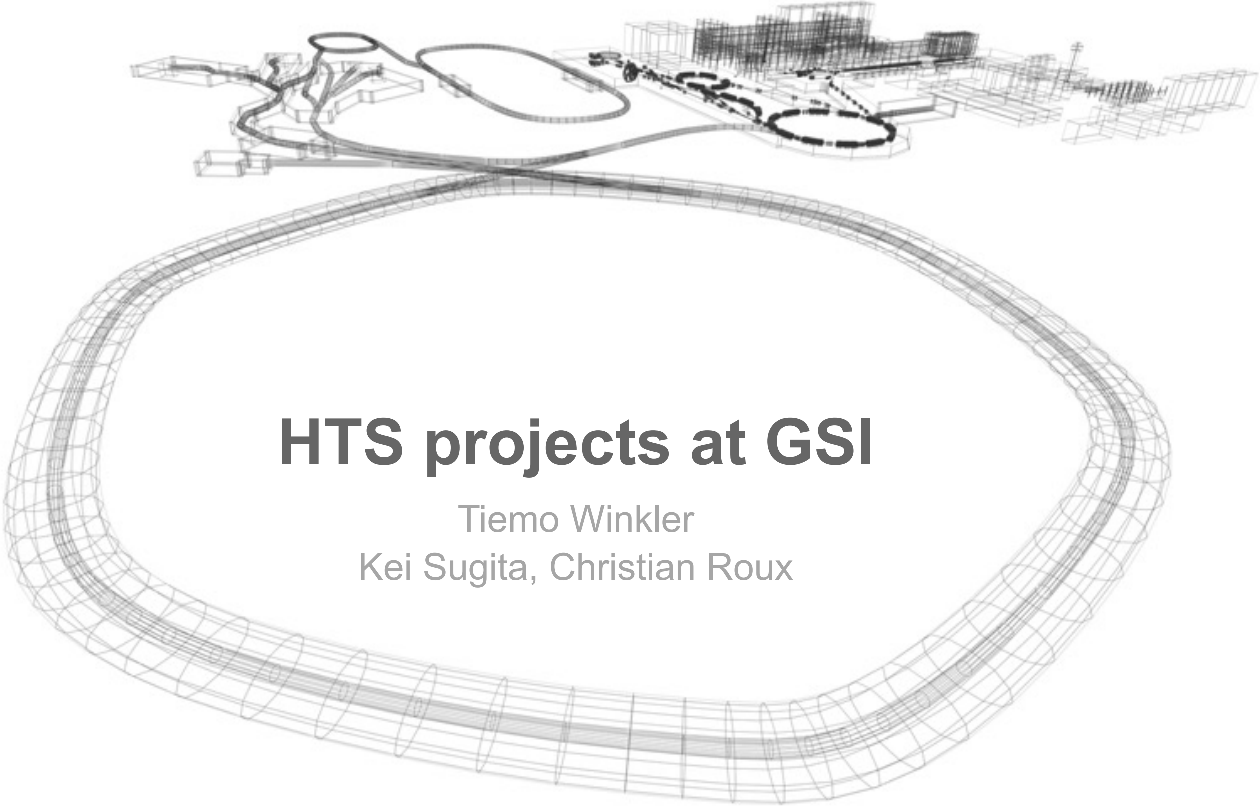


HTS projects at GSI

Tiemo Winkler
Kei Sugita, Christian Roux

Overview

- iFAST project
  - HTS cable for fast ramped applications

- HTS beam steering magnet

WP/Task structure and objectives

- Design Parameters for a round, high current, low AC loss HTS ReBCO cable
- Application: fast ramped, high field accelerator magnets
- Milestone: M24
- Deliverable: M32 Report on cable parameters
- Members:
  - Institute of Electrical Engineering (IEE), Slovak Academy of Sciences, Slovakia
  - ILK Dresden, Germany
  - GSI, Germany
  - EMS Chair, University of Twente (UT), Netherlands

Magnet Design - preliminary

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

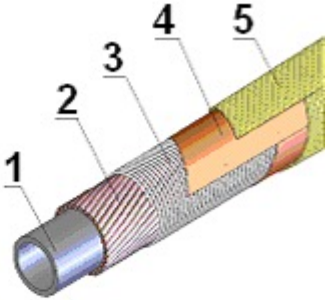
- Cooling channel diameter: tbd
- Length:
  - 200 m - 300 m (per pole)
  - 400 m – 600 m (per magnet)
  - All open for discussion

- Max allowed AC loss depends on cooling capacity.

All parameters can evolve during the project. This is a starting point.

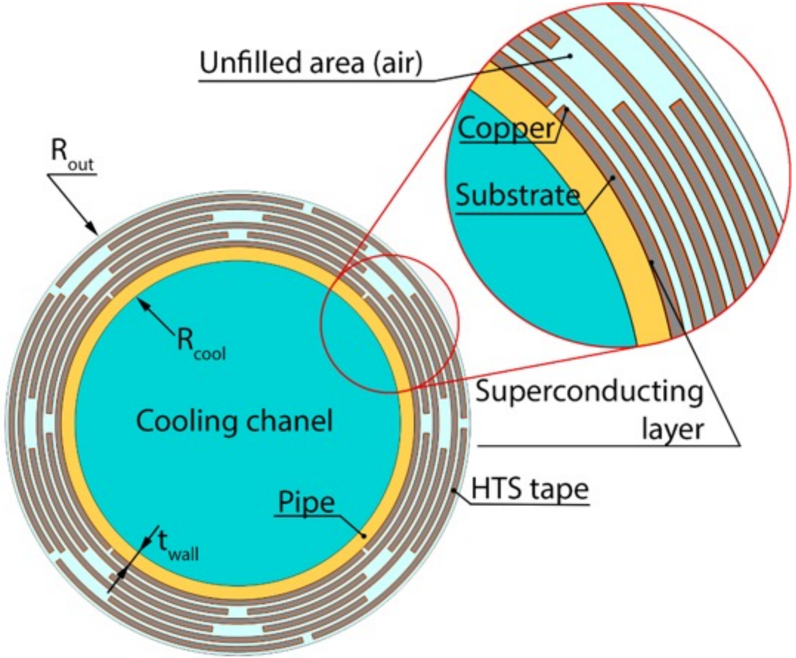
Cable layout

CORC by ACT, advancedconductor.com

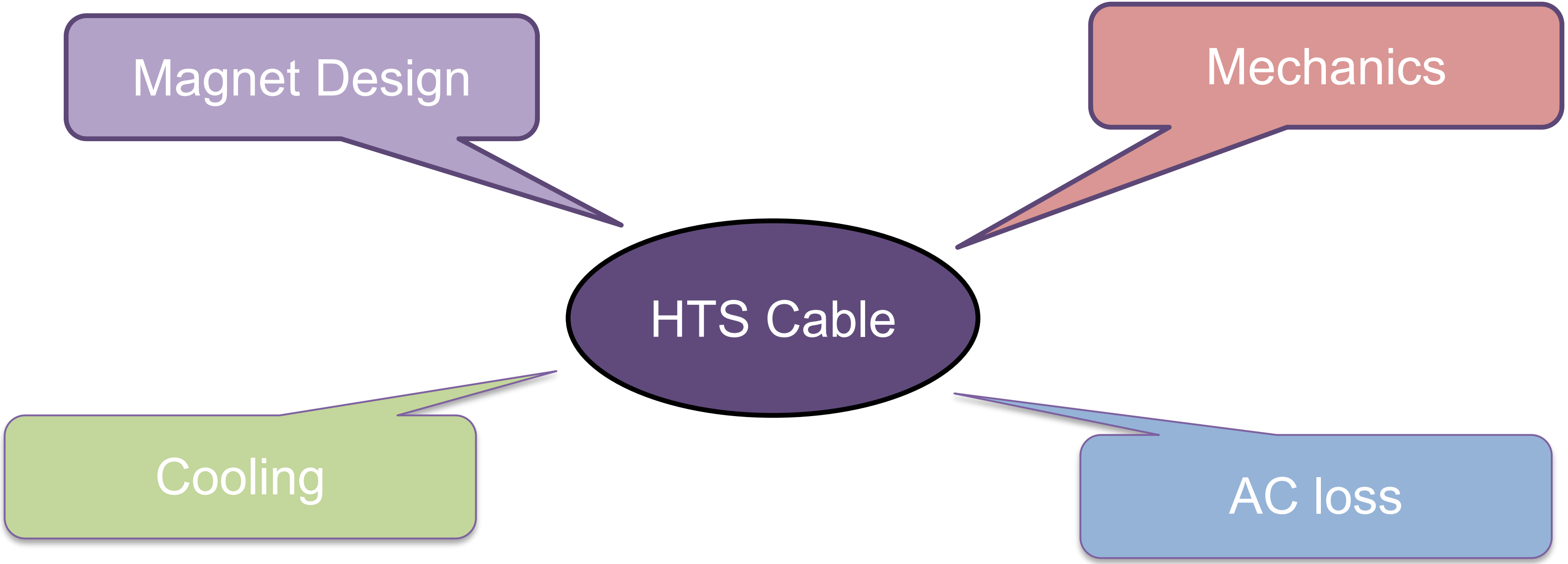


Starting point:

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



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


Magnet Design
Mechanics
HTS Cable
Cooling
AC loss

AC loss estimate for CORT cable

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:

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

=> Increasing the operating temperature alone won't solve this problem!

AC loss estimate for CORT cable

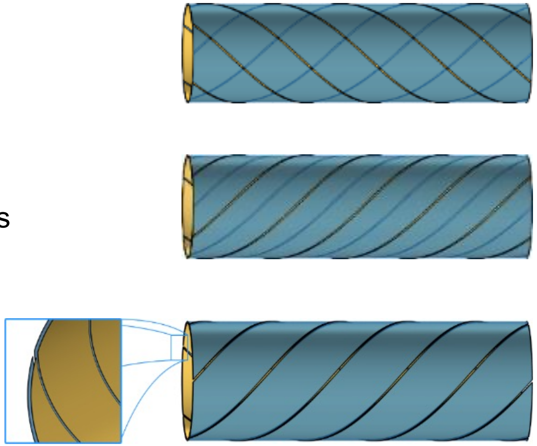
$$\Gamma = \frac{Q_{cable}}{L_{cable} S_{cable}} \frac{2\mu_0}{B_{max}^2}$$

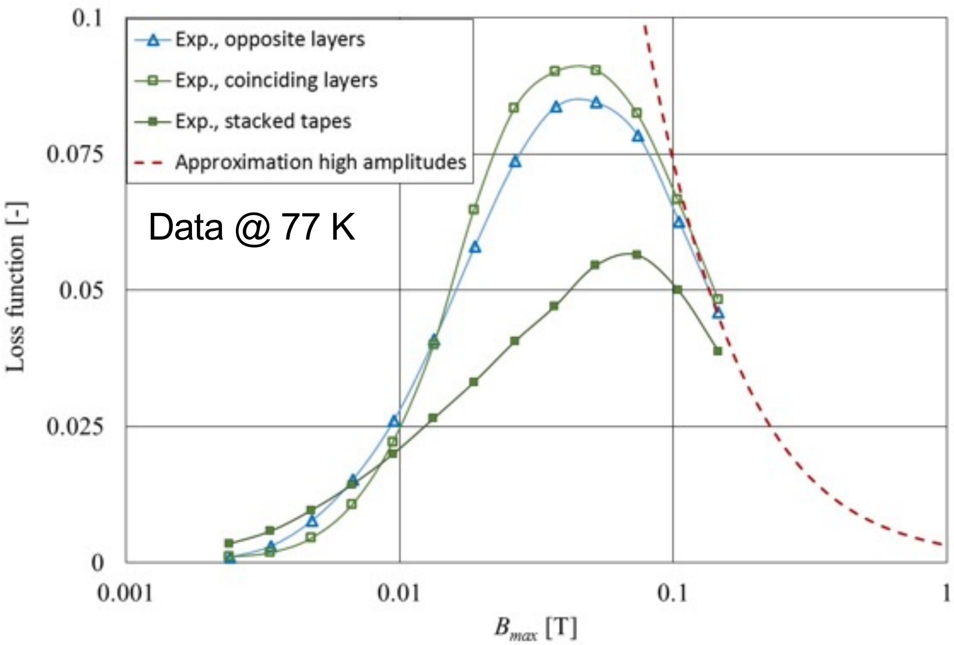
3 samples: 2 x 5 tapes

Opposite layers

Coinciding layers

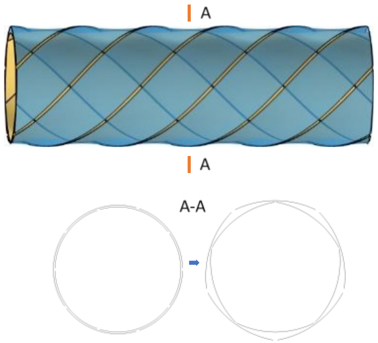
Stacked tapes

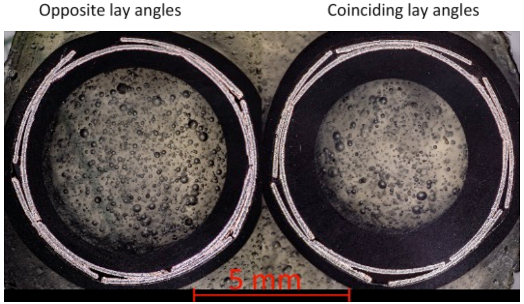




AC loss estimate for CORT cable

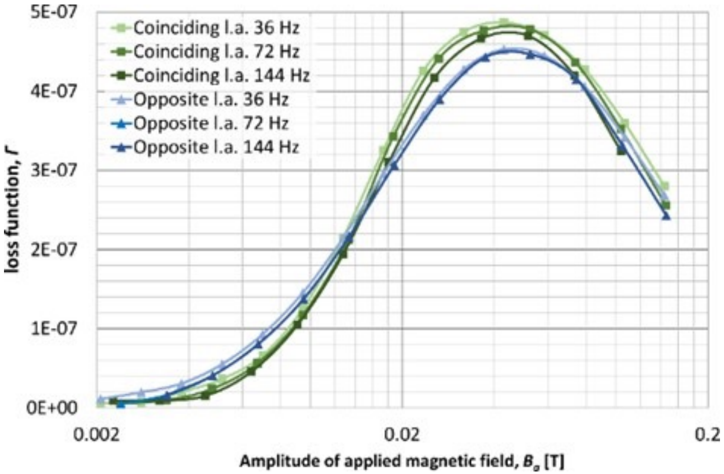
Coupling loss depends on
electrical contacts between tapes





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

AC loss measured at 77.3 K



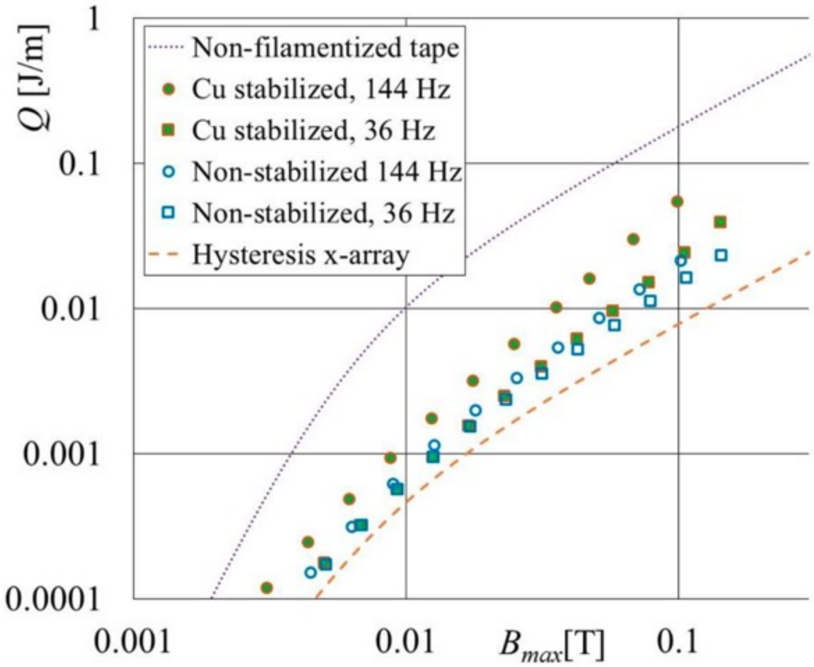
no frequency dependence
=> no coupling currents

AC loss – tape striation

Sample:

- 230 mm length, 10 mm former diameter,
- 12 mm wide tape with 19 filaments
- wf = 0.5 mm wide, gaps of wg = 0.1 mm
- lay angle α = 67 degrees

Additional coupling loss for the Cu stabilized sample



https://doi.org/10.1109/TASC.2024.3364133

AC loss and cooling - striation

From last years meeting:

$$Q_{hT} = \frac{2}{\pi cos\alpha} B_{max} I_c w$$

AC loss for a ramp from 1.9 T to 7.5 T:

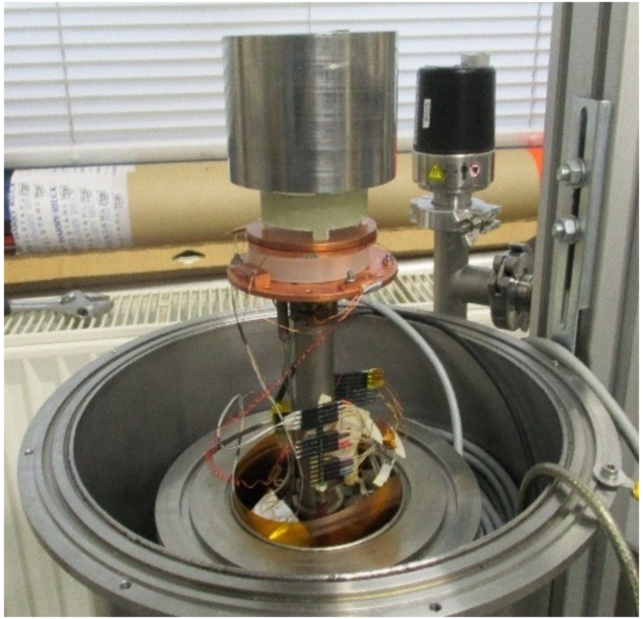
373 W/m

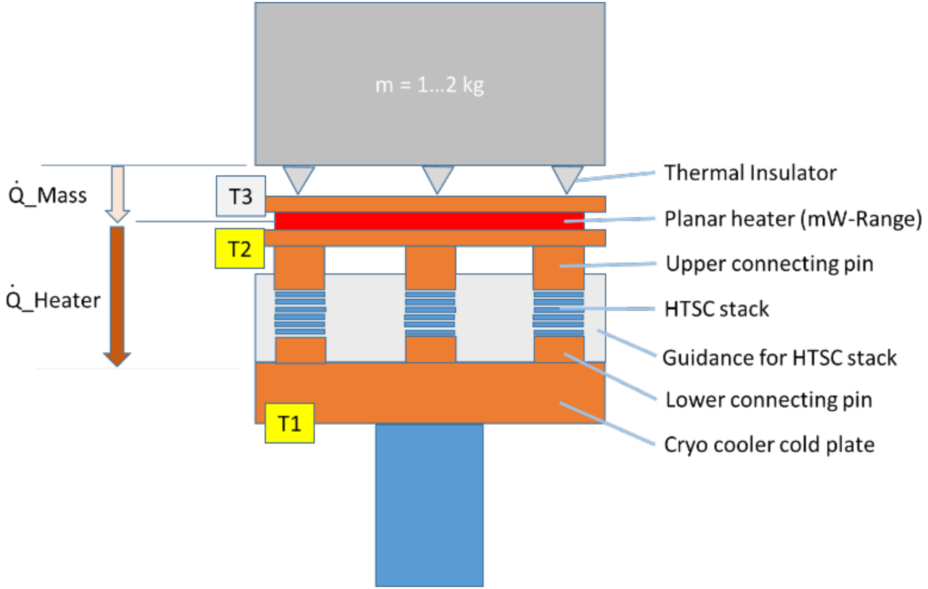
Extending the ramp from 1 sec to 10 sec and introducing 0.5 mm wide filaments:

4.6 W/m

factor of **80** reduction

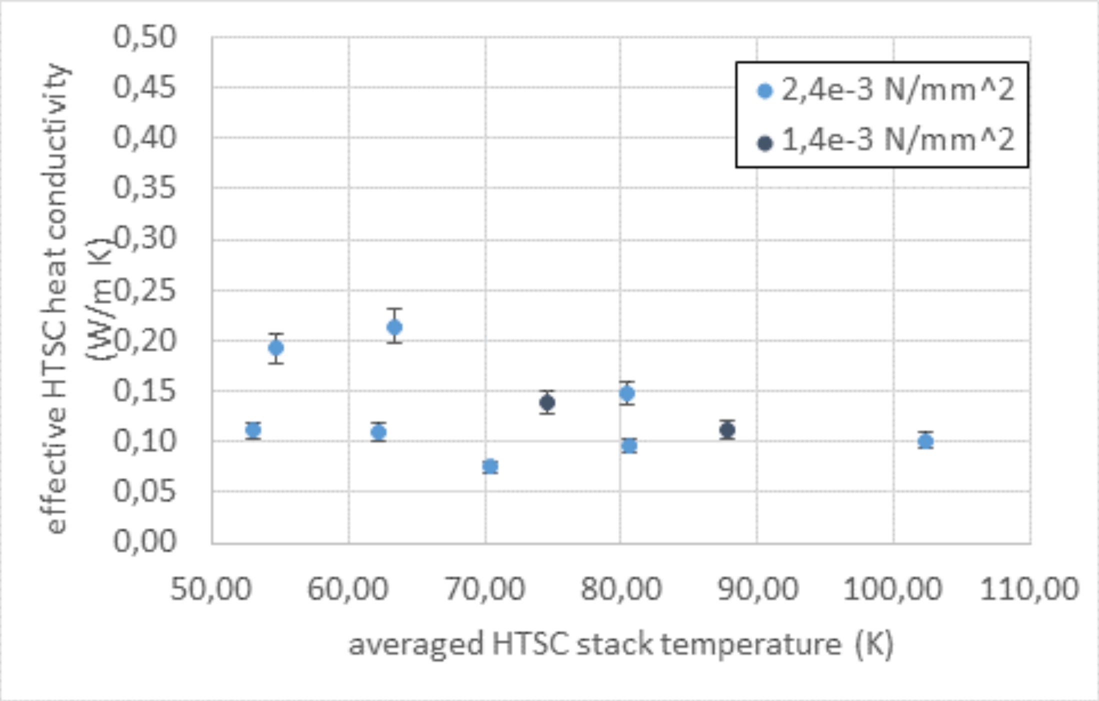
Thermal Conductivity Measurements





Experimental setup for investigation of the heat conduction of HTS materials

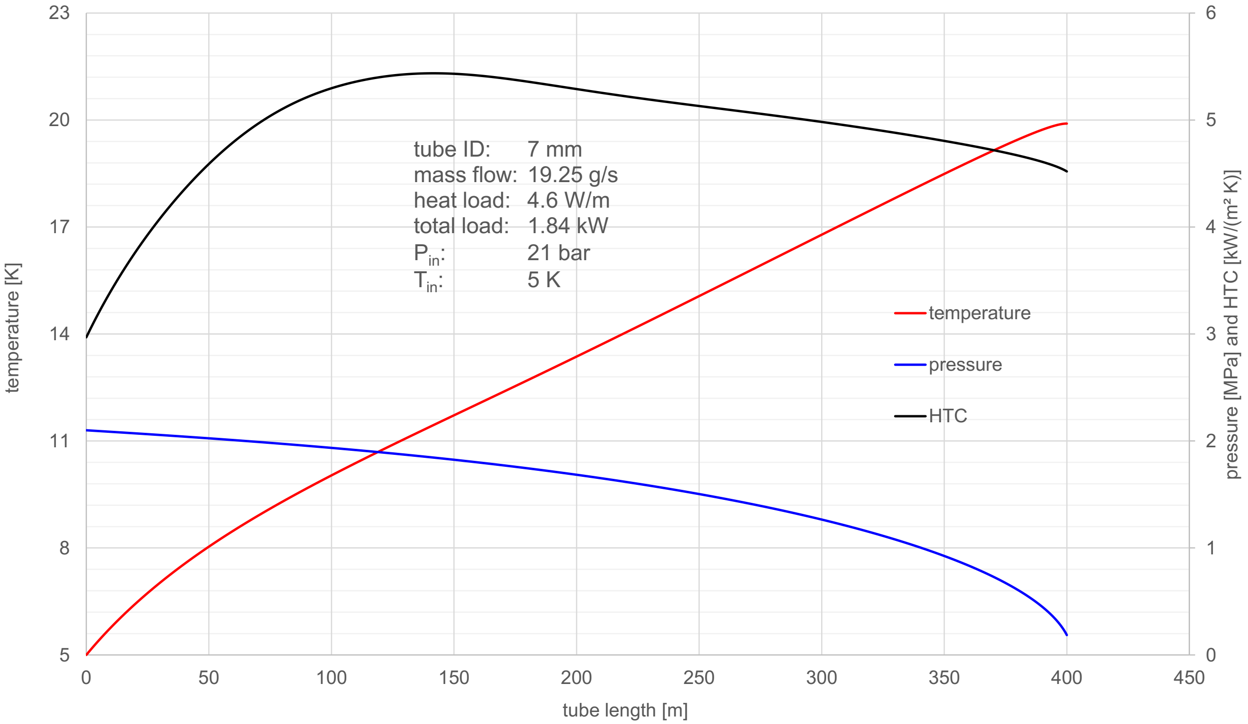
Thermal Conductivity Measurements



Experimental result:
heat conductivity plotted over the averaged HTSC stack temperature

Effective thermal conductivity for 25 tapes

Temperature distribution along cable



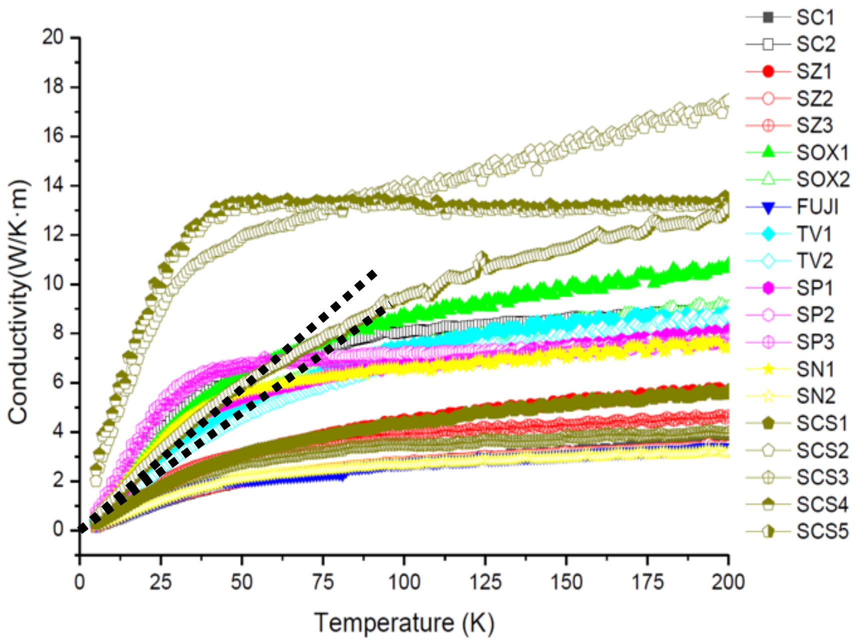
Using 0.13 W/m*K between tapes

Best guess thermal conductivity @Bratislava @4...20K

- ILK: λ=0.17 W/m/K @30K @240 kPa
- Zhang 2022: λ=2.5..2.9 W/m/K @30K @135 MPa
- λ linear with pressure? !
- Zhang 2022 suppl. data: linear with temperature
- Bratislava: 1kg pulling 4mm tape around diameter 8mm → 613 kPa
- Linear fit @30K @613kPa: λ=0.177 W/m/K

- λ linear below 40K →

temperature [K]:	4	13	20	30
λ [W/m/K] :	0.023	0.077	0.128	0.177

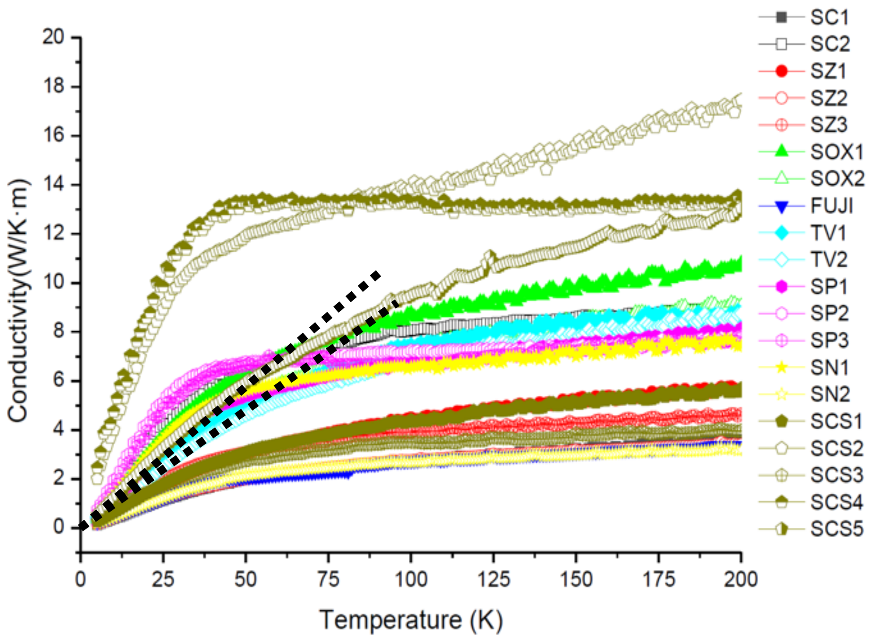


Best guess thermal conductivity @Bratislava @4...20K

- ILK: λ=0.17 W/m/K @30K @240 kPa
- Zhang 2022: λ=2.5..2.9 W/m/K @30K @135 MPa
- λ linear until yield strength 40 MPa
- Zhang 2022 suppl. data: linear with temperature
- Bratislava: 1kg pulling 4mm tape around diameter 8mm → 613 kPa
- Linear fit @30K @613kPa: λ=0.192 W/m/K

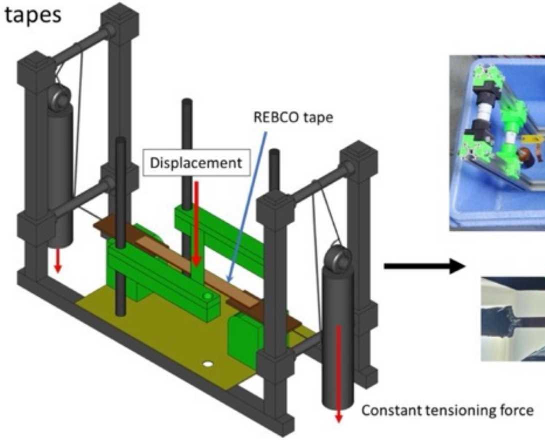
- λ linear below 40K →

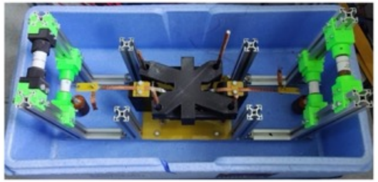
temperature [K]:	4	13	20	30
λ [W/m/K] :	0.026	0.083	0.128	0.192



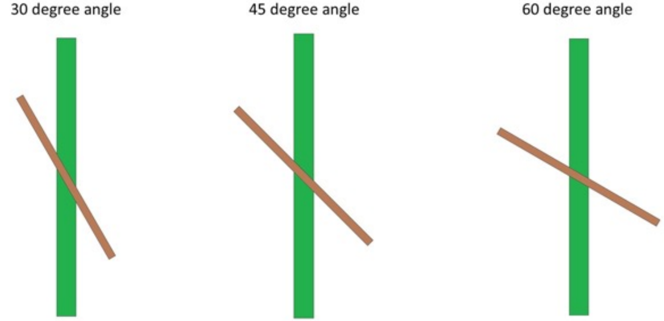
HTS tape mechanics

Measurement method for characterization of bending limits of HTS REBCO tapes





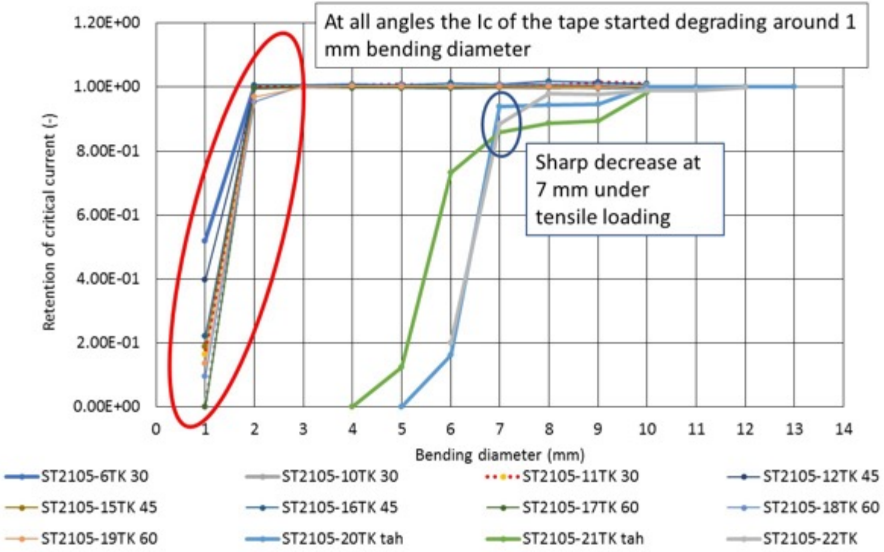
Brown: HTS tape
Green: inprinting tool with circular cross-section

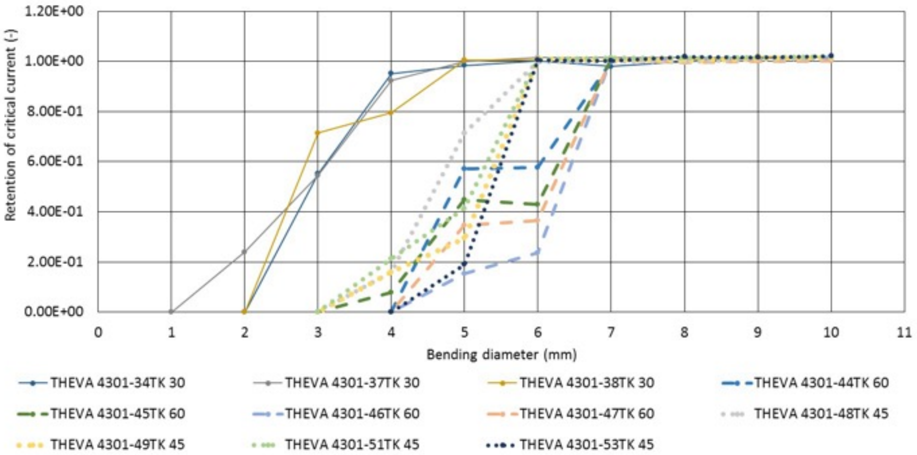


THEVA 4301 Pro Line	
Width	3 mm
Buffer Layer	3.5 µm
REBCO layer	3.1 µm
Substrate layer	100 µm
Silver layers (top and bottom	2 µm
Copper layers (top and bottom)	10 µm

Shanghai Superconductor Technology	
Width	3 mm
Buffer Layer	some nm
REBCO layer	2 µm
Substrate layer	30 µm
Silver layers (top and bottom	2 µm
Copper layers (top and bottom)	5 µm

HTS tape bending - results





Striated AC loss samples

AC losses were measured on following samples:

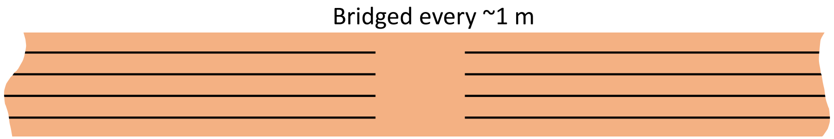
Samples **1**-**3**. Single 12mm wide tape wound turn to turn on 10mm diameter round former. The thickness of copper stabilizing layers were declared as **3.5**, **5** and **10** µm respectively.

Sample **4.** Two 12 mm wide tapes wound in one layer on 10mm diameter round former.

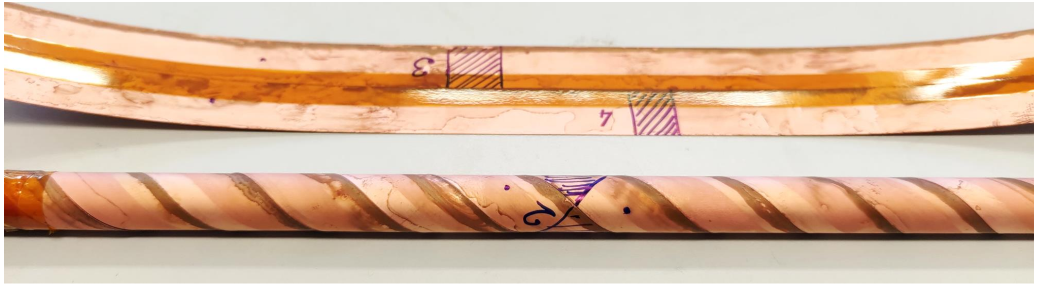
Sample **5**. Four 12 mm wide tapes wound in two layers on 10mm diameter round former.

Samples **6**, **7**. Four 12 mm wide tapes wound in two layers on 10mm diameter round former. Sample **6** is made of ordinary filamented tape. While sample **7** contains tapes with non-filamented bridges in the middle of the cable with 1 cm length which connected all filaments.

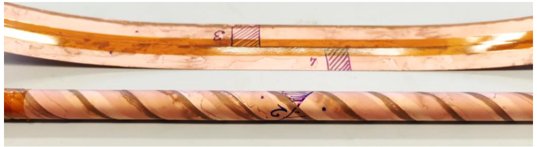
Striated AC loss samples



Samples **6**, **7**. Four 12 mm wide tapes wound in two layers on 10mm diameter round former. Sample **6** is made of ordinary filamented tape. While sample **7** contains tapes with non-filamented bridges in the middle of the cable with 1 cm length which connected all filaments.

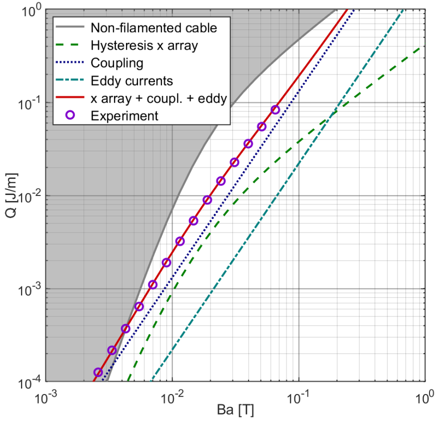


Striated AC loss results

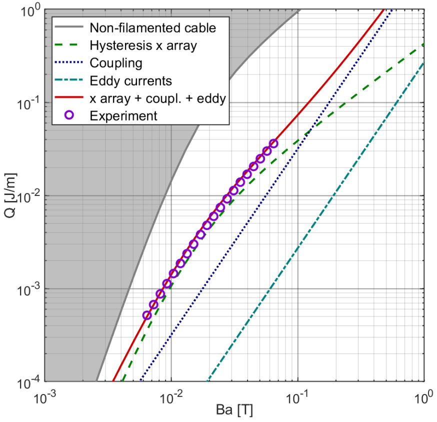


72 Hz

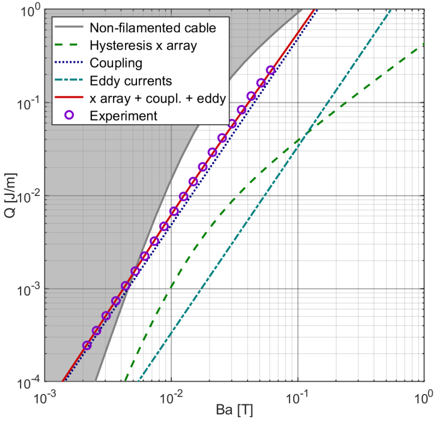
2 tapes, 10 filaments, 5 µm Cu



4 tapes, 22 filaments, 3.5 µm Cu



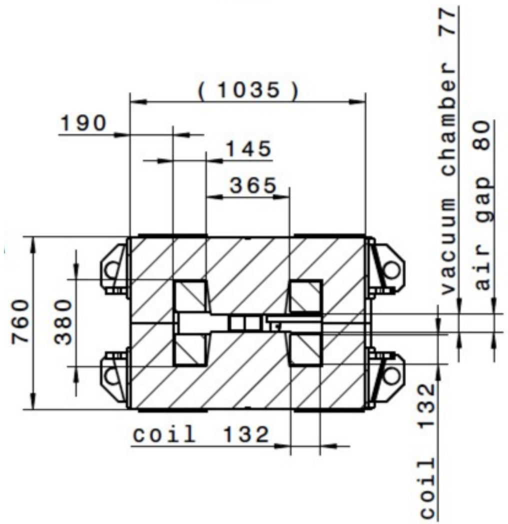
4 tapes, 22 filaments, 10 µm Cu + bridges

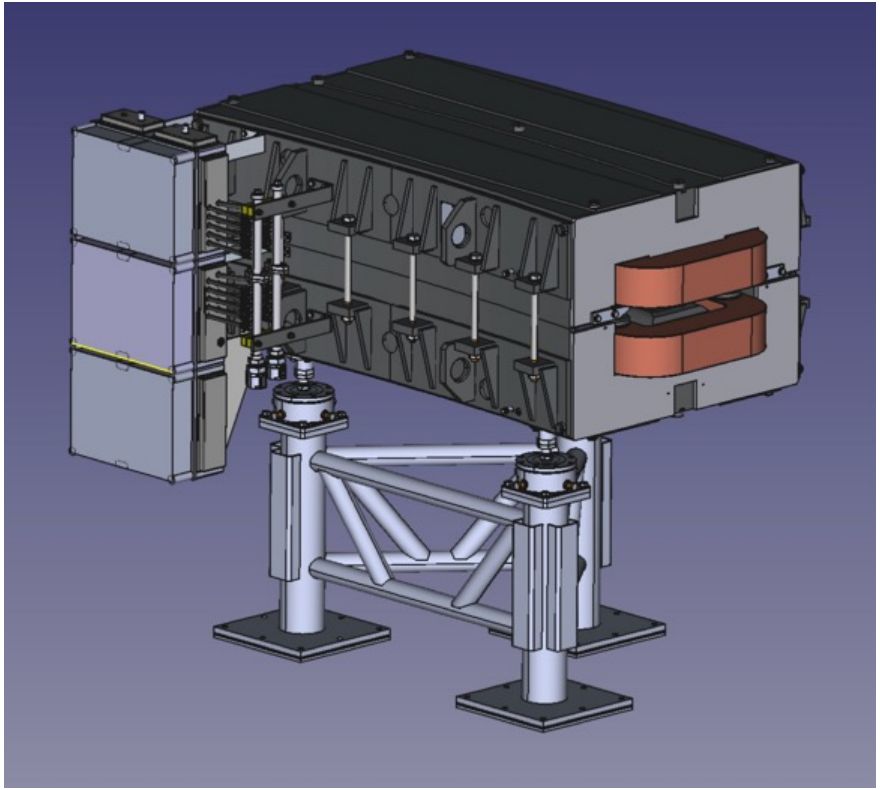


HTS beam transfer magnet

GSI Beam Steering Magnet

- 12.5° 13 Tm normal conducting magnet
- H-Frame yoke design
- 2x 100 turn water cooled copper coils

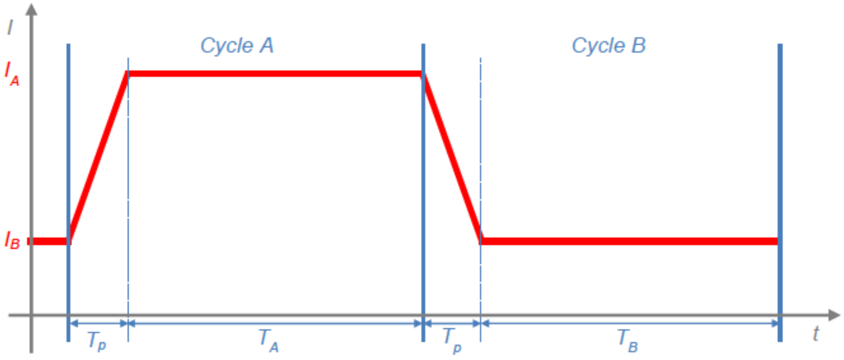




What do we want to do

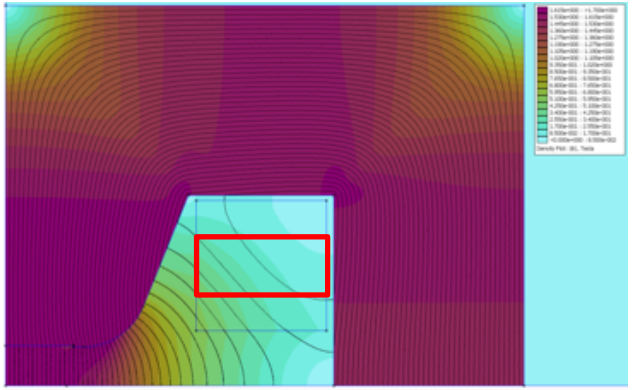
- Multiple operation modes
  - DC to 0.5 Hz
- No cryogenic fluids => dry cooling
- Reuse exiting hardware as much as possible
  - Yoke
  - Power converter
  - Cabling

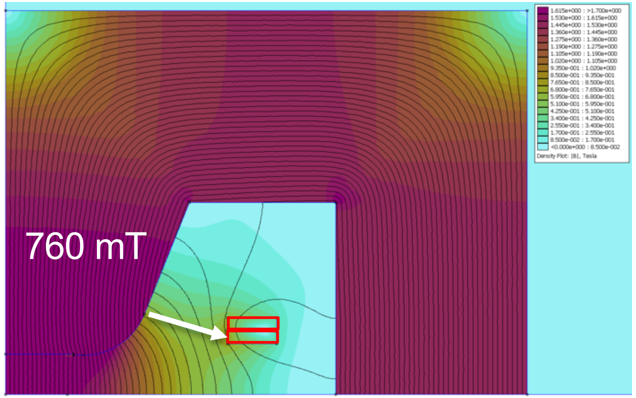
- Design concept
  - HTS racetrack coils
  - Install assembly of cryostat and coil in space of copper coils
- Challenge: Coil cooling during ramping

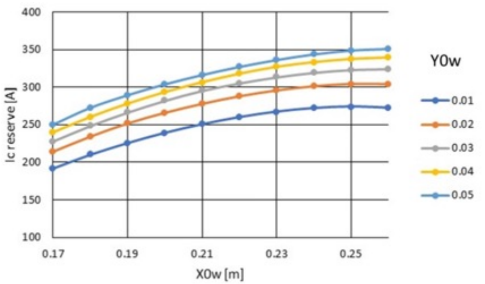


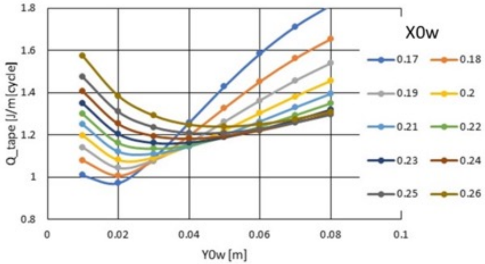
Parameter	Value
Field in Gap	1.6 T
Max Current	534 A
Ramp rate	1 T/s
DC Power	46 kW

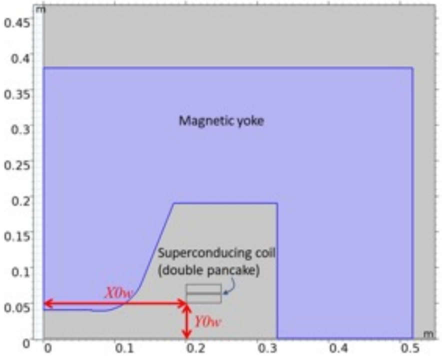
Magnetic field and AC loss

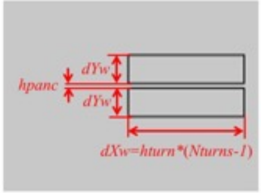












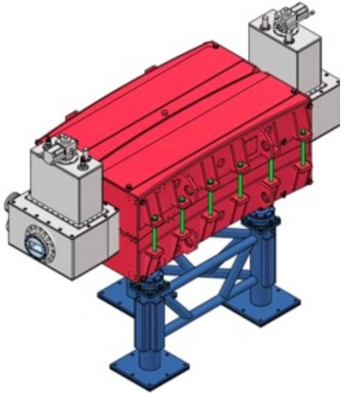
- 2D-Model in Comsol
- Parametric coil position
  - => Ic reserve and hysteresis loss
  - Verification with 3D model for two full cycle calculation shows good agreement

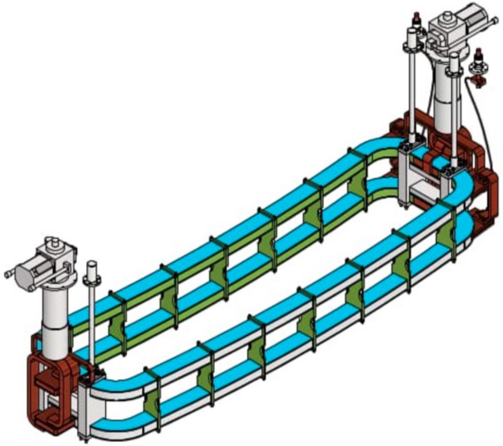
Units	Copper Coil	HTS Coil
b3	0,363	0,401
b5	0,159	0,162
b7	-0,002	-0,001
b9	-0,003	-0,002

Design

- Exoskeleton cryostat, e.g. frame with walls plated on, non-conductive contact areas to limit eddy-currents in cryostat
- Operating temperature: 50 K
- No thermal shield
- Fully encased double racetrack coils
- Option for one cryocooler on each extremity, SHI SRDK-500B
- 1 mm spacing between turns to reduce AC loss in conductor

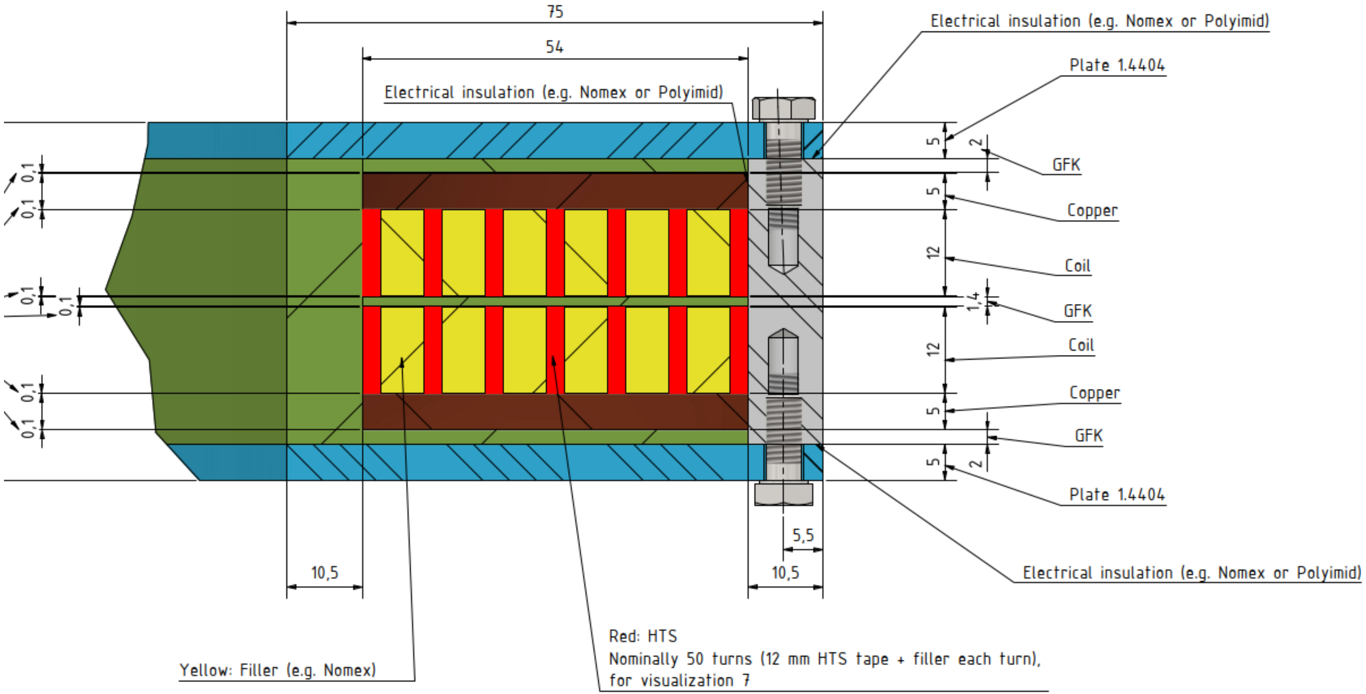
Static losses		
Support	3 W	system
Current Leads	54 W	system
Ohmic losses joints	20 W	system/coil
Radiation (ambient)	6 W	system/coil
Sensors	2 W	system/coil





Dynamic losses		
Stainless steel components	1.76 W 0.44 W	system/coil Peak power deposition during 1 T/s / 0.5 T/s ramp
	0.19 W 0.048 W	system/coil Mean power deposition during cycle
Thermobus	3657 W 914 W	coil Peak power deposition during 1 T/s / 0.5 T/s ramp
	398 W 99 W	coil Mean power deposition during cycle
HTS hysteresis loss	230 J/cycle	coil Peak power deposition during 1 T/s / 0.5 T/s ramp
	25 W	coil Mean power deposition during cycle

Coil Cross-Section



Duty cycle

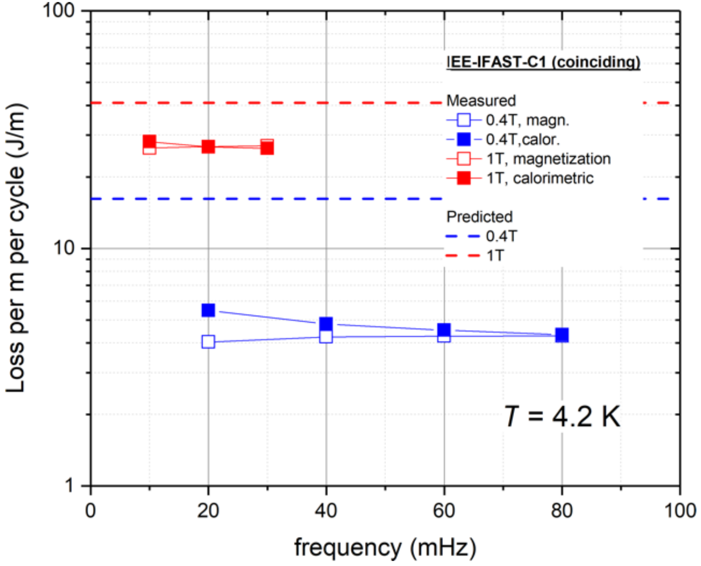
- Energy saving strongly depend on operation duty cycle.
- A magnet with a wide range of set points and long operation times is a good candidate for an upgrade
- Magnets that are very fast switched (e.g. > 0.5 Hz) are challenging for dry cooling

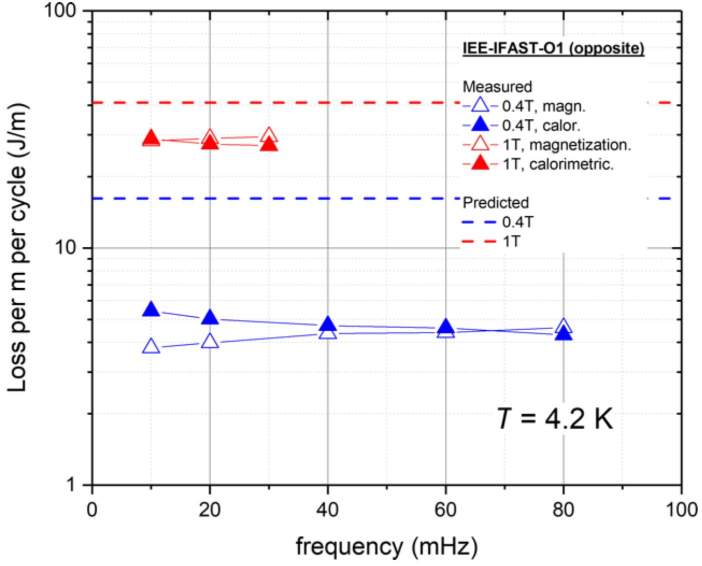
The end

Backup

AC loss estimate for CORT cable

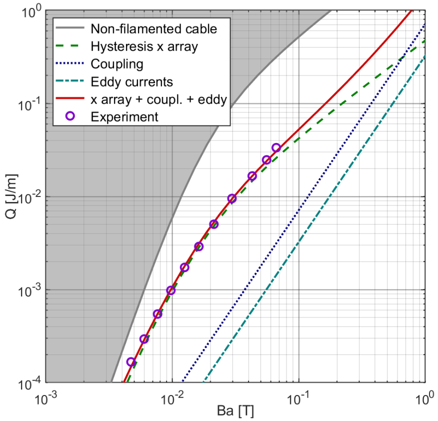
- Measurements at 4 K @ UT
- Deviation due to higher I_c compared to 77 K



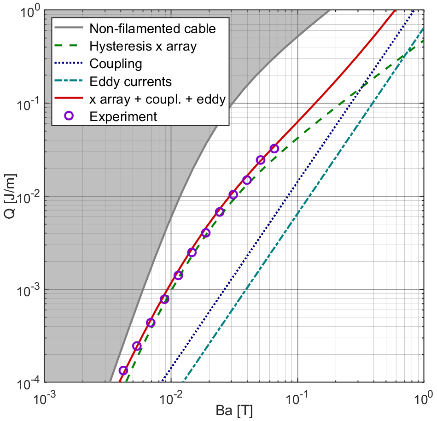


3 μm Cu

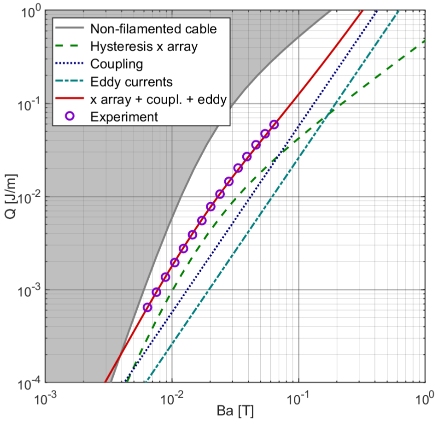
18 Hz



36 Hz

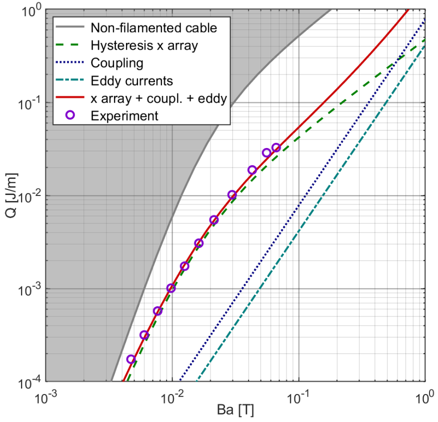


144 Hz

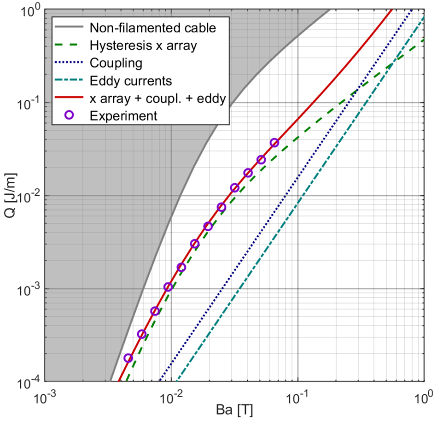


5 µm Cu

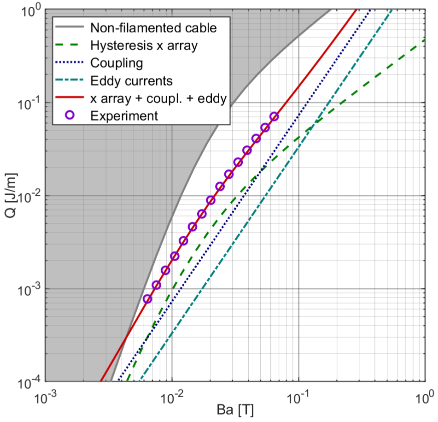
18 Hz



36 Hz

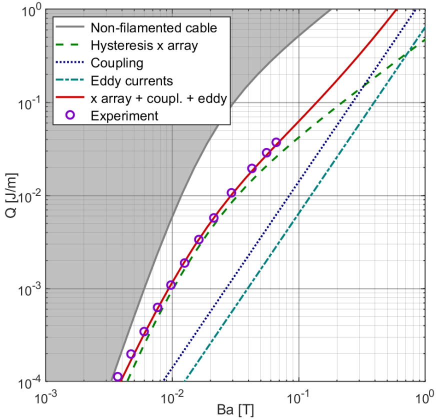


144 Hz

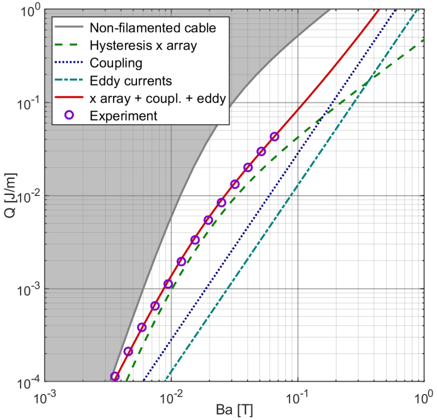


10 µm Cu

18 Hz



36 Hz



144 Hz