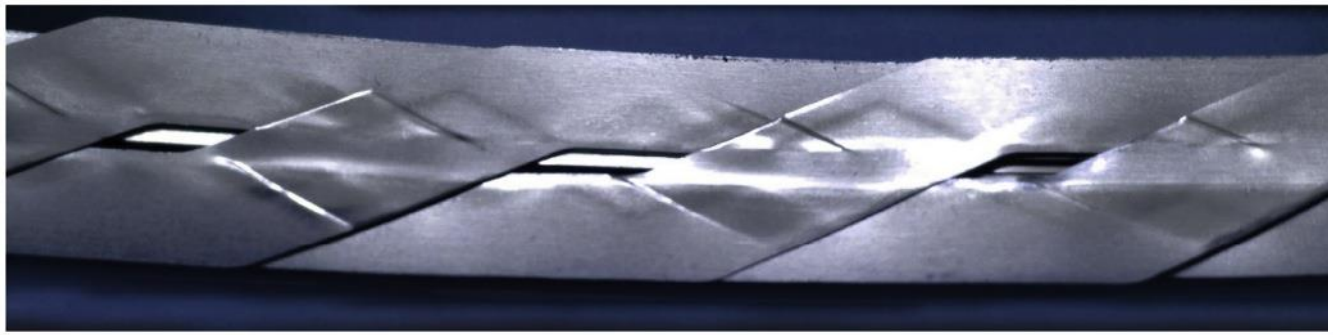
- Impregnation is obligatory
- Looked at different resins
  - CTD101G, CTD101K, etc.
- With glass sleeve insulation

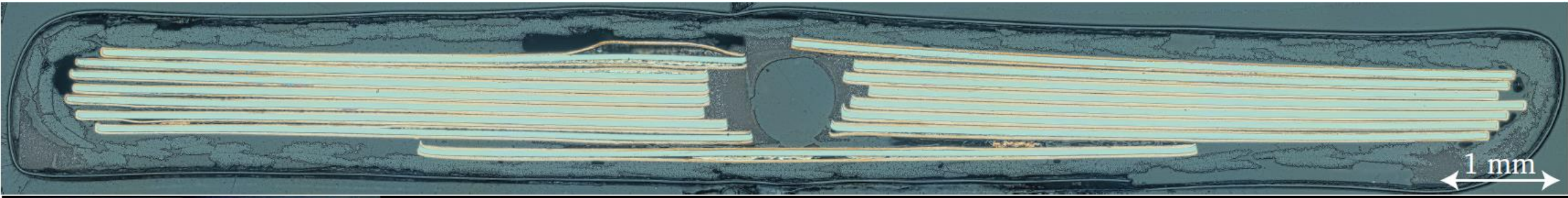


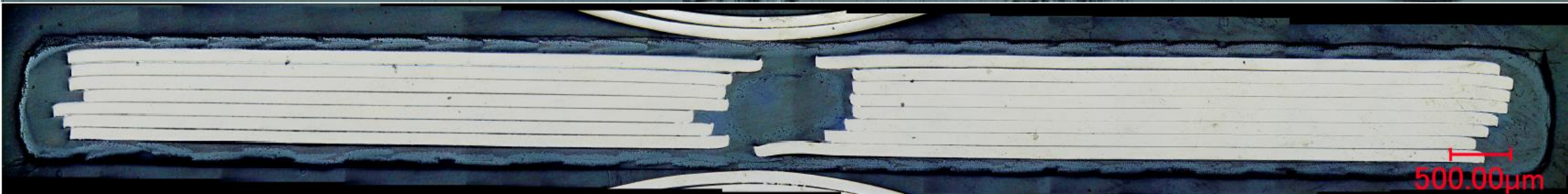
UNIVERSITY OF TWENTE.



By courtesy of M. Dhalle, U. Twente

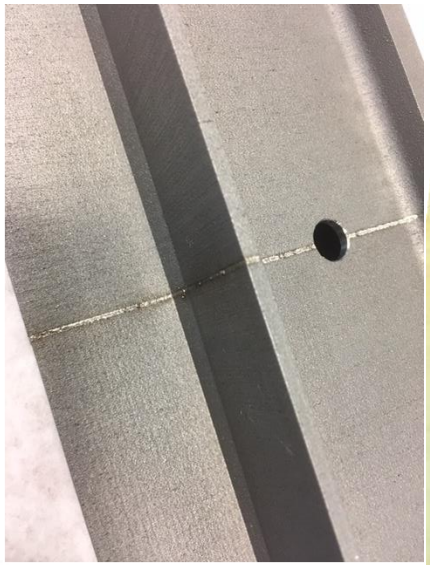


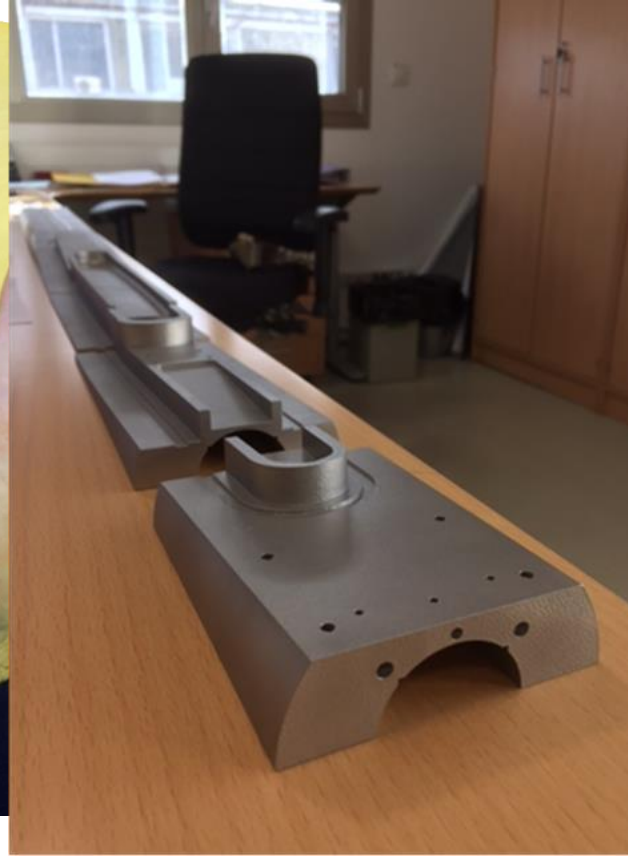


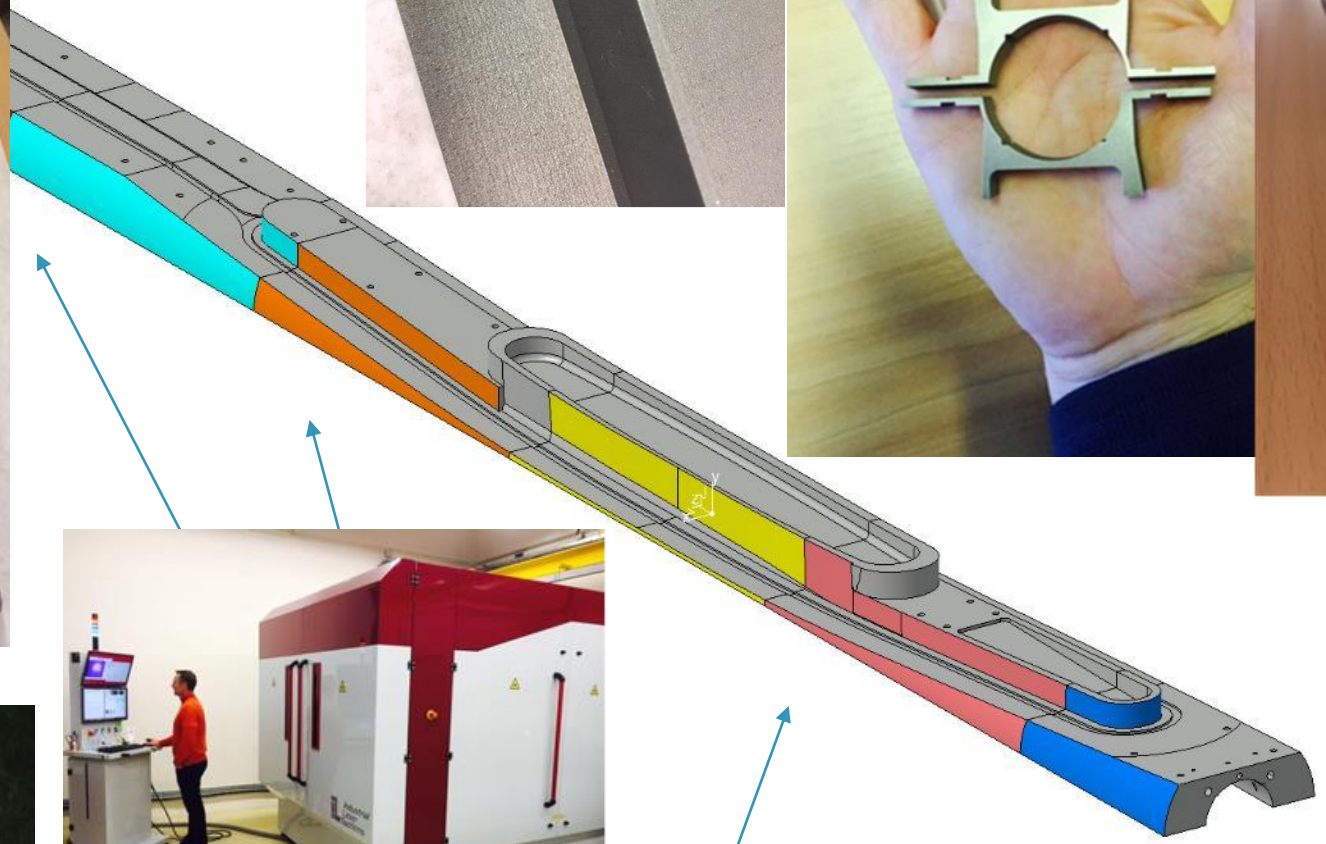


FORMER 3D PRINTING

Material 316L
stainless steel



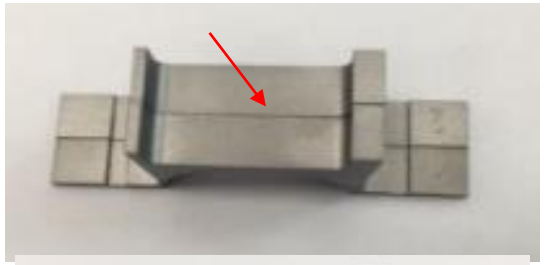


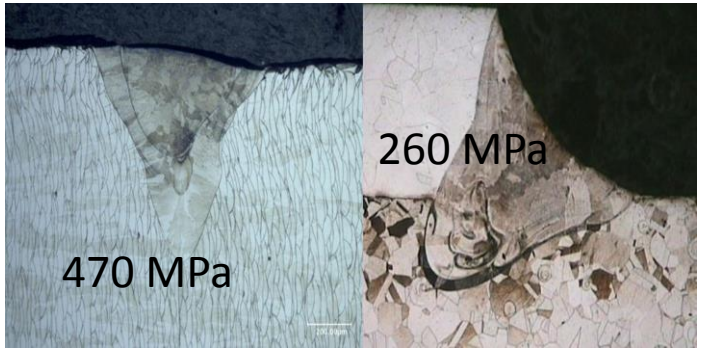


CERN laser welding

Laser welding section
max length 218 mm

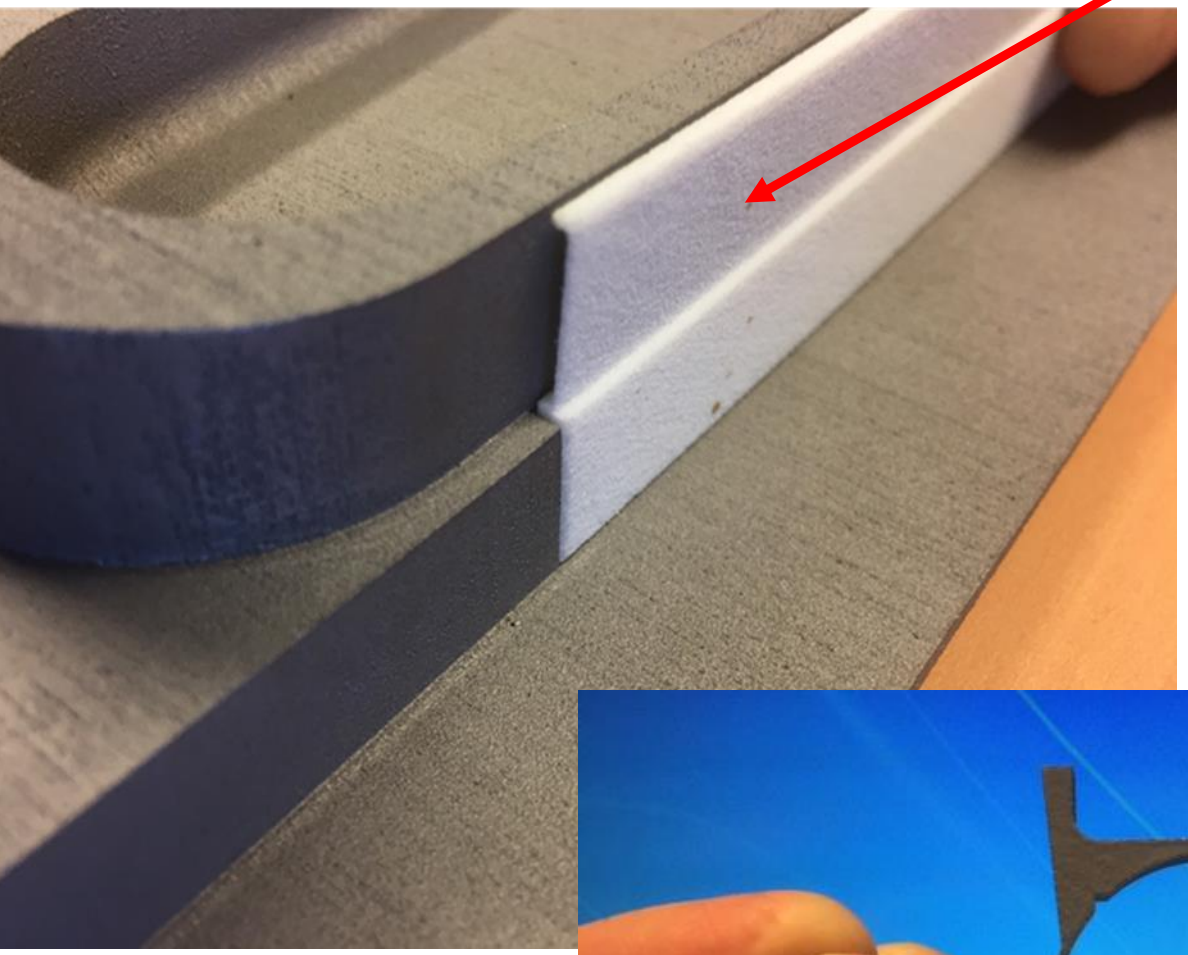
Test weld

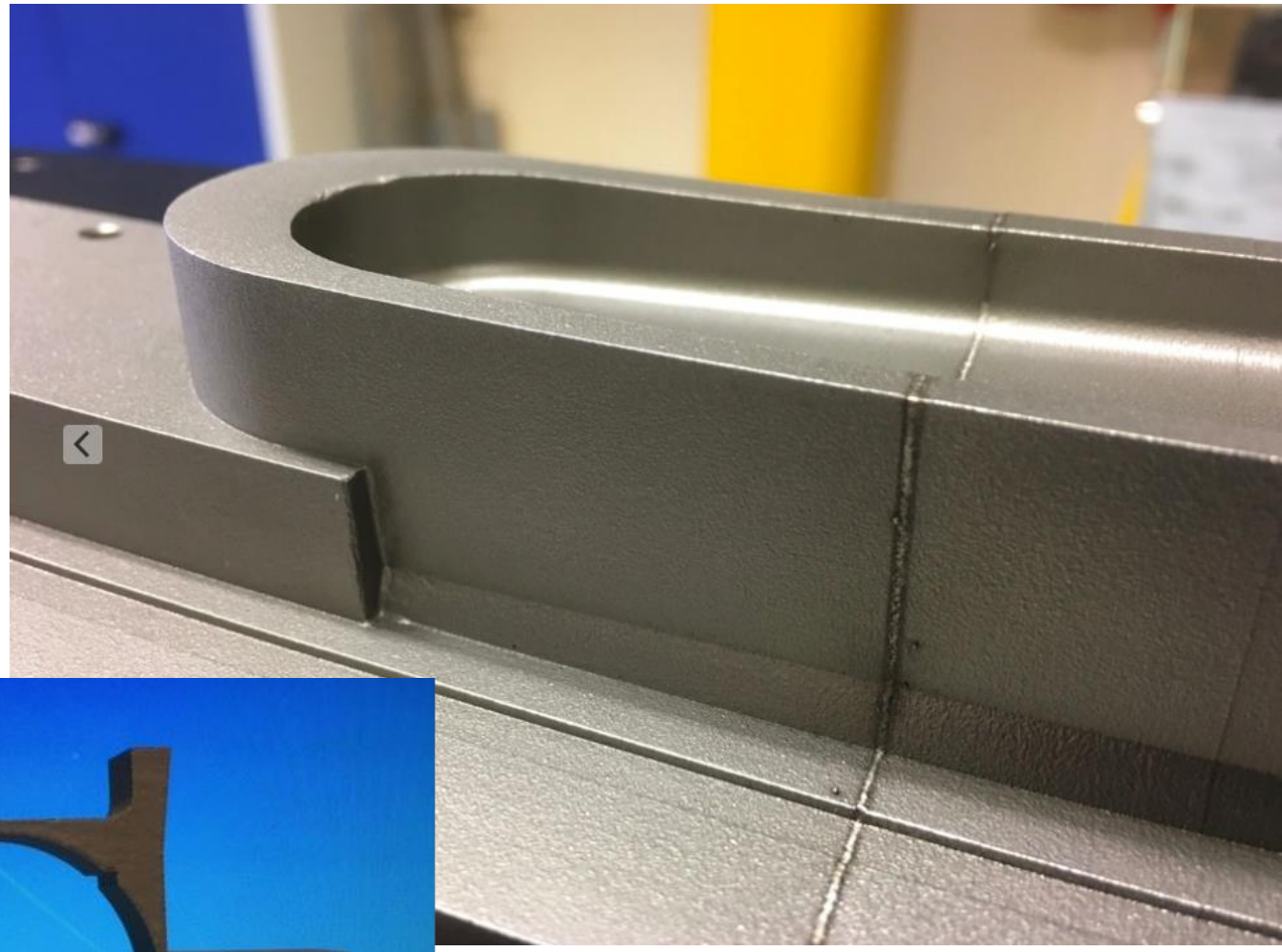


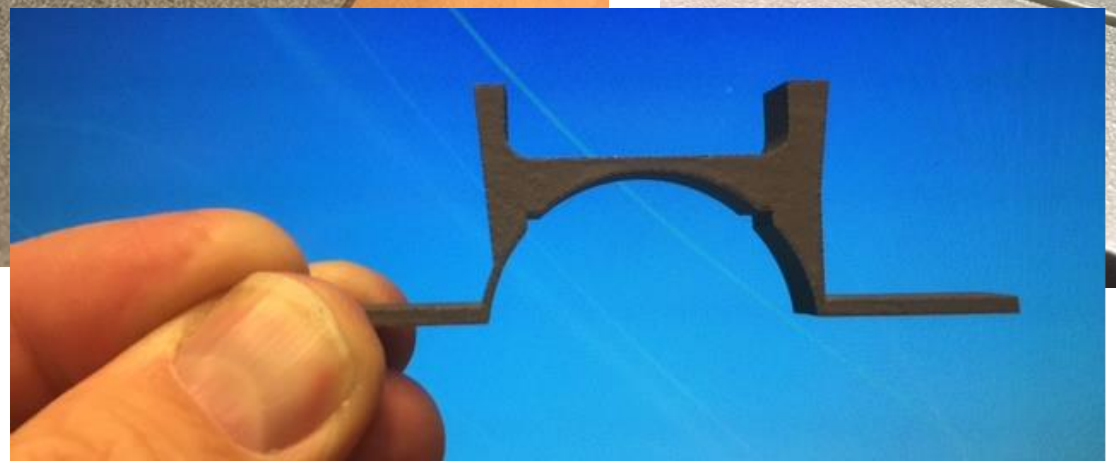


FORMER DETAIL

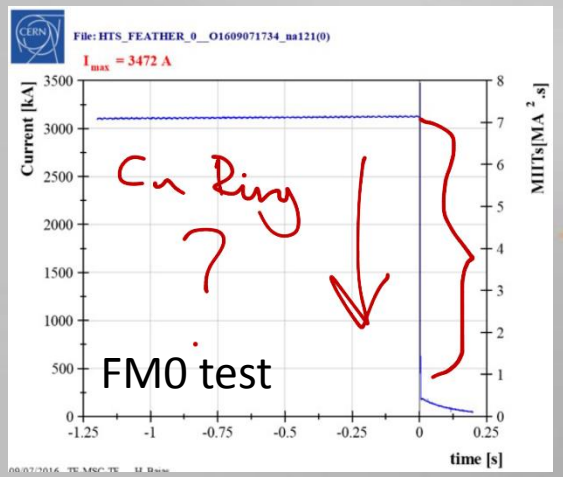
3D printed former (STST 316L) and
layer jump cover (glass filed Nylon)

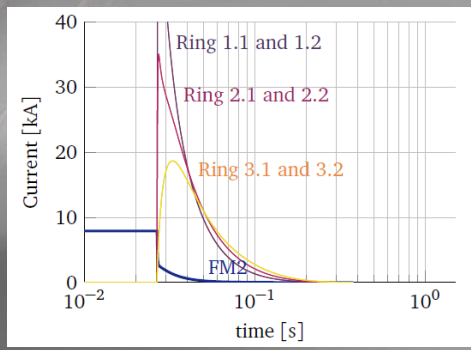


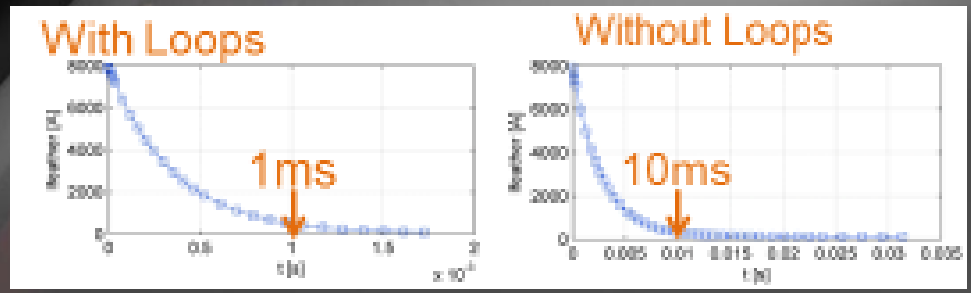




COPPER RINGS CURRENT EXTRACTION







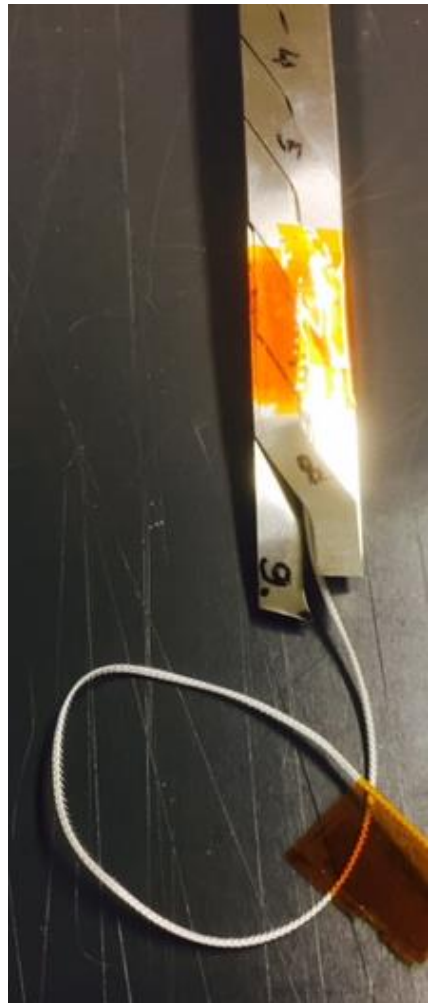
Energy extraction and

Inserting central wire.

2mm dia steel guide wire

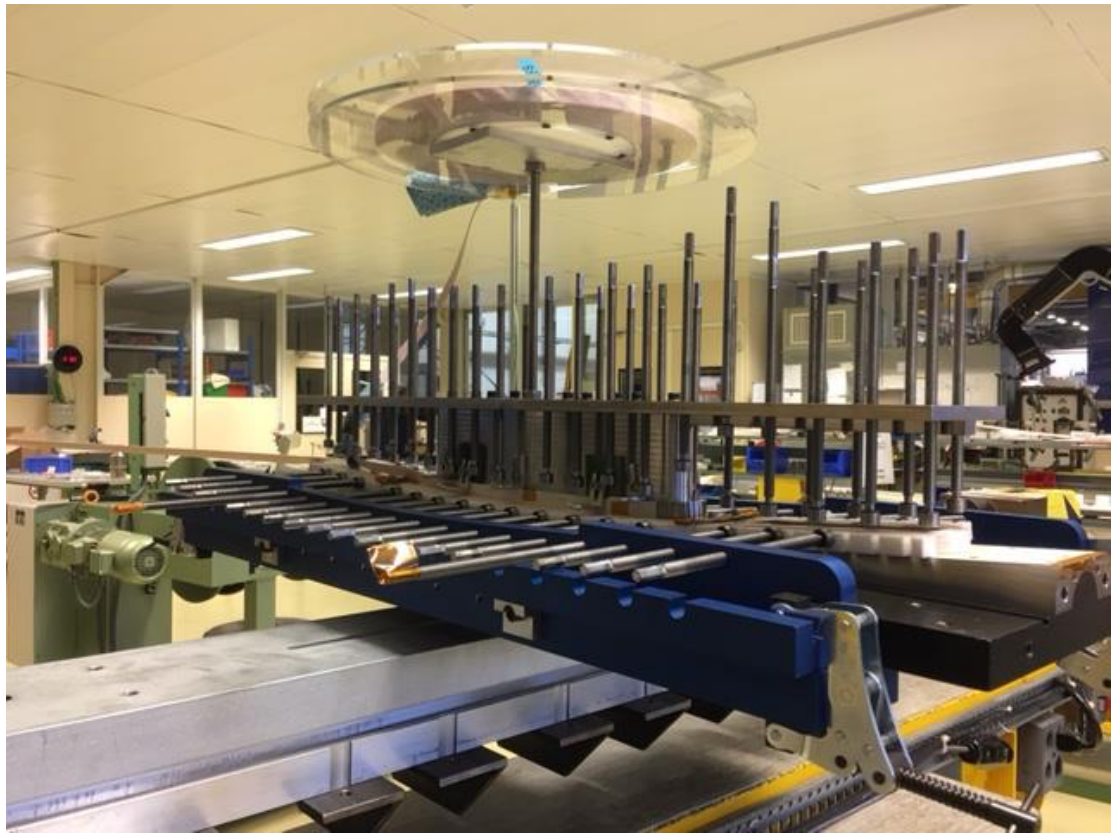
Wire straitening tool

24 to 37m cable table



Glass insulated wire inside cable

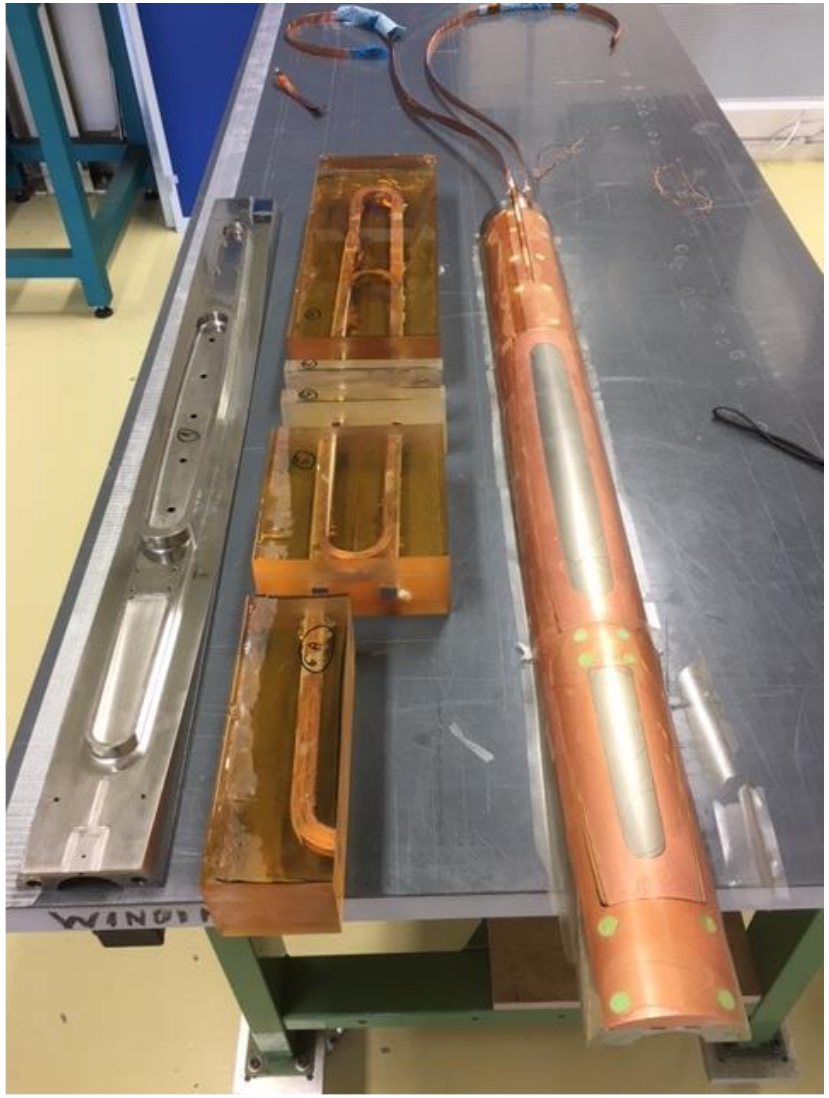
Coil winding



Winding tools apply a low pressure ~ 3 MPa to put tapes into electrical contact.

Winding tension 5 kg

GOOD CONTACT BETWEEN TAPES, FULLY IMPREGNATED



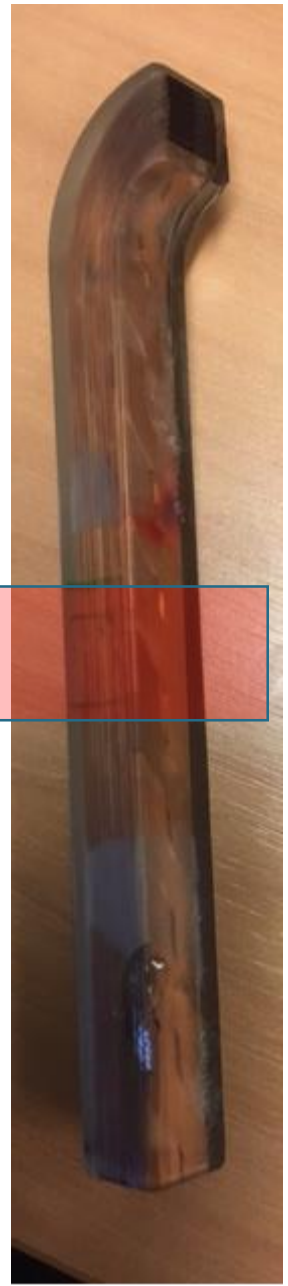
Dummy coil impregnation test

Coil Straight section

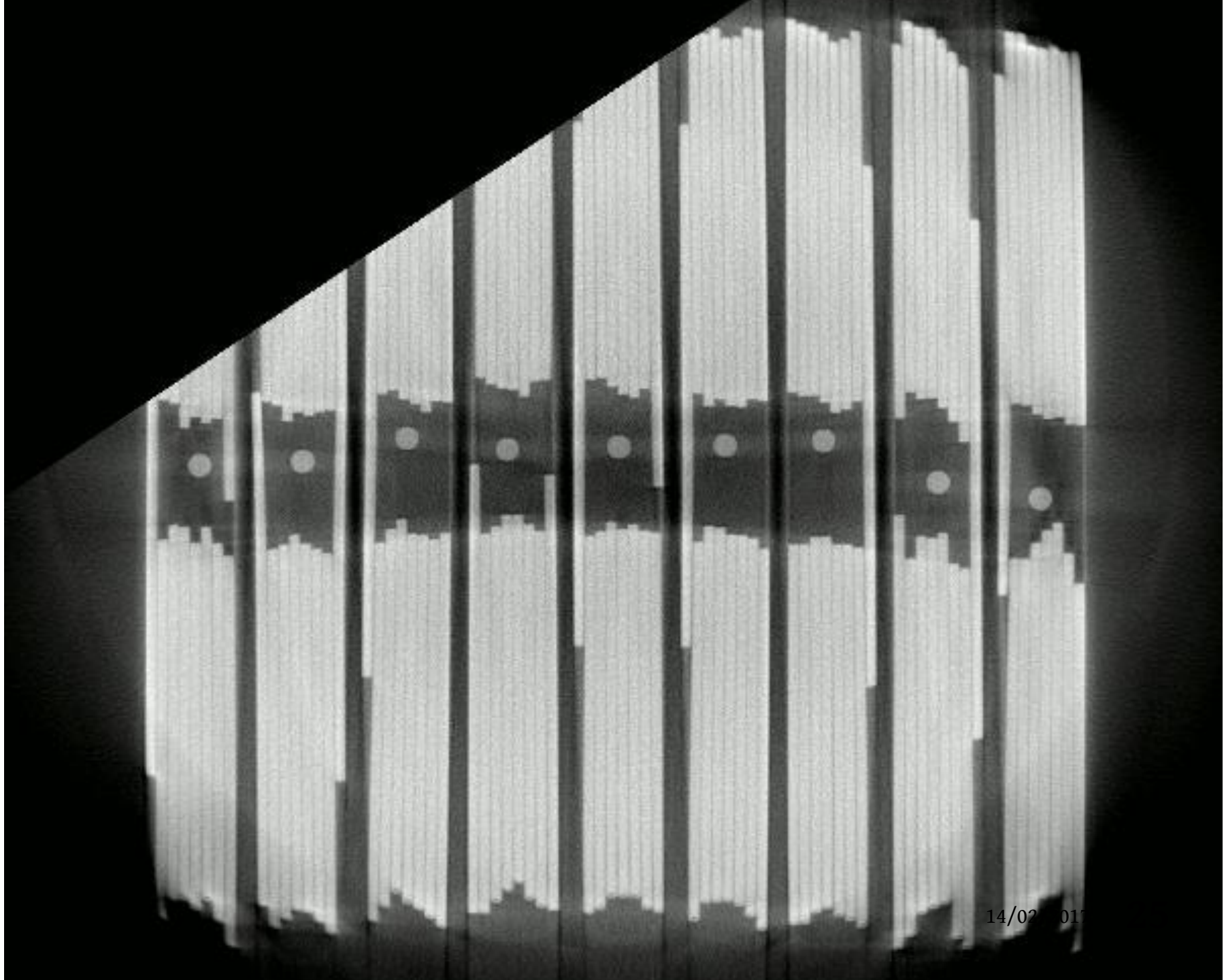
Coil end

~ 1 e-9 Ohm M^2Twente

TOMOGRAPHY

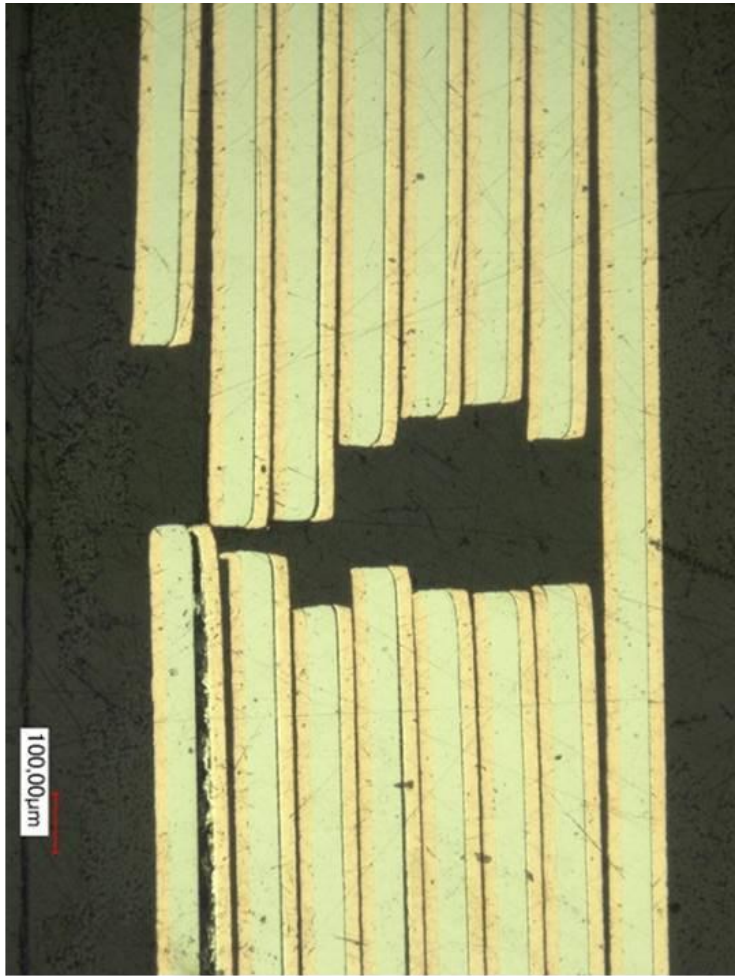


2 cm section movement in Z direction

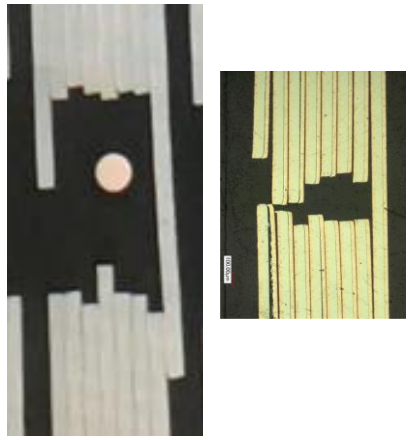


Cable design changes (thickness , pitch, central channel).

Dummy old cable design (NZ)



New design

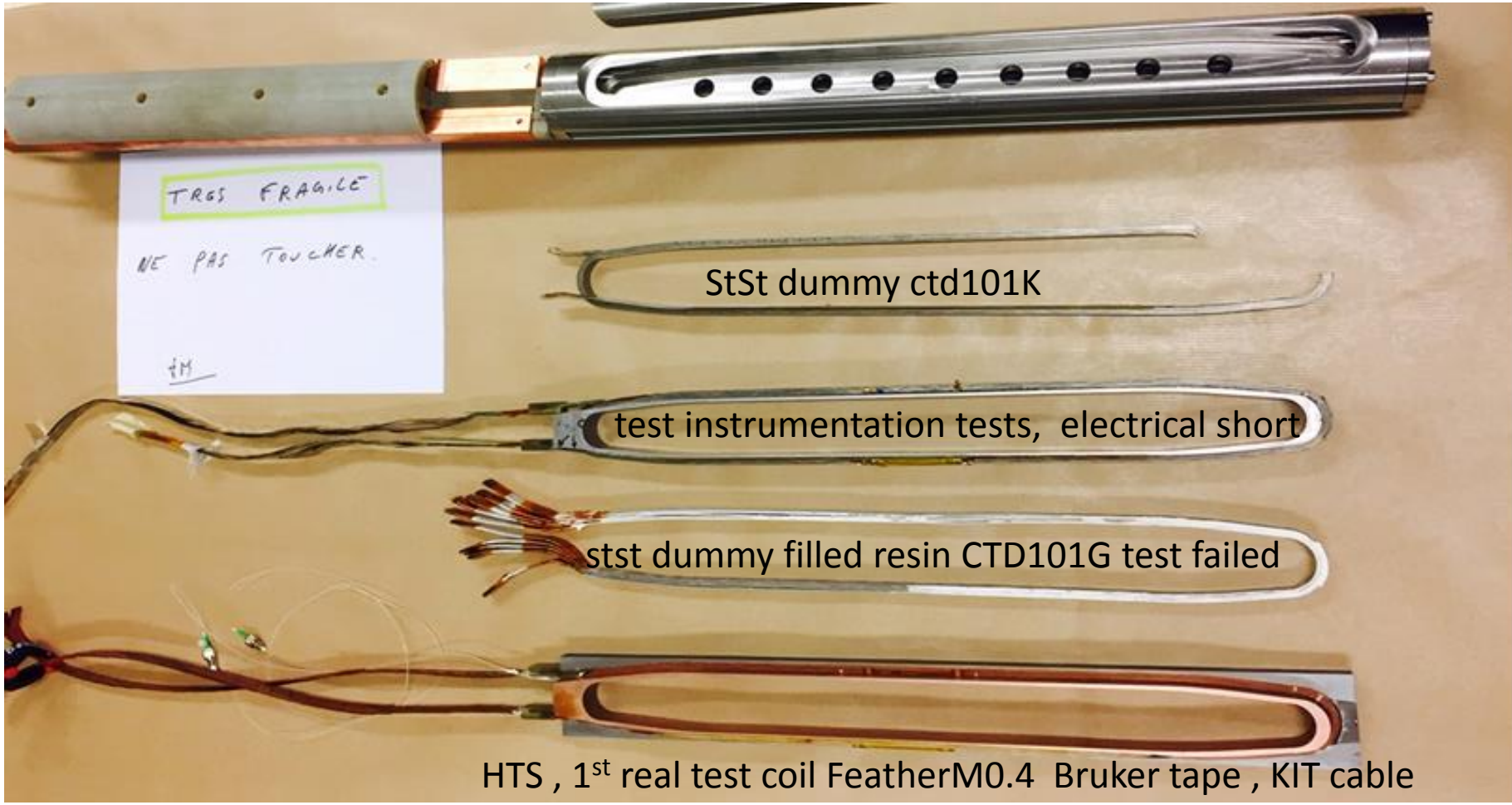


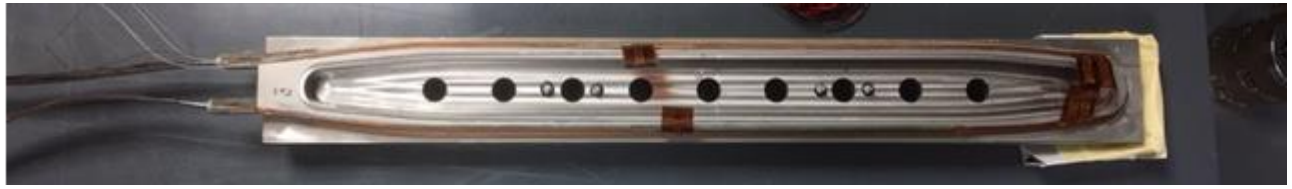
Changes in cable design has made it difficult to test efficiently the design that we will actually wind into a magnet.

The thickness changes have been particularly difficult

Quench detection wire must be removed from the last design.

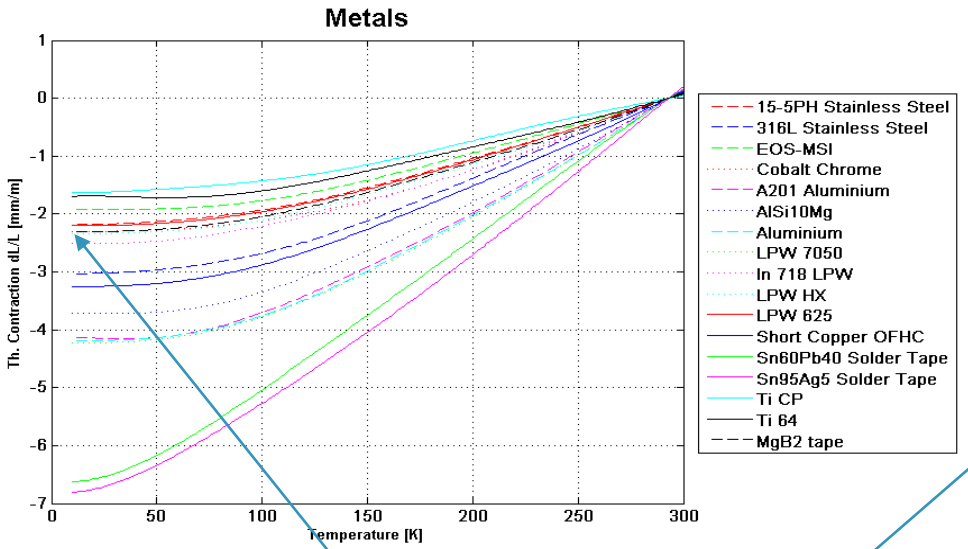
Coil Development



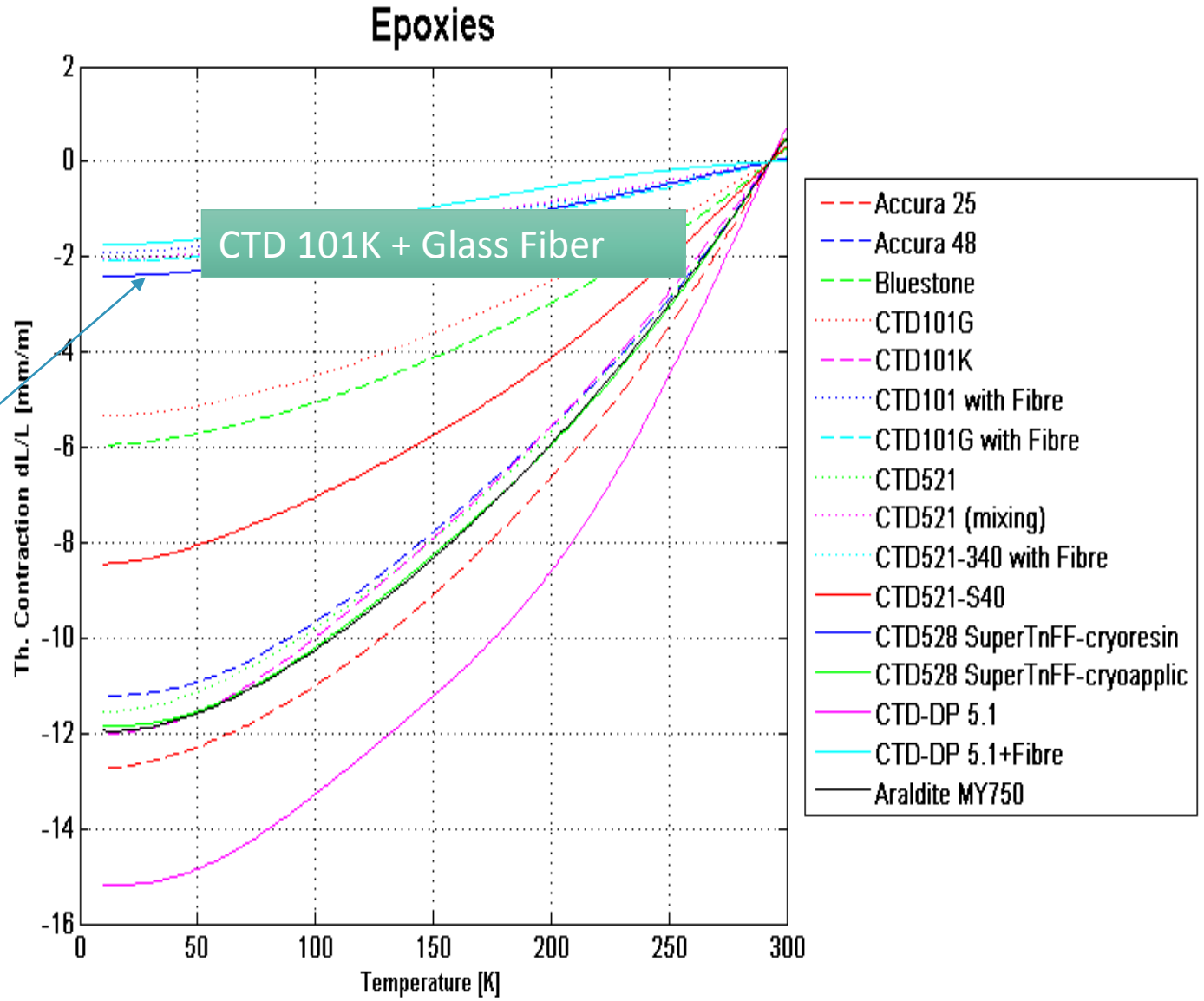


FeatherM0.5, SuperOx cable the next Feather ZERO to be tested.

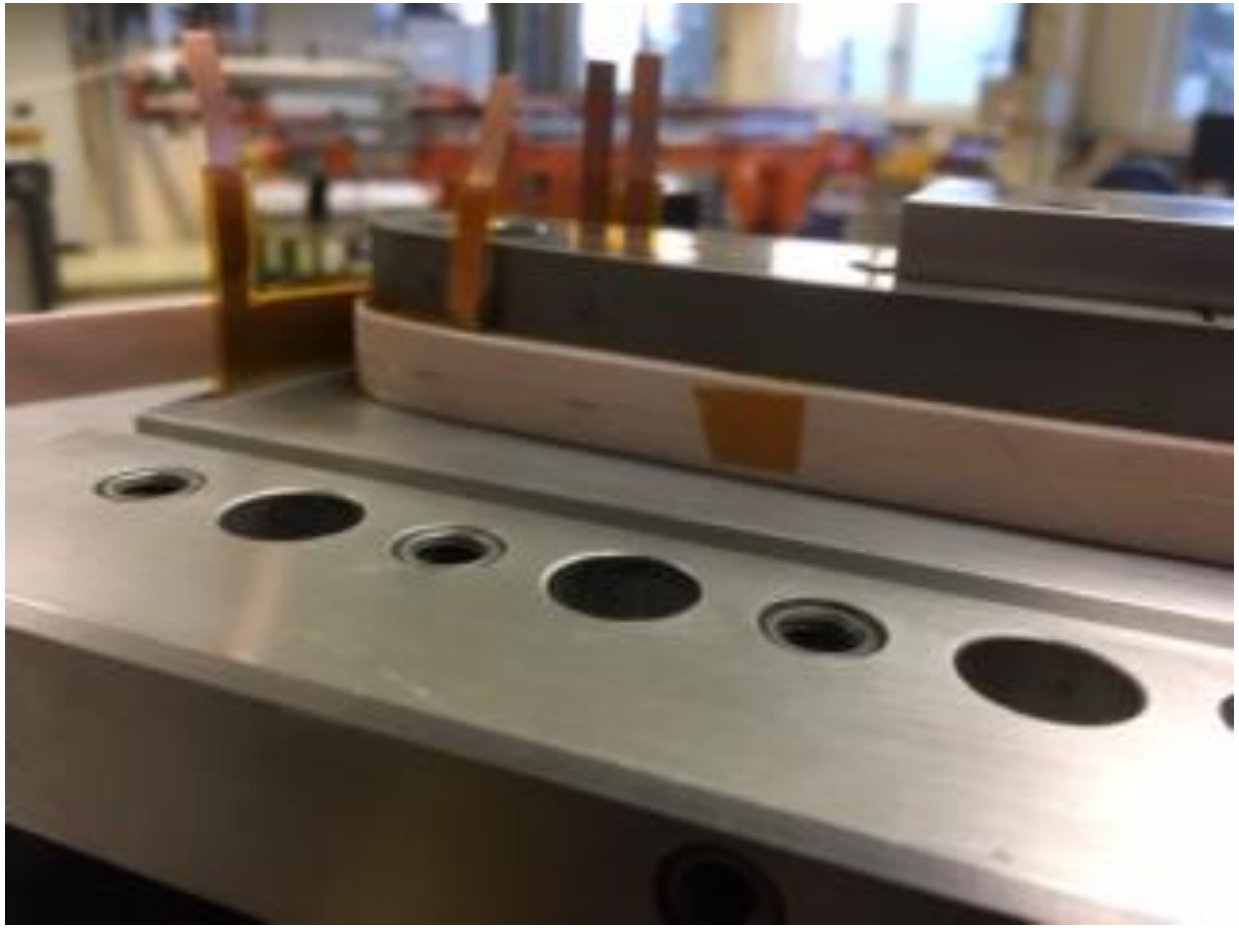
IMPREGNATION RESIN AND GLASS SLEEVE

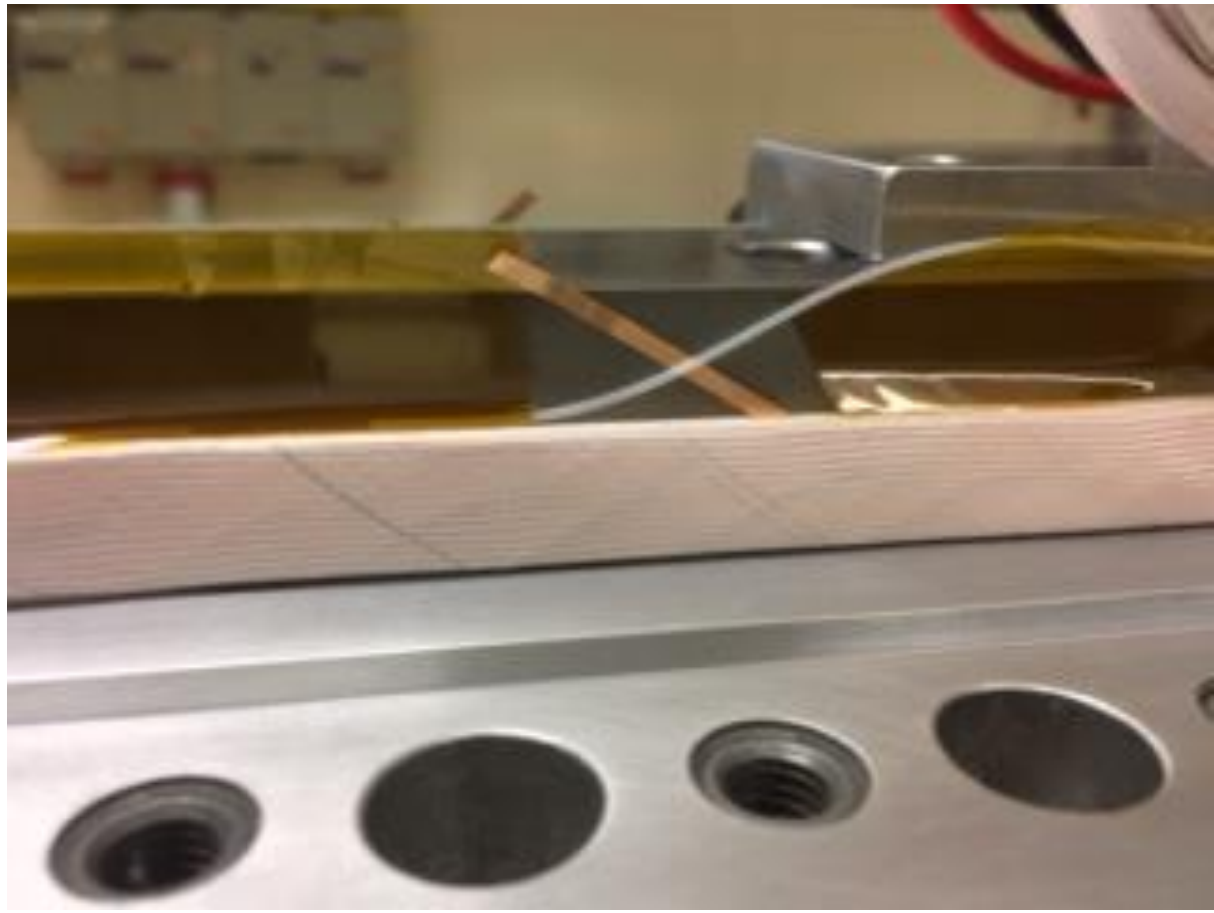


Glass sock + CTD101K matches thermal contraction of REBCO tape.

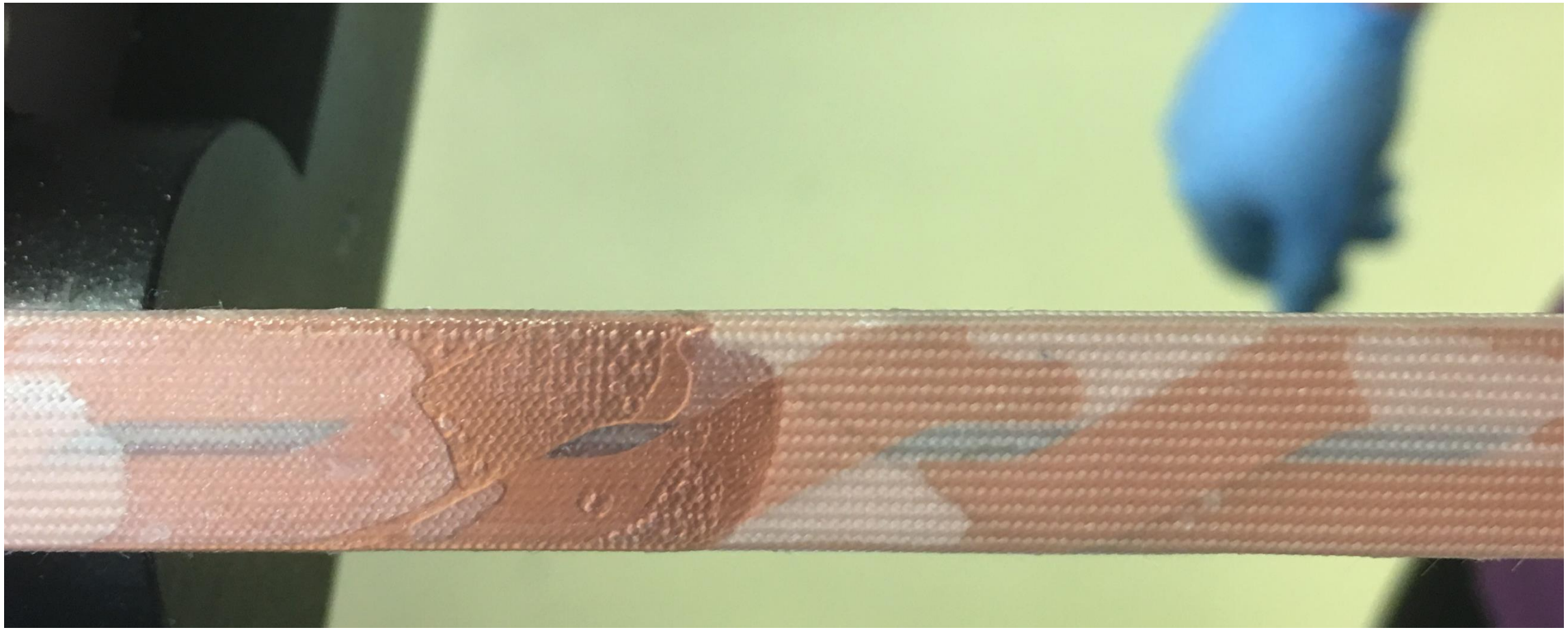


FIBER OPTIC TEMPERATURE SENSORS



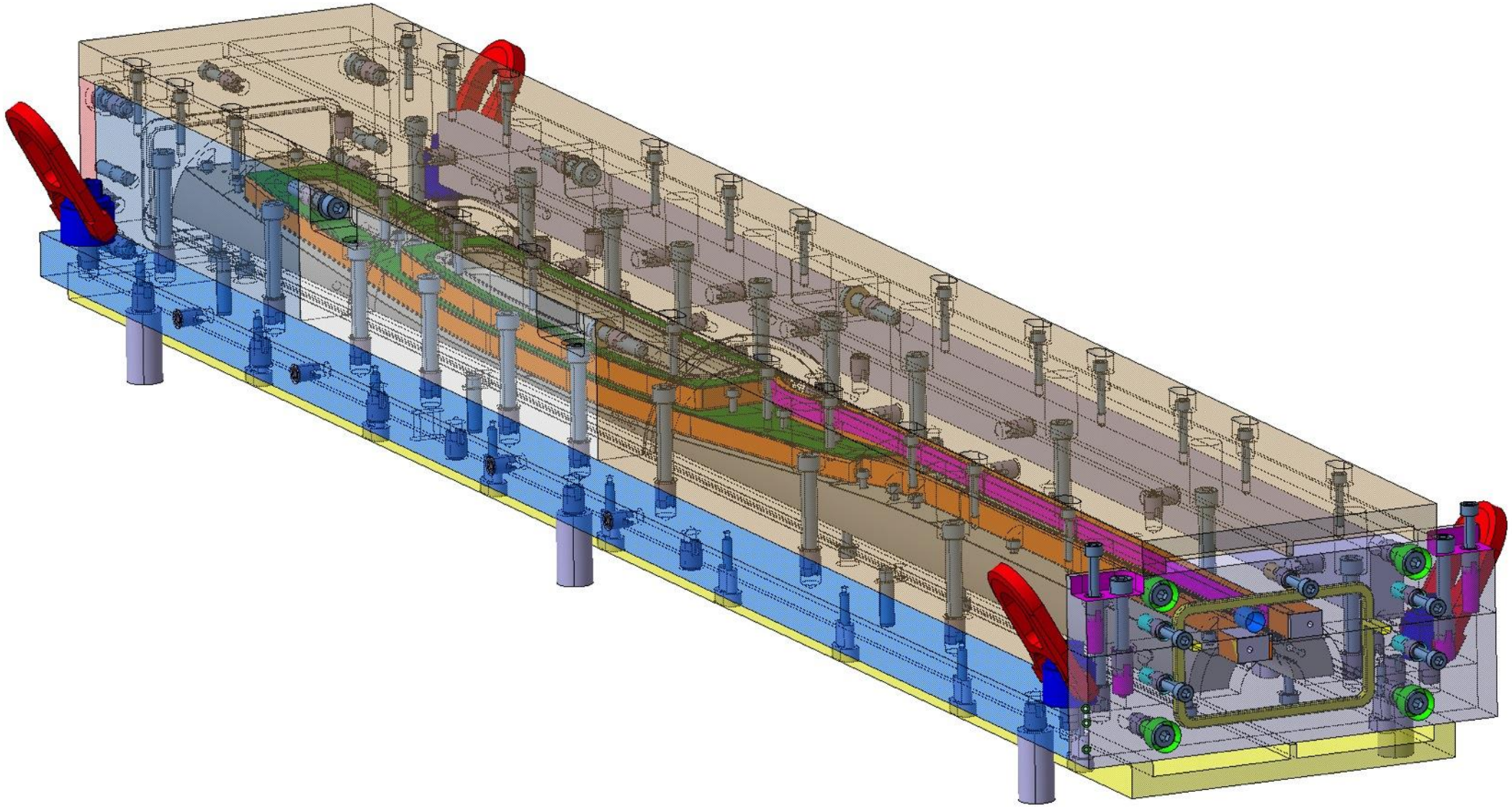


Looking through the glass sleeve



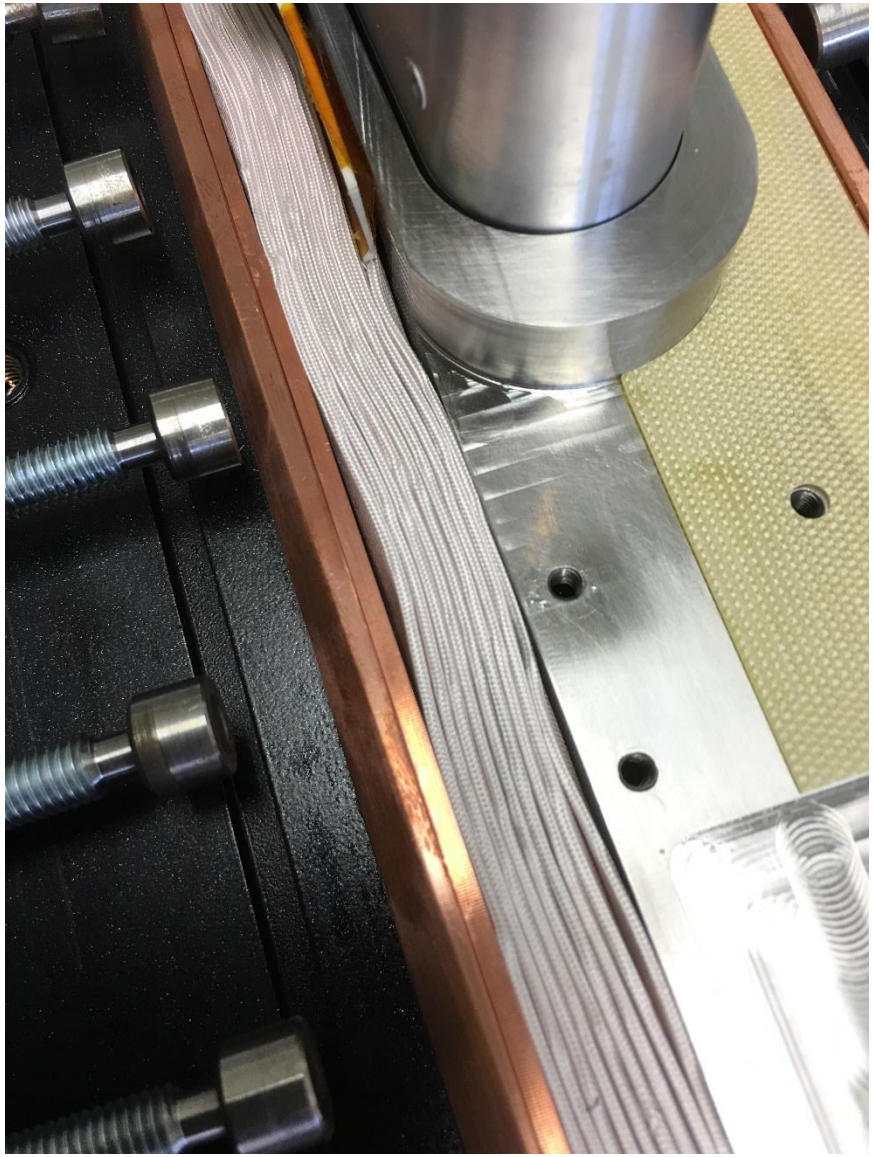
To be able to see through the glass sleeve an alcohol wash is used.

IMPREGNATION.

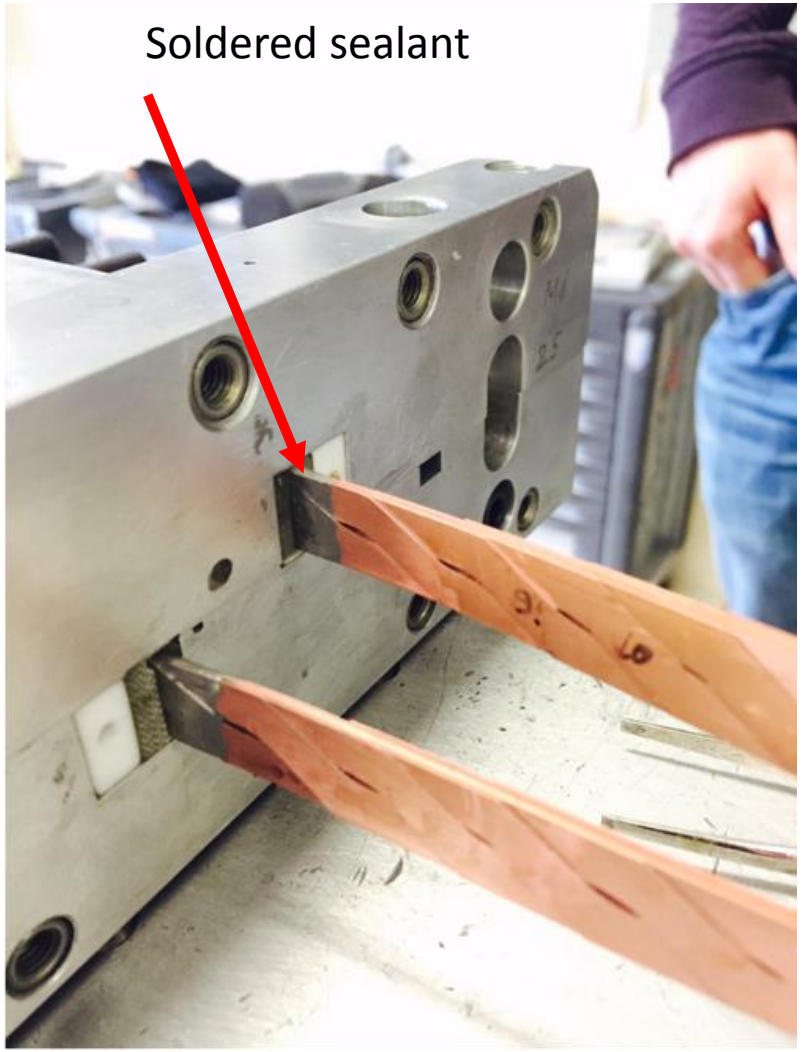


Multi-part mold

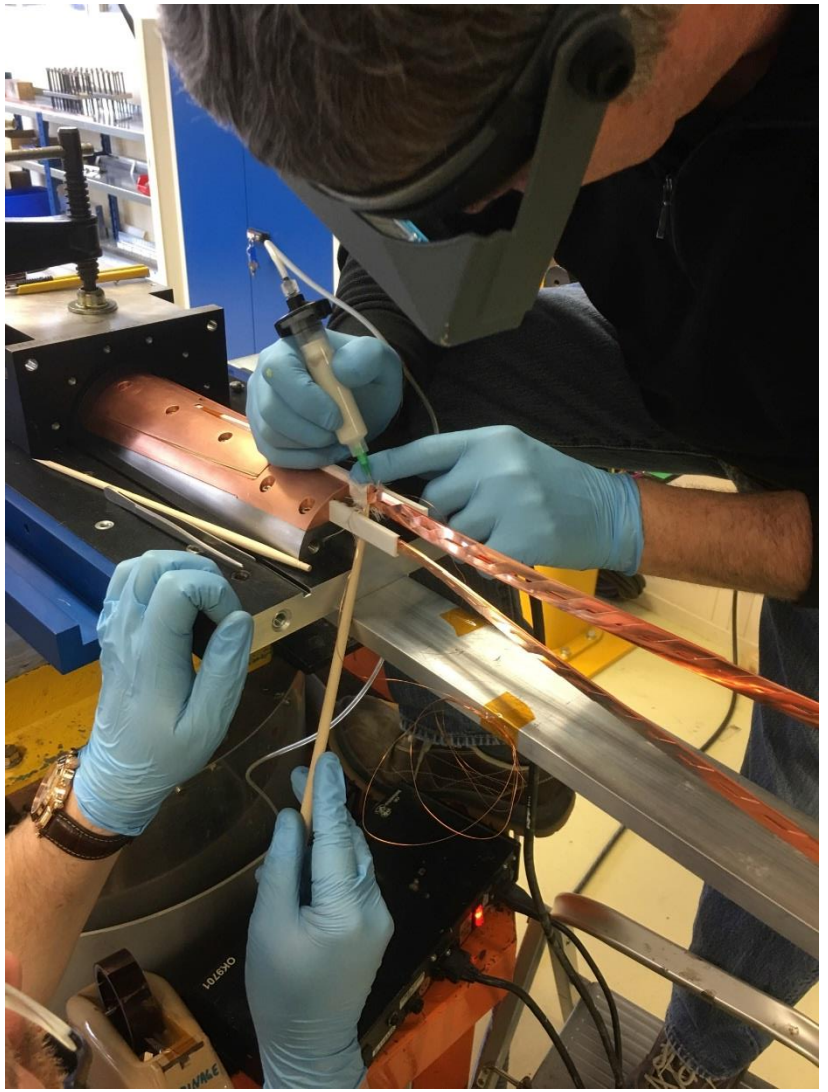
Wave in coil before compression was applied



SEALING COIL MOLD

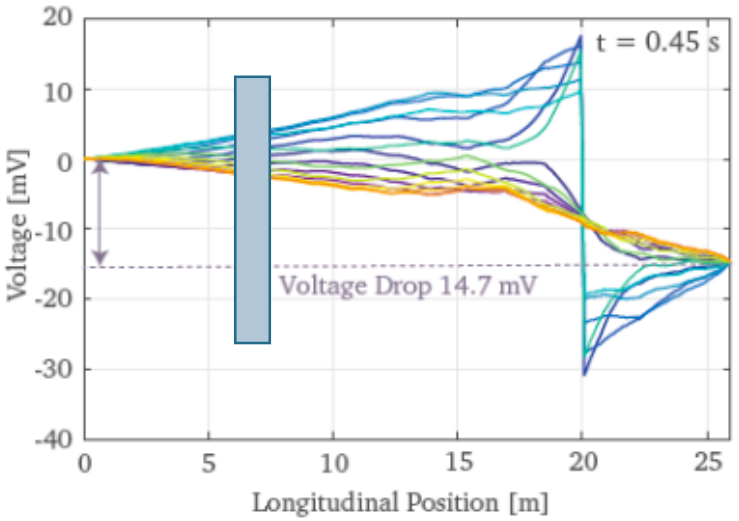


Sealed cable with solder Feather zero.4



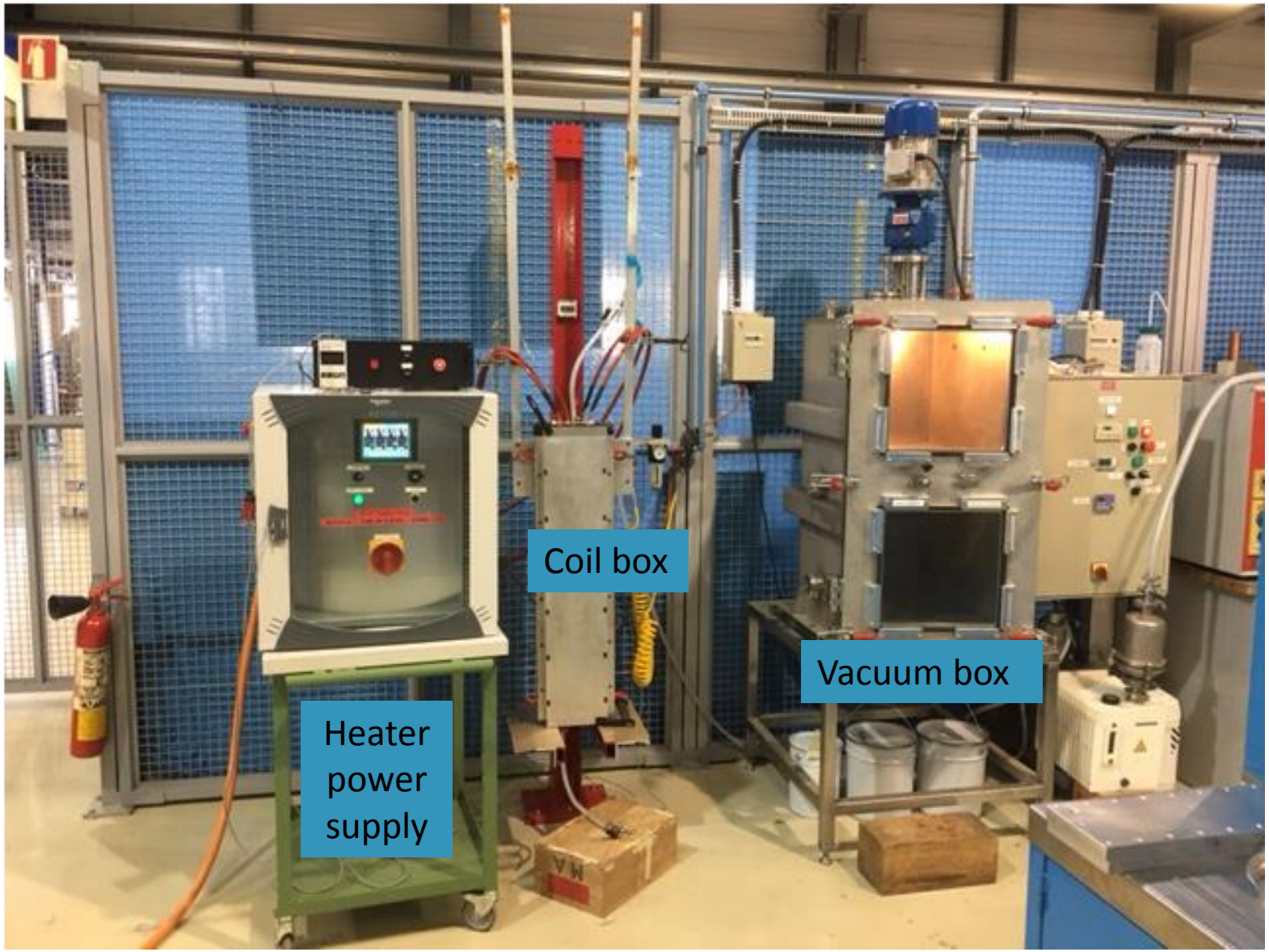
Sealed cable with silicone sealant “caf4” with pressurized injection system

Quench voltage along cable



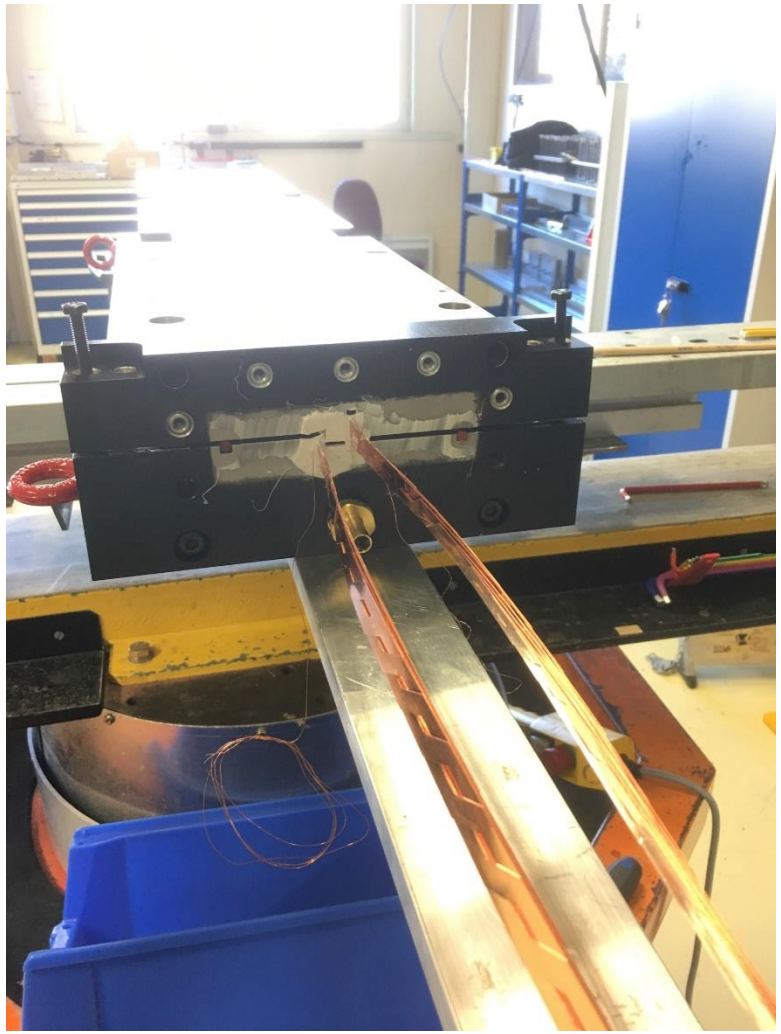
Soldered seal limits voltage detection so we moved to a silicone seal.

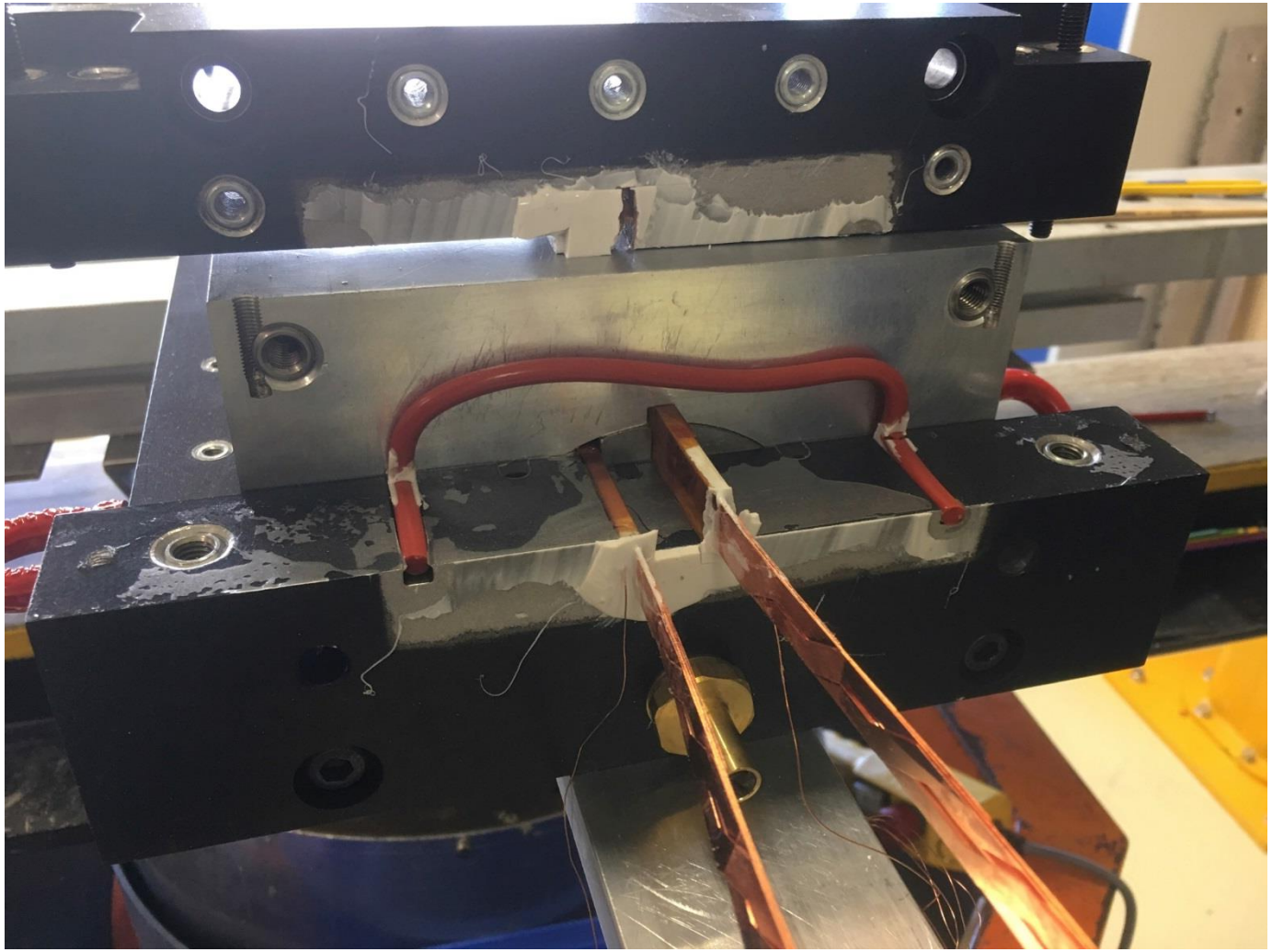
IMPREGNATION



Vacuum impregnation system

Opening the mould

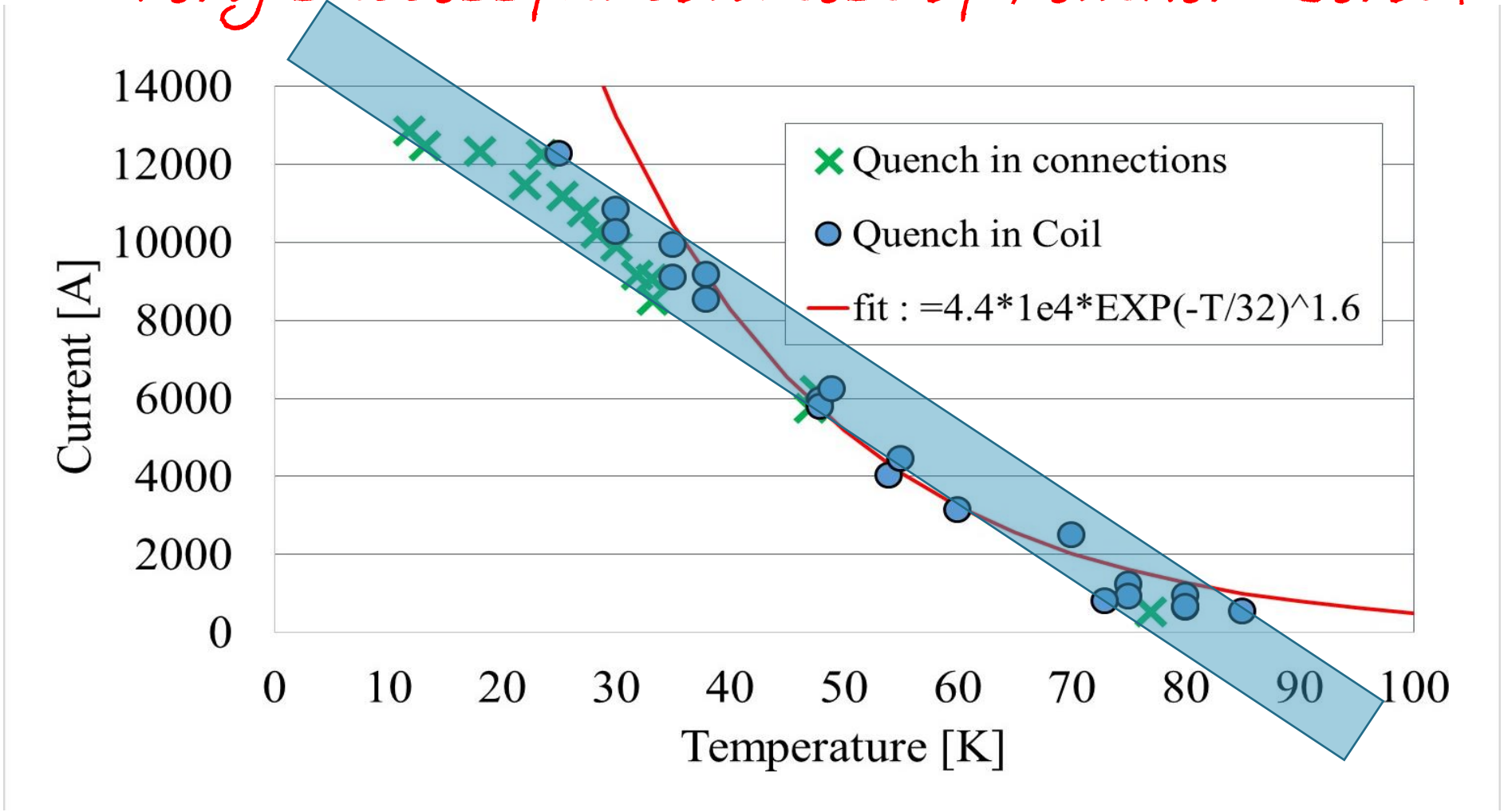




Joints

FEATHER0.4 TEST RESISTIVE JOINT AT THE HIGHER TEMPS.

Very successful cold test of Feather-Zero.4



LAP JOINT INTERNAL TAPE RESISTANCE

- Electrical resistance of REBCO lap joints characterized at 4.2 K versus field and at 77 K
- Three topologies of lap joint investigated: no substrates (Type 1), one substrate (Type 2) or two substrates (Type 3) interleaved in between the HTS layers.

- **Lowest resistances measured for Type 0 at 4.2 K**:
  - 11.6 nΩ·cm^2 for Bruker,
  - 36 nΩ·cm^2 for SuperPower and SuperOx tapes
  - 151 nΩ·cm^2 for AMSC tapes.
  - 825 nΩ· cm^2 for SUNAM (excessive value, could be smaller)
  - **Type 0 resistance almost unchanged (<20%) vs. field and temperature**

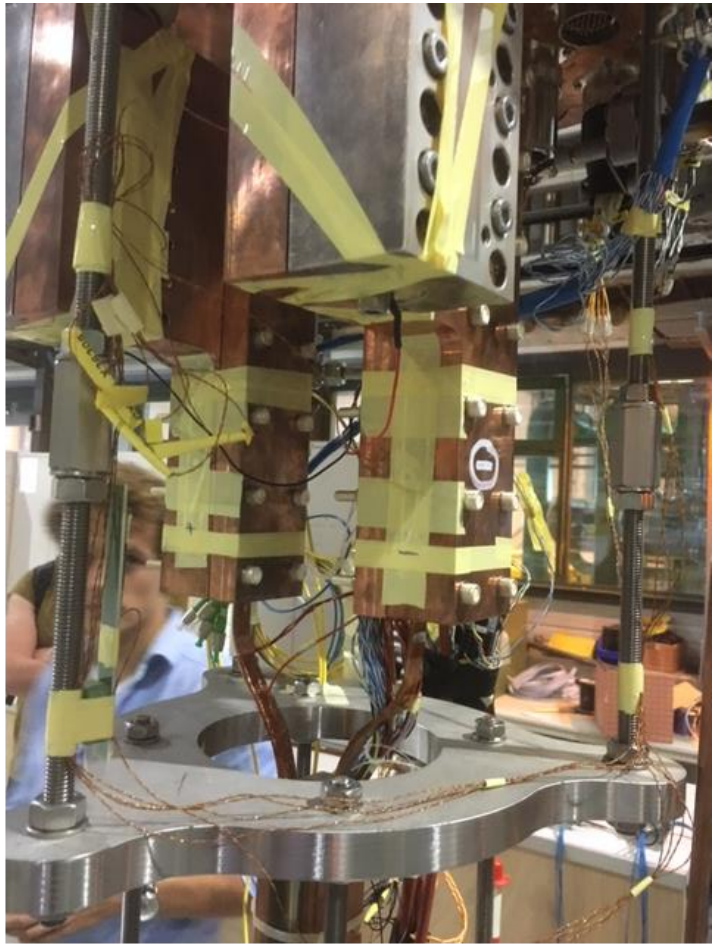
- **Type 1** joints: **7-16** times more resistive compare to **Type 0** (except SuNAM*)
- **Type 2** joints **10-25** times more resistive compare to **Type 0** (except SuNAM*)

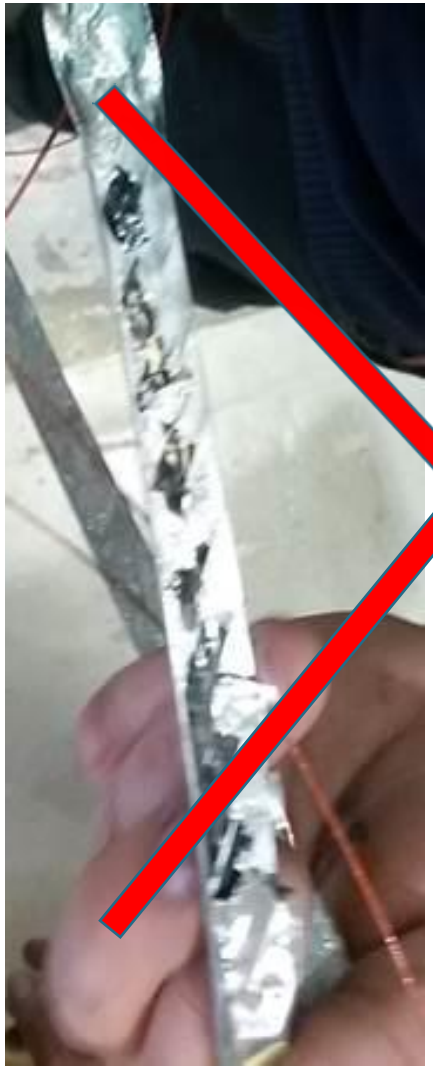
- **On-going work:**
  - RRR measurement of Cu stabilizer
  - Characterization of 12 mm wide splices

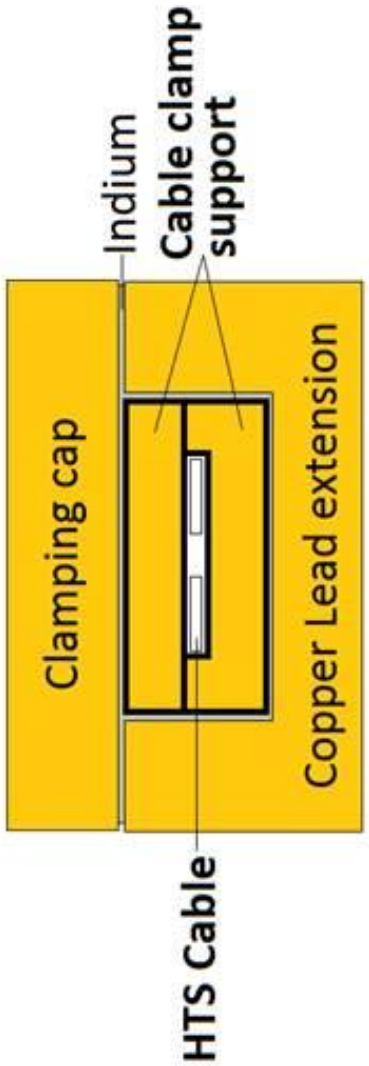
***** measured excessive internal resistance on this batch

J. Fleiter and A. Ballarino, "In-Field Resistance of REBCO Electrical Joints at 4.2 K", *CERN internal note 2015-10* , EDMS Nr: 1562549.

Dismountable Joints between cable and current leads

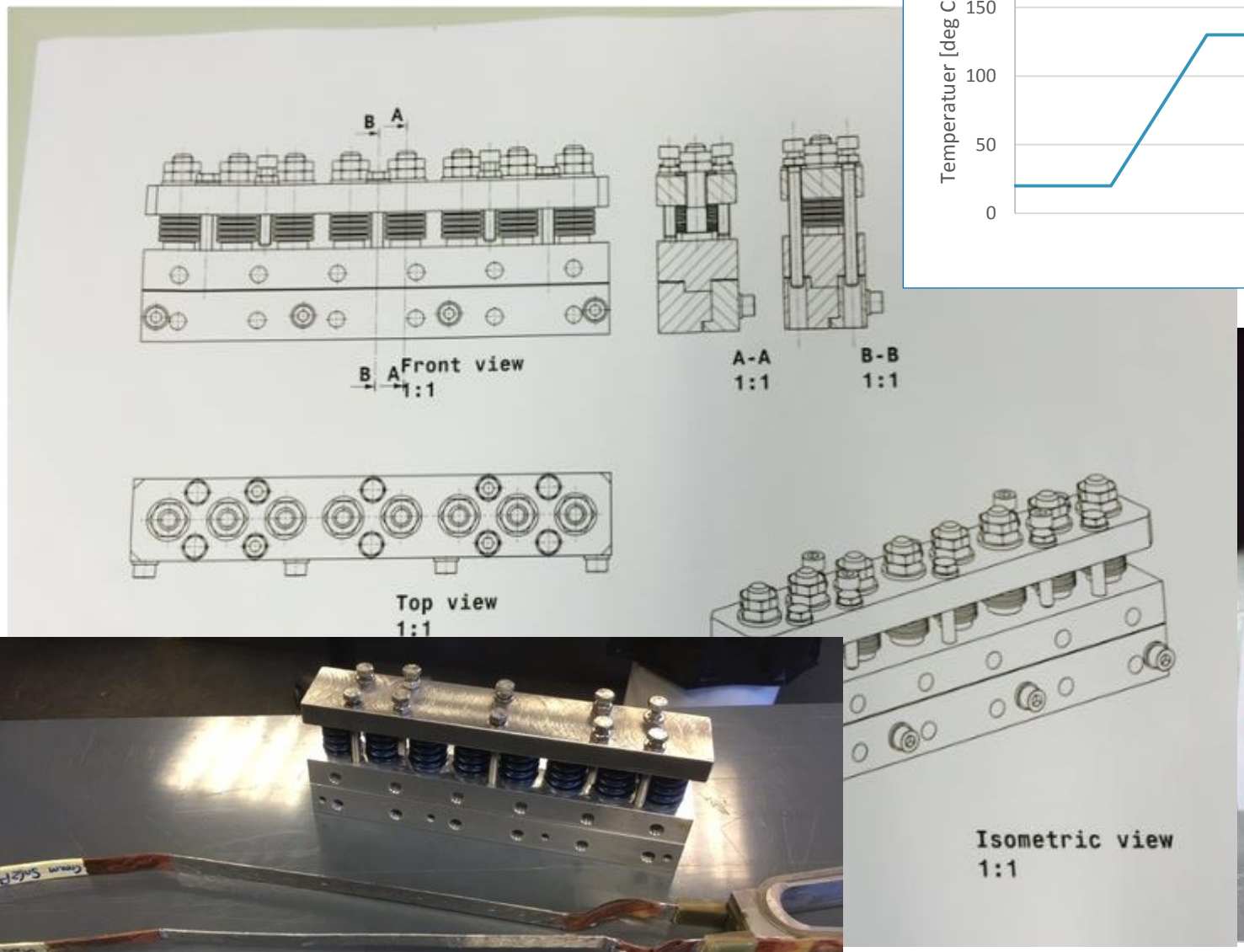


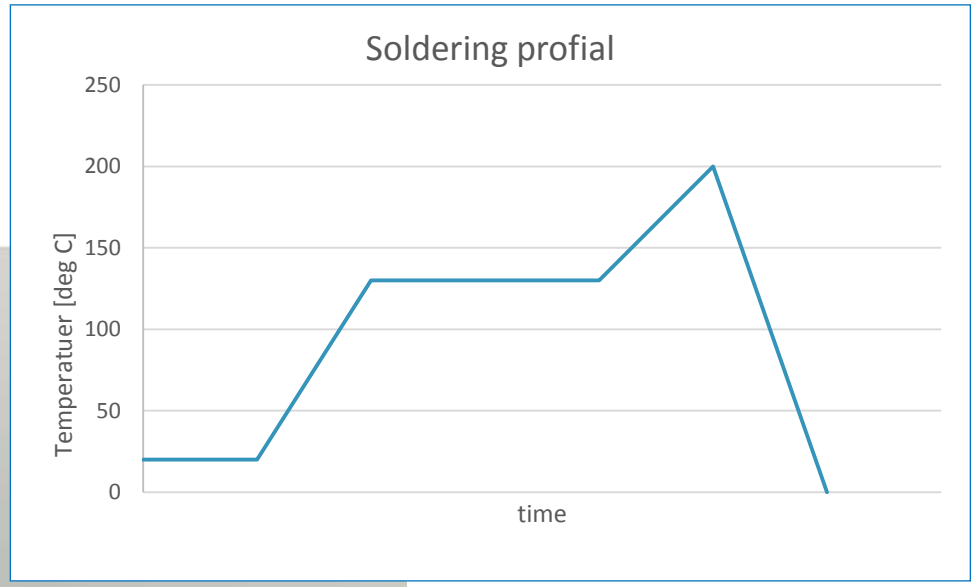




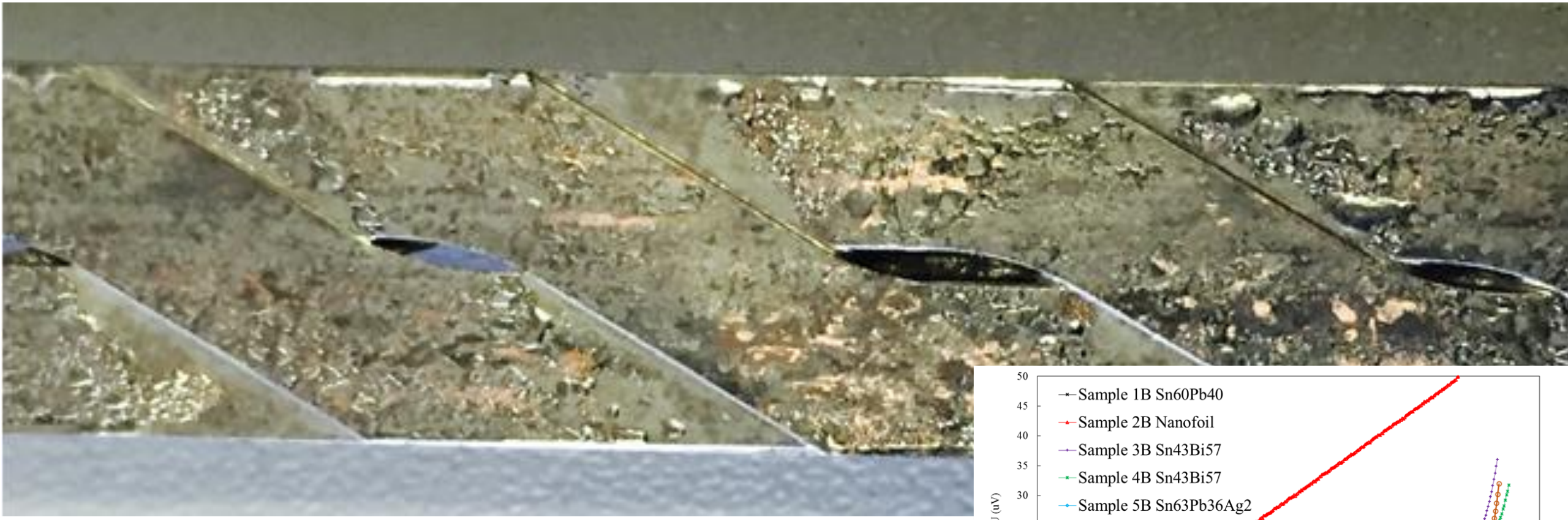
To avoid delamination we soldered a thin copper sheet on top of the REBCO side of the cable.
However the indium joint gives high resistance at elevated test temperatures.

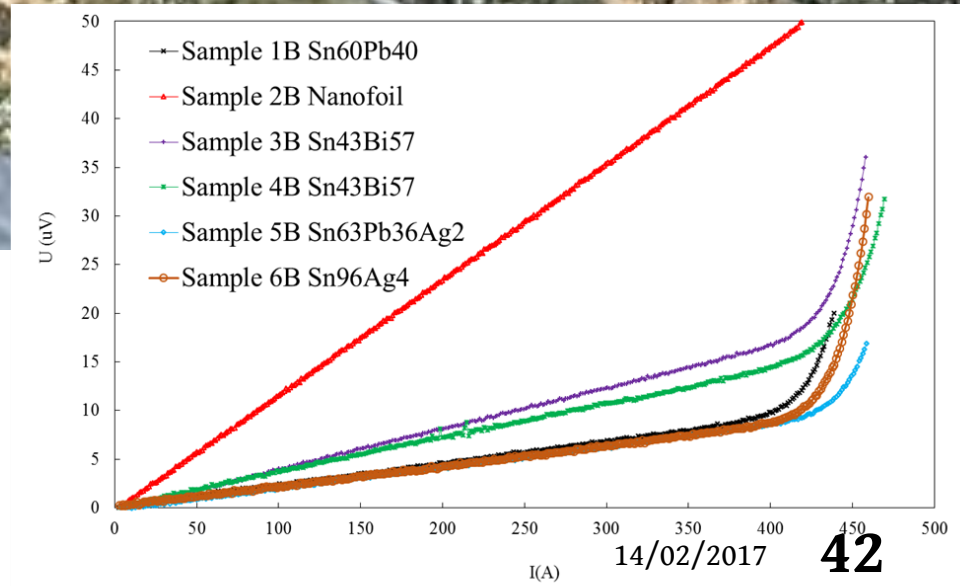
SOLDERING TOOLING





ROEBEL SOLDERED



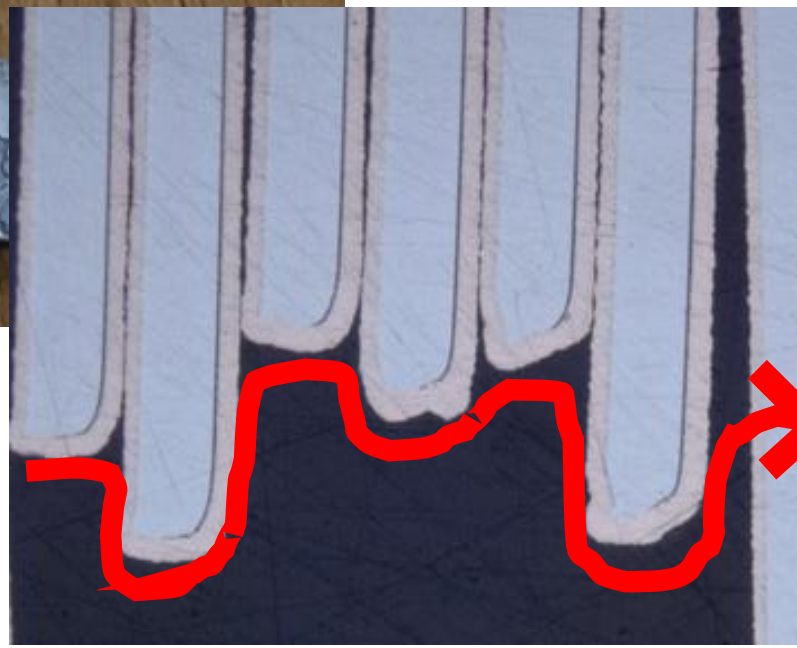


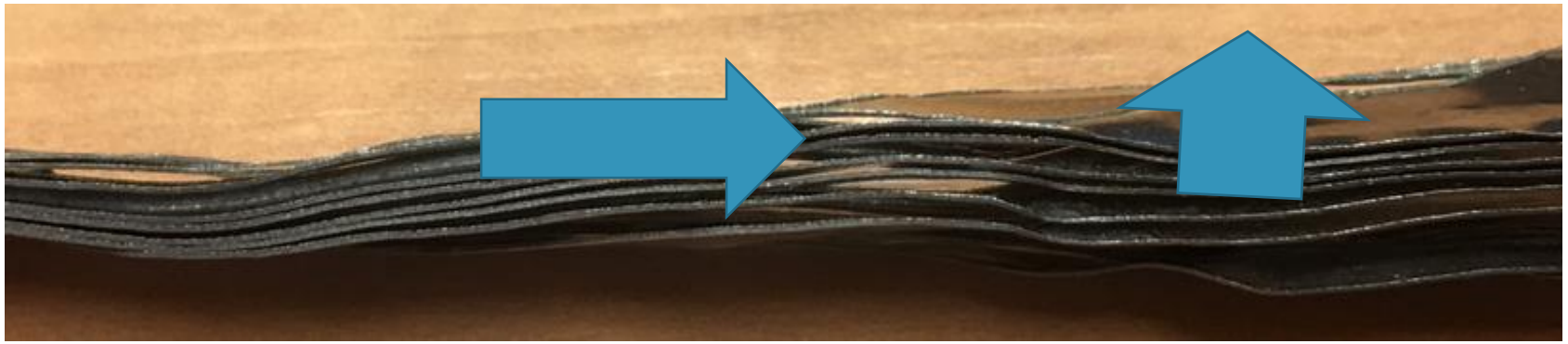
We like!

- The thin layer of solder [solder thermal contraction 6 mm/m].
- Fully soldered surface between the tapes.
- Very low 3 Mpa pressure during soldering
- Low temperature if possible.

JOINT

Soldered Robel joint 10 mm / tape of good electrical every 300 mm



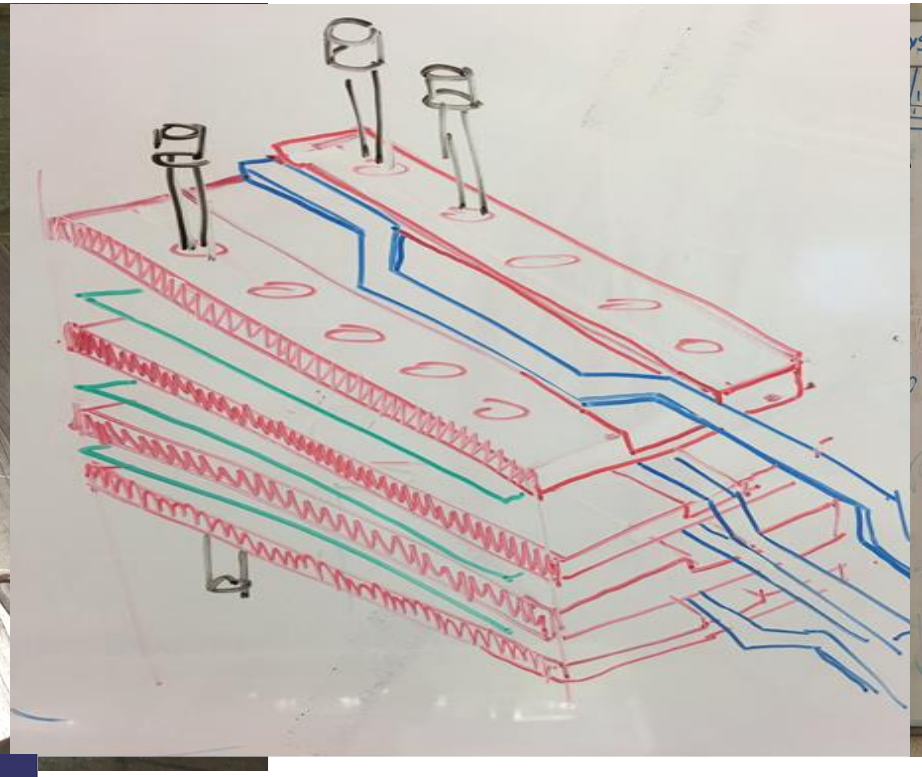


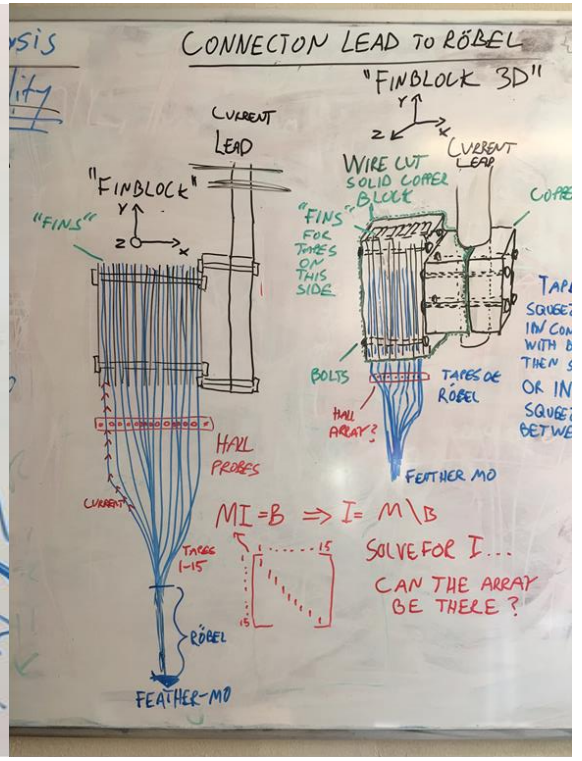
Resistance through steel tapes
Only Thin 0.02 mm copper
around the edges

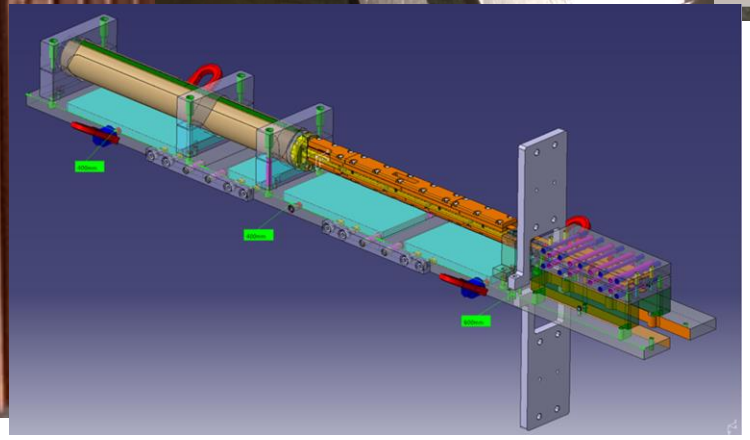
Staircase design is also limited needing long joints : 20 mm tape joint for a 300 mm overall

We have designed a new joint design that will be incorporated into the feather magnets
170mm tape joint for 170mm overall joint length. "Fin-Block"

Low Resistance Roebel Cable joint (Fin-Block)

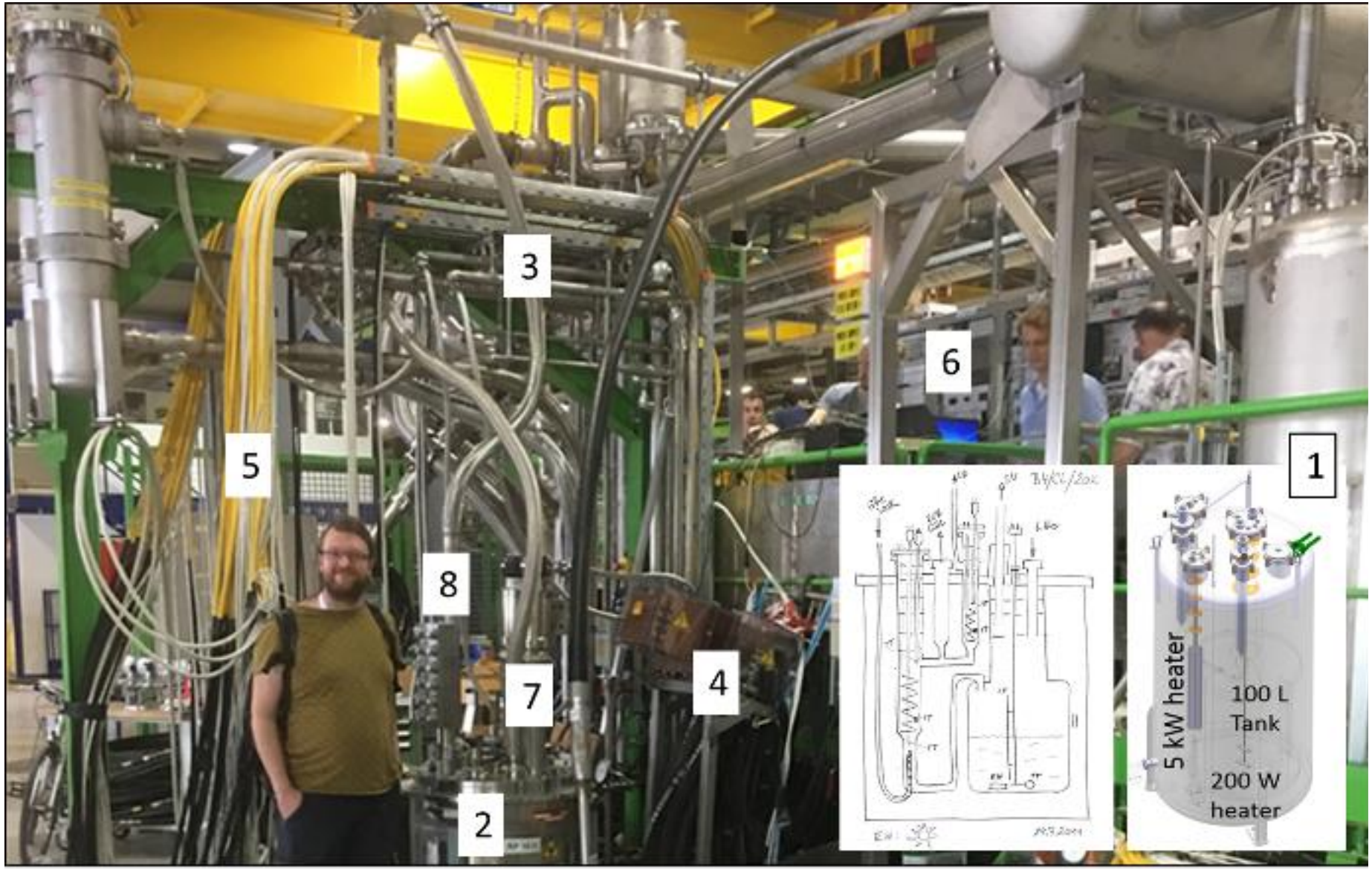






1)Each tape has a copper plate soldered to the superconducting side
2)The plates can move relative to each other to allow cable to move due to coil winding that displaces the tapes .
3) copper area allows current to bypass adjacent tapes to the current lead or other joint.
4) A gas or liquid cooling slot adds joint cooling on each tape.

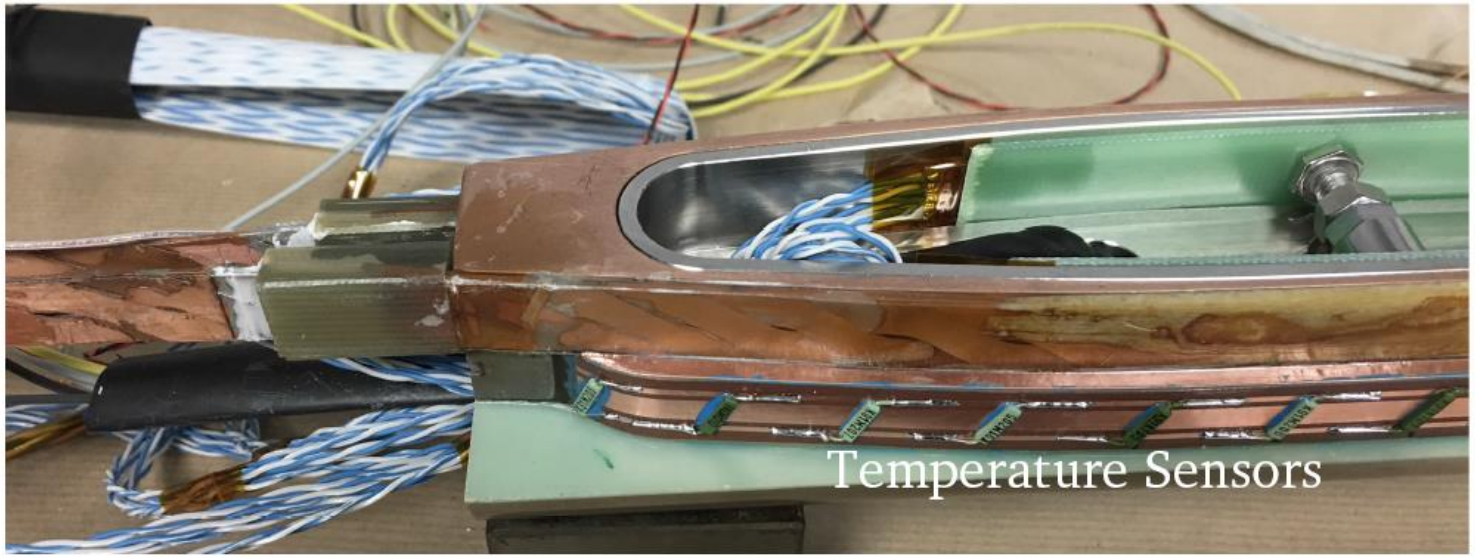
HTS VARIABLE TEMPERATURE TESTS



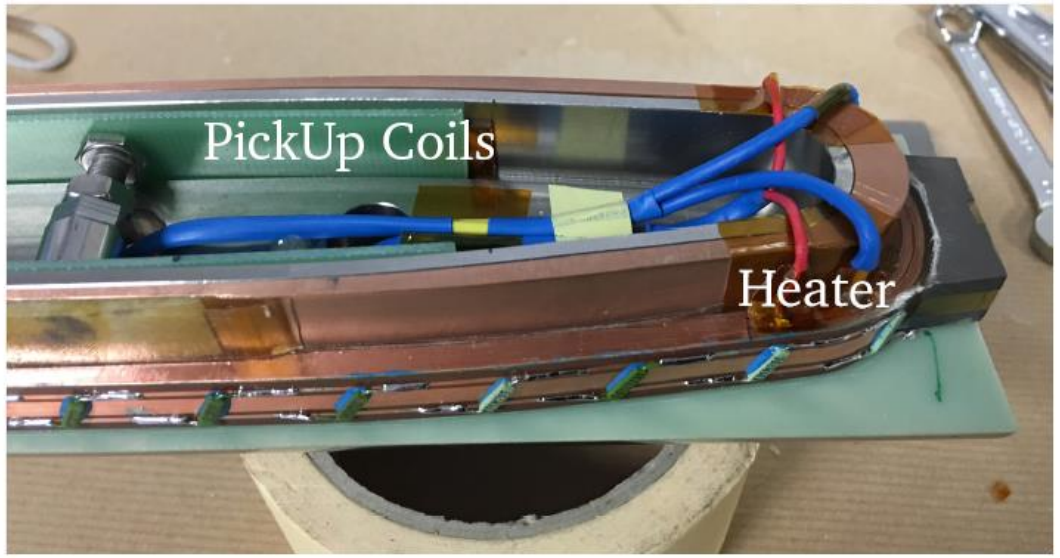
Quench Detection Sensors

- Voltage taps.....work at > 20K temp!
- Pick-up coils.....still to be proven
- Temperature sensors (CCS , Fibre).....still to be proven
- Acoustics.....we have the sensors but not installed yet , soon!

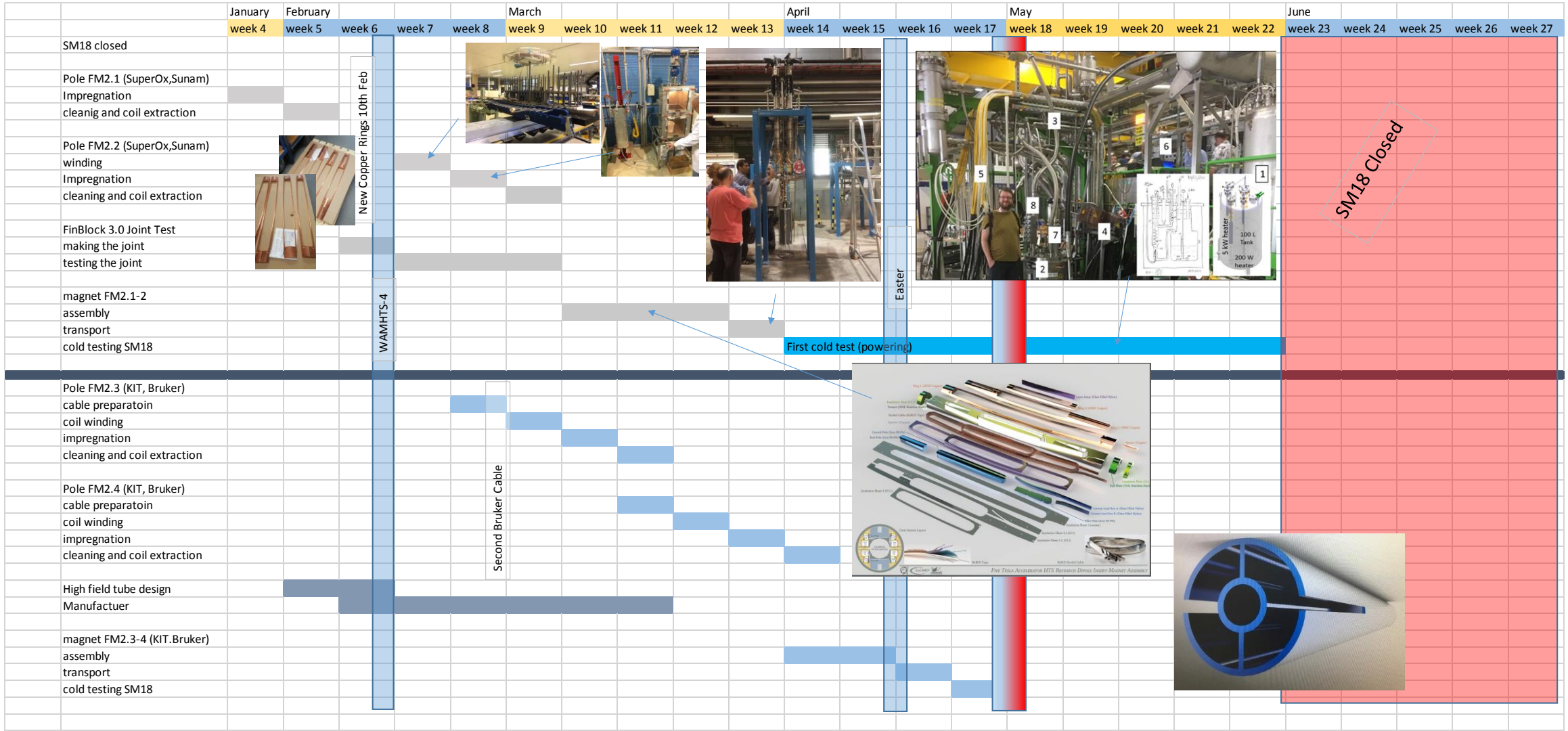
Lead End

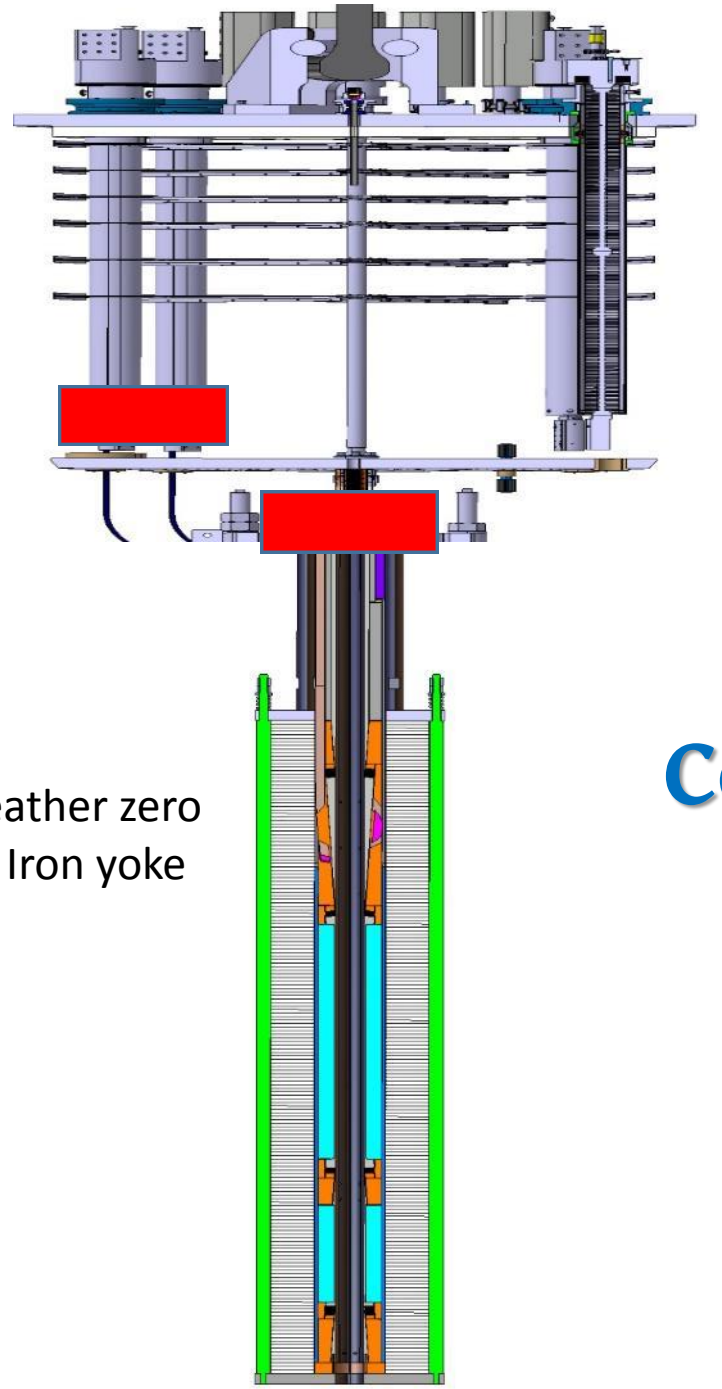


Turn End



PLANNING


January
February
March
April
May
June
week 4
week 5
week 6
week 7
week 8
week 9
week 10
week 11
week 12
week 13
week 14
week 15
week 16
week 17
week 18
week 19
week 20
week 21
week 22
week 23
week 24
week 25
week 26
week 27
SM18 closed
Pole FM2.1 (SuperOx,Sunam)
Impregnation
cleanig and coil extraction
Pole FM2.2 (SuperOx,Sunam)
winding
Impregnation
cleaning and coil extraction
FinBlock 3.0 Joint Test
making the joint
testing the joint
magnet FM2.1-2
assembly
transport
cold testing SM18
Pole FM2.3 (KIT, Bruker)
cable preparatoin
coil winding
impregnation
cleaning and coil extraction
Pole FM2.4 (KIT, Bruker)
cable preparatoin
coil winding
impregnation
cleaning and coil extraction
High field tube design
Manufactuer
magnet FM2.3-4 (KIT.Bruker)
assembly
transport
cold testing SM18
New Copper Rings 10th Feb
WAMHTS-4
Second Bruker Cable
Easter
First cold test (powering)
SM18 Closed



Feather zero
In Iron yoke

Connecting magnet to
current leads?

Test temp 80 He Gas to 5 K!

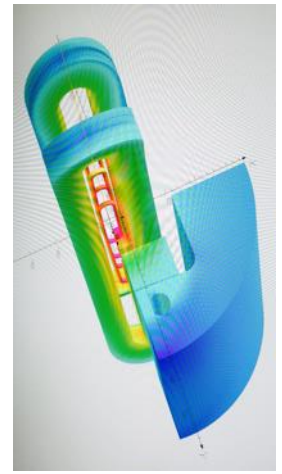
Current lead heat exchanger

HTS
link

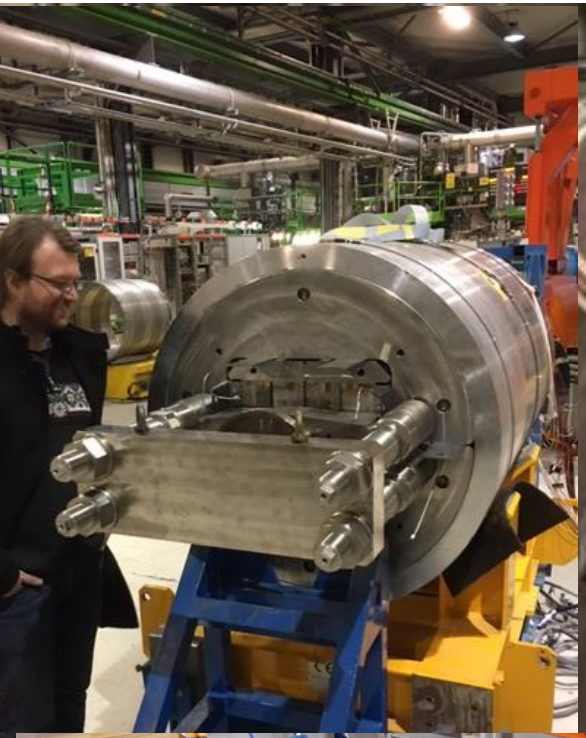
F2 in Freacs2

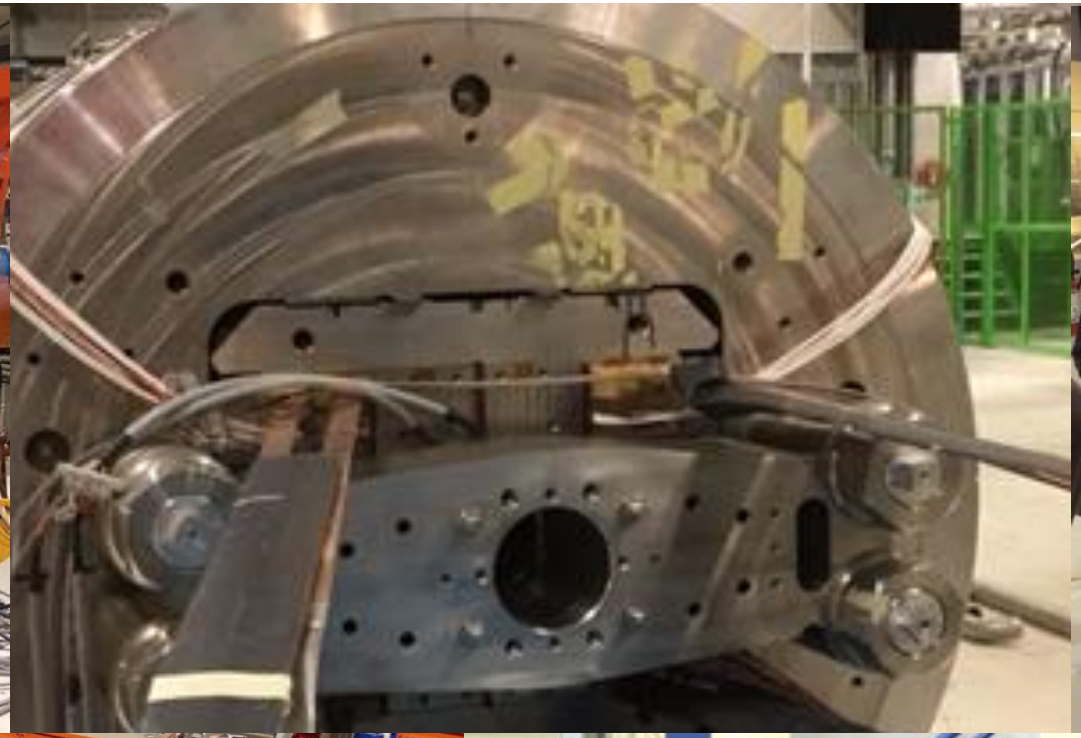
F-Zero

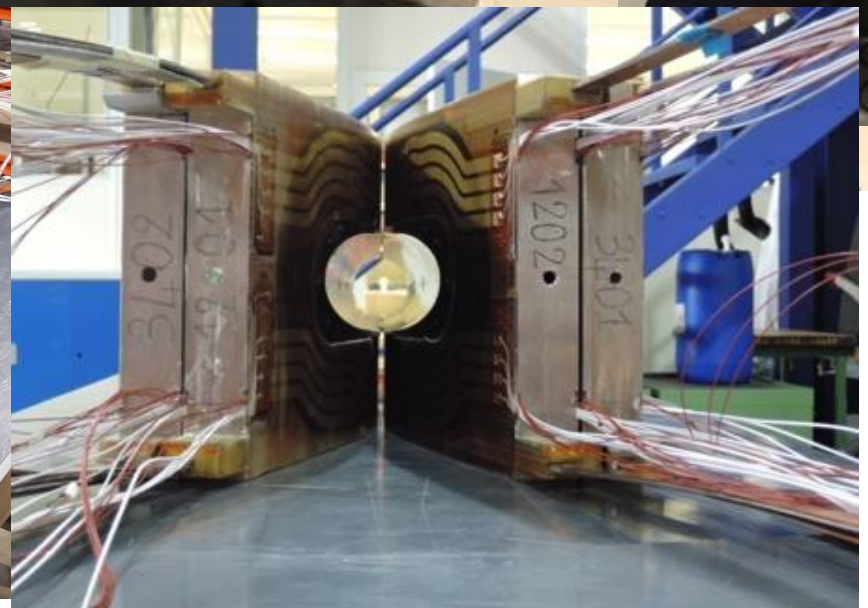
COLD TESTING IN GAS !

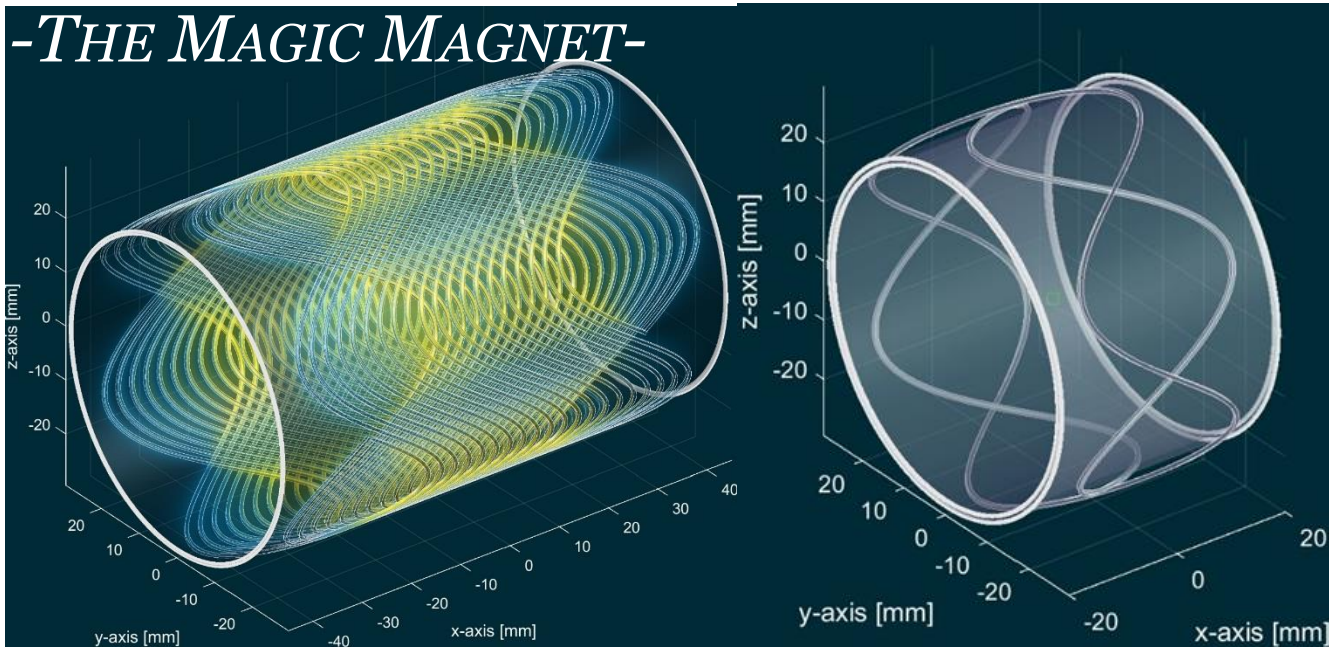


FRESAC2 13T BACKGROUND









Lts test planned

HTS laser cut for high field

One more technology that may prove to be necessary

Persistent Current Shim Coils for Accelerator Magnets

E3SPRESSO

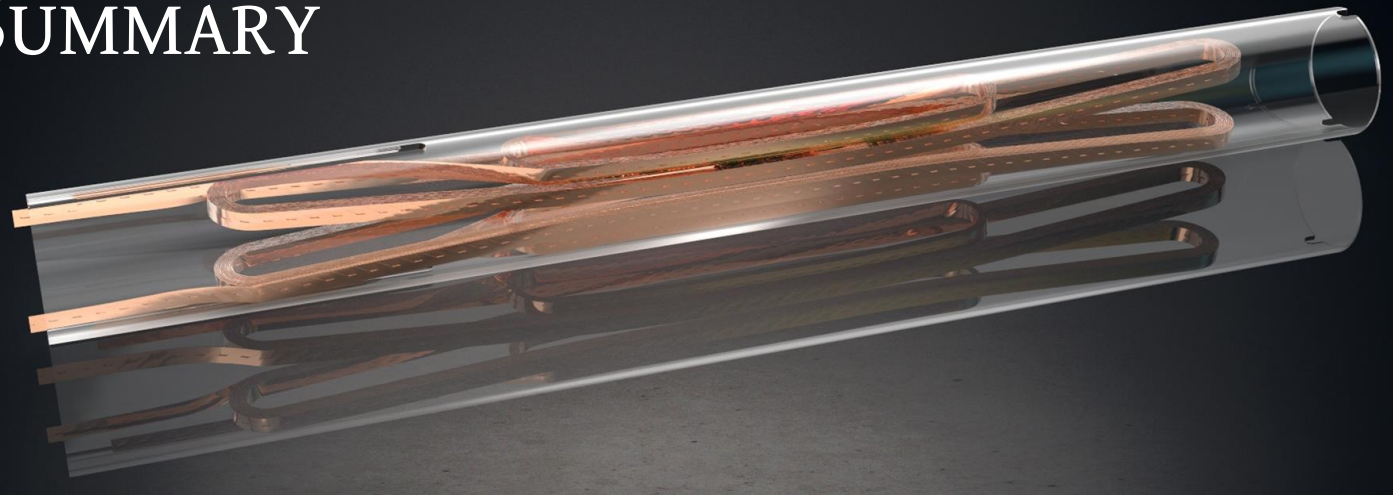
External Energy Extraction Symbiotic Protection System for Series Operation

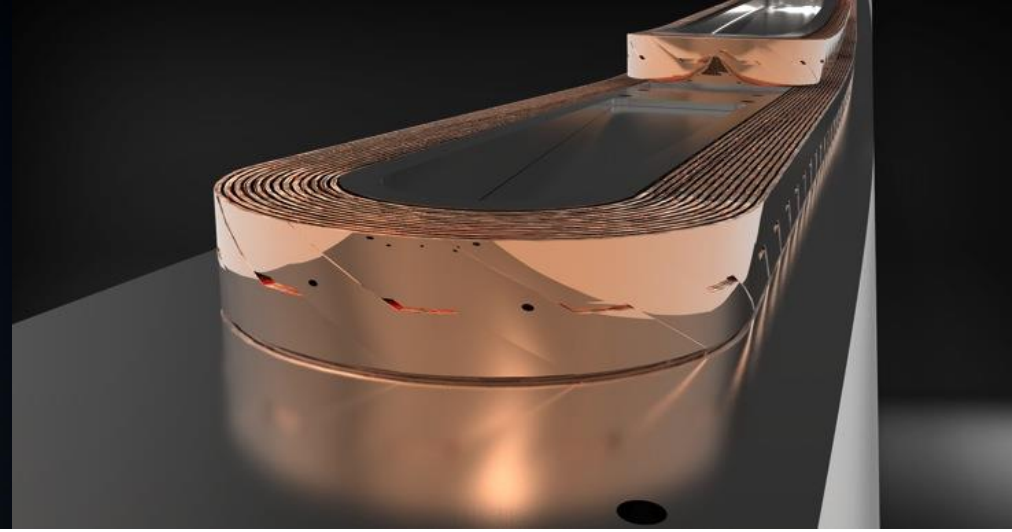
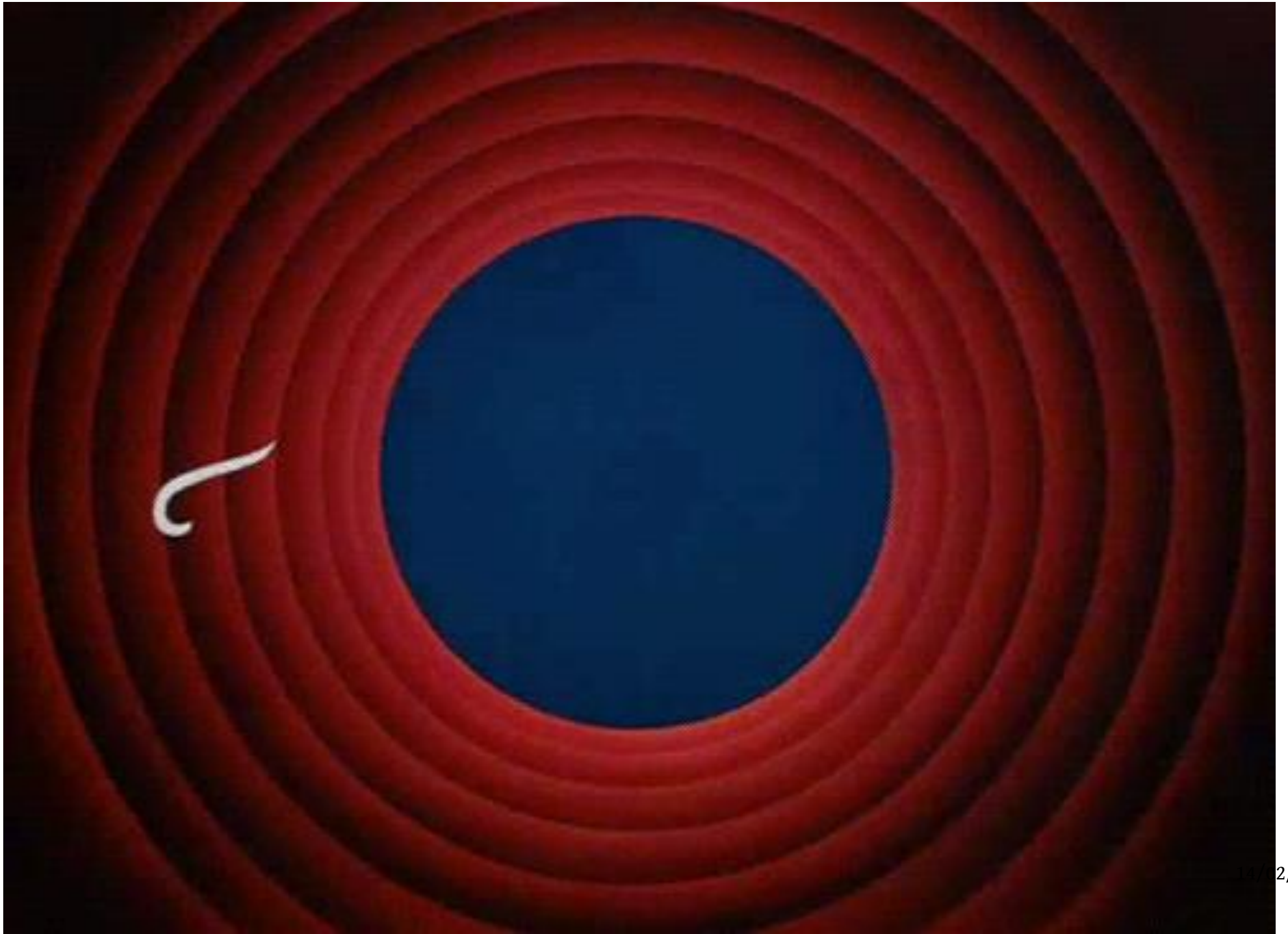
A Quench Protection System for High Field Superconducting Magnets

- Now doesn't that look appealing? -

*[1] J. van Nugteren et. Al. "**E3SPreSSO - A Quench Protection System for High Field Superconducting Magnets**", Technical Report, CERN 2016*
[2] A. Ballarino, T. Taylor, "Scaling of superconducting switches for Extraction of Magnetic Energy", IEEE Transactions on Applied Superconductivity, 2010

Summary





- Dr. Jeroen Van Nugteren has developed a multi-physics program that can predict: current distribution, quench, and much more!
- We have a multi strand 10 kA cable. (current re-distribution!)
- Accelerator Field quality looks to be achievable.
- Cable must be impregnated.
- Joint design, Fin-block joint will be tested in Feather2 .
- We are taking advantage of the angular dependence.