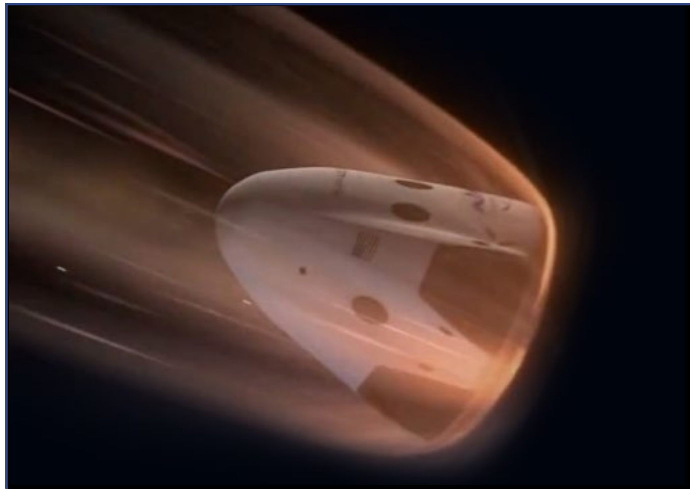
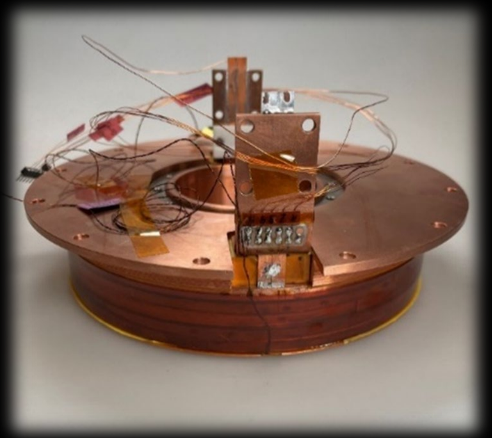
M1Or3E-05

Design, fabrication and test of high temperature superconducting magnet for heat flux and radio blackout mitigation experiments in plasma wind tunnels

Sonja I. Schlachter[1], Antje Drechsler[1], Rainer Gehring[1], Matthias Eisele[1], Frank Gretschmann[1], Frank Hornung[1], Sascha Westenfelder[1], Johann Willms[1], Veit Große[2], Anis Smara[2], Matthieu Dalban-Canassy[3], Alexander Behnke[4], Georg Herdrich[4], Johannes Oswald[4], Adam S. Pagan[4], Bernd Helber[5], Alan Viladegut[5], Andrea Lani[6]

[1] Karlsruhe Institute of Technology, Institute for Technical Physics, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[2] THEVA Dünnschichttechnik GmbH, Rote-Kreuz-Str. 8, 85737 Ismaning, Germany
[3] ABSOLUT SYSTEM SAS, 2 rue des Murailles, Seyssinet-Pariset, 38170, France
[4] University of Stuttgart, Pfaffenwaldring 29, Stuttgart, 70569, Germany
[5] von Karman Institute for Fluid Dynamics, Waterloosesteenweg 72, Sint-Genesius-Rode, 1640, Belgium
[6] Katholieke Universiteit Leuven, Celestijnenlaan 200b, Leuven, 3001, Belgium





Outline

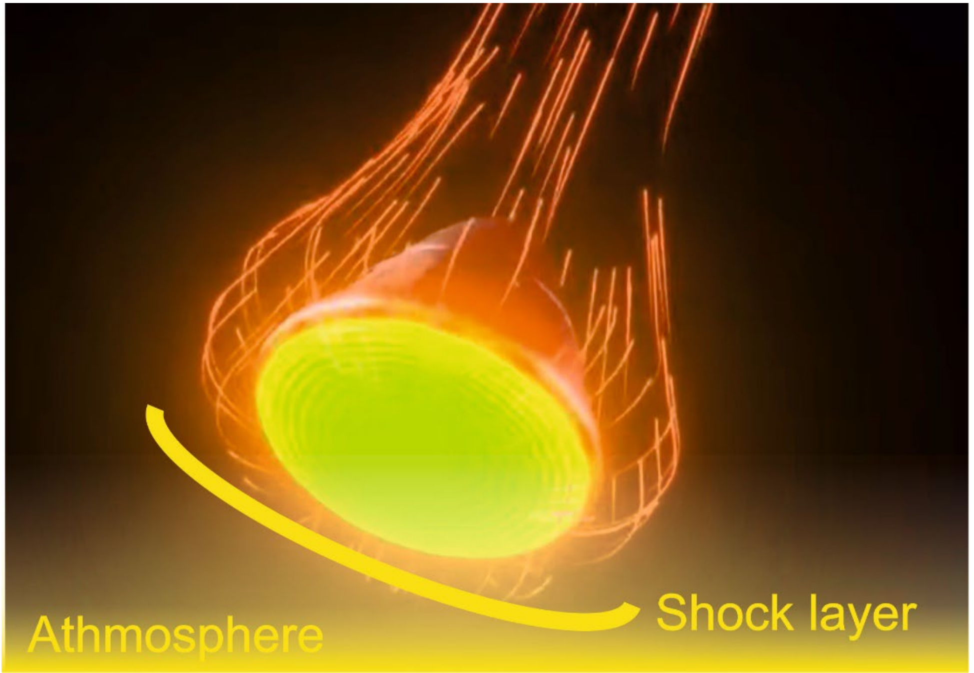
- Problems during Reentry of Space Vehicles
  - Heating
  - Radio blackout
- Solution: Influence Plasma with Magneto-Hydrodynamic Effects
- MEESST Project
- MEESST Magnet and Cryogenic System
- Robotic Magnet Winding
- Magnet Test @ KIT
- Conclusions and Outlook

Reentry of Space vehicles: Heating

Problem during reentry at hypersonic speed:

- Compression of air at leading edge
  → Formation of hot shock layer
  → Radiation heating
- Convective heating from flow of hot gas past surface

➢ *T* exceeding 2000°C



State-of-the-Art Solutions

- Thermal protection systems (TPS), e.g.
  - Ultra High Temperature Ceramics
  - Insulators and Ultra High Thermal Conduction Materials
  - …

Reentry of Space vehicles: Radio Blackout

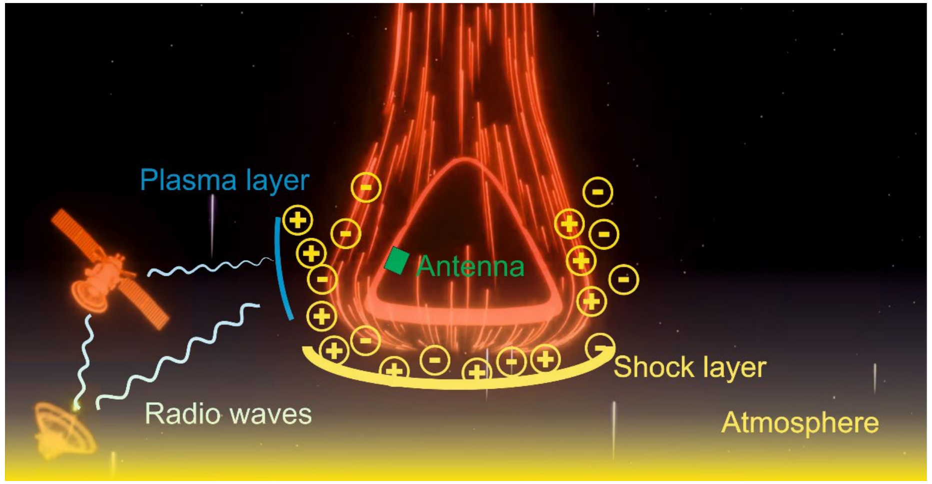
Problem:

Hypersonic flow creates plasma layer around vehicle.
Dense plasma layer has high plasma frequency

$$f_e = \frac{\omega_e}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} > f_{radio}$$

→ reflection of RF signals: 'Radio Blackout'

→ Loss of communication with ground stations / satellites



Missions and duration of blackout phases:

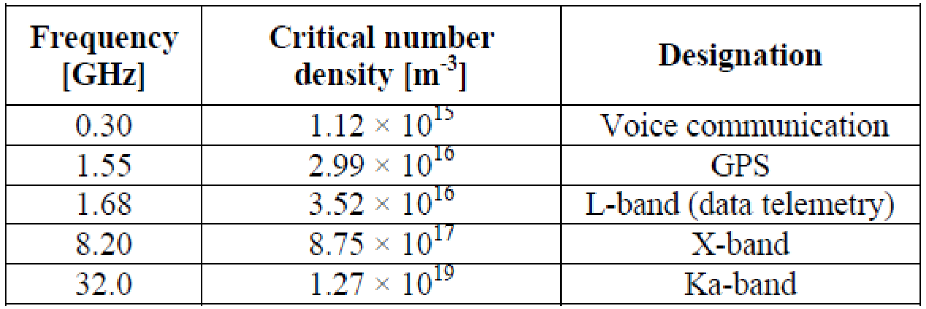
- Gemini 2: ~ 4 min.
- Apollo: ~ 3 min.
- Mars Pathfinder: ~ 30 sec.
- Space Shuttles ~ 30 min.

Solutions (passive or active):

→ Aerodynamic shaping (sharp edge not blunt)

→ Injection of quenchants to reduce ionization level

→ ….



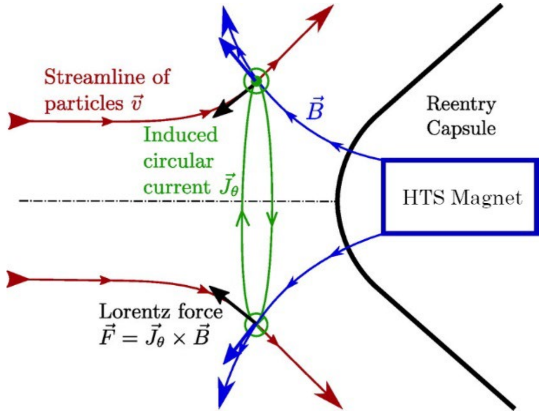
Frequency [GHz]	Critical number density [m^{-3}]	Designation
0.30	1.12×10^{15}	Voice communication
1.55	2.99×10^{16}	GPS
1.68	3.52×10^{16}	L-band (data telemetry)
8.20	8.75×10^{17}	X-band
32.0	1.27×10^{19}	Ka-band

M. Kim and A. Gülhan, *Proceedings of 5th International Conference on Recent Advances in Space Technologies* - RAST2011, Istanbul, 2011, pp. 412-417, doi: 10.1109/RAST.2011.5966868.

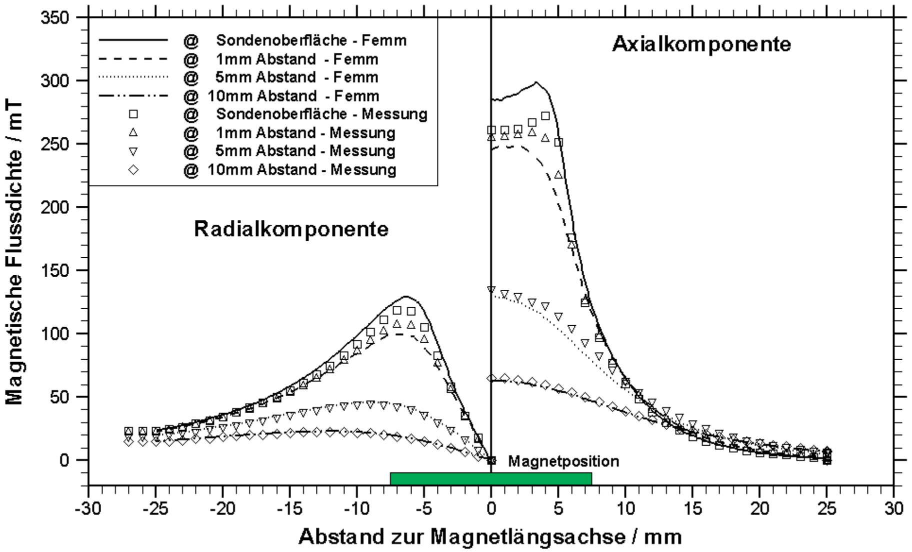
Solve Problems with Magneto-Hydrodynamic Effects

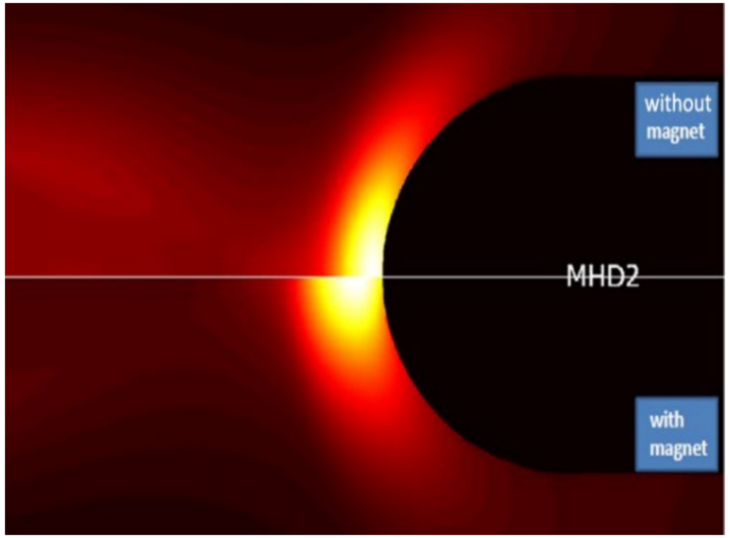
- Influence Plasma with Magneto-Hydrodynamic Effects

Magnetic field configuration and acting forces:



Experiments at IRS Stuttgart: Stand-off distance change under applied field (normal magnet)





Andreas J. Knapp; “Experimentelle Untersuchung von magnetohydrodynamischen Einflüssen auf Plasmaströmungen“, PhD Thesis, University of Stuttgart (2012).

- Amplify effects by using an HTS Magnet → MEESST

Magneto-Hydrodynamic Entry Systems for Space Transportation (MEESST)

- EU-Funding: grant agreement No.899298
- Call/Topic: FET-Open Challenging Current Thinking
- Duration: 10/2020 –09/2024 (incl. extension)
- Budget: 3.48 M€

MEESST

Consortium and roles:

Modelling:

KU Leuven (BE)
Project coordinator
Code harmonization

University of Luxembourg (LU)
Radio blackout modelling

University of Southampton (UK)
Code harmonization

AEDS SARL (CH)
Radiative heat transfer modelling

HTS Magnet and Cryogenic System:

Theva Dünnschichttechnik (DE)
HTS tape design and production

Karlsruhe Institute of Technology (DE)
HTS Magnet design and production

Absolut System (FR)
Cryogenic system design and production

Plasma Experiments:

Von Karman Institute (BE)
Experimental radio blackout research

Institute of Space Systems (DE)
Experimental heat flux research
Code harmonization

Dissemination:

Neutron Star Systems
Project dissemination

Heat Flux mitigation Experiments at IRS

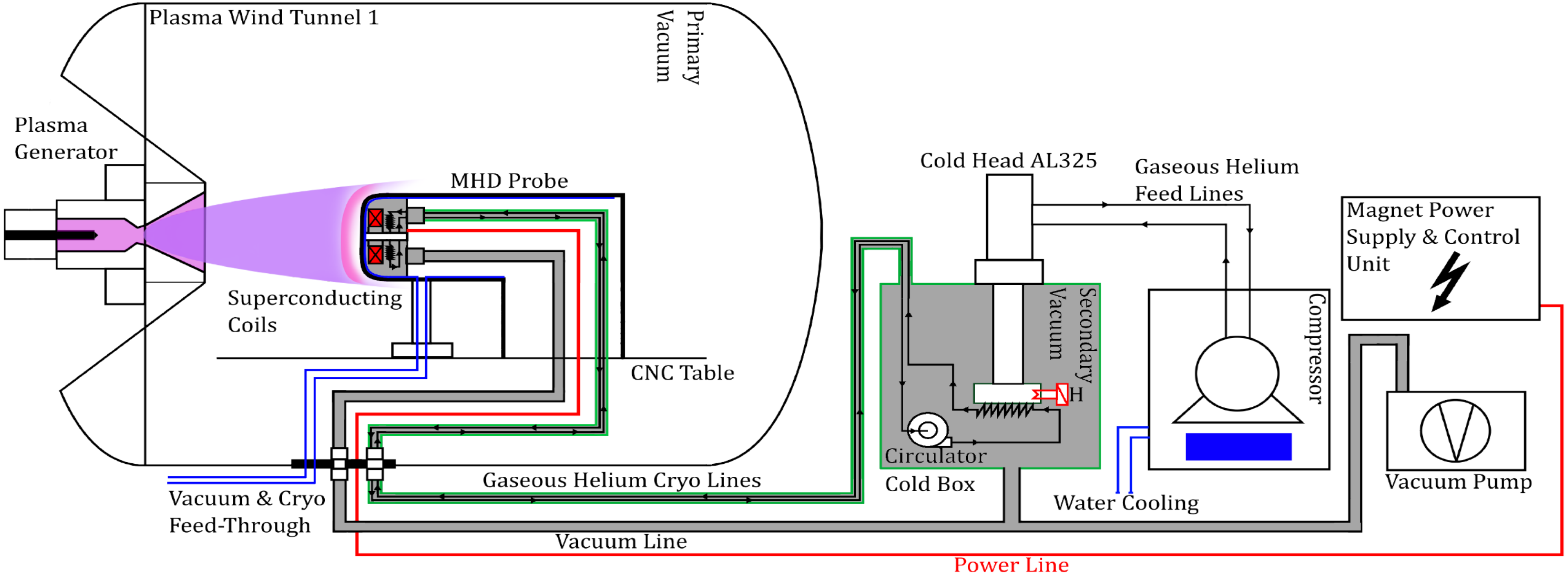
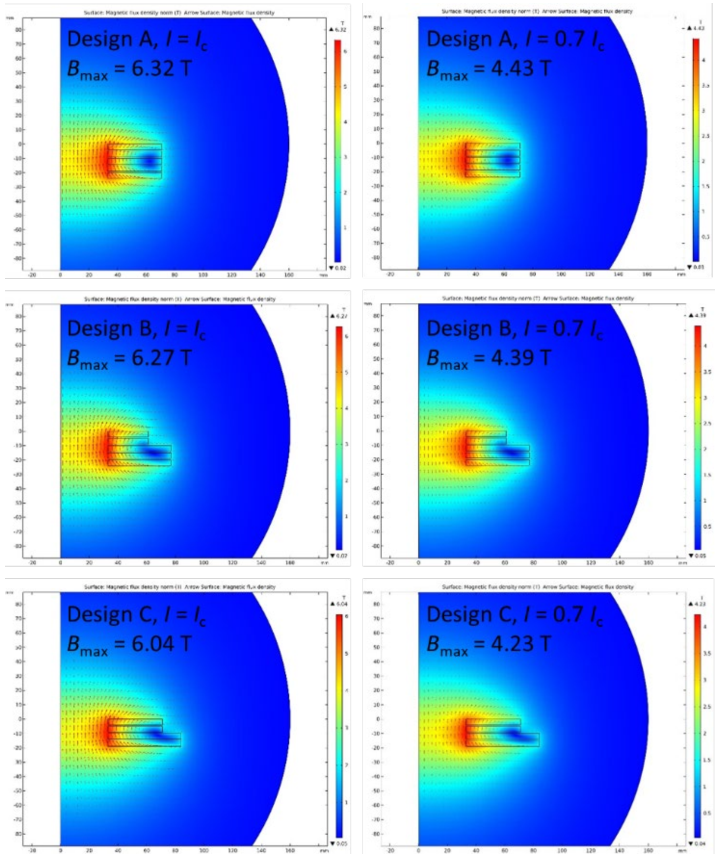


Fig. 5.: System architecture schematic of the MHD plasma probe with indications of the required peripheral systems to operate the HTS magnet.

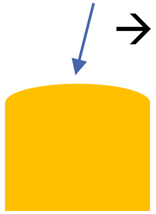
J.W. Oswald *et al.* “MHD Flow Manipulation Experiments in High Enthalpy Air Plasma”, submitted to Proceedings of International Symposium on Space Technology, June 3-9, 2023, Kurume, Japan

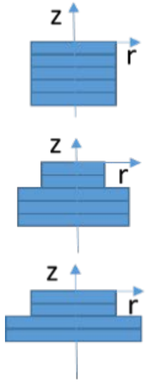
Calculation of Field Distribution (Different Geometries)

Total conductor length: 900 m; width 4 mm, R_i = 33 mm, 4-5 pancakes



Curved cryostat –
→ bring magnet close to plasma

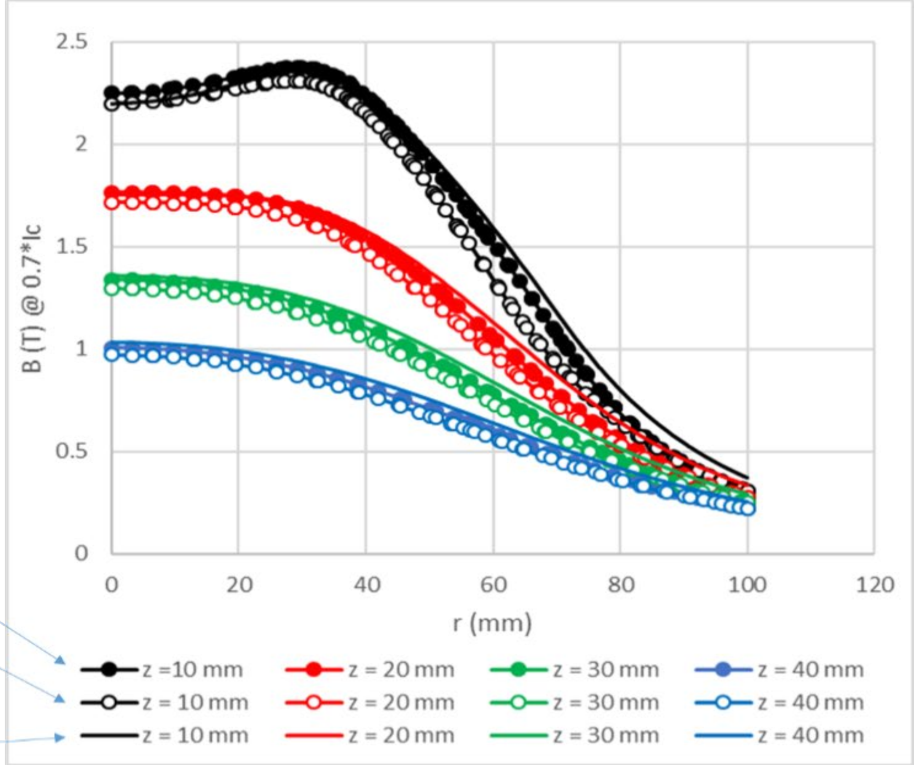




5 equal pancakes:
→ R_i= 33 mm, R_a = 71 mm

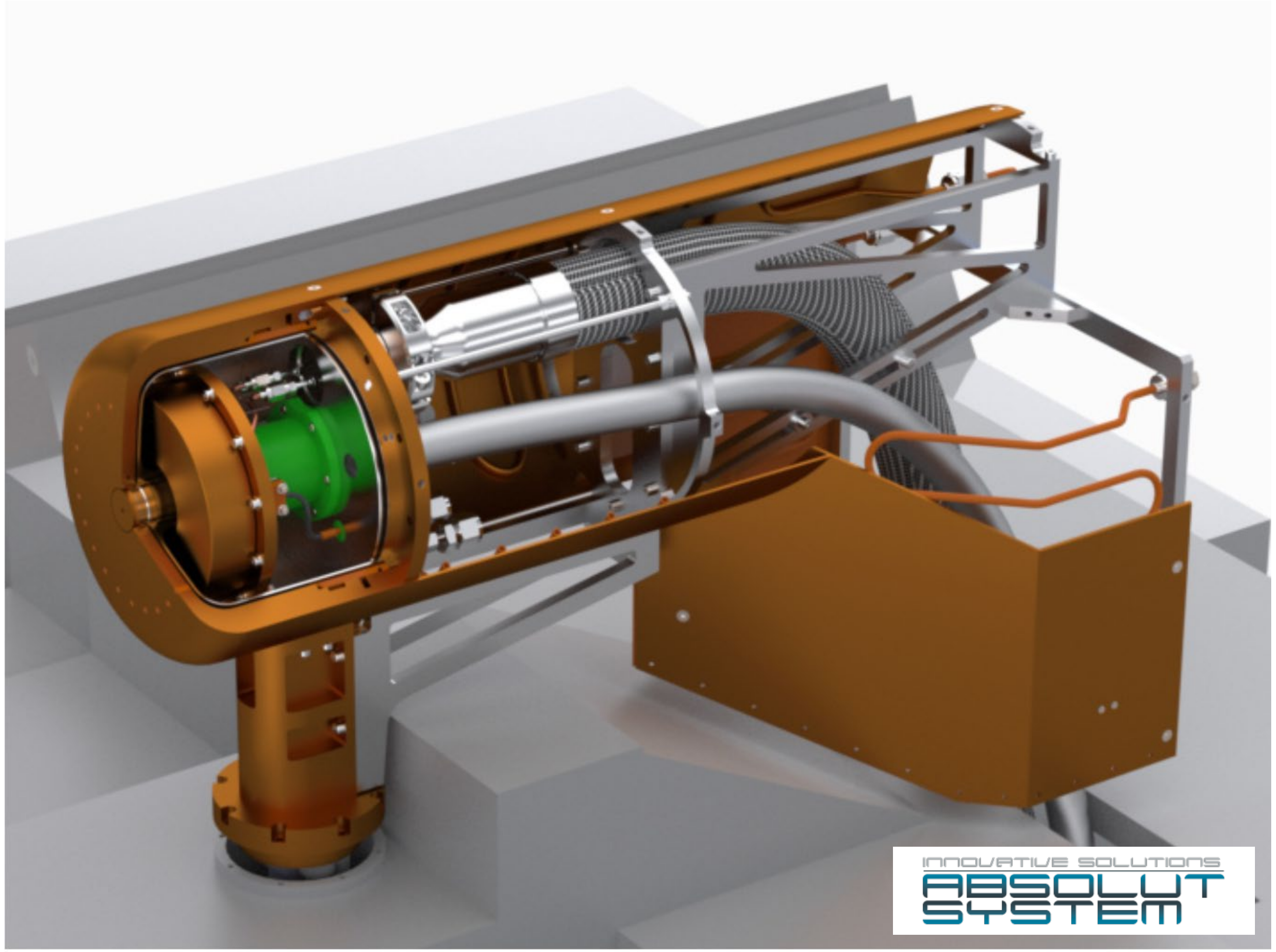
2 small + 3 large pancakes:
→ R_i = 33 mm, $R_{a1,2}$ = 61 mm, $R_{3,4,5}$ = 77 mm

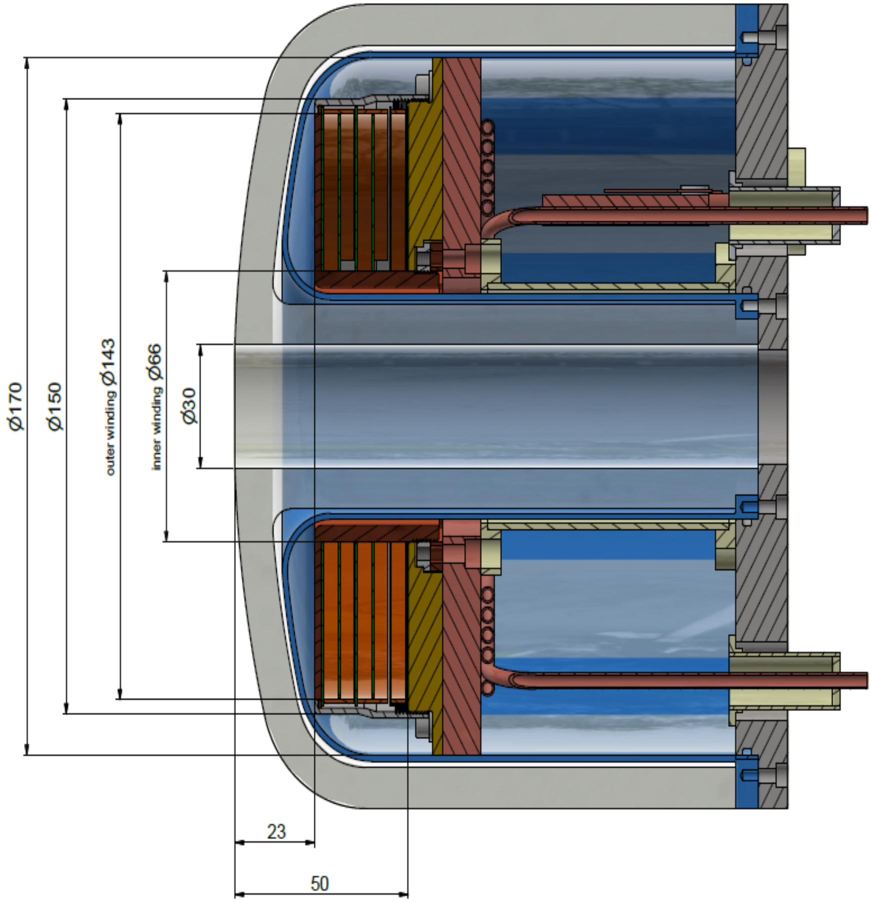
2 small + 2 large pancakes:
→ R_i = 33 mm, $R_{a1,2}$ = 71 mm, $R_{3,4,5}$ = 84 mm



z = axial distance from winding end

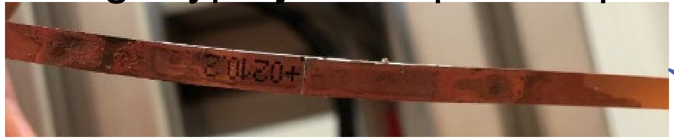
MEESST: Magnet and Cryostat Design





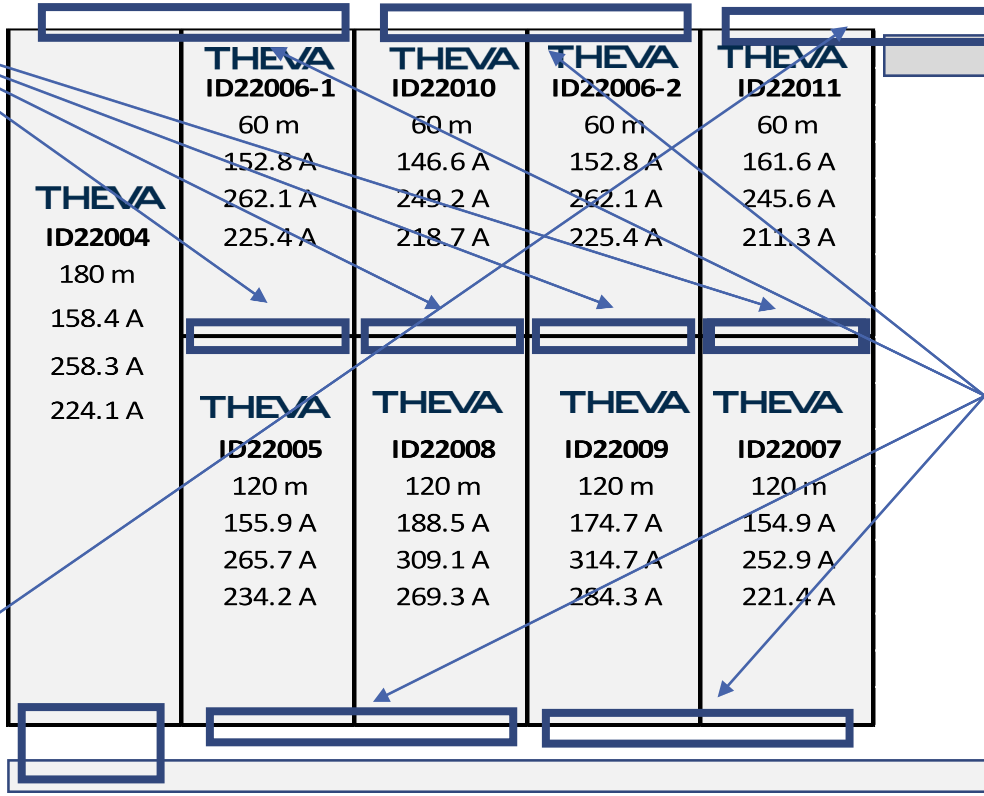
Conductors and Joints

bridge-type joint: tape-to-tape



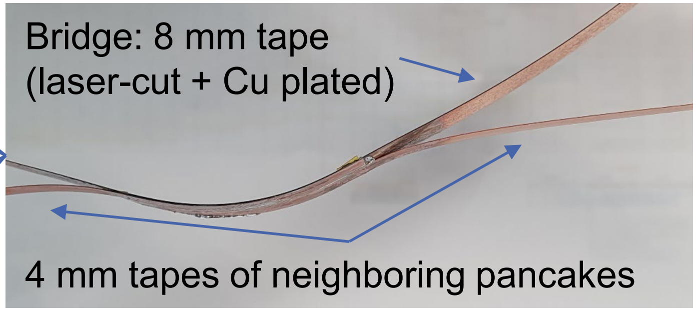
Face-to-face joint: CL → PC

ID
Length
$I_{c,min}$
$I_{c,max}$
$I_{c,avg}$



PC 1	PC 2	PC 3	PC 4	PC 5
THEVA **ID22004** 180 m 158.4 A 258.3 A 224.1 A	THEVA **ID22006-1** 60 m 152.8 A 262.1 A 225.4 A	THEVA **ID22010** 60 m 146.6 A 249.2 A 218.7 A	THEVA **ID22006-2** 60 m 152.8 A 262.1 A 225.4 A	THEVA **ID22011** 60 m 161.6 A 245.6 A 211.3 A
	THEVA **ID22005** 120 m 155.9 A 265.7 A 234.2 A	THEVA **ID22008** 120 m 188.5 A 309.1 A 269.3 A	THEVA **ID22009** 120 m 174.7 A 314.7 A 284.3 A	THEVA **ID22007** 120 m 154.9 A 252.9 A 221.4 A

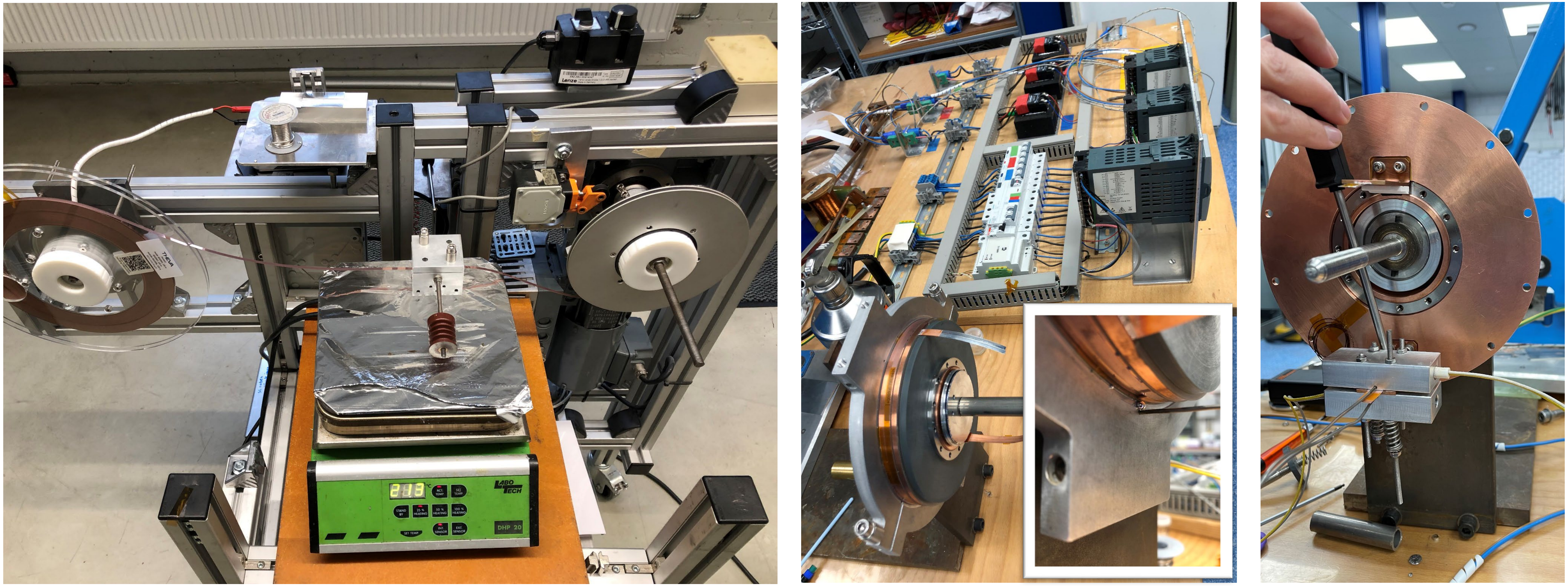
bridge-type joint: PC-to-PC



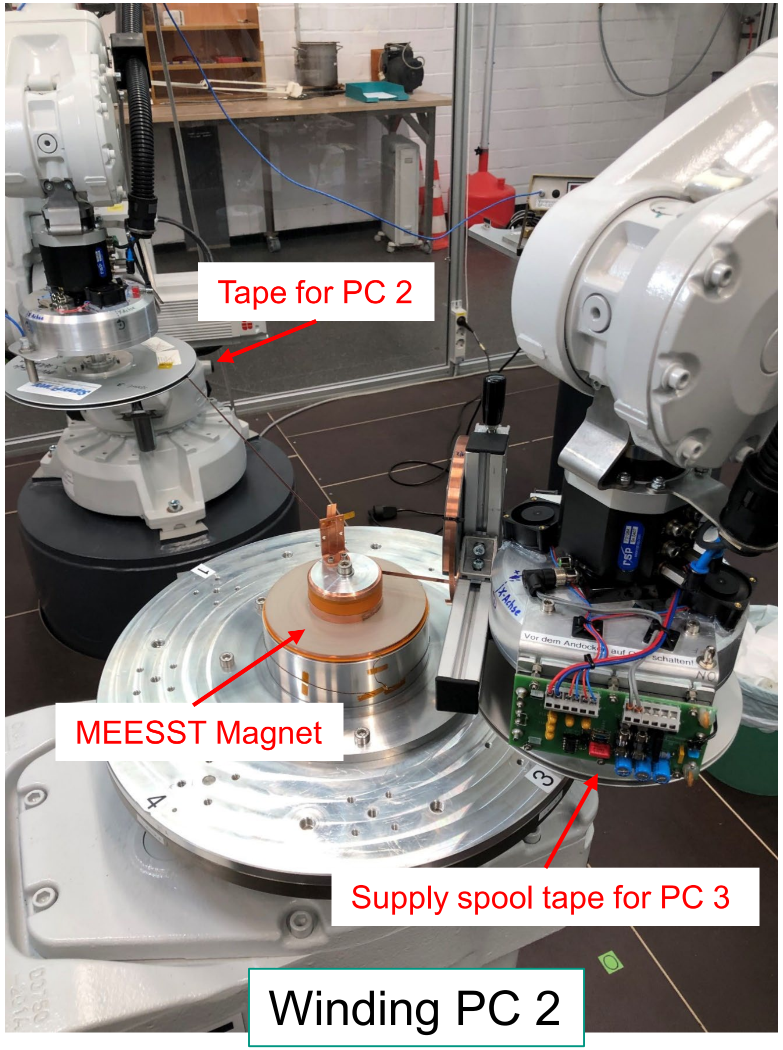
Bridge: 8 mm tape
(laser-cut + Cu plated)

4 mm tapes of neighboring pancakes

Soldering of Joints (InAg3 Solder)

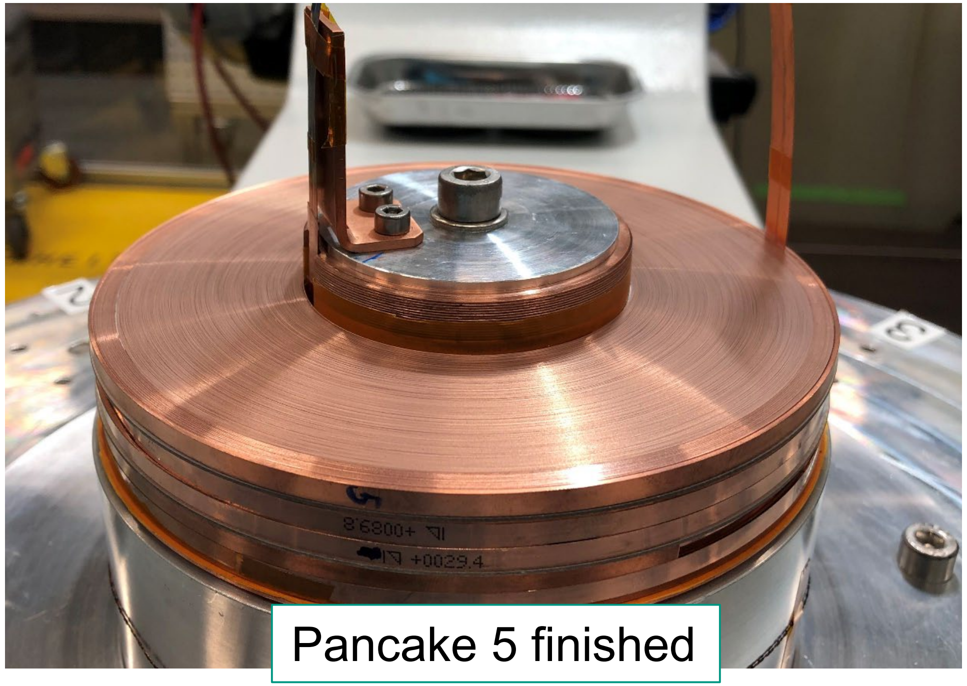


Robotic Magnet Winding @ KIT



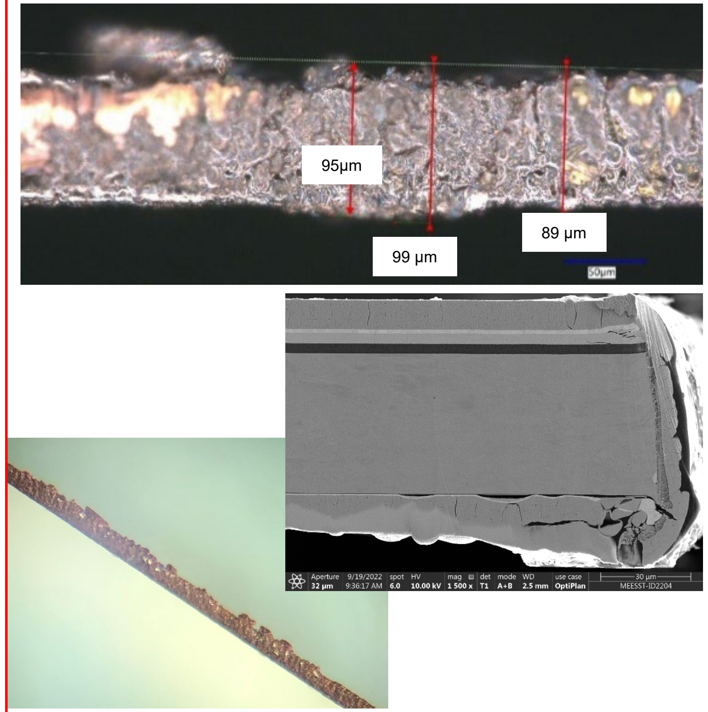
Winding PC 2

- New robotic winding facility @ KIT
- Very precise winding possible
- Easy change of orientation, e.g. during soldering processes
- Future: winding of complicated 3D geometries, e.g. saddle coils, etc.



Pancake 5 finished

MEESST Magnet Windings

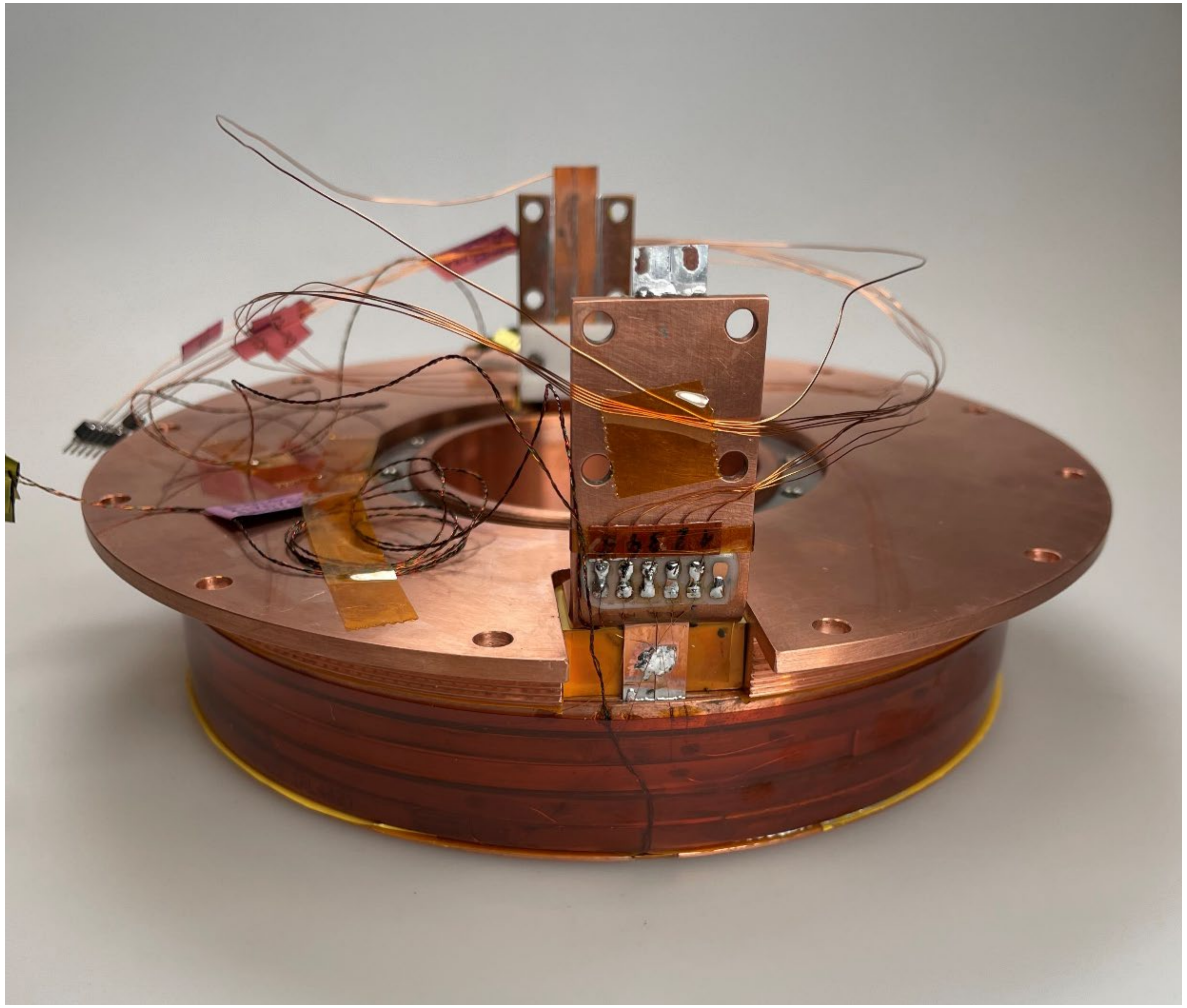


Pancake #1			Pancake #2			Pancake#3			Pancake #4			Pancake #5		
Winding No.	Tape-Position		Winding No.	Tape-Position		Winding No.	Tape-Position		Winding No.	Tape-Position		Winding No.	Tape-Position	
0	378.5	Inside	0	3	Inside	0	119.6	Inside	0	275.8	Inside	0	329.8	Inside
39.8	369.8		23	8		50	108.8		40	266.8		71	313.3	
62	364.8		61	17.8		54	107.6		118	247.4		75	312.2	
100	354.8		110	29.8		68	104.2		261	203.6		107	303.8	
160	337.6		215	62.4		73	103		317	183.6		160	288.6	
215	319.8		296	91.8		101	95.8		328	179.4		228	266.8	
262	302.6		339	109.2		138	85.8		337	175.8		277	249.4	
312	283.6		359	118		159	79.8		381	158.5		320	233	
345	270.4		370	122.8	Joint	216	62.2		387	156.2	Joint	336	226.6	
381	254.4		370	60	Joint	283	39.4		387	121	Joint	352	220	
386	251.2		375	59.4		306	31		404	113.6		372	211.6	
391	249.6	Outside	**391**	52.2	Outside	322	25		428	103.6		376	210.2	Joint
						343	6.6		455	91.6		376	378	Joint
						381.5	1.4	Joint	458	90.2		390	372.2	
						381.5	61.8	Joint	**459**	89.8	Outside	422	357.6	
						405	52					**423**	357.5	Outside
						432	40.4							
						457	29.4	Outside						
R_inner	33.07	mm	R_inner	33.17	mm	R_inner	33.07	mm	R_inner	33.07	mm	R_inner	33.07	mm
R_outer	71.58	mm	R_outer	71.5662	mm	R_outer	71.558	mm	R_outer	71.4965	mm	R_outer	71.59532	mm
th_tape	**0.09850**	**mm**	**th_tape**	**0.09820**	**mm**	**th_tape**	**0.08400**	**mm**	**th_tape**	**0.08350**	**mm**	**th_tape**	**0.09084**	**mm**
Length calculated	128.55	m	Length calculated	128.65	m	Length calculated	150.36	m	Length calculated	150.93	m	Length calculated	139.22	m
Length real	128.9	m	Length real	127.6	m	Length real	150.6	m	Length real	150.8	m	Length real	140.1	m

- Theoretical winding number with 75 µm thick tape: ***n* ~ 511**
- Achievable winding numbers very different for 5 pancakes due to strongly enlarged thickness at cutting edge (tapes from early cutting trials)

➢ **Voids in winding pack**
→ Turn-to-turn heat transfer ???
→ Movement of conductors (Lorentz forces) ???
→ Delamination???

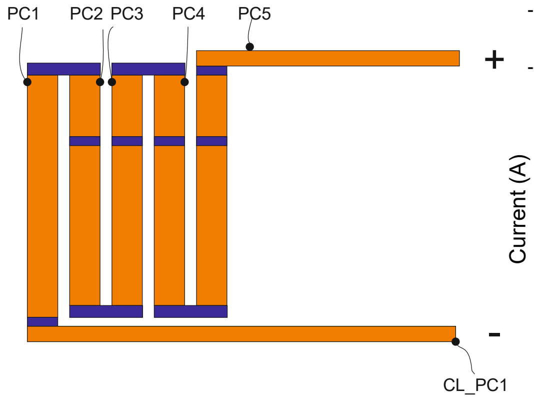
Magnet Test in KITs VATESTA Facility



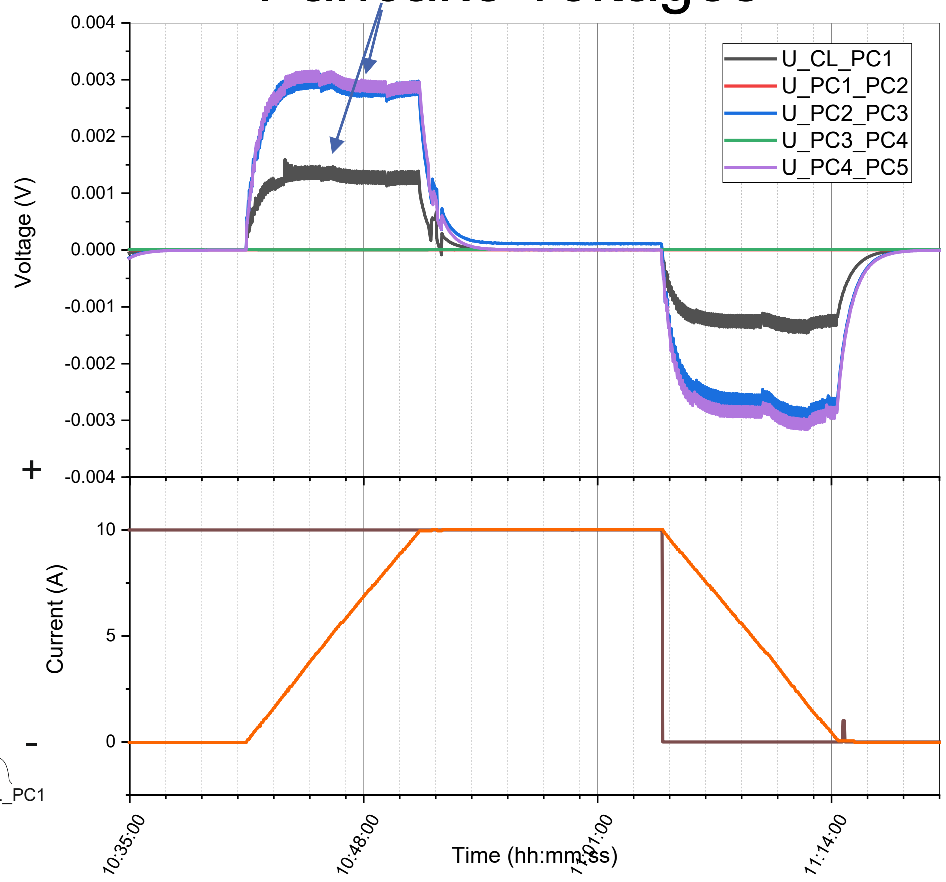
Current Leads

MEESST magnet

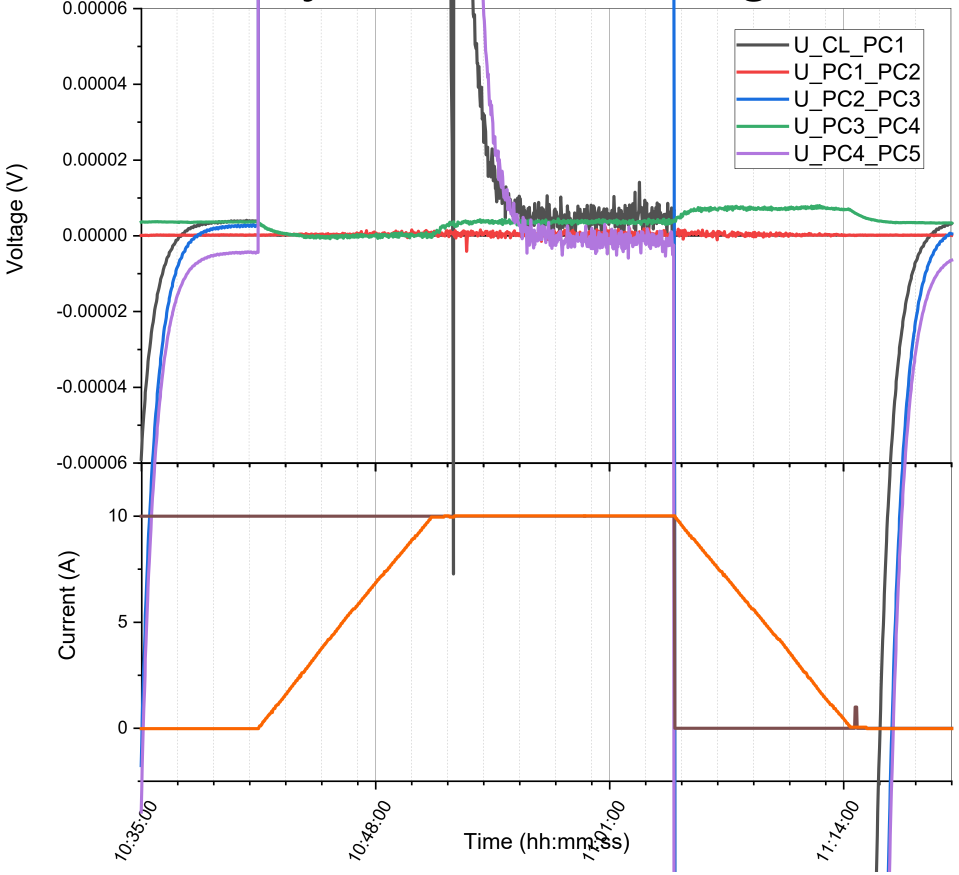
Magnet Test with Low Currents, e.g. 10 A



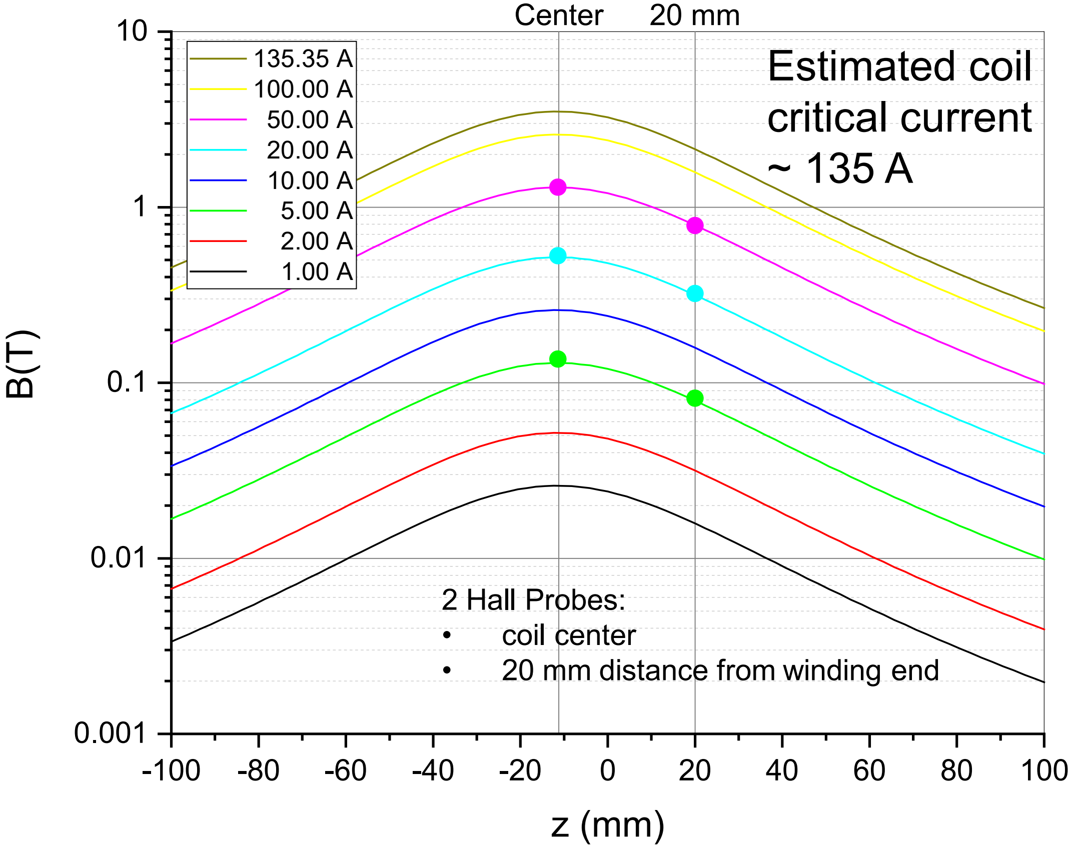
Pancake voltages



Only resistive voltages

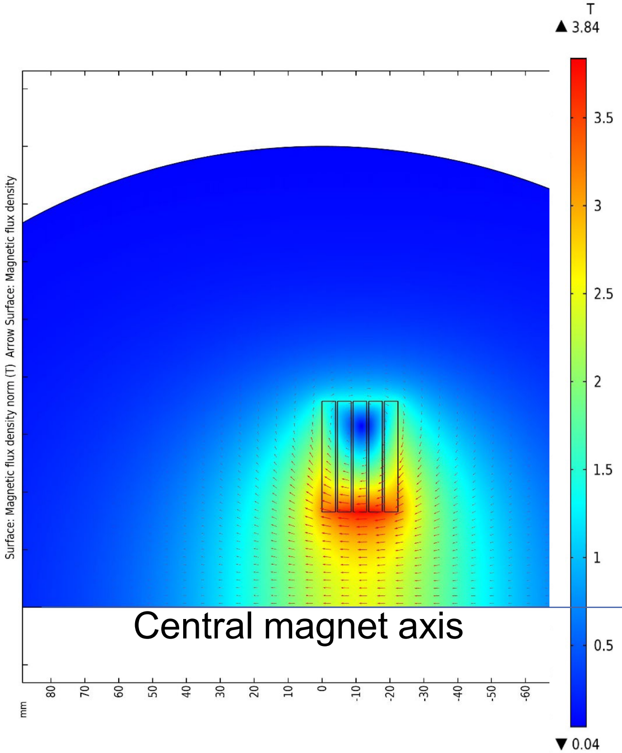


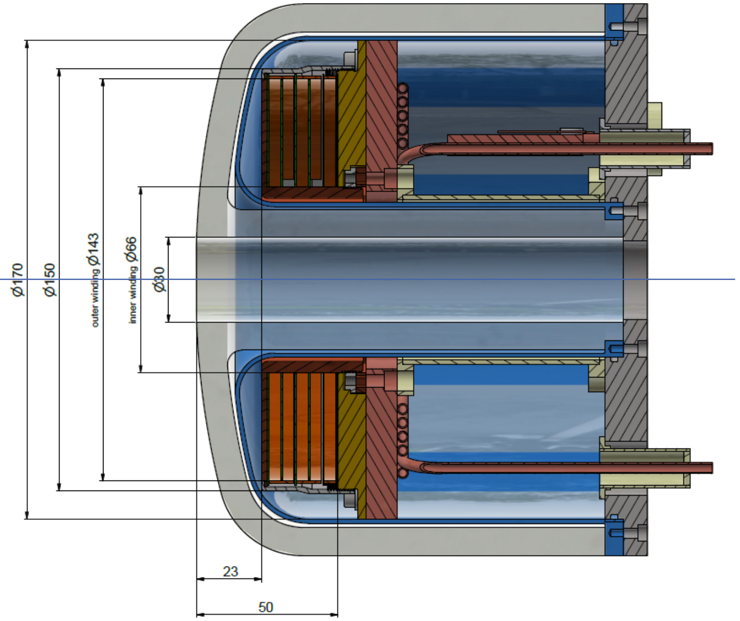
Magnetic Field Simulation and Measurement



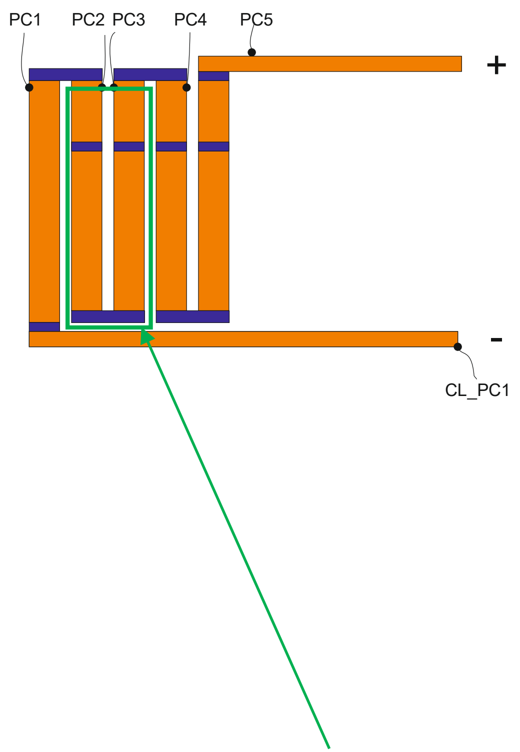
Estimated coil critical current ~ 135 A

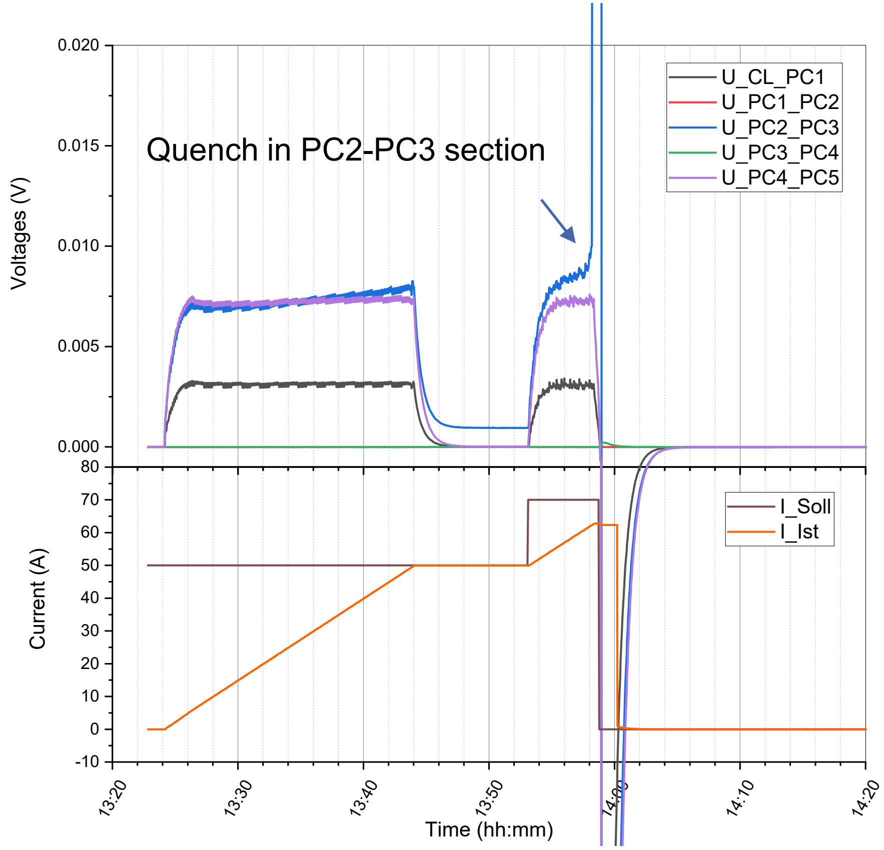
2 Hall Probes:
- coil center
- 20 mm distance from winding end

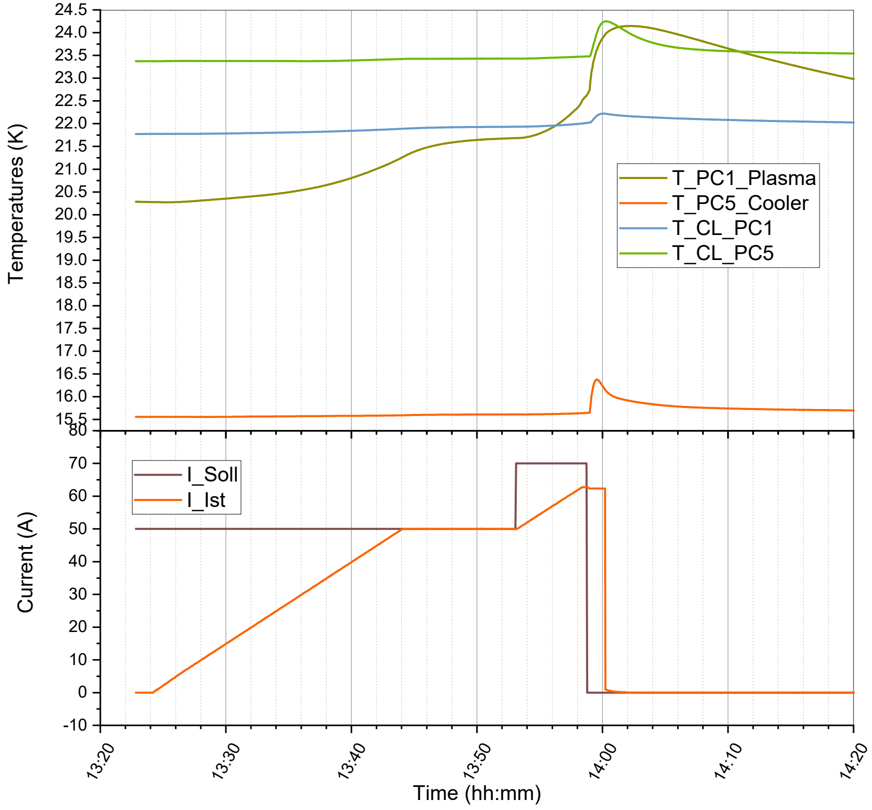




Test at higher currents

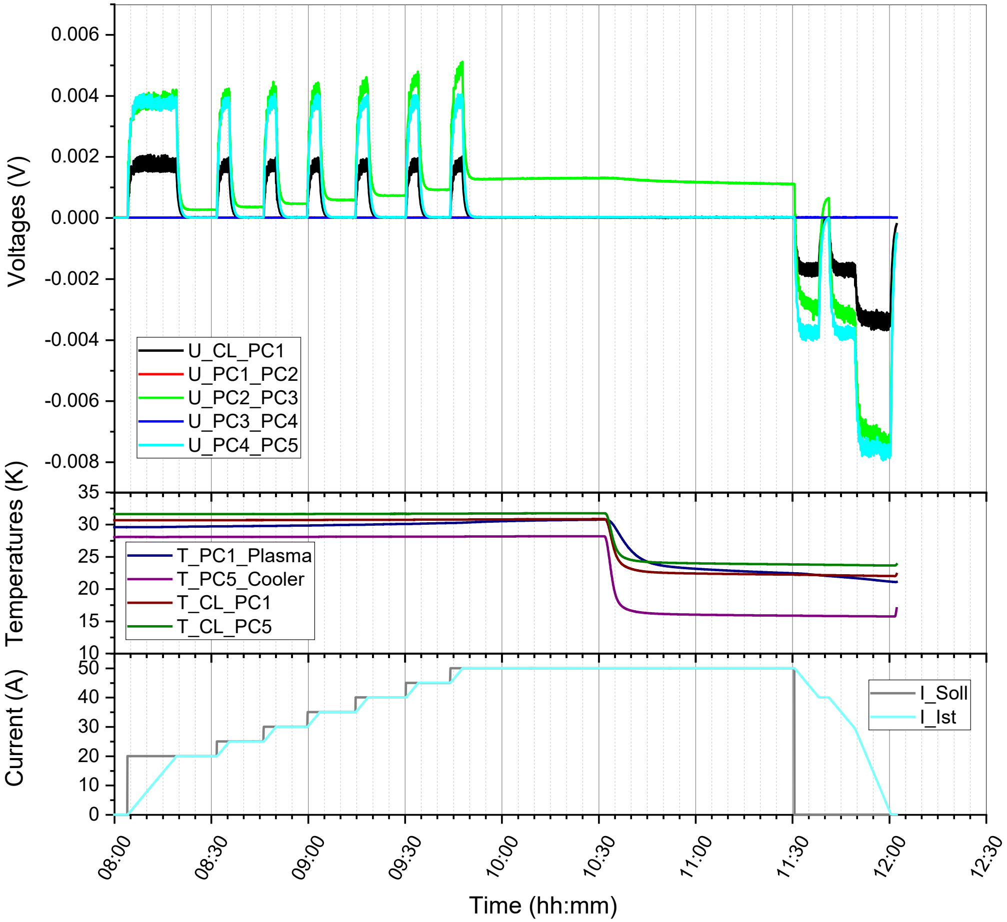


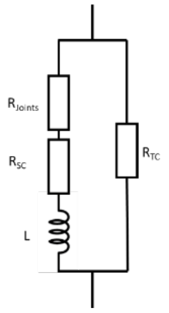


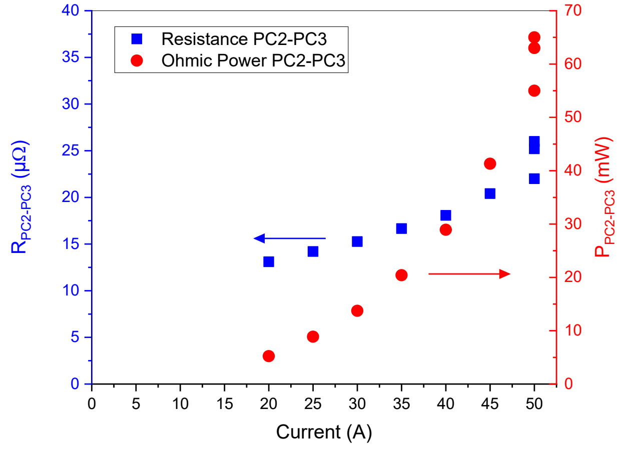


- Quench at ~ 62 A in section PC 2 - PC 3 consisting of
  - 2 Pancakes
  - 3 Joints

Measurement at ~ 30 K







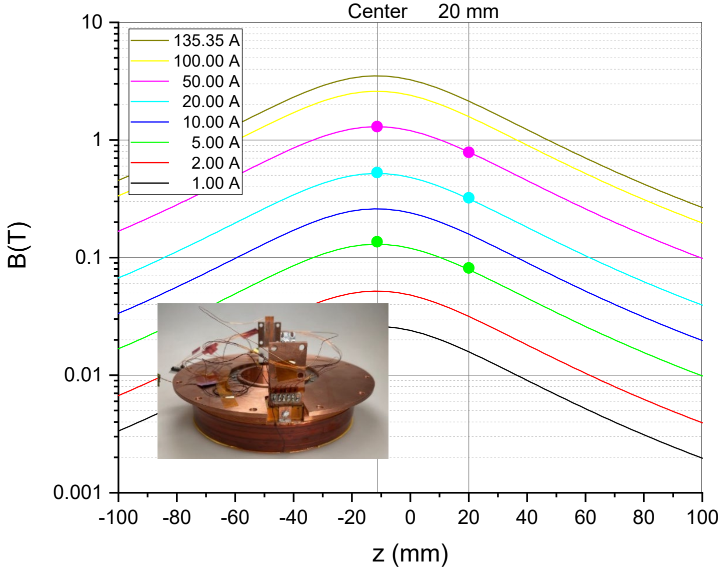
Resistance change with increasing current due to:

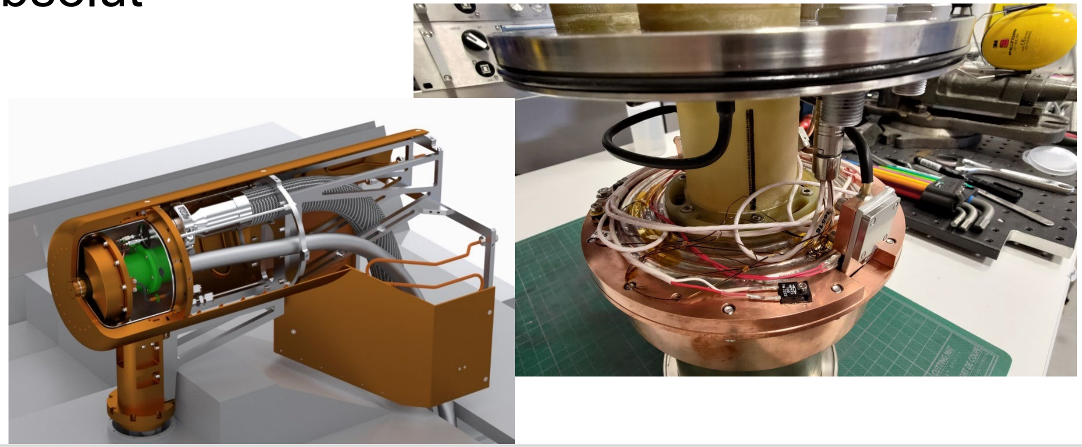
- Nonlinear Superconductor behavior: $E(I) = E_0 \cdot \left(\frac{I}{I_c}\right)^n$
  - Local heating → I_c reduction
- Temperature dependent change of specific resistances

Stable operation at I = 50 A, T ~ 30 K possible for ~ 45 min

Summary and Outlook

- An HTS magnet for application in plasma experiments has been designed and manufactured
- Winding has been performed with robotic winding facility @ KIT
- Thick edges in conductor → Low winding numbers in pancake coils
- Quench of magnet in test at KIT facility – stable operation only up to 50 A
- Fields up to 0.7 T in Plasma should be achievable
- Magnet is currently being installed in the cryostat @ Absolut System (Grenoble)
- Installation of magnet and cryogenic system is scheduled for 07-08/2023
- Plasma experiments in Q3/2023
- Transfer to VKI in Q4/2023





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Further Info:
sonja.schlachter@kit.edu
https://meesst.eu