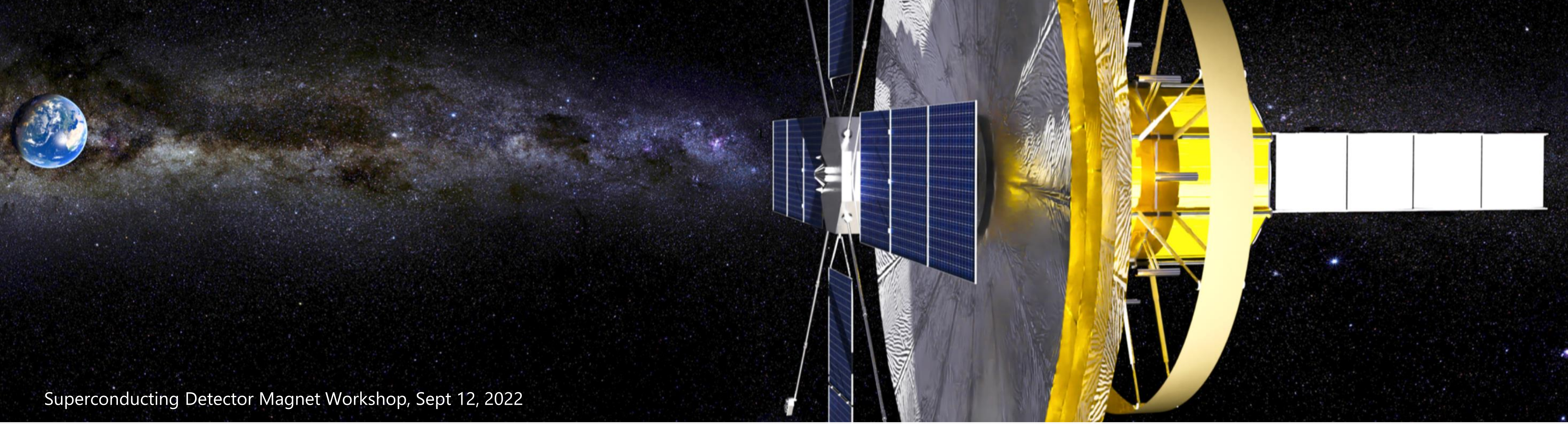

Superconducting Detector Magnet Workshop, Sept 12, 2022

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

Tim Mulder, Tommaso Bagni, Markus Czupalla, Alexey Dudarev, David Fehr, Daniel Louis, Christian von Byern, Waclaw Karpinski, Thomas Kirn, David Kohlberger, Matthias Mentink, Dominik Pridöhl, Tobias Schalm, Kai-Uwe Schröder, Arndt Schultz von Dratzig, Carmine Senatore, Thorsten Siedenburg, Helder Silva, Davide Uglietti, Michael Wlochal, Jannik Zimmermann and Stefan Schael

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

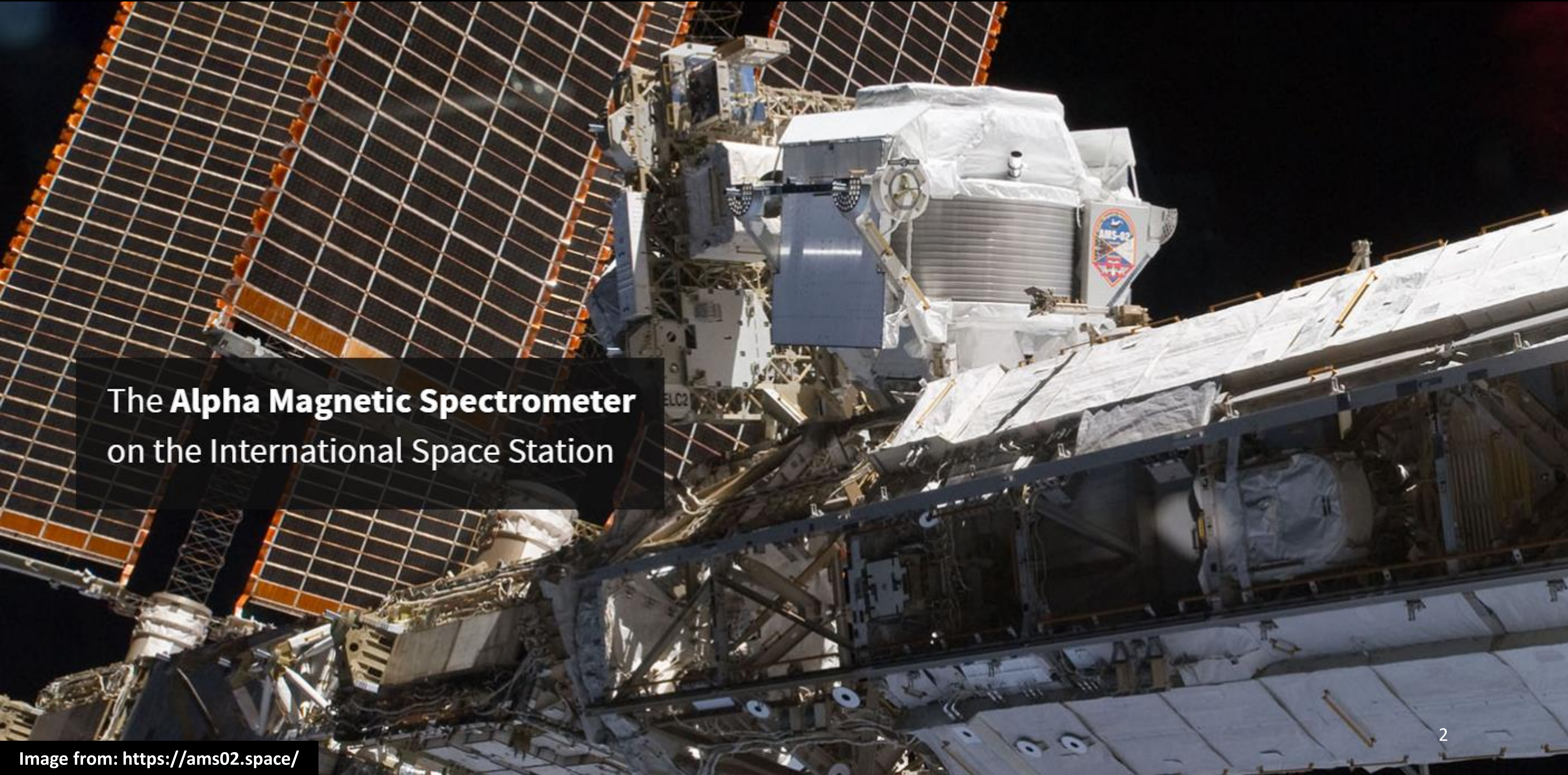
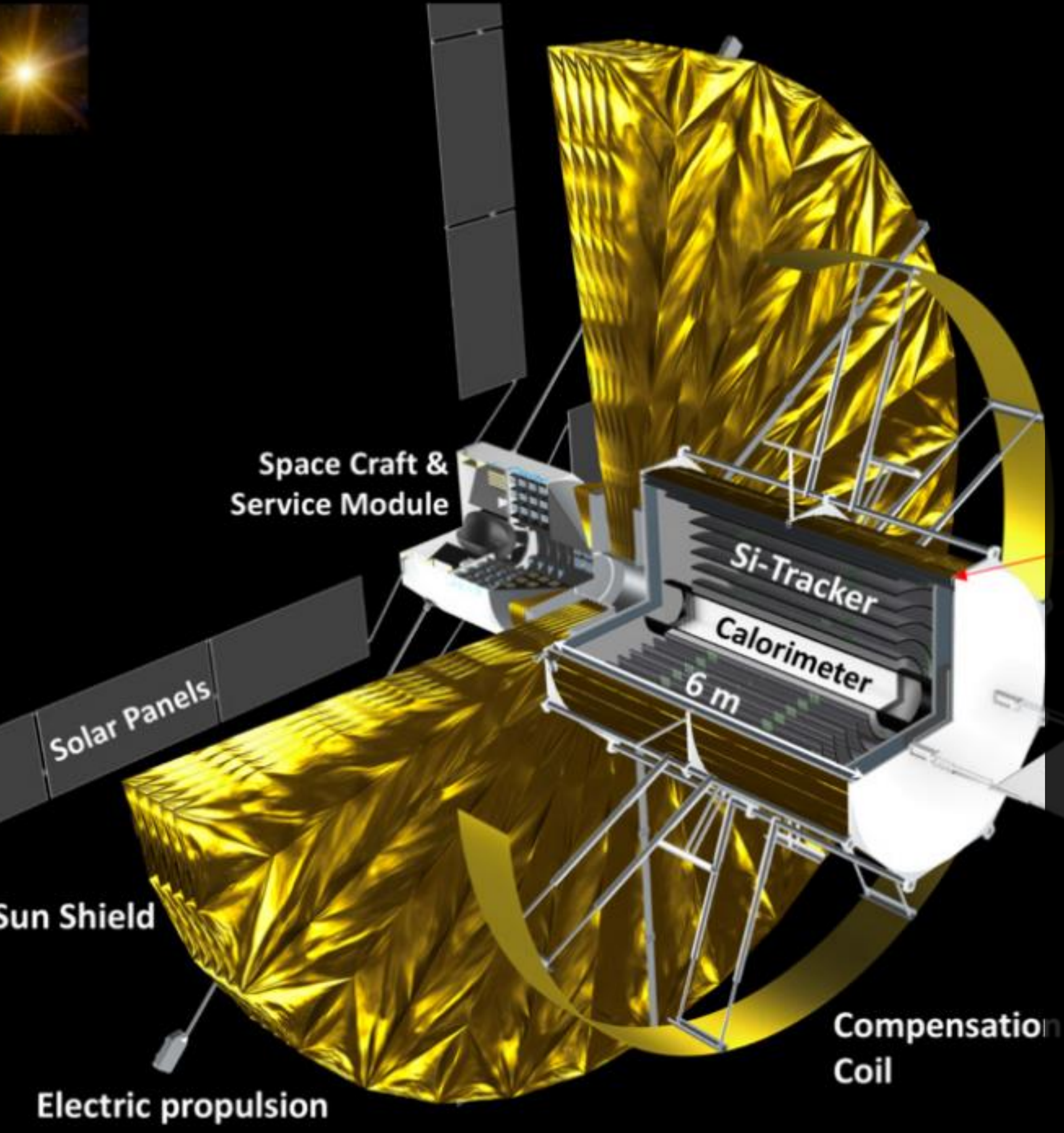


Image from: https://ams02.space/

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.
- Main magnet is a 6 m long, 4 m diameter 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.
- Comp. coil is a 1.5 m long, 8 m diameter HTS solenoid.

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]
  - ~4 Tons for the magnet system,
  - ~16 Tons of detector equipment,
  - ~20 Tons of auxiliary equipment and cabling.
- Launched with SpaceX's Starship rocket.

AMS Pathfinder mission:

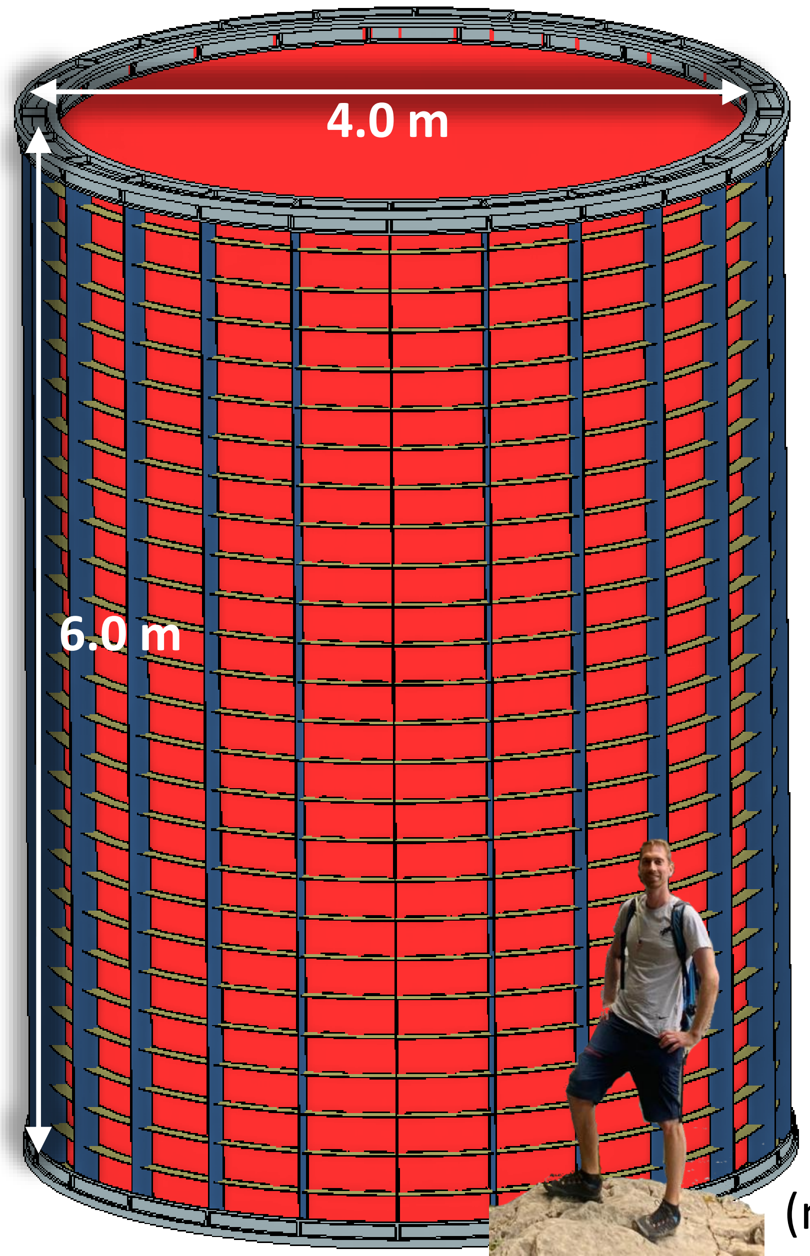
- First radiation cooled HTS magnet in space of such size.
- Test the operation at L2.
- Controls, radiation cooling etc.

[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 ~3 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 system will have a large stored energy of approximately 14 MJ -> 9 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)

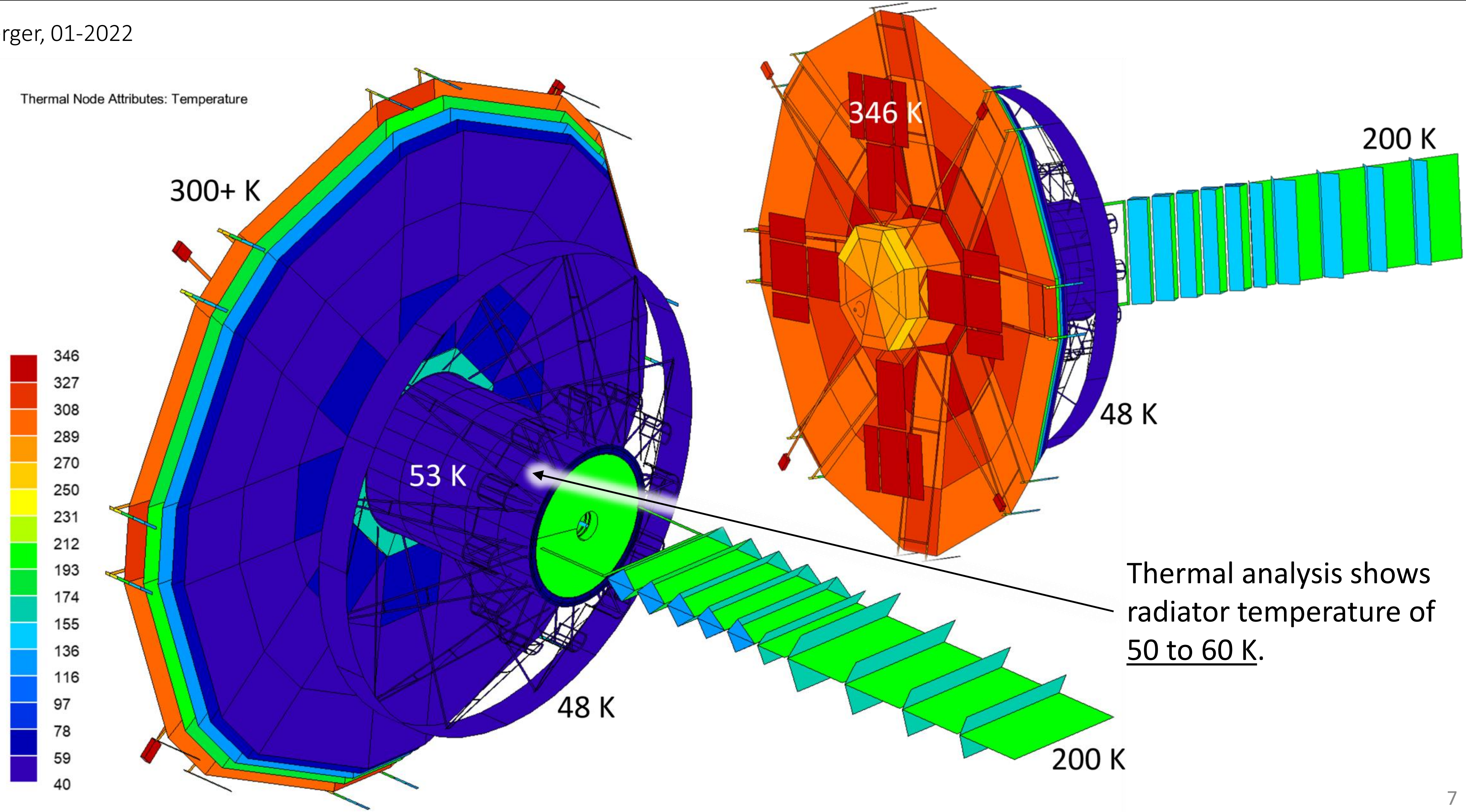
Table of properties for the AMS-100 main solenoid and compensation coil.

	Main	Compensation	Combined	Unit
Coil radius	2.0	4.0		m
Coil length	6.0	1.5		m
Tape width	12	12		mm
Stabilizer	Al-6063	Al-6063		
Cable thickness	2.85	2.85		mm
Cable width	16	16		mm
Layers	1	1		-
Turns	376	94		-
Inductance	286	114	287	mH
Number of tapes	18	18		-
Total tape length	85	43	128	km
Operating current	10.0	-10.0		kA
Cable mass	1090	545	1635	kg
Stored Energy	14.3	5.7	14.4	MJ
Energy Density*	14	11	9	kJ/kg

*Considering only the mass of the cable.

Thermal Analysis of AMS-100

D. Kohlberger, 01-2022



Thermal analysis shows radiator temperature of <u>50 to 60 K</u>.

Magnetic Field and Stability

Design **B-field of 0.65 T** in the center, ~1 T on the conductor at the edge of the solenoid.

B-field of 0.5 T when then compensation coil is on.

Operating temperature range of 50 to 60 K:

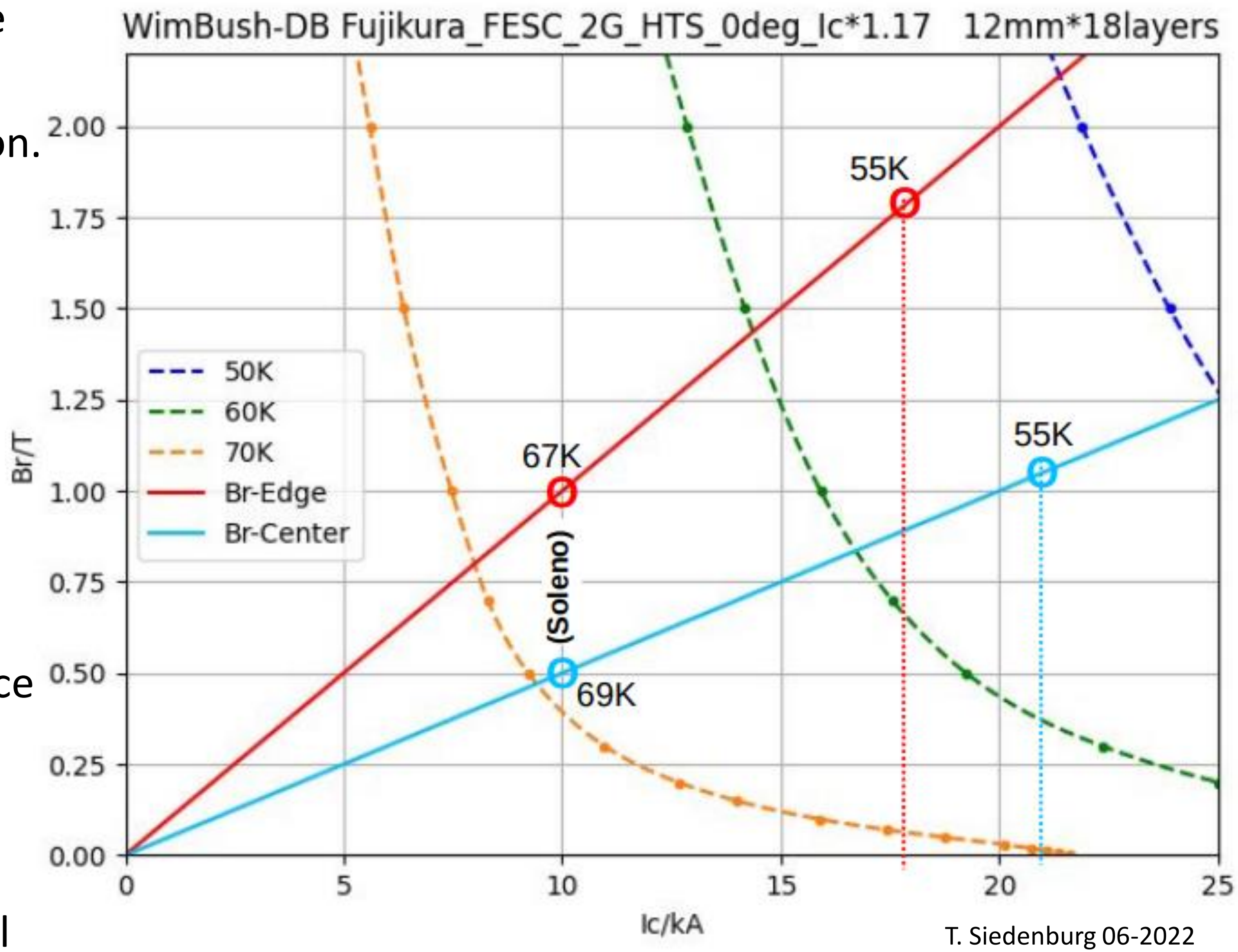
- ΔT of 12 K @ 55 K

Large temperature margin is important:

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

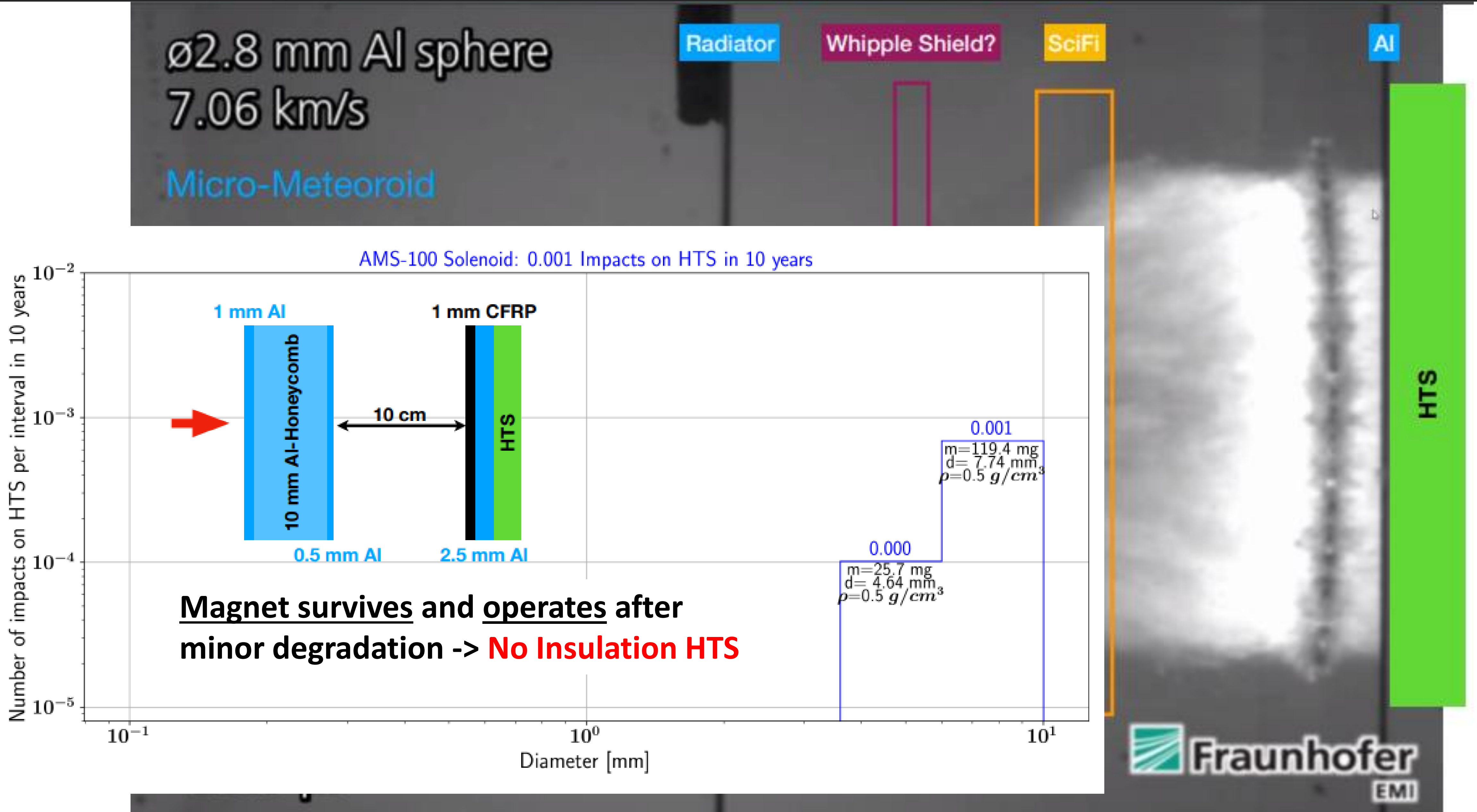
Smart spacing of the conductor / additional HTS tape is envisioned at the coil extremities to reduce the peak field. And allow possible operation at higher current/magnetic field.

The field homogeneity is not an operation critical parameter.



T. Siedenburg 06-2022

Dangers of Space: Micrometeorite Impact

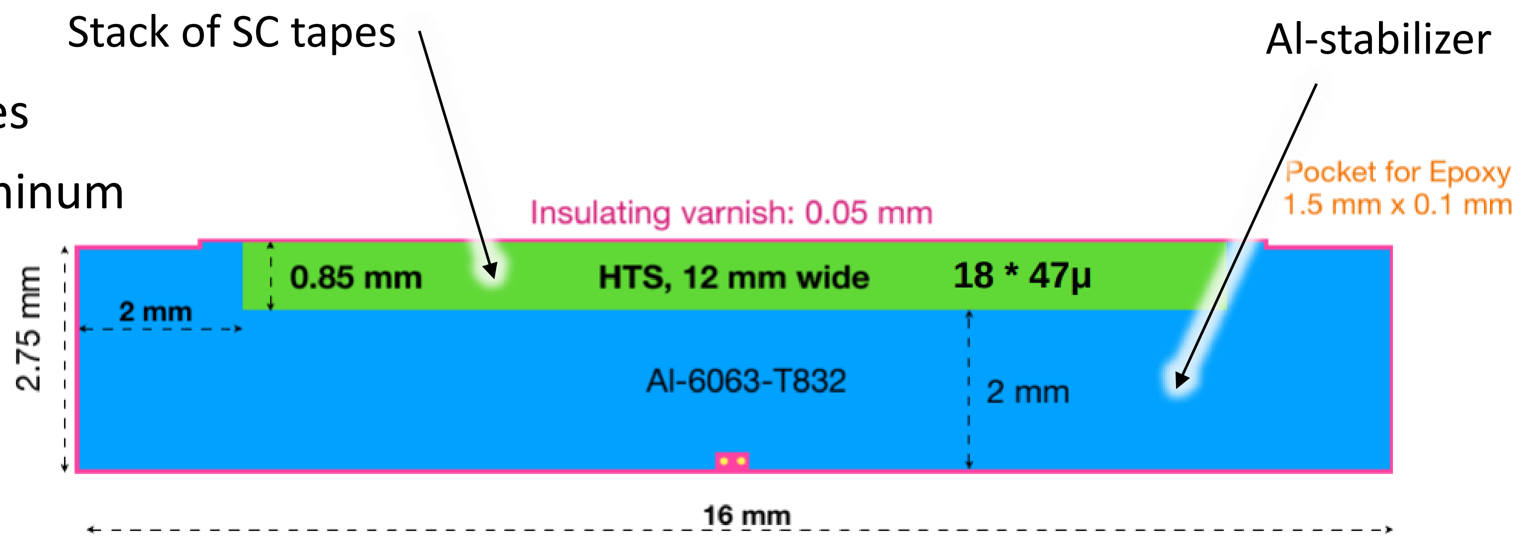


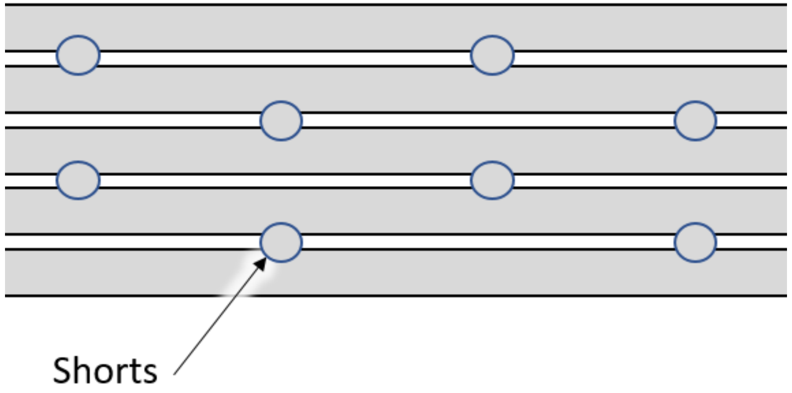
Magnet survives and **operates** after minor degradation -> No Insulation HTS

Conductor and Coil Layout

Current conductor layout:

- Stack of eighteen 12 mm wide HTS tapes
- HTS stack is soldered to tin-coated aluminum (6000 series) conductor stabilizer.
- Conductor thickness of 2.75 mm.
- Outer surface anodized / varnished to provide turn-to-turn insulation.



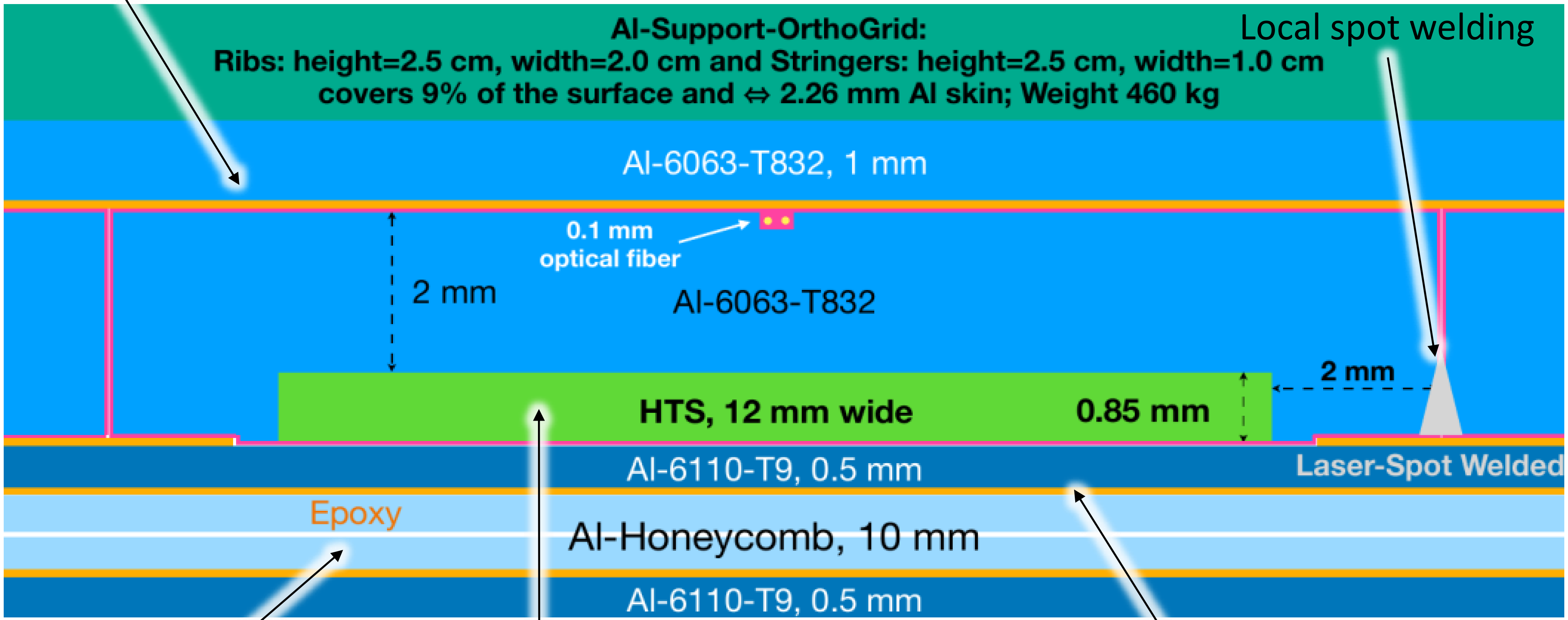


Shorting turns by (EB / laser) point welding.

- 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



Honeycomb for mechanical stiffness

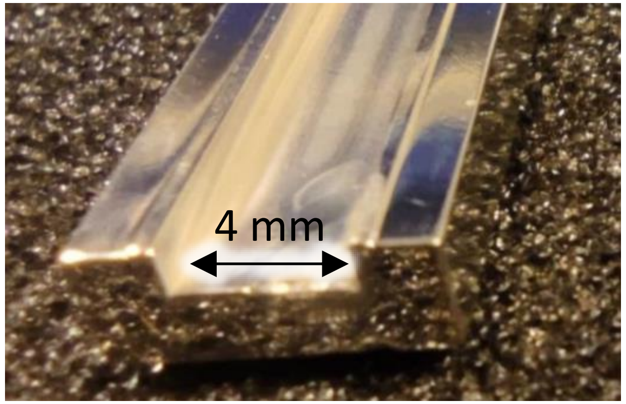
Stack of HTS tapes

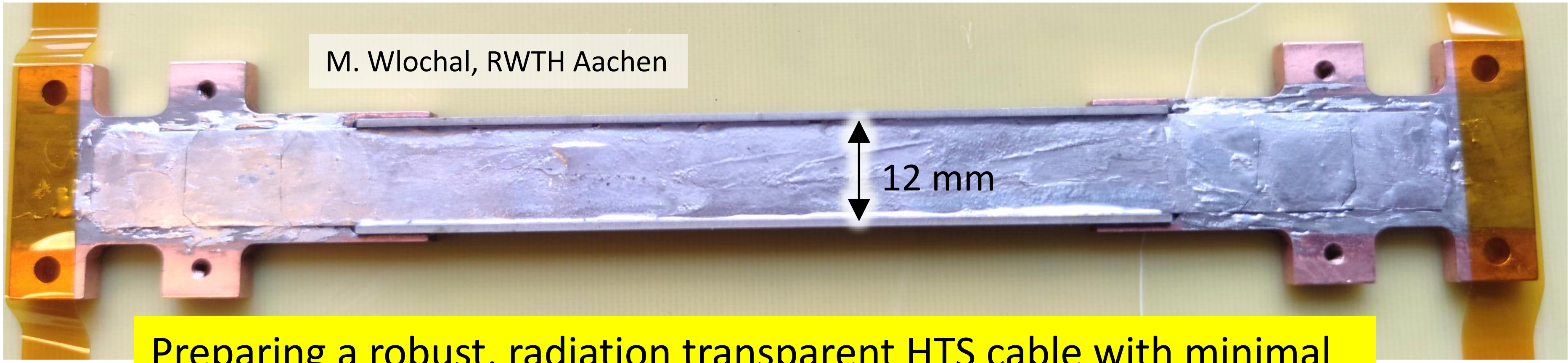
Epoxy between layers

X_0 = 10.2% = Thickness of structure / Radiation length

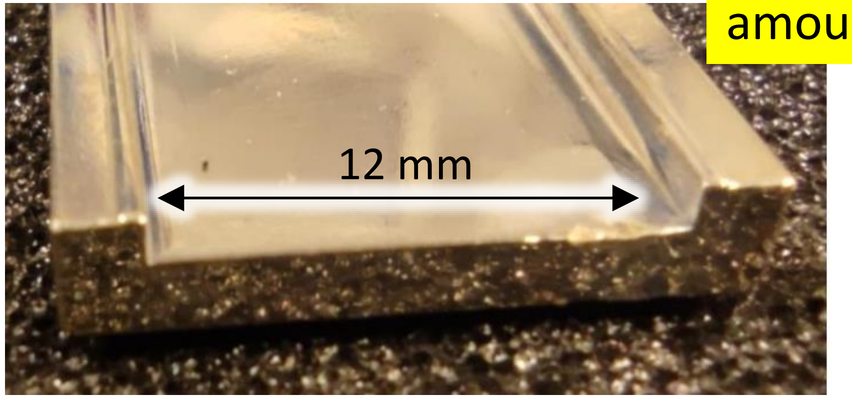
Conductor Testing: Single- and Multi-Tape Samples

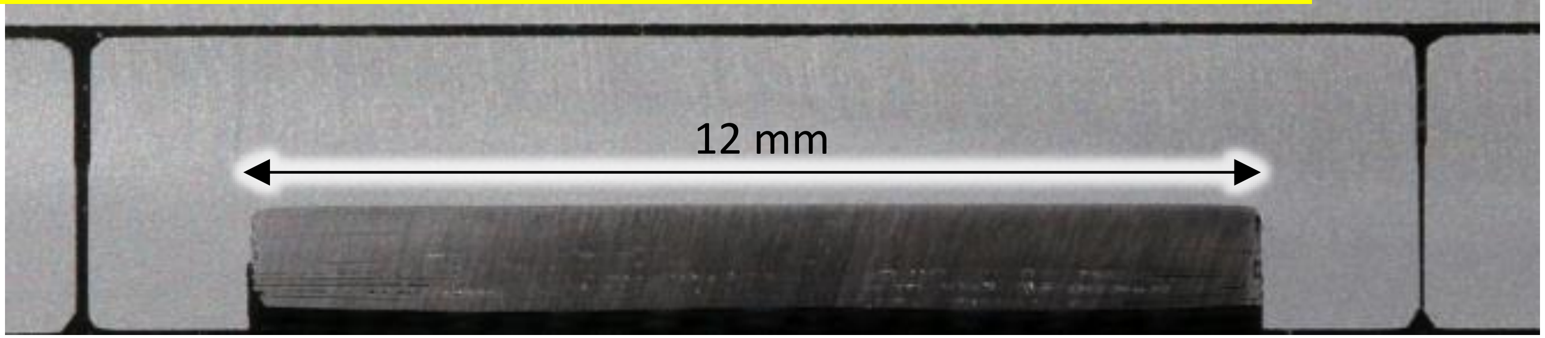
- Single tapes have been extensively characterized ✅.
- Many short samples of Al-alloy stabilized multi-tape HTS conductors are in preparation.
- Few-tape samples in good agreement with expectations.
- Next: more tapes, bending, micro-meteorite impact testing, etc.





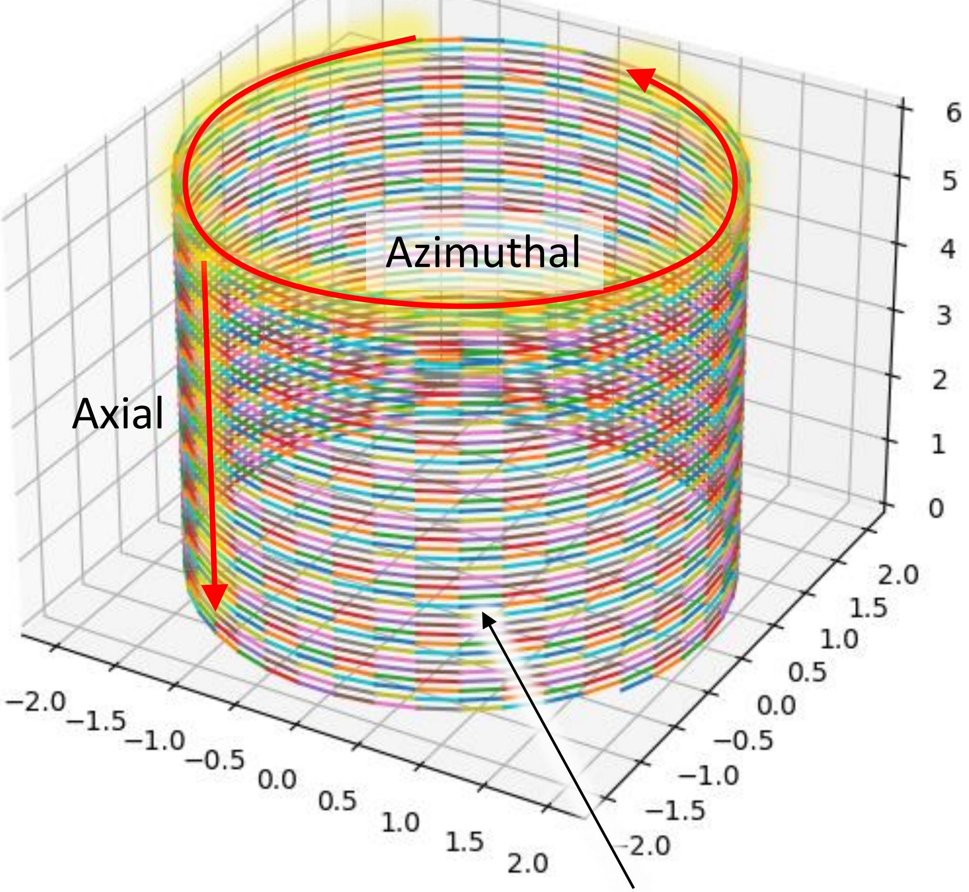
Preparing a robust, radiation transparent HTS cable with minimal amount of solder and proper bonding is still a **major challenge**!





Thermal-ElectroMagnetic Quench Model

Thermally and electrically connected:
Axial and azimuthal direction

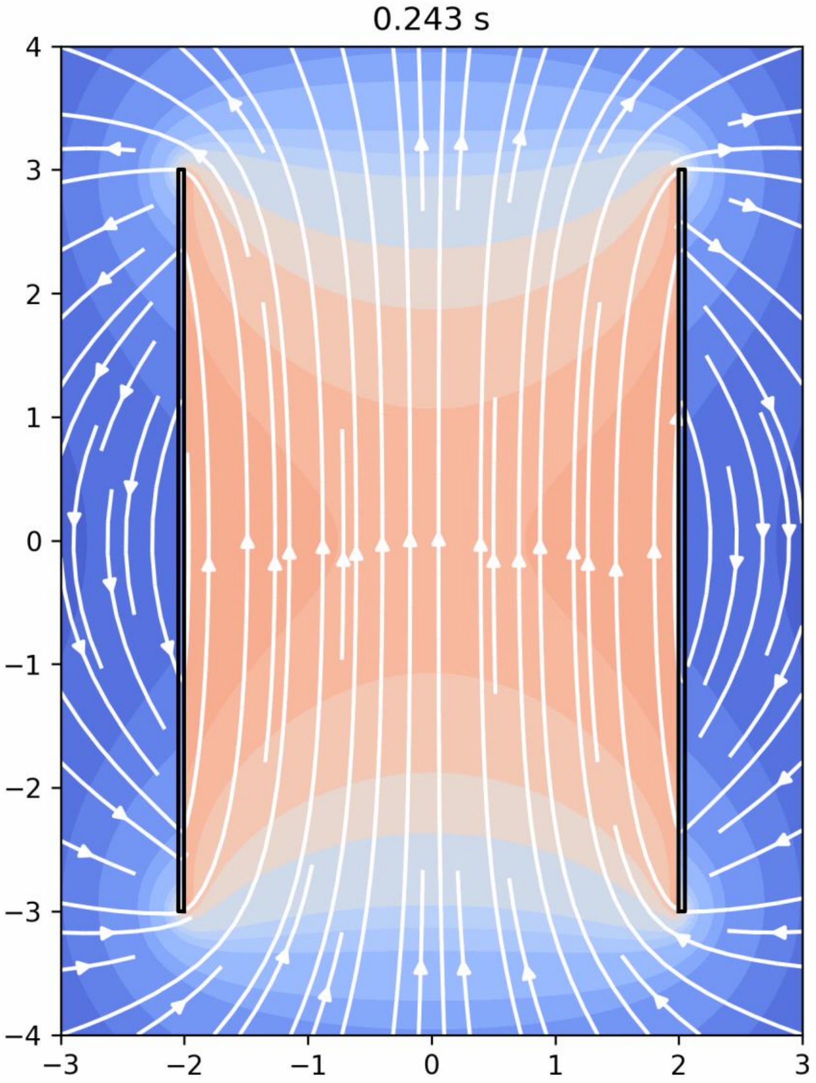


Turns divided in to line elements

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 e.g. micrometeorite impact).
- Other structural elements, such as end-flanges and ribs, are not yet included in the model.
- Simulations performed using a previous design iteration: 428 turns, an operating current of 13.5 kA and a field of 1 T.

Thermal-ElectroMagnetic Quench Model



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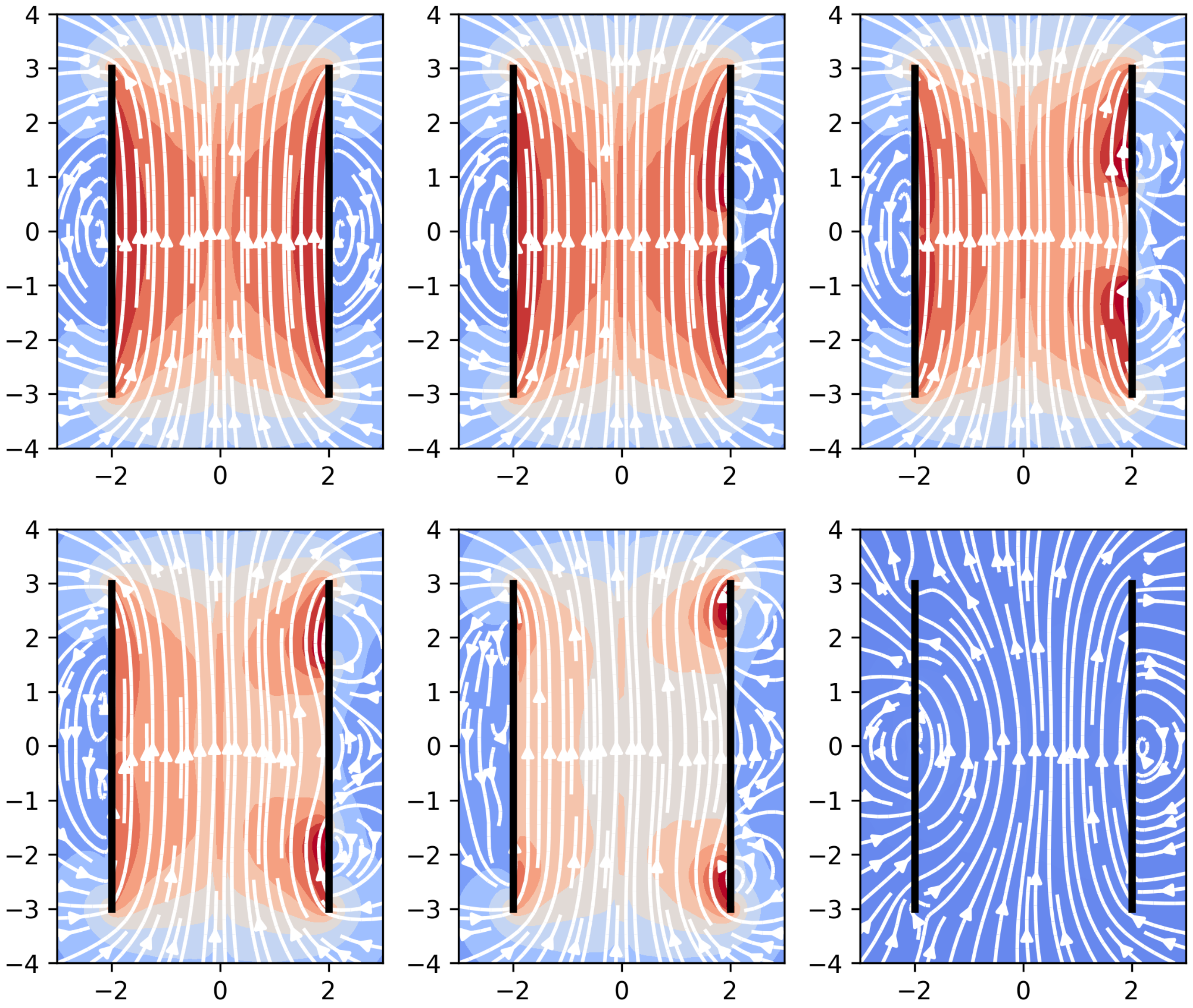
Quench Behavior and Survival



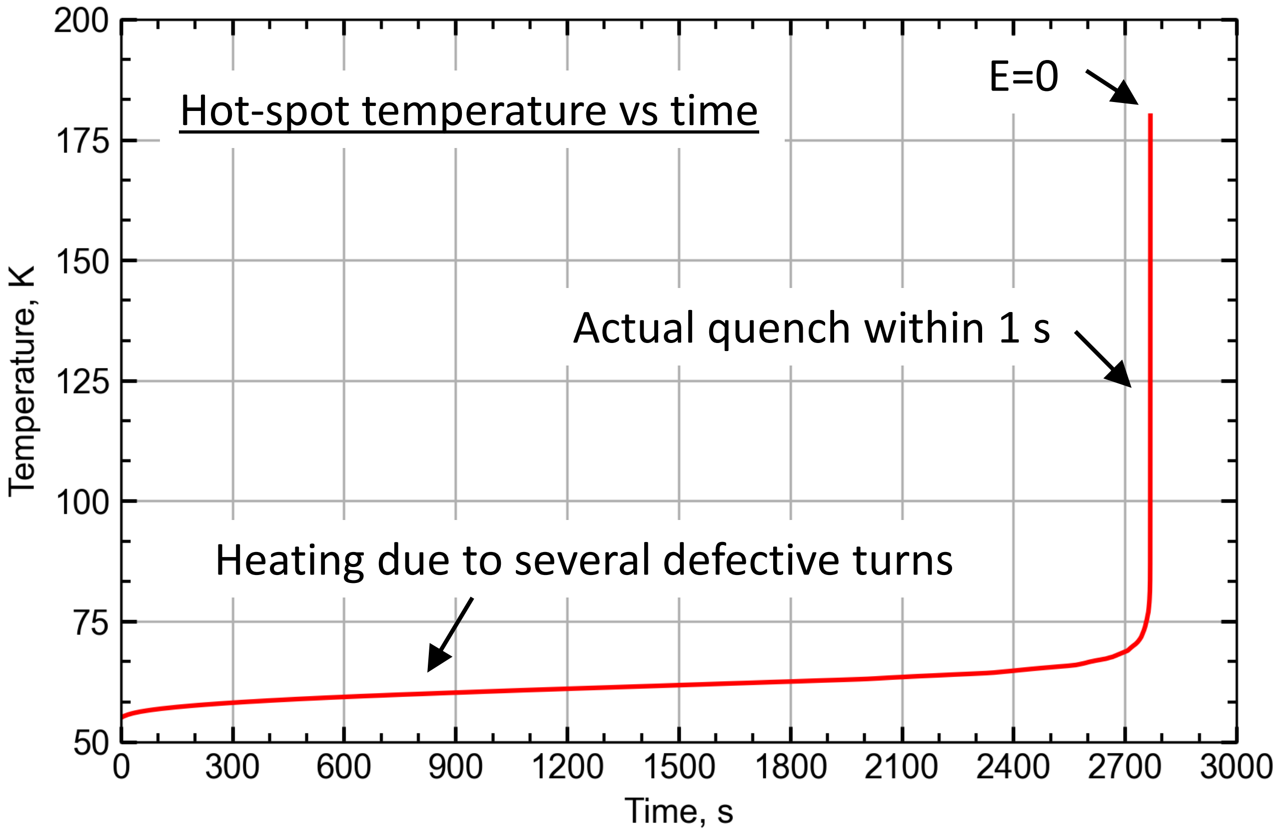
Quench behavior of the non-insulated AMS-100 main solenoid:

- 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):

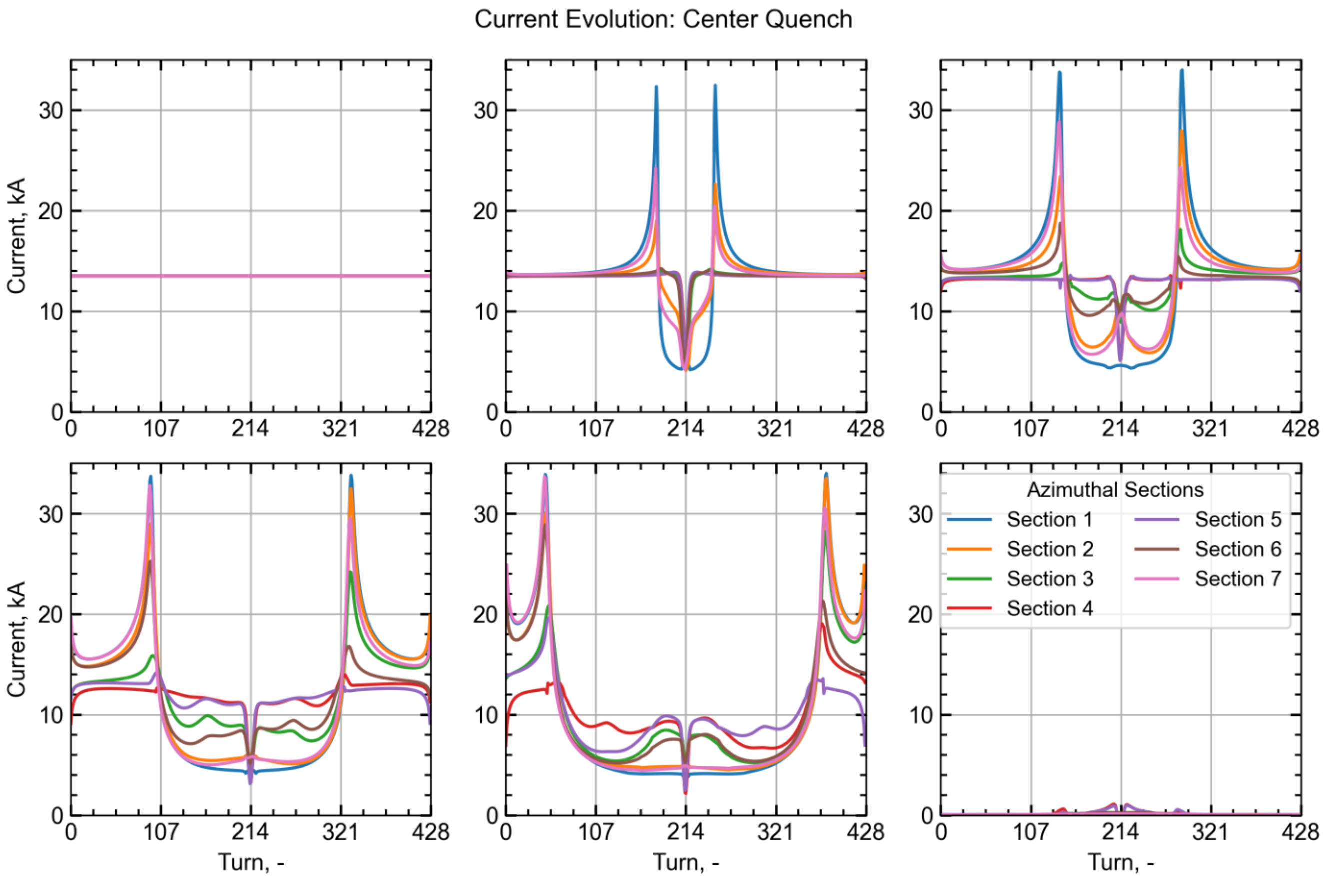
- Current bypasses the defective turn via its turn-to-turn resistance.
- ~ 4 W of heating in the axial resistance per turn.
- Slow thermal runaway in the order of hour(s).
- All energy dissipated within the magnet during the quench, no external extraction.
- Conventional protection methods, such as quench 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 > 2.5 x I_{op} 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.

Simulated Quench Behavior and Survival

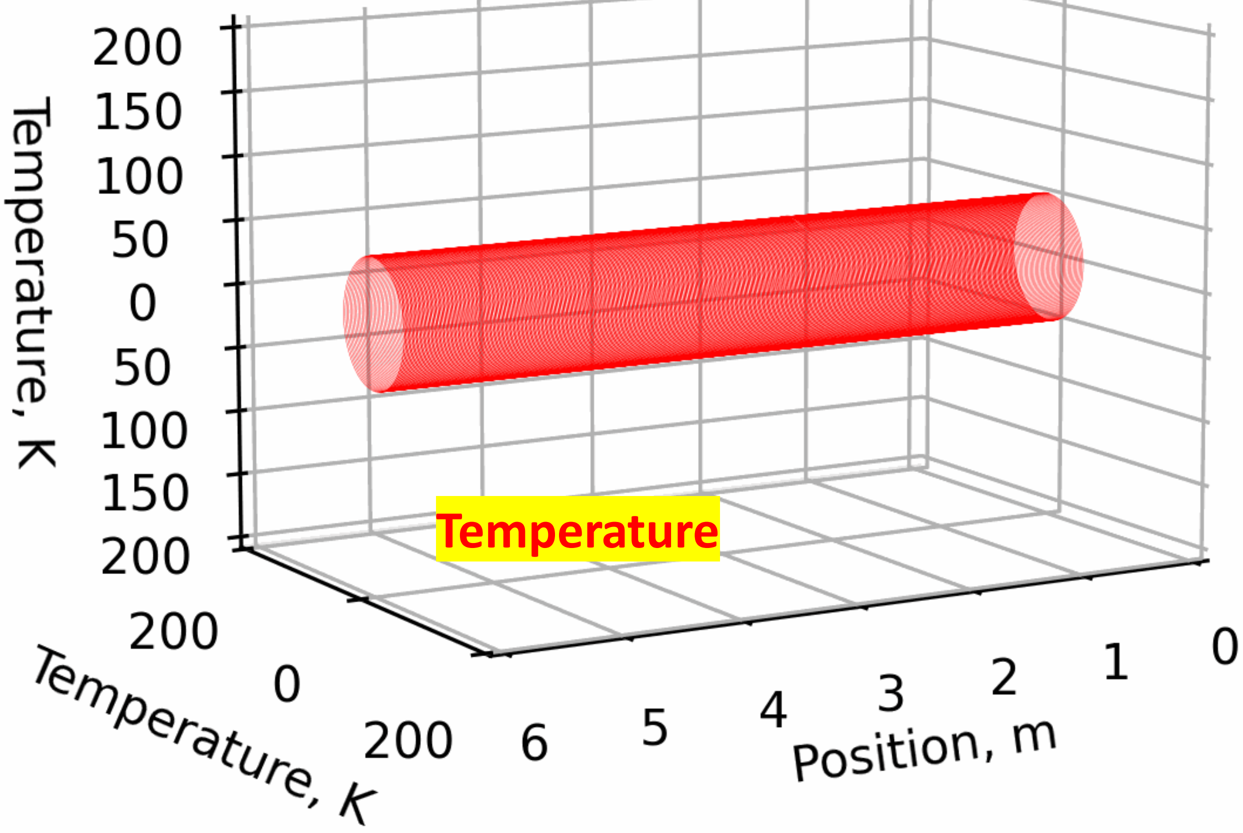
428 turn main solenoid, I_{op} = 13.5 kA, B = 1 T.

t = 0.2428 s

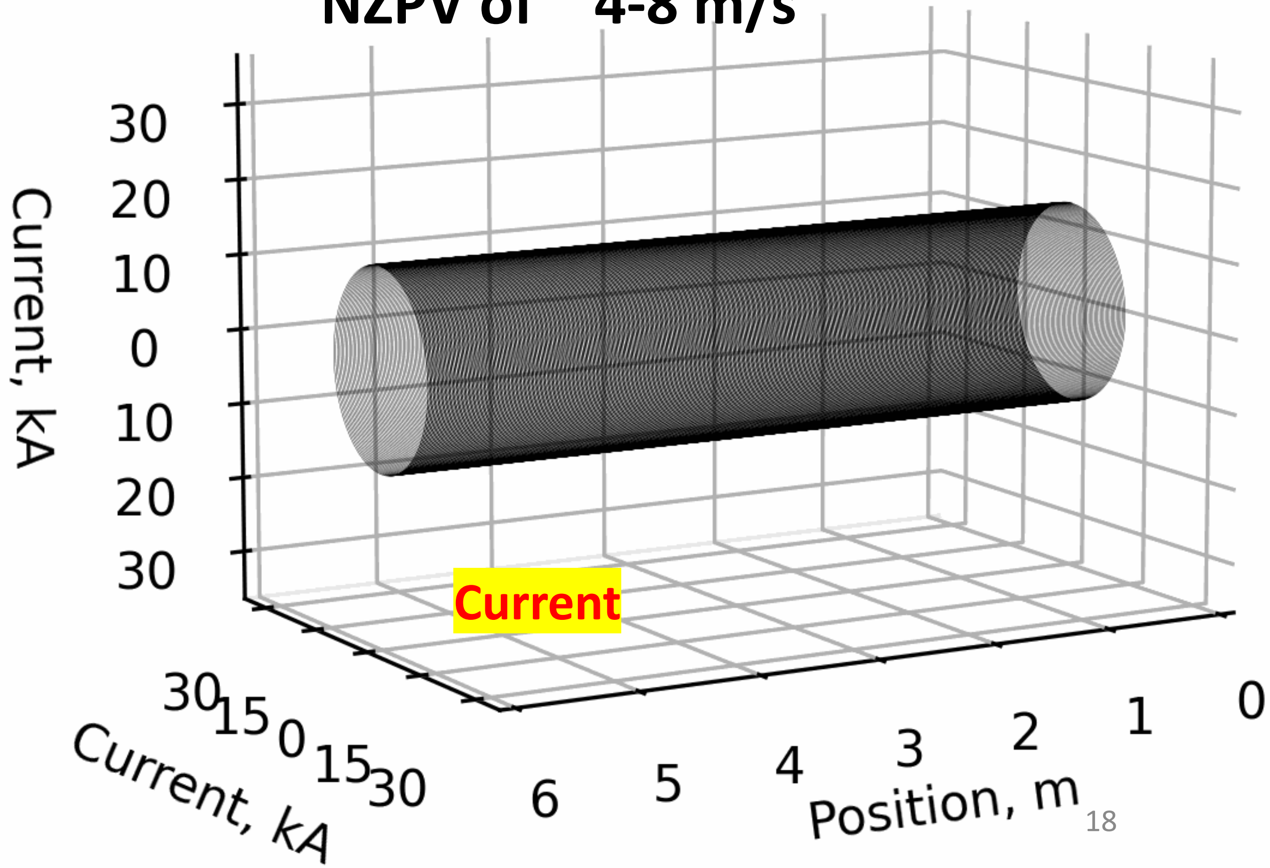
t = 0.2428 s

Simulations indicate that the main solenoid is thermally self-protected.

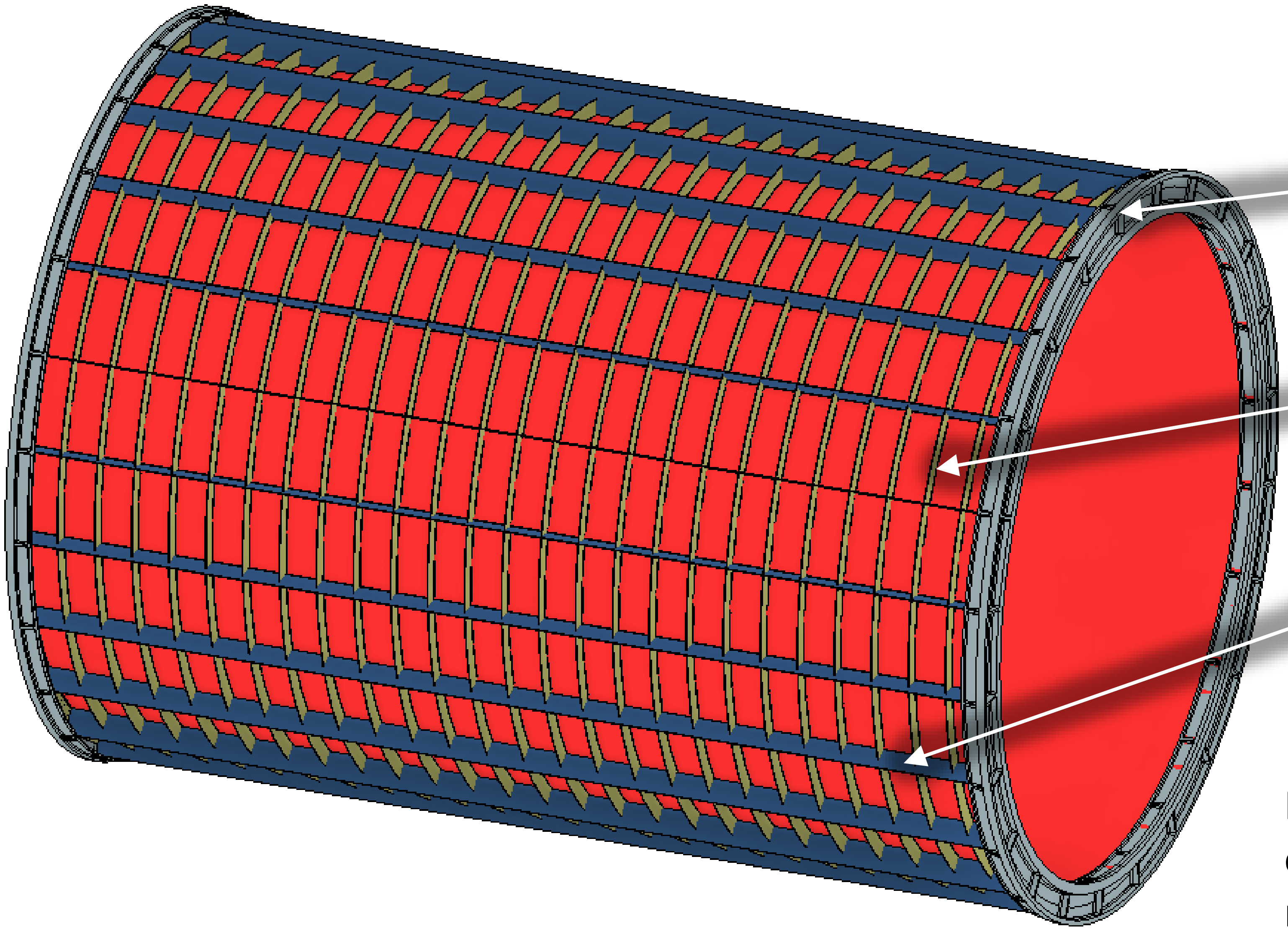
Peak hot-spot near extremities



NZPV of ~ 4-8 m/s



End-flanges, Ribs and Stringers



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

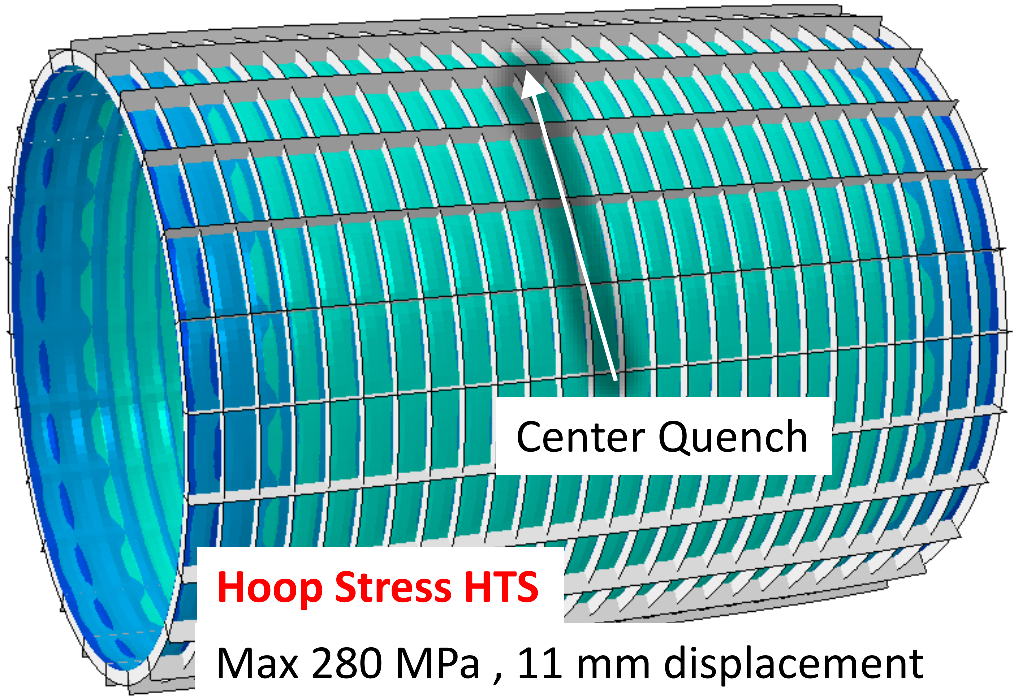
Ribs (yellow): Mechanical support of the magnet during operation and quench events.
Circular, allows quench-back.

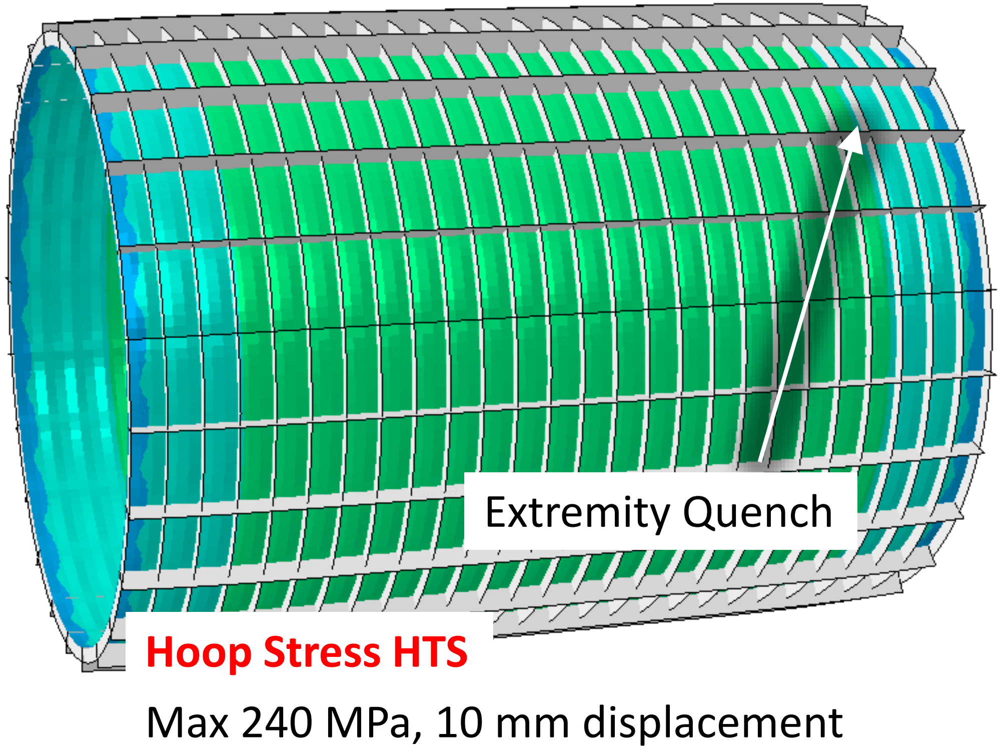
Stringers (blue): Mechanical support during launch.

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.
- 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 (~300 MPa) caused by radial Lorentz force.
- Support structure requires optimization.

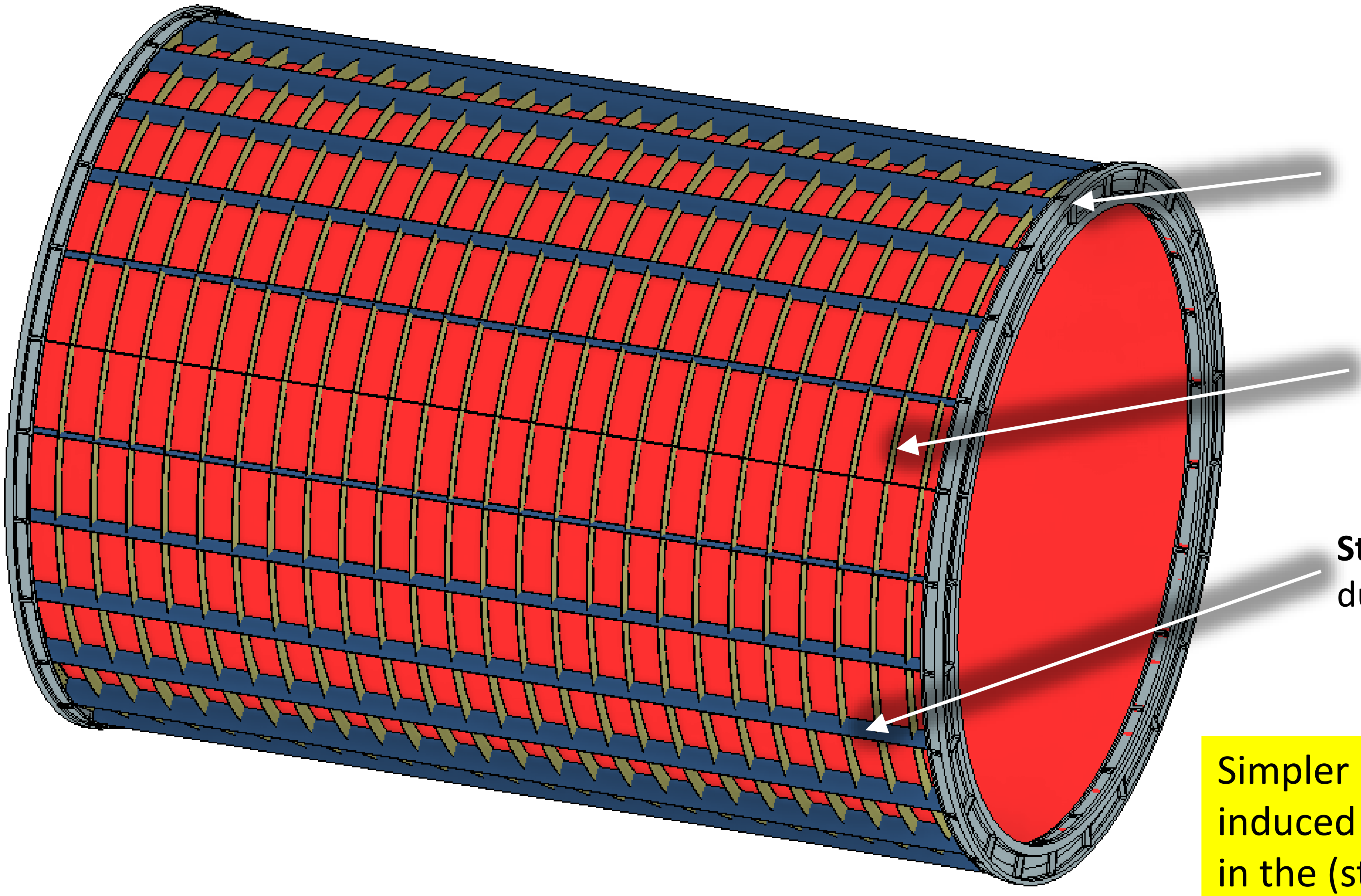




J. Zimmermann & D. Pridöhl, RWTH Aachen

Boundary condition: outer rings fixed to circular shape, free thermal shrinkage

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.

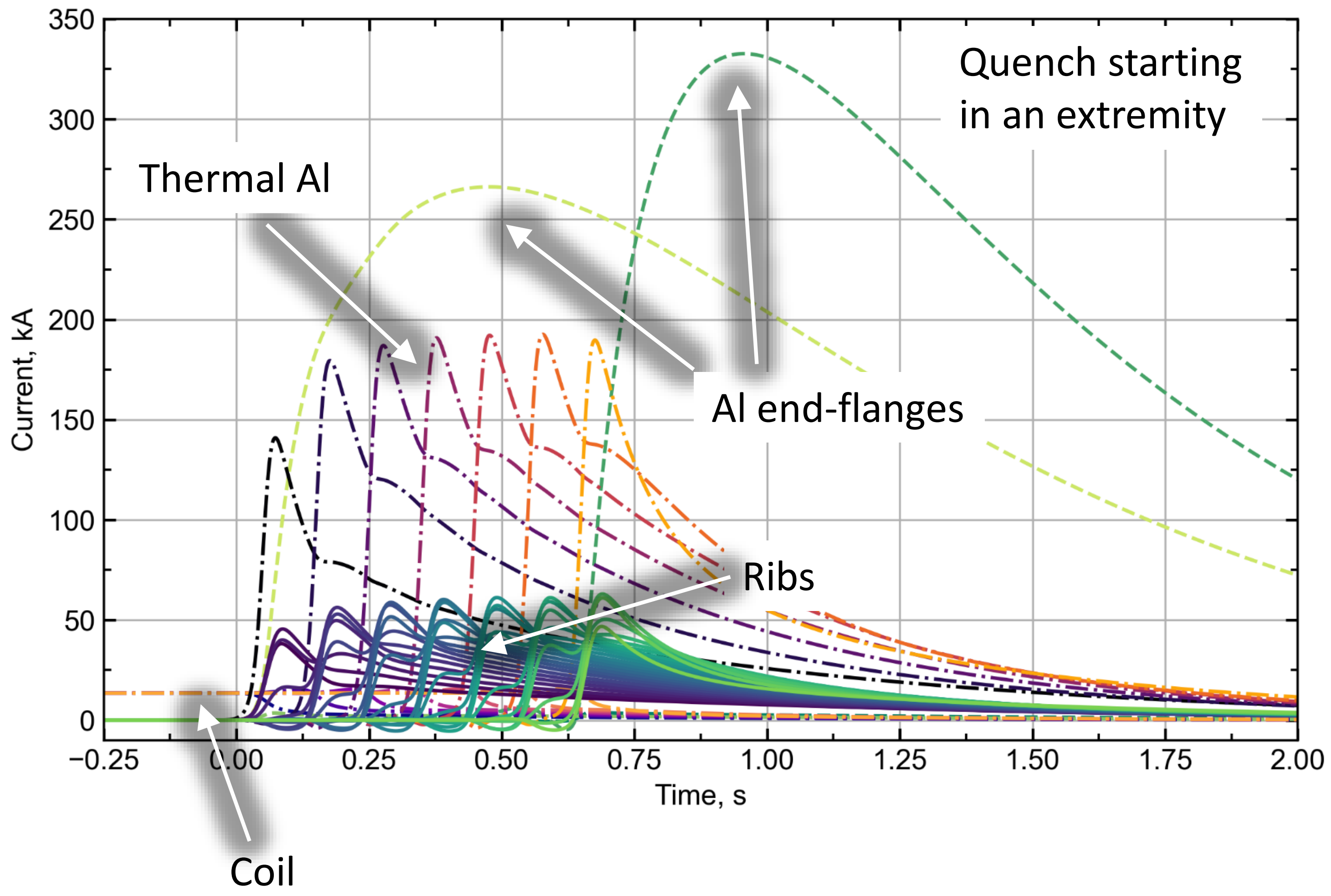
Simpler 2D Model is set up to estimate induced currents and energy dissipation in the (structural) circular components.

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

Simpler 2D 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.
- 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 %**)

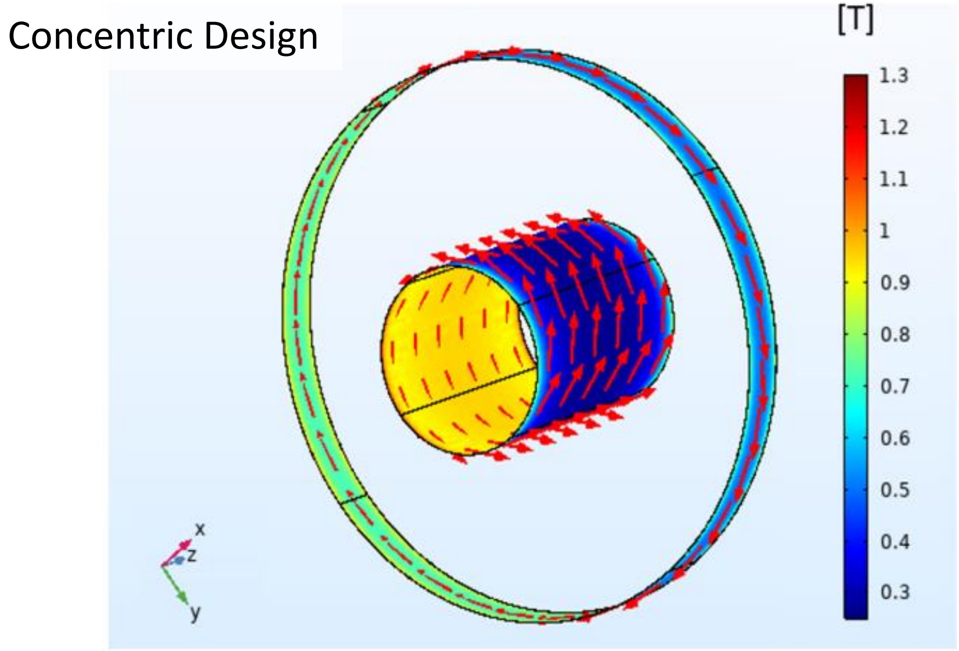
Quench from an extremity:
Total Energy: 33.7 MJ
In conductor: 17.5 MJ (**52%**)
In ribs: 7.1 MJ (**21%**)
In flanges: 2.7 MJ (**8%**)
In thermal aluminum: 6.4 MJ (**19%**)

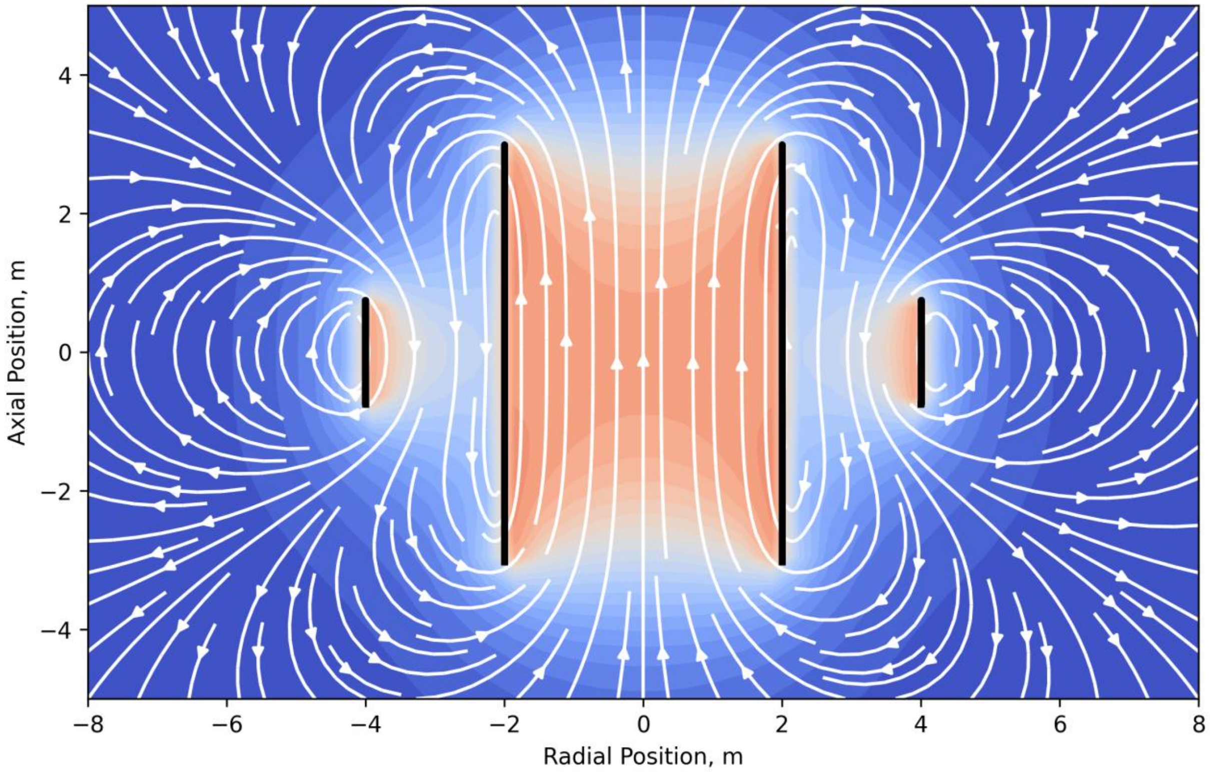
- Large fraction (50 %) of the stored energy is dissipated in the ribs, flanges and thermal aluminum.
- Will result in a much lower hot-spot temperature.
- Induced current in the structural elements result in a lower mechanical load on the conductor itself.
- Slows down the quench process.
- Expected that further mechanical optimization will reduce the mass and dimensions of the ribs and end-flanges.
- Expected reduction of energy dissipated in the ribs and end-flanges from 30% -> 10-20 %.
- <u>One model that includes the main solenoid, compensation coil and all structural components needed.</u>

Remaining Challenge: Compensation Coil

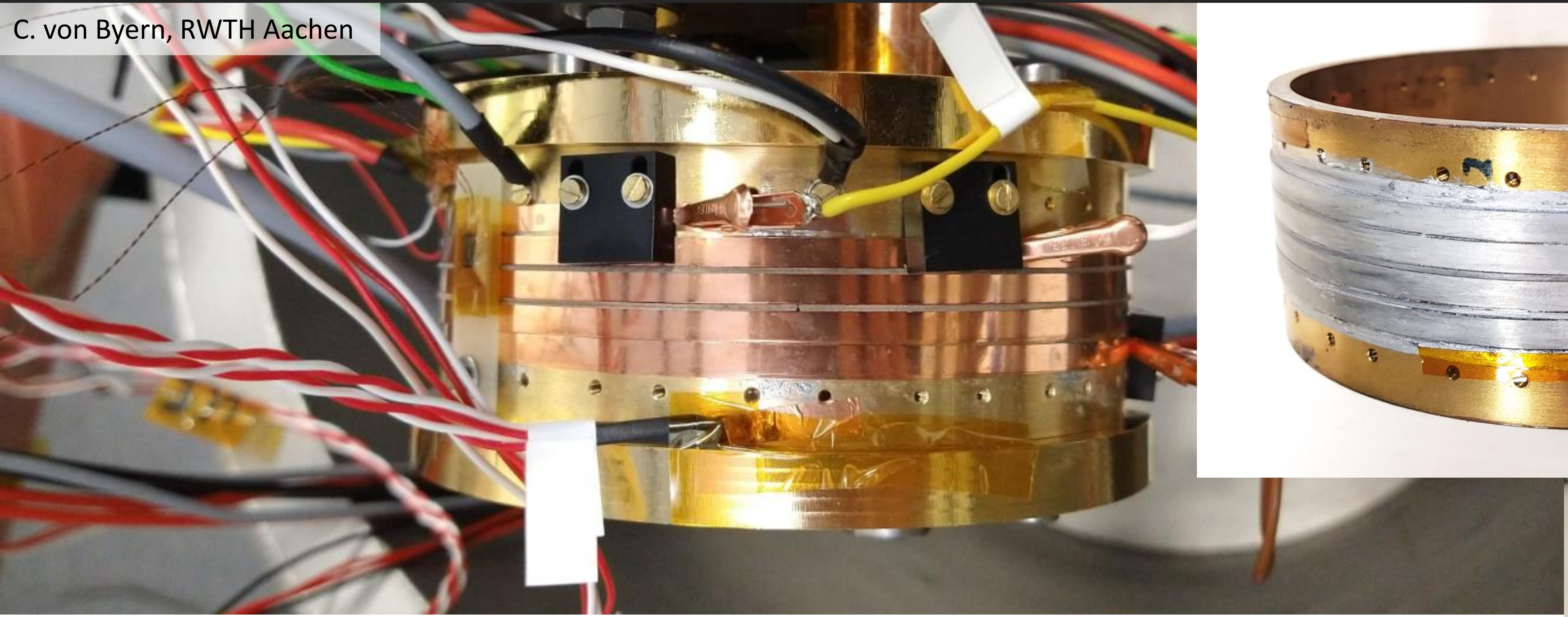
There is a non-zero background field at L2, magnetic torque -> magnet tries to align to this B-field.

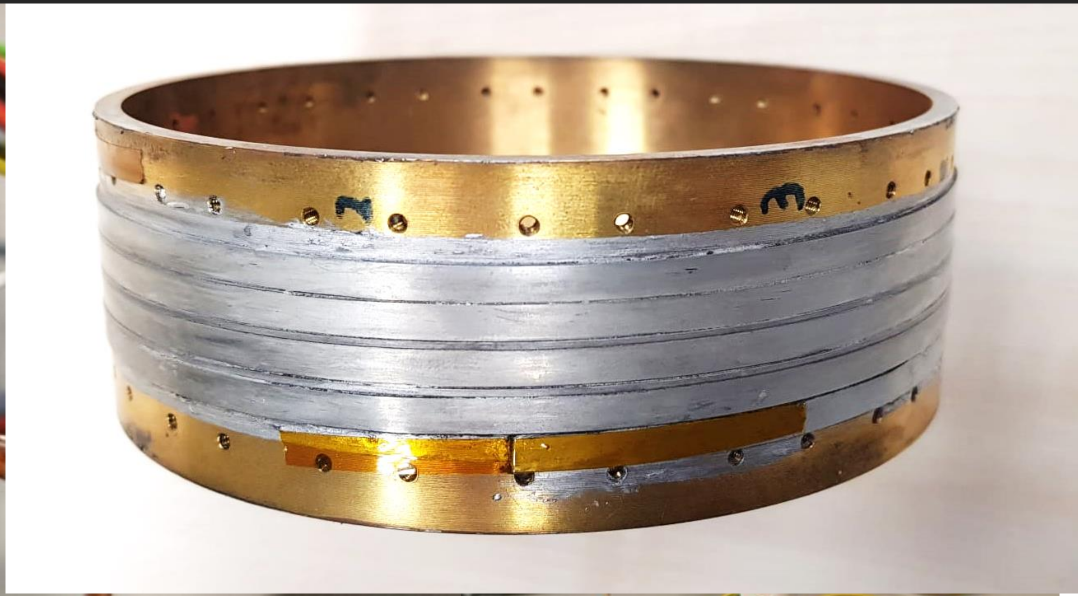
- Compensation coil is needed to have altitude control.
- Concentric comp. coil with a radius of 4 m under investigation (to fit in to the cargo bay of the rocket).
- All current designs are inherently unstable and a strong support structure is essential.
- 2D axisymmetric quench model including the compensation coil and struct. components in development.





AMS-100 Demonstrator Coils


C. von Byern, RWTH Aachen

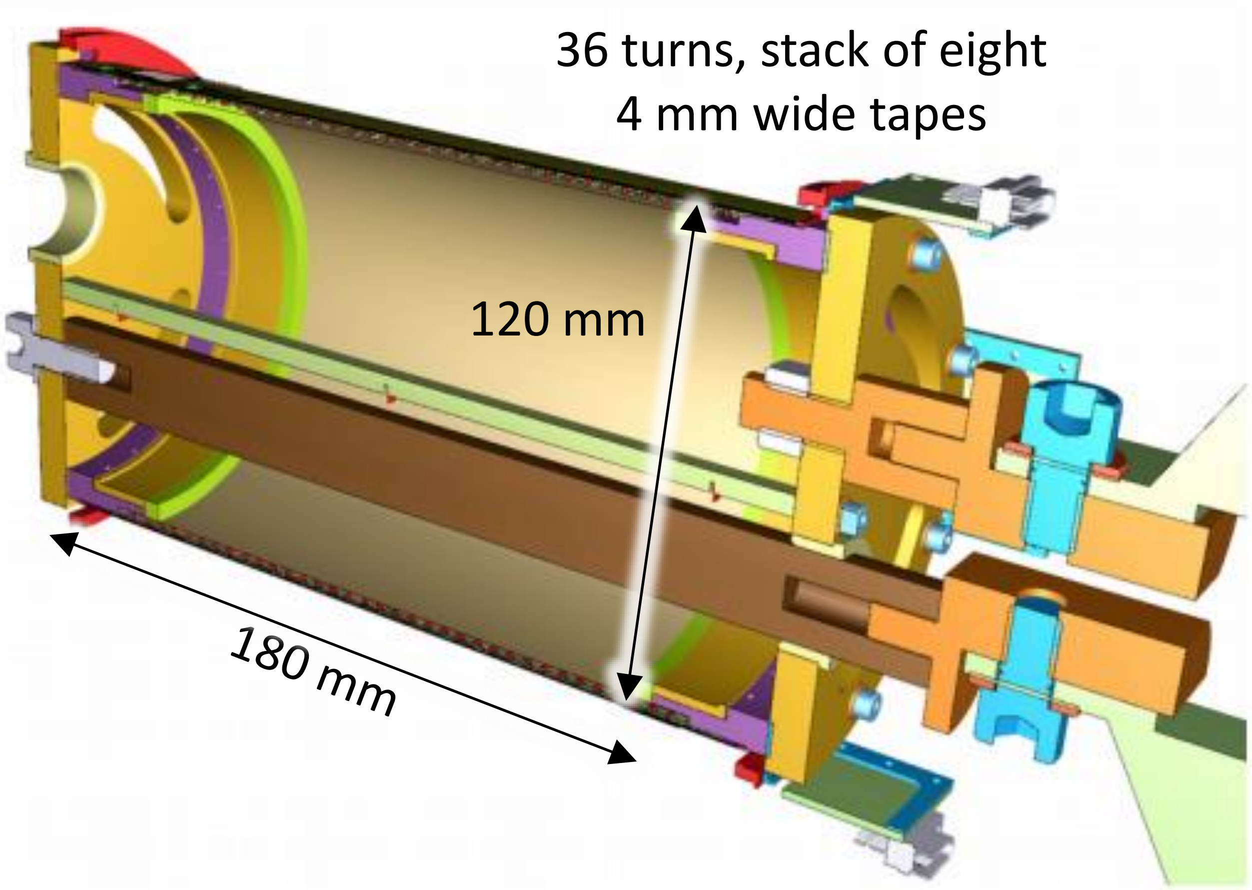


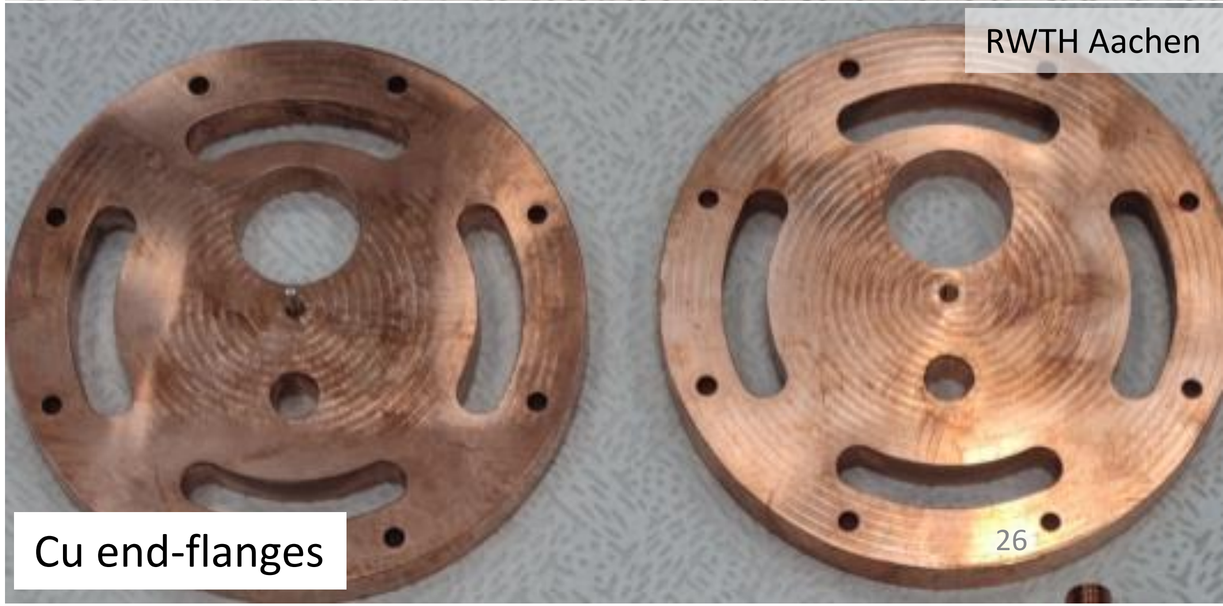

D. Uglietti, EPFL

<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.

AMS-100 Demonstrator Coils





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

Conclusions

- AMS-100 magnet system faces many design challenges due to its
  - ultra-thin 0.5 T HTS coil,
  - large stored energy of 14 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.
- The magnet system is in its early design phase. Several iterations are expected to fine-tune its design.

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