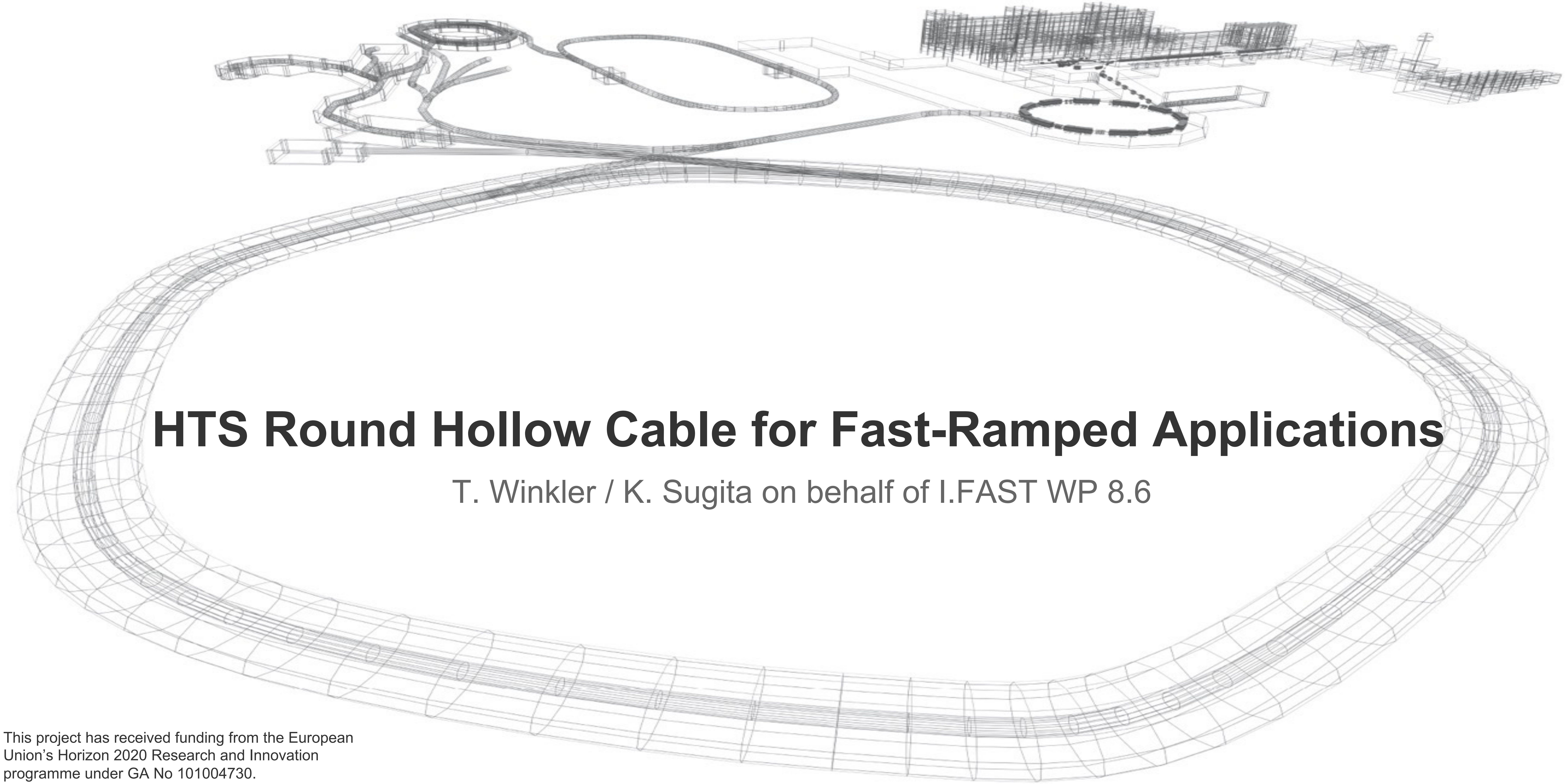


HTS Round Hollow Cable for Fast-Ramped Applications

T. Winkler / K. Sugita on behalf of I.FAST WP 8.6

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under GA No 101004730.

Goals & Project Members

Design Parameters for a round, high current, low ac loss HTS ReBCO cable

Application: fast ramped, high field accelerator magnets

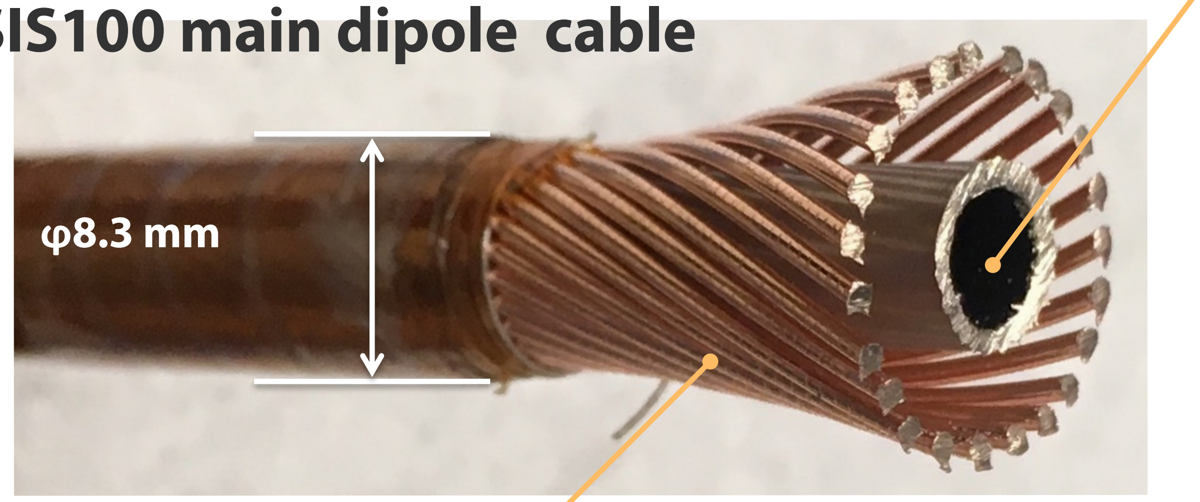
Members:

- Institute of Electrical Engineering (IEE), Slovak Academy of Sciences, Slovakia
- ILK Dresden, Germany
- GSI, Germany
- EMS Chair, University of Twente (UT), Netherlands

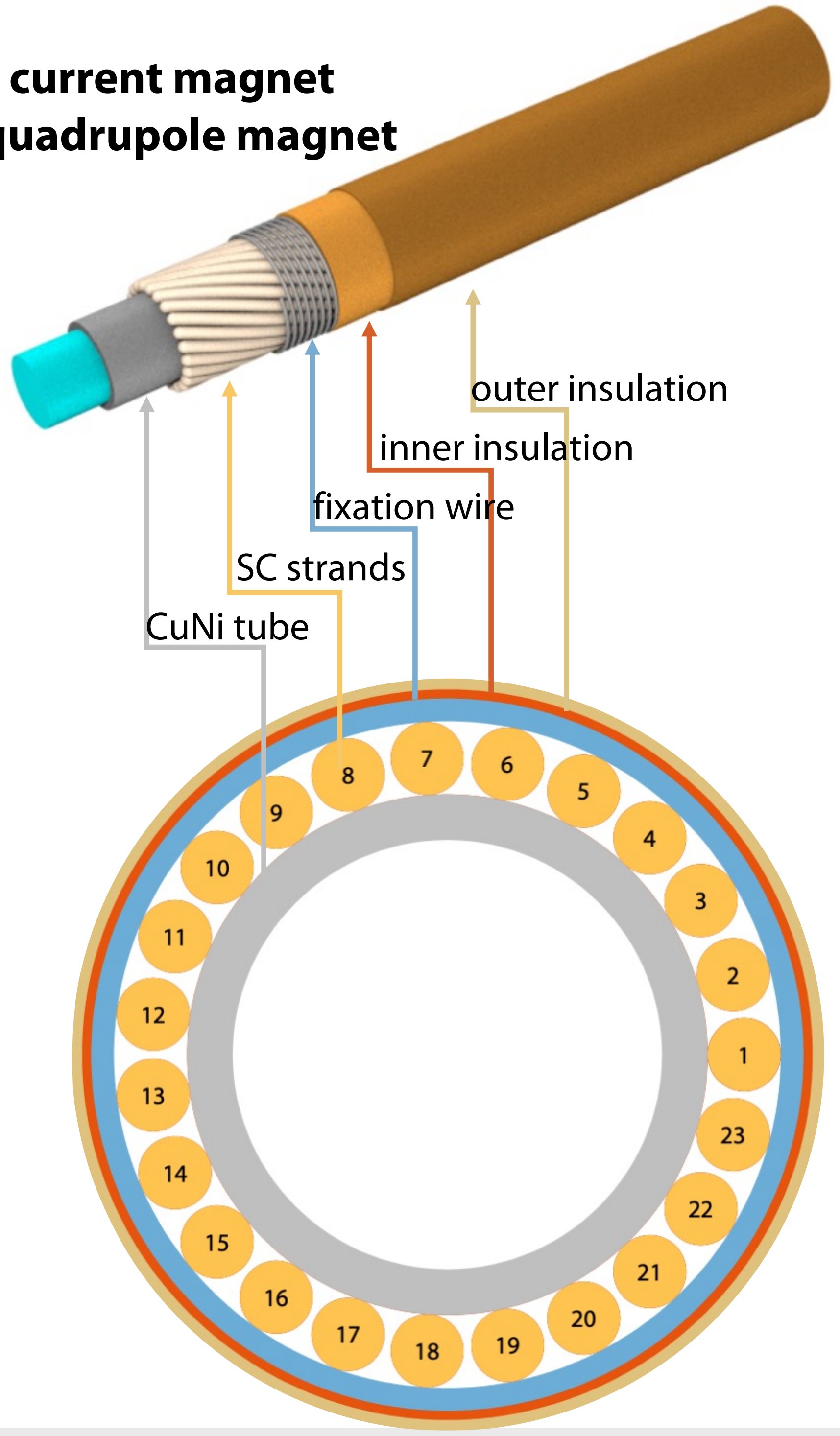
LTS (NbTi) experiences from FAIR SIS100

Cables

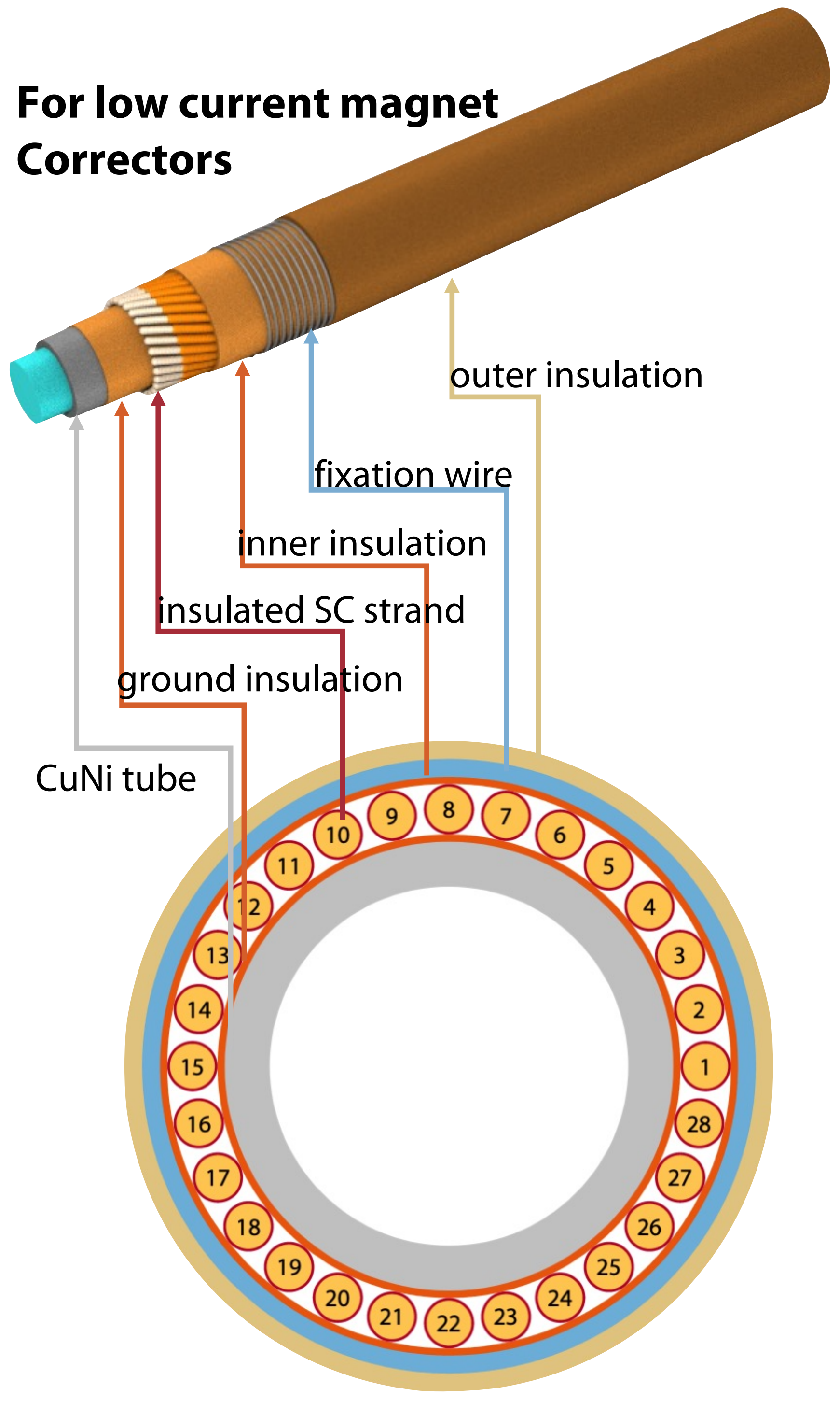
SIS100 main dipole cable



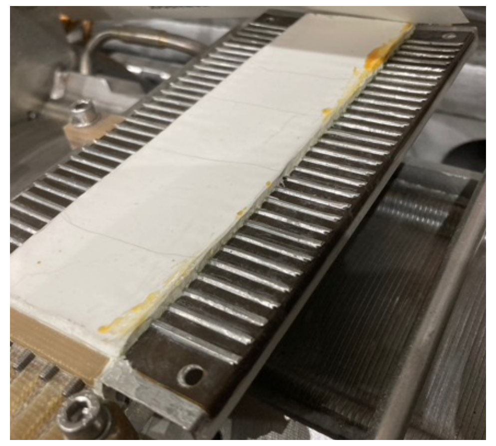
For high current magnet
Dipole/quadrupole magnet



For low current magnet
Correctors



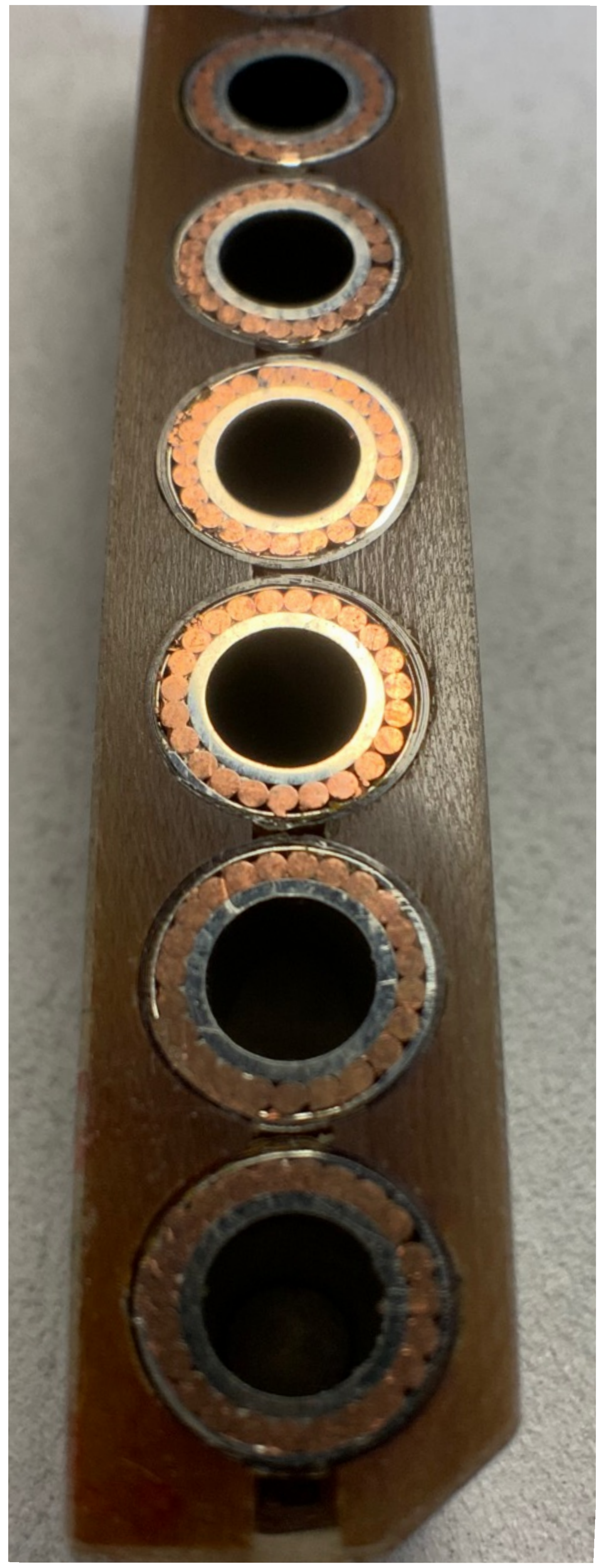
- **Dry** and **wet** cable technology
  - **Dry (SIS100 dipole magnet):** polyimide tape insulation
  - **Wet (JINR magnets):** liquid epoxy with glass fibre tape insulation
    - pro: good thermal contact / con: short storage time due to degradation of wet-epoxy
- **Low current cable**
  - insulated wires, connected in series after coil winding and yoke installation (terminal box)
  - low current operation
  - one of strand is used for quench detection (Mutual Inductance Detector)



	Material		High current magnet	Low current magnet
1	Cooling tube		CuNi, inner ϕ 4.71, outer ϕ 5.71	CuNi, inner ϕ 4, outer ϕ 5
2	Ground insulation around the tube		no	Polyimide tape
3	Superconducting strand	bare strand diameter	0.8 mm	0.5 mm
		insulation around the strand	-	0,05
		number of strands	23	28
		Transposition pitch	50 mm	50 mm
4	Fixation wire	material	NiCr 8020/ 2.4869	Synthetic
		diameter (mm)	0,25	0,2
5	Outer insulation (inside)	material	Polyimide tape	Polyimide tape
6	Outer insulation (outside)	material	Glass fibre	Polyimide tape
	Cable diameter		8.3 mm	7.2 mm
	Operation current		13.2 kA	250 A (strand) / 6.75 kA (cable)
	Current ramp-rate		28 kA/sec.	1250 A/sec. (strand) / 33.75 kA/sec. (cable)

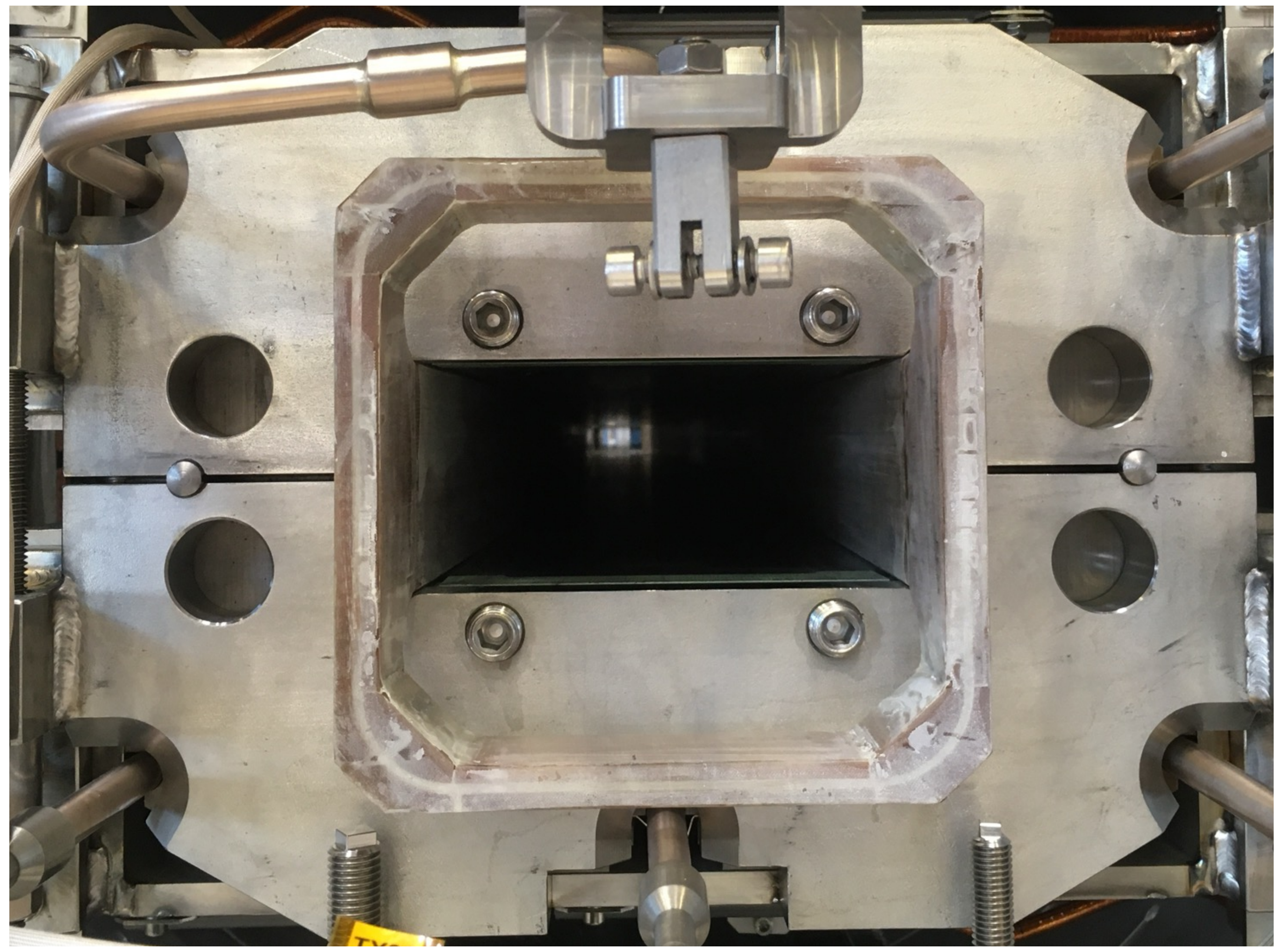
LTS (NbTi) experiences from FAIR SIS100

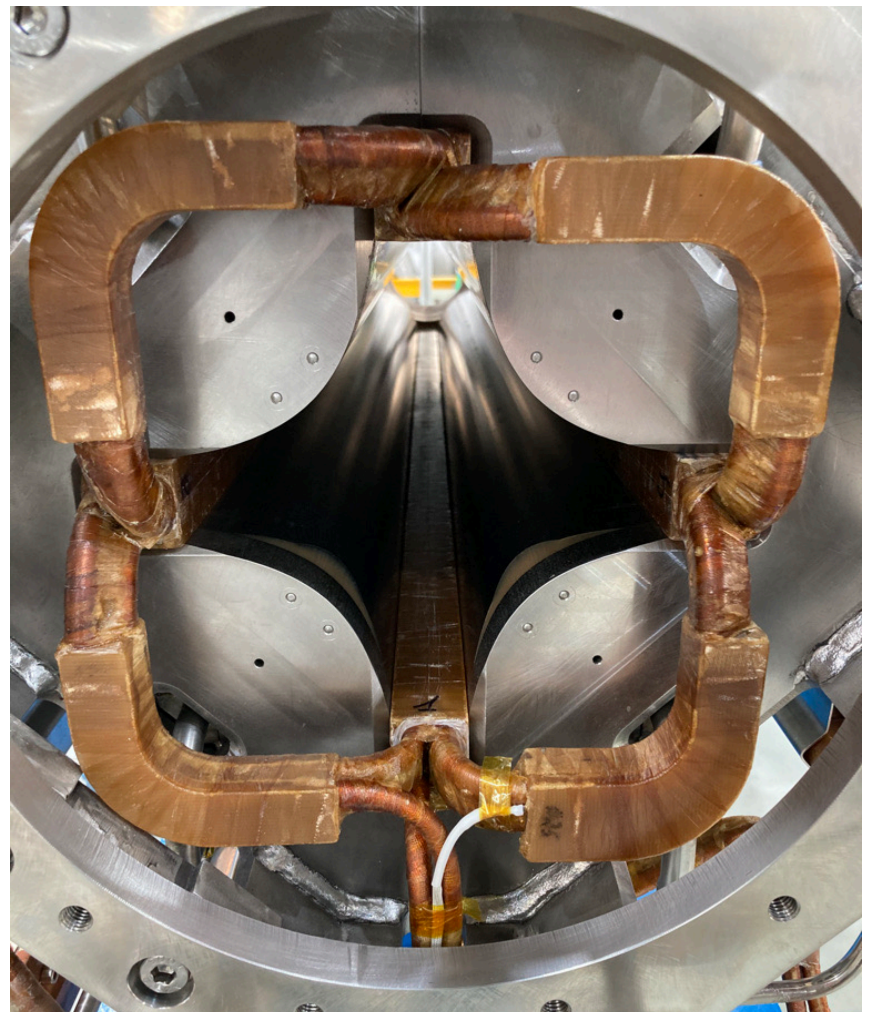
- Coil

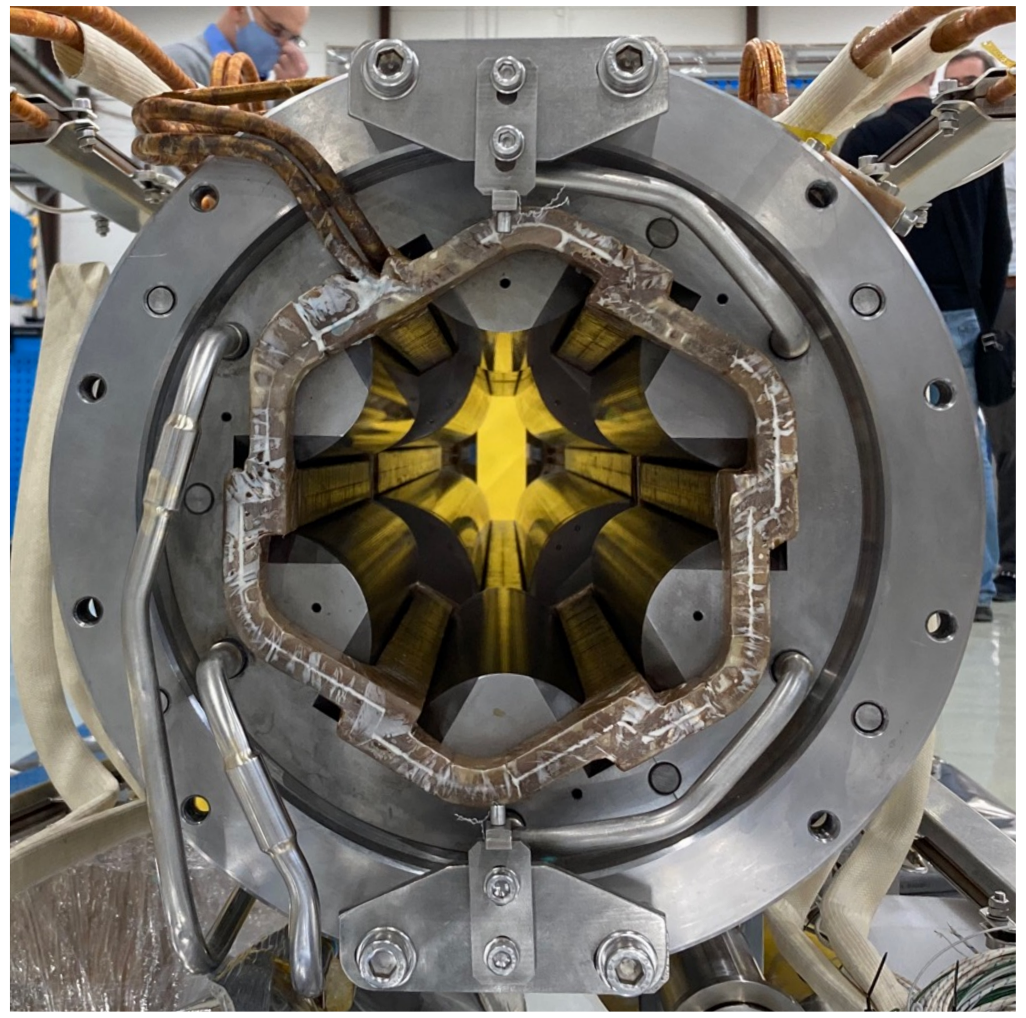


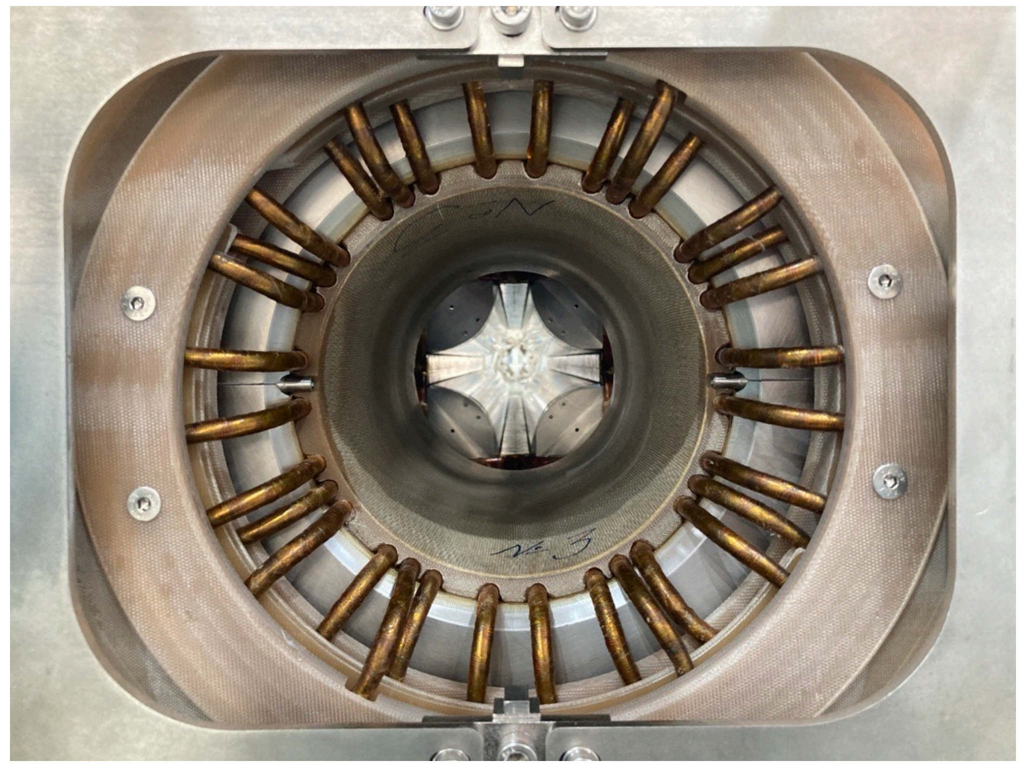
- **Embedded in the G11 support structure**
  - rigid mechanical structure

- Magnet









- **Superferric type**
  - main dipole magnet
  - quadrupole magnet
  - chromaticity sextupole magnet
- **Cosine-theta type**
  - horizontal / vertical combined steering magnet
  - quadrupole / sextupole / octupole nested multipole corrector magnet

Application SISX00

- Future synchrotron
- cos-θ-Design (dipole)
- Mag. Field in Aperture: 1.9 T - 6.5 T
- Mag field ramp rate: 0.5 T/s – 1 T/s
- Magnet length: 7.76 m
- Aperture diameter: 85 mm
- Operating temperature: 4.2 K
- Coil requirements: 450 kA*turn per pole

- Cable Considerations:
- Sustained force: 2 kN/m
- Cable diameter: ~10 mm
- Operating current : up to 30 kA (?)
- Min bending radius: ~20 mm

- Cooling channel diameter: tbd
- Length:
- 200 m — 300 m (per pole)
- 400 m — 600 m (per magnet)

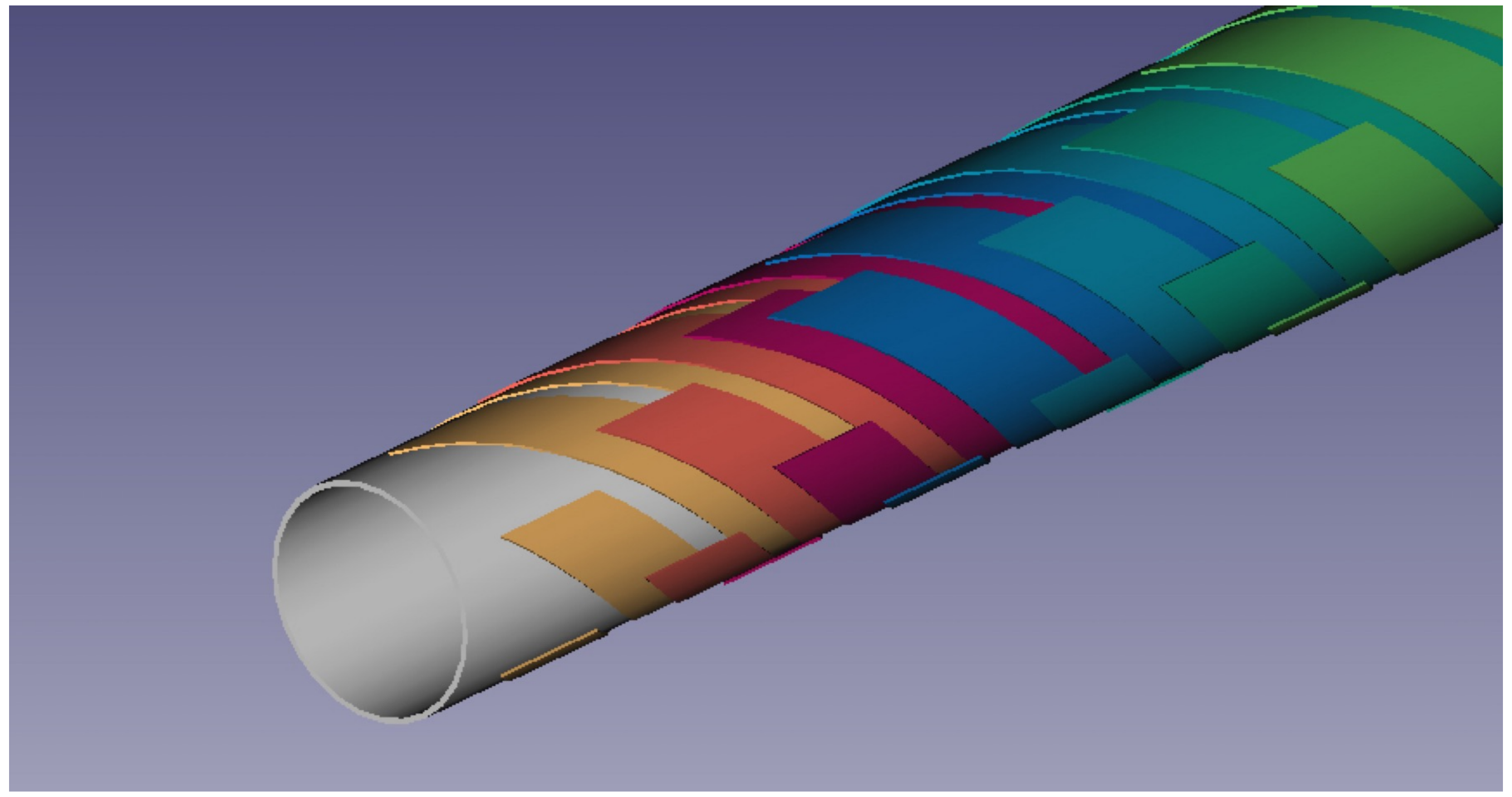
- All open for discussion

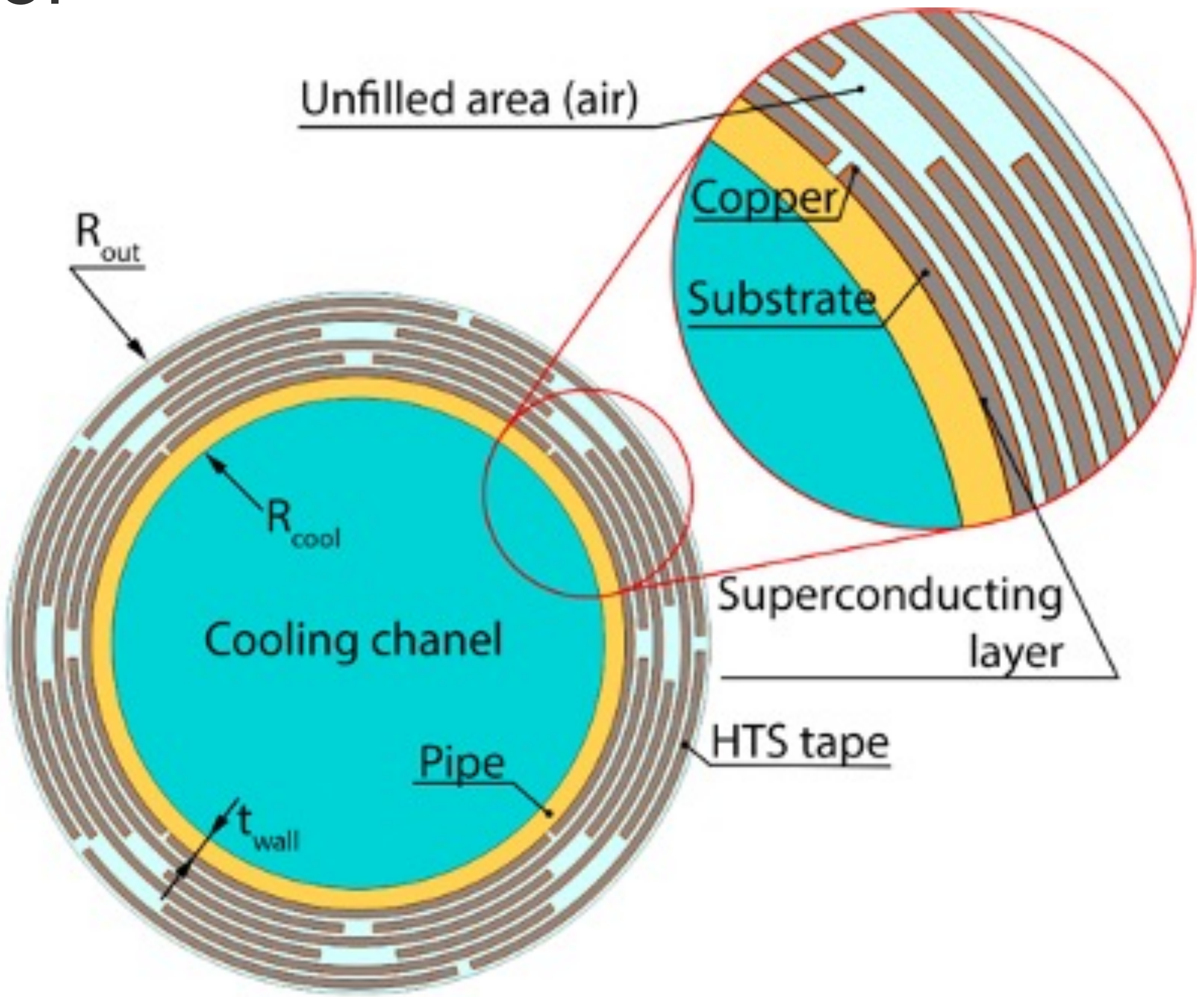
Cable Layout

- Starting point:
- SIS100 cable (GSI/JINR) (LTS)
- CORC/CORT type cable (ACT/IEE) (HTS)

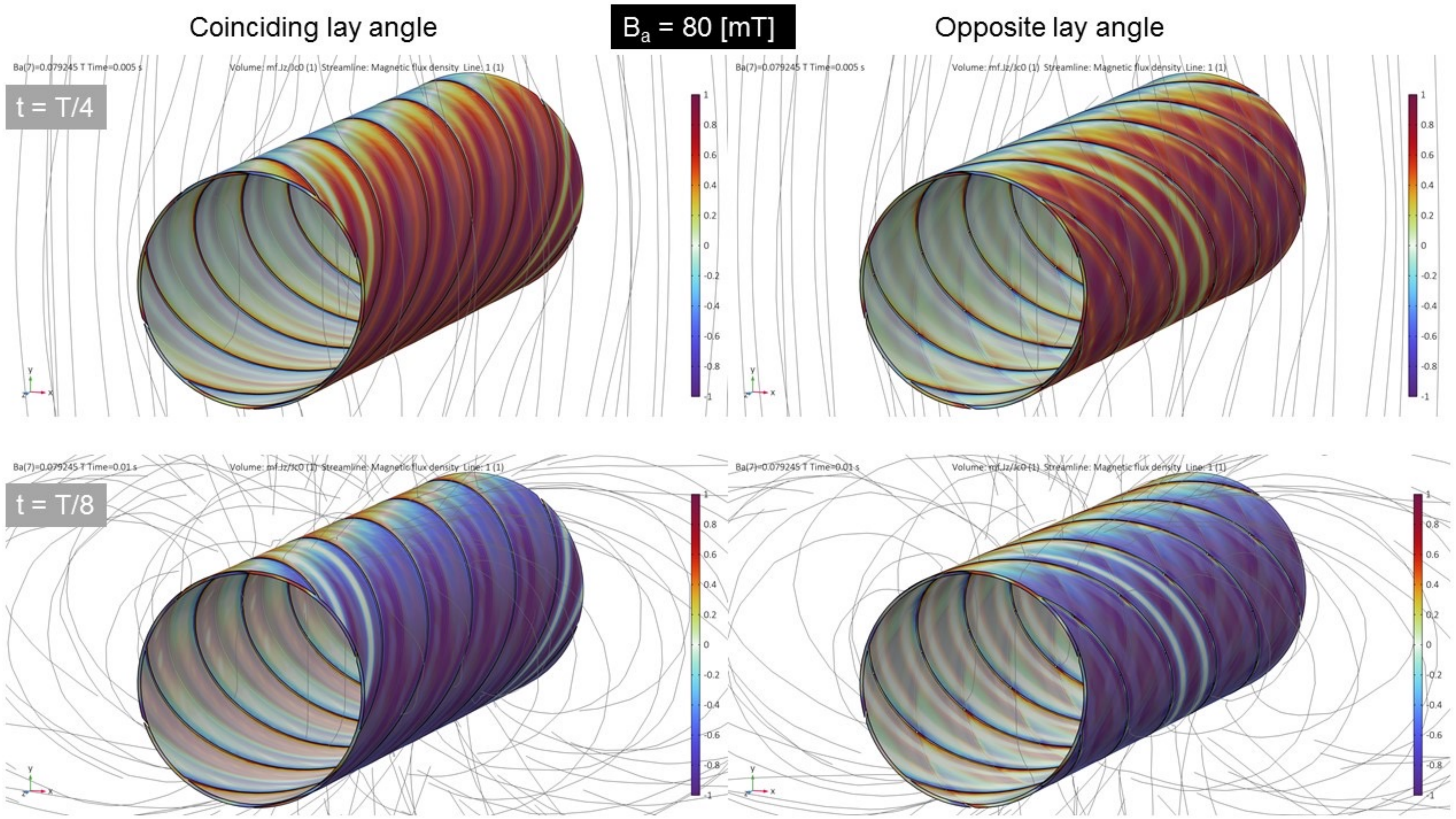
Advanced Conductor Technology

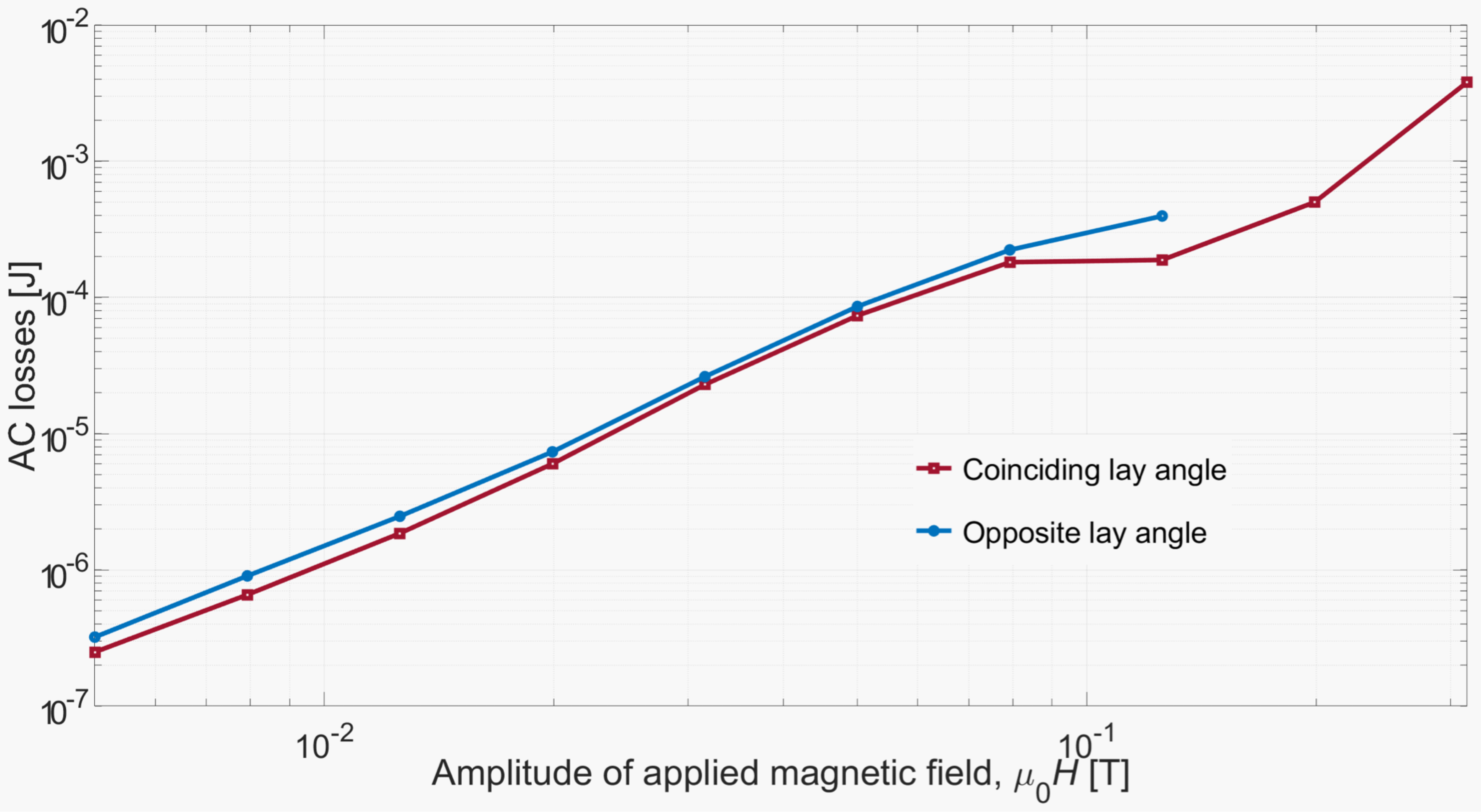
- Idea: use good direct cooling properties, and windability of SIS100 cable and apply it to HTS



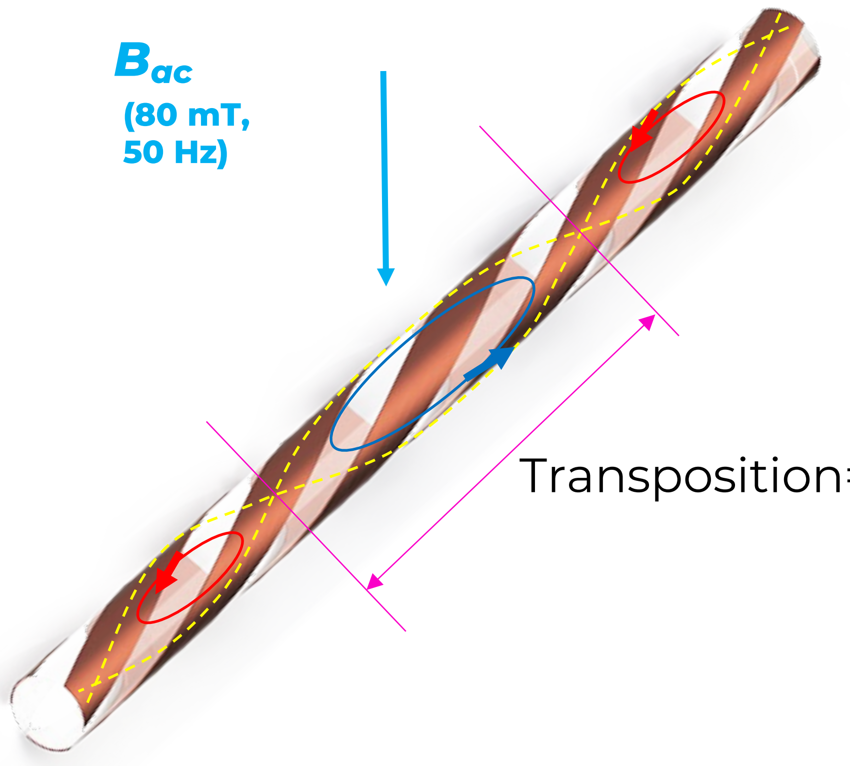


AC loss - winding direction theory





Theoretical modelling shows little difference between different winding directions for consecutive layers.



$$\vec{J} = J_{c0} tanh\left(\frac{|E|}{E_0}\right)\left(\frac{E_x}{|E|}\hat{i} + \frac{E_y}{|E|}\hat{j} + \frac{E_z}{|E|}\hat{k}\right)$$

Solovyov, M. and Gömöry, F.
Supercond. Sci Technol. 32 (2019) 115001

AC loss - Magnetisation loss theory

assumptions: tapes are in magnetic field higher than the penetration field, e.g. saturation of screening currents

$$Q_{h,CORT} = B_{max} N I_c \frac{1}{\pi cos\alpha} w$$

In an alternative from LTS strands, with diameter d_f:

$$Q_{h,LTS} = B_{max} N I_c \frac{8}{3\pi} d_f$$

Assuming w = 3mm and d_f = 3 µm:

$$\frac{Q_{h,CORT}}{Q_{h,LTS}} = \frac{3}{8cos\alpha} \frac{w}{d_f} \approx \frac{w}{2d_f} = 500$$

AC loss - Magnetisation loss at 77 K

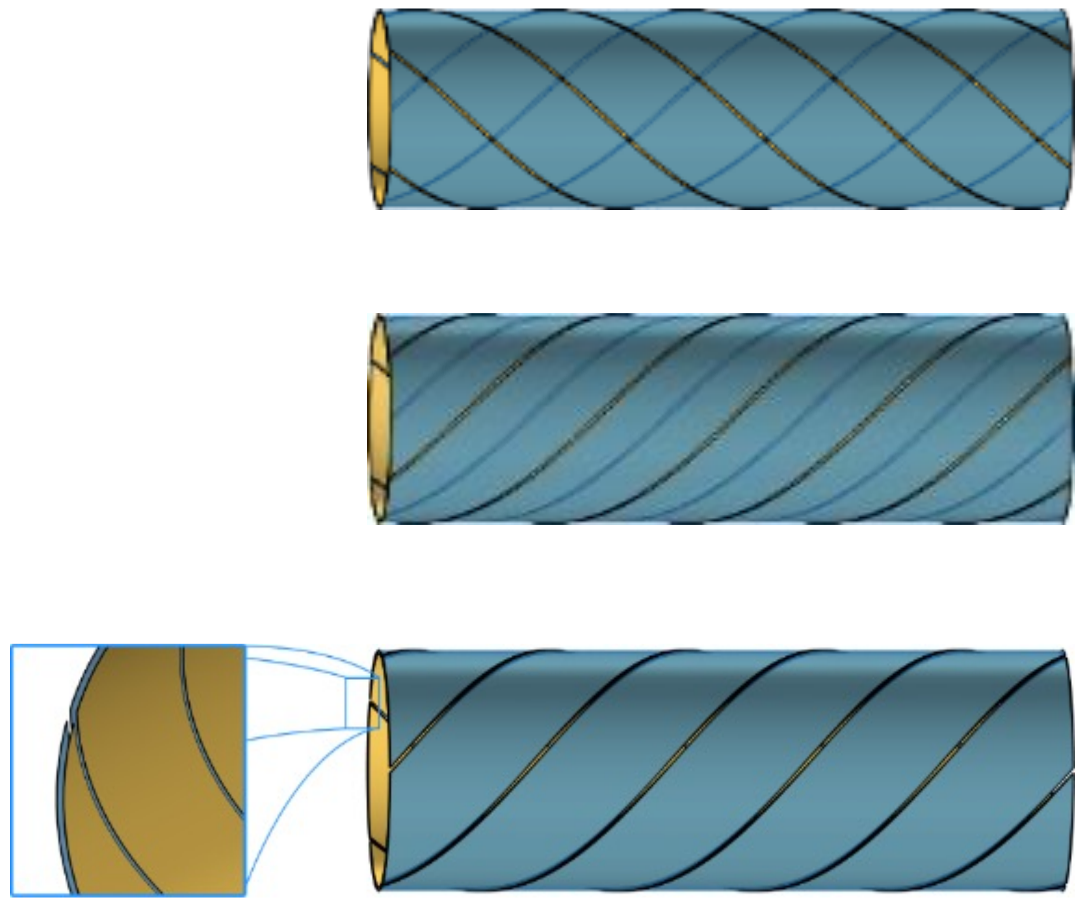
$$\Gamma = \frac{Q_{cable}}{L_{cable} S_{cable}} \frac{2\mu_0}{B_{max}^2}$$

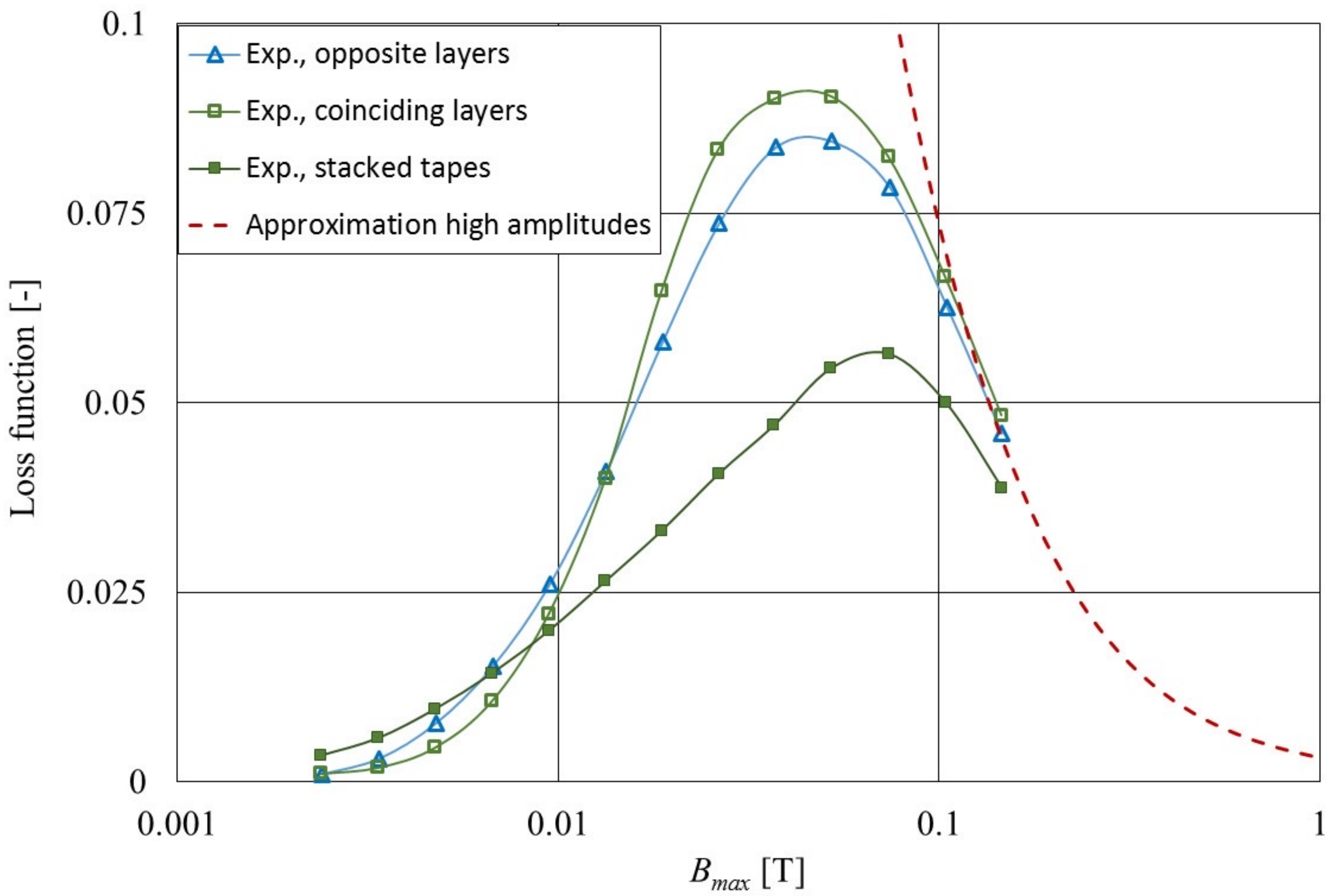
3 samples: 2 x 5 tapes

Opposite layers

Coinciding layers

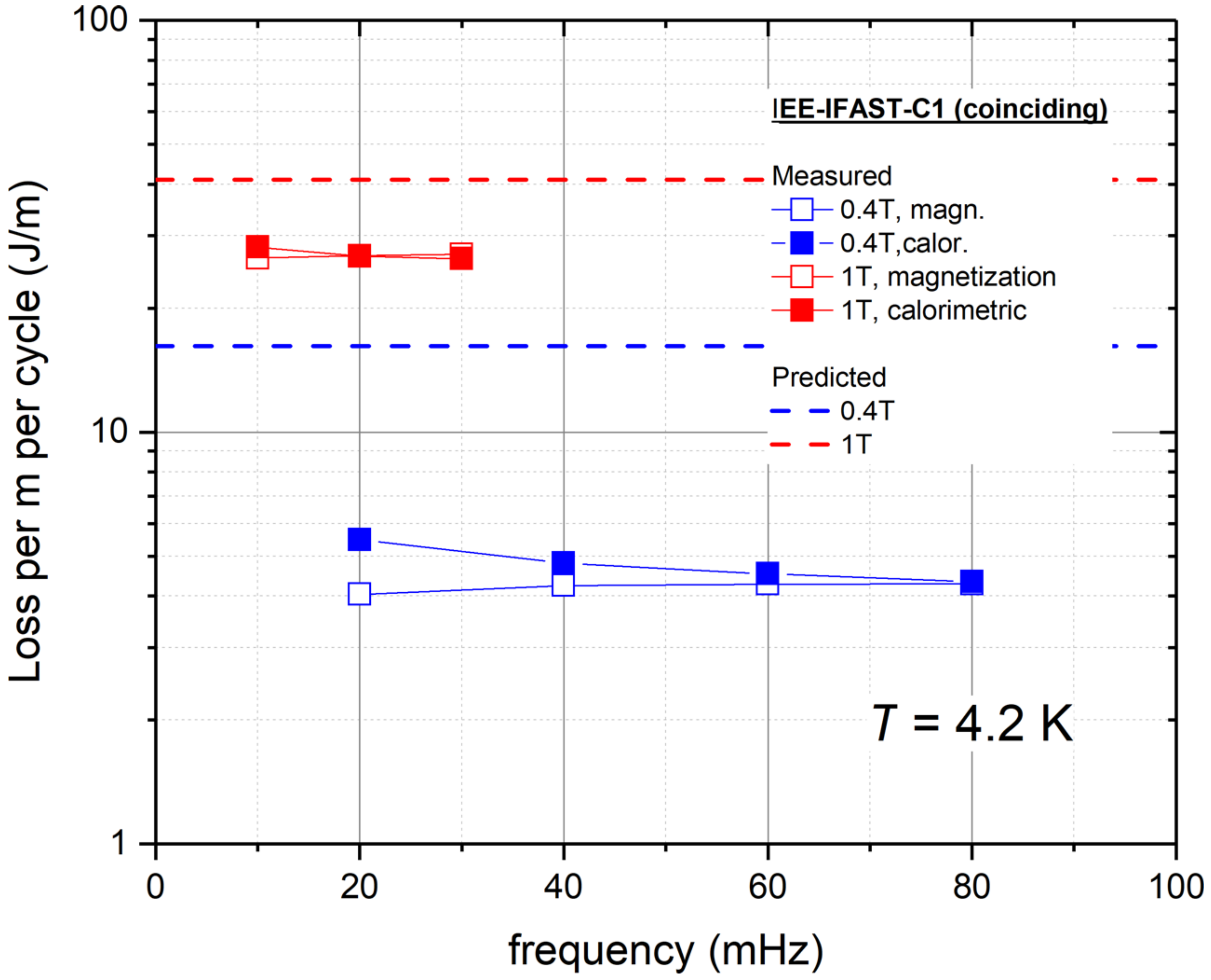
Stacked tapes

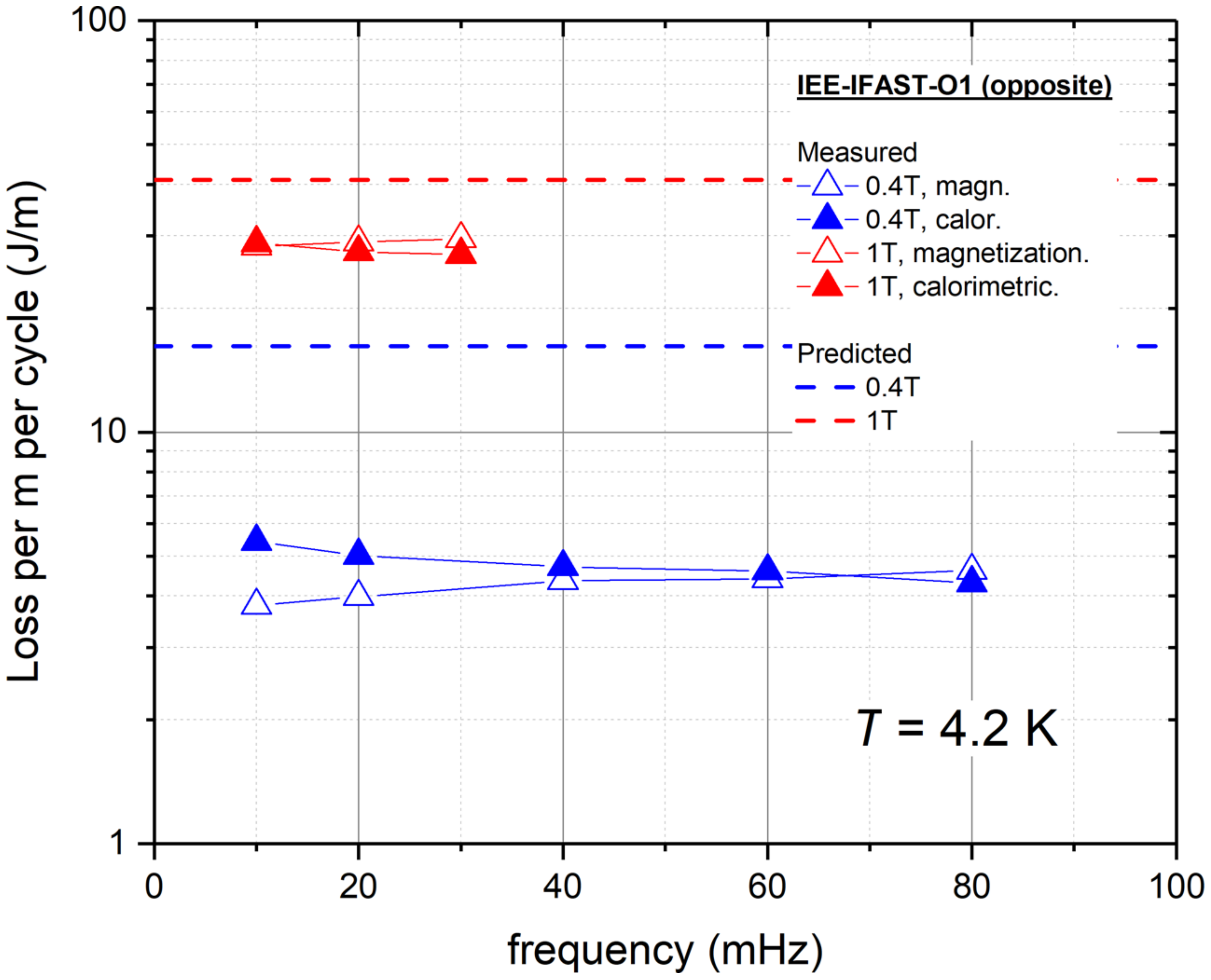




Measurements at 77 K @ IEE

AC loss - Magnetisation loss at 4 K



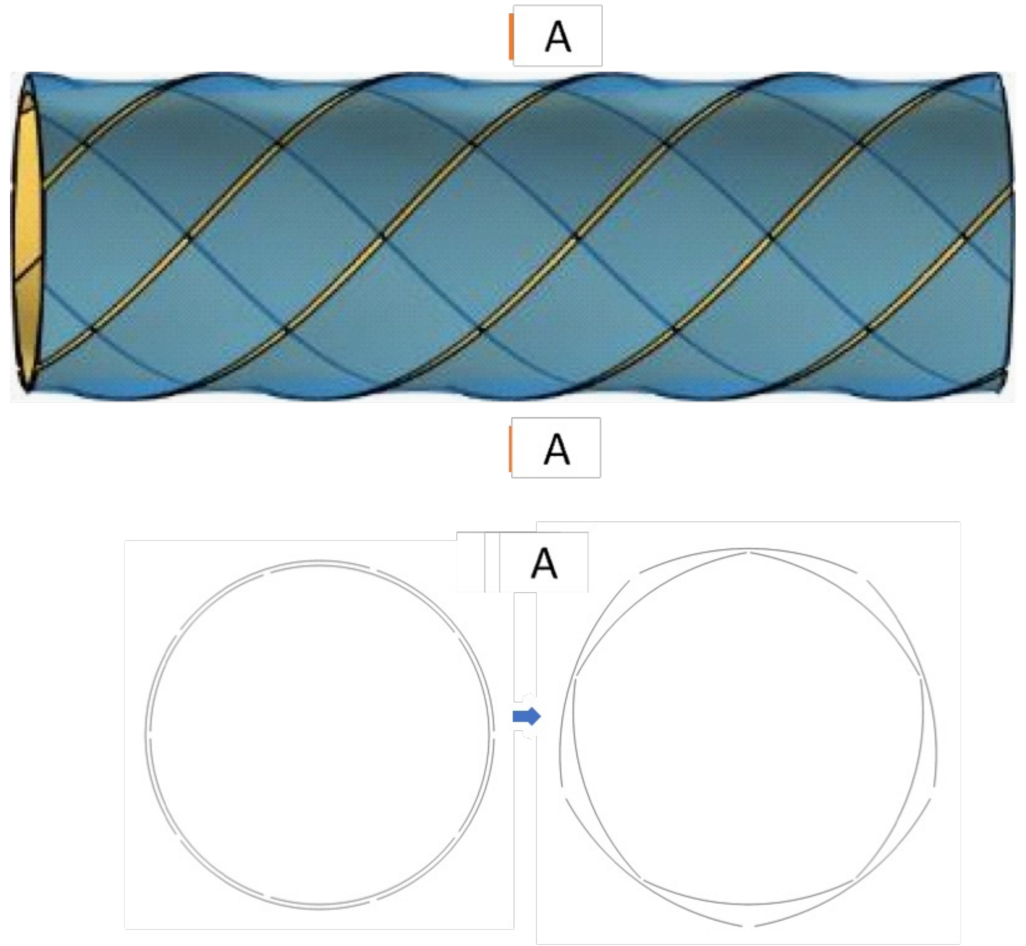


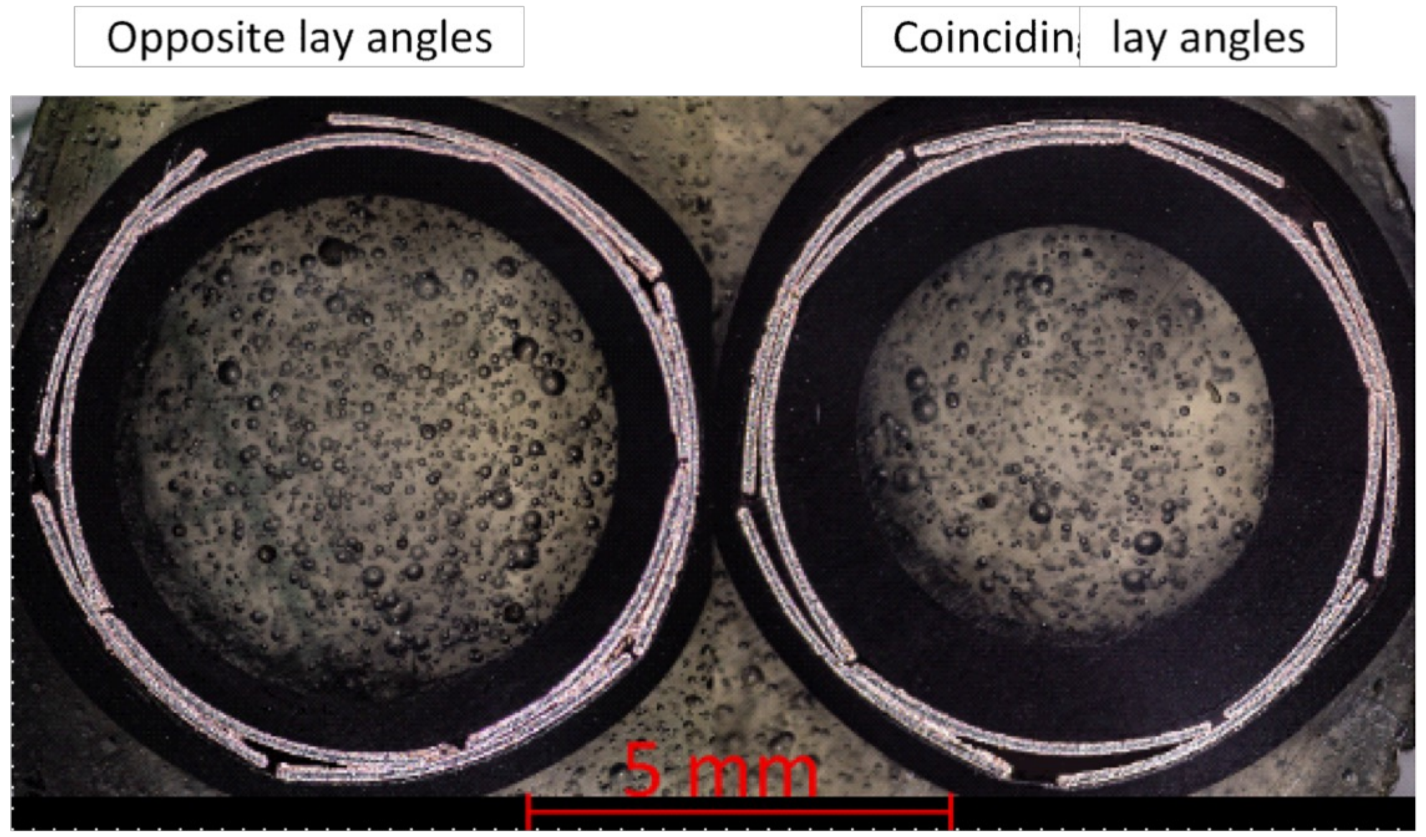
Measurements at 4 K @ UT

Deviation due to higher I_c compared to 77 K

AC loss - Coupling loss

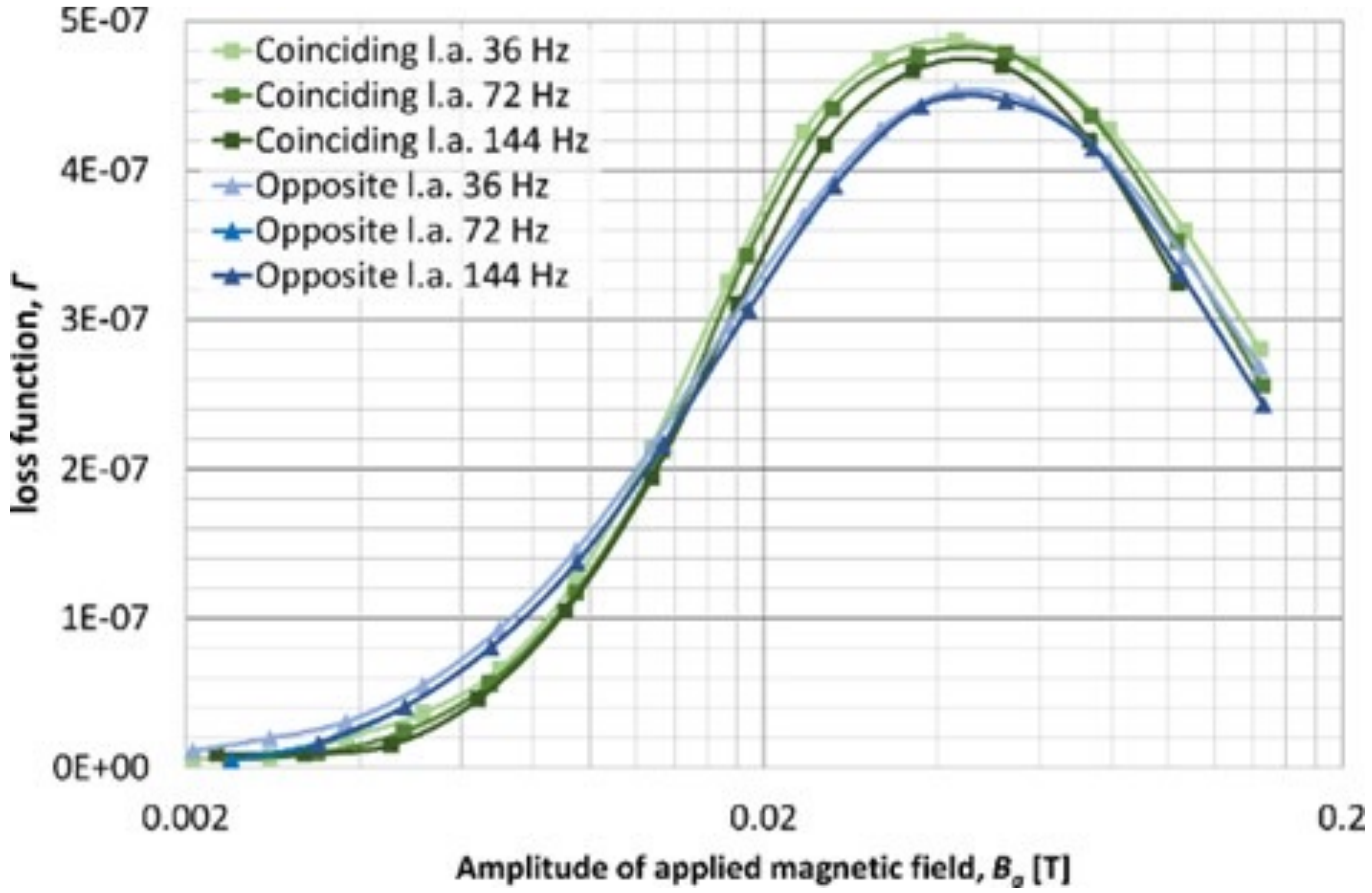
Coupling loss depends on
electrical contacts between tapes





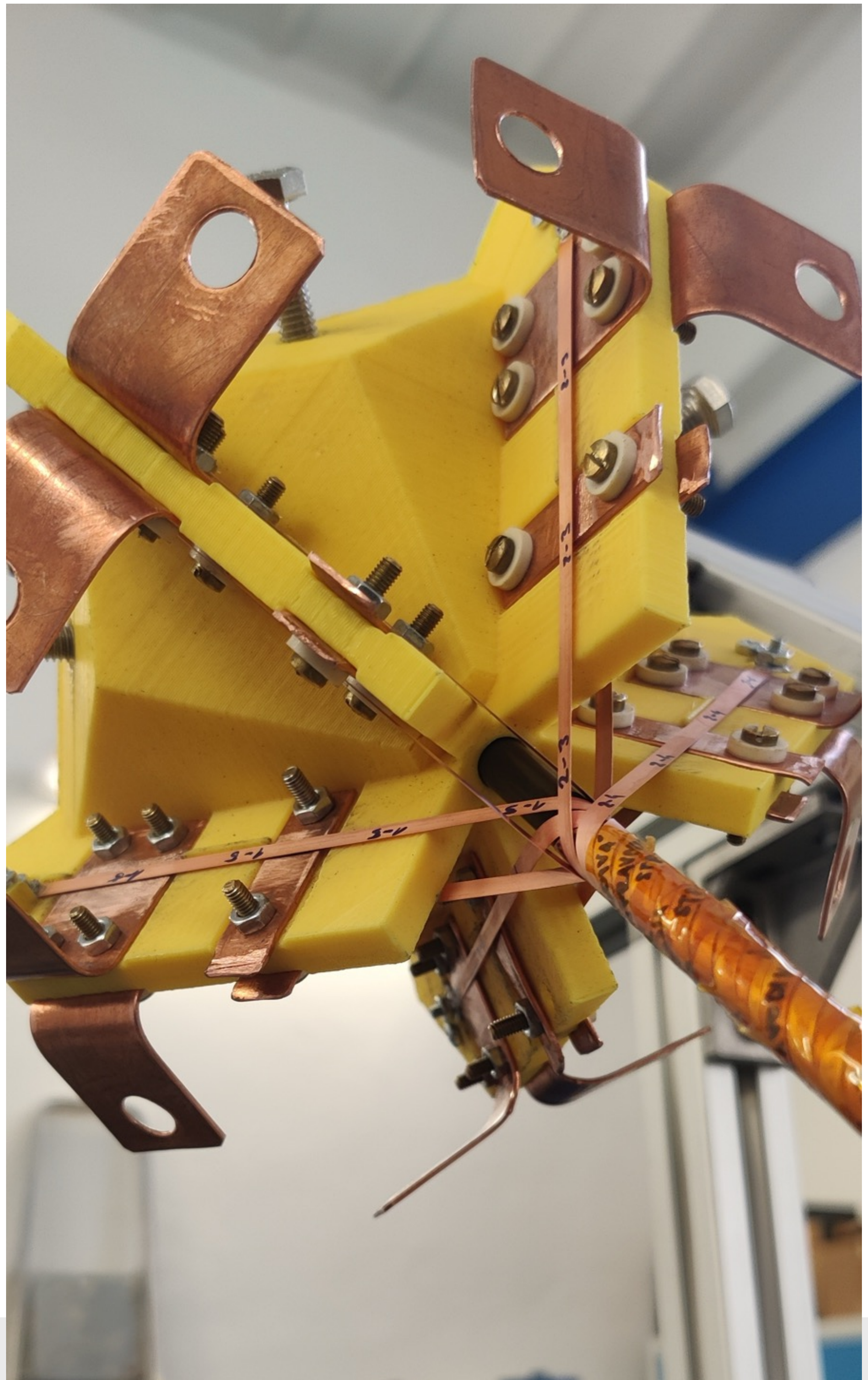
Modeling and cross sections show that tape contacts are very limited.

AC loss measured at 77.3 K



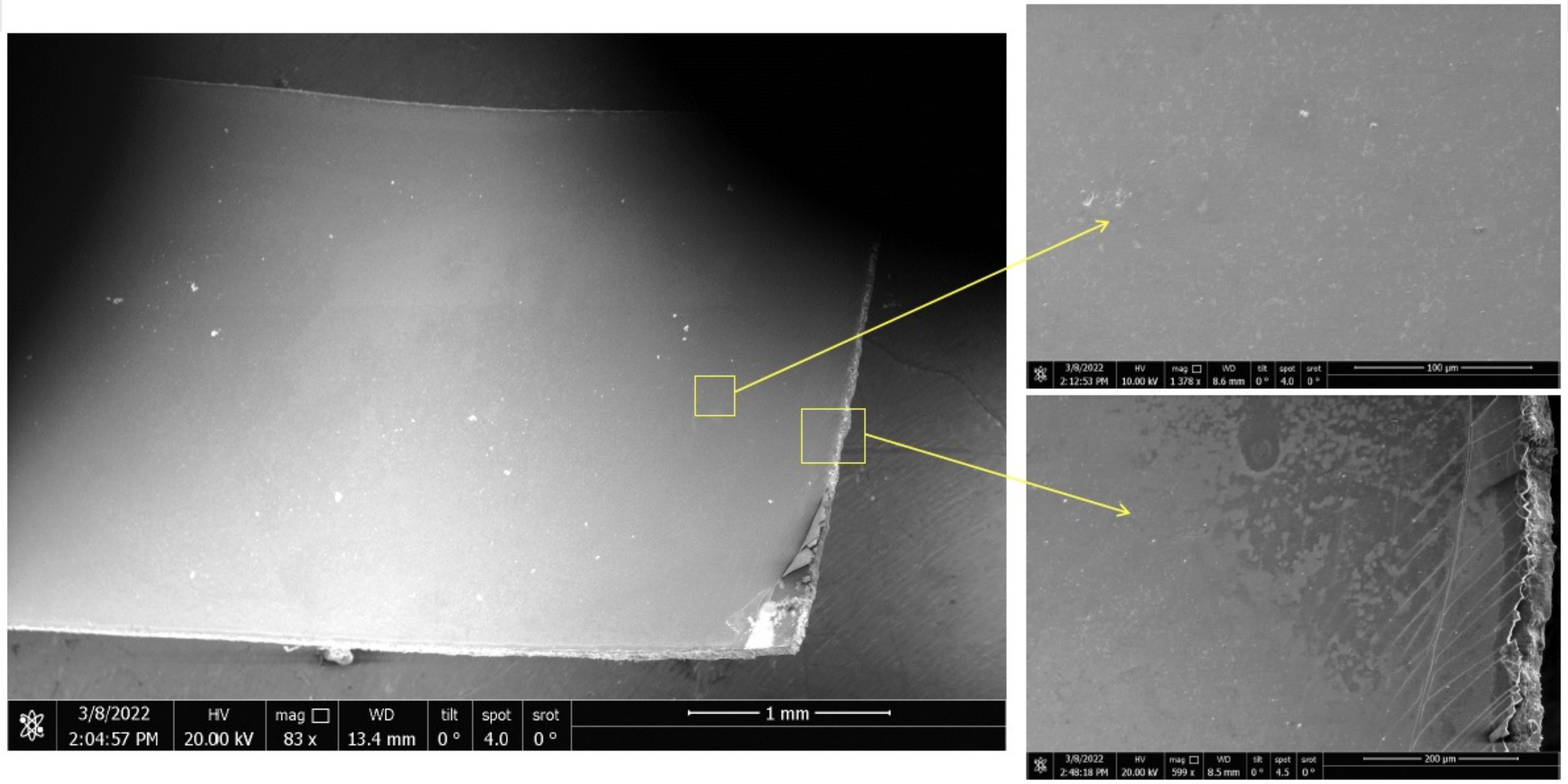
no frequency dependence
=> no coupling currents

Mechanics - Sample Manufacturing



Mechanics - Tape Bending

Compessive bending 5 mm, 45 deg



Experimental procedure

bent around a circular former core

↓

cooled by liquid N_2 for a few minutes

↓

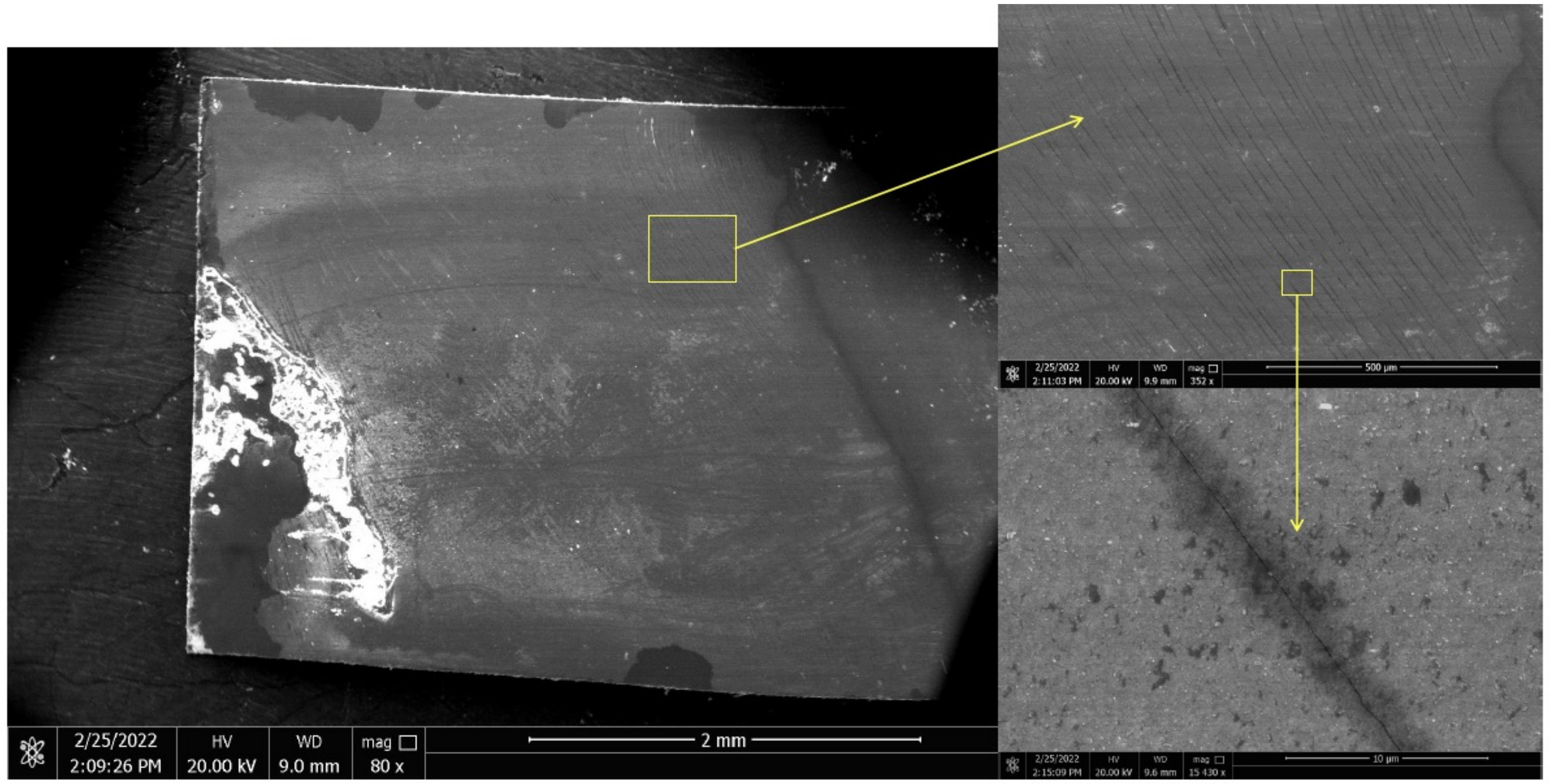
part of the bent tape was cut

↓

the Cu and Ag layers were removed by etching

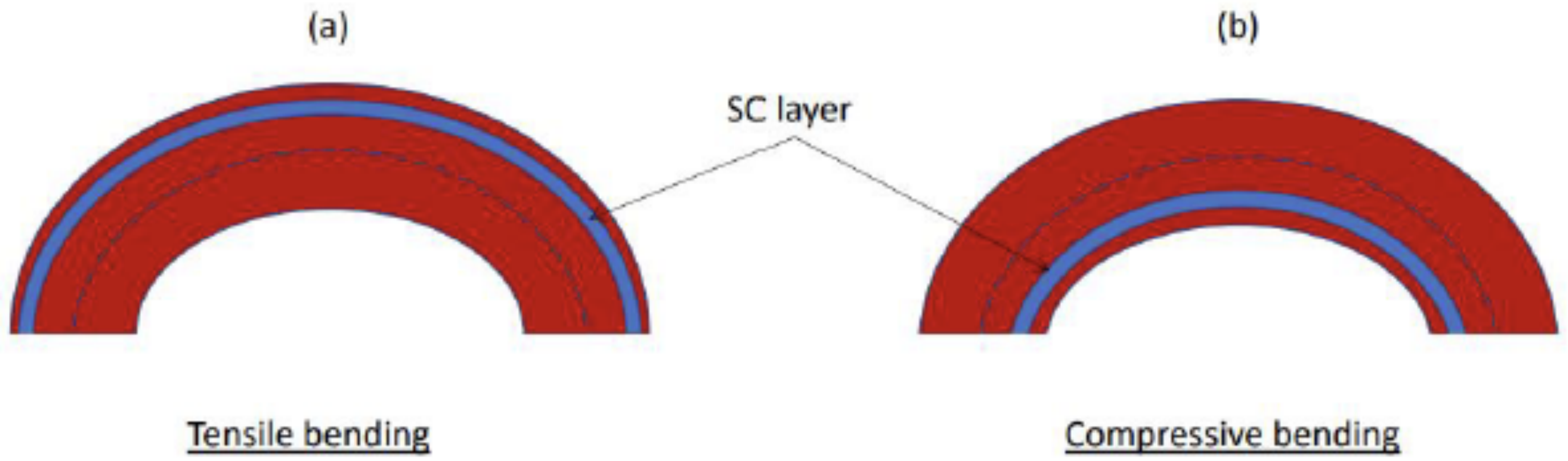
↓

SEM analysis



Tensile bending 5 mm, 45 deg

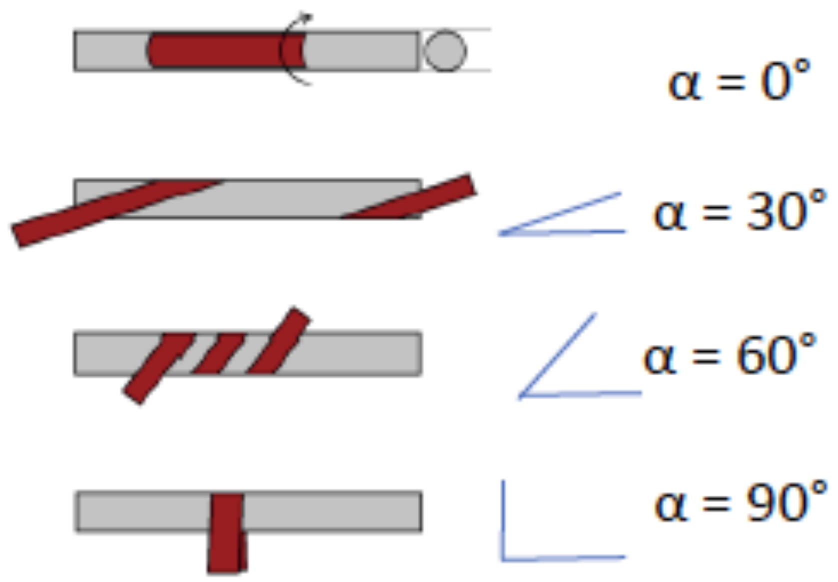
Mechanics - Tape Bending



Angle bending: α = 45°
Former diameter:
- 3 mm
- 4 mm
- 5 mm
- 6 mm
- 7 mm
- 8 mm
- 9 mm
- Reference (no bending)

Conclusions
Lower former diameter lead to:
- higher density of the cracks
- cracks are longer and wider

Former diameter: 3 mm
Angle bending:



Conclusions
Cracks follow tube axis in 80-95% and ReBCO crystal planes in 5-20%

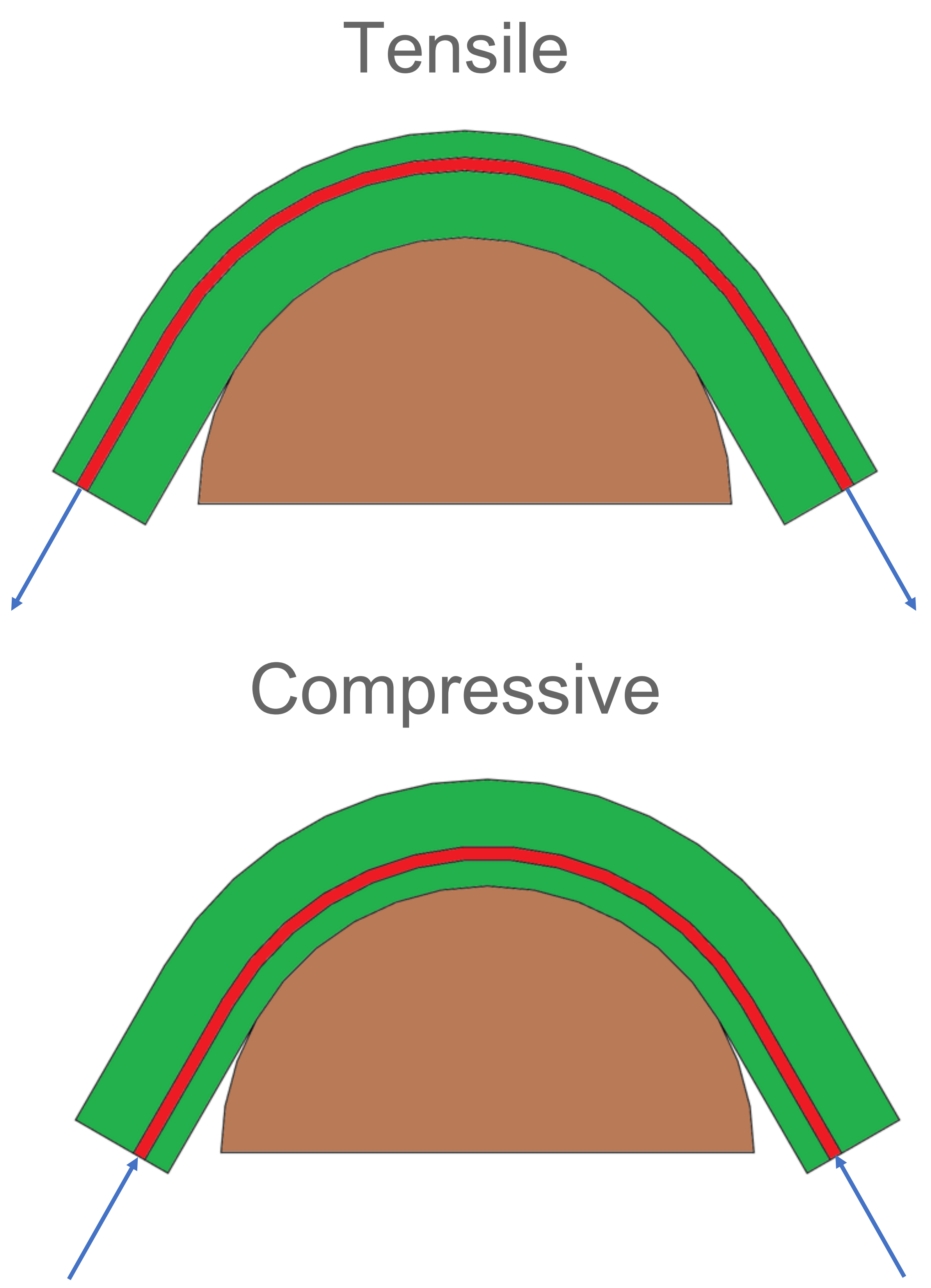
Angle bending: α = 45°
Former diameter:
- 3 mm } planed
- 4 mm
- 5 mm
- 6 mm
- 7 mm
- Reference (no bending)

Conclusions
There were found no cracks or other damage after compressive bending considering 7,6,5 mm former diameters

Planed

I_c measurement vs. former diameter considering compressive bending

Mechanics - Tape Bending



We find approximate centre of stiffness of the tape
(the layers are not symmetrical)

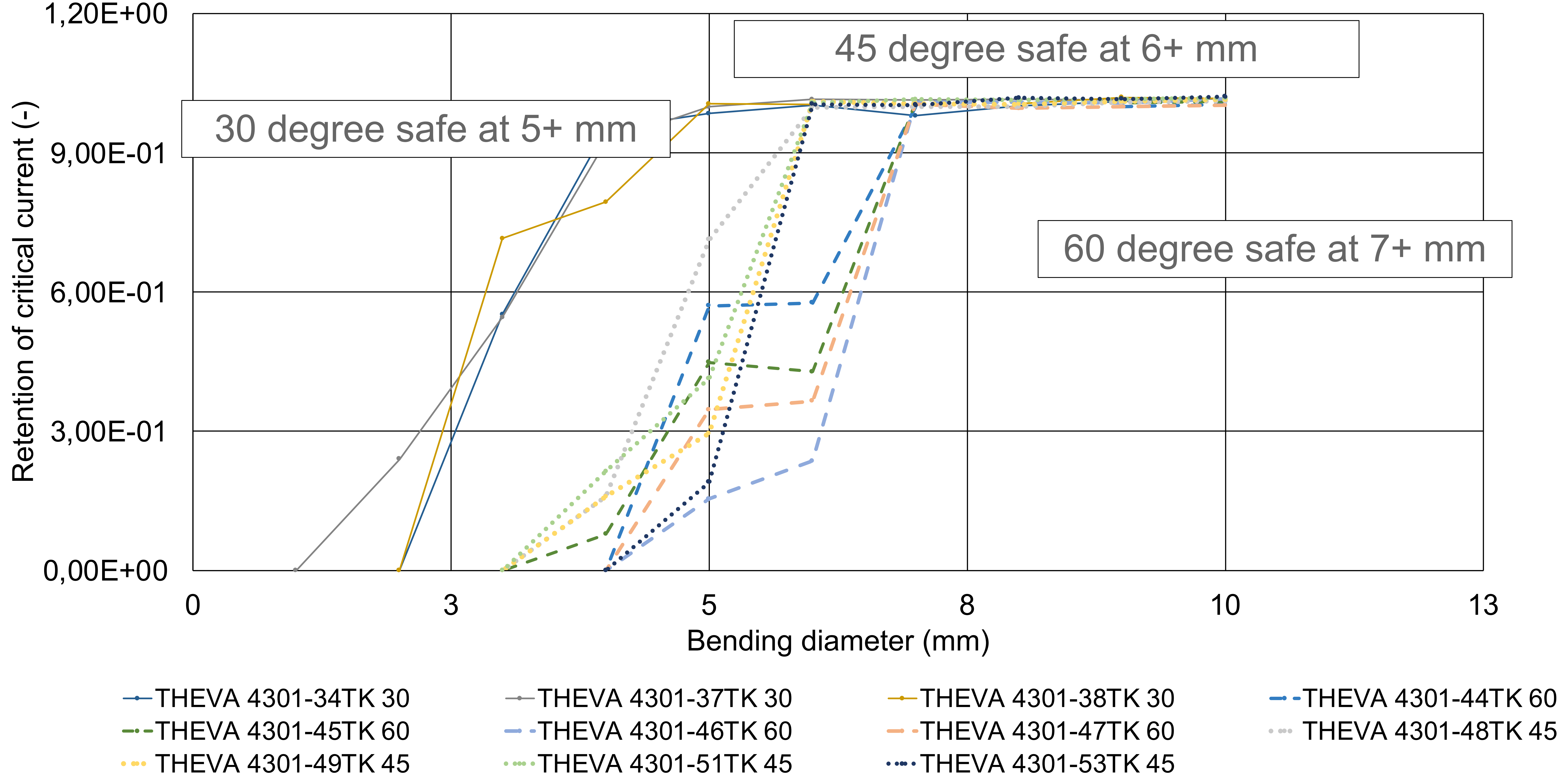
$$h_{shift} = \left[h_{Hastelloy} - \left(\frac{E_{REBCO}}{E_{Hastelloy}} \times h_{REBCO} \right) - \left(\frac{E_{Buffer}}{E_{Hastelloy}} \times h_{buffer} \right) \right] /2$$

$$h_{NA} = h_{Copper} + h_{Silver} + h_{REBCO} + h_{buffer} + h_{shift}$$

And from the geometry we can find the resulting strain in SC layer

$$\varepsilon_{compressive} = \frac{-(h_{REBCO} + h_{Buffer} + h_{shift})}{R + h_{NA}}$$

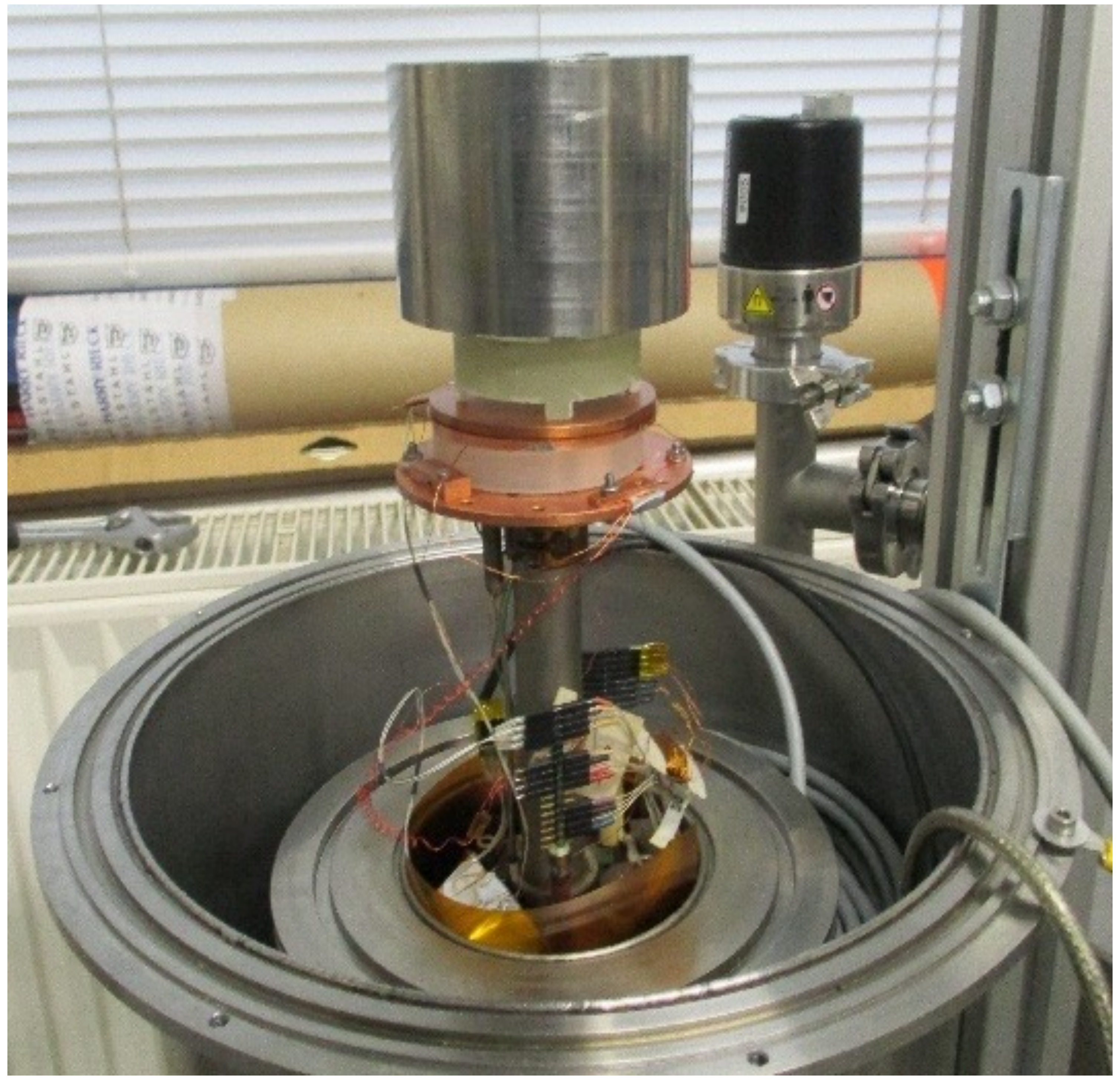
Mechanics - Tape Bending



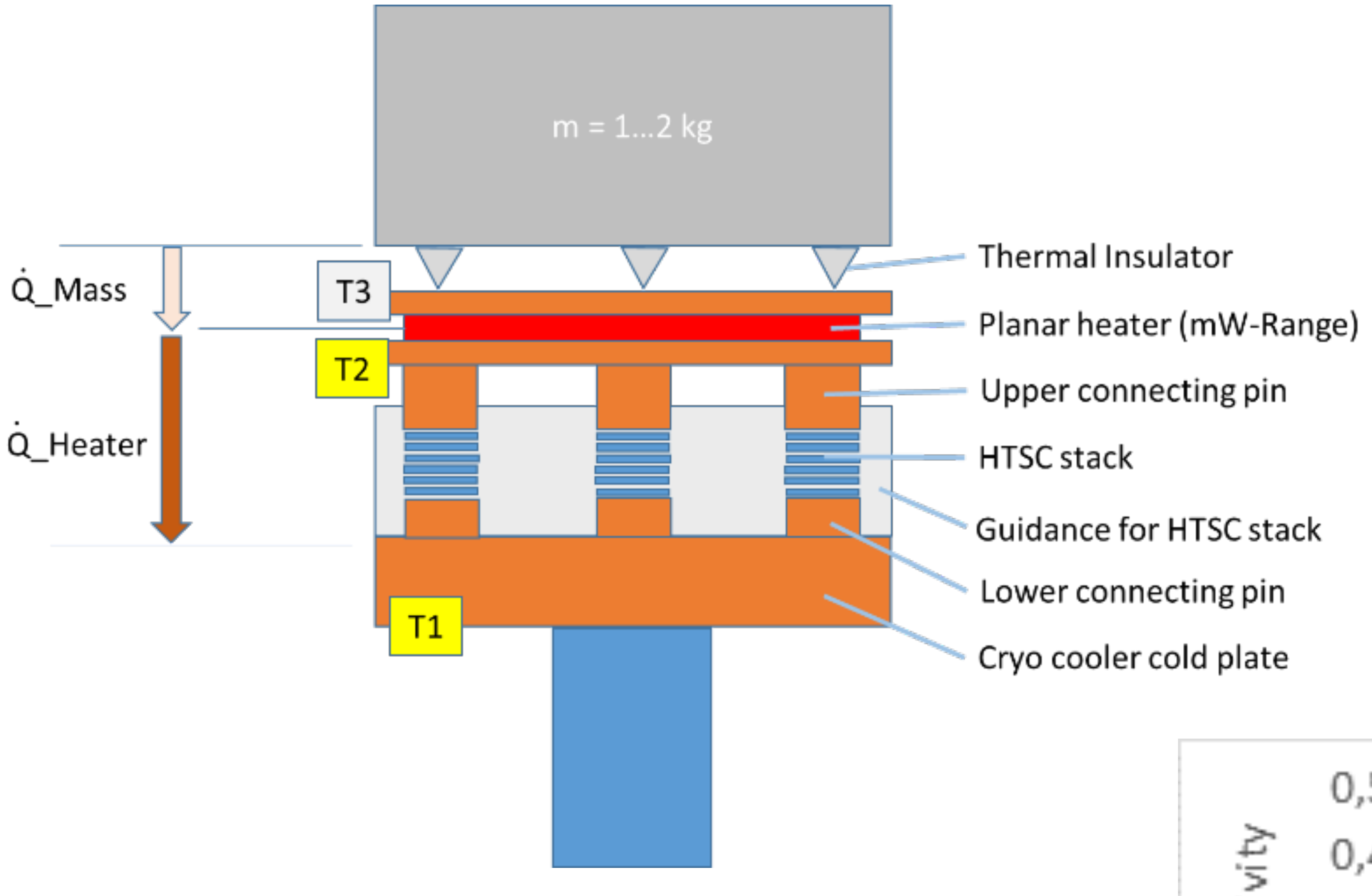
Measurements at 77 K @ IEE

Cooling - Tape to Tape

ILK Dresden



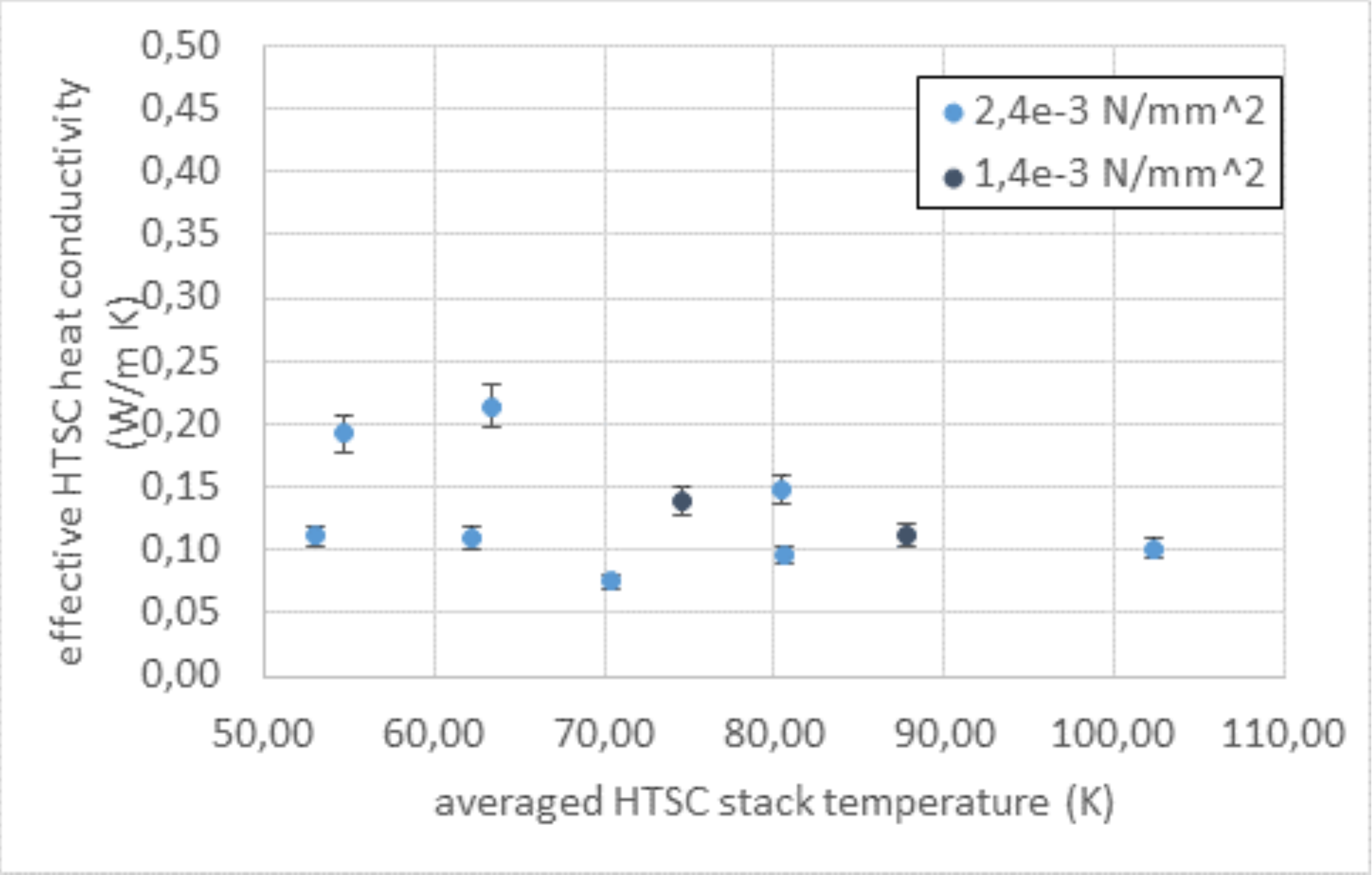
Experimental setup for investigation of the heat conduction of HTS materials



Experimental result:

heat conductivity plotted over the averaged HTSC stack temperature

Effective thermal conductivity for 25 tapes

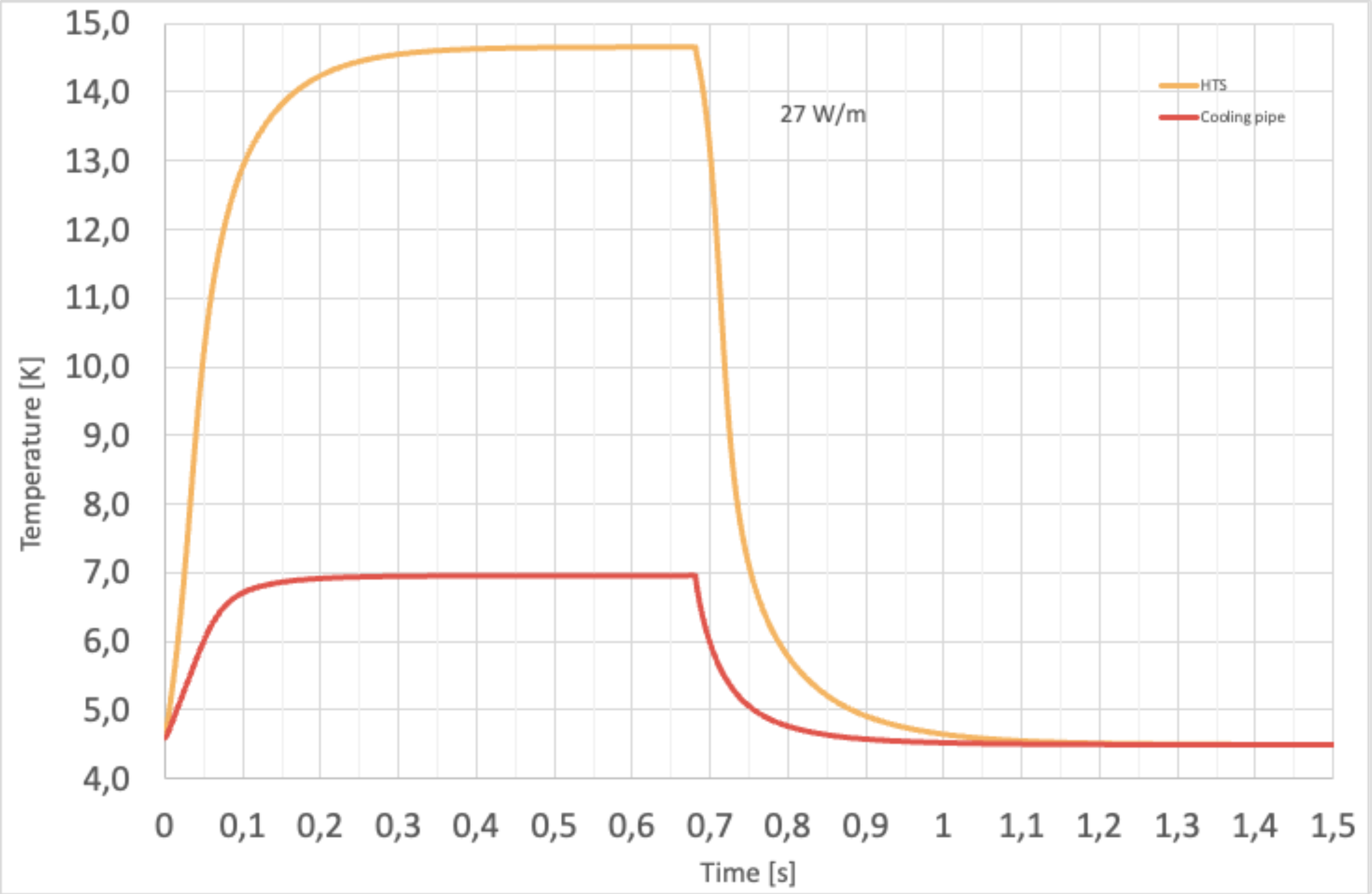


Cooling

- Increasing cycle duration to help deal with high AC loss
- Use thermal heat capacity as buffer during ramp
- During plateau cable/magnet can cool down again

- For SIS300 cycle the loss is in the order of 390 J/cycle/m

- In case of a stretched cycle:
  - Ramp duration from 1s
  - to 10 sec



Thank you very much for your attention
Questions?