HTS coils:
Design, operation, experimental results, simulations & examples

T. Mulder

TE-MPE-PE Section Meeting, July 13 2022

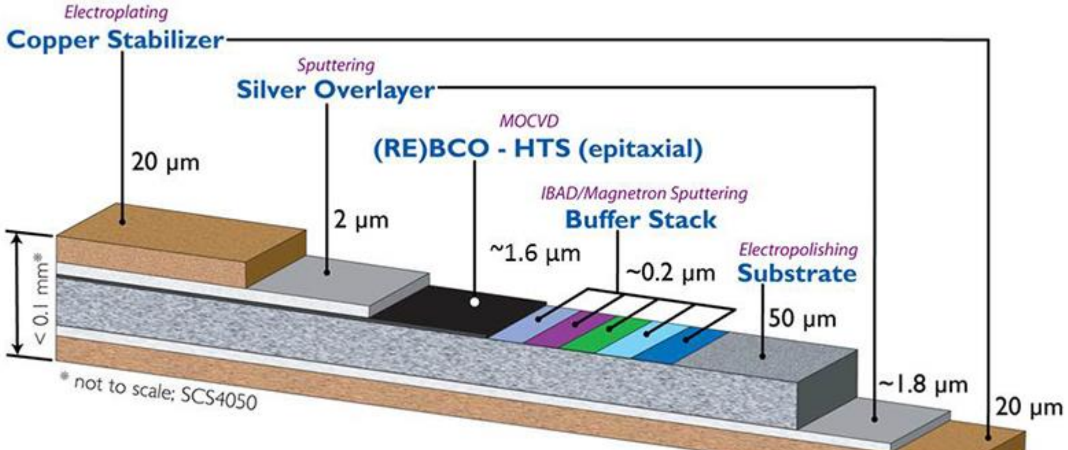
High Temperature Superconductors

1G HTS: BSCCO 2212 (round) & 2223 (tape)

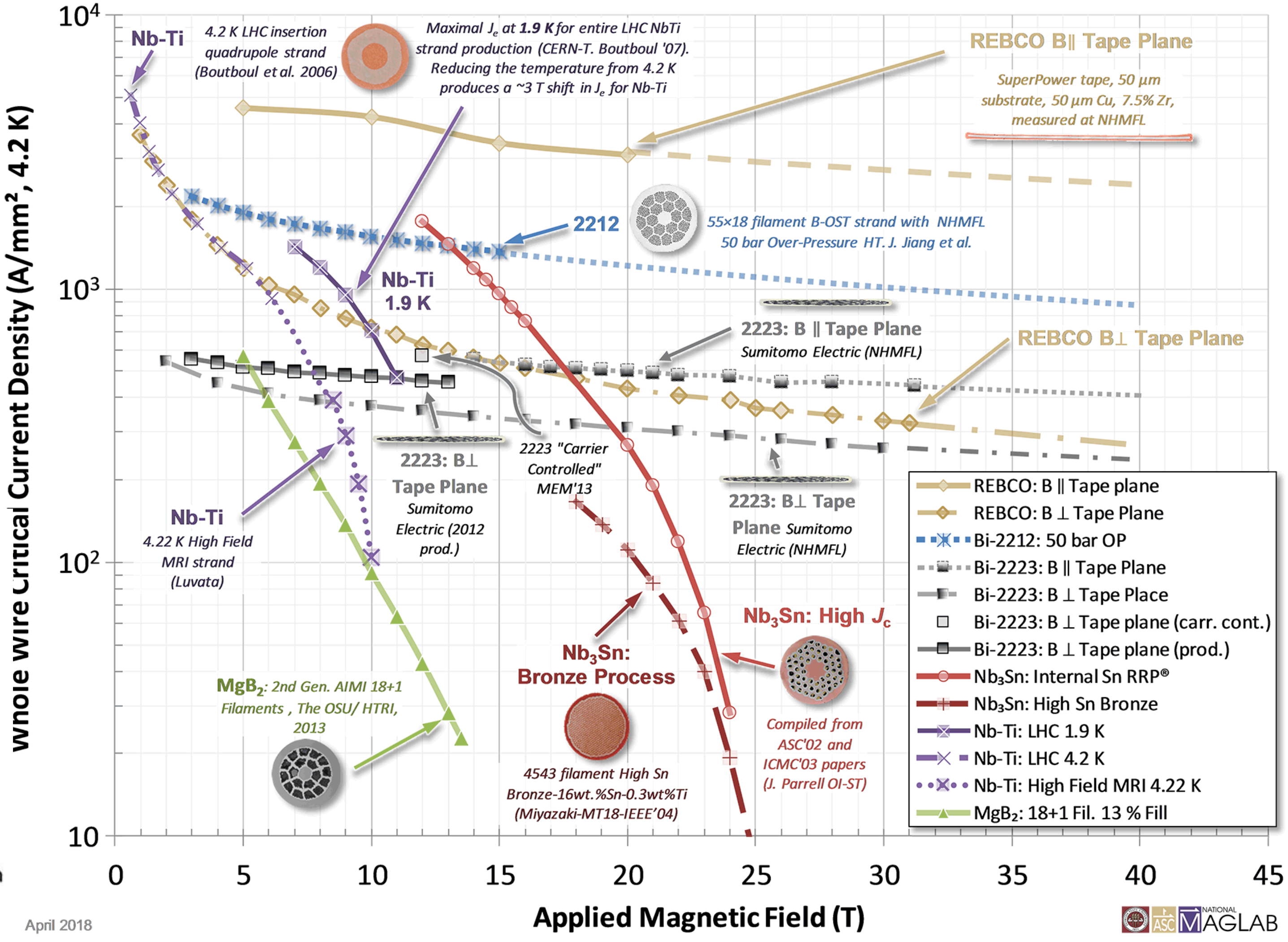
2G HTS: ReBCO (tape)

→ **Ceramic, but bendable, solderable & no heat treatment required.**

(Picture courtesy of ACT)

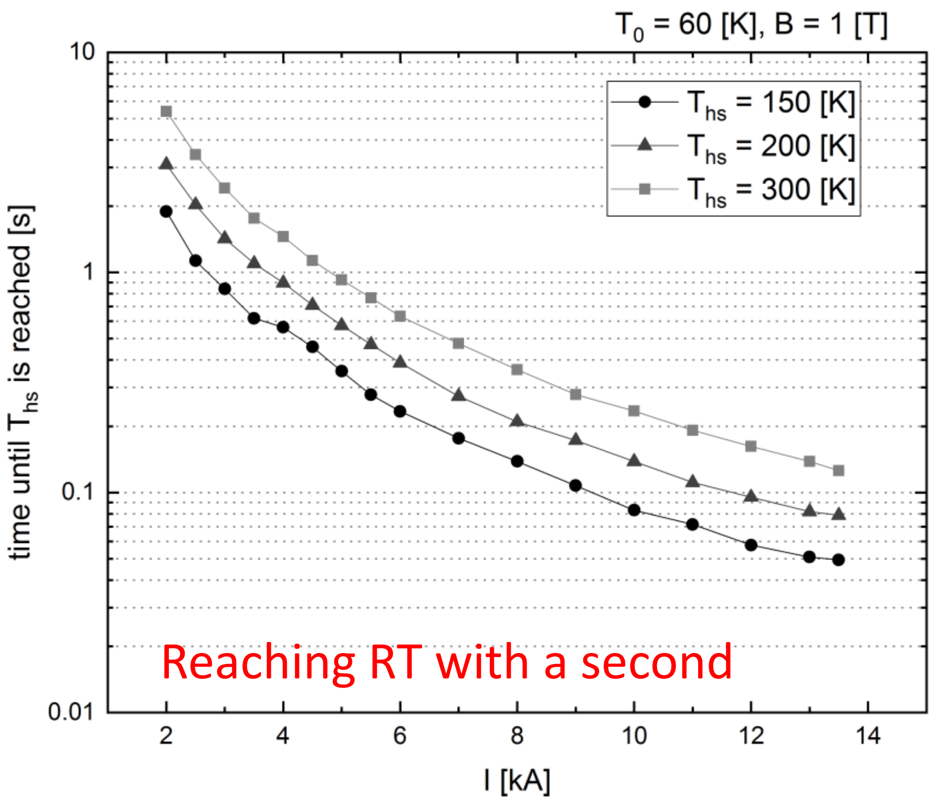


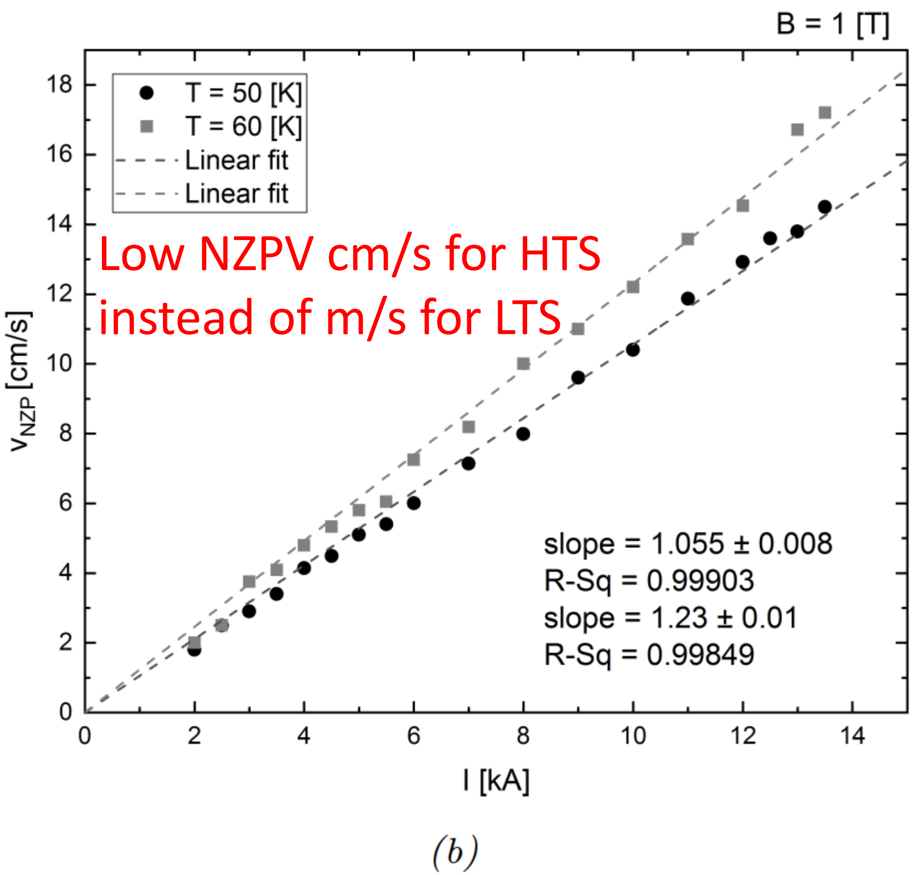
Img from: https://www.superpower-inc.com/Technology.aspx



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Why NI Coils





(b)

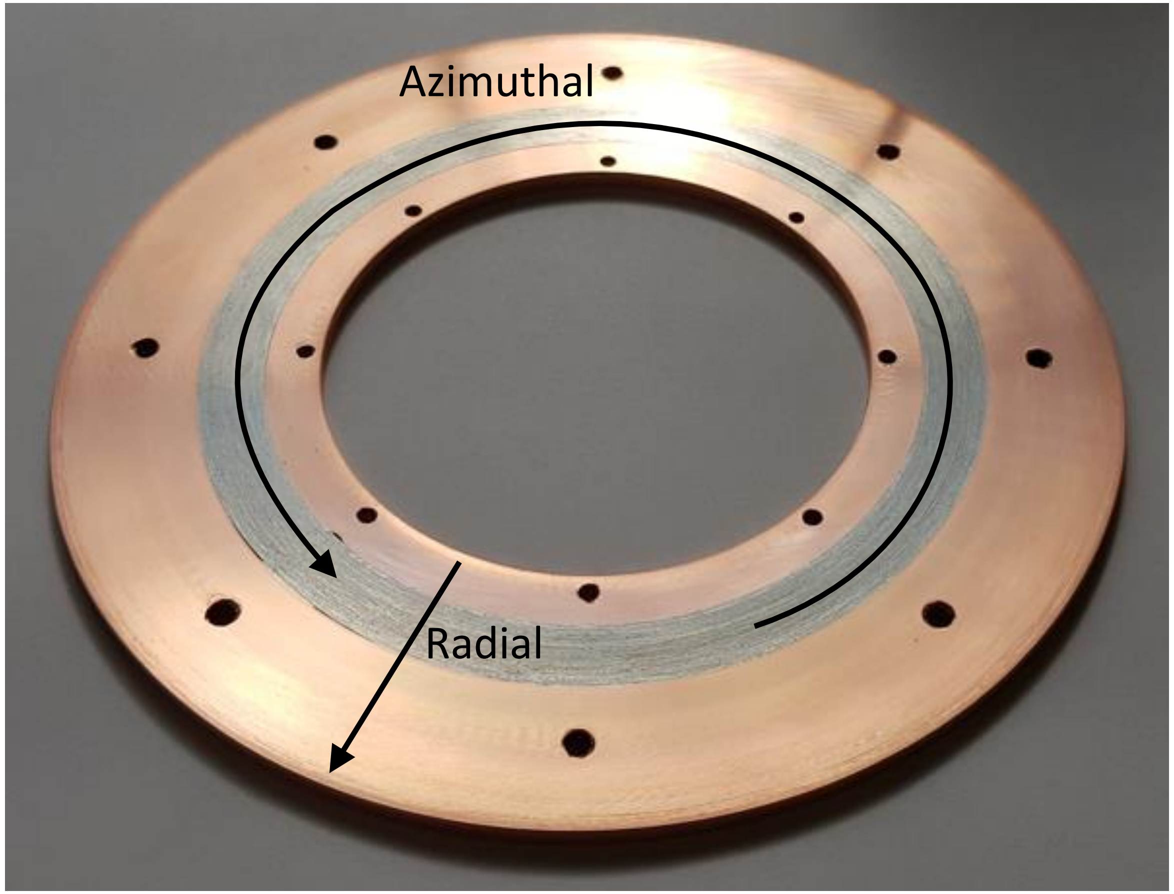
Two Solutions:

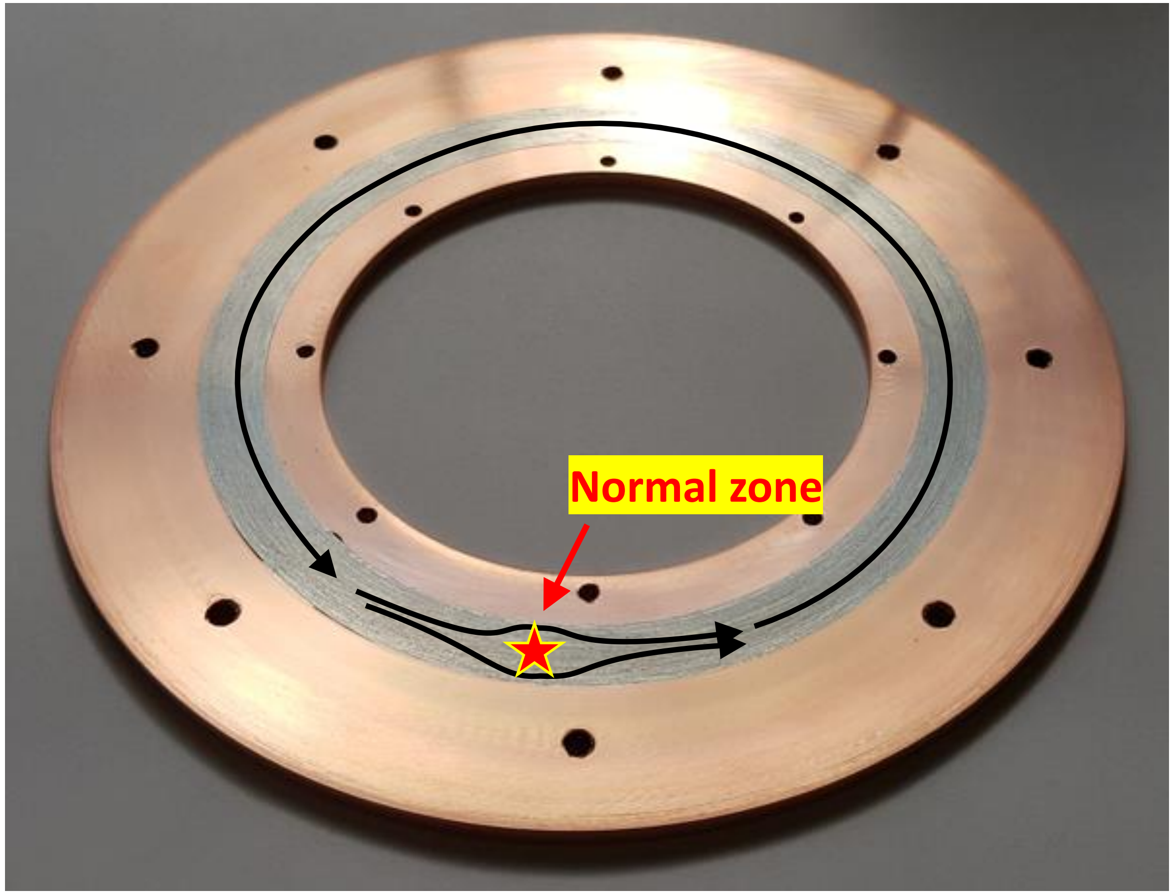
- **Detect and extract current within a few hundred ms.**
- **Allow current to bypass the normal spot -> NI Coils.**

Figures from the master thesis of B. Goelema on the conductor of the AMS-100 magnet.

HTS NI Coils

Parallel path for the current around a normal zone.





Downside -> Difficult operation and field homogeneity not ensured

No-Insulation Coils: Basic Principle

NI Coil: Operation in Current Control Mode

Time Constant: $\tau = L/R$

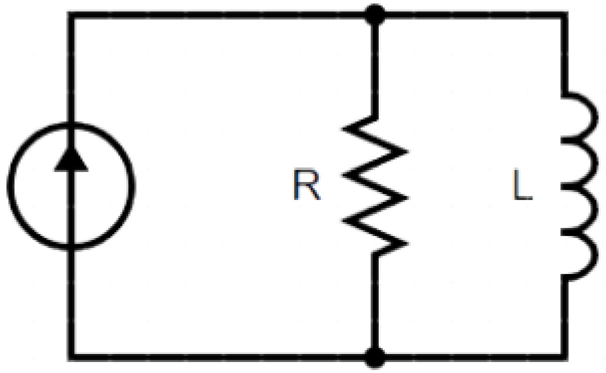
Coil Current: $I_{sc} = I_0\left(1 - e^{\frac{-t}{\tau}}\right)$

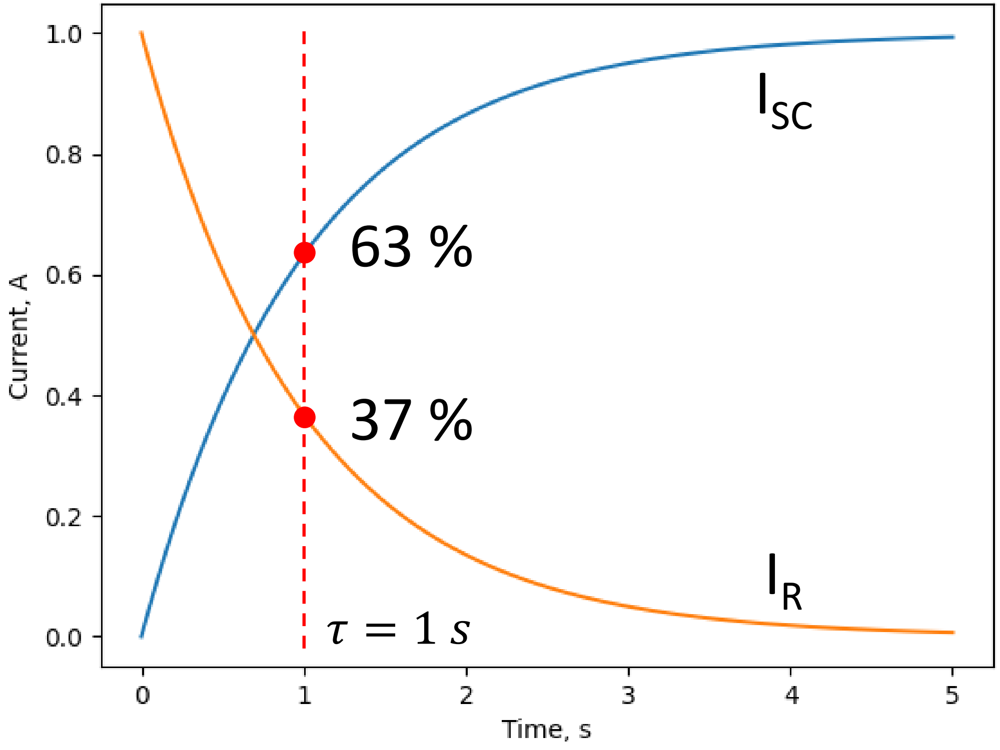
Short Current: $I_R = I_0 e^{\frac{-t}{\tau}}$

Voltage: $V = I_R R$

~5 times τ to get current in a NI coil!

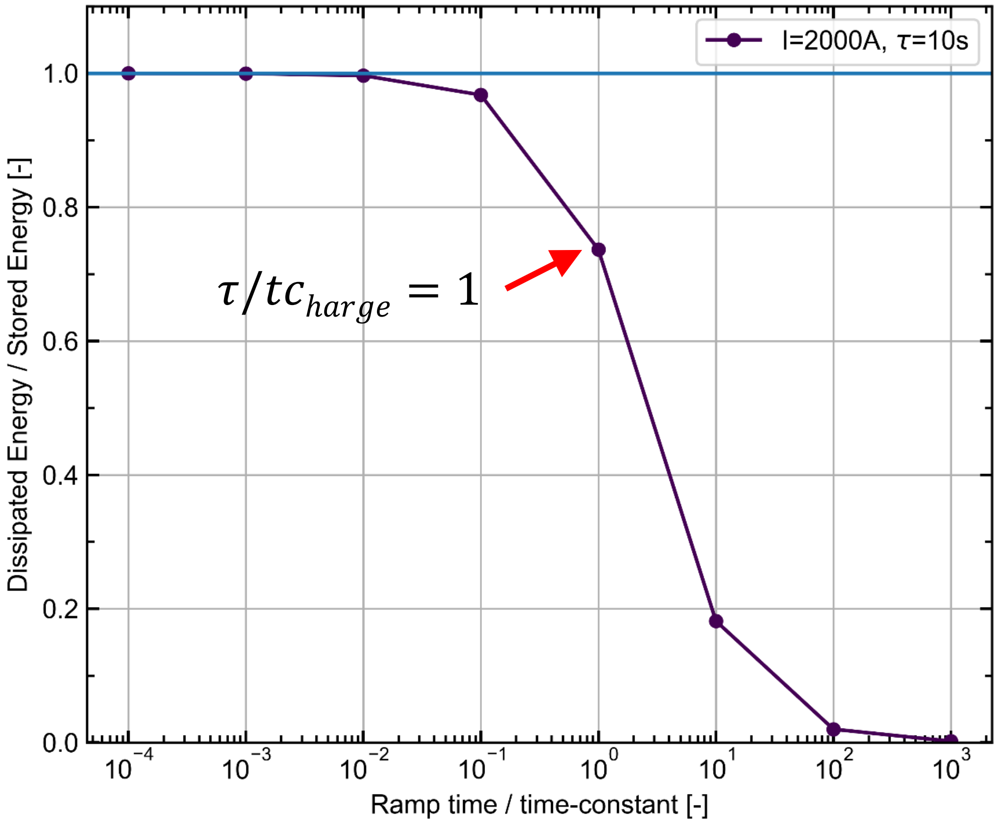
Heat dissipation: $P = I_R^2 R$.

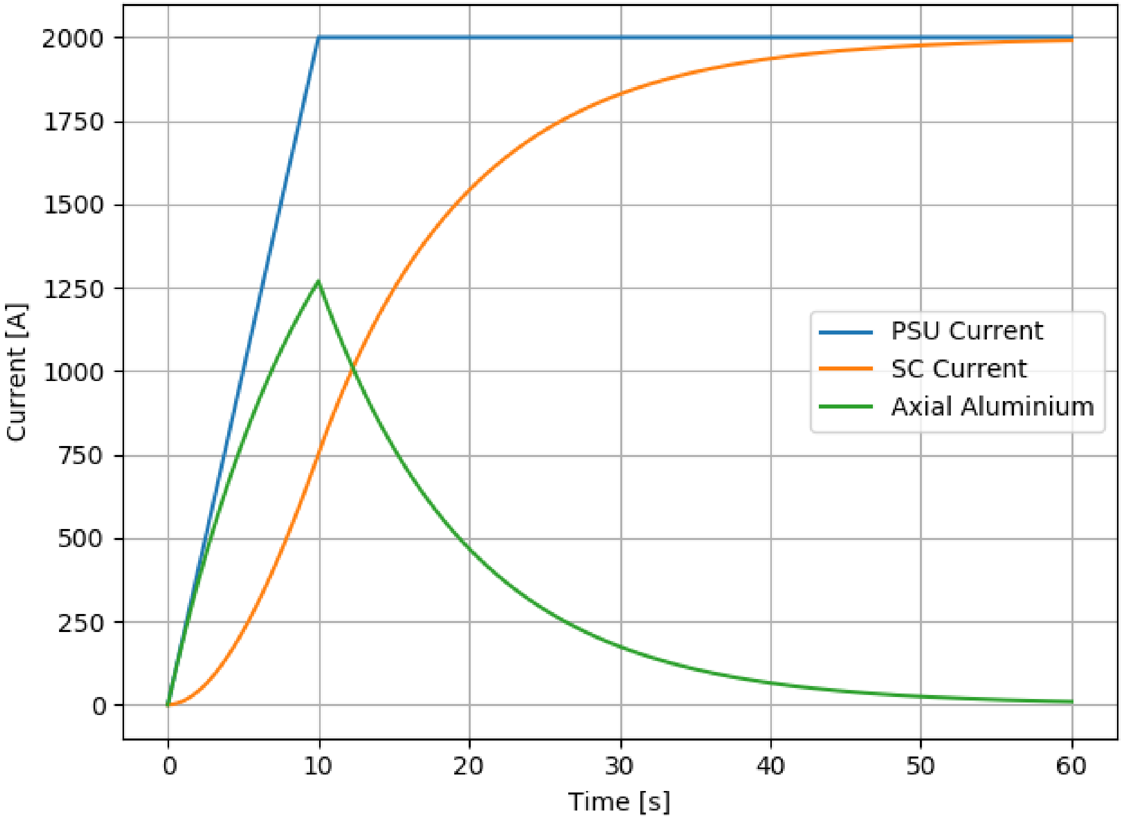




No-Insulation Coils: Operation

How fast can you charge a NI COIL?

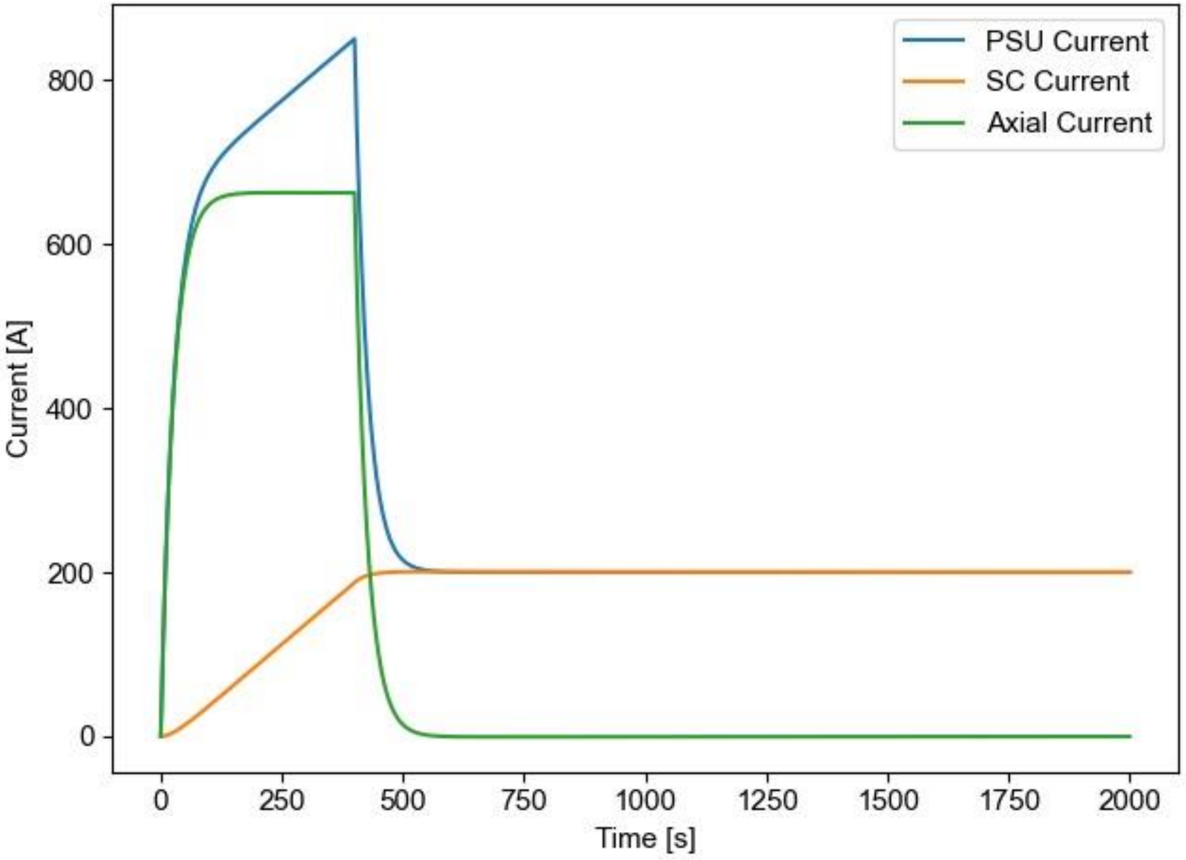


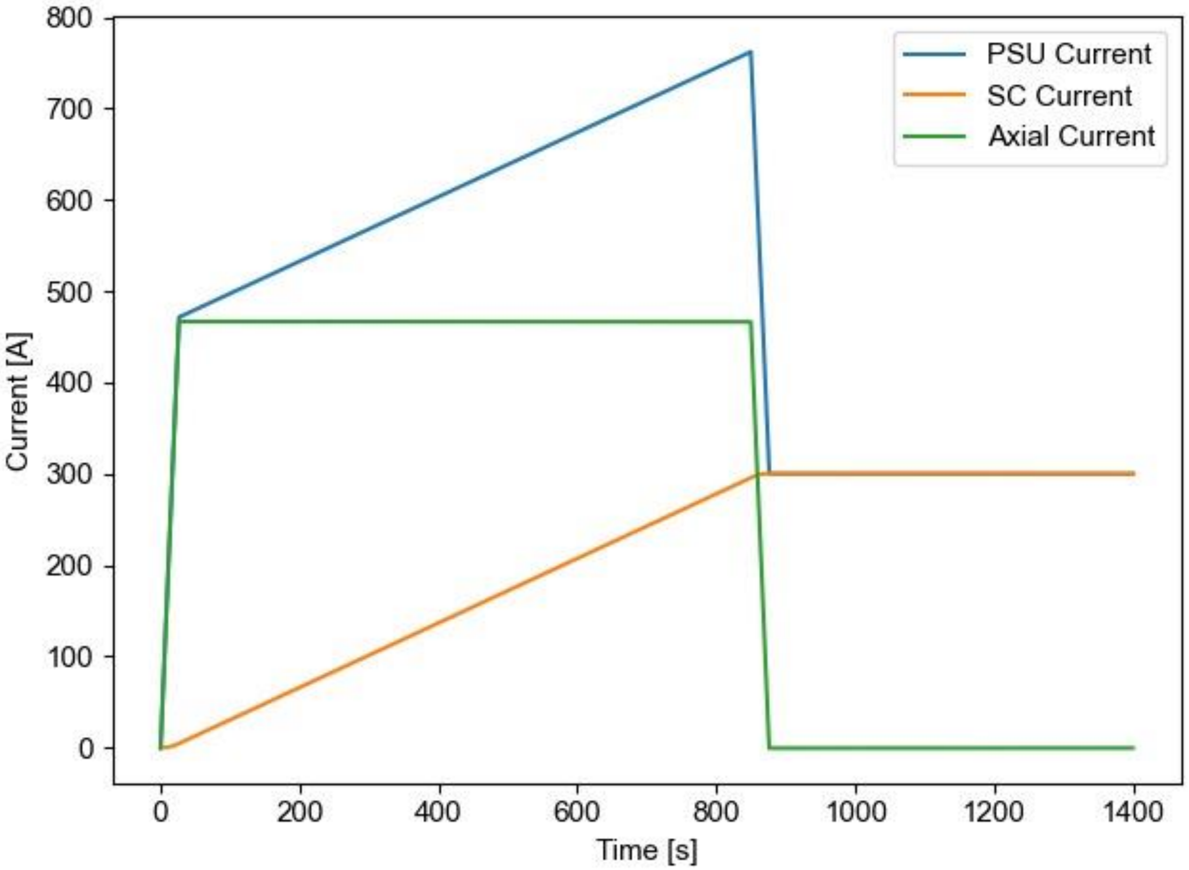


High τ means a long charge time if cooling is limited. Can we speed things up?

No-Insulation Coils: Operation -> Fast Charge

Charging can be accelerated by going to overcurrent.
High ohmic losses, less static loss as the charge is much quicker.
PSU should provide a current >> I_{op}.

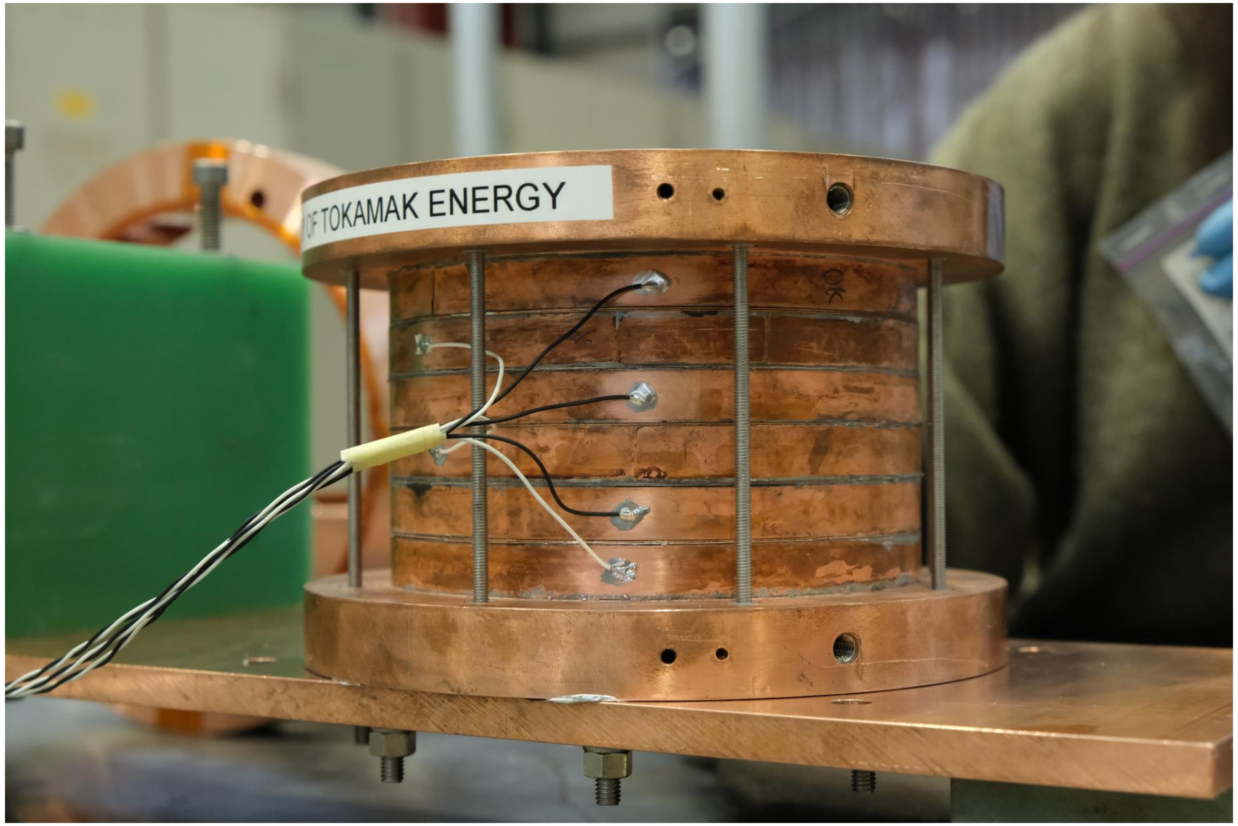




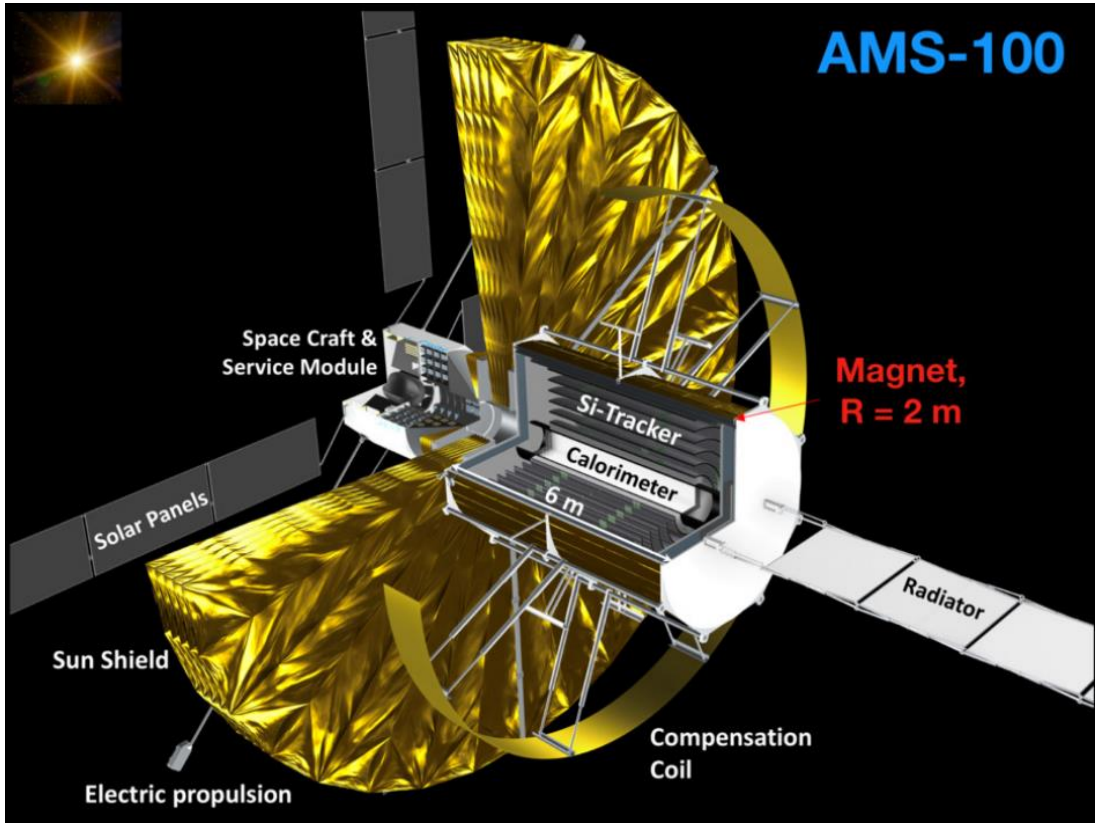
Example calculated ramp schemes for the NI solenoid TE-MSC tested at the cryolab, CERN July 2021.

Practical Examples

Operation of an HTS NI solenoid

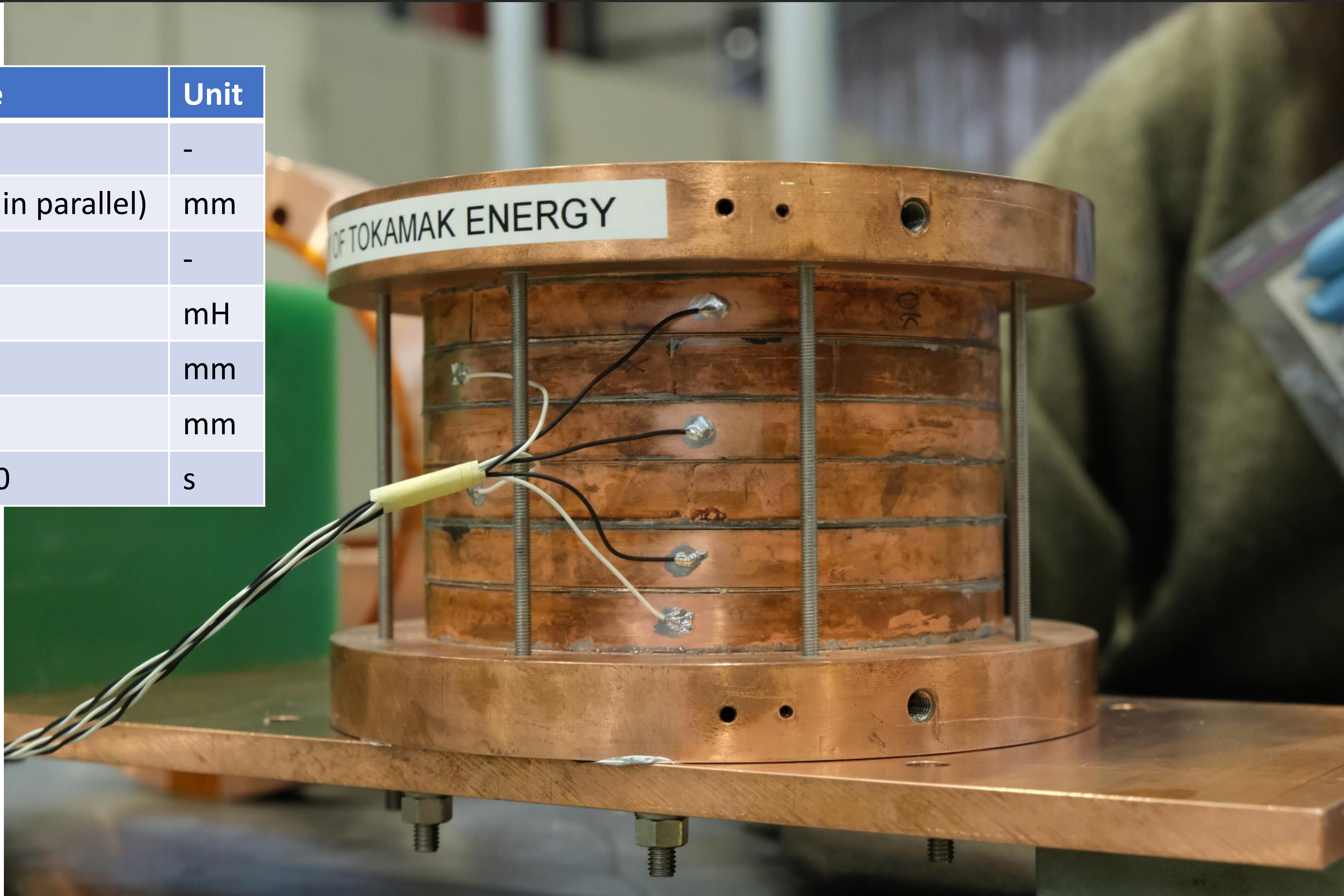


Design and Quench Simulation



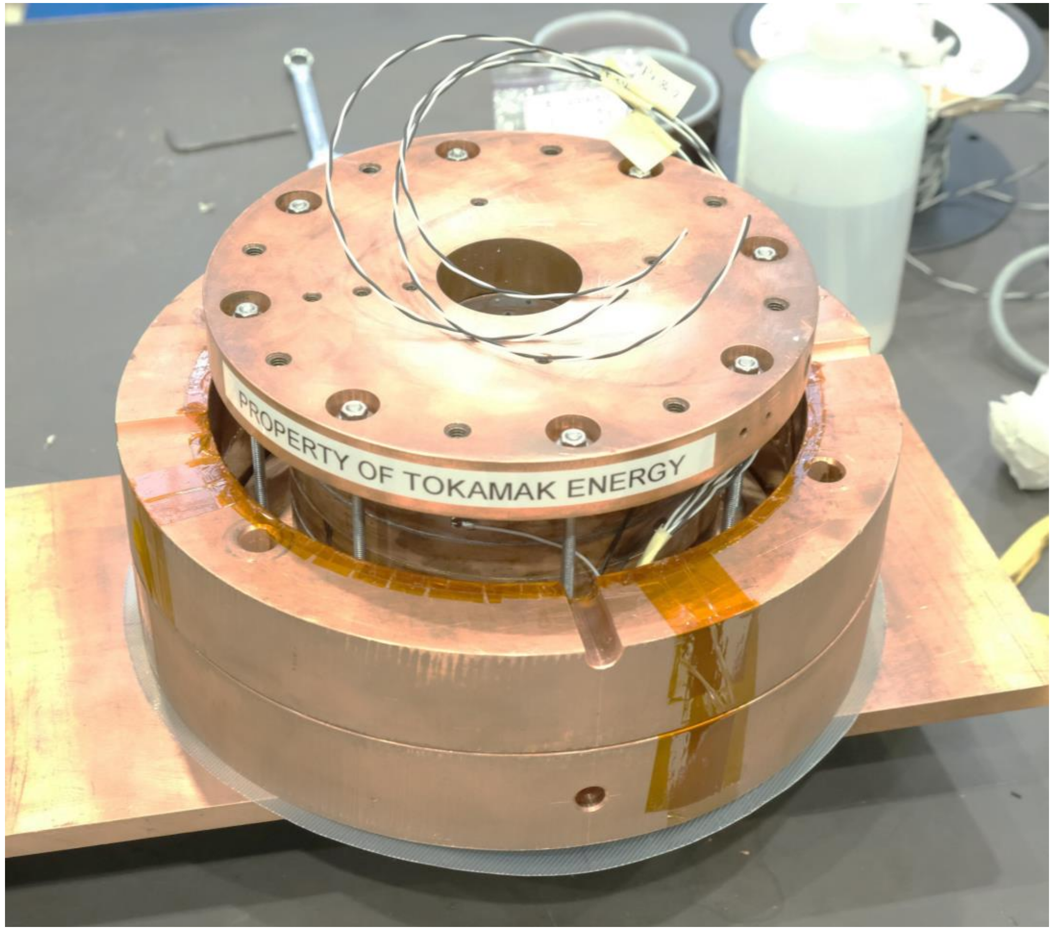
Demo3 Test

	Value	Unit
Pancakes	6	-
Tape-width	12 (2 in parallel)	mm
Nr. of turns	~205	-
Inductance	74	mH
Bore-diameter	50	mm
Outer Diameter	140	mm
Time constant (20 K)	~3800	s



Demo3 Test

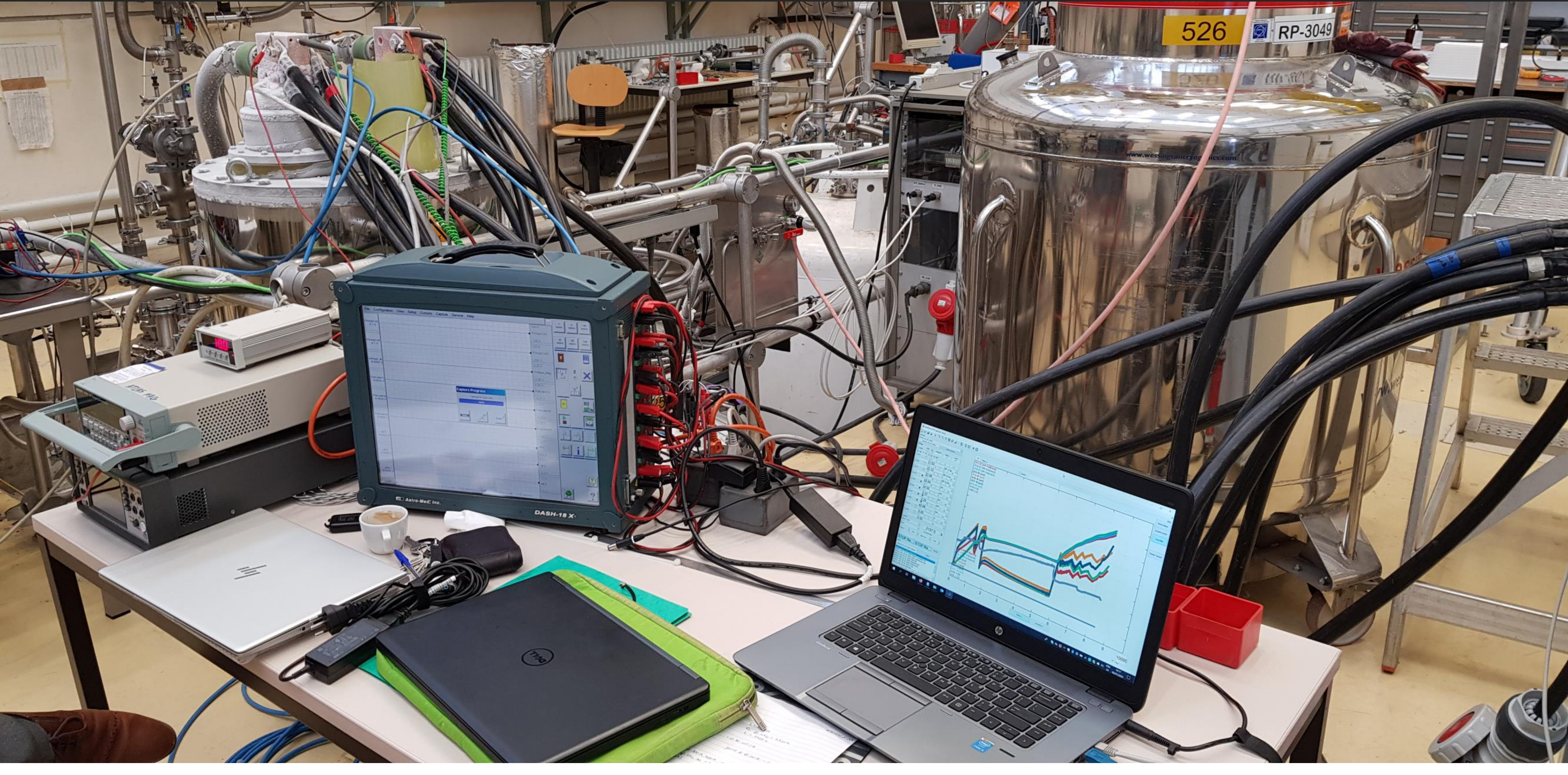
3 Hall probes in the bore of the magnet.



Three Cu cylinders to shield the high dB/dt in case of a quench.

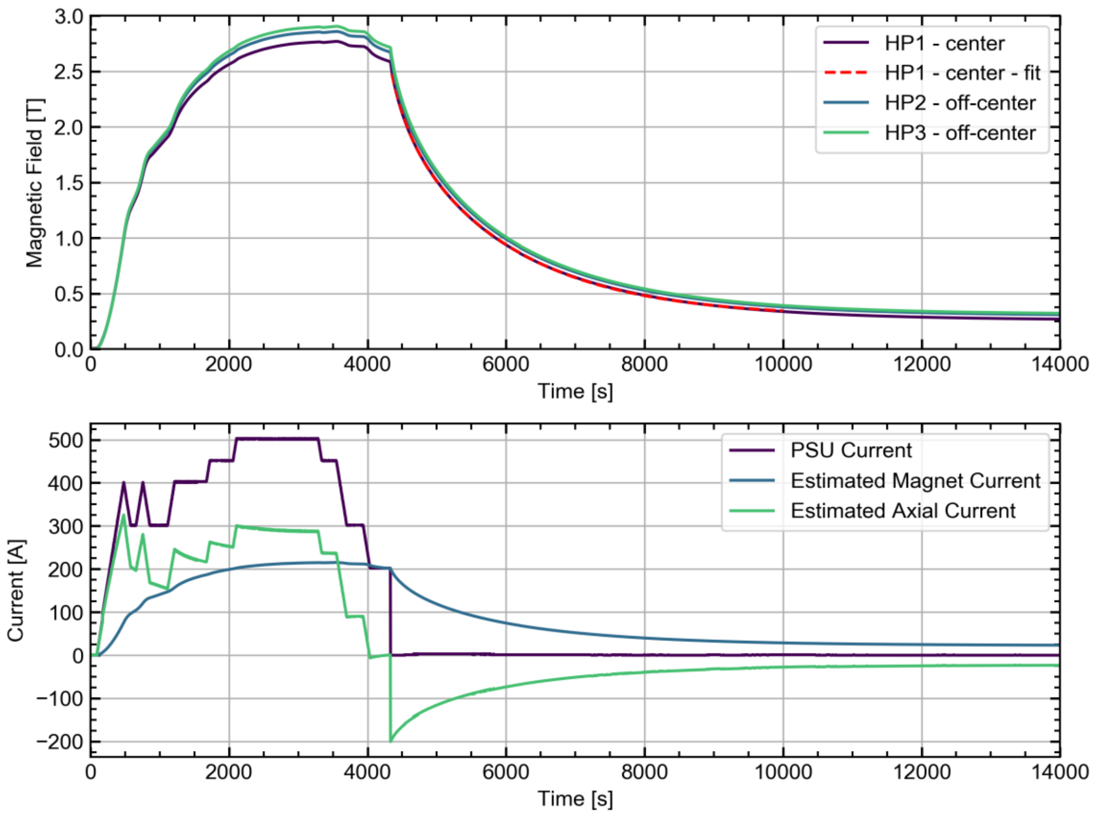
Full insert.

Demo3 Test

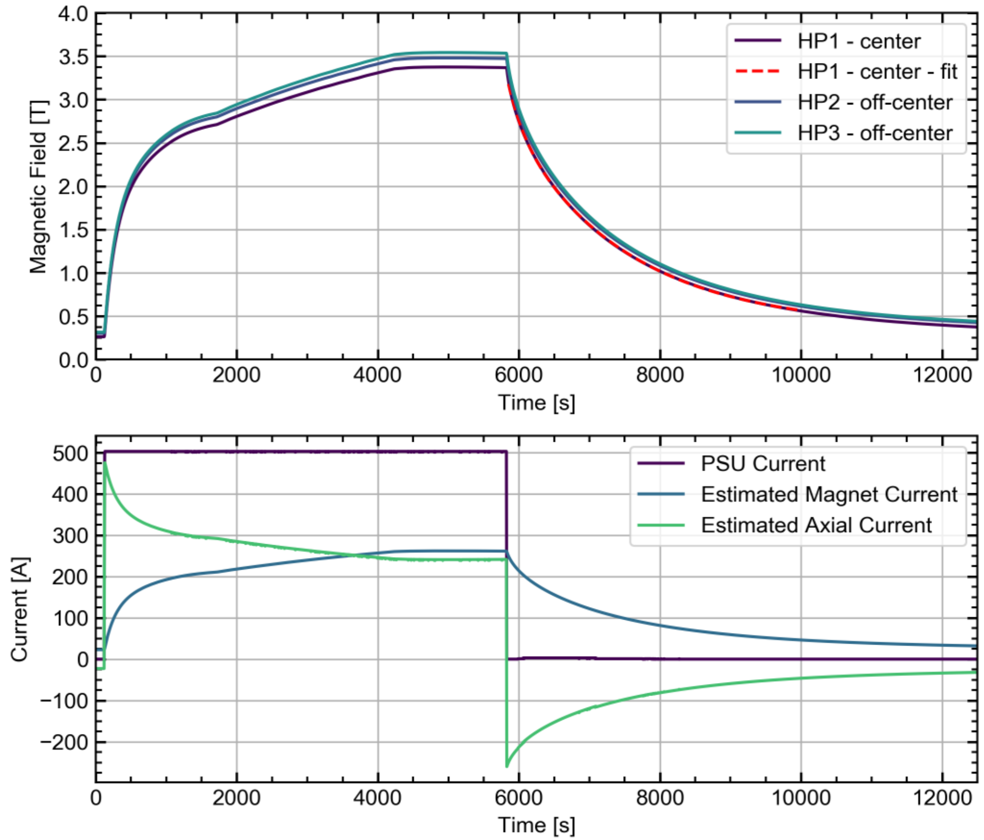


Demo3 Test – LN2

First test in LN2 -> Checking equipment and pre-cooling



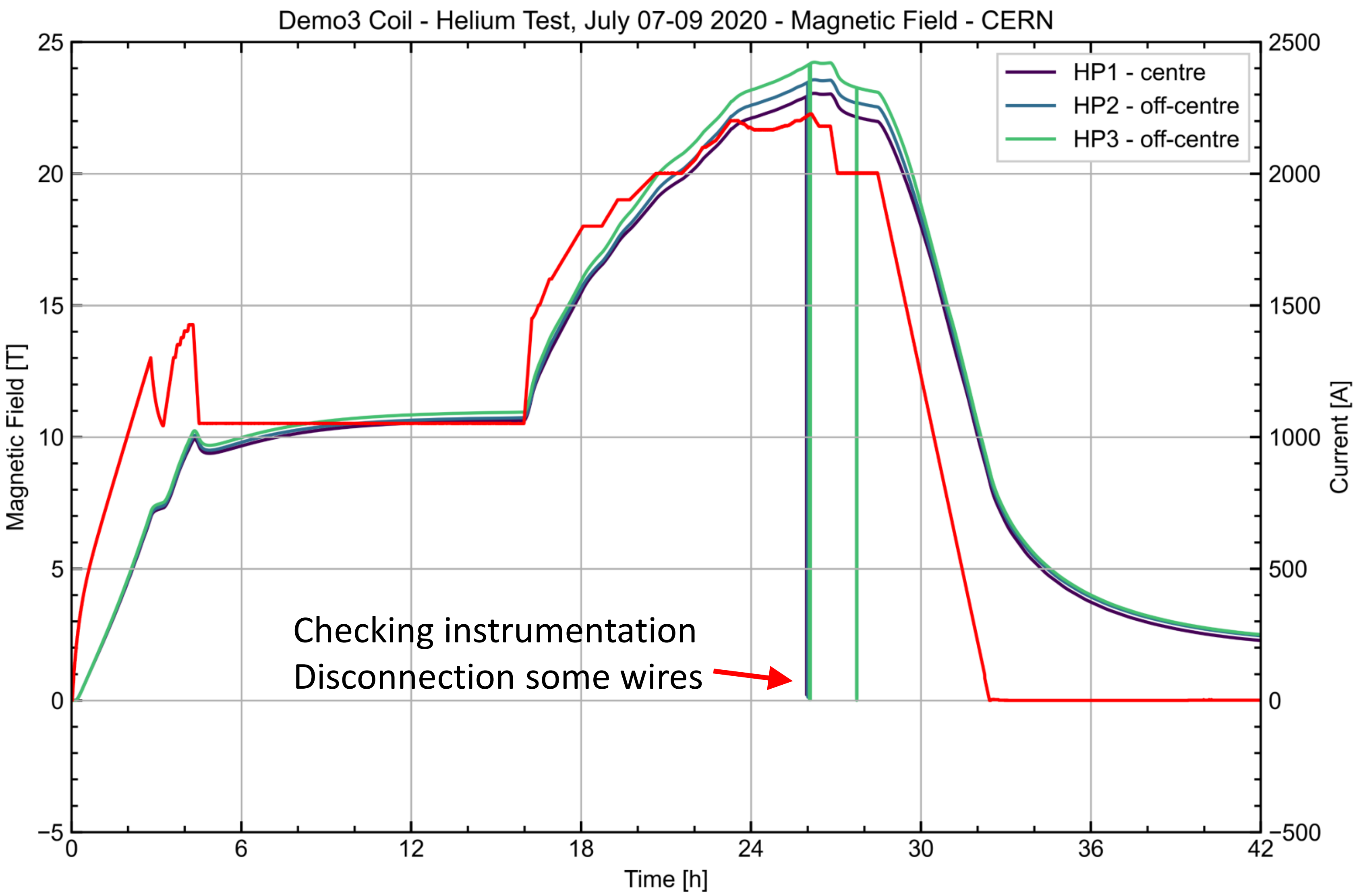
Slow ramp and plateaus.



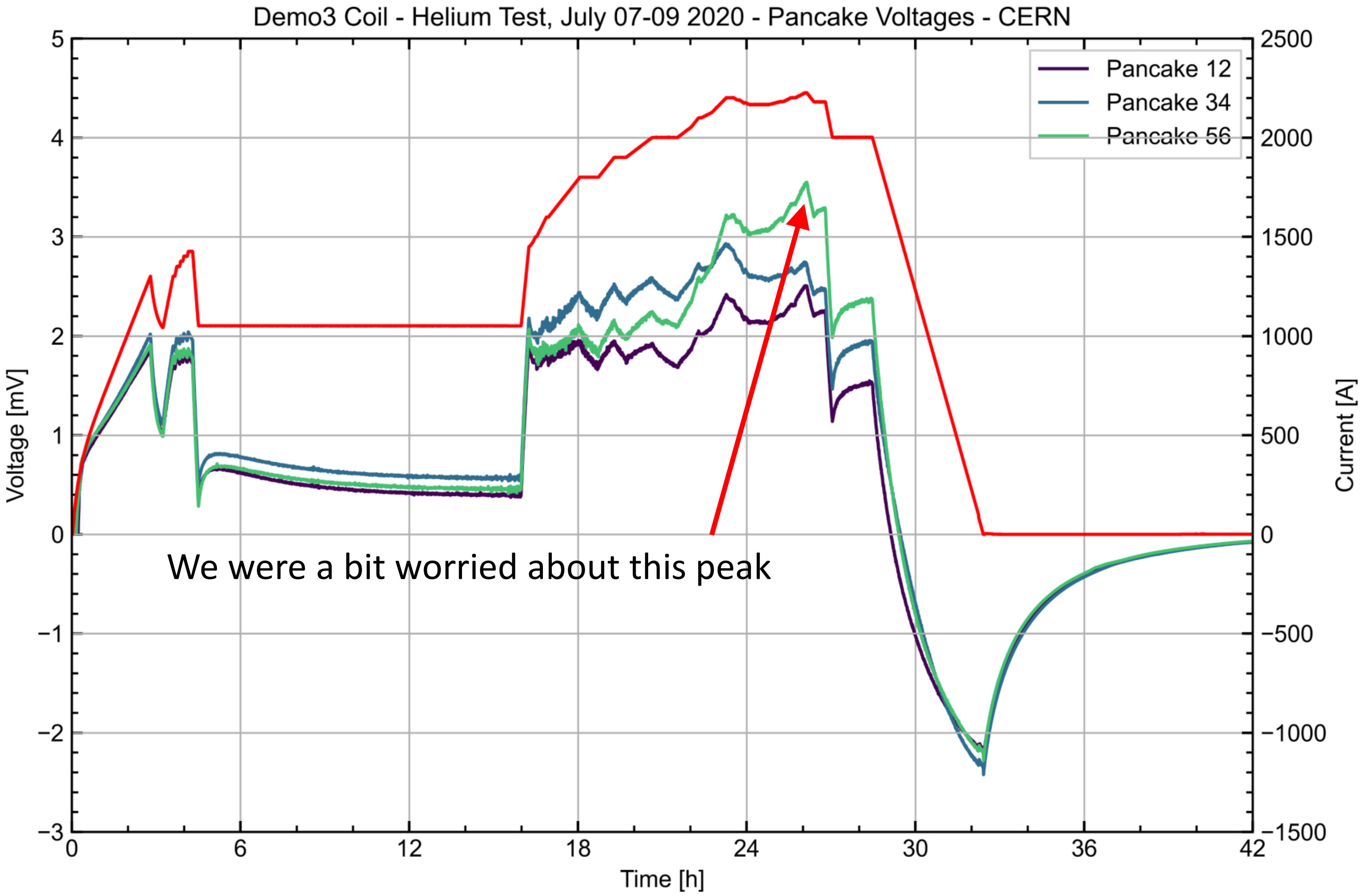
Step to 500 A.

Note that the critical current was about 350 A at 77 K.

Demo3 Test – Test Run 1

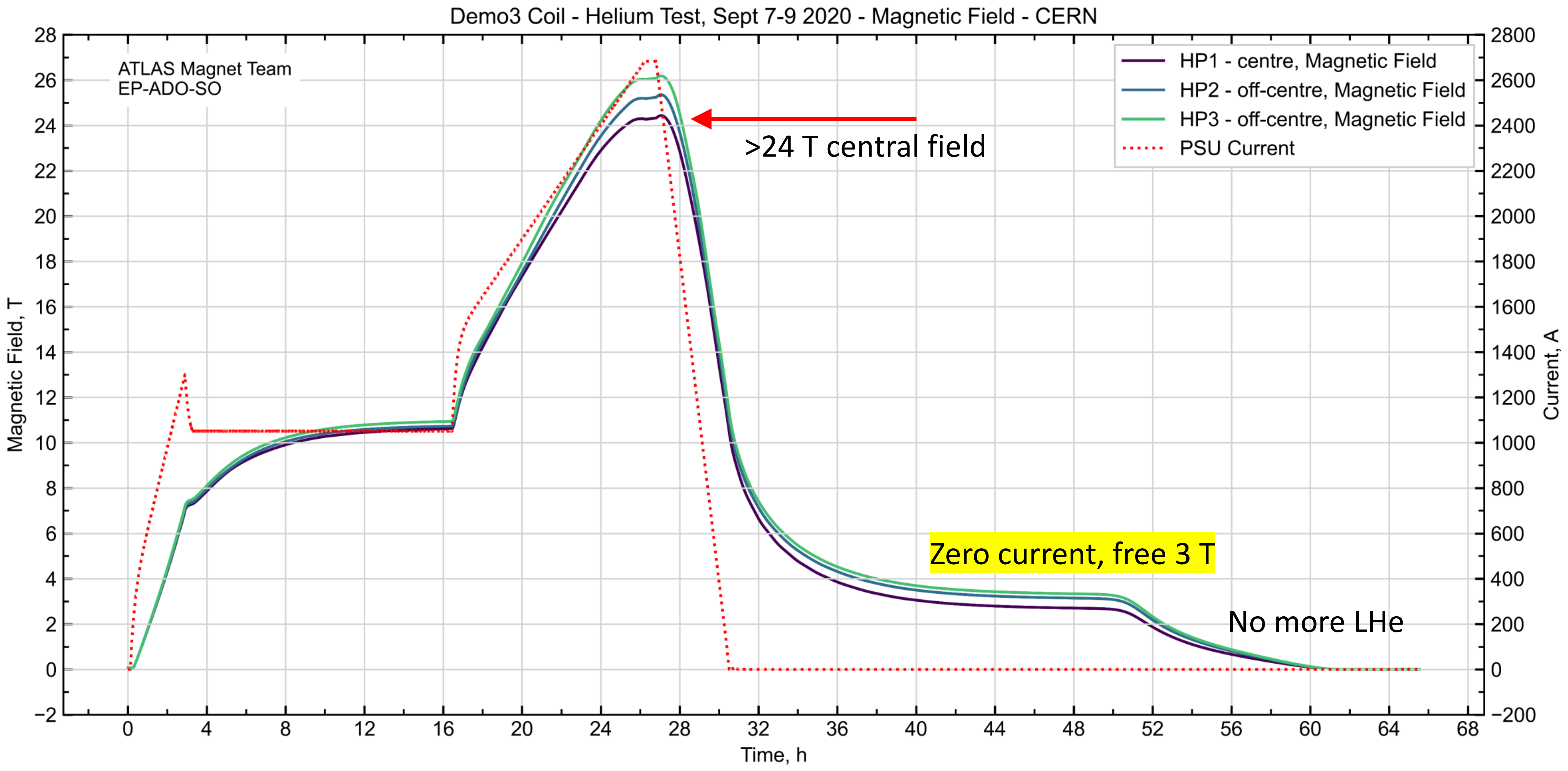


Demo3 Test – Test Run 1

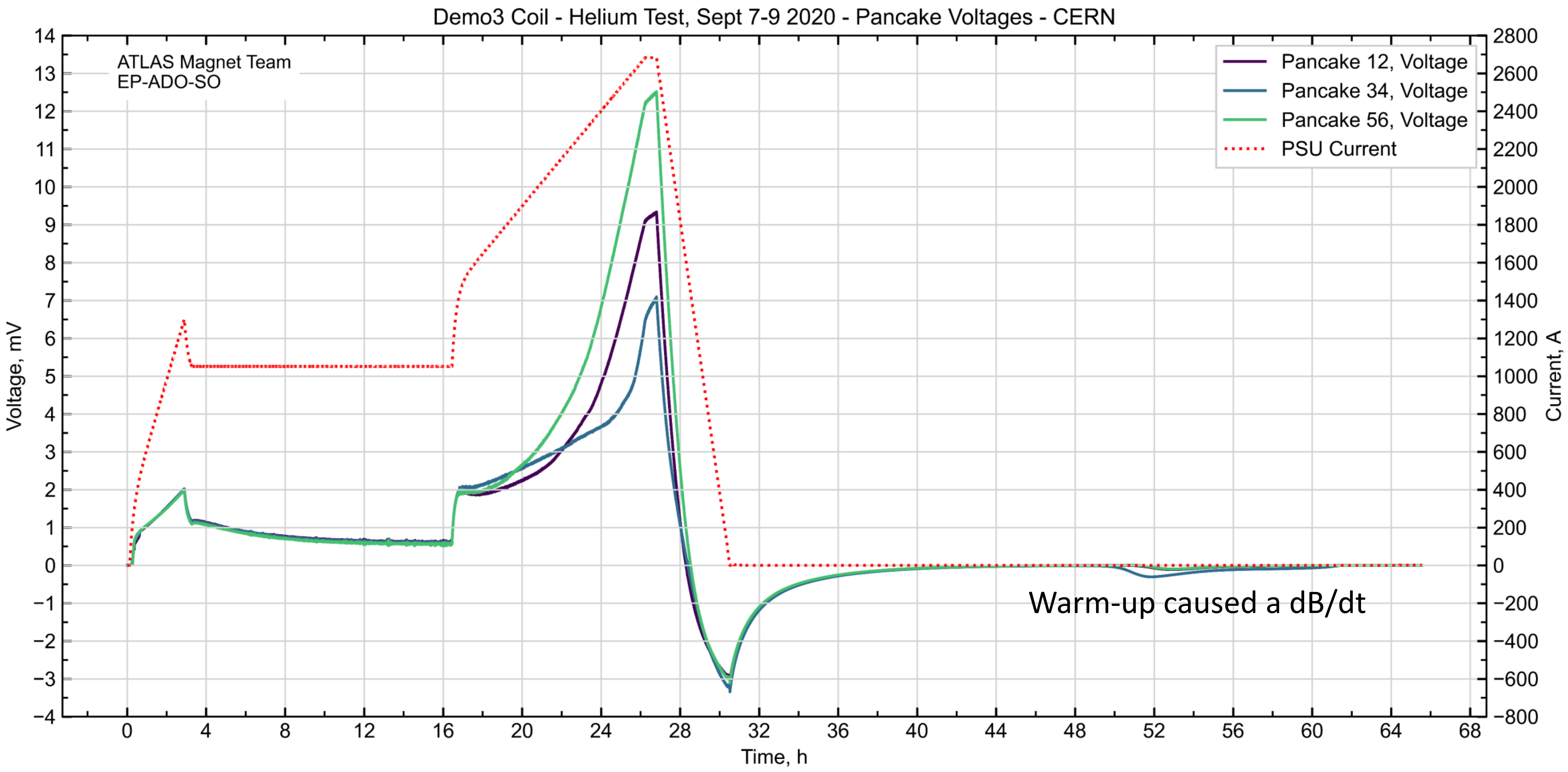


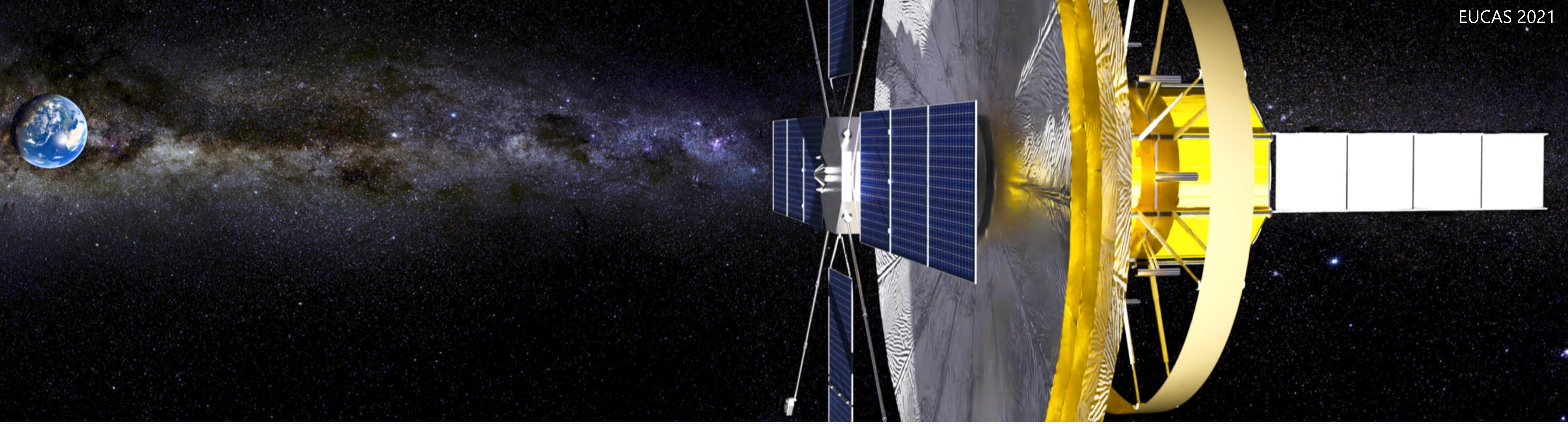
We were a bit worried about this peak

Demo3 Test – Test Run 2



Demo3 Test – Test Run 2





Development of the Large Ultra-Thin HTS Magnet System for the AMS-100 Experiment in Space

Tim Mulder, Jannik Zimmermann, Dominik Pridöhl, Tommaso Bagni, Alexey Dudarev, Daniel Louis, Christian Kaeseberg, Waclaw Karpinski, Thomas Kirn, Matthias Mentink, Milou Van Rijnbach, Kai-Uwe Schröder, Arndt Schultz von Dratzig, Carmine Senatore, Thorsten Siedenburg, Helder Silva, Davide Uglietti, Michael Wlochal and Stefan Schael

RWTH AACHEN UNIVERSITY

EPFL

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AMS-100 A Magnetic Spectrometer – Successor of AMS-02

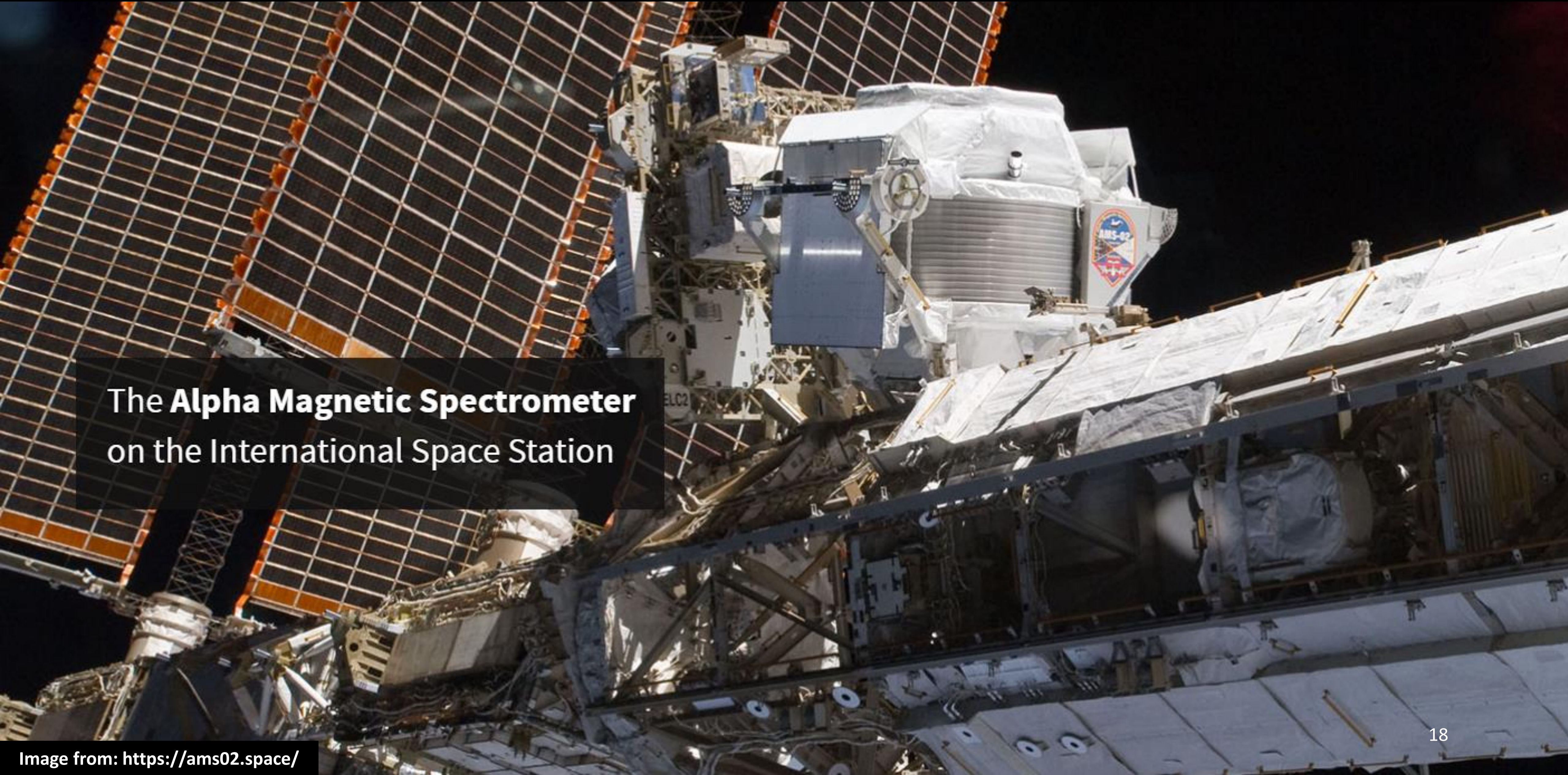
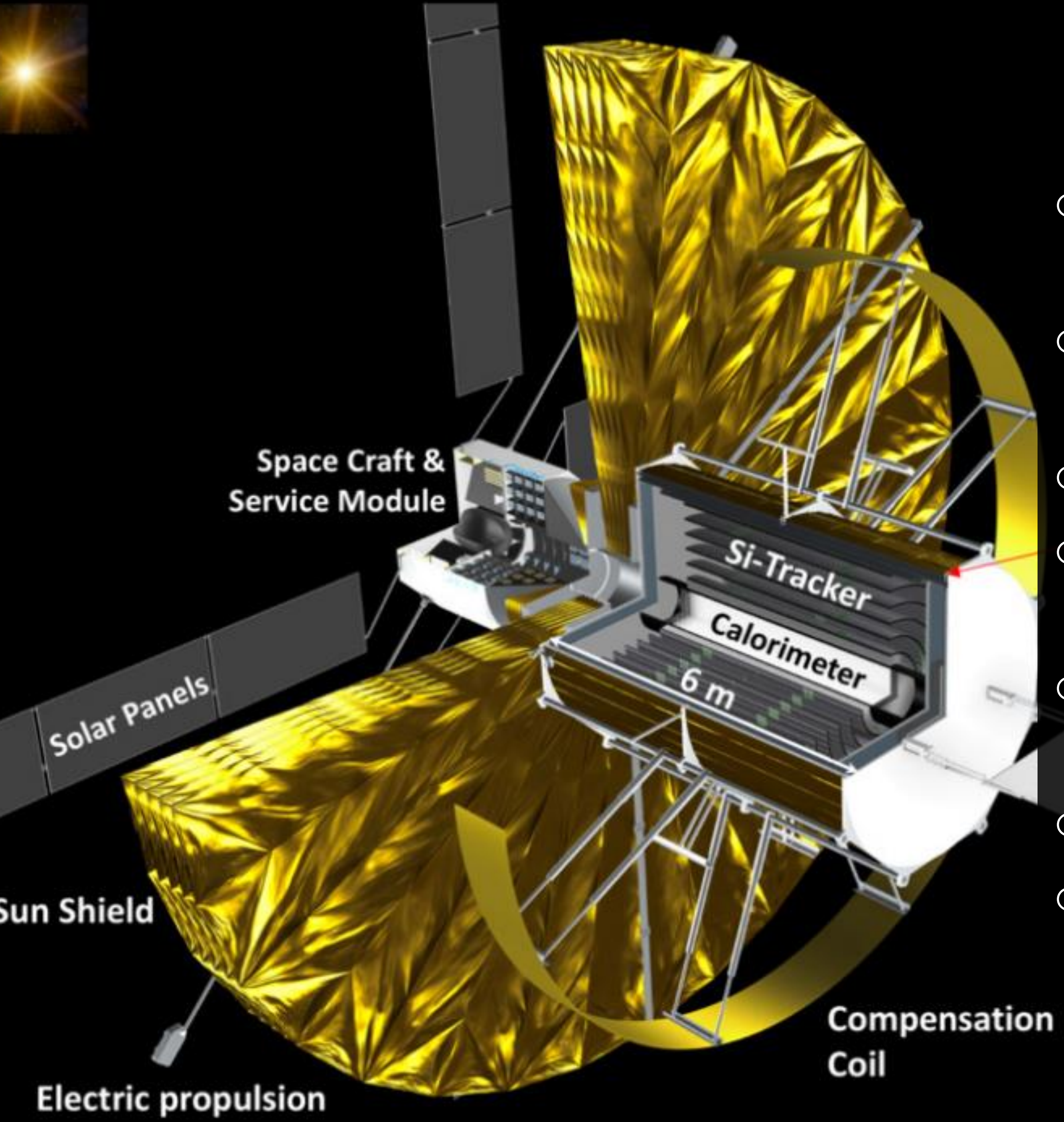


Image from: https://ams02.space/



AMS-100: Overview

- Magnetic Spectrometer to be send to Lagrange Point 2 (1.5 Mkm from earth).
- Probing high energy cosmic rays, in particular anti-protons and anti-deuterons.
- Geometric acceptance of 100 m^2 sr.
- Magnet is a 6 m long, 4 m diameter, 1 T HTS ultra-thin solenoid.
- No active cooling, only passive cooling using radiators.
- Electrical/thermal/mechanical challenge.
- Compensation coil needed to correct magnetic torque during operation.

The Expedition to Lagrange Point 2

Vehicle and Launch:

- Target launch year: 2039.
- Operational for 10+ years.
- Total estimated mass of AMS-100: 40 Tons[1]
  - ~2 Tons for the magnet system,
  - ~18 Tons of detector equipment,
  - ~20 Tons of auxiliary equipment and cabling.
- Launched with SpaceX's Starship rocket.

AMS Pathfinder mission:

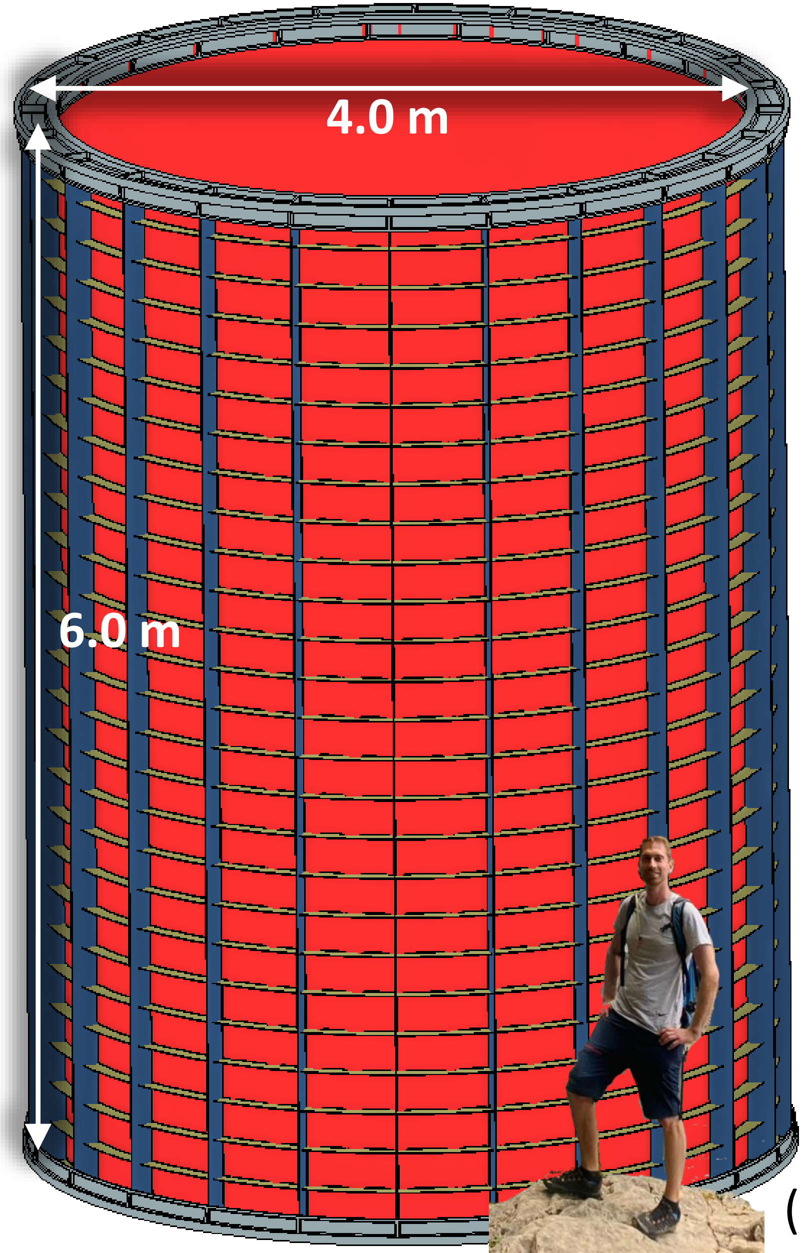
- First radiation cooled HTS magnet in space of such size.
- Test the operation at L2.
- Controls, radiation cooling etc.

[1] AMS-100: The Next Generation Magnetic Spectrometer in Space – An International Science Platform for Physics and Astrophysics at Lagrange Point 2, S. Schael et al., Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip., vol. 944, 2019

AMS-100: Design Challenges

- Radiation transparency is important -> thin ~4 mm thick aluminium stabilized conductor. The coil pack needs to provide mechanical stability for the magnet system. Major mechanical challenge.
- Coil needs to survive stresses caused by launch, cool down and magnet powering.
- The AMS-100 magnet will have a large stored energy of approximately 34 MJ -> 21 kJ/kg. HTS materials are very stable and are difficult to quench. However, they also have the downside that HTS magnets are also difficult to protect, mainly due to the low NZPV.
- Controlled Resistance coil -> turns are shorted with a controlled resistance. High enough resistance to charge to coil in a timely fashion, but low enough to protect the magnet in case of a failure event. Major electrical and thermal challenge.
- Magnetic torque needs to be compensated. Can be achieved with a compensation coil. However, given the diameter of the main solenoid, difficult to fit in the rocket's cargo bay.

AMS-100: A Magnetic Spectrometer



(me, for scale)

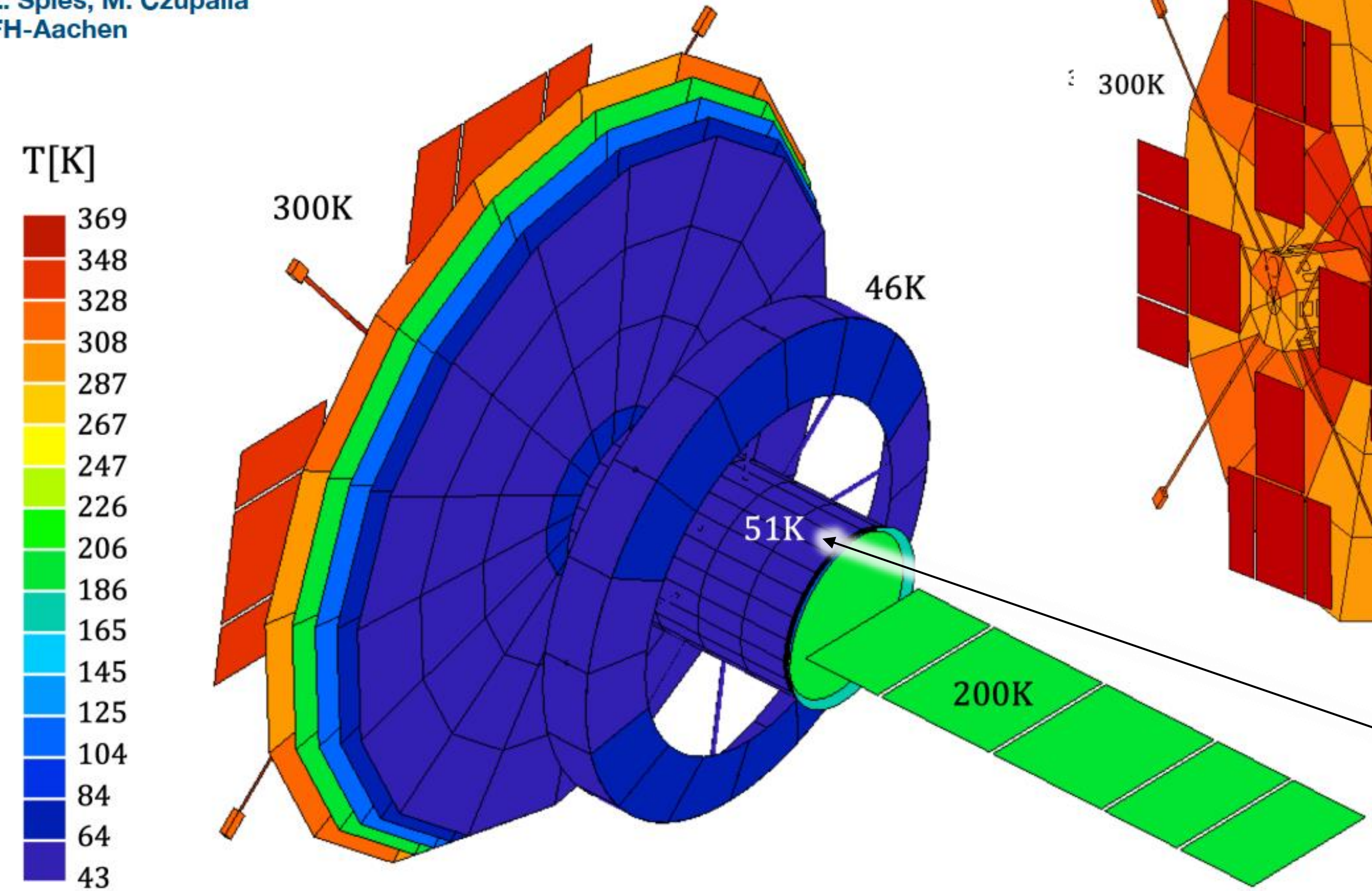
Table of properties for the AMS-100 and Pathfinder coils.

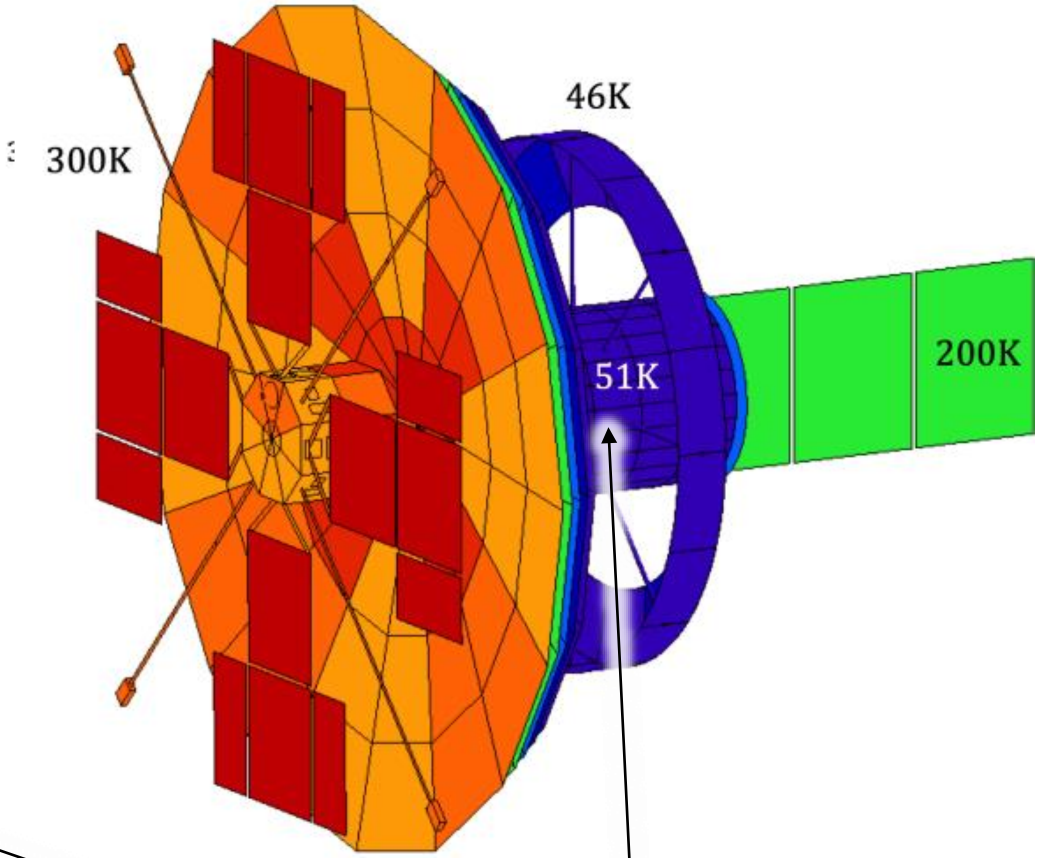
	AMS-100	AMS-100 Pathfinder	Unit
Coil radius	2.0	0.6	m
Coil length	6.0	1.8	m
Tape width	12	12	mm
Layers	1	1	-
Turns	428	128	-
Inductance	377	10.5	mH
Number of tapes	20	20	-
Total tape length	109	10	km
Operating current	13.5	13.5	kA
Stored Energy	34	1	MJ
Energy Density*	21	7	kJ/kg
Wall thickness	~5	~5	mm

*Considering only the mass of the conductor.

Thermal Analysis of AMS-100

L. Spies, M. Czupalla
FH-Aachen





Thermal analysis shows magnet-radiator temperature of 50 to 60 K.

Magnetic Field and Stability

Design B-field of 1 T in the center, 1.07 T // to the conductor in the center of the solenoid.

Operating temperature range of 50 to 60 K:

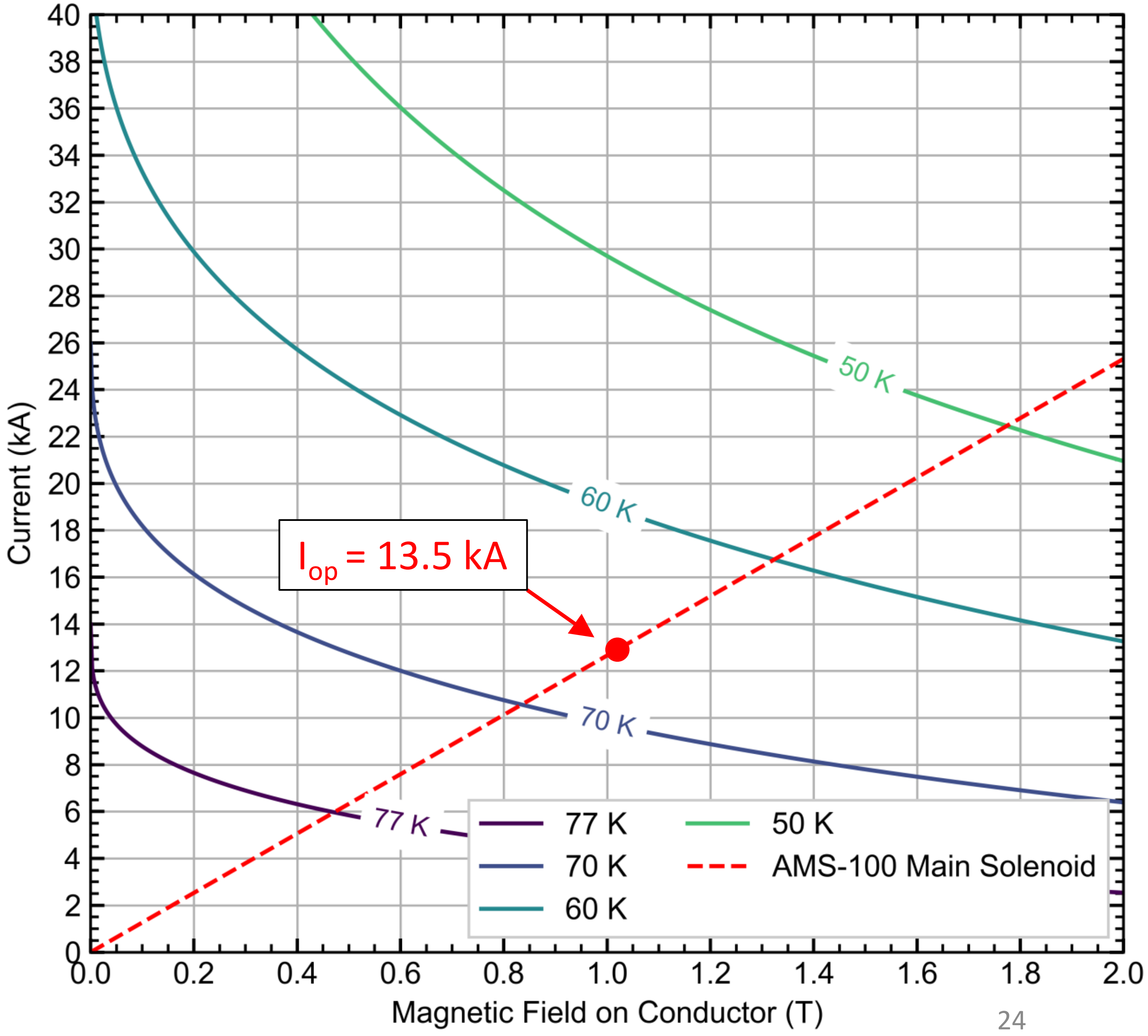
- ΔT of 7 K @ 60 K
- ΔT of 17 K @ 50 K

Large temperature margin is important:

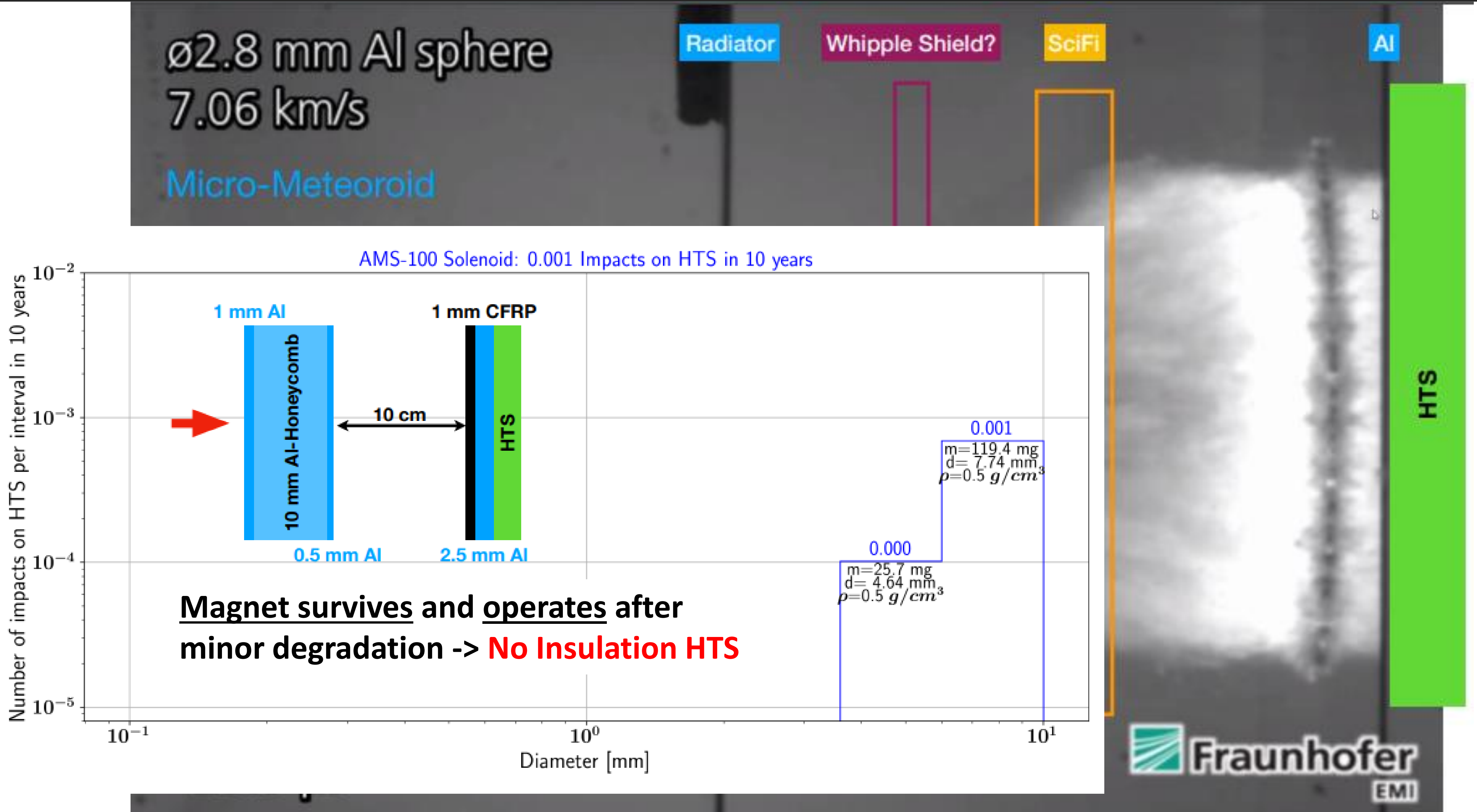
- cooling power is very limited,
- high energy density,
- no intervention possible.

Smart spacing of the conductor / additional HTS tape is envisioned at the coil extremities to reduce the peak field. Without this, there will be 1.5 T on the conductor.

The field homogeneity is not an operation critical parameter.



Dangers of Space: Micrometeorite Impact

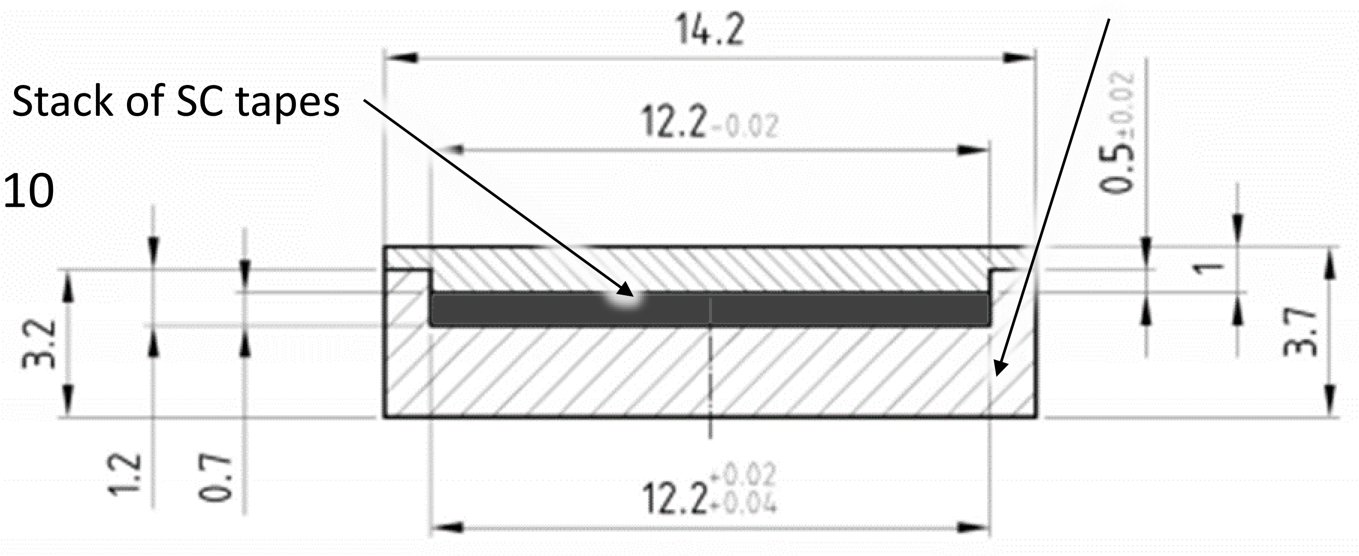


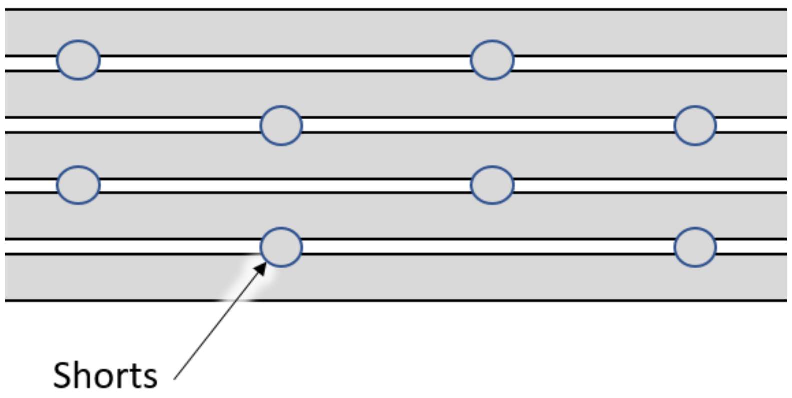
<u>Magnet survives</u> and <u>operates</u> after minor degradation -> No Insulation HTS

Conductor and Coil Layout

Current conductor layout:

- Stack of twenty 12 mm wide HTS tapes, 25 µm substrate of 5 µm of stabilizer.
- HTS stack is soldered to tin-coated aluminum (6110 series) conductor stabilizer.
- Conductor closed by welded cap.
- Conductor thickness of 3.7 mm.
- Outer surface anodized to provide turn-to-turn insulation.





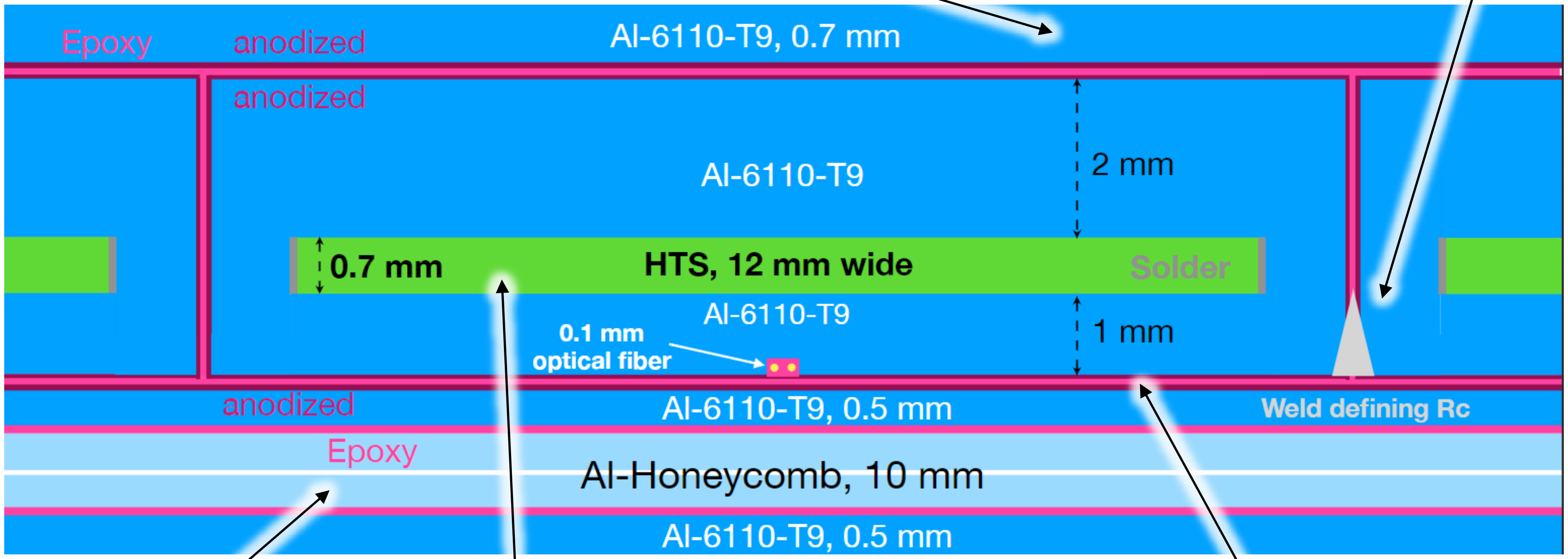
Shorting turns by (EB / laser) point welding.

- 1 mm^2 weld provides a turn-to-turn resistance of about 3e-5 Ω.
- AMS-100 -> 1250 mm^2 per turn (10 % of the circumference) covered with point welds of 1 mm^2 -> τ = 10 hours.
- Provides mechanical strength and provides thermal/electrical path.
- Shorts are within the envelope of the conductor pack.
- To be tested and to be demonstrated.

Structure of the Main Solenoid

Al-alloy skin for mechanical strength and axial thermal conductivity

Local spot welding



Honeycomb for mechanical stiffness

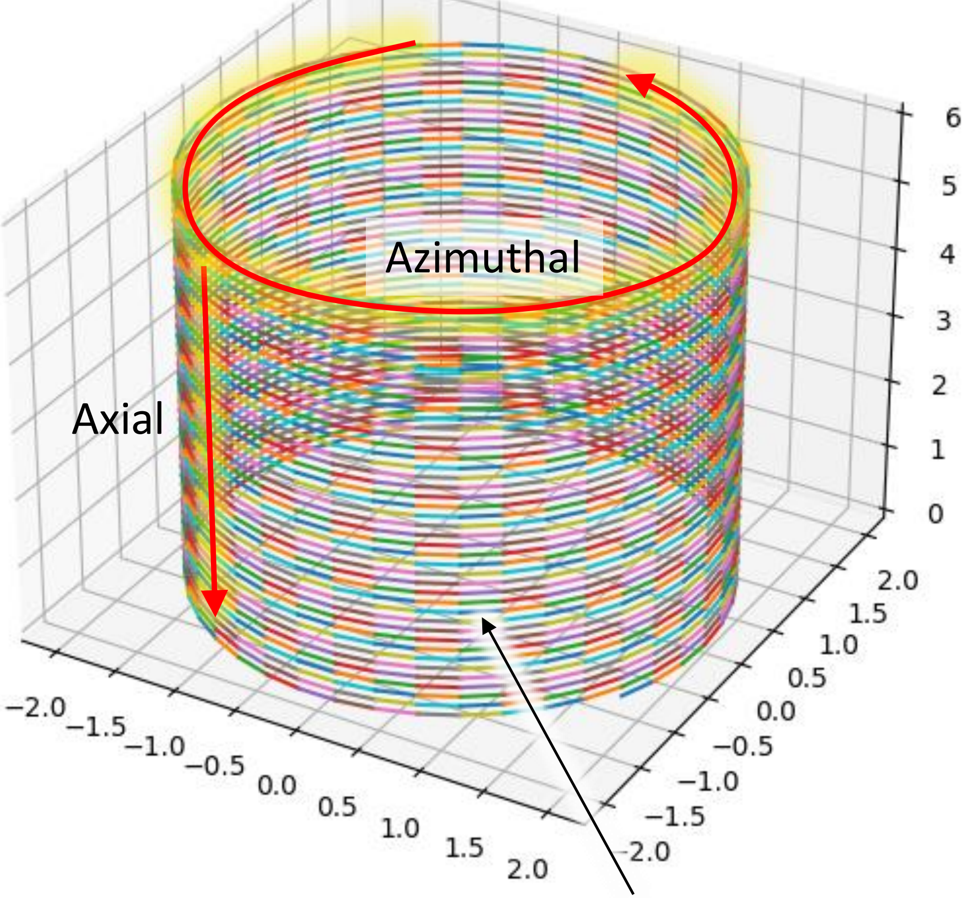
Stack of HTS tapes

Epoxy between layers

X_0 = 11% = Thickness of structure / Radiation length

Electric-thermal-magnetic Quench Model

Thermally and electrically connected:
Axial and azimuthal direction

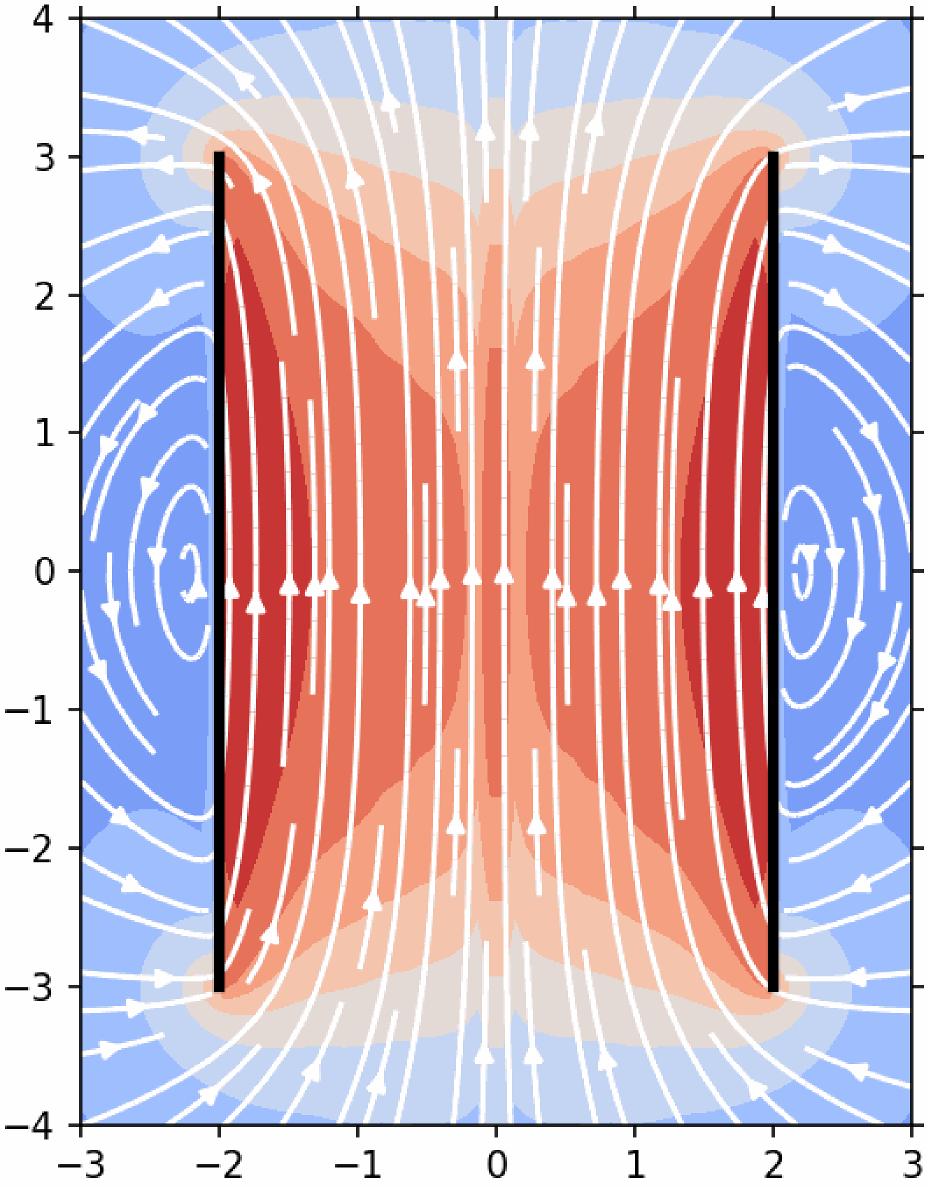


Turns divided in to line elements

Quench behavior of the non-insulated AMS-100 main solenoid

- Quench behavior of the AMS-100 main solenoid is studied for several quench scenarios.
- Quasi 3D thermal, electrical and magnetic nodal-network model is built using python.
- Results from this model are analyzed in ANSYS/Abacus to evaluate the resulting mechanical response.
- Model studies the effect of slow thermal runaway and consequently a fast quench as function of a small defect.
- Not enough resolution at the moment for sudden and very local defects (due for i.e. micrometeorite impact).
- Other structural elements, such as end-flanges and ribs, are not yet included in the model.

Electric-thermal-magnetic Quench Model



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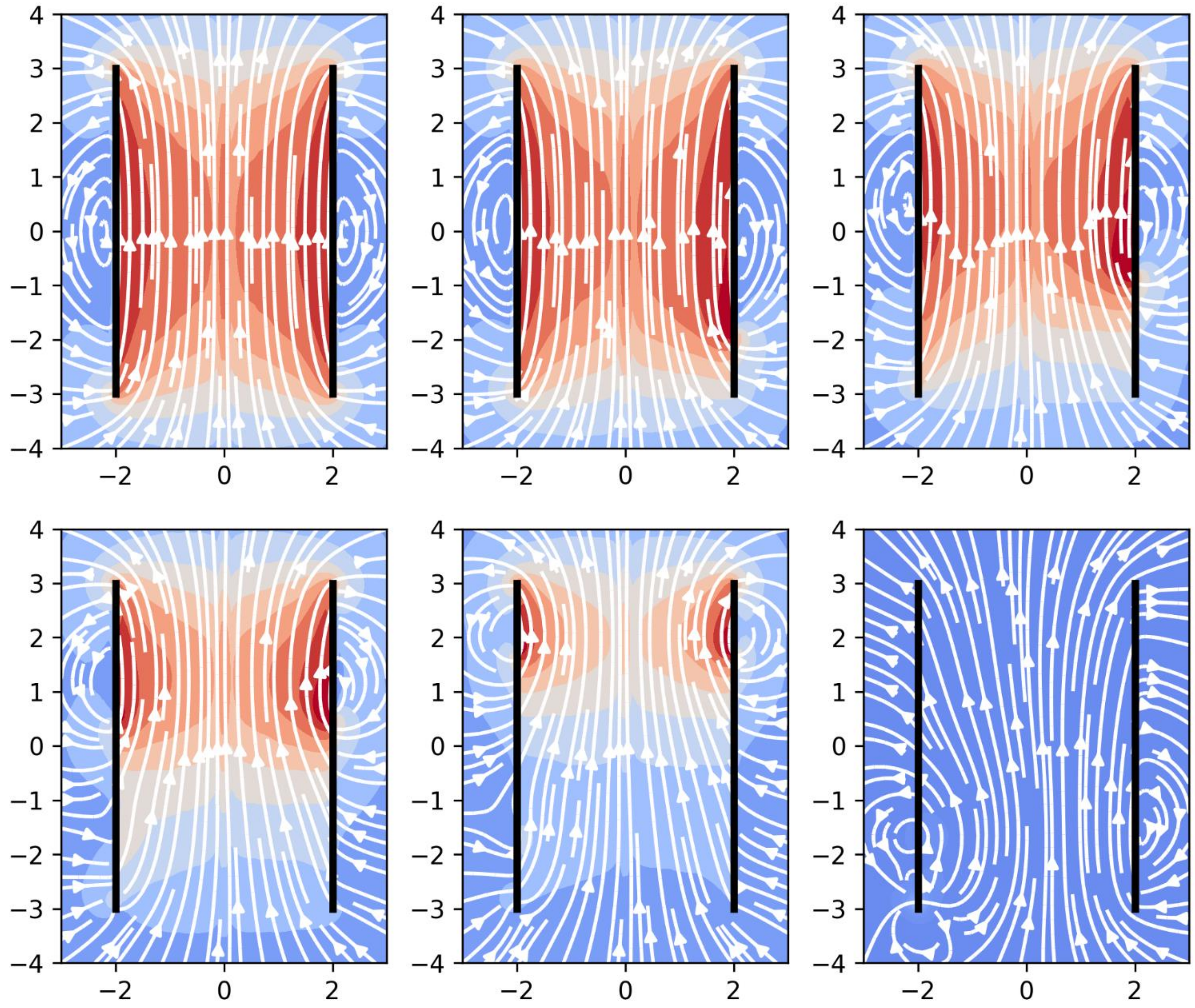
← Magnetic field evolution during a quench that started in an extremity of the solenoid (and on the right part of the graph). Locally current is pushed outwards towards the extremities.

* Singularity at r=0

Quench Behavior and Survival



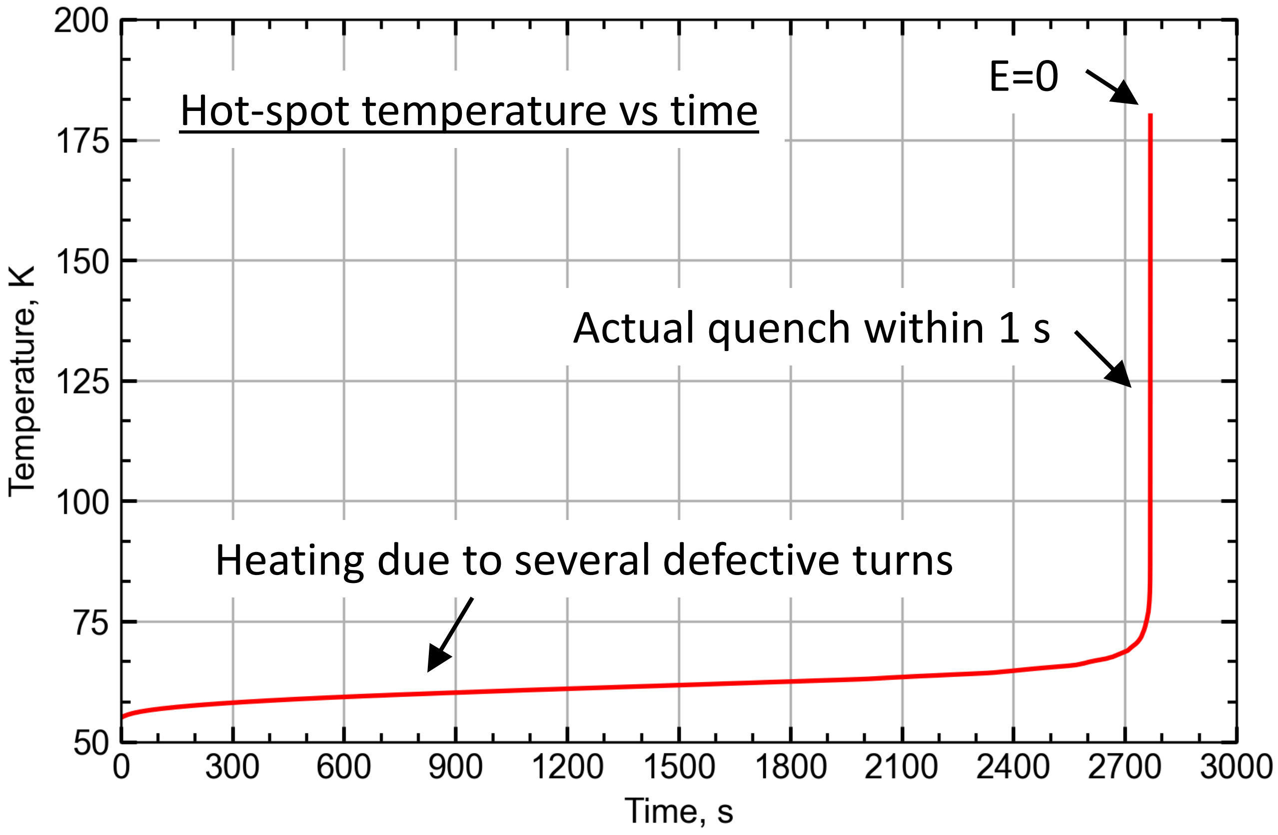
Quench behavior of the non-insulated AMS-100 main solenoid:

- Quench propagation is driven by inductive effects instead of thermal NZP.
- Current is pushed to adjacent turns, these turns reach I_c and consequently quench themselves.
- Hot-spots are observed near the coil extremities as current (and thus energy) is pushed towards those.
- Mechanical ripple follows the normal zone.
- Thermal run-away is slow, but the quench is fast < 1 s.

Quench Behavior and Survival

Investigated slow thermal runaway due to defective turn(s):

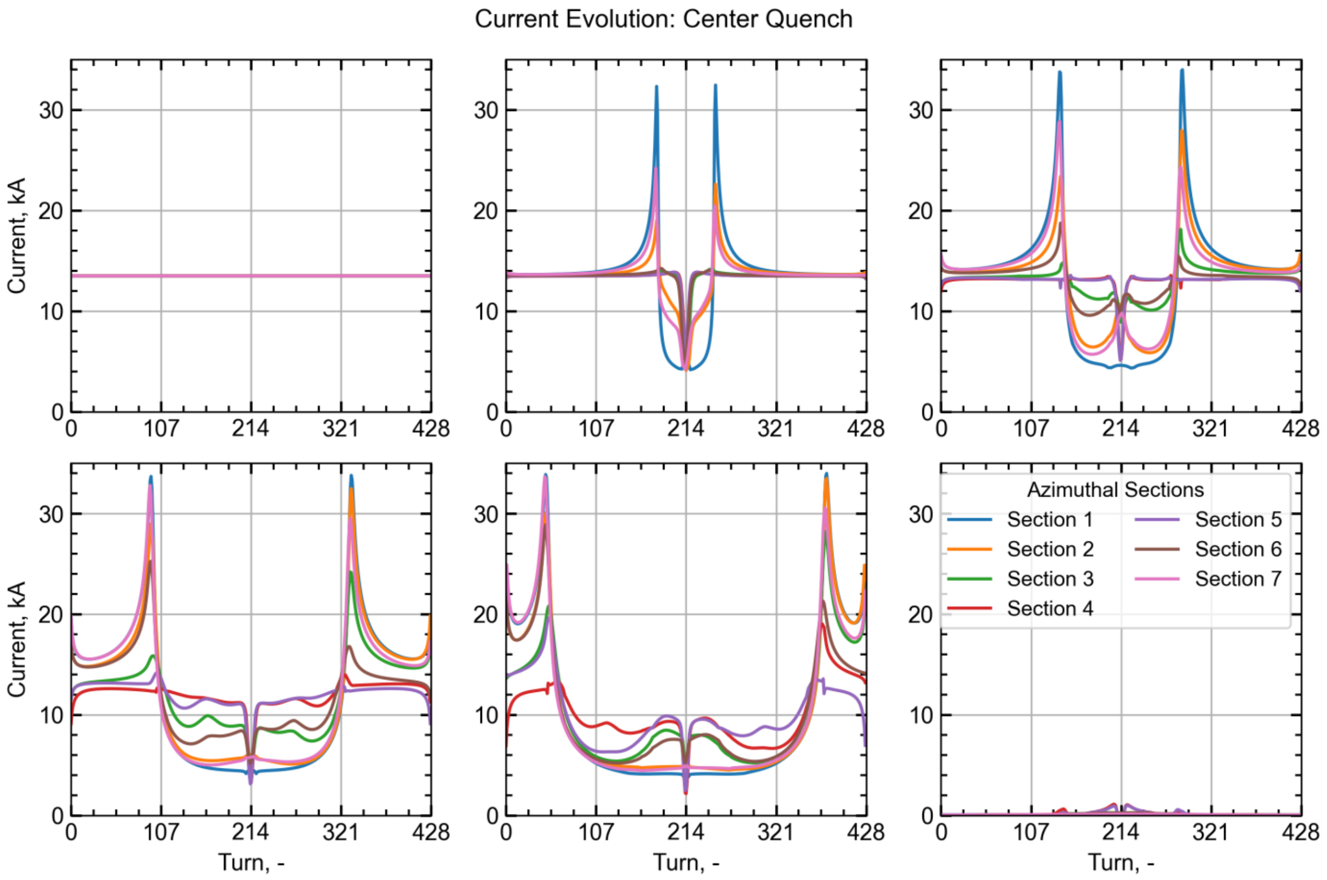
- Current bypasses the defective turn via its turn-to-turn resistance.
- ~ 4 W of heating in the axial resistance per turn.
- Slow thermal runaway in the order of hour(s).
- All energy dissipated within the magnet during the quench, no external extraction.
- Conventional protection methods, such as quench heaters, are ineffective.
- Quench at an extremity gives the highest hot-spot temperature of ~190 K.
- Last iteration of the conductor layout is able to cool away heat from one defective turn.



Quench Behavior and Survival

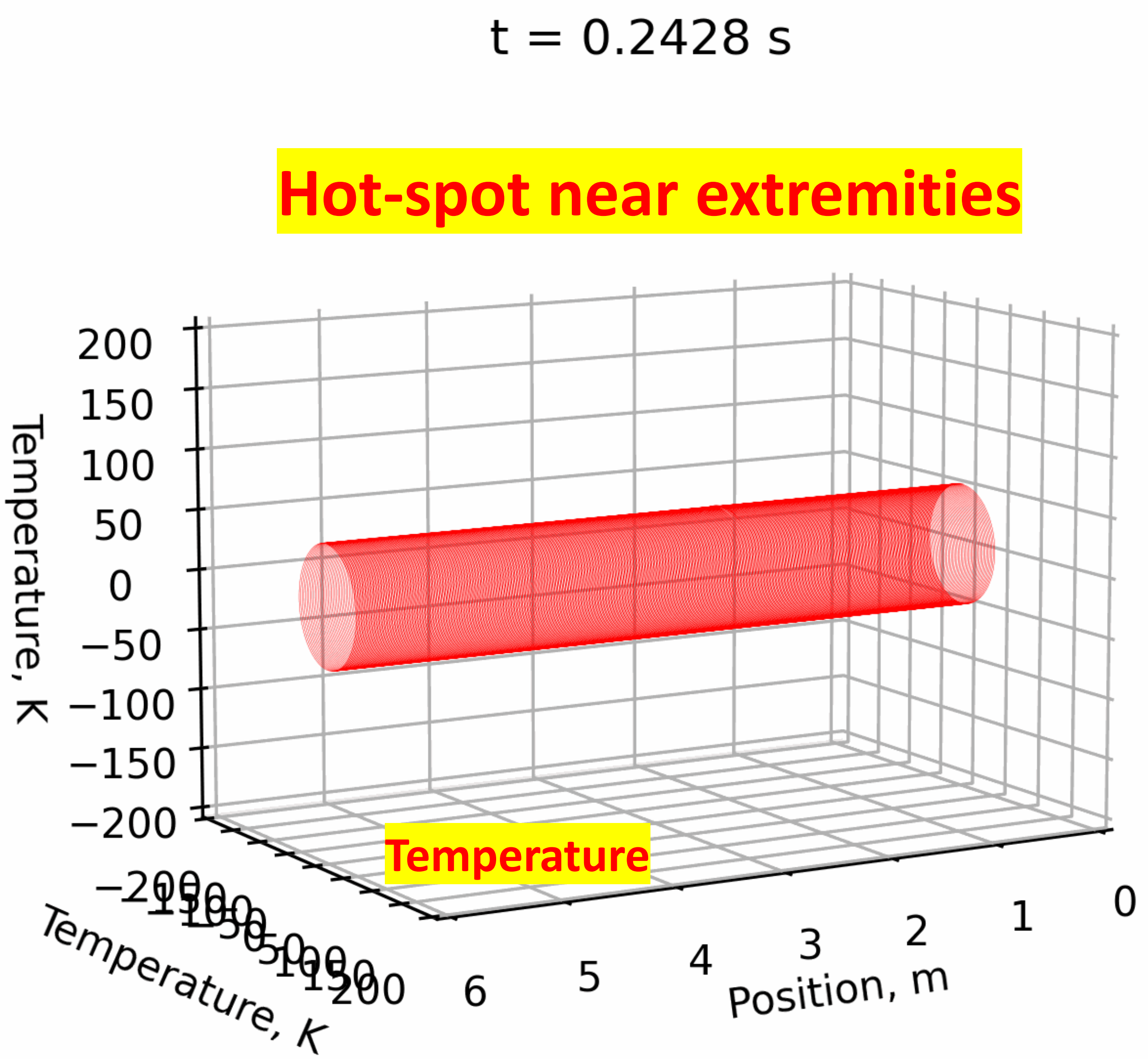
Investigated slow thermal runaway due to defective turn(s):

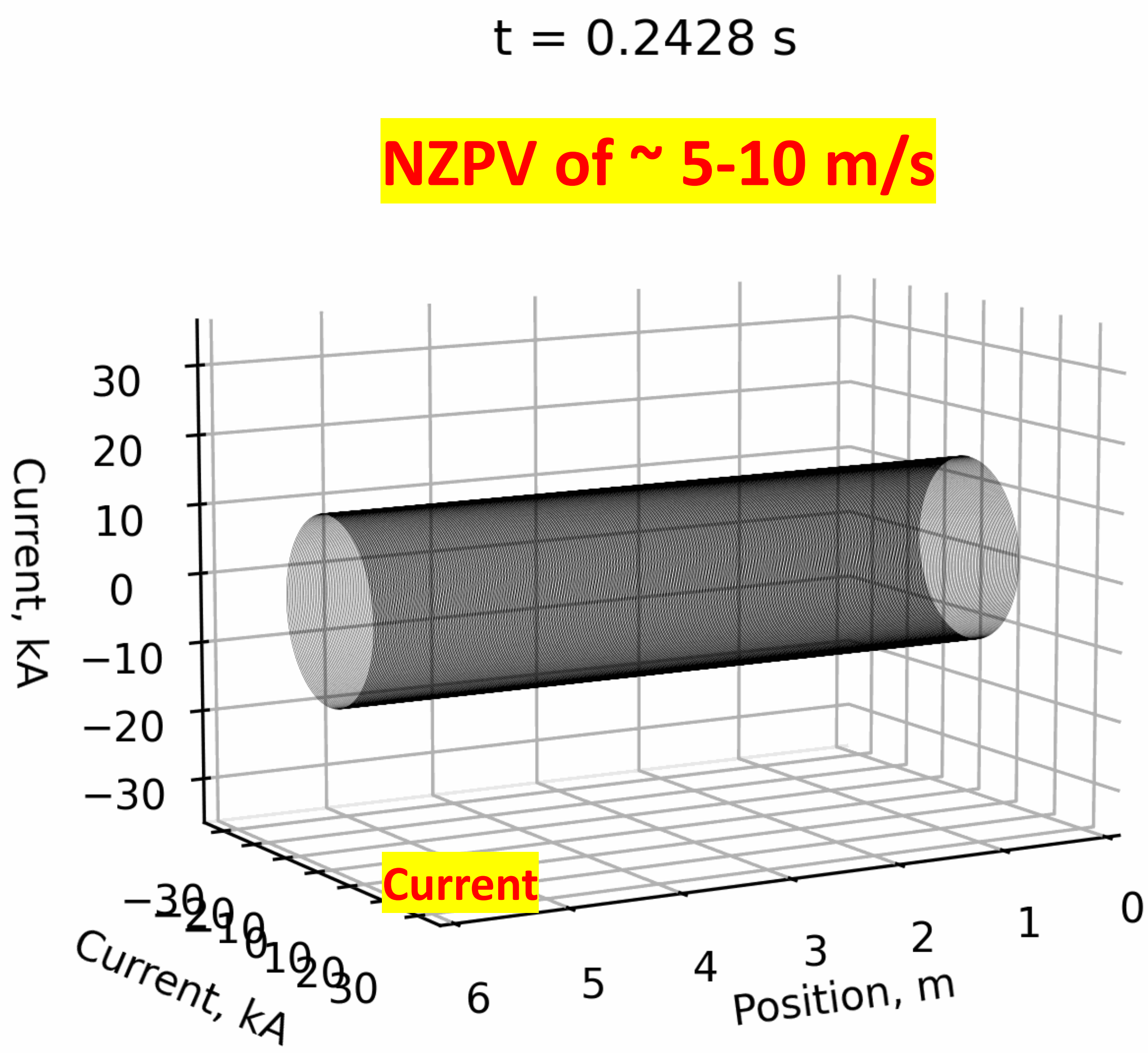
- NZP is driven by inductive components.
- Current is pushed to adjacent turns, these turns reach I_c and consequently quench themselves.
- High current of > 30 kA reached for a short period of time.
- Local Lorentz force doubled during a quench.
- Mechanical ripple follows the front of the NZ.
- A quench starting in the center gives the lowest hot-spot temperature.
- A quench starting in an extremity gives the highest hot-spot temperature on the other extremity (all current/energy is pushed towards the other extremity).



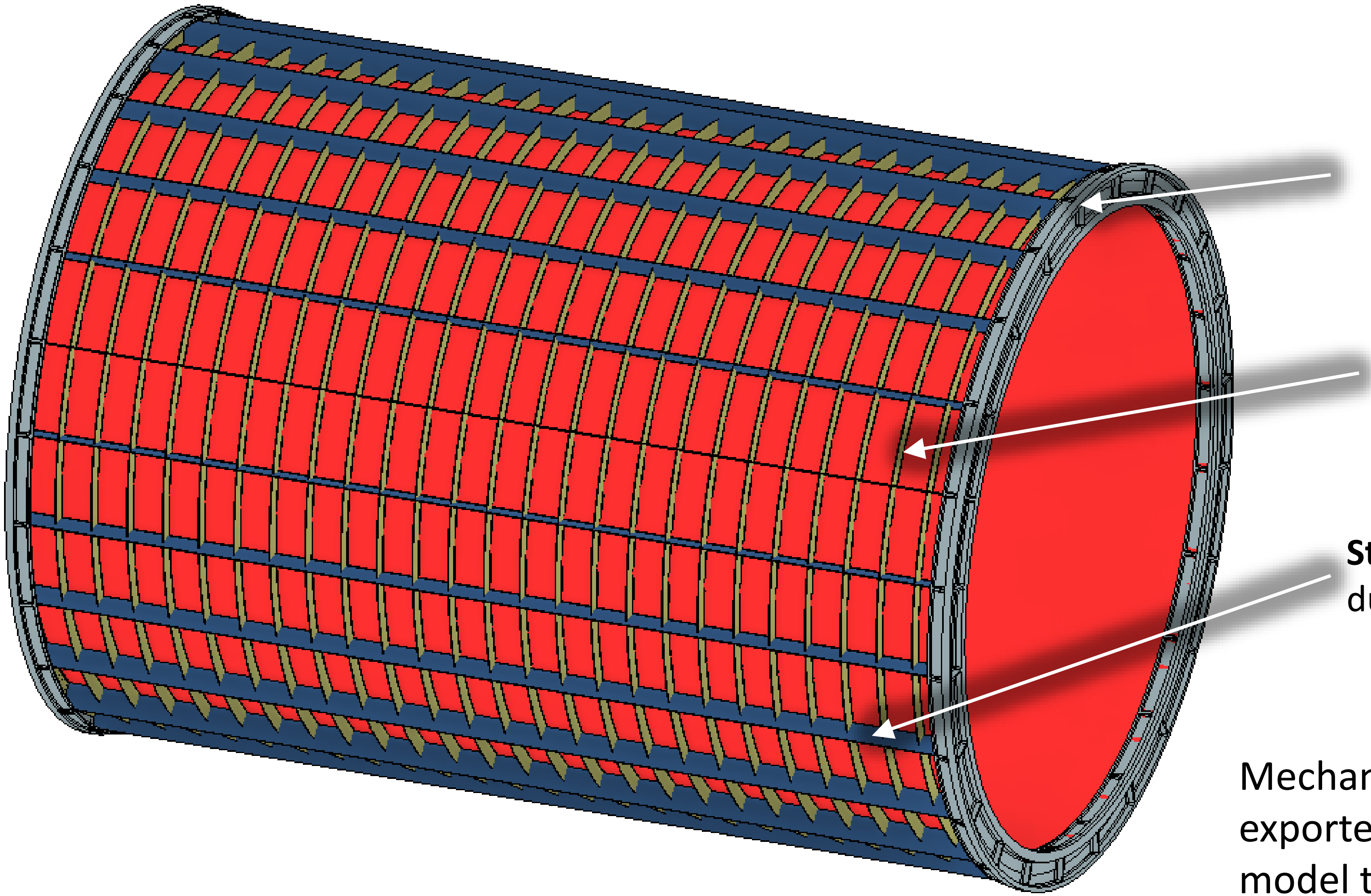
Quench in the center of the magnet in azimuthal section 1.

Quench Behavior and Survival





End-flanges, Ribs and Stringers



End-Flanges (grey): Mechanical support of the magnet during manufacturing, launch and operation.
Circular, allows quench-back.

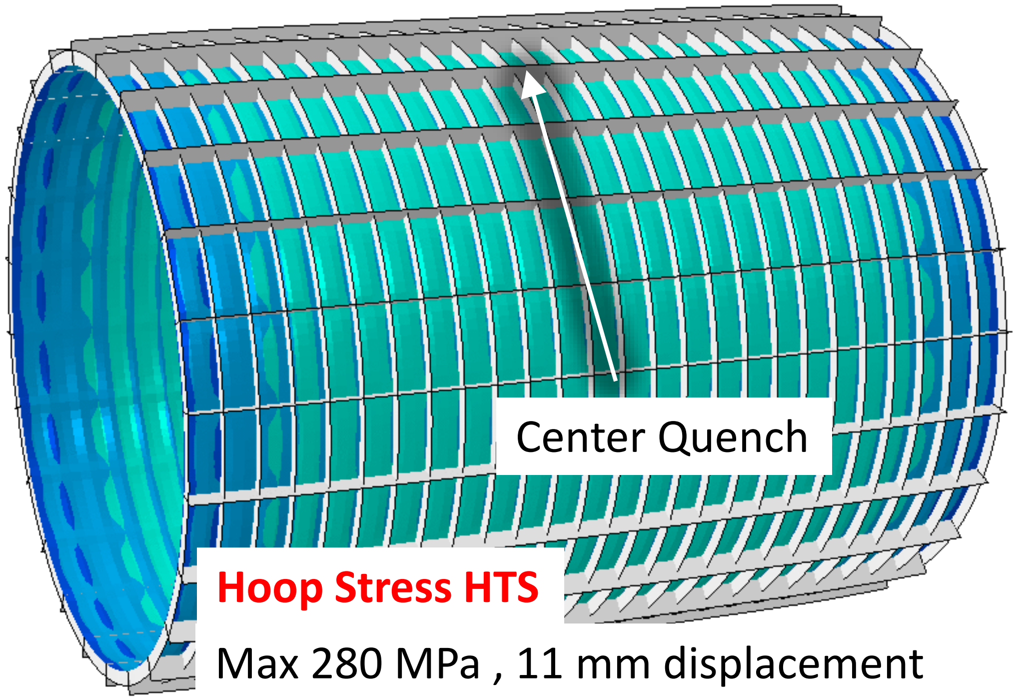
Ribs (yellow): Mechanical support of the magnet during operation and quench events.
Circular, allows quench-back.

Stringers (blue): Mechanical support during launch.

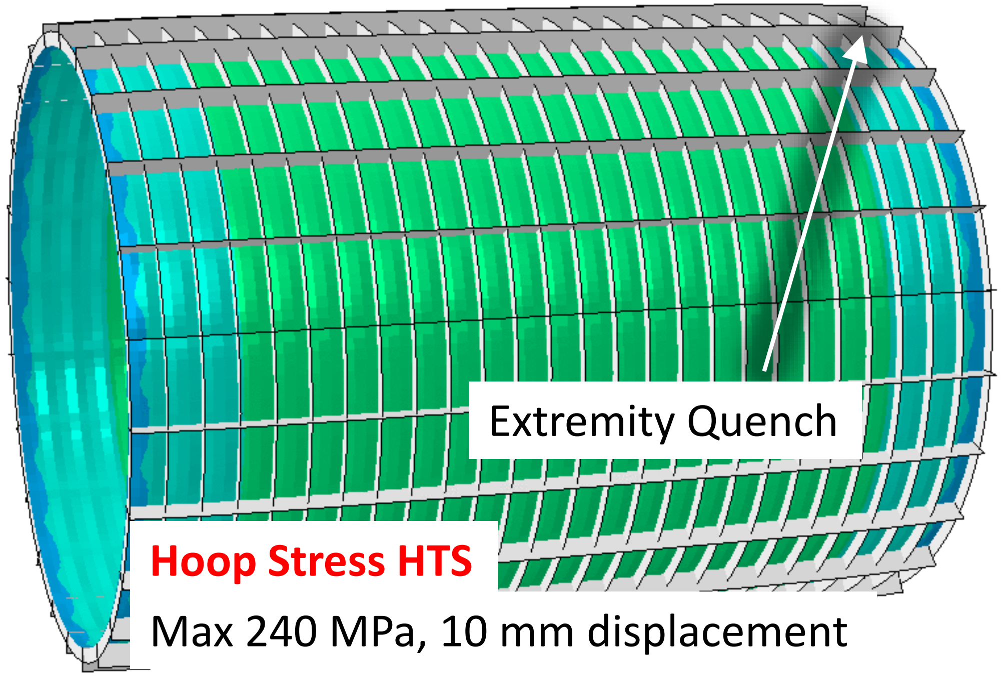
Mechanical load on the conductor is exported from the thermal-electrical model to Abaqus.

Mechanical Quench Analyses

- Shell model set-up in Abaqus to calculate stress in the HTS, Al-alloy conductor and structural components.
- Model includes the conductor, ribs and stringers.
- Boundary condition: outer rings fixed to circular shape, free thermal shrinkage

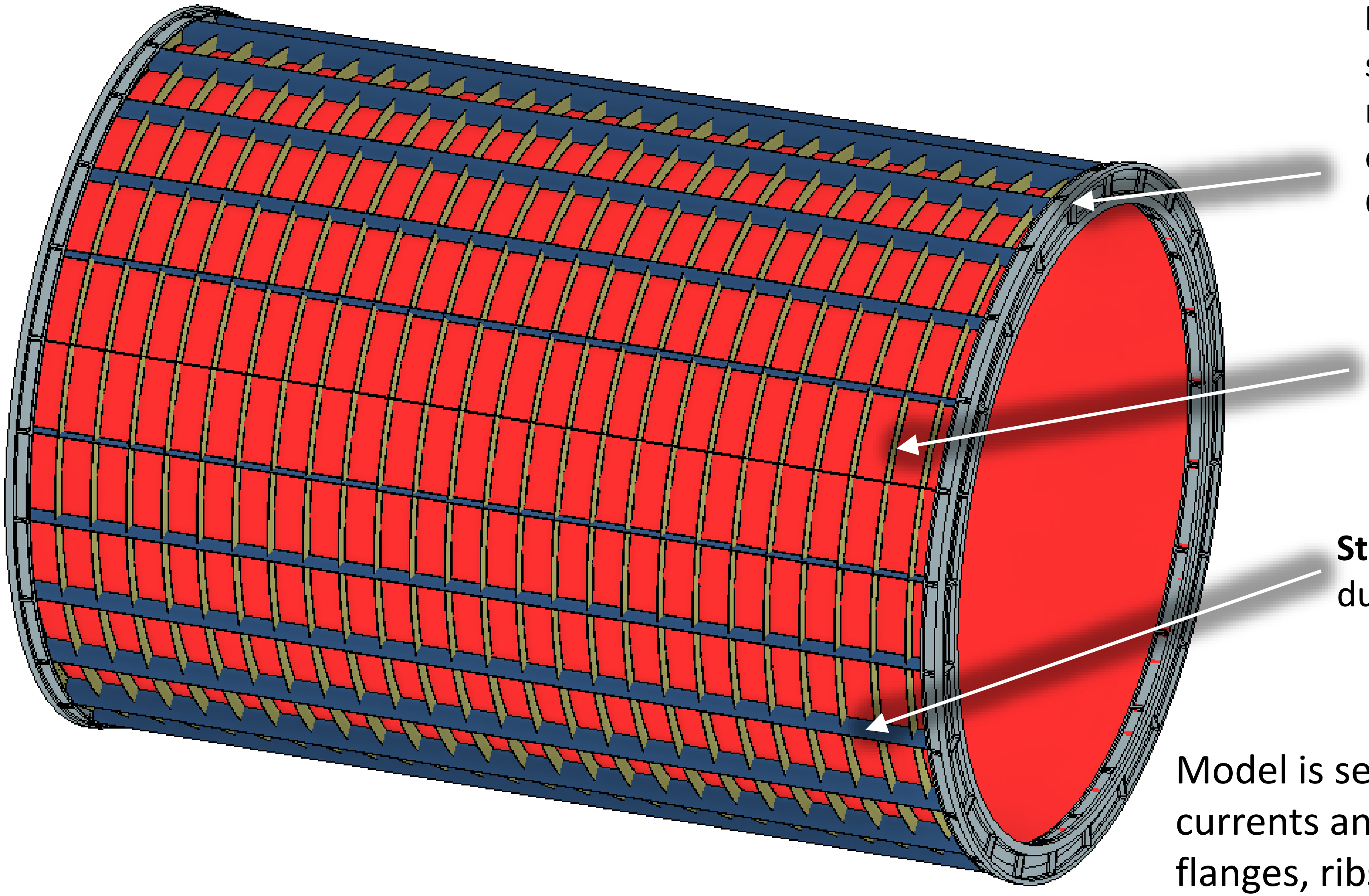


- Stress in the conductor is almost tripled during a quench due to enormous induced current.
- Ribs locally reduce the stress in the conductor.
- Stress in the conductor due to thermal gradients not critical, strength of the epoxy to be validated experimentally.
- Peak stress caused by radial Lorentz force.



J. Zimmermann & D. Pridöhl, RWTH Aachen

End-flanges, Ribs and Stringers



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Stringers (blue): Mechanical support during launch.

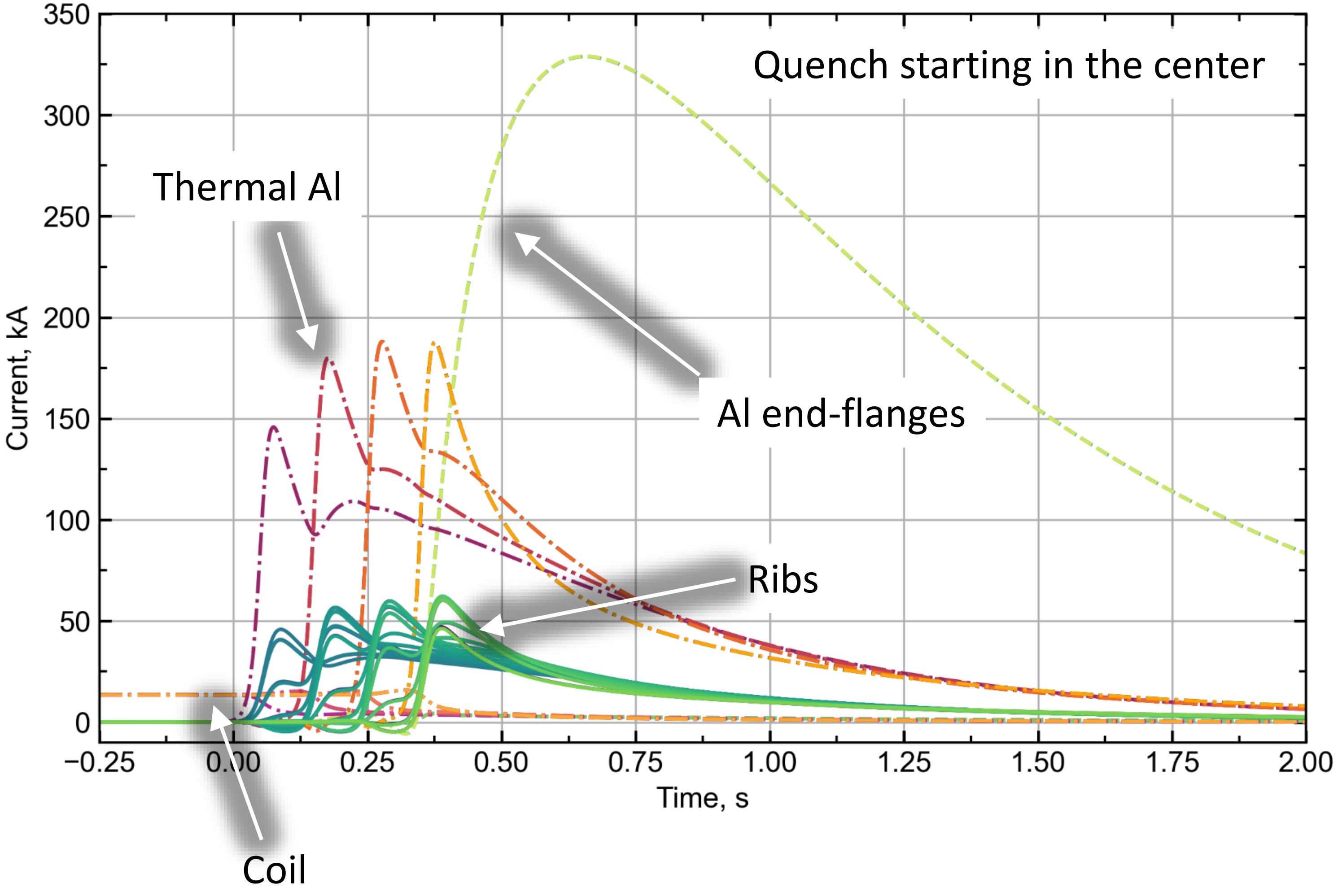
Model is set up to estimate induced currents and energy dissipation in the end-flanges, ribs and other circular components.

AMS-100 - End-flanges and Ribs: Quench-back

Model to estimate induced currents and losses in other components:

- Coil (divided in to 7 sections)
- Thermal aluminum (7 sections)
- End-flanges (2x Al alloy, 2x SS)
- Ribs (25 pieces, Al alloy)

- Coil sections are quenched 0.1 s after each other.
- 300-350 kA induced in the Al end-flanges.
- 50 kA induced in each of the ribs (1 MA total).
- 1 MA induced in the thermal aluminum.



Optimization of the ribs and end-flanges is ongoing, results are preliminary.

AMS-100 - End-flanges and Ribs: Quench-back

Model to estimate induced currents and losses in other components:

- Coil (divided in to 7 sections)
- Thermal aluminum (7 sections)
- End-flanges (2x Al alloy, 2x SS)
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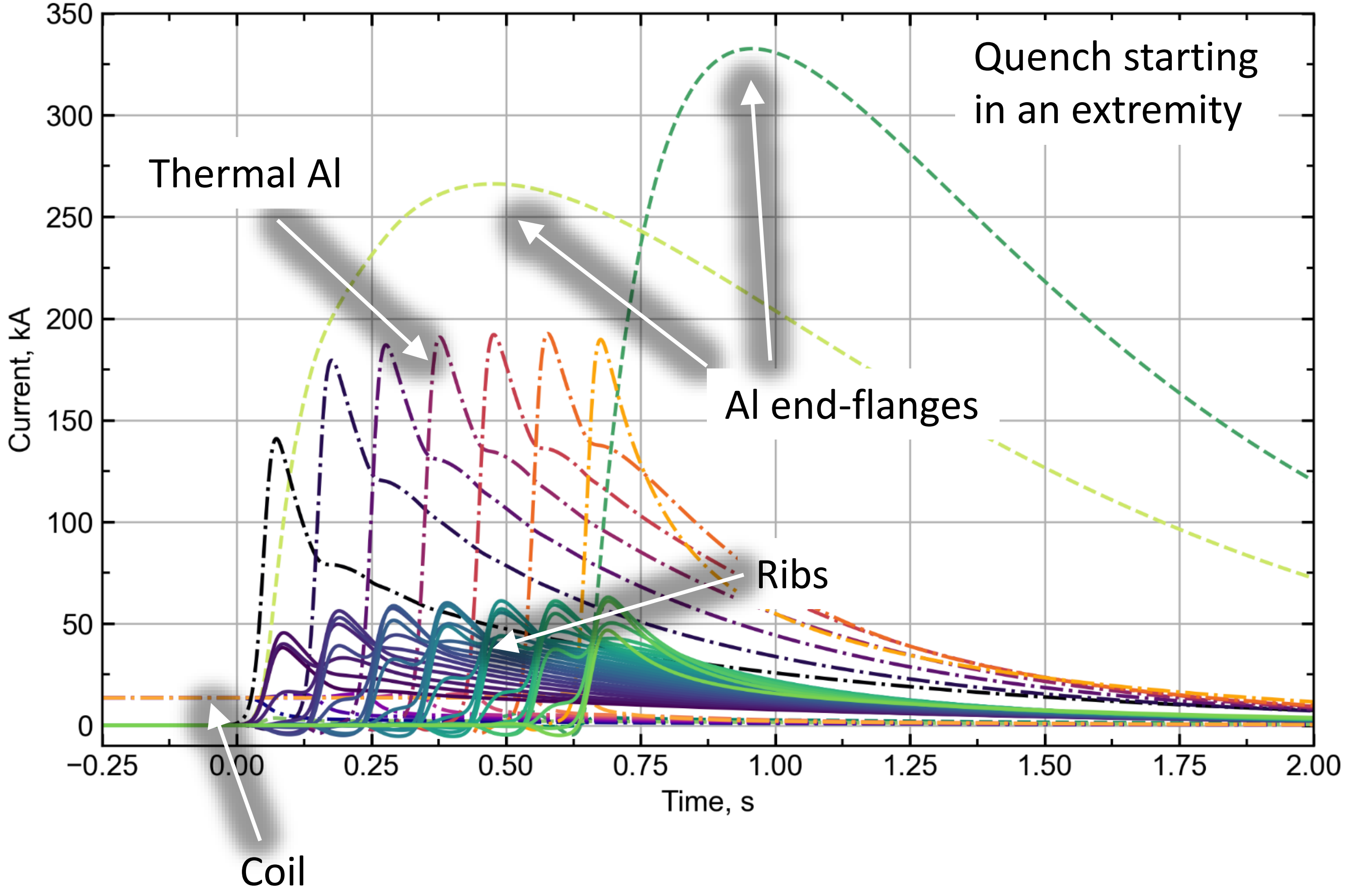


- Coil sections are quenched 0.1 s after each other.
- 250-350 kA induced in the Al end-flanges.
- 50 kA induced in each of the ribs (1 MA total).
- 1 MA induced in the thermal aluminum.

Optimization of the ribs and end-flanges is ongoing, results are preliminary.

AMS-100 - End-flanges and Ribs: Quench-back

Quench from the center:
Total stored energy: 33.7 MJ
In conductor: 17.2 MJ (**51%**)
In ribs: 7.4 MJ (**22%**)
In flanges: 2.7 MJ (**8%**)
In thermal aluminum: 6.4 MJ (**19 %**)

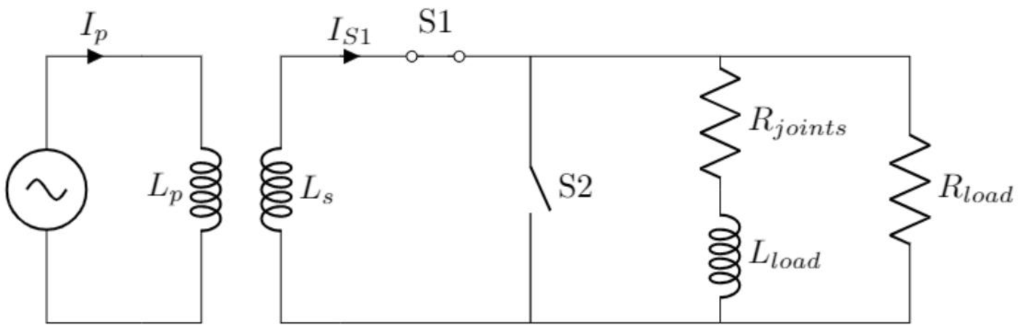
Quench from an extremity:
Total Energy: 33.7 MJ
In conductor: 17.5 MJ (**52%**)
In ribs: 7.1 MJ (**21%**)
In flanges: 2.7 MJ (**8%**)
In thermal aluminum: 6.4 MJ (**19%**)

- Large fraction (50 %) of the stored energy is dissipated in the ribs, flanges and thermal aluminum.
- Will result in a much lower hot-spot temperature.
- Induced current in the structural elements result in a lower mechanical load on the conductor itself.
- Slows down the quench process.
- Expected that further mechanical optimization will reduce the mass and dimensions of the ribs and end-flanges.
- Reduction of energy dissipated in the ribs and end-flanges from 30% -> 10-20 %.
- Next step: to merge sub-models to get one model that includes individual turns that allows quench-back in all structural components.
- Next step: use model to optimize mechanical structures + conductor/magnet layout.

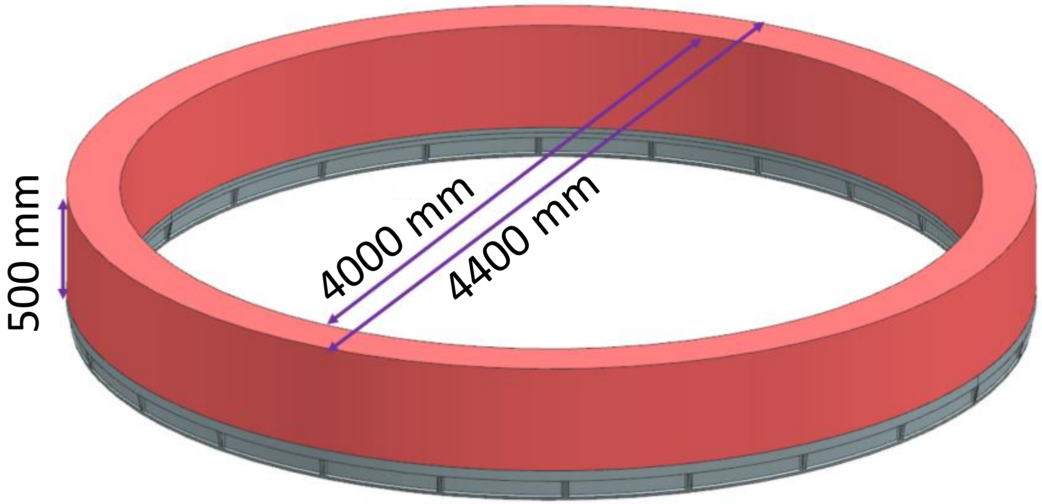
Remaining Challenge: Powering the Main Solenoid

Ramping of a radiation cooled NI coil:

- Limited cooling of **~ 30 W** available at 55 K.
- Non of the detector equipment will be powered during ramp, full use of radiators for the coil and its PSU.
- Ramp time of 100-400 hours is foreseen with a magnet time constant of 10-20 hours.
- Resistive ramp losses are dependent on the ratio of ramp-time and time constant of the magnet, **< 15 W**.
- Coupling-losses are present, not dominating.
- Magnet powered by a flux-pump to limit heat load to the cold mass.
- Flux-pump requires SC switches, which require heaters to operate, needs to be cooled by the radiators, **< 15 W**.
- Losses in the joints **< 2 W** at nominal current.



Limited space for the flux pump and all other services of the magnet system.

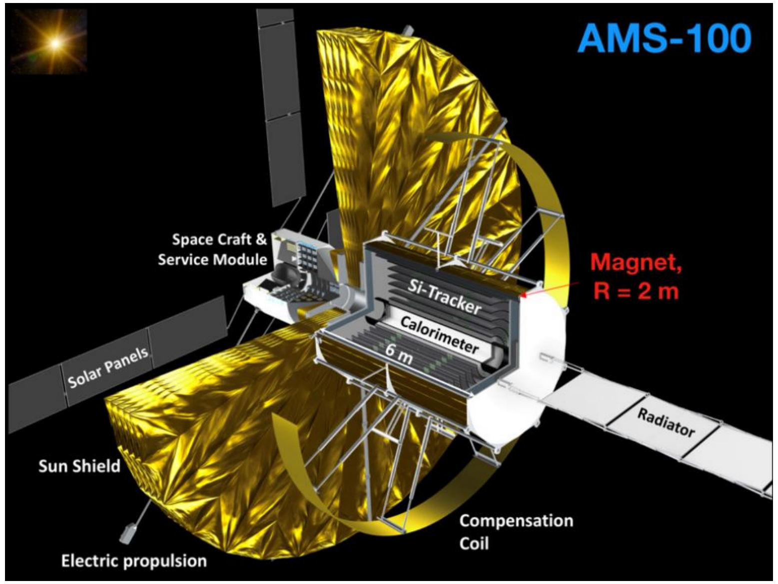


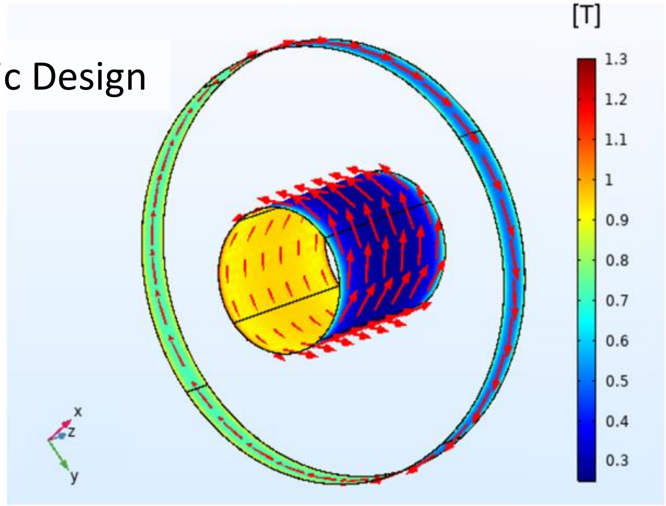
500x200 rectangular cross section available near one of the end-flanges.

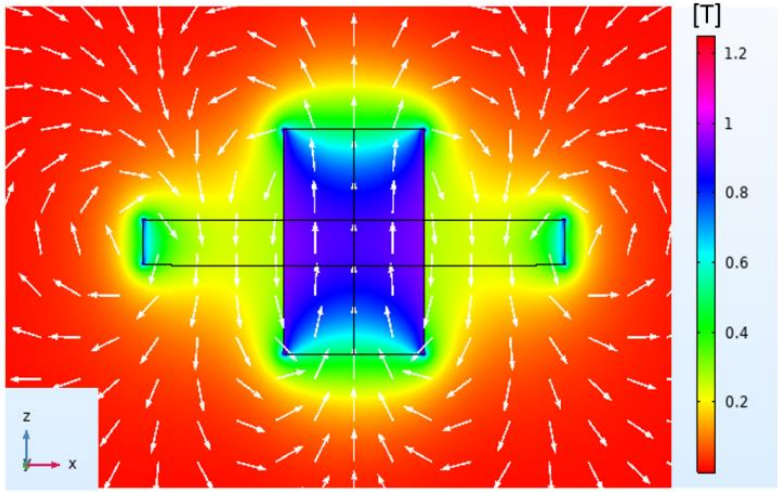
Remaining Challenge: Compensation Coil

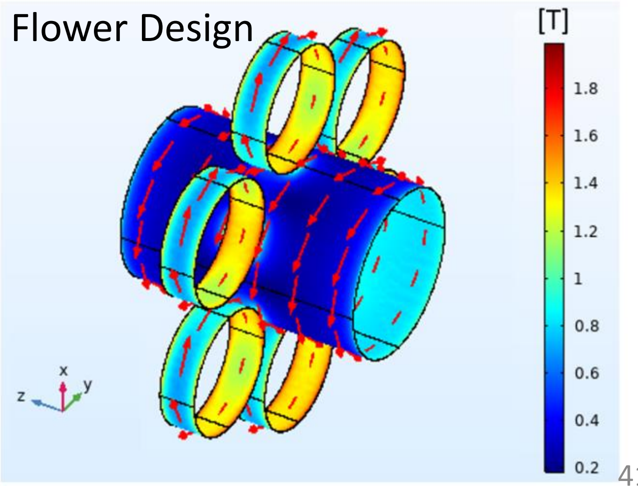
There is a non-zero background field at L2, which means there will be magnetic torque -> magnet tries to align to this B-field.

- Compensation coil is needed to have zero magnetic momentum.
- Several designs are in investigation, concentric and flower design are currently the most promising.
- Currently, compensation coil(s) do not fit inside the cargo bay of the rocket -> solution needs to be found, not there yet.
- All current designs are inherently unstable and a strong support structure would be essential. Worse during a quench.

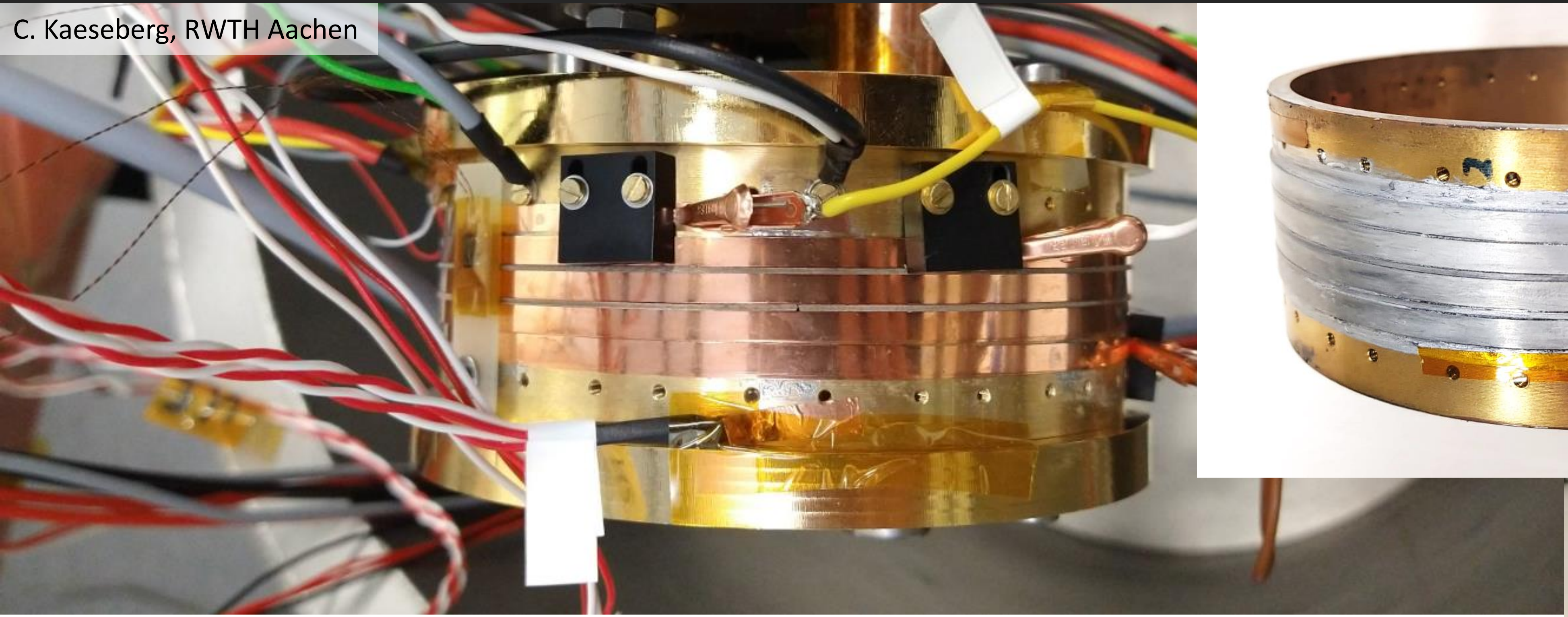




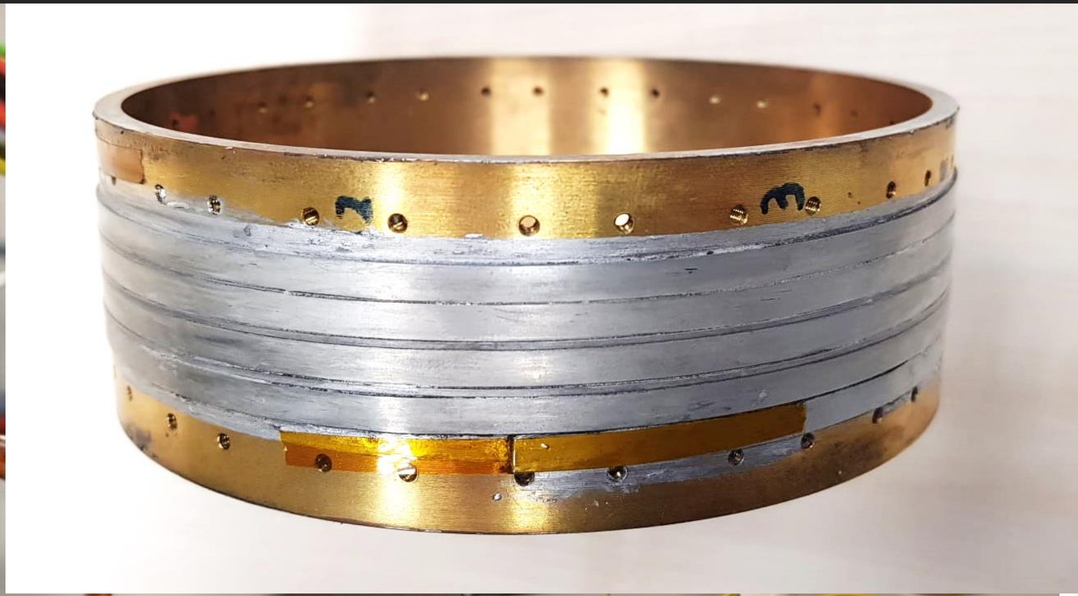




AMS-100 Demonstrator Coils



C. Kaeseberg, RWTH Aachen

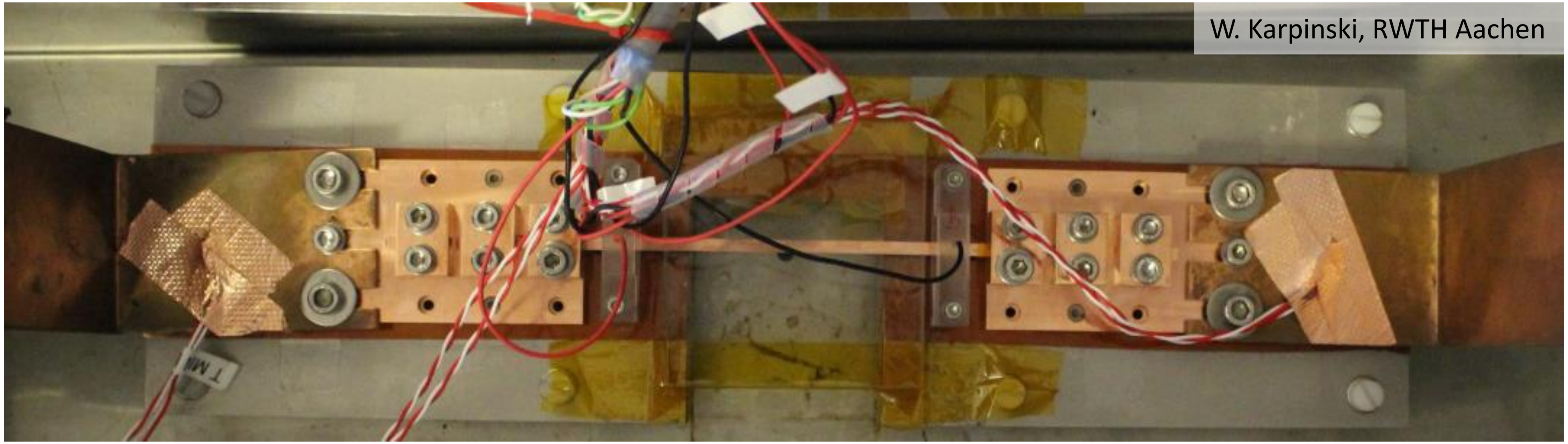


D. Uglietti, EPFL

<u>Several compact demonstrator coils are envisioned and in preparation.</u>

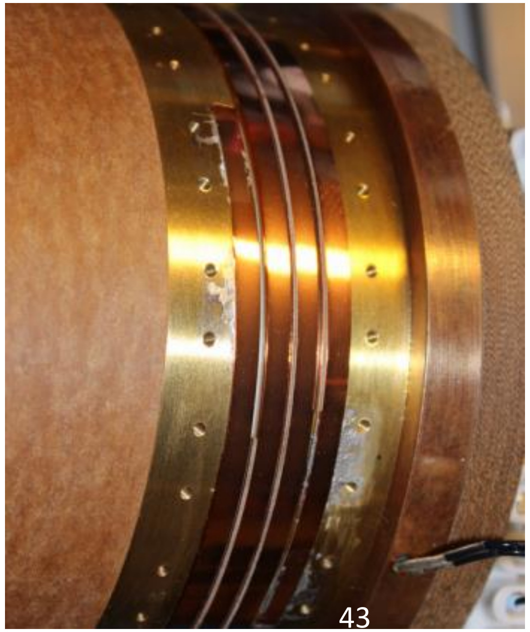
- Test preparation procedures and components.
- Validate models and results (mechanical, electrical and thermal).
- Coils will be pushed to their limits.
- Starting with small, few turn demonstrator coils, later moving to larger coils and the coil for the pathfinder mission.

HTS Tape Validation and Characterization

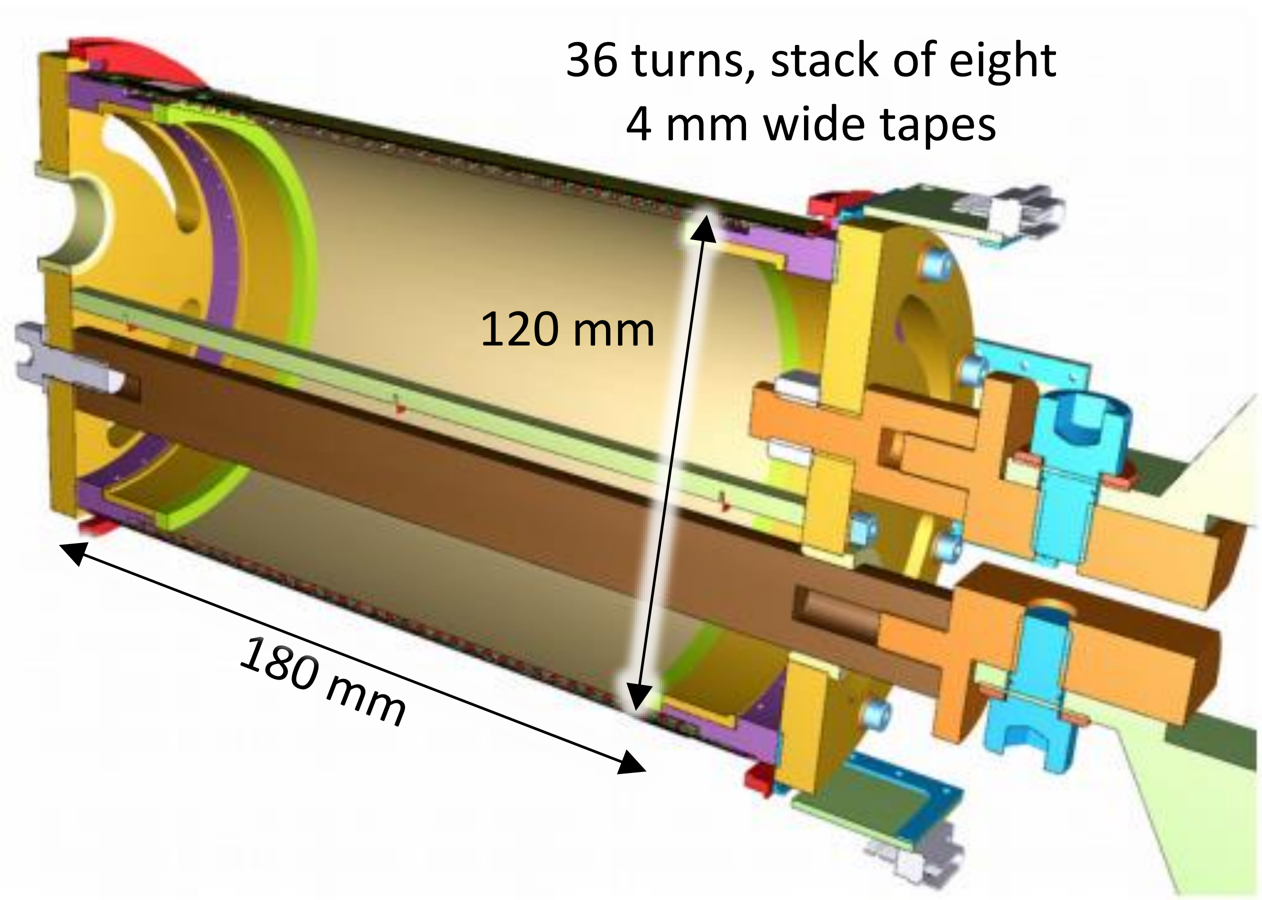

W. Karpinski, RWTH Aachen

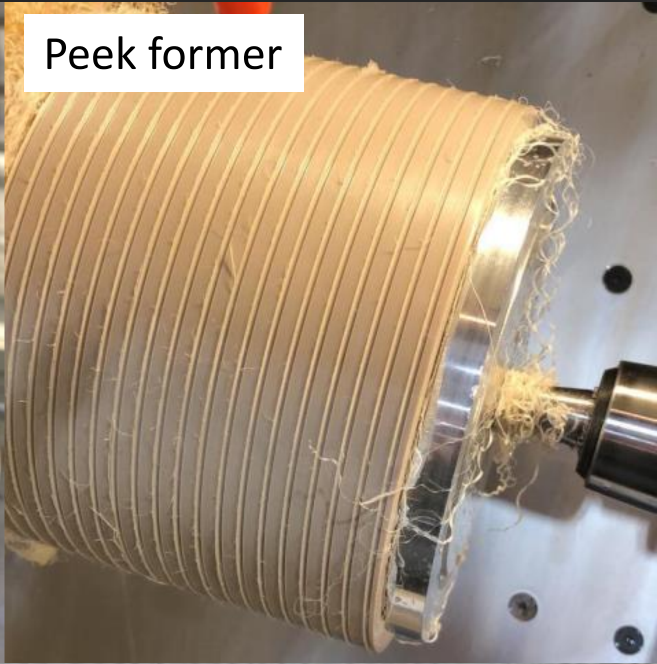
Tape tests performed at RWTH Aachen, EPFL, CERN & University of Geneva.

- Single tape $I_c(T, B)$ tests to validate their performance.
- Soldered tape stack tests to test stacking and soldering methods.
- Vacuum soldering testing.
- Bending, winding and soldering tape on a round former.



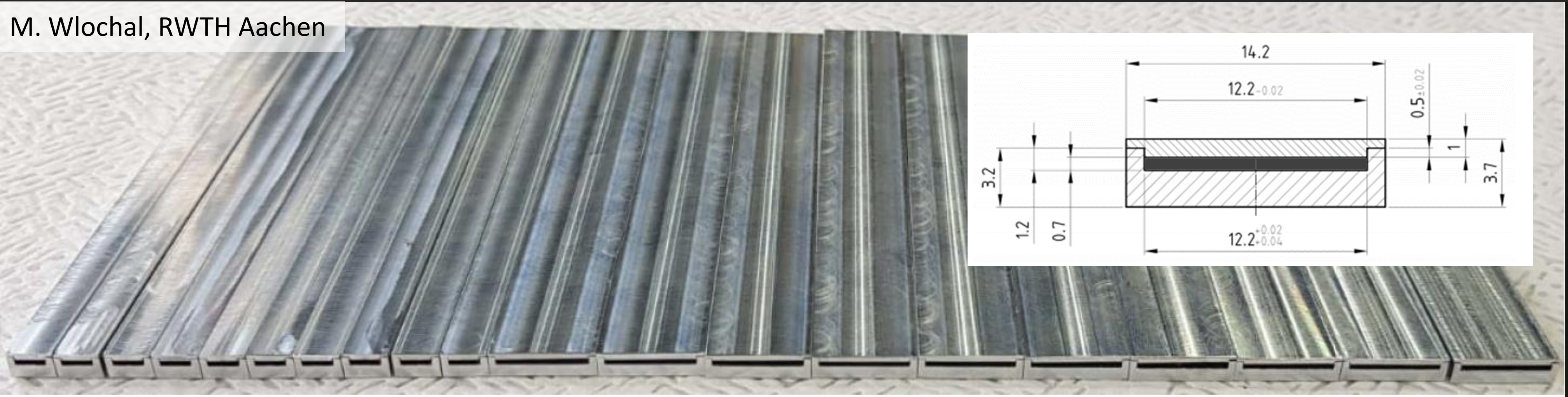
AMS-100 Demonstrator Coils

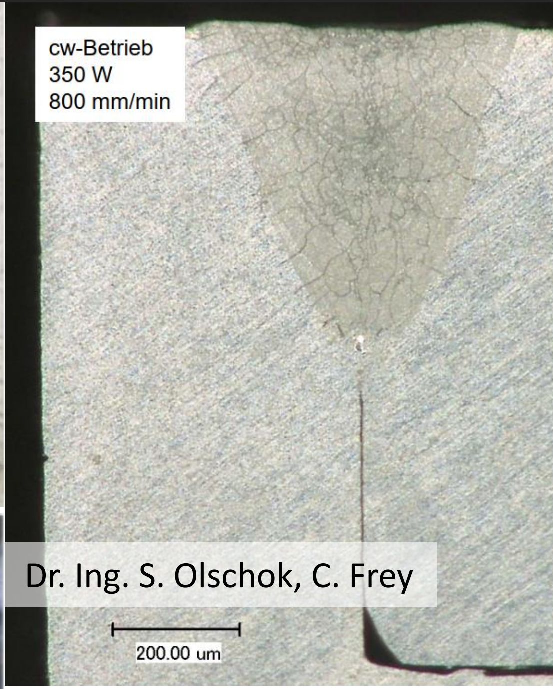




- Compact demonstrator in preparation for validating the electrical-thermal-magnetic model.
- Testing all preparation methods.
- Heavily instrumented.
- Testing at 4 K up to 5 T and 20 – 60 K in S.F.

Al-stabilized HTS Conductor

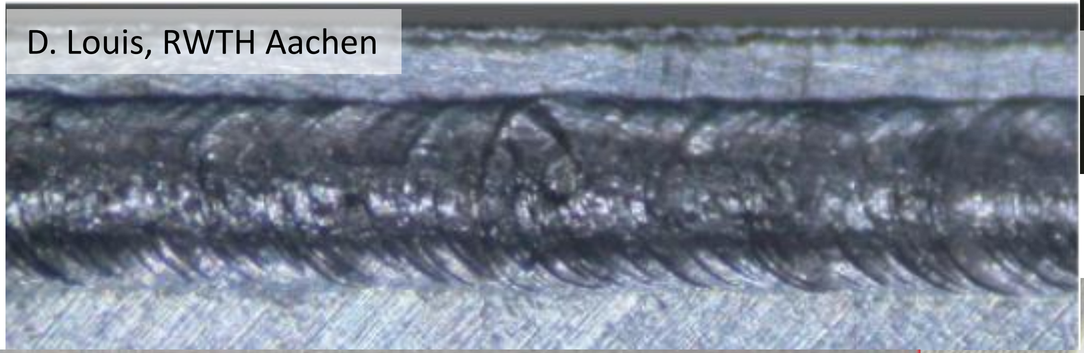


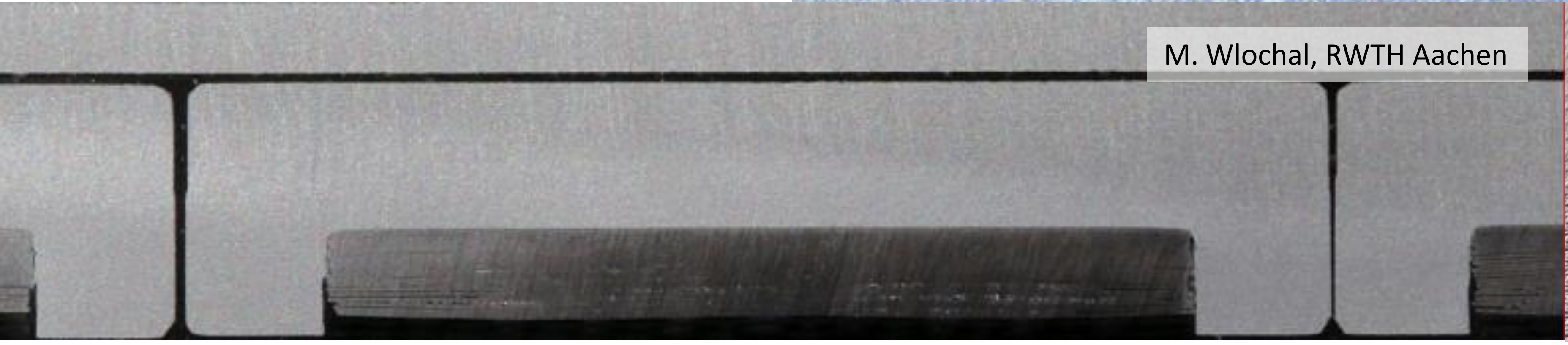


Challenge: Al-stabilized HTS conductor.

Several test welds have been done.

Test campaign in full swing.





Conclusions

- AMS-100 magnet system faces many design challenges due to its
  - ultra-thin 1T HTS coil,
  - large stored energy of 34 MJ,
  - very limited cooling via external radiators,
  - requirement to survive high-vibration launch conditions,
  - requirement to fit the magnet and its compensation coil(s) inside a rocket.
- Quench model is under development that predicts the quench behavior of the main solenoid, the resulting hot-spot temperature and mechanical load on the conductor.
- Testing of materials and preparation procedures is ongoing. Several small demonstrator coils are in preparation to test different design aspects of the AMS-100 magnet, tests scheduled for 2021-2022.
- AMS-100 Magnet System is still in its early design phase. We still expect several design iterations in the near future to fine-tune the design.