Magnetic Density Separation Magnet: A SC NbTi magnet demonstrator

CSE European Cryogenic Days
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Outline:

- MDS principle
- Assembly
- First Cooldown
- Protection System
- Sorting tests at Umincorp facility
- Follow up
- Demonstration movie

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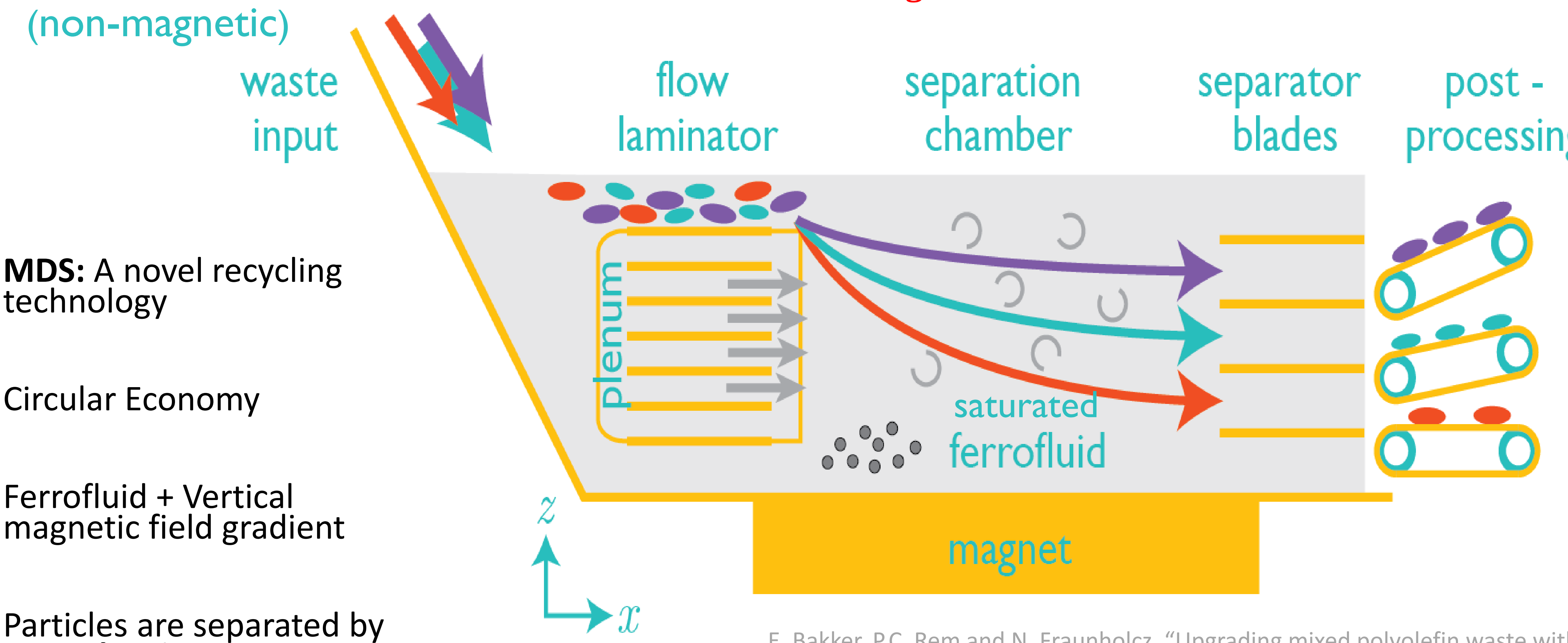
[3] Technical University of Delft
[4] Umincorp Rotterdam

Magnetic Density Separation

$$F_{mag}(z) \propto M_s B(z)$$

- **MDS:** A novel recycling technology
- Circular Economy
- Ferrofluid + Vertical magnetic field gradient
- Particles are separated by **mass density**



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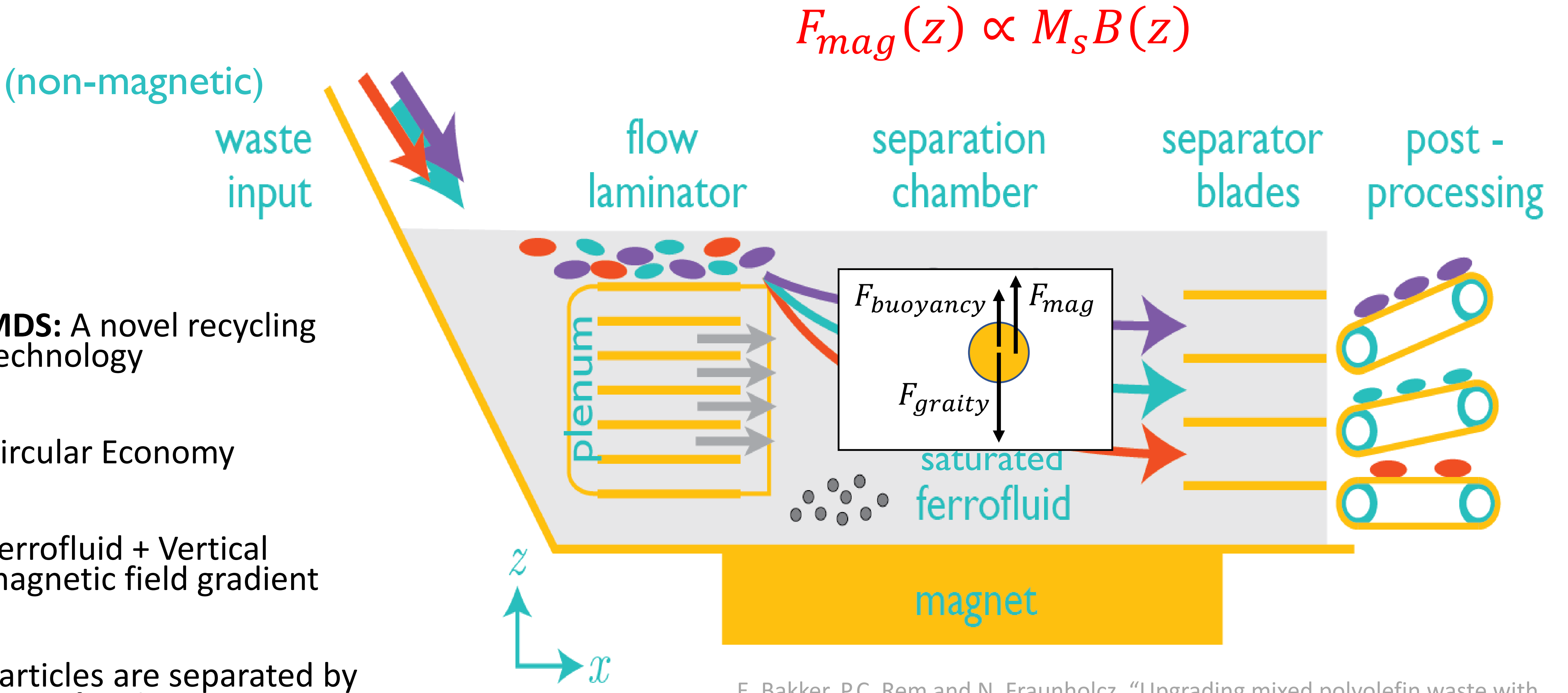

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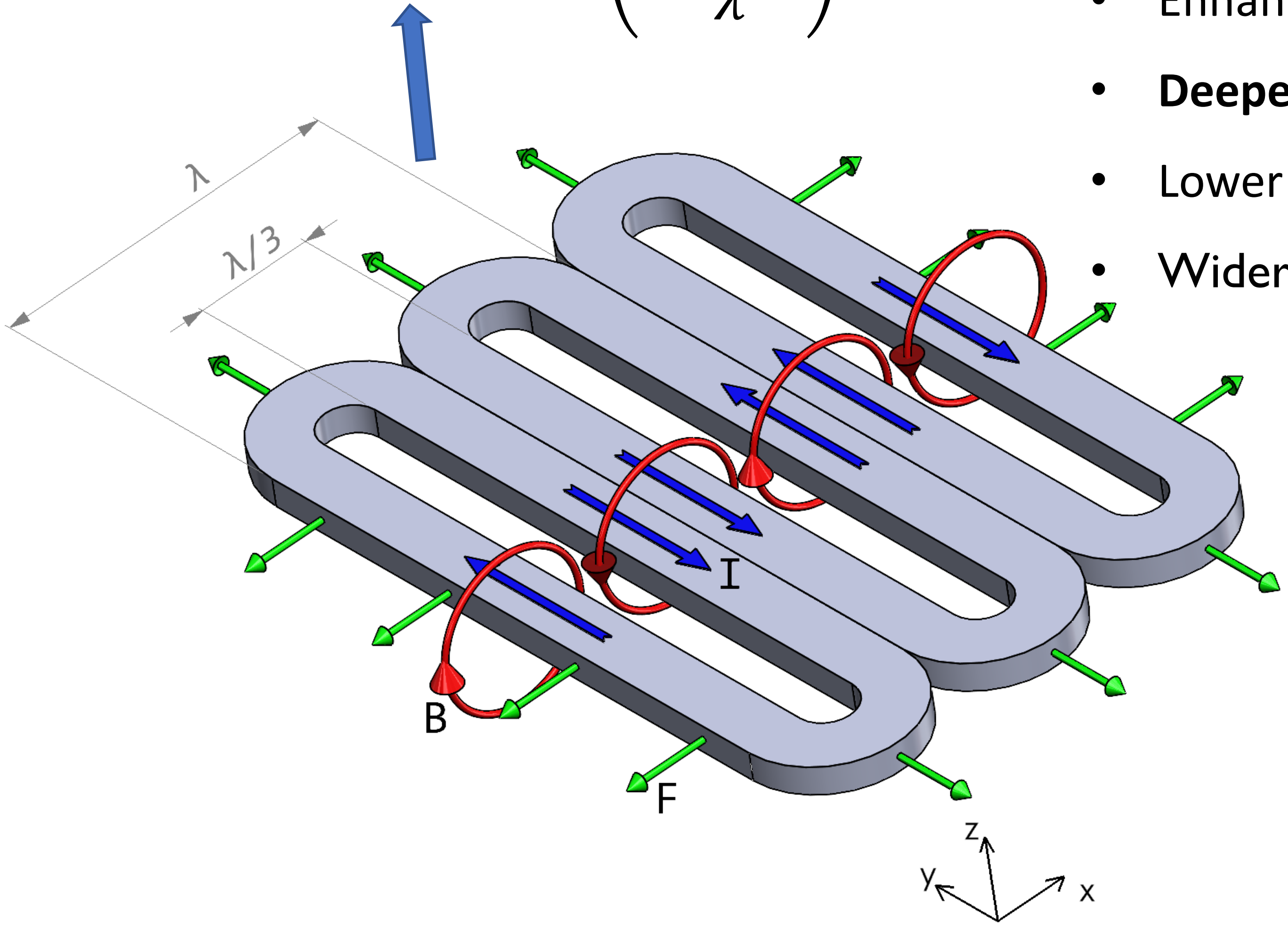
Why use *superconductors* in MDS?

$$|H|(z) \approx H_0 \exp\left(-\frac{2\pi}{\lambda} z\right)$$



Higher magnetic **field strength** (H_0) & **Larger periodicity** (λ):

- Enhanced separation **resolution** (e.g. for similar plastics)
- **Deeper** usable fluid bed (higher throughput)
- Lower OPEX, more **dilute** ferrofluid possible
- Wider density **range** (e.g. electronic waste)

Project goal: demonstrator magnet

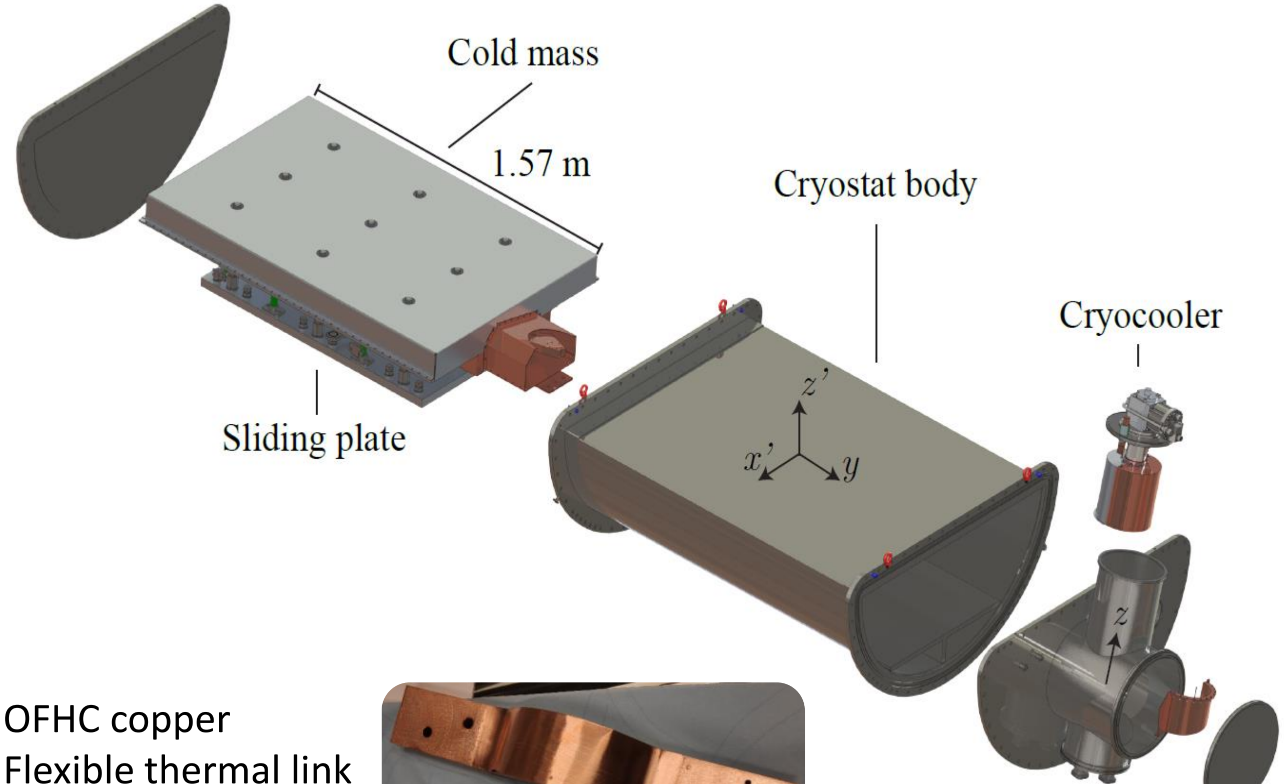
- **3 NbTi/Cu racetrack coils**
- 5 T peak magnetic field
- λ = 600 mm
- Targeted application: electronic waste

J. J. Kosse et al. "Optimum Coil-System Layout for Magnet-Driven Superconducting Magnetic Density Separation", IEEE Transactions on Magnetics (2021)
J. J. Kosse et al. "Fundamental Electromagnetic Configuration for Generating One-Directional Magnetic Field Gradients", IEEE Transactions on Magnetics (2021)
J. J. Kosse et al. "Mechanical design of a superconducting demonstrator for magnetic density separation", SuST (2021)

How do we cool the magnet?

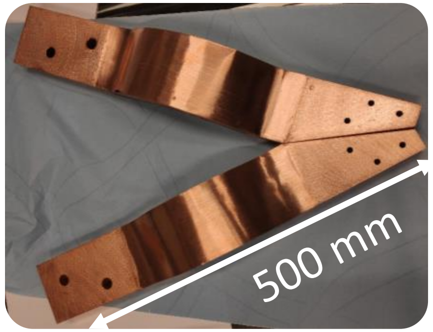
- NbTi has a critical temperature of 9 K
  - But I_{op} **decreases steeply with temperature**
- Design temperature of 4.5 K
  - LHe bath cooling is ideal but…not really!
    - Brings magnet further for cryostat surface
- Conduction cooling – Interesting challenge
  - Large surface area – Radiation
  - Heavy cold mass + coil-fluid attraction – Conduction
  - Minimize thermal gradients from magnet to cold-finger is difficult
- Magnet plus cryostat top plate on a 12° angle
  - Cryocooler is vertical

Magnet on a 12° angle
Cooler vertical for efficiency



OFHC copper
Flexible thermal link

Assembled from 300
0.2 mm thick foils

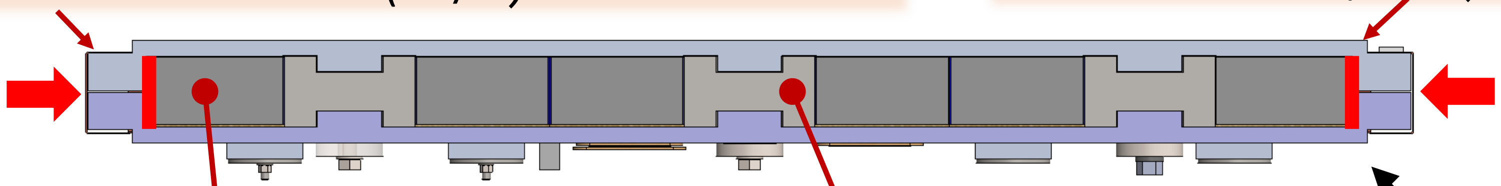


Pre-Stress by thermal contraction.

Pre-Stress guaranteed by differences in thermal contraction. Allow no release of the coils from the yokes

Cassette: Aluminium $(\Delta L/L)_{293\rightarrow 4.2K}$ -0.41%

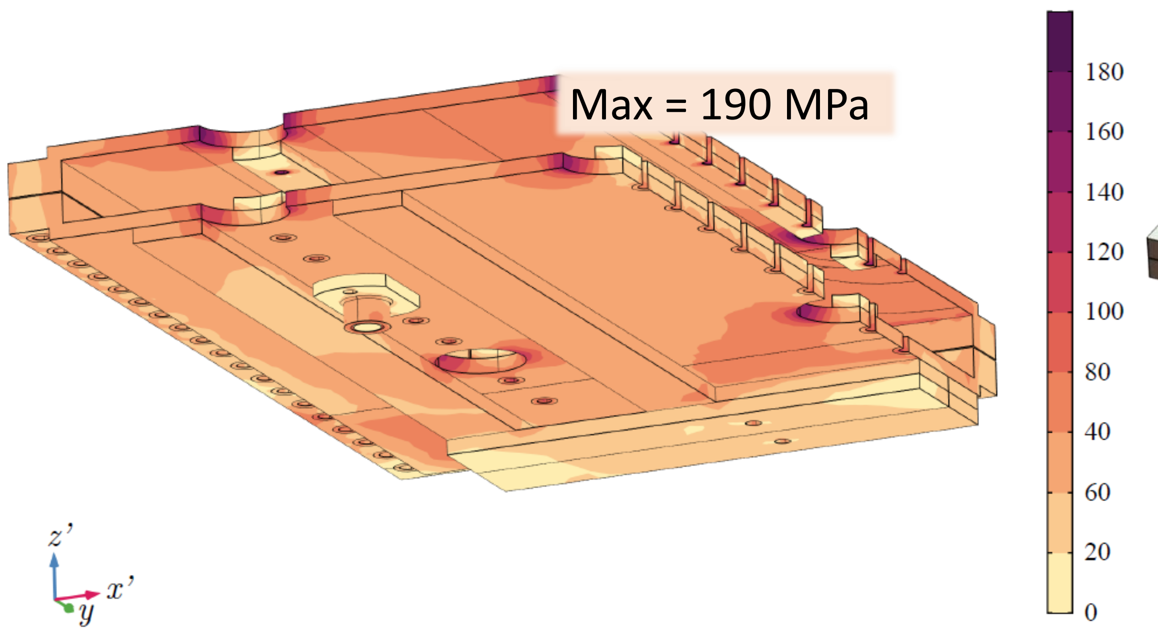
Shims: Ti-6Al-4V $(\Delta L/L)$ -0.17%

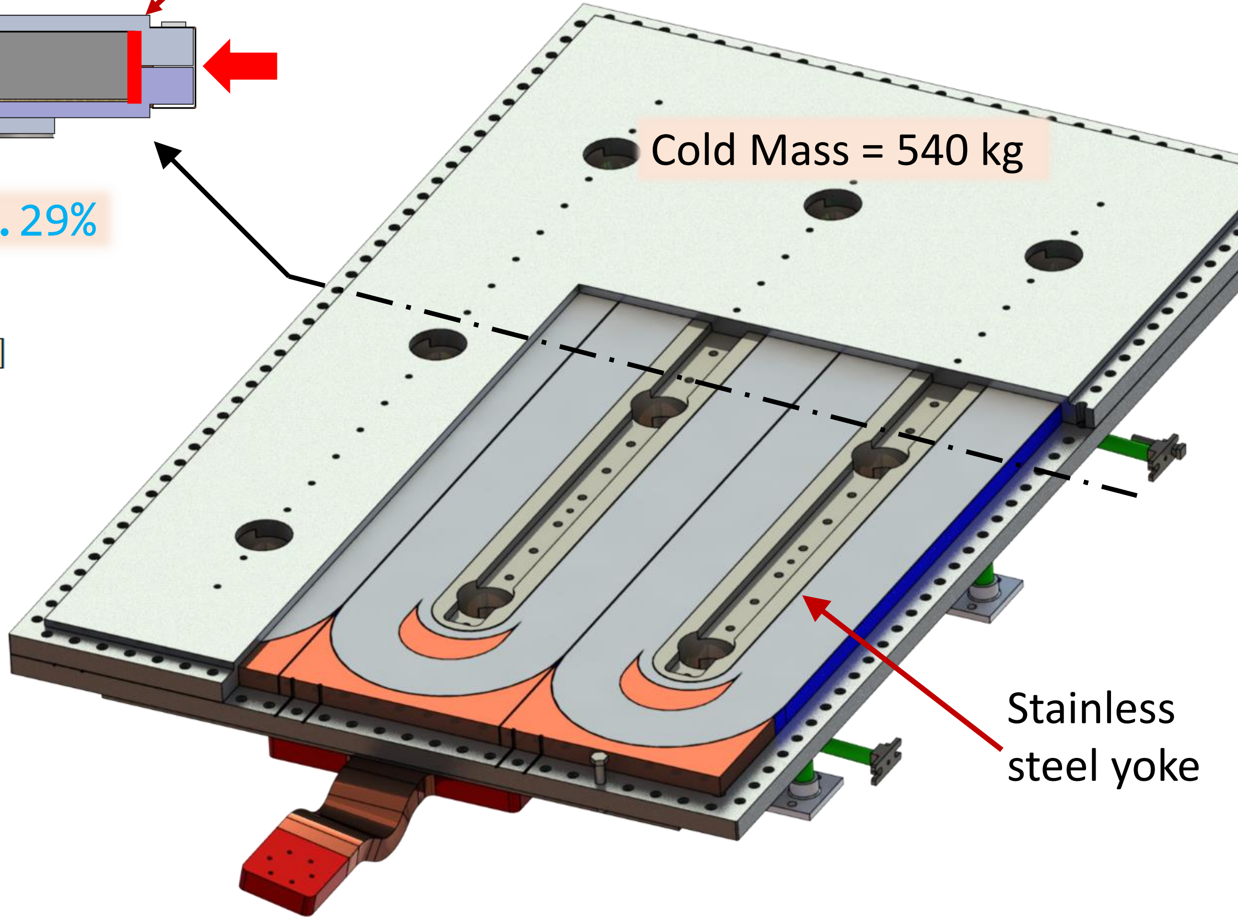


Winding Pack $(\Delta L/L)$ -0.35%

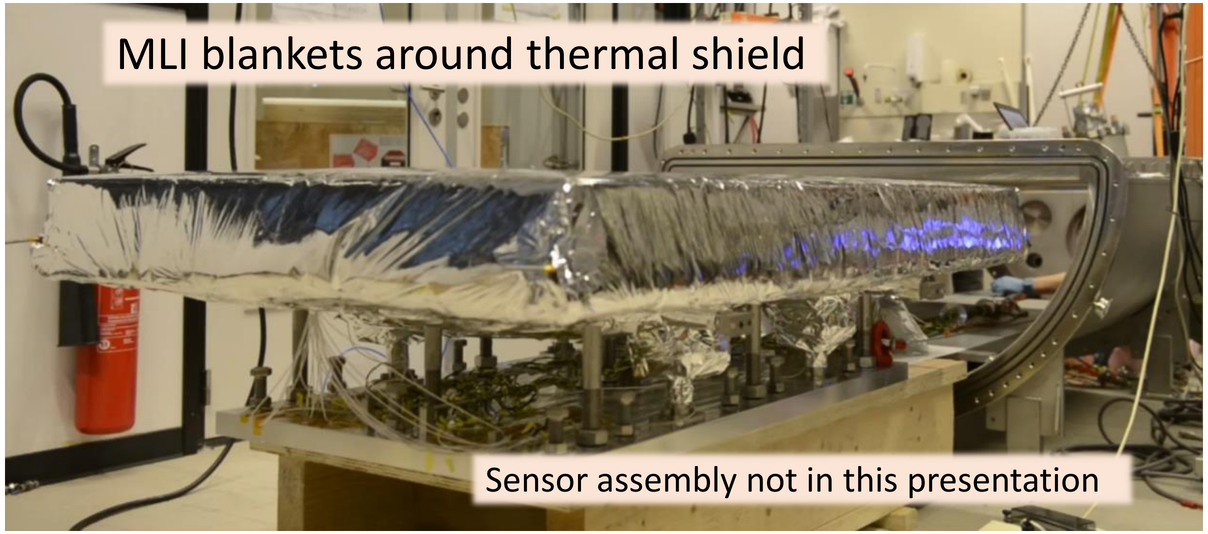
SS-Yoke $(\Delta L/L)$ -0.29%

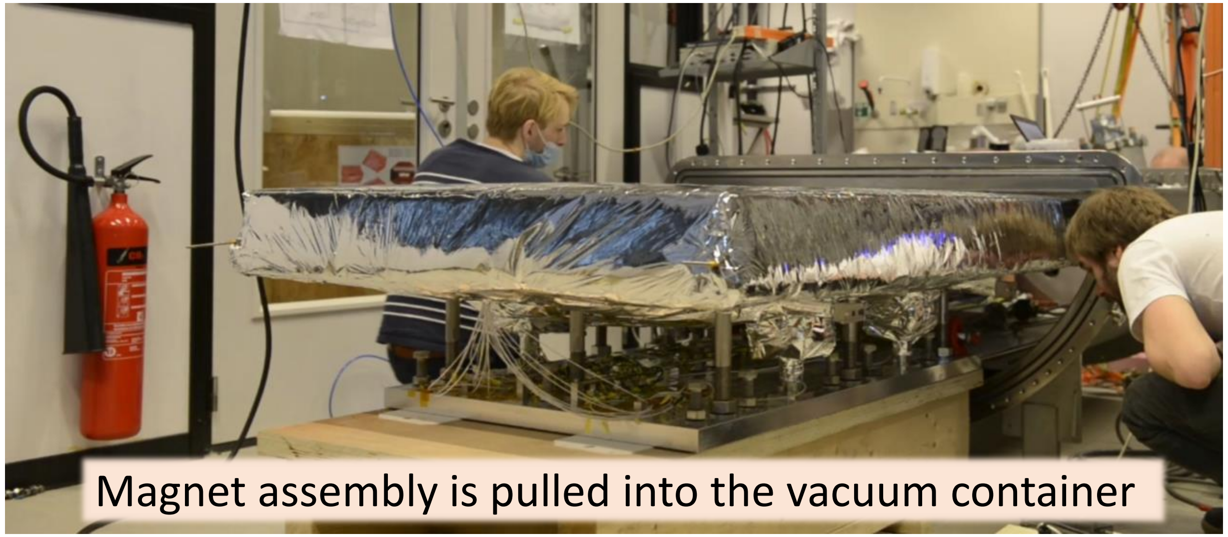
Magnet cold and energized





Teamwork: Assembling the system.





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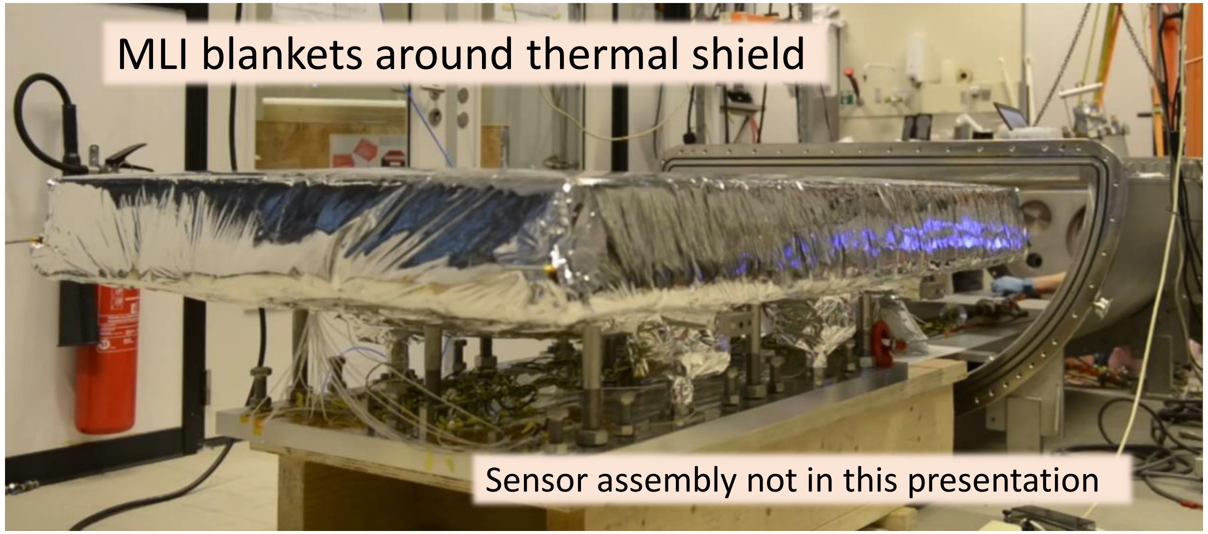
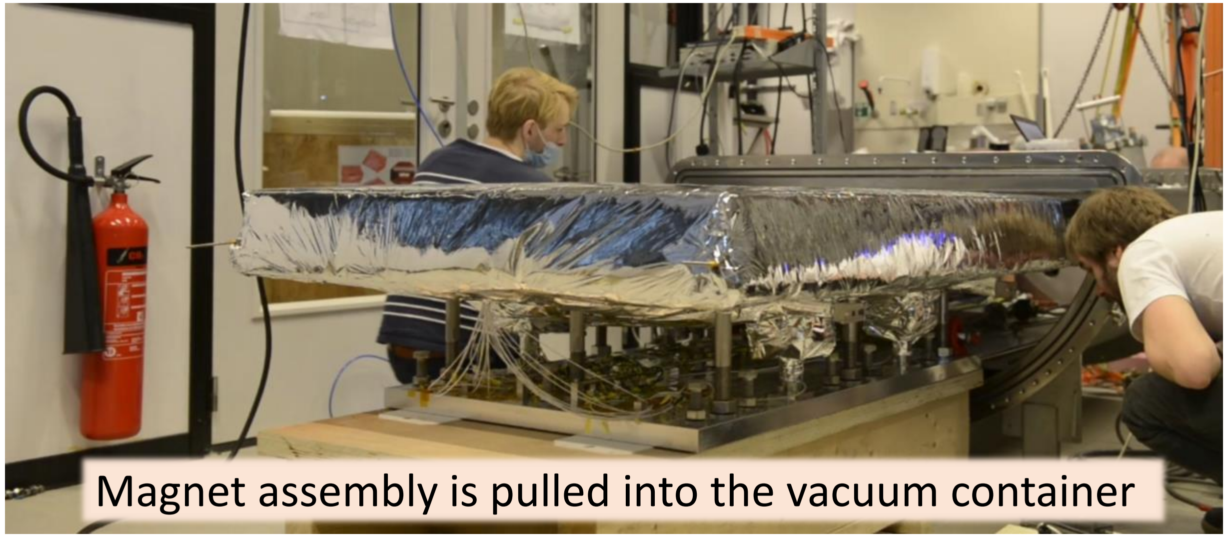
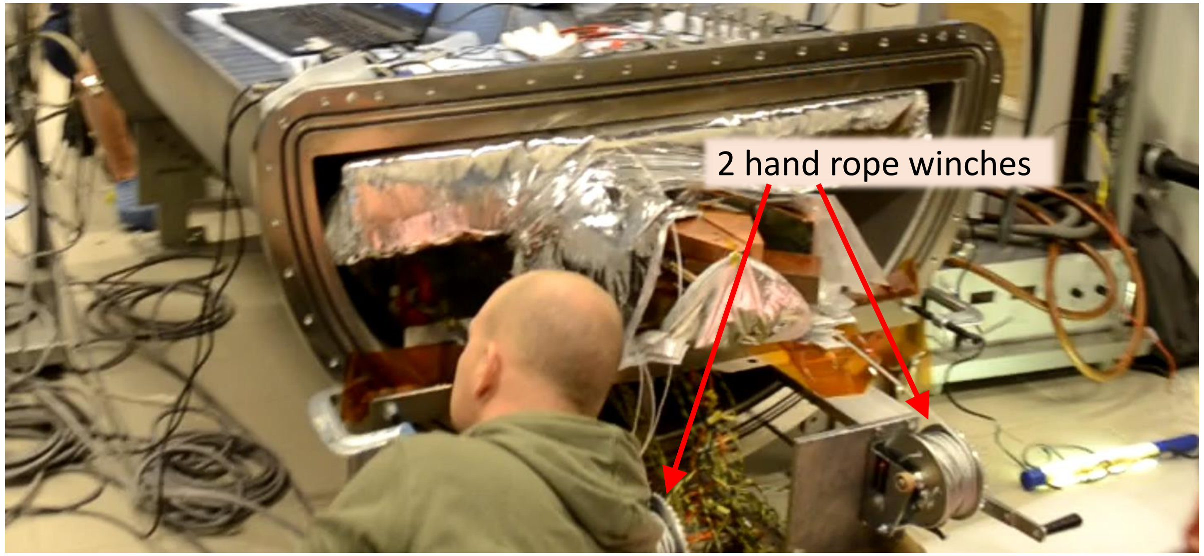
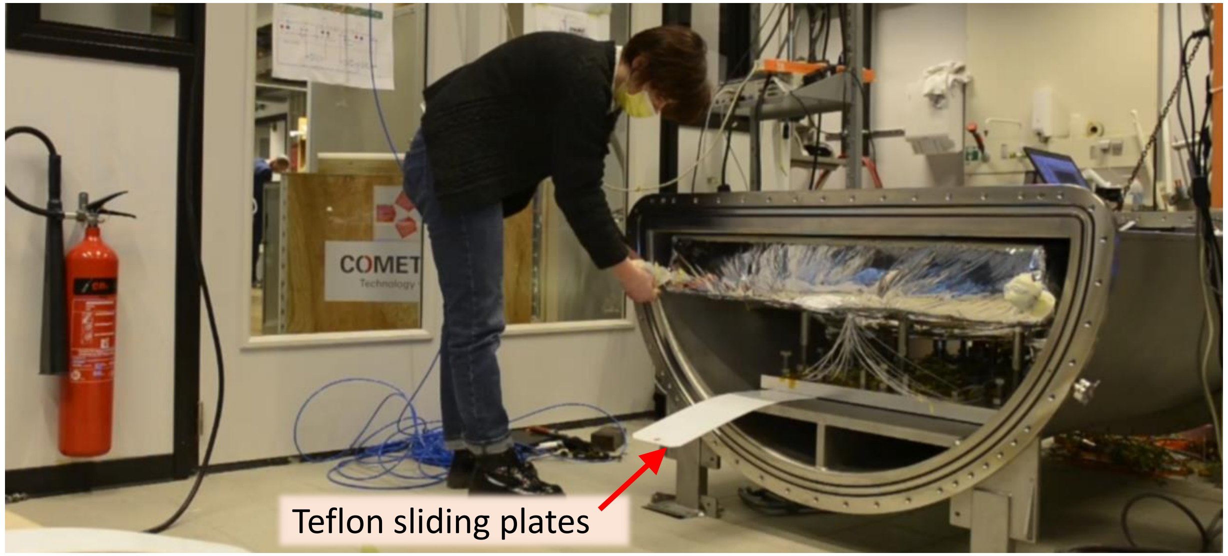




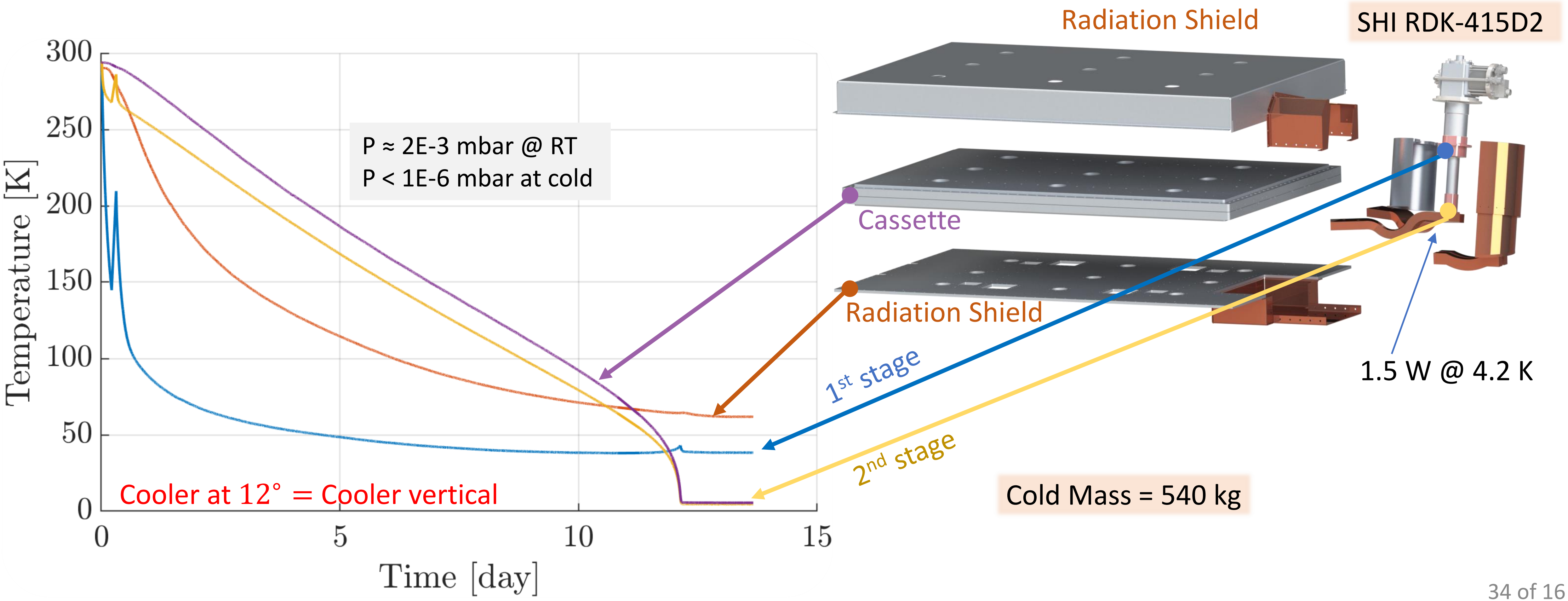




First Cooldown

As modelled, cool-down time was about 13 days.
But → Magnet temperature = 5.5K
For a temperature margin of 2.0K → 4.5K is needed
→ 1 K left to operate at design current of 300A

Extensive thermal characterisation reveals a thermal short through MLI seams.
Repair was deemed possible but time-consuming and likely not necessary.



Design current of 300A reached without training

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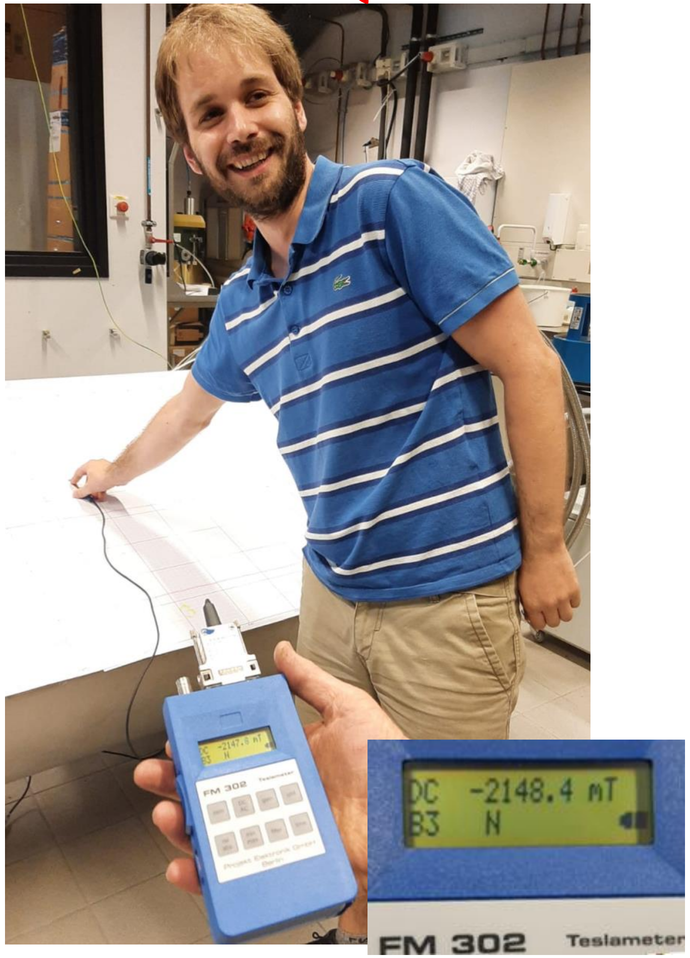
18 May 2022 → **2.15T**

Design current reached

→ 300A ←

NO TRAINING QUENCHES



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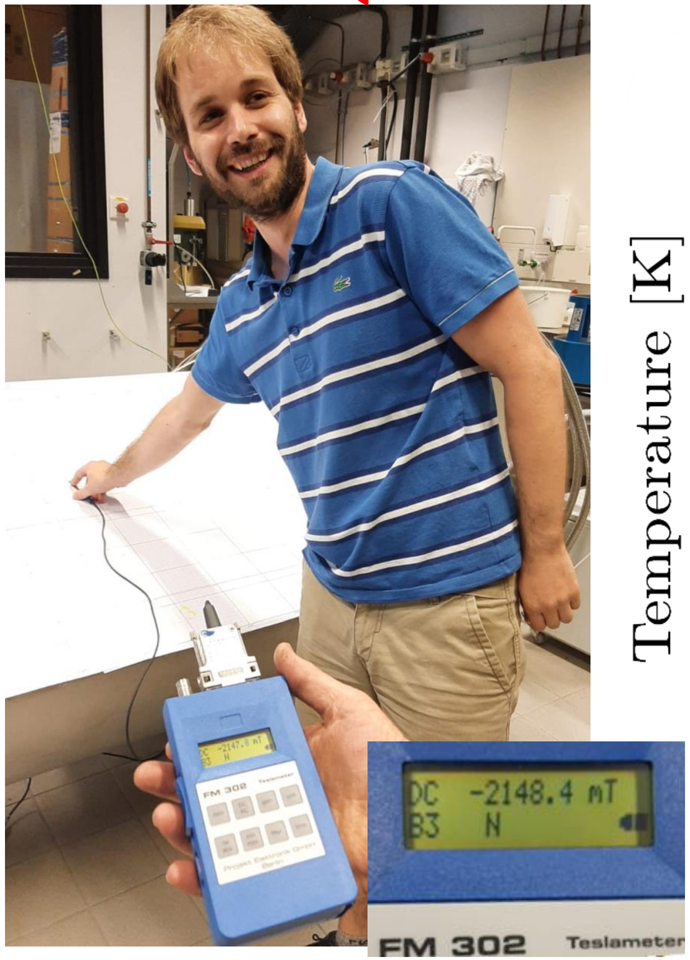
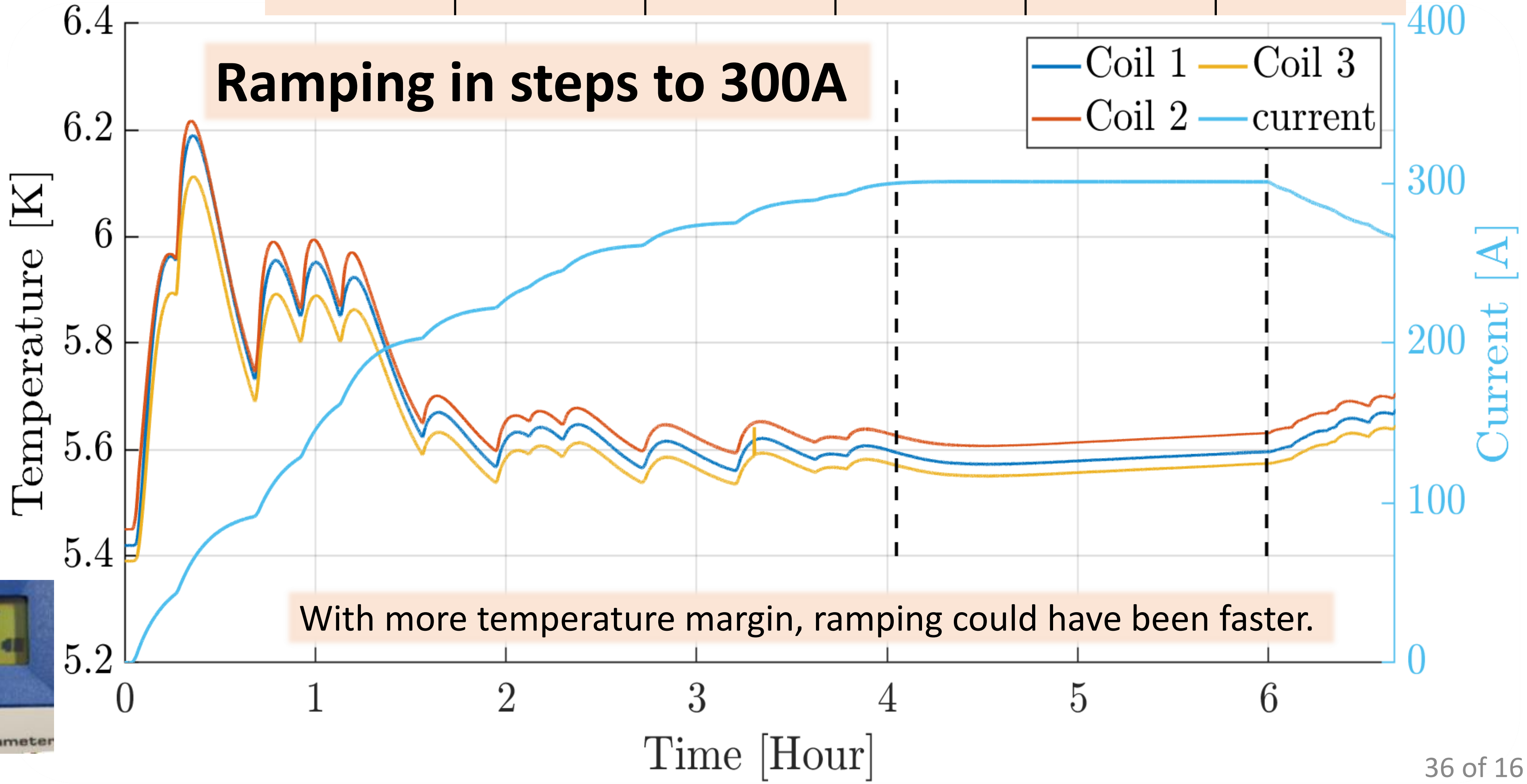
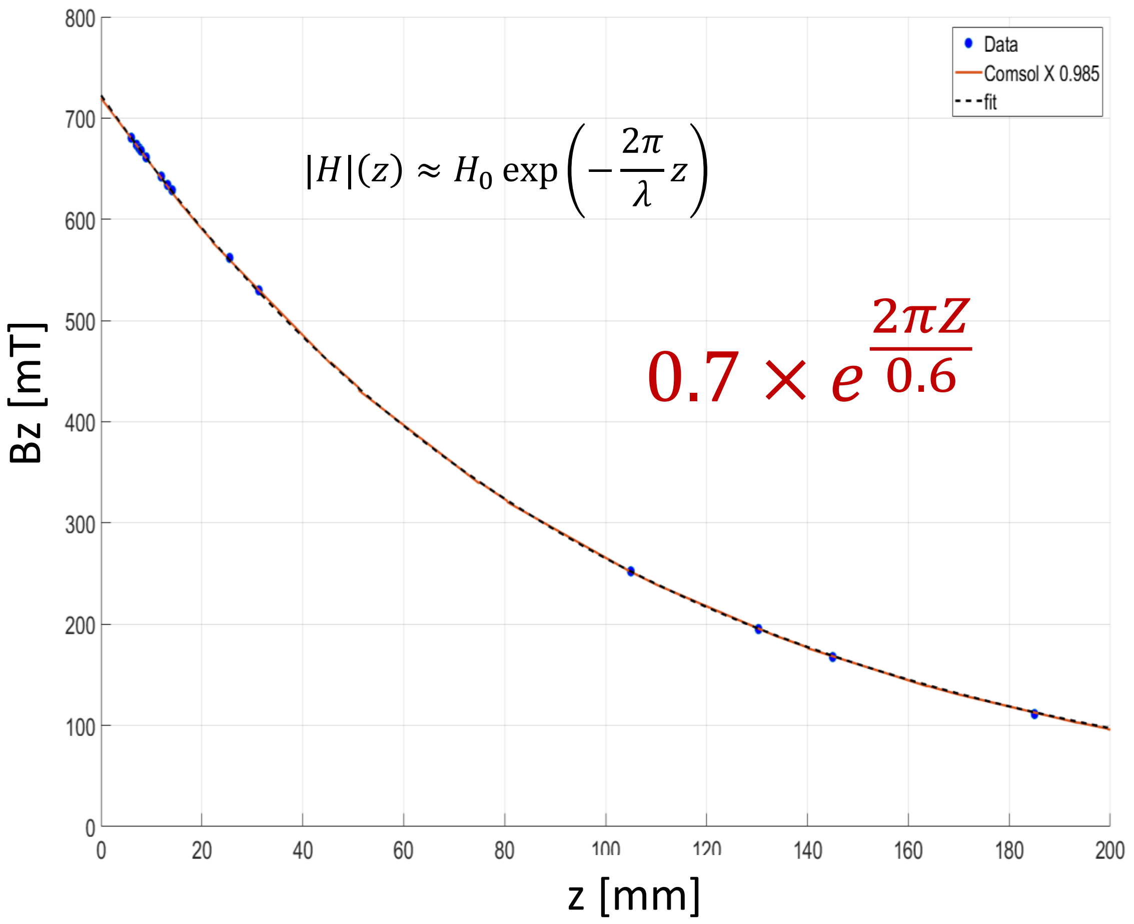


NbTi superconductor properties at operation point					
I	I_c	I/I_c	B_{peak}	T_{op}	T_{cs}
300 A	752 A	0.4	5.4 T	5.6 K	6.3 K



Magnetic Field Measurements

Measured Bz (z) exponential decay length matches model



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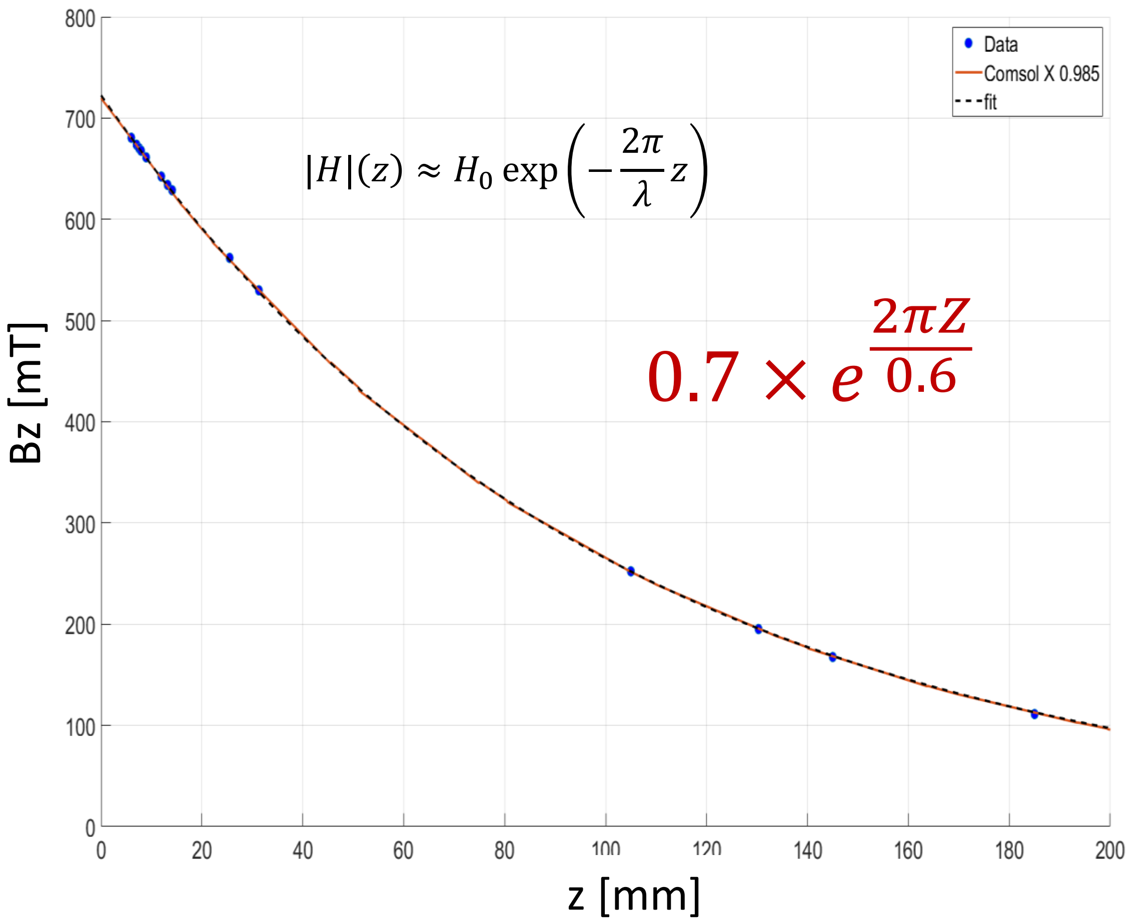
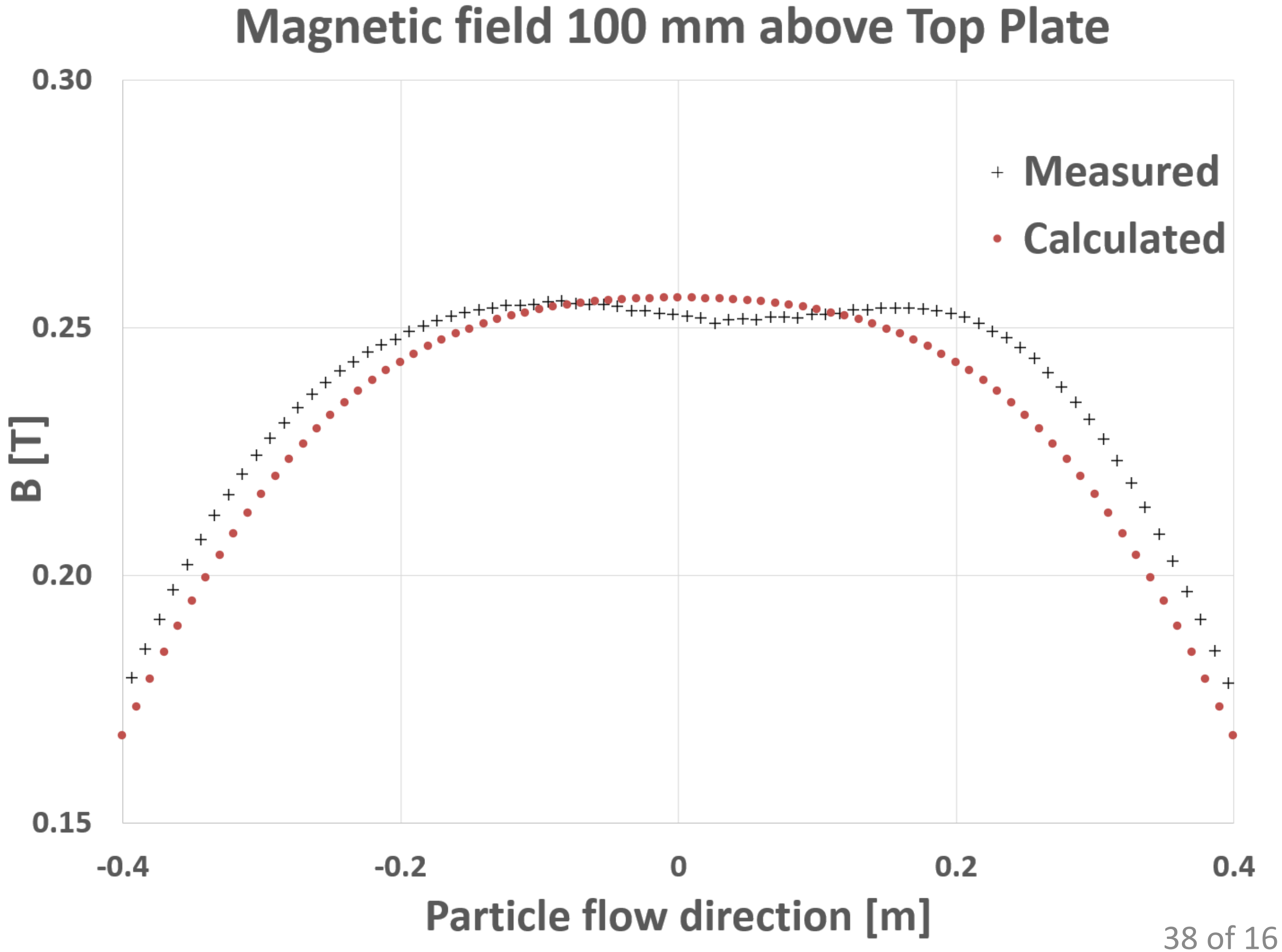


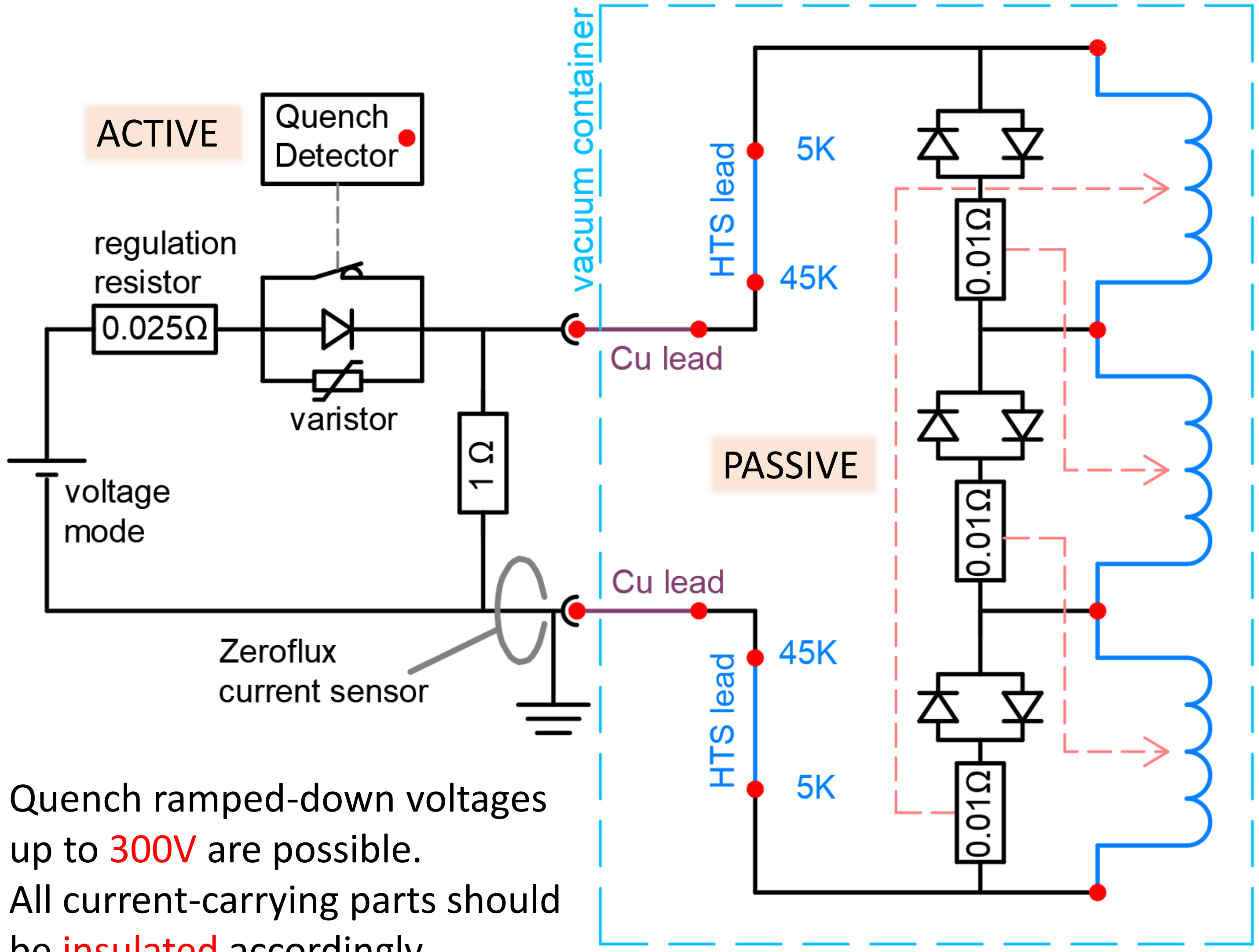
Magnetic Field magnitude is within 1.5% of the expected values. Apparently the magnet is 1.4 mm further from the top plate than designed. (Note: test current here is 100 A, 300 A is maximum)



Passive/Active Coil Protection System

The **Stored Energy in the coils** at **300A** = ½ · L · I² = ½ · 16,4 ·300² = 740 kJ

→F1 racing car (800kg) at a speed of 160 km/h !



Quench ramped-down voltages up to 300V are possible.
All current-carrying parts should be insulated accordingly.

Passive/Active Coil Protection System

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The **Stored Energy in the coils** at **300A** = $\frac{1}{2} \cdot L \cdot I^2 = \frac{1}{2} \cdot 16{,}4 \cdot 300^2 = 740$ kJ

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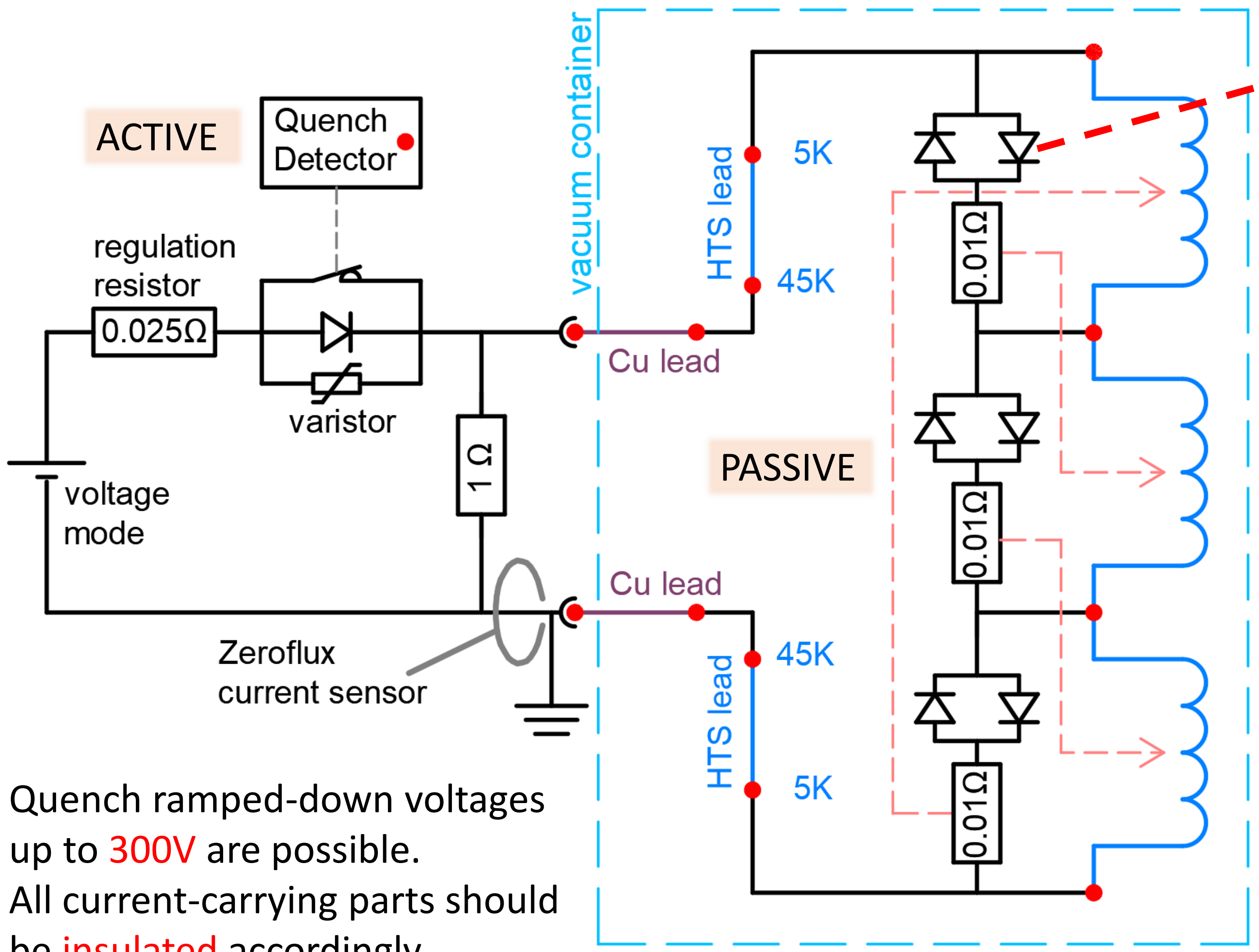
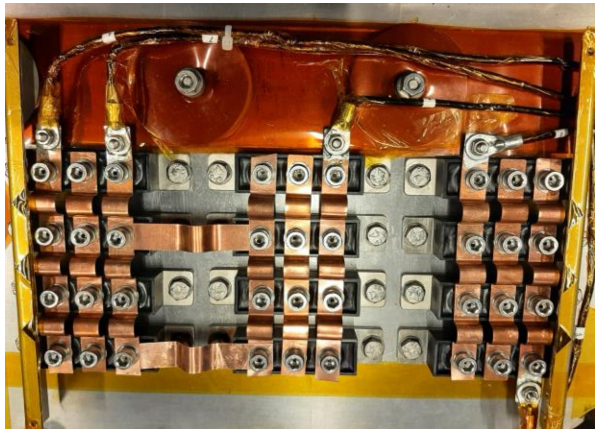
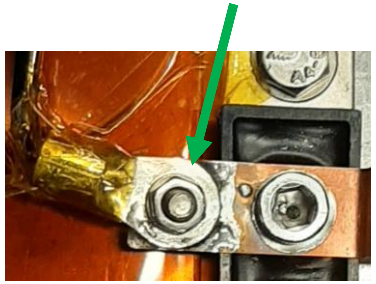




Schottky Diodes
- Anti-parallel
- Redundant
- Bolted on cassette
- Soldered & bolted



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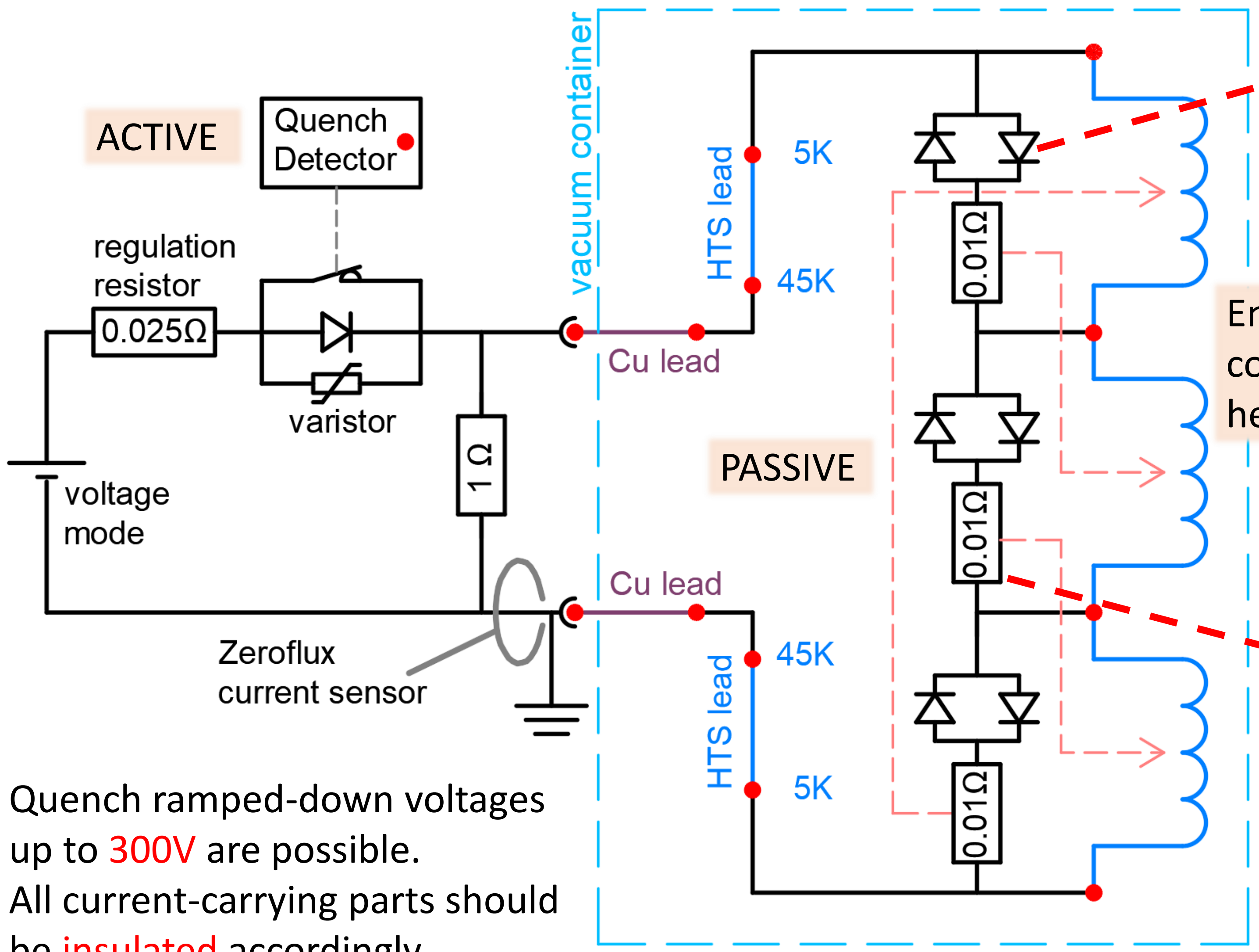

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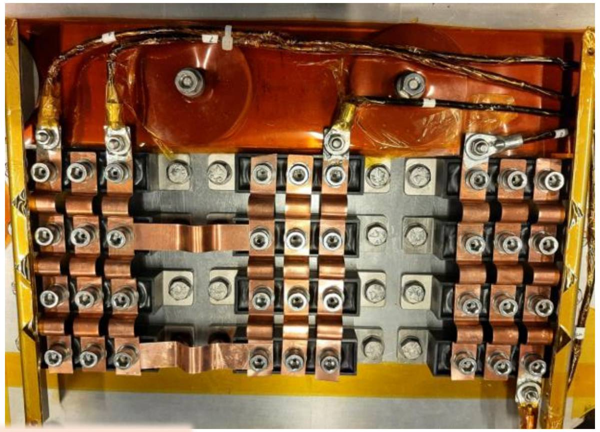

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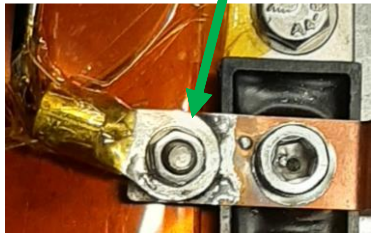

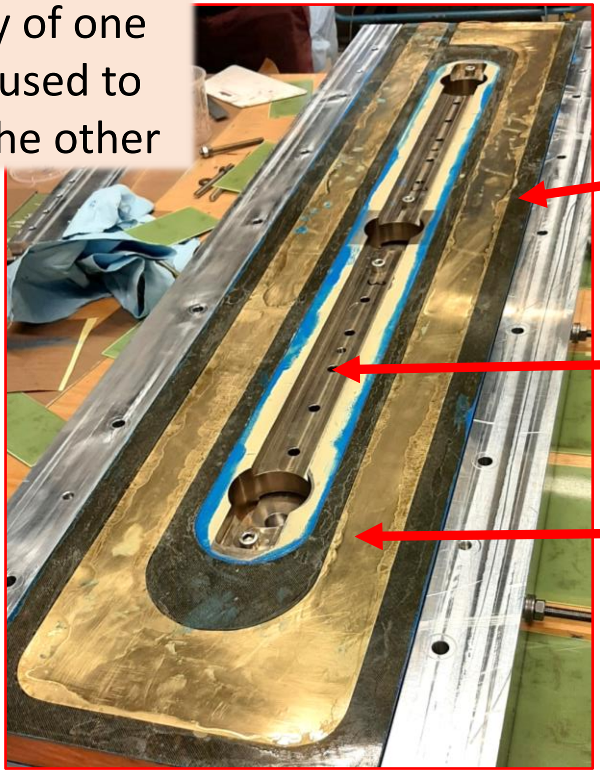

Energy of one coil is used to heat the other

Coil, 1.45 m long

SS yoke

Brass quench heater

Passive/Active Coil Protection System

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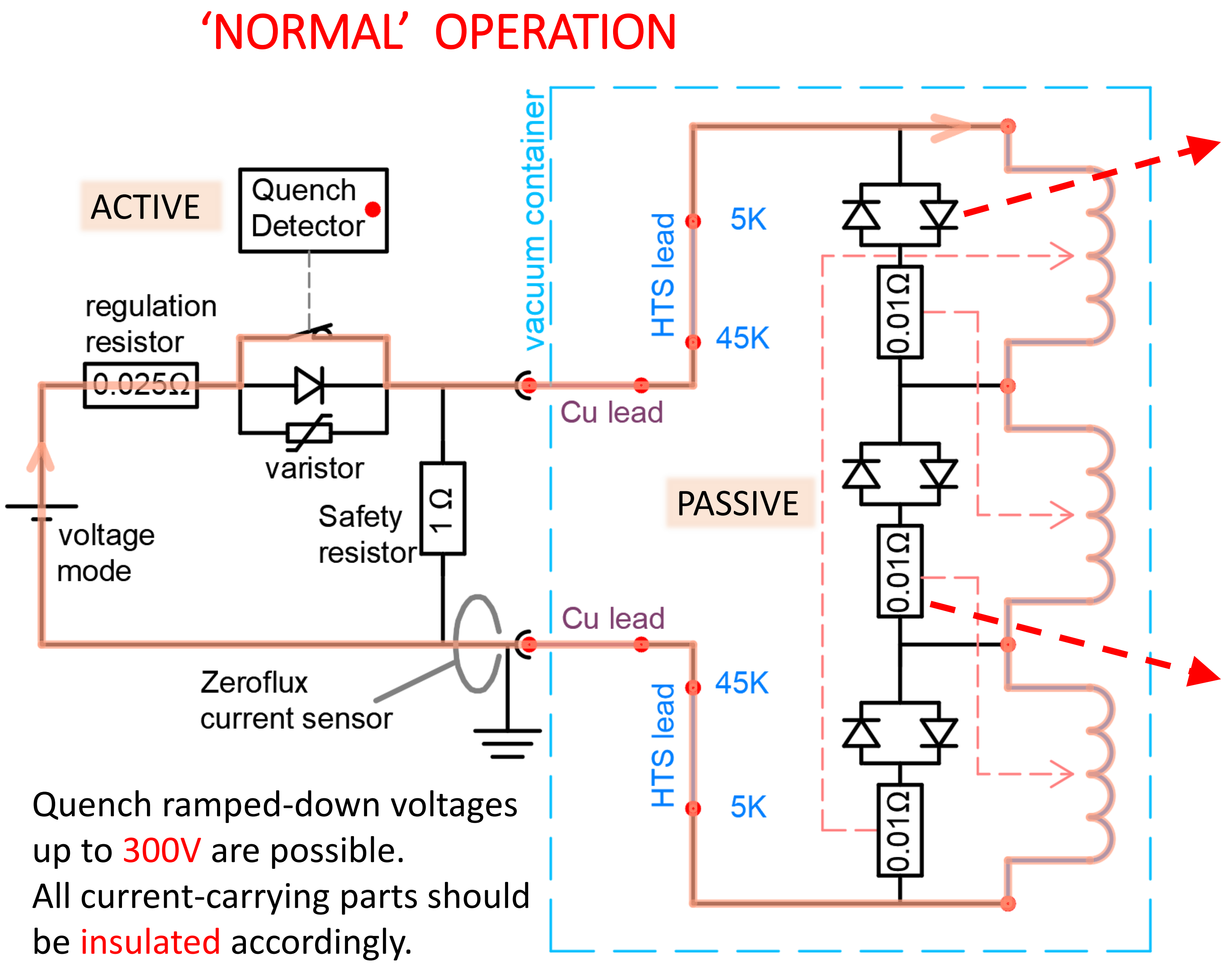

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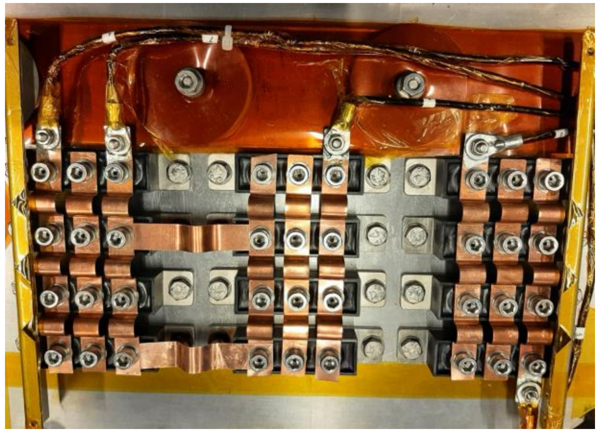

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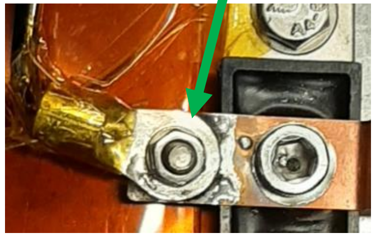

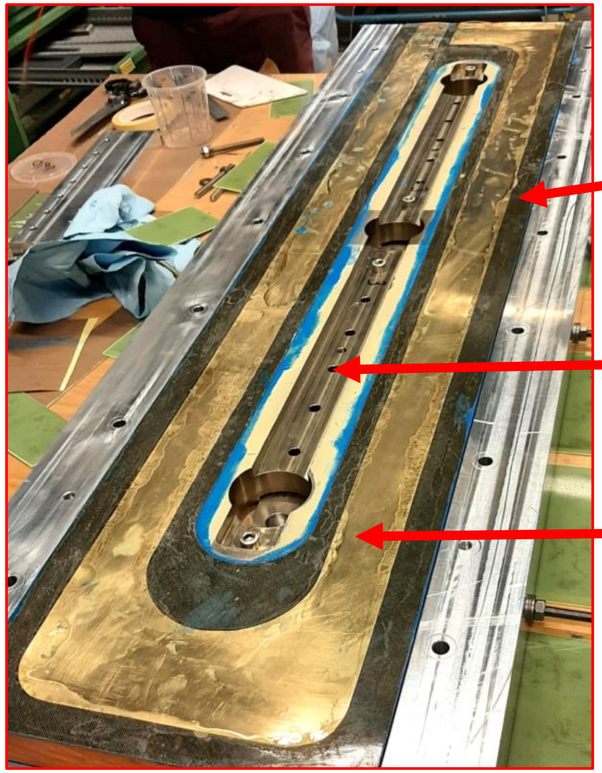

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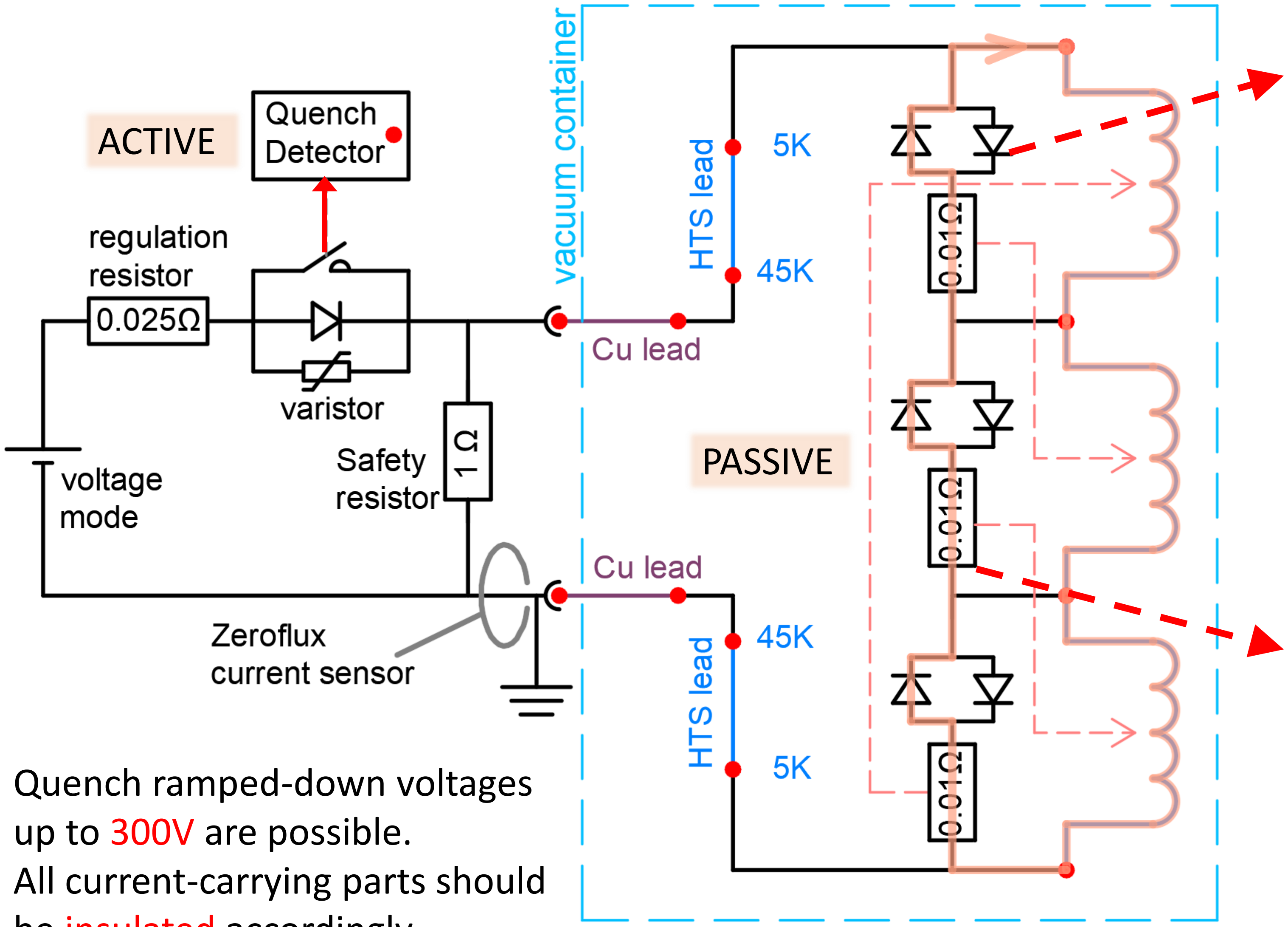
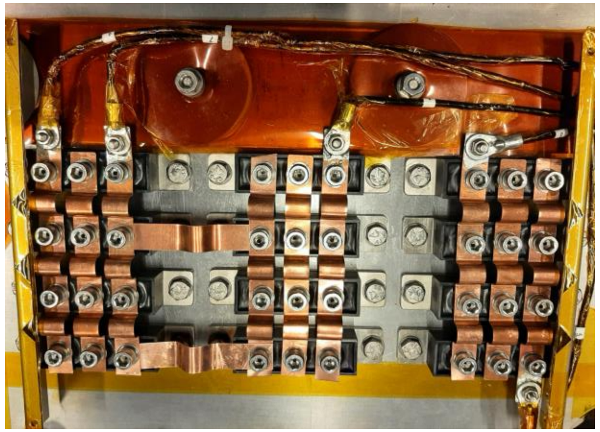
TRIP DECAY after any event





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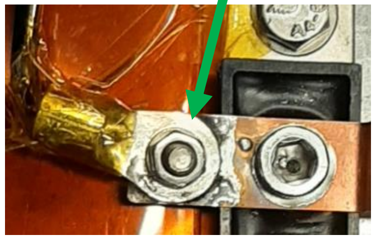

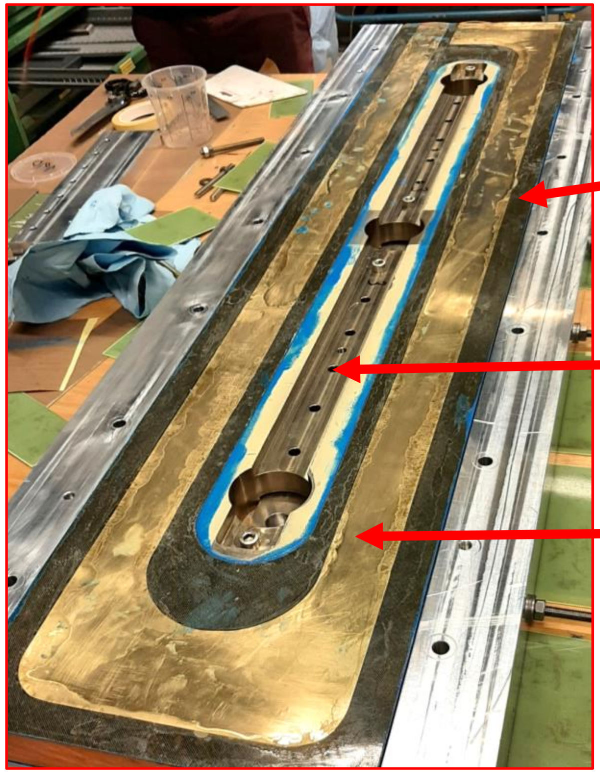

Coil, 1.45 m long

SS yoke

Brass quench heater

Quench ramped-down voltages up to 300V are possible.
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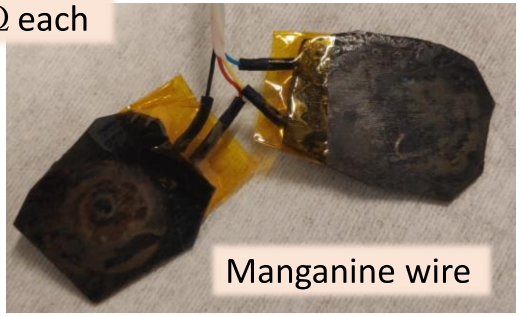
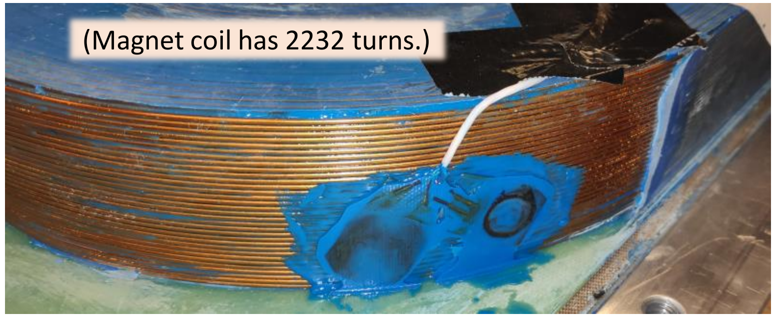
Effective Protection System

To test the quench behaviour, two small spot-heaters are placed at the head of one of the coils.





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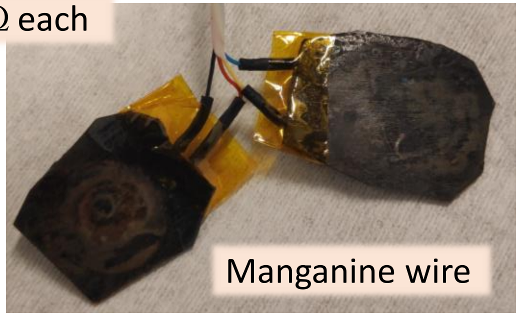
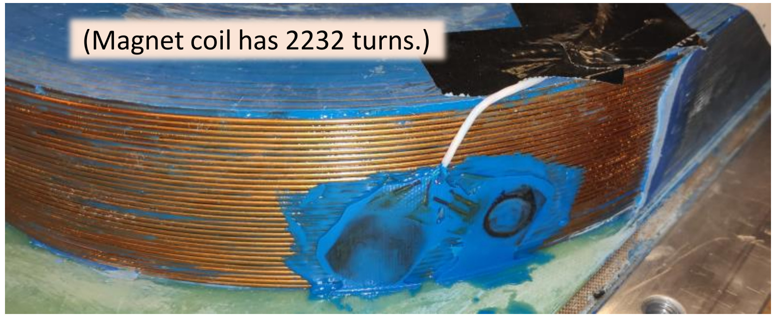
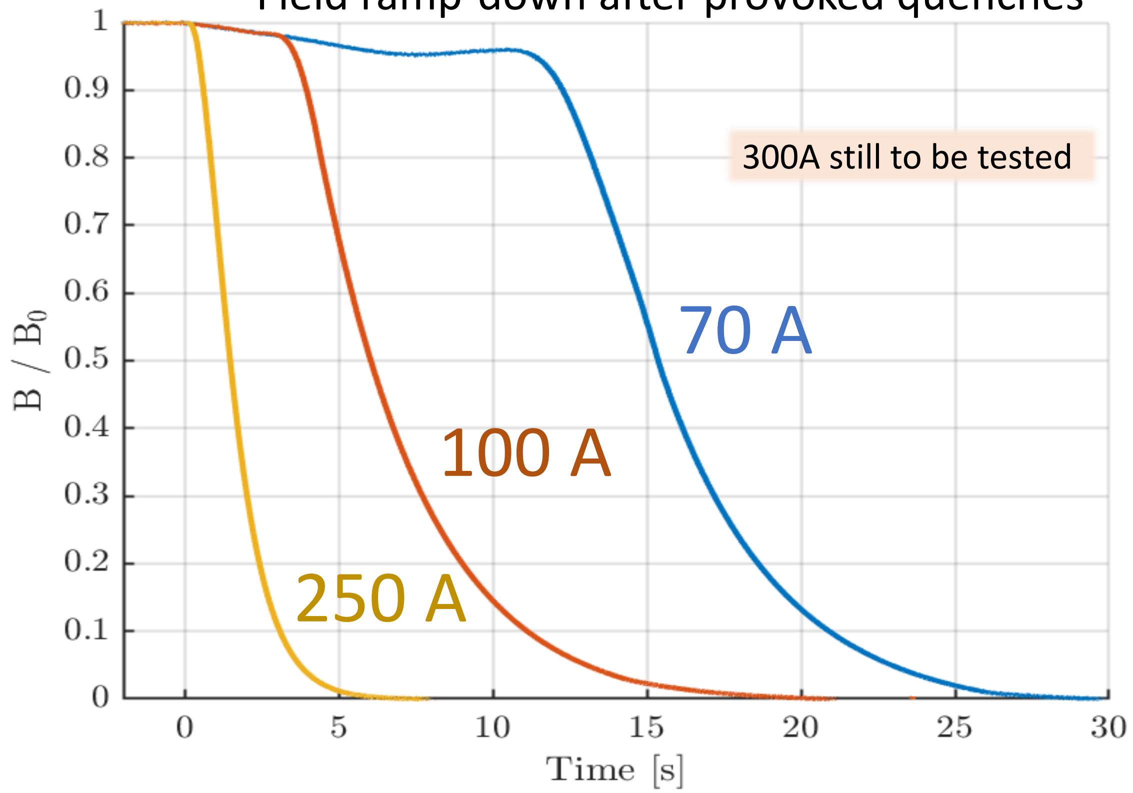
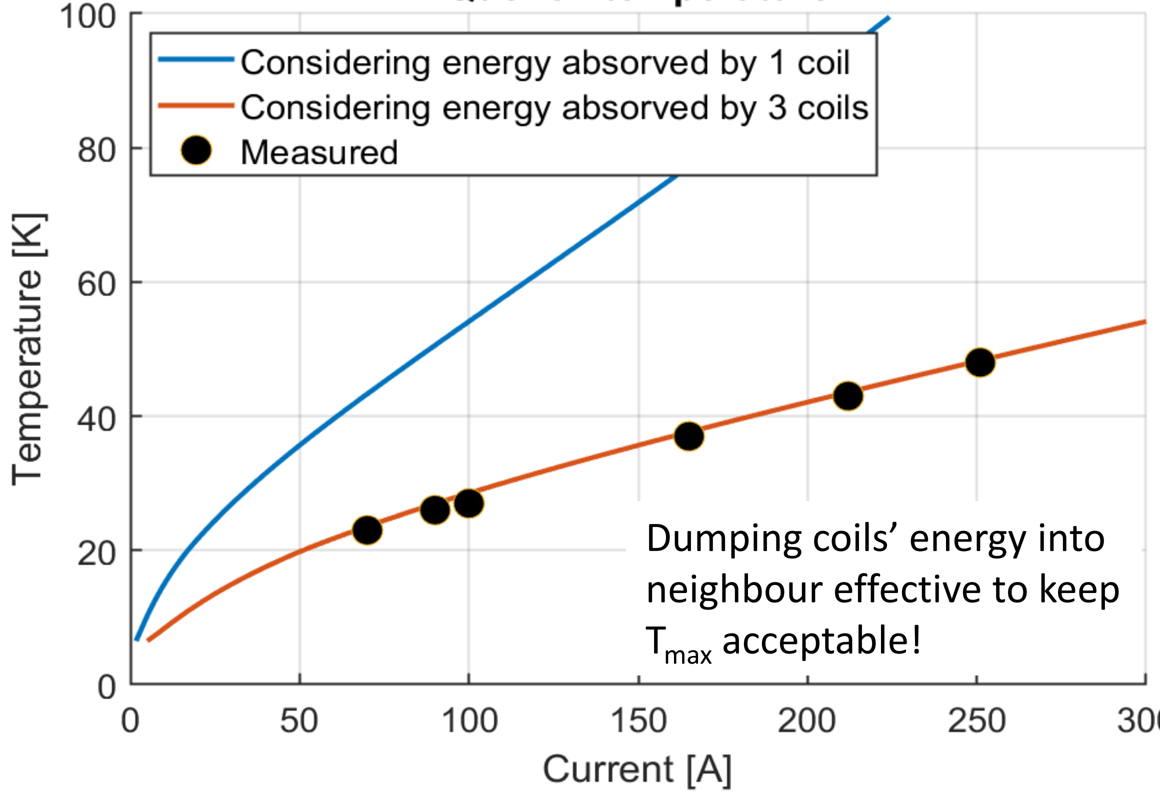




Field ramp-down after provoked quenches



Quench temperature



Dumping coils' energy into neighbour effective to keep T_{max} acceptable!

Successful preliminary sorting tests at Umincorp

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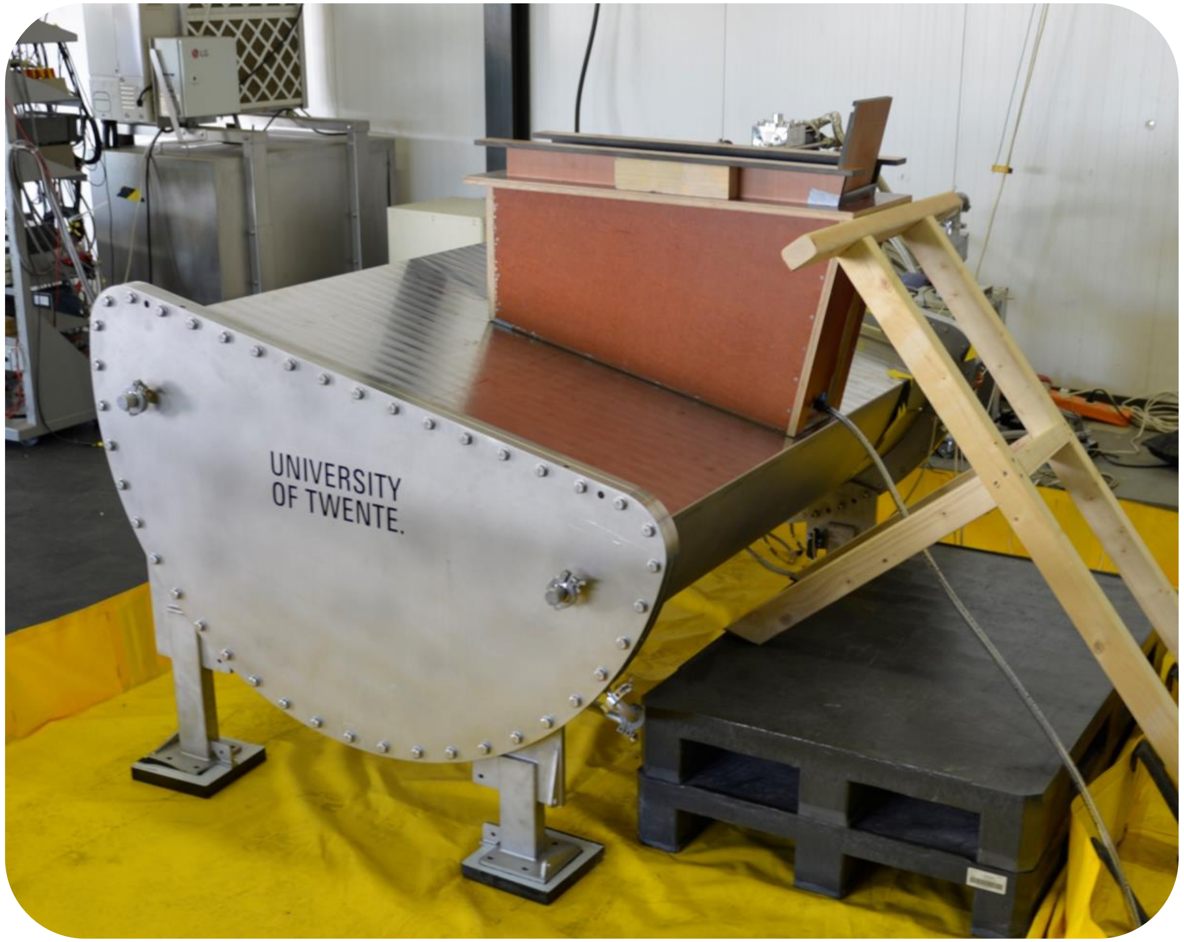
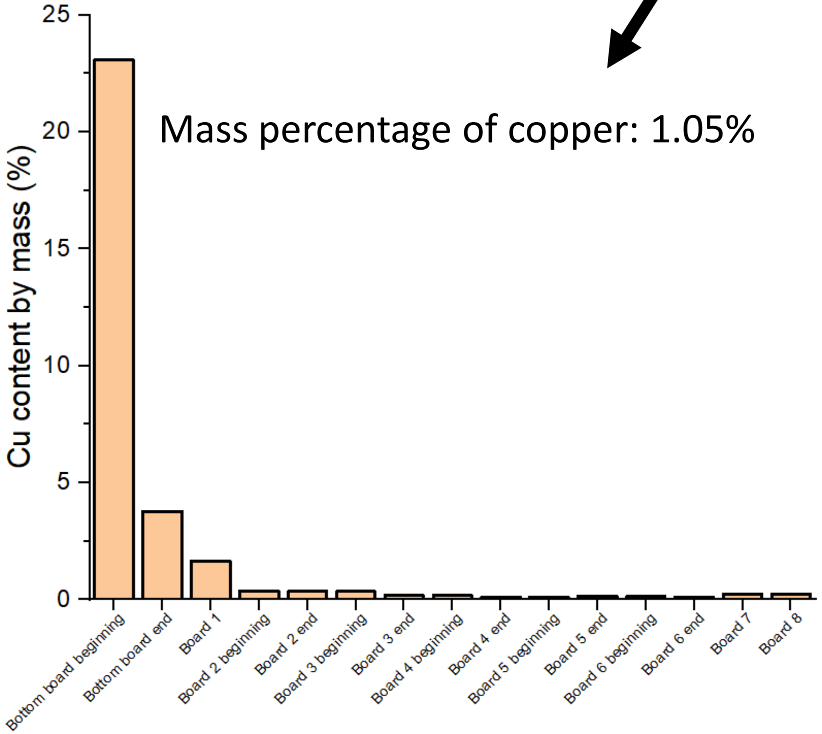
TU Delft, Umincorp and UT

E-waste: High magnetic fields enable low-cost sorting

- Recover precious metal from electronic components
- Recover of metal from shredded cables



10 cm



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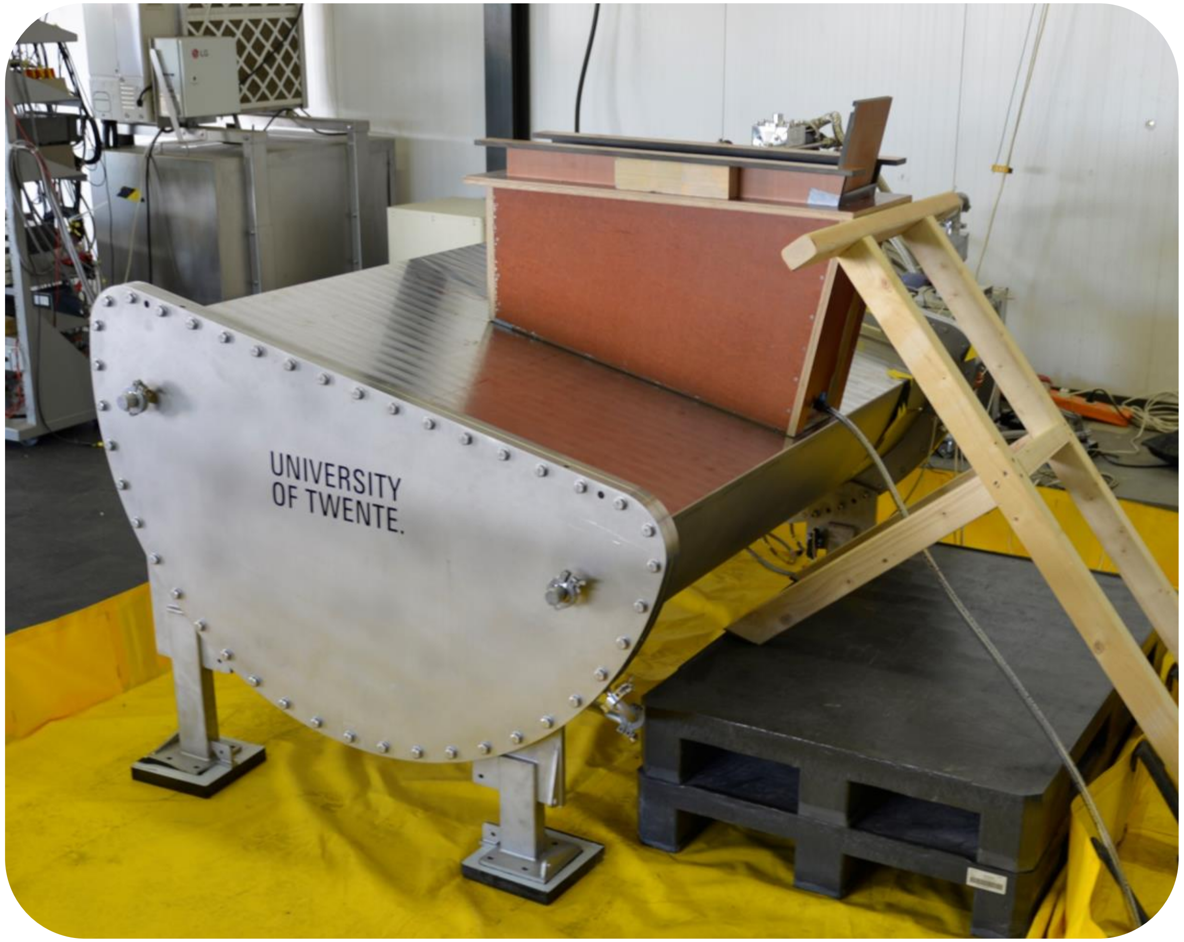
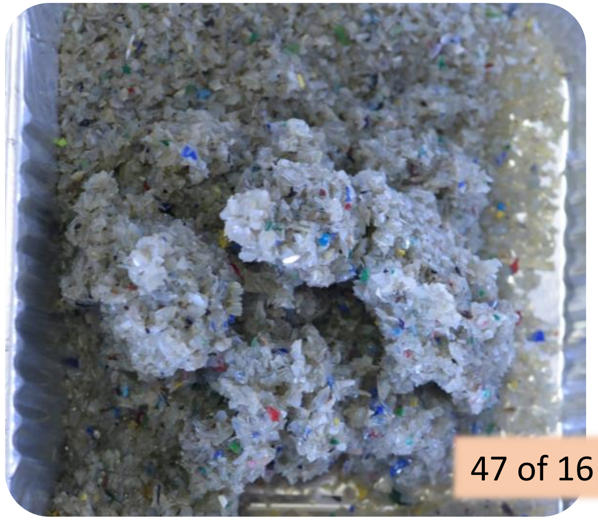


10 cm

Plastic:

High resolution increases end-product purity

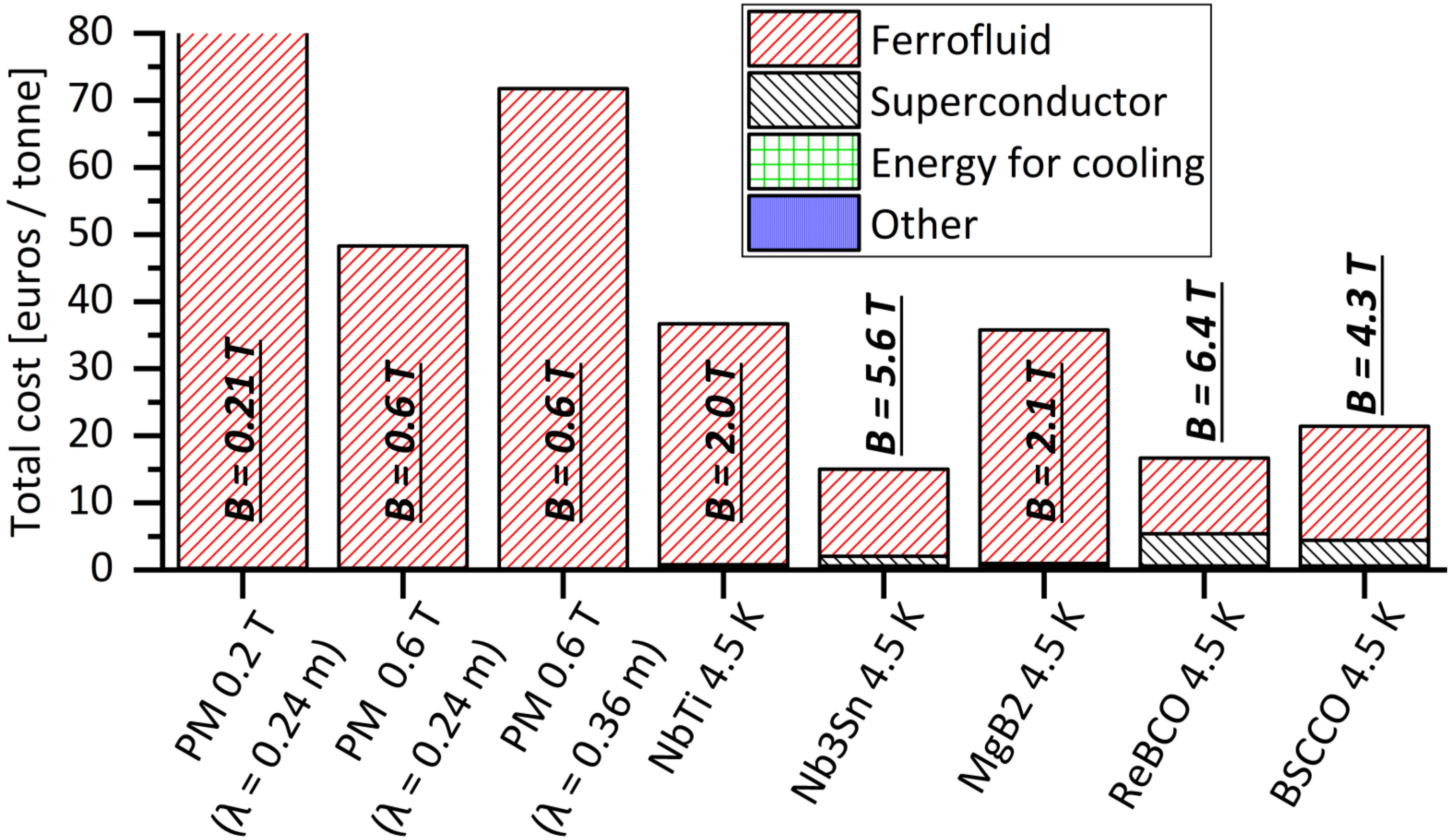
Cleaning fine PET from metal, sand and rubber



Follow up

- **NbTi was used for this demonstrator**
- However, economical study reveals that:
  “higher-magnetic field magnet pays itself back”
- ReBCO magnet would allow for **high-density sorting at low cost**

Over 10 years with a 80% running time.



Optimal magnet design

CAPEX + OPEX ↓

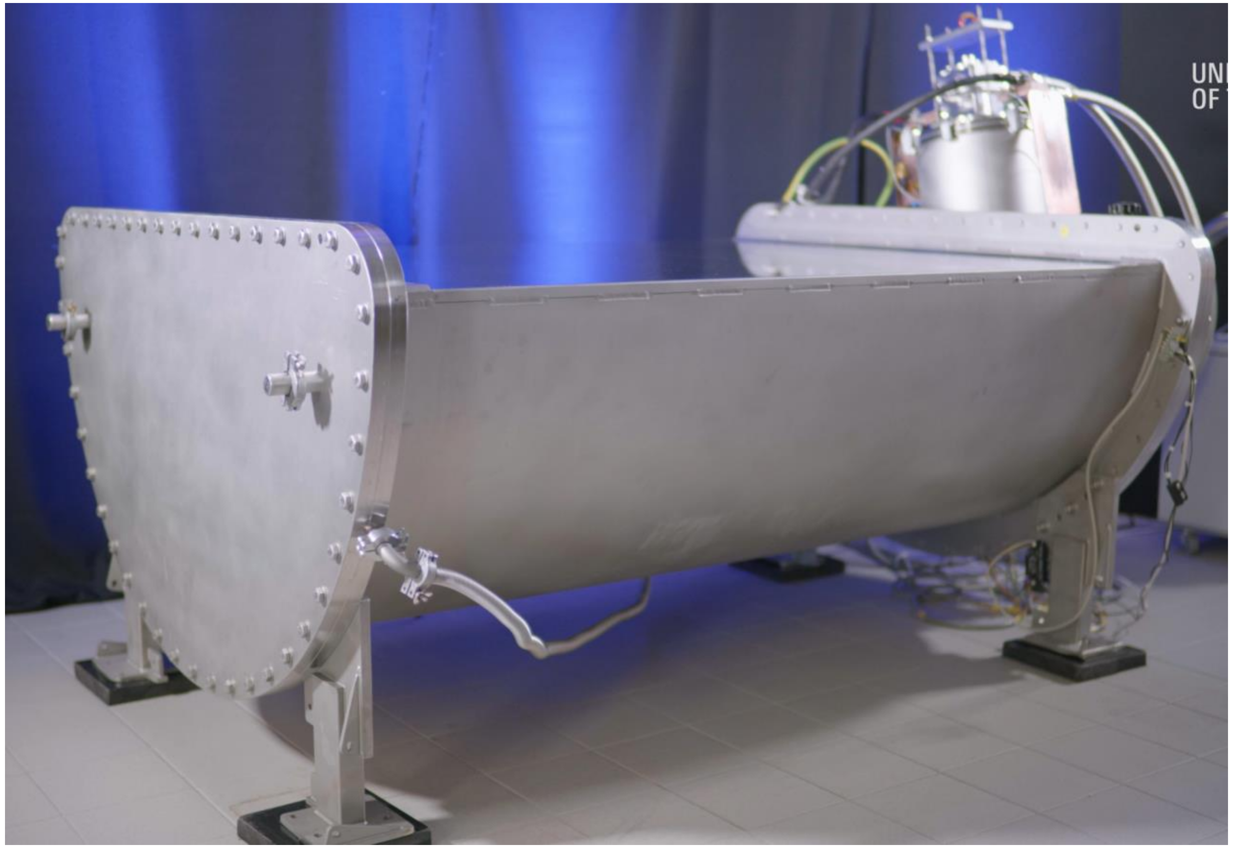
Assumptions:

- ρ_{max} = 14 000 kg/m^3
- Pure FF_{cost} = 30 €/L
- *FF_{lost} = 4.8 L/ton

*This value regards diluted ferrofluid. Pure FF_{lost} is proportional to its saturation magnetization value

Conclusions

- First conduction-cooled superconducting MDS system assembled successfully
- Cool-down time 13 days, as preicted
- Final temperature 1K > target value, due to a thermal short in the MLI
- 300 A current- & 2 T field targets reached (within 1.5% due to tolerances) .
- Successful preliminary waste-sorting tests at the **Umincorp** facility in Rotterdam are ongoing
- Future systems using ReBCO-coils will have the lowest operation costs.



First → Demonstration movie with Manganese(II) chloride tetrahydrate solution

($MnCl_2 \cdot 4H_2O$ is paramagnetic and transparent)

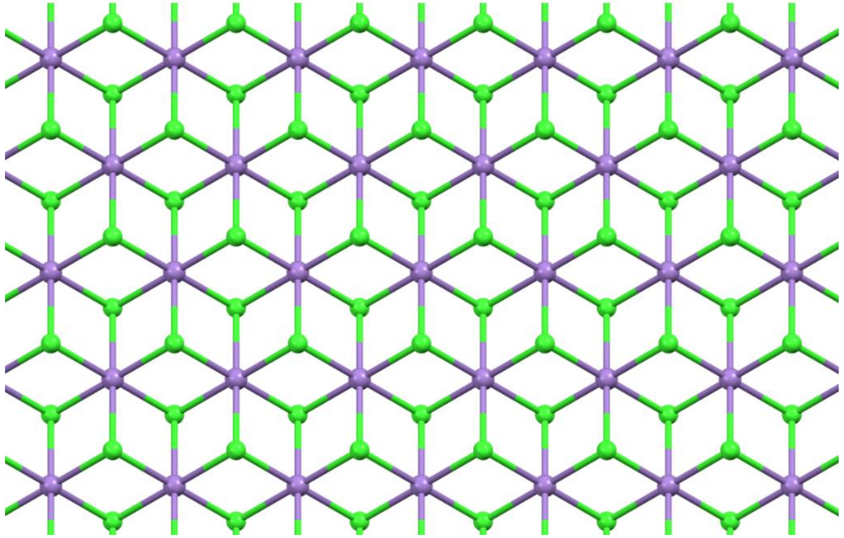
Later → Questions

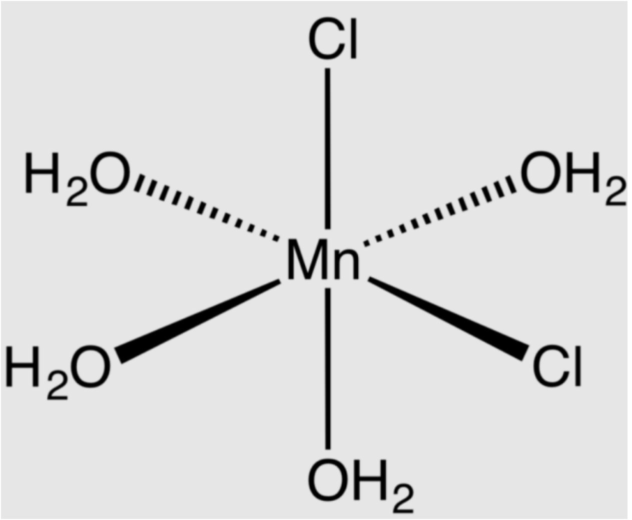
MDS Demonstration Movie

For this demonstration the Ferrofluid could not be used, because it is [redacted]

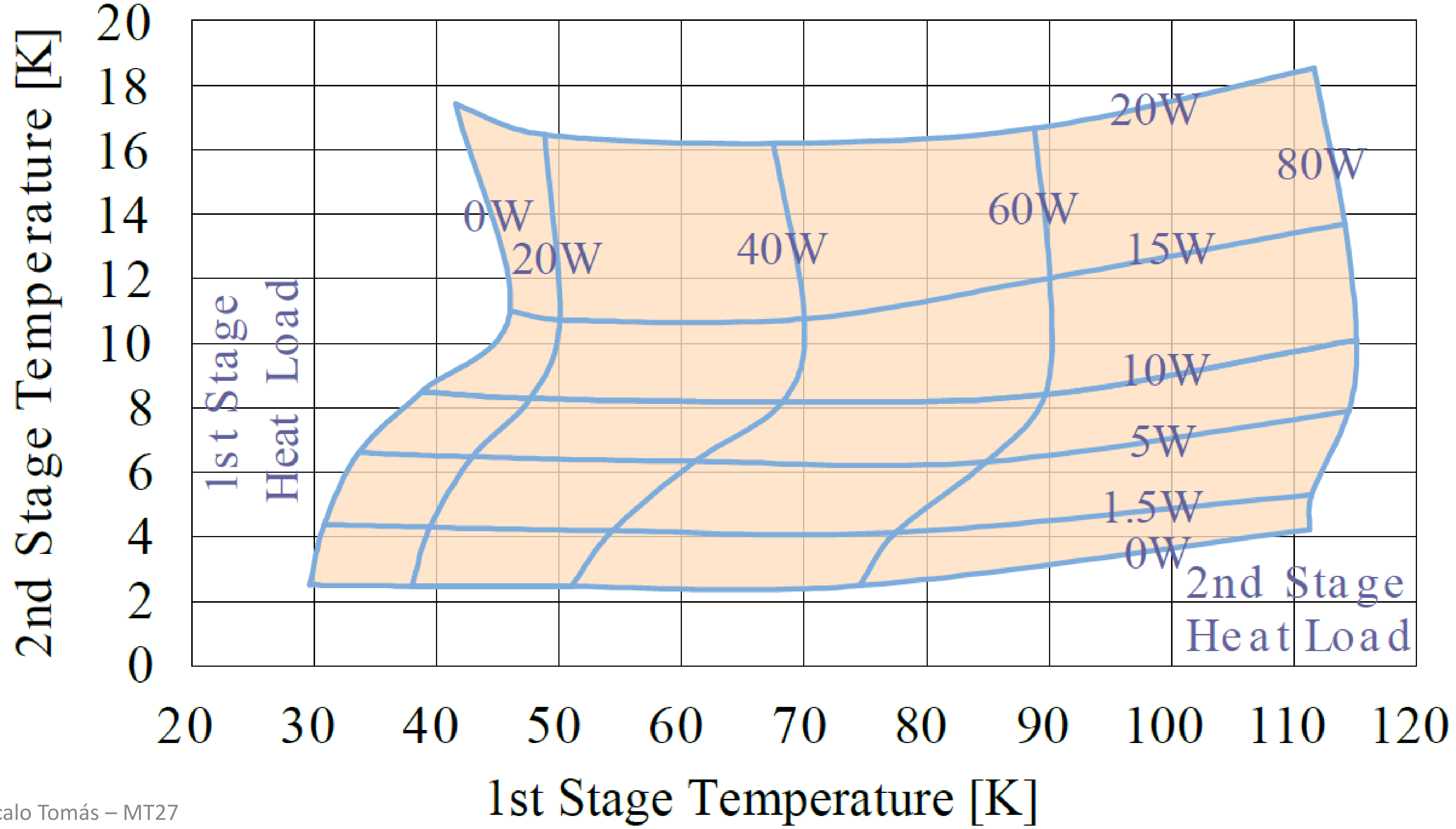
Manganese(II) chloride tetrahydrate solution $MnCl_2{\cdot}4H_2O$ is paramagnetic and transparent.
https://en.wikipedia.org/wiki/Manganese(II)_chloride

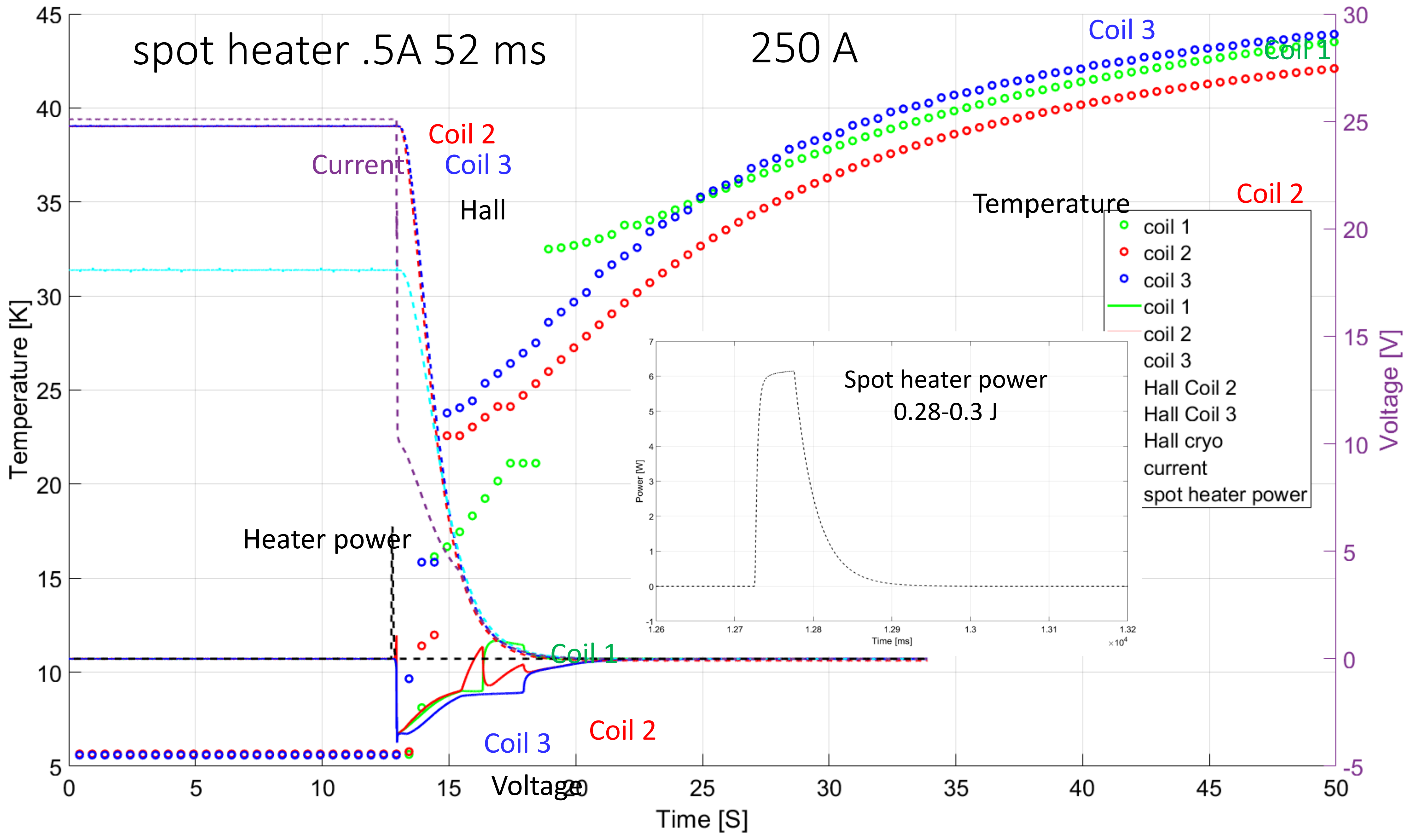
https://vimeo.com/724447751/0ee6e758ff





SHI RDK-415D2





spot heater .5A 52 ms
250 A
Coil 3
Coil 1
Coil 2
Current
Coil 3
Hall
Temperature
Coil 2
coil 1
coil 2
coil 3
coil 1
coil 2
coil 3
Hall Coil 2
Hall Coil 3
Hall cryo
current
spot heater power
Spot heater power
0.28-0.3 J
Power [W]
Time [ms]
Heater power
Coil 1
Coil 3
Coil 2
Voltage
Temperature [K]
Voltage [V]
Time [S]

Thermal layout of cold mass

- Single cryocooler conduction-cooled system

Aluminum radiation shield
+3 multilayer insulation blankets

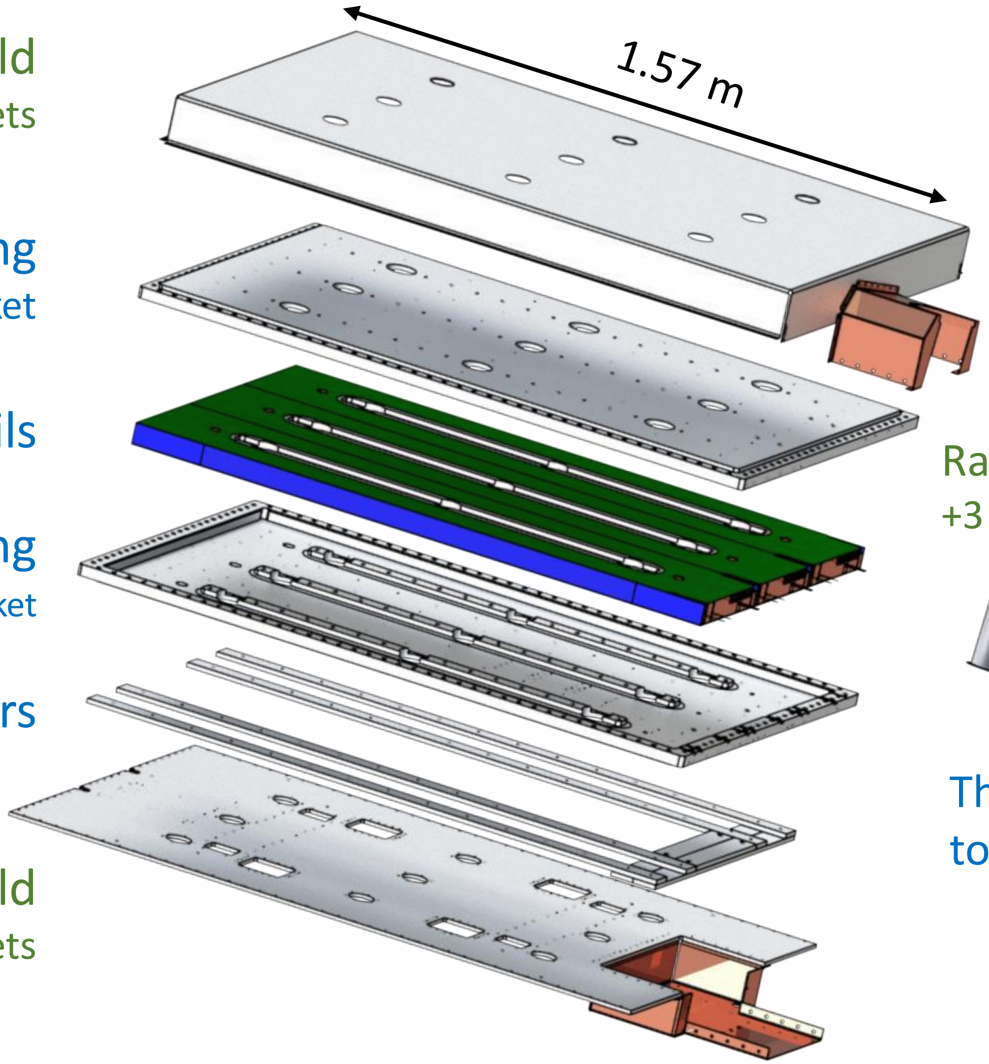
Al alloy coil casing
+1 multilayer insulation blanket

3 NbTi racetrack coils

Al alloy coil casing
+1 multilayer insulation blanket

5N pure Al heat drain bars

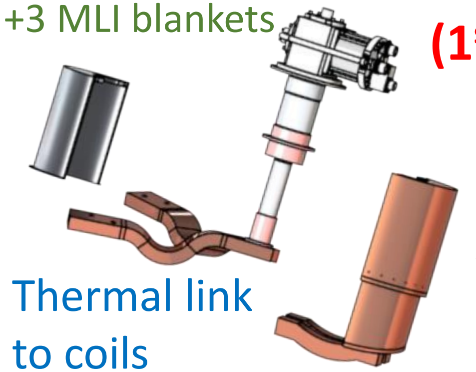
Al radiation shield
+3 multilayer insulation blankets



Heat budget [W]	1st stage	2nd stage
Radiation	9.8	0.14
Support structure	3.1	0.26
Current leads	27	0.18
Total	40	0.58

1.5 W GM cooler @4.2K
(1st stage 60 W @77K)

Radiation shield
+3 MLI blankets



Thermal link
to coils

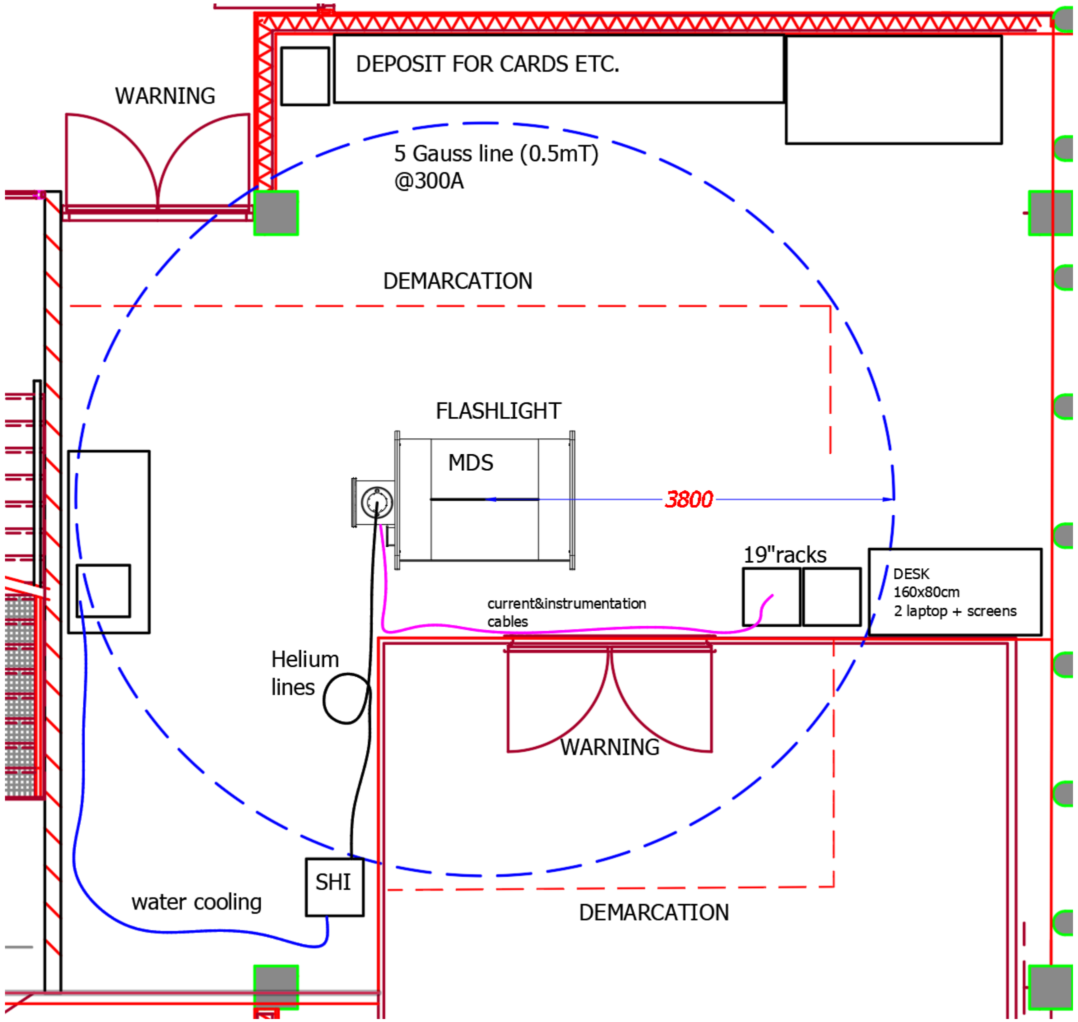
Radiation shield
+3 MLI blankets

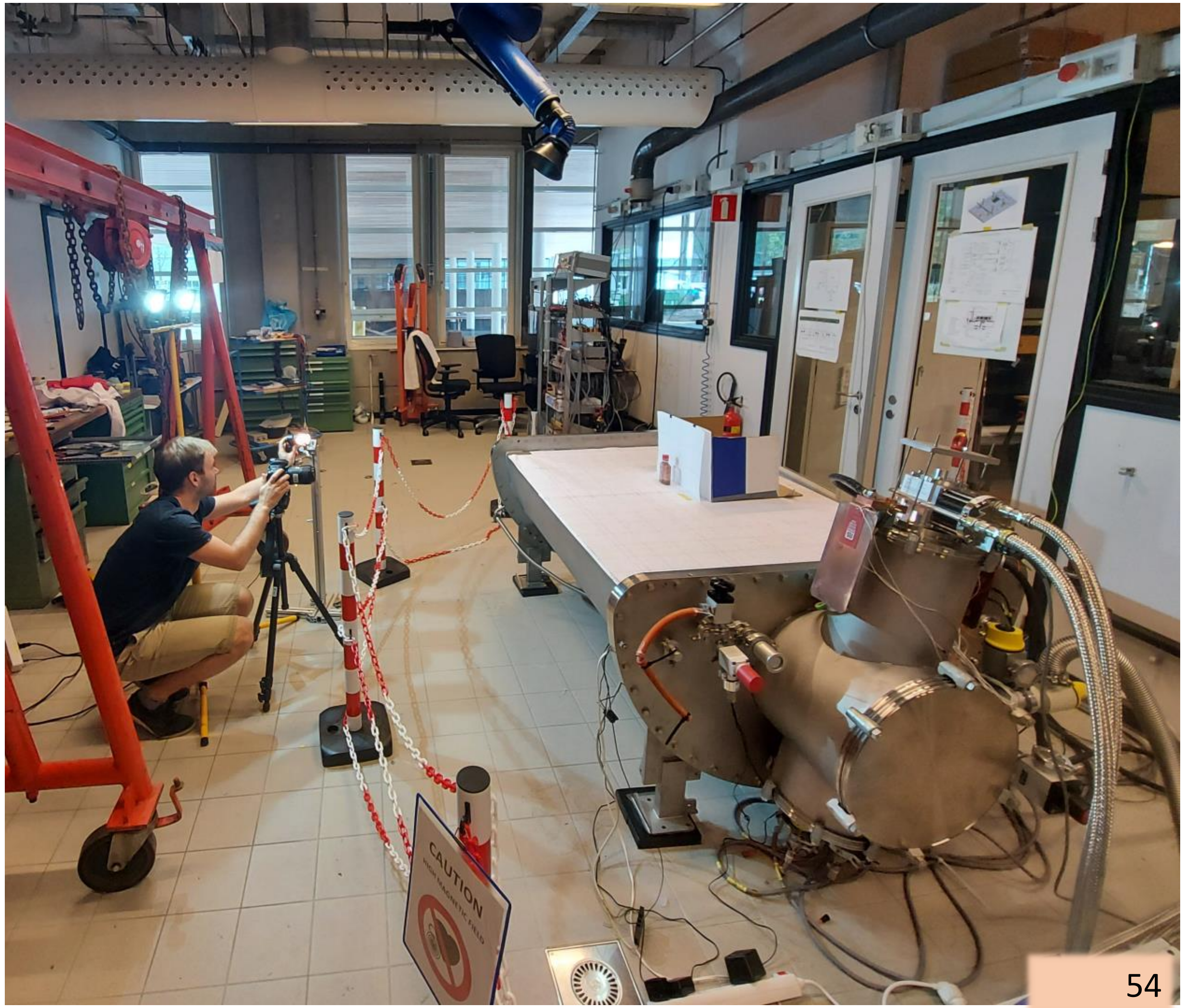
Thermal link
to radiation shield

Safety → 5 Gauss line

At 300A the 5 Gauss line has the shape of an ellipse with 3.8m for the long axis and 3.5m for the short axis. Almost the complete 60% of the available floor area is covered. Warnings and demarcations were placed.

Safety Floorplan





Make the coils rectangular.

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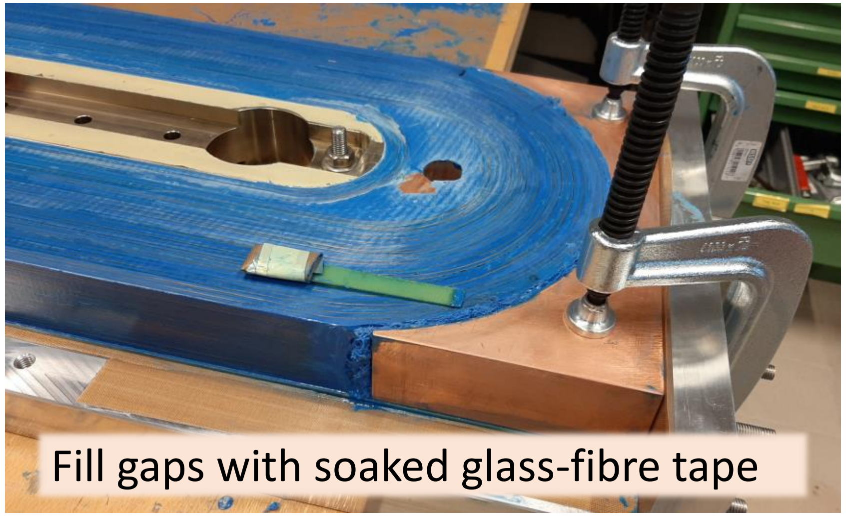
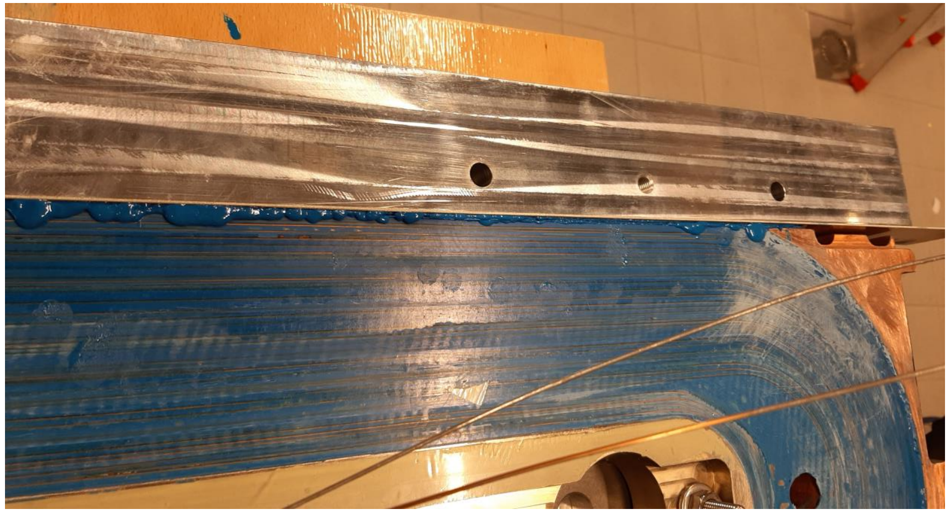
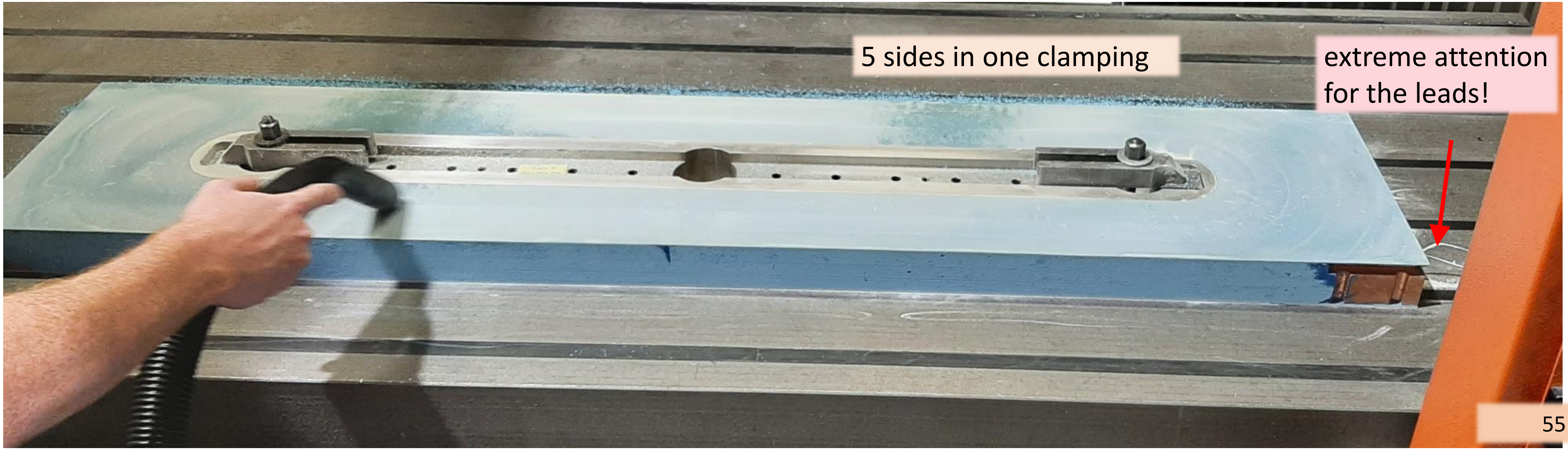
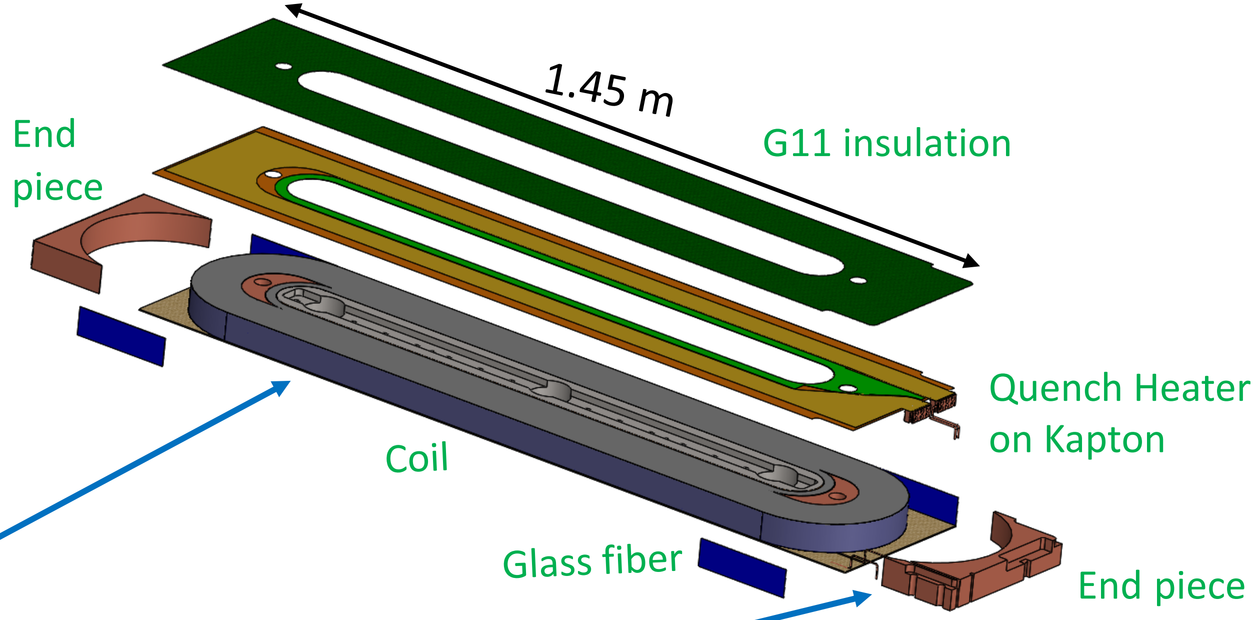
- Coils // and no gaps
- Winding goes per layer!
- Always ends too small
- Oversize with Glass/Stycast
- Milling needed to get ±0.1 mm
- Special tooling
- METAL B.V. Nijverdal
- Planned machine maintanance afterwards (remove all fibres)

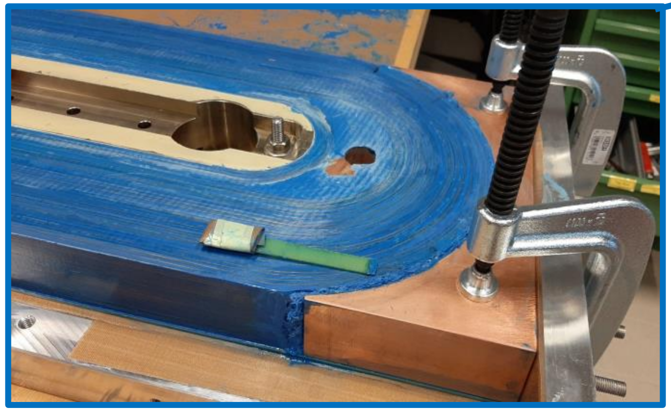






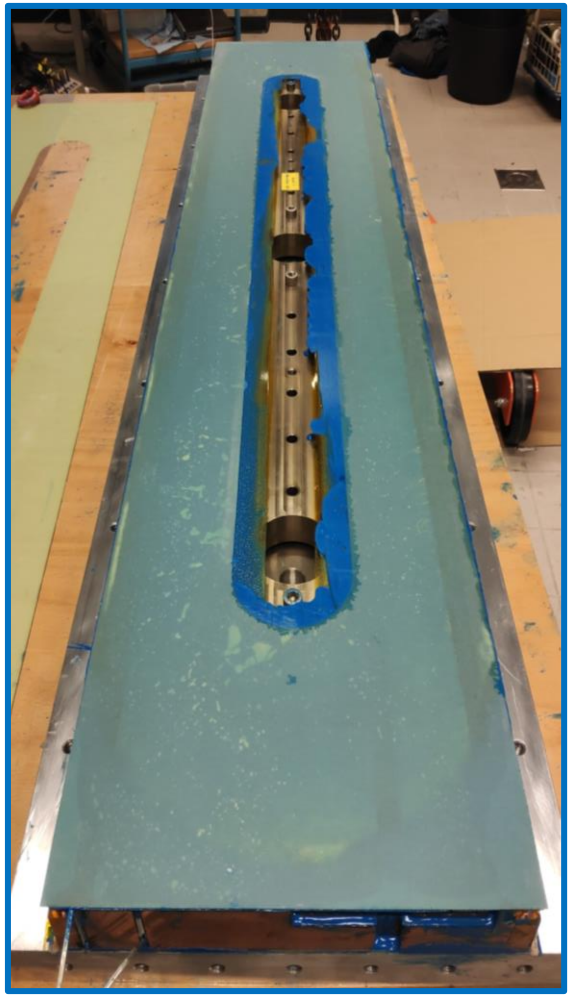
Coil winding and assembly





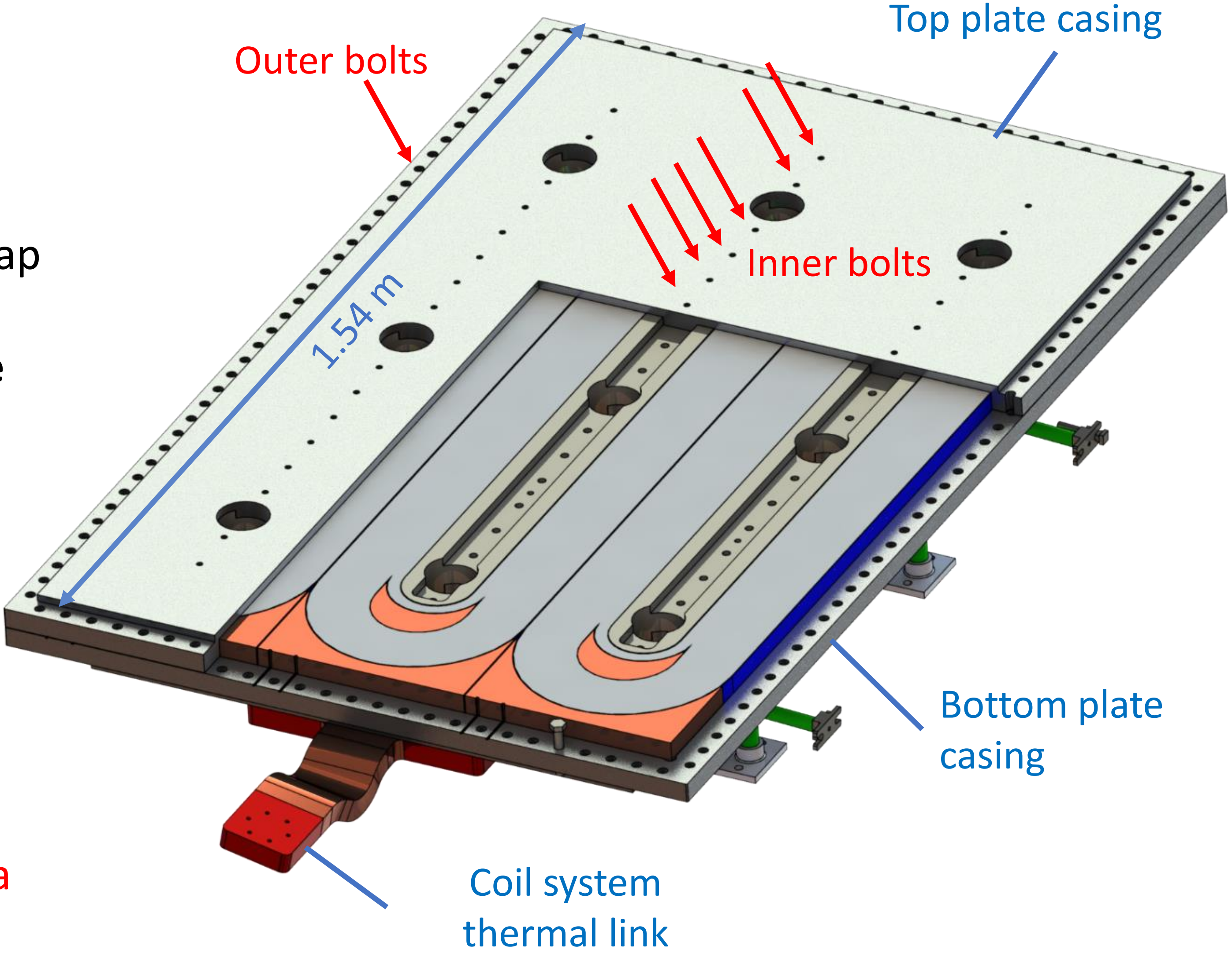
End piece glued to coil

- ✓ Wet winding
- ✓ G11/glass ground insulation
- ✓ Brass quench heater
- ✓ End piece for shaping



Aluminum alloy casing enclosing the coils

- **Two-part thin high-strength aluminum casing**
  - Keeps coils in place
  - Shrink fits around coils upon cool-down
  - Coils under compression always
  - Ti shims around coils ensures < 0.1 mm gap
- **Conduction coil cooling through bottom plate casing**
  - Good thermal contact required
- **Top plate casing cool down through the coils**
  - Good thermal contact required
- **Aluminum casing plates not perfectly flat**
  - Large number of bolts required
  - Contact area and gap with coils requires a minimum



Magnetic Field Testing in spring 2022

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First field of 0.2T on 17 February 2022.
Field is low and still safe, time to play ☺

19” Racks with:

- 400 A power supply
- Power Resistor&Diodes
- Monitoring Devices

18 May 2022 → **2.15T**
Operation Current reached
→ 300A ←
NO TRAINING QUENCHES