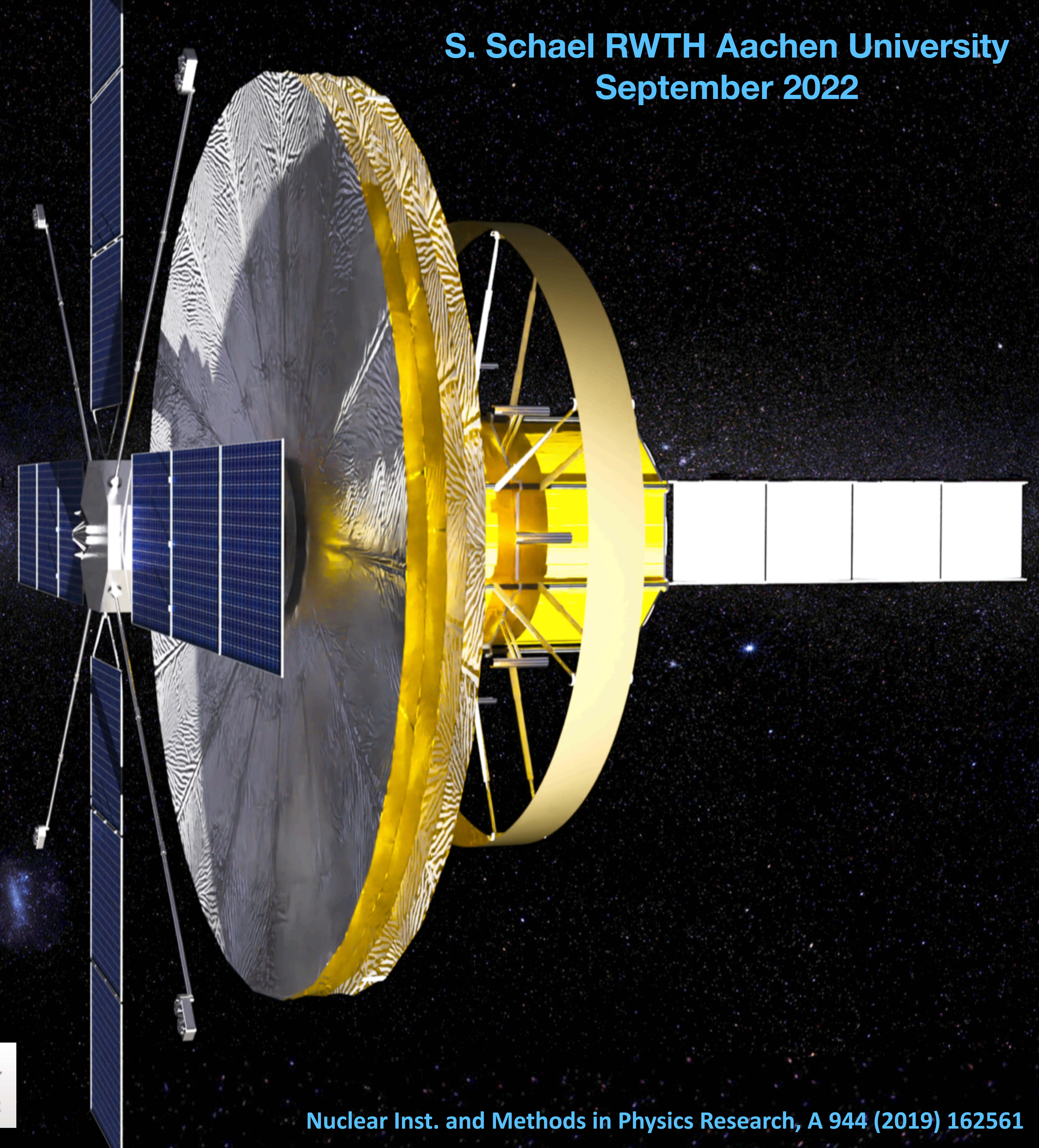
AMS-100

S. Schael RWTH Aachen University
September 2022

A Magnetic Spectrometer with an acceptance of 100 m^2 sr in Space



Structural- & Thermal Design, Service Module, Sunshield & Magnet

T. Bagni, Ch. von Byern, M. Czupalla, B. Dachwald, A. Dudarev, D. Fehr, H. Gast, D. Louis, T. Mulder, W. Karpinski, Th. Kirn, D. Kohlberger, M. Mentink, D. Pridöhl, S. Schael, T. Schalm, K.-U. Schröder, A. Schultz von Dratzig, P. Seefeldt, C. Senatore, Th. Siedenburg, H. Silva, D. Uglietti, A. Vaskuri, M. Wlochal, J. Zimmermann

RWTH AACHEN UNIVERSITY
FH AACHEN UNIVERSITY OF APPLIED SCIENCES
EPFL
CERN
UNIVERSITÉ DE GENÈVE
DLR

Nuclear Inst. and Methods in Physics Research, A 944 (2019) 162561

Major Cosmic Ray Experiments 2022

DAMPE

TA

LHAASO

AMS-02

MAGIC

CTA

HAWC

ISS CREAM

CALET

Fermi

HESS

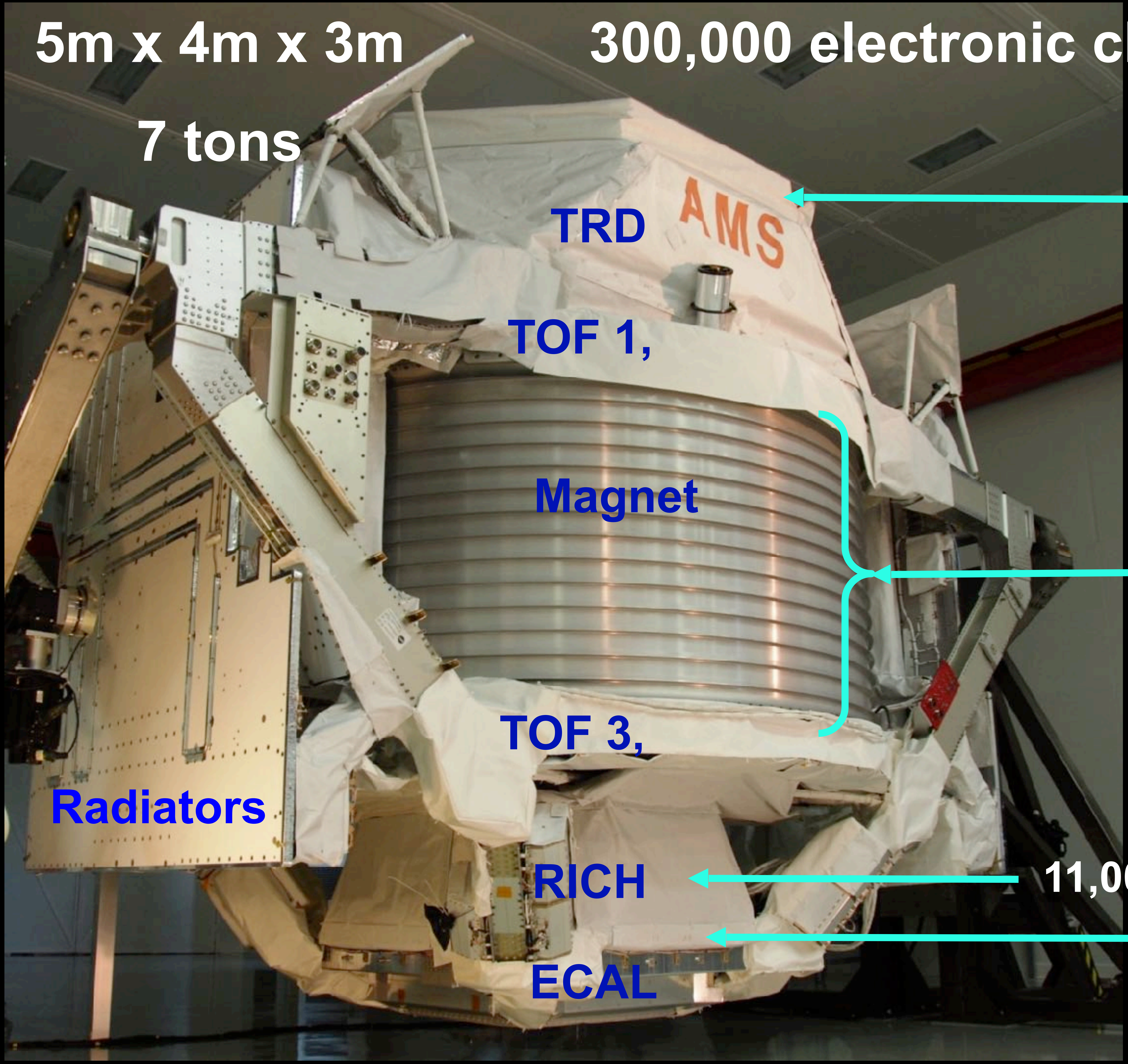
Auger

Ice Cube

We have only one magnetic spectrometer in space: AMS-02

In Space since May 2011

It took 600 Physicists and Engineers from 16 Countries and 60 Institutes 17 years to construct the Alpha Magnetic Spectrometer.



Silicon layer

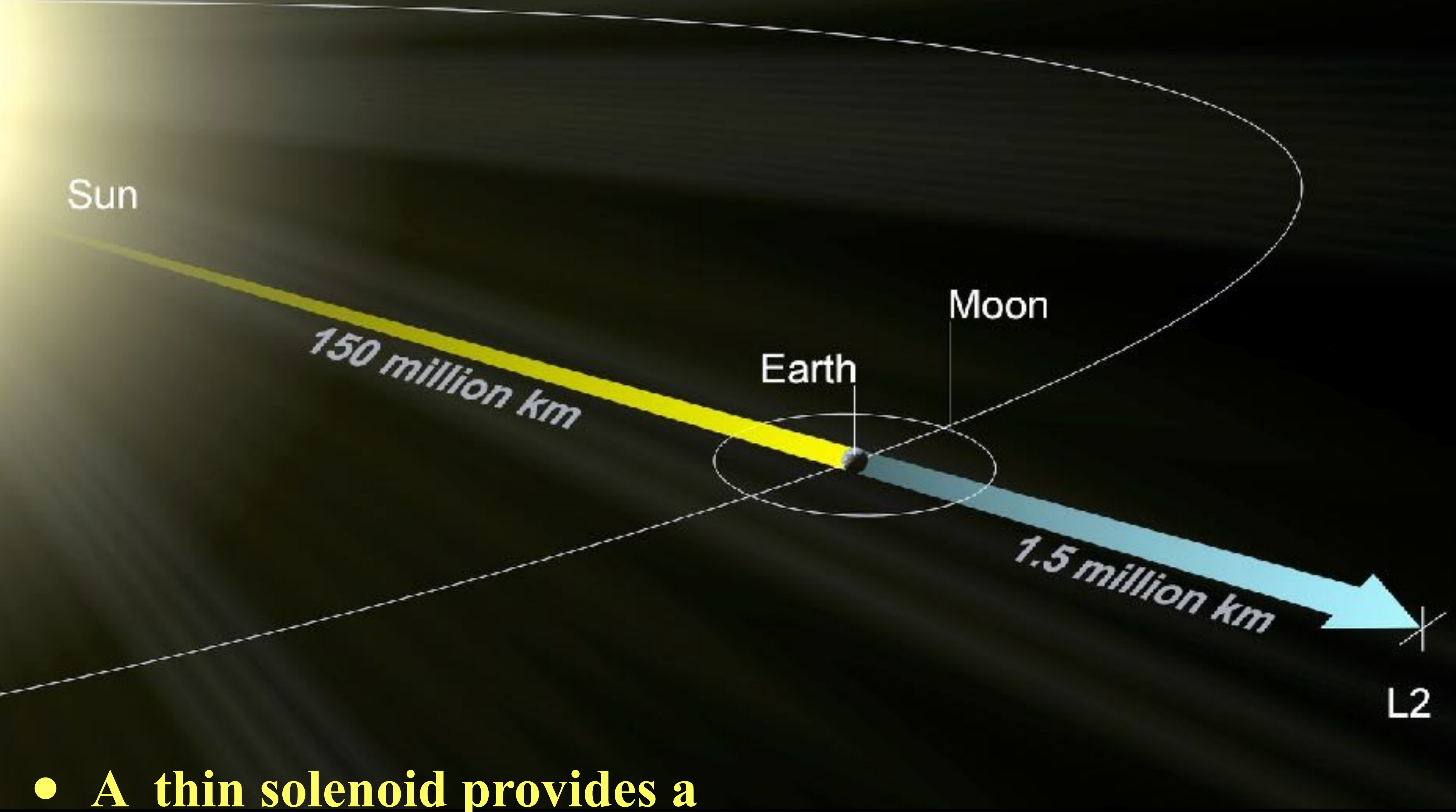
7 Silicon layers

11,000 Photo Sensors

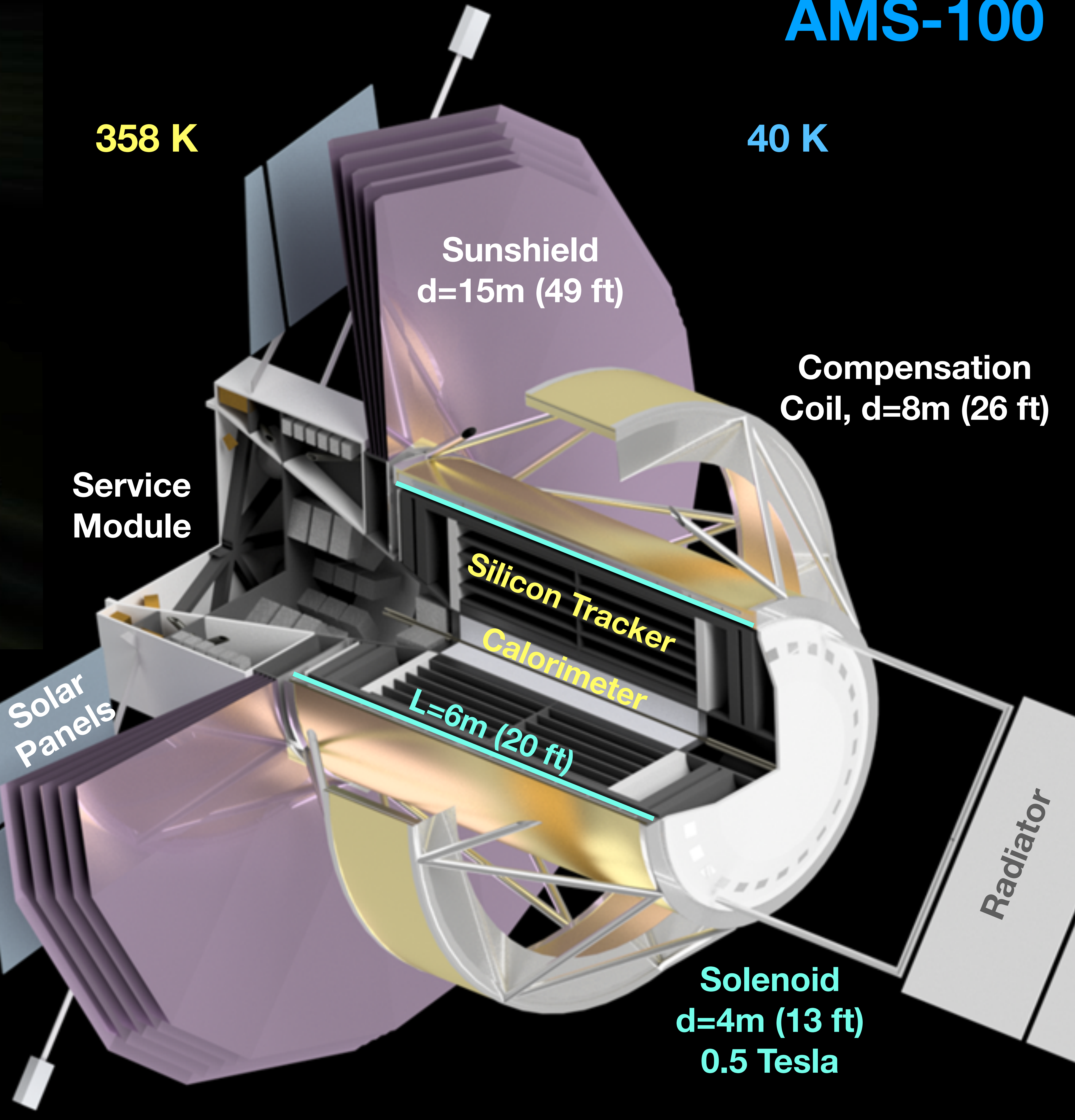
Silicon layer

We have to start now to work on the next generation magnetic spectrometer in space !

AMS-100



- A thin solenoid provides a magnetic field of 0.5 Tesla.
- The solenoid is operated at 60 K behind the sunshield in thermal equilibrium with the environment.
- A compensation coil balances the magnetic dipole moment of the solenoid.
- The solenoid is instrumented on the inside with a silicon tracker and a calorimeter system.



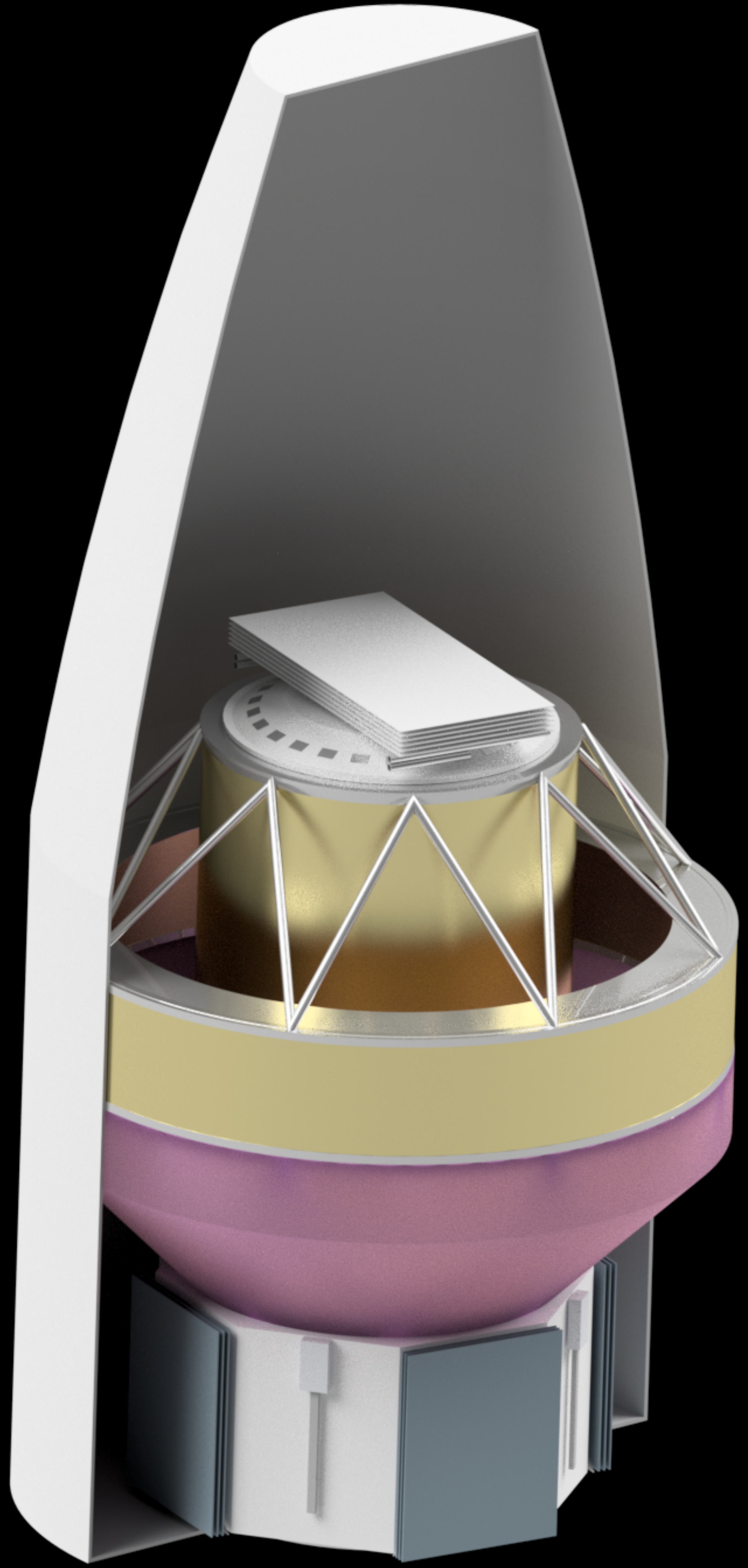
Electric Propulsion

Weight
40 t

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



Starship's 8 m (26 ft) diameter
payload dynamic
envelope

SpaceX

- In 2019, the cost per launch for Starship was estimated by SpaceX to be as low as US$2 million.
- Elon Musk has said in 2020 that, with a high flight rate, they could potentially go even lower, with a fully-burdened marginal cost on the order of US$10 per kilogram of payload launched to low Earth orbit.

NASA LUVOIR space telescope

AMS-100: A Magnetic Spectrometer

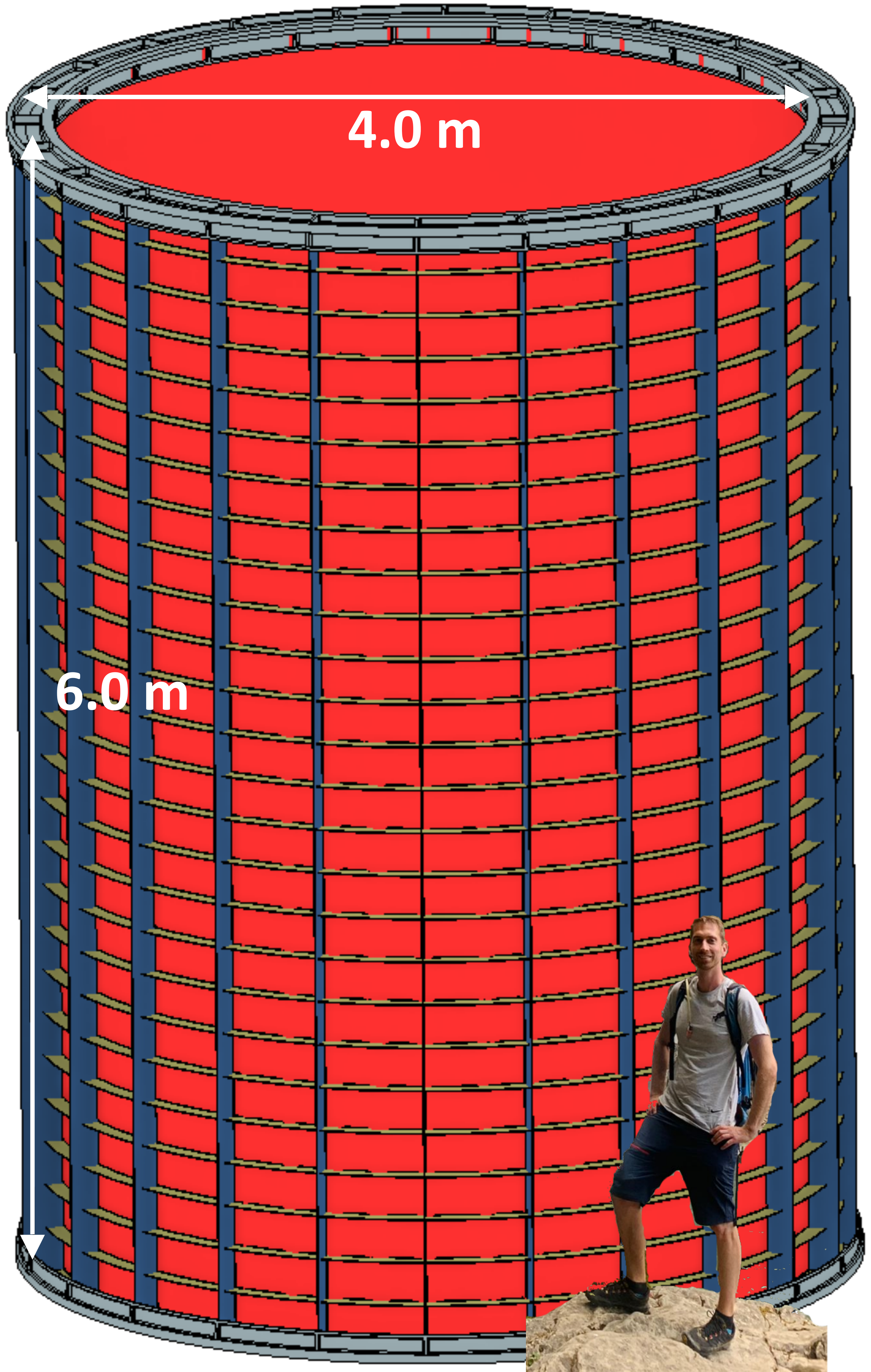


Table of properties for the AMS-100 main solenoid and compensation coil.

	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.

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 the compensation coil is on.

Operating temperature range of 50 to 60 K:

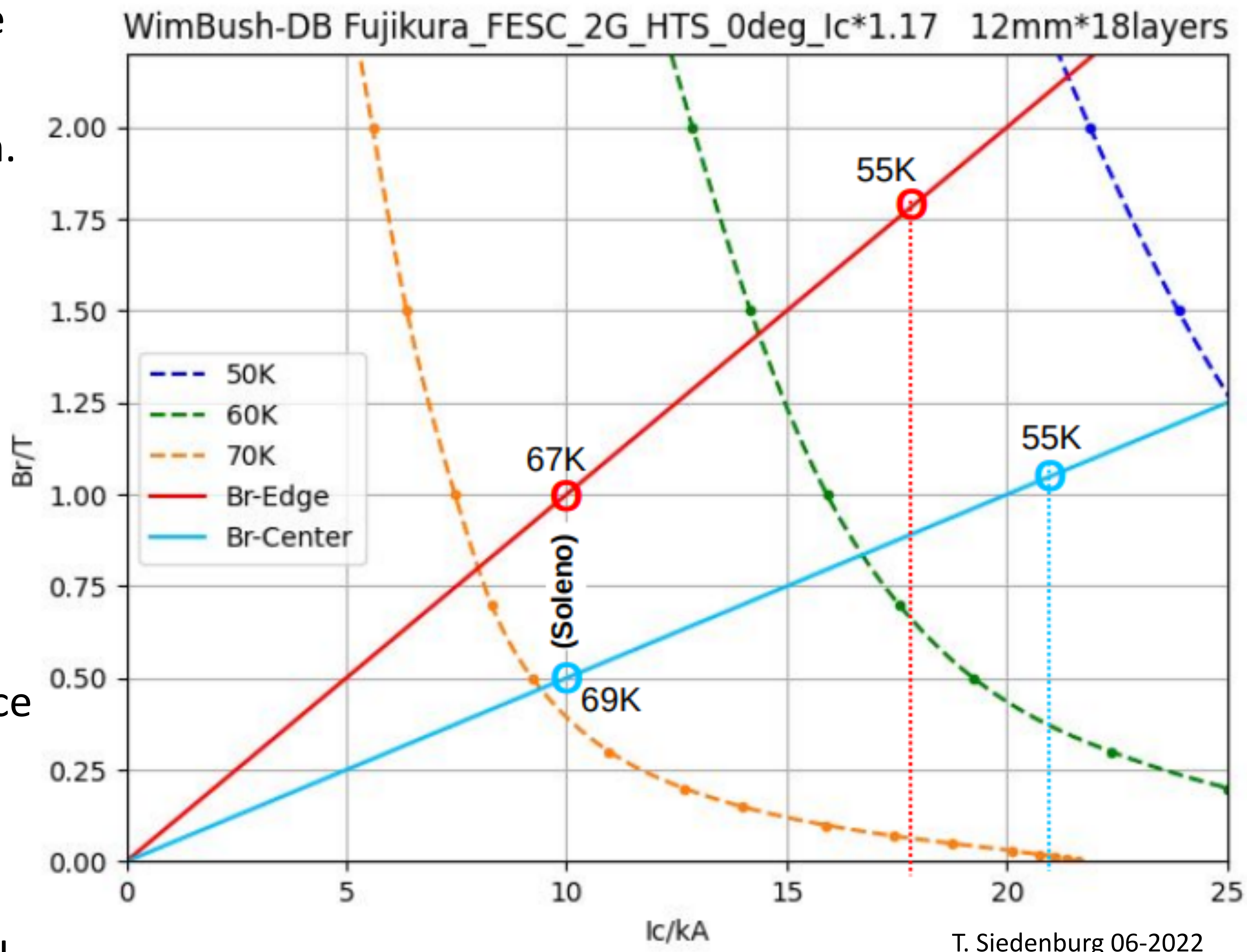
- ΔT of 12 K @ 55 K

Large temperature margin is important:

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

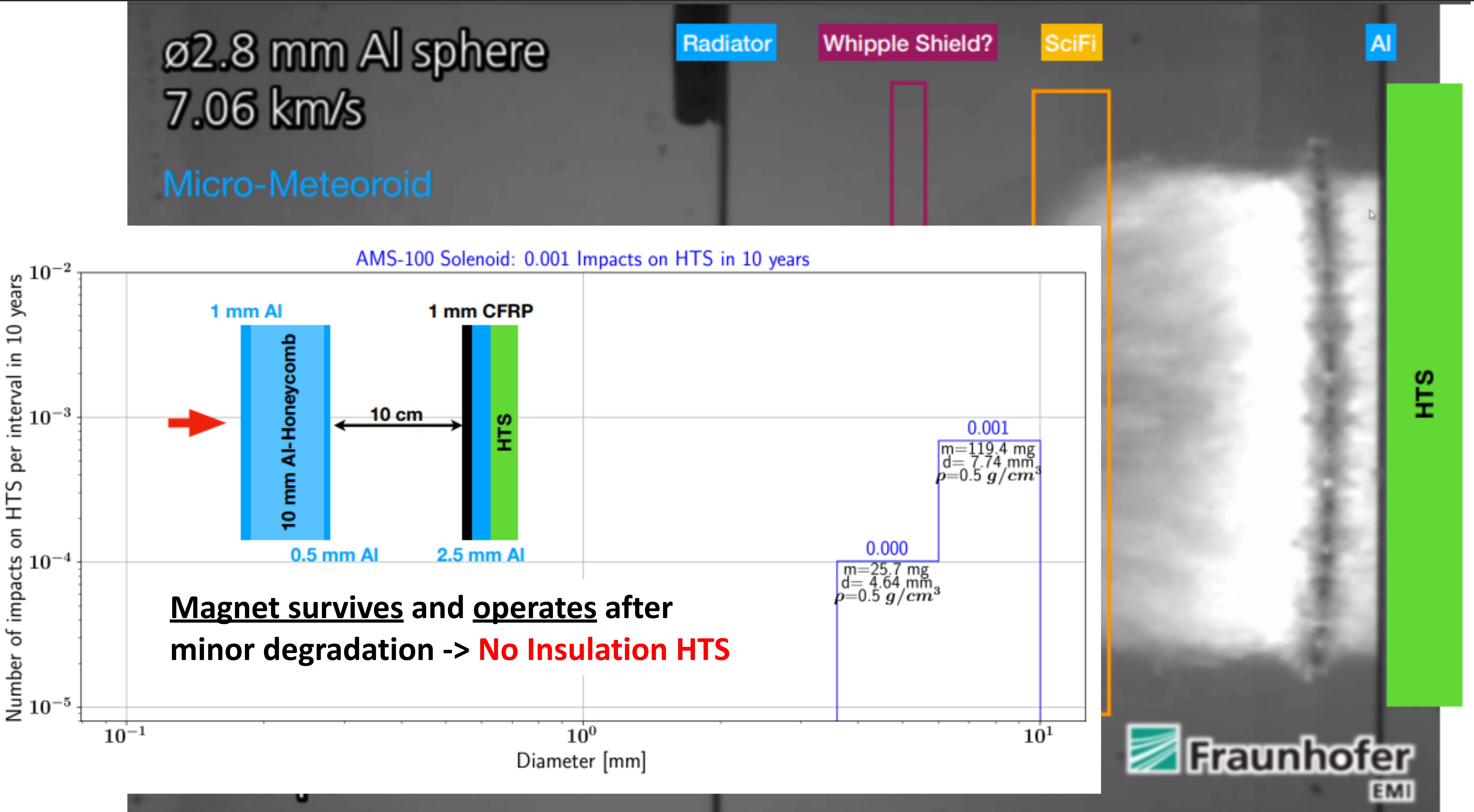
Smart spacing of the conductor / additional HTS tape is envisioned at the coil extremities to reduce the peak field. And allow possible operation at higher current/magnetic field.

The field homogeneity is not an operation critical parameter.



T. Siedenburg 06-2022

Dangers of Space: Micrometeorite Impact

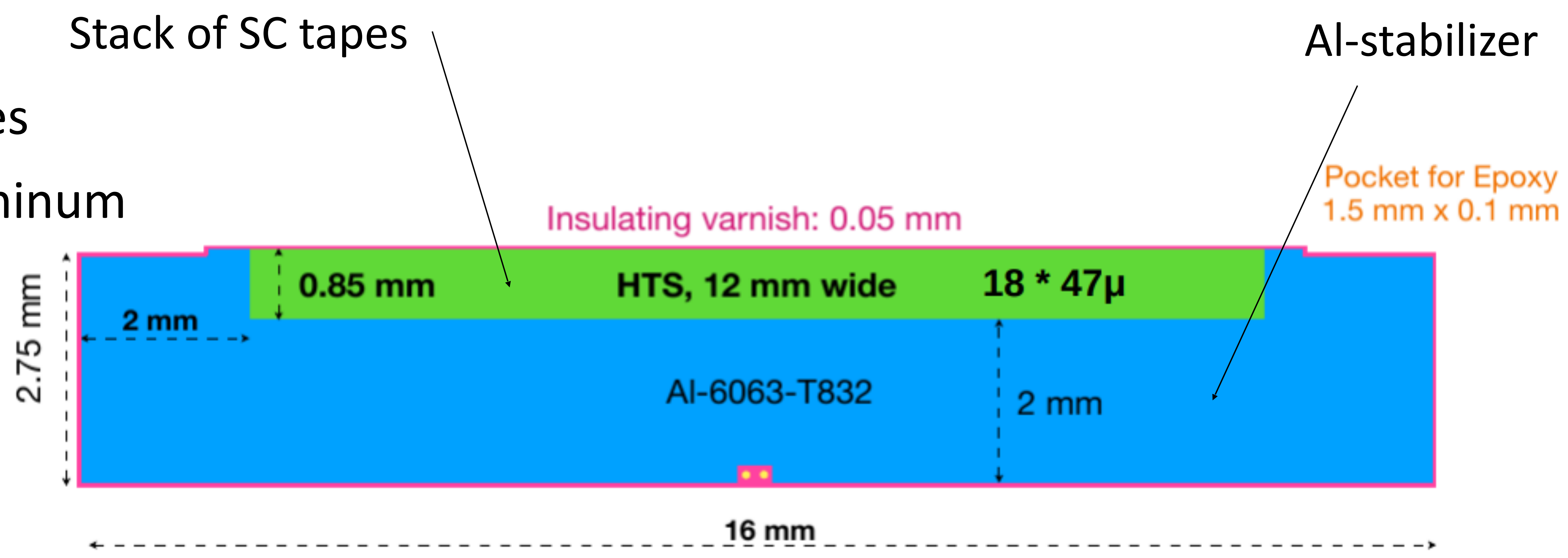


<u>Magnet survives</u> and <u>operates</u> after minor degradation -> No Insulation HTS

Conductor and Coil Layout

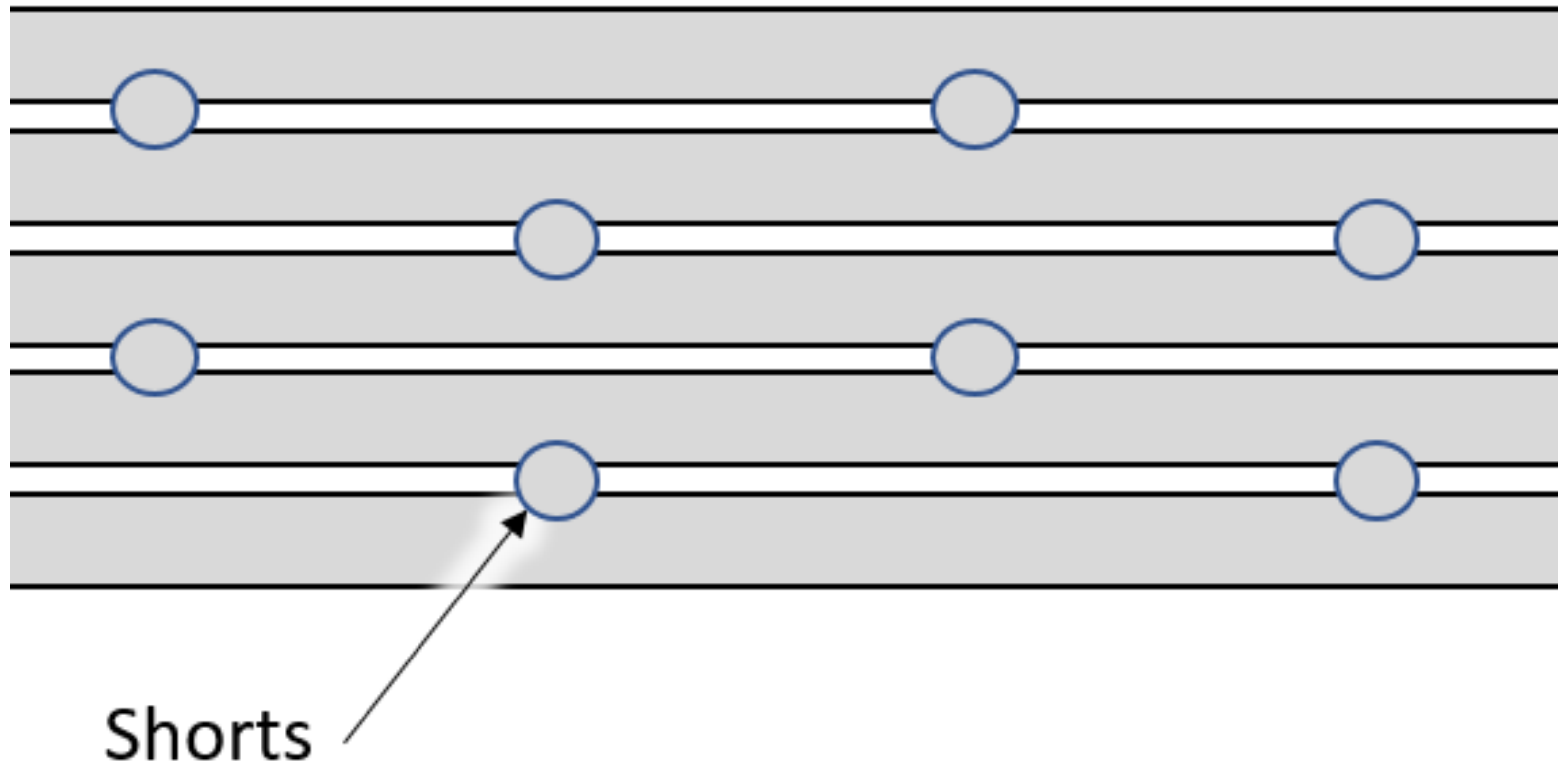
Current conductor layout:

- 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.

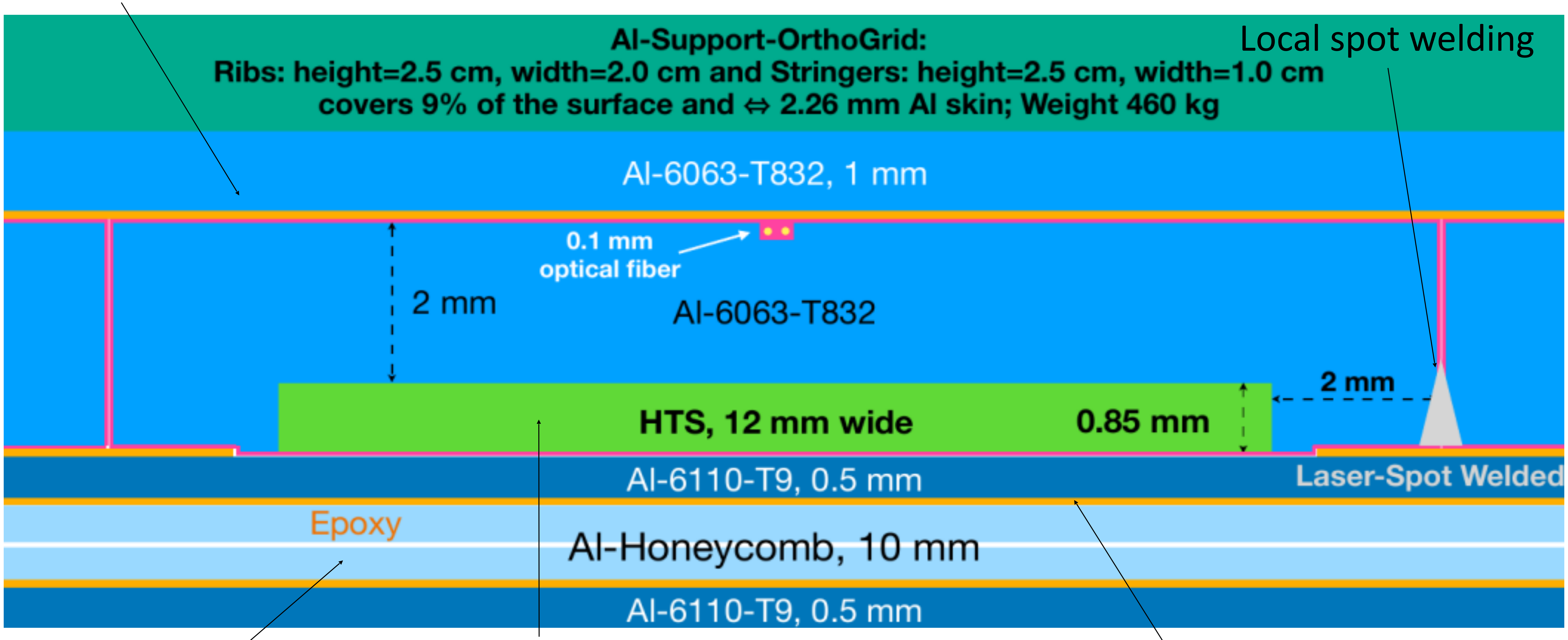
- 1 mm^2 weld provides a turn-to-turn resistance of about 3e-5 Ω.
- AMS-100 -> 1250 mm^2 per turn (10 % of the circumference) covered with point welds of 1 mm^2 -> $\tau = 10$ hours.
- Provides mechanical strength and provides thermal/electrical path.
- Shorts are within the envelope of the conductor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



Al-Support-OrthoGrid:
Ribs: height=2.5 cm, width=2.0 cm and Stringers: height=2.5 cm, width=1.0 cm
covers 9% of the surface and ⇔ 2.26 mm Al skin; Weight 460 kg

Honeycomb for
mechanical stiffness

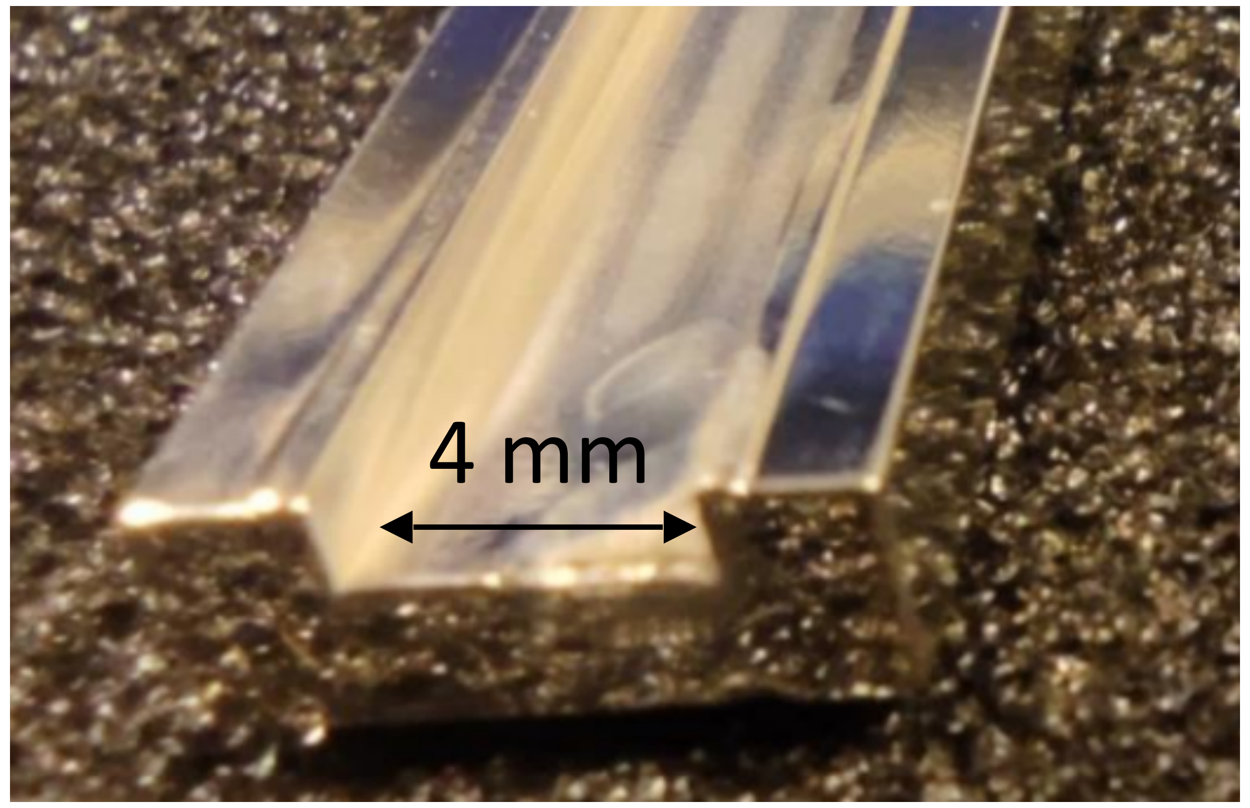
Stack of HTS tapes

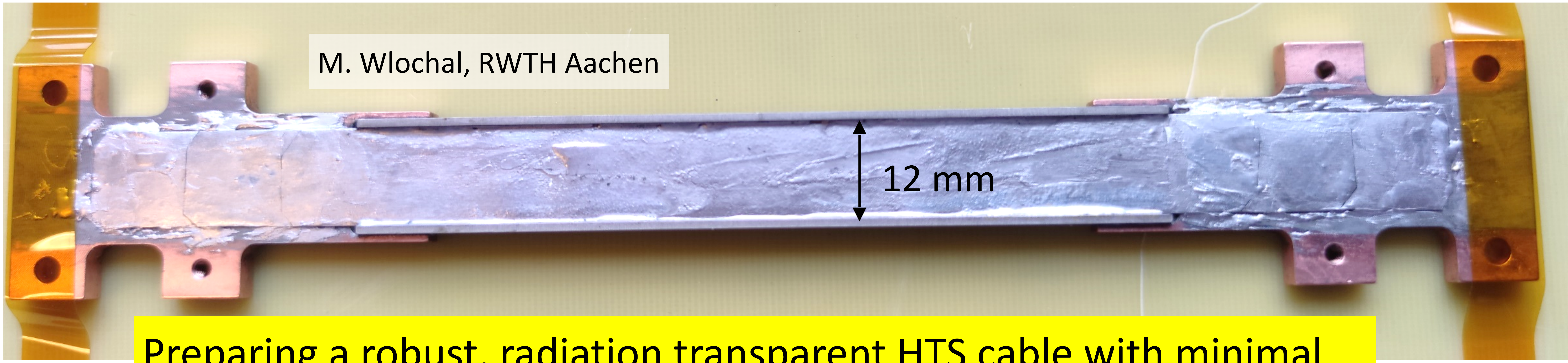
Epoxy between layers

X_0 = 10.2% = Thickness of structure / Radiation length

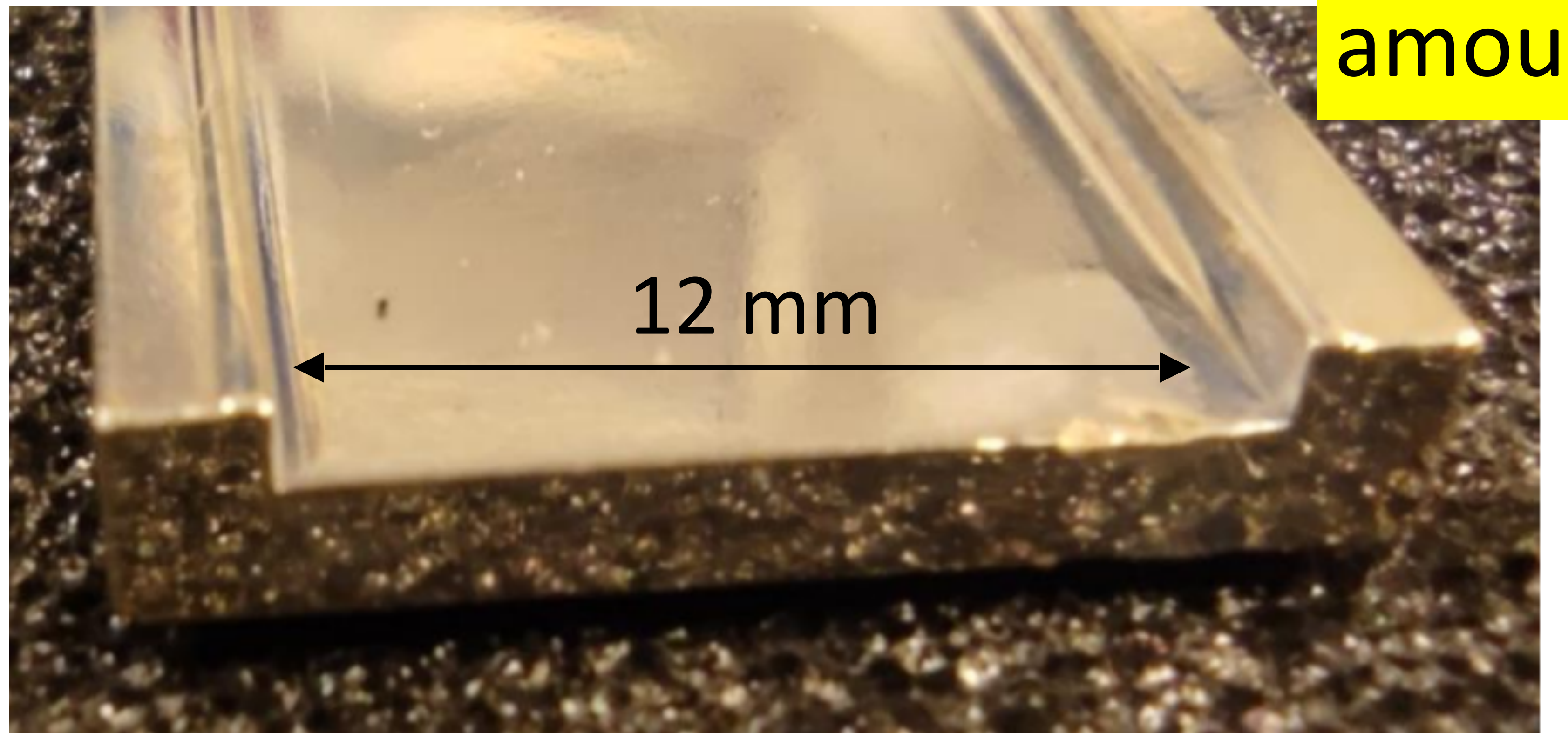
Conductor Testing: Single- and Multi-Tape Samples

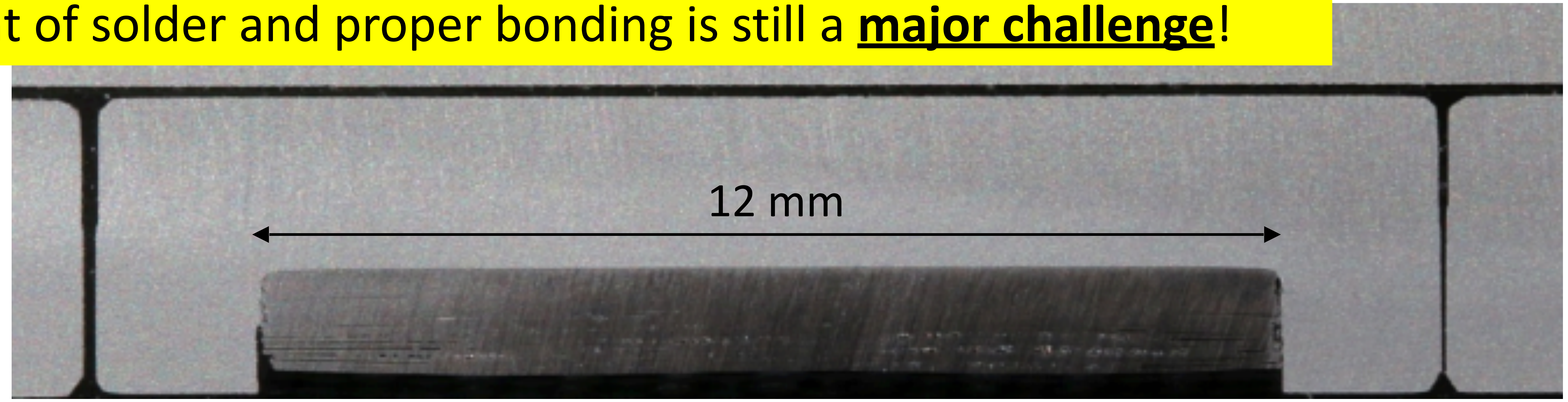
- Single tapes have been extensively characterized .
- Many short samples of Al-alloy stabilized multi-tape HTS conductors are in preparation.
- Few-tape samples in good agreement with expectations.
- Next: more tapes, bending, micro-meteorite impact testing, etc.



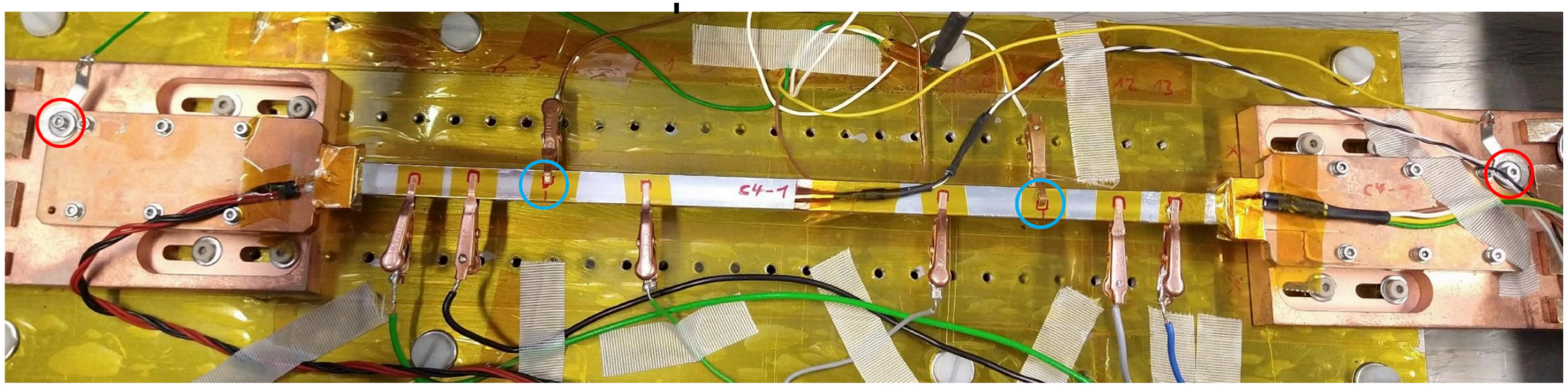

M. Wlochal, RWTH Aachen

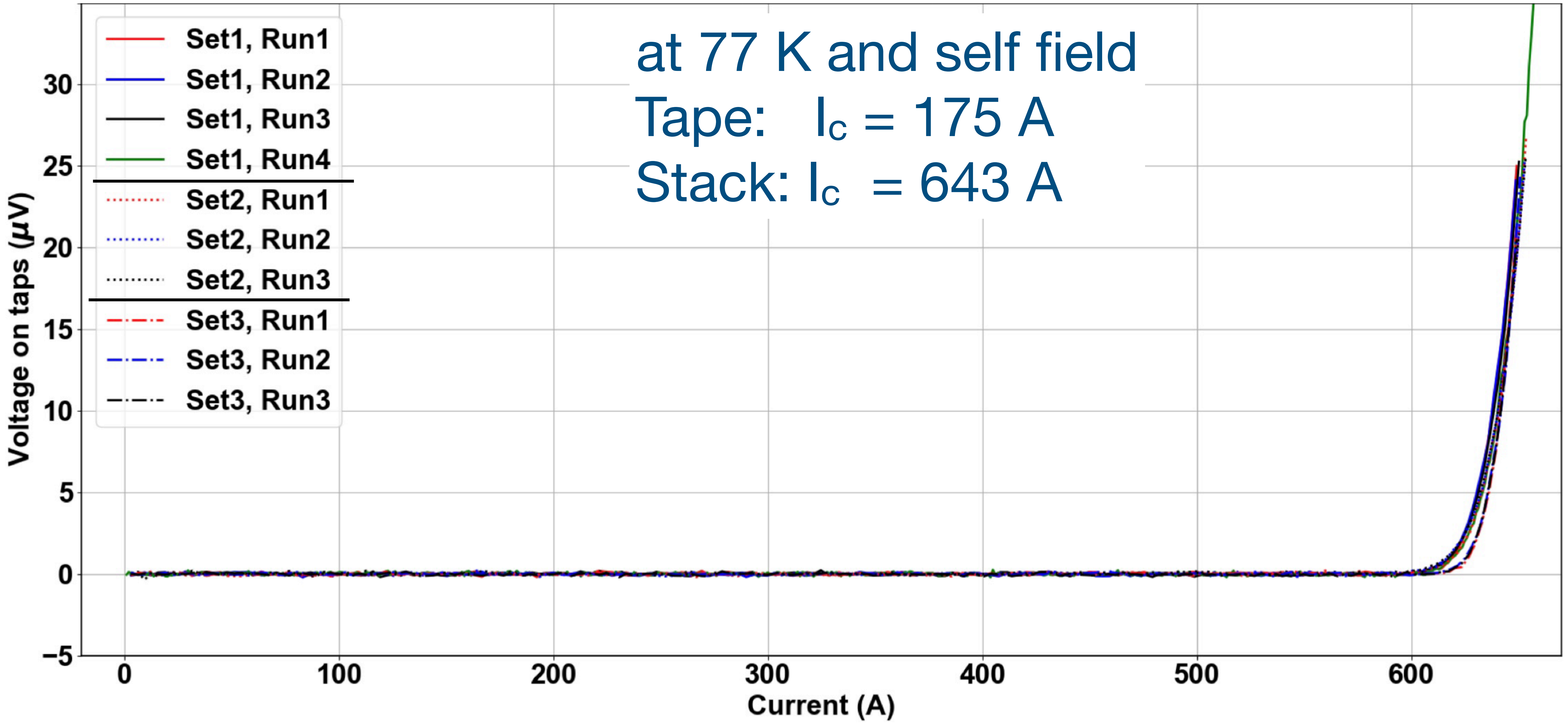
Preparing a robust, radiation transparent HTS cable with minimal amount of solder and proper bonding is still a **major challenge**!





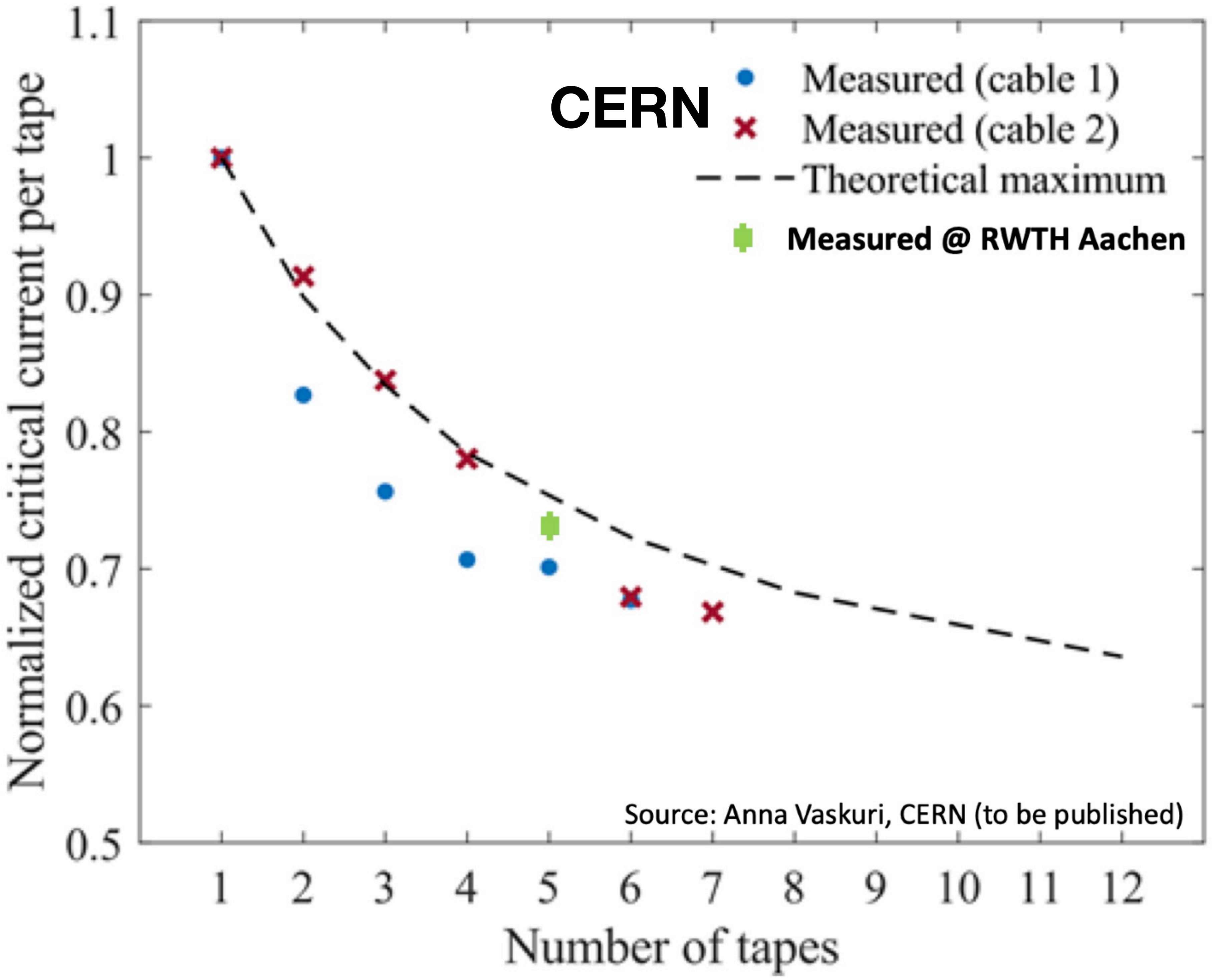
Stack of 5 HTS Tapes (4 mm wide)




at 77 K and self field

Tape: I_c = 175 A

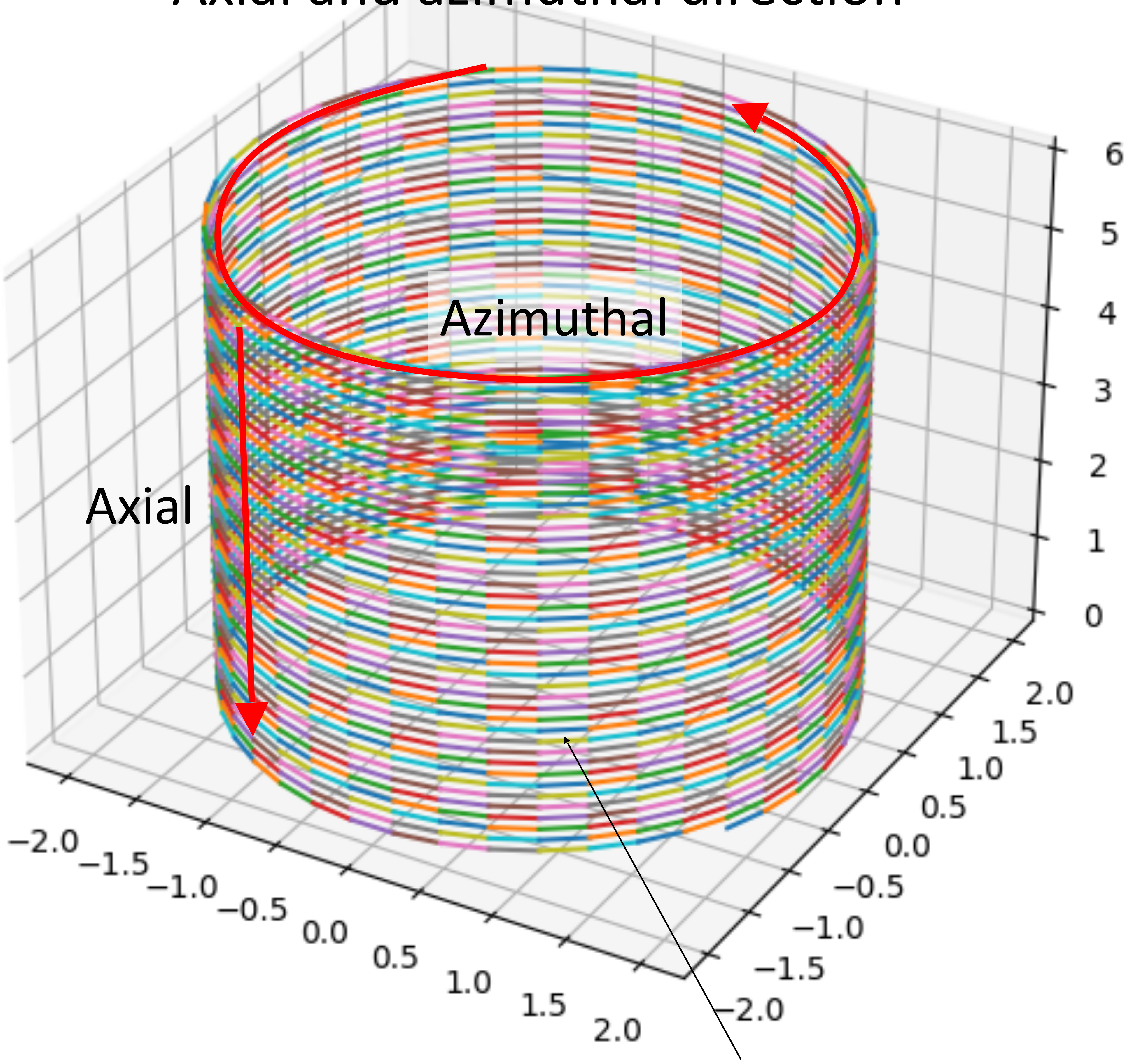
Stack: I_c = 643 A



Source: Anna Vaskuri, CERN (to be published)

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.

Simulated Quench Behavior and Survival

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

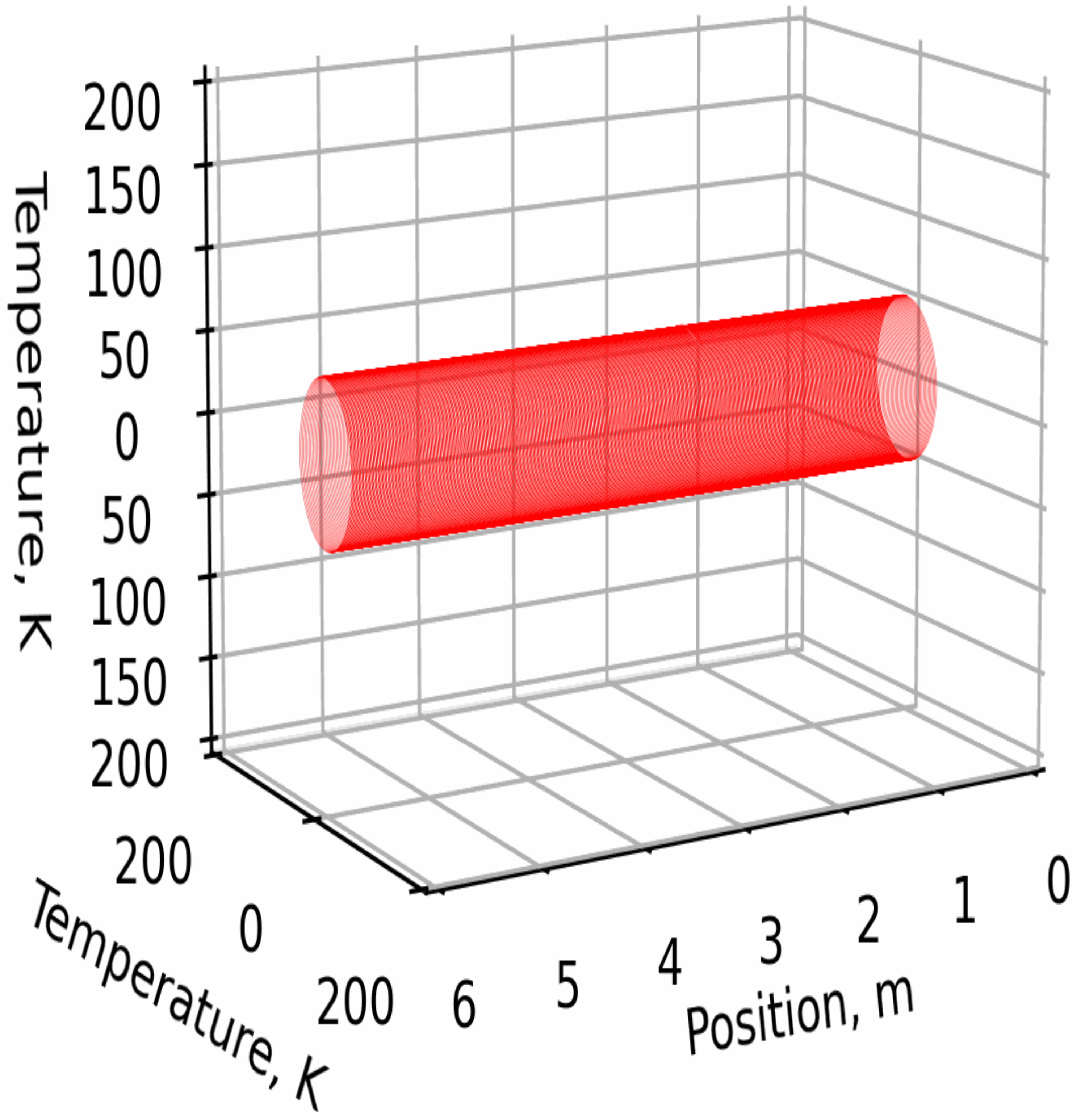
t = 0.2428 s

t = 0.2428 s

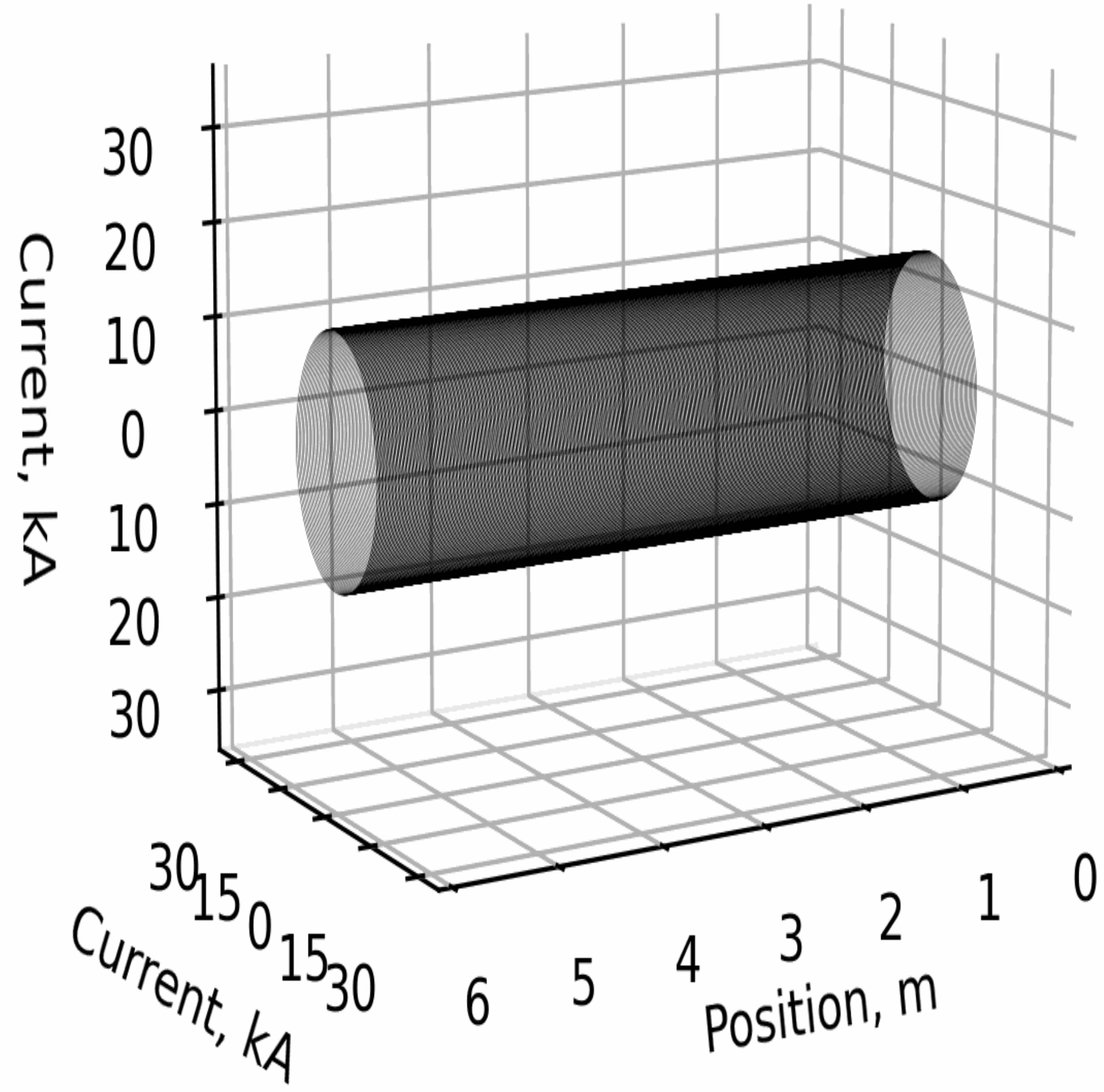
Simulations indicate that the main solenoid is thermally self-protected.

Peak hot-spot near extremities

NZPV of ~ 4-8 m/s

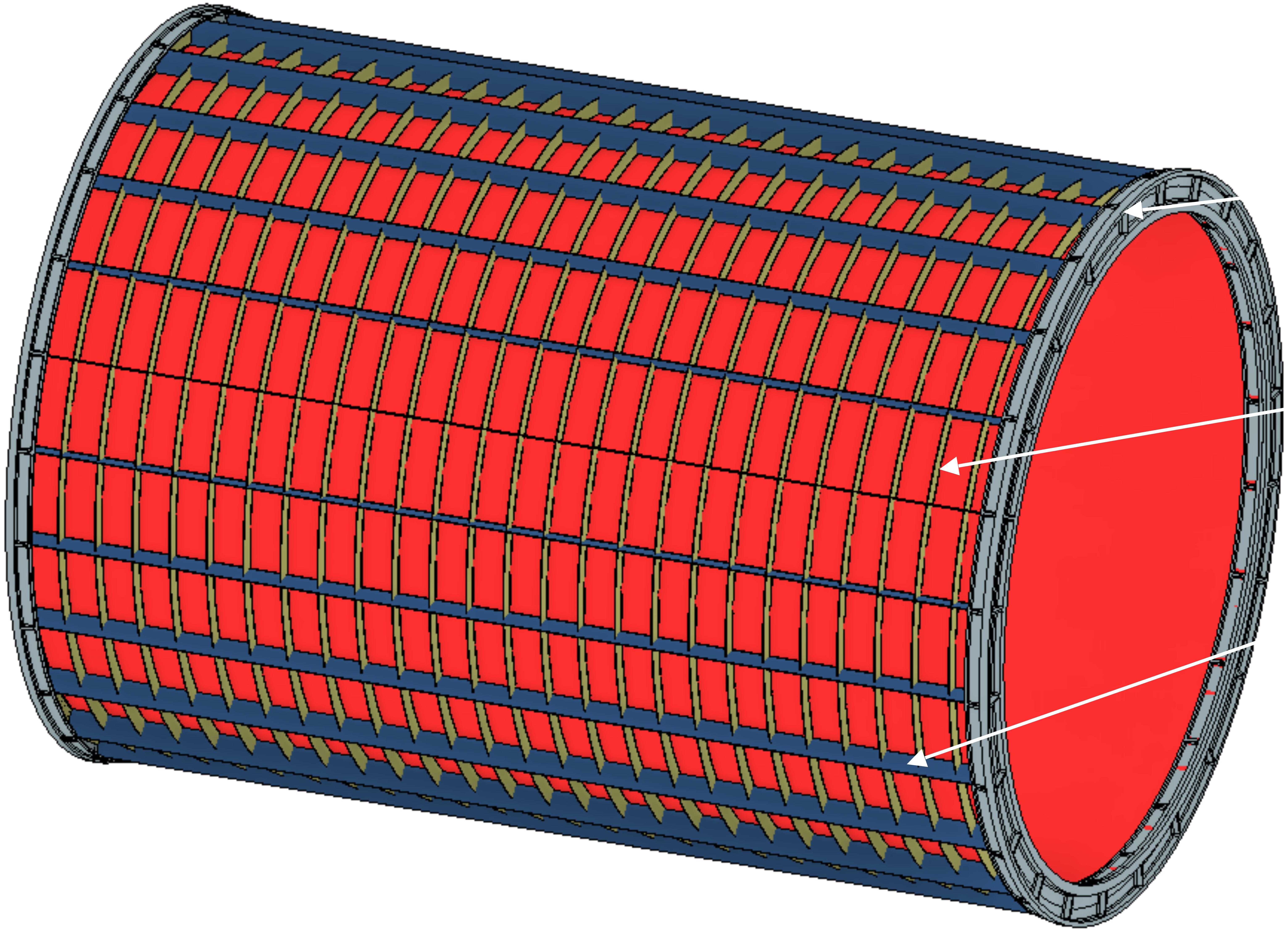


Temperature



Current

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.

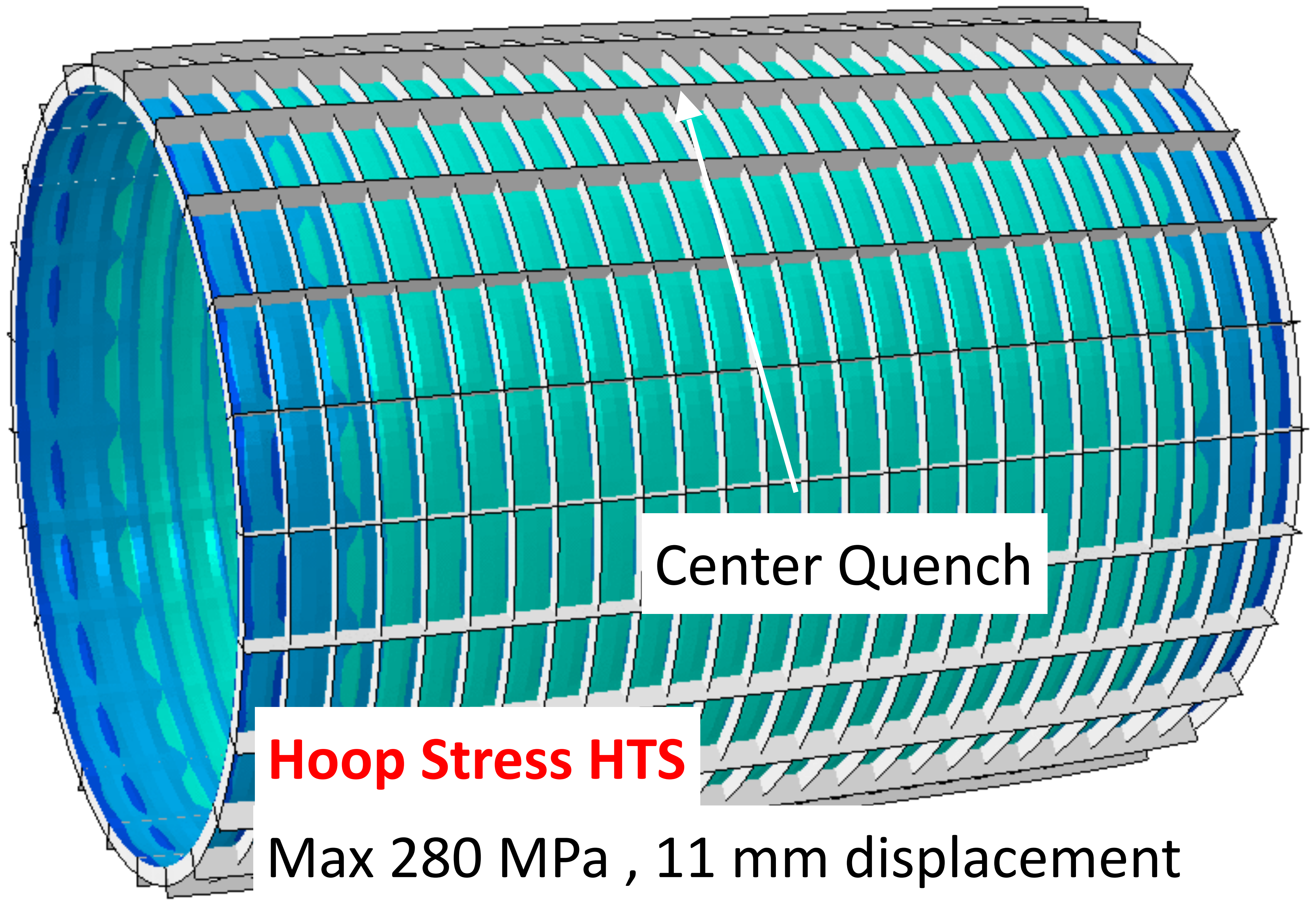
Stringers (blue): Mechanical support during launch.

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.

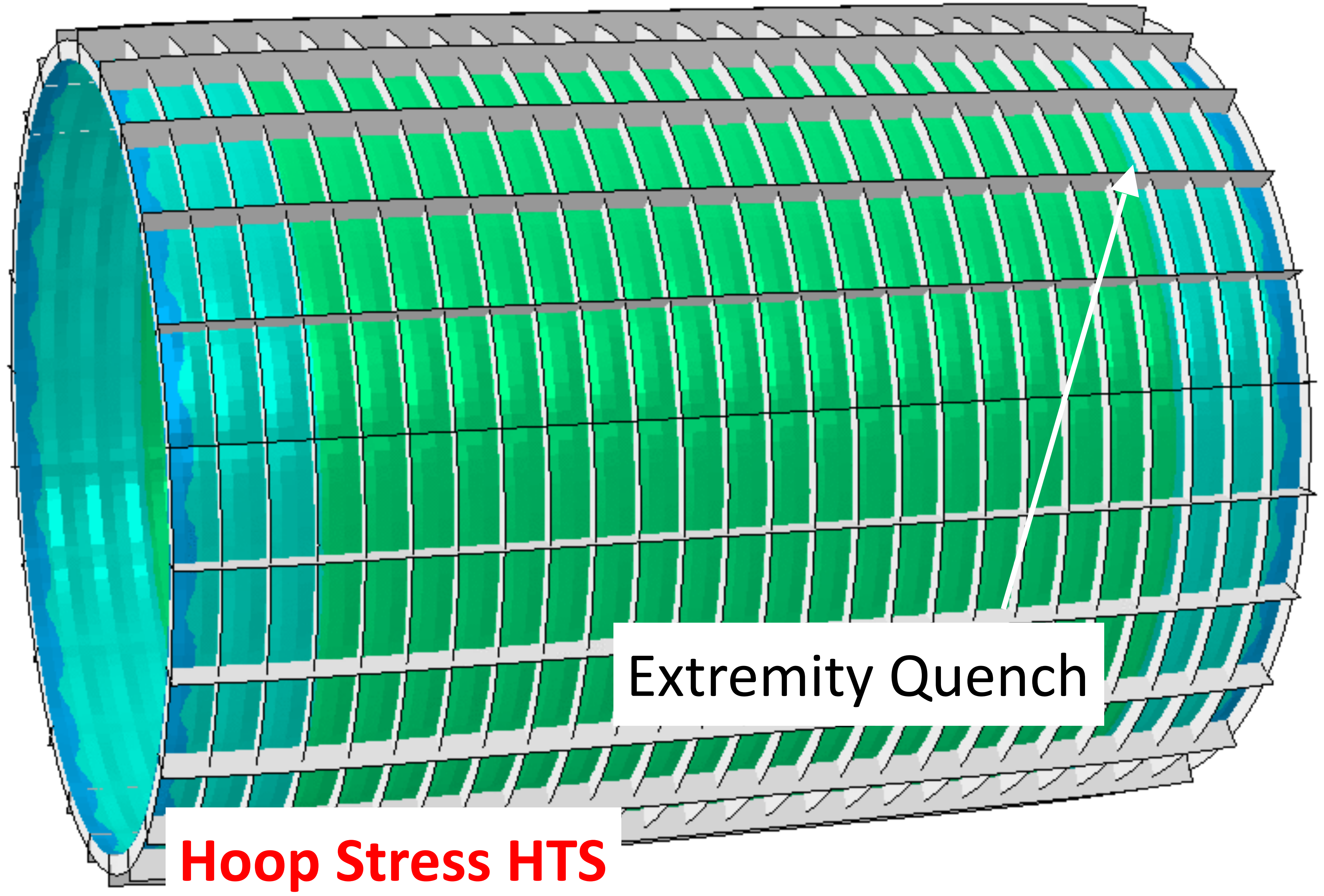
- Ribs locally reduce the stress in the conductor.
- Stress in the conductor due to thermal gradients not critical, strength of the epoxy to be validated experimentally.
- Peak stress (~300 MPa) caused by radial Lorentz force.
- Support structure requires optimization.



Center Quench

Hoop Stress HTS

Max 280 MPa , 11 mm displacement



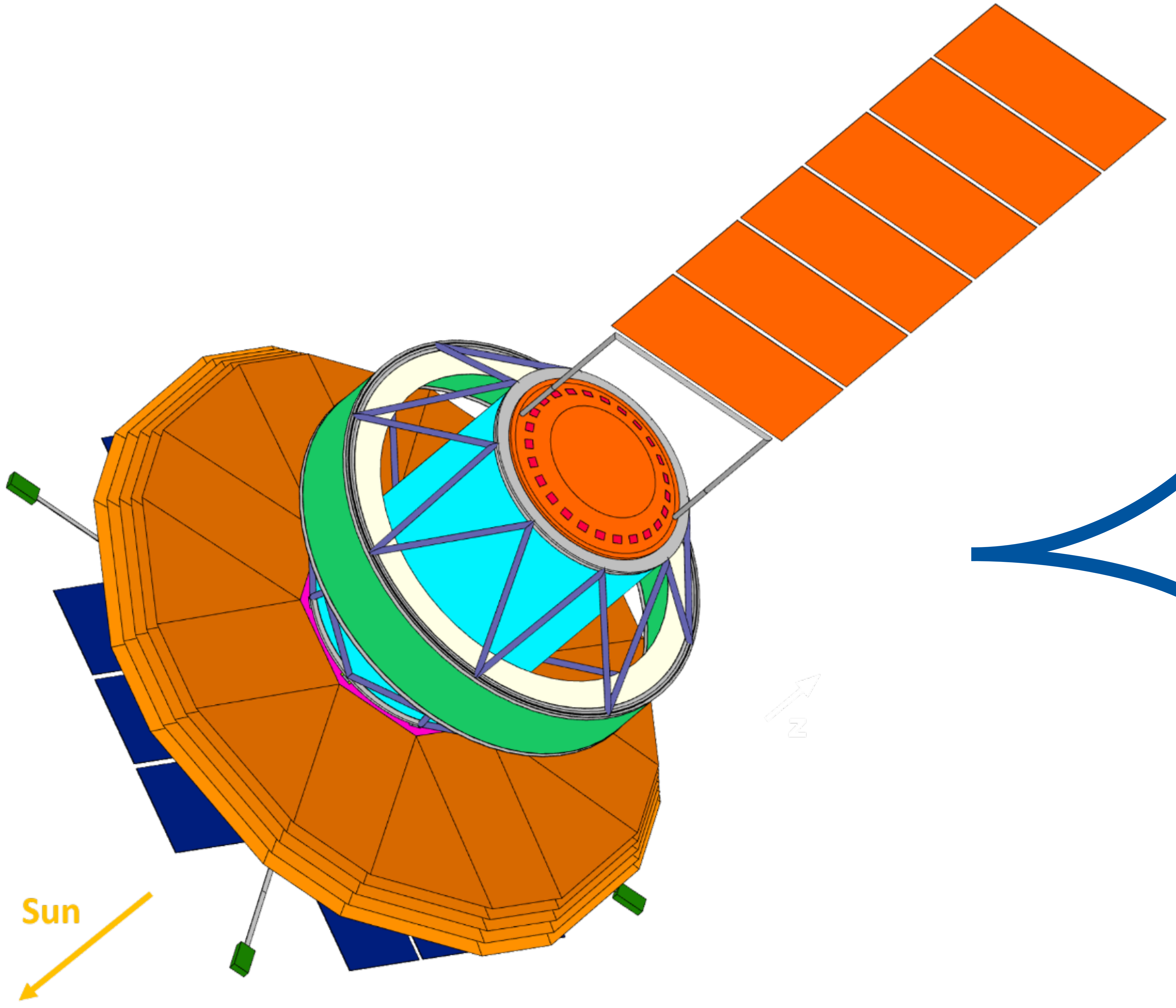
Extremity Quench

Hoop Stress HTS

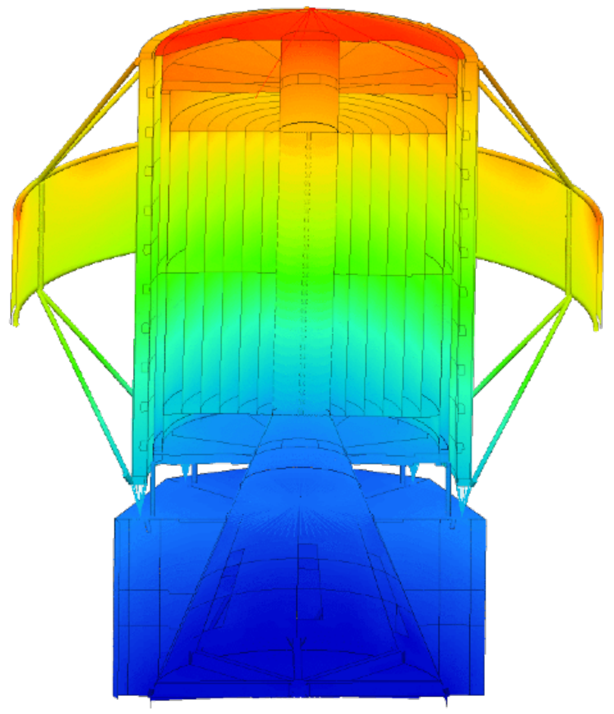
Max 240 MPa, 10 mm displacement

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

ARCHITECTURE | MODELS

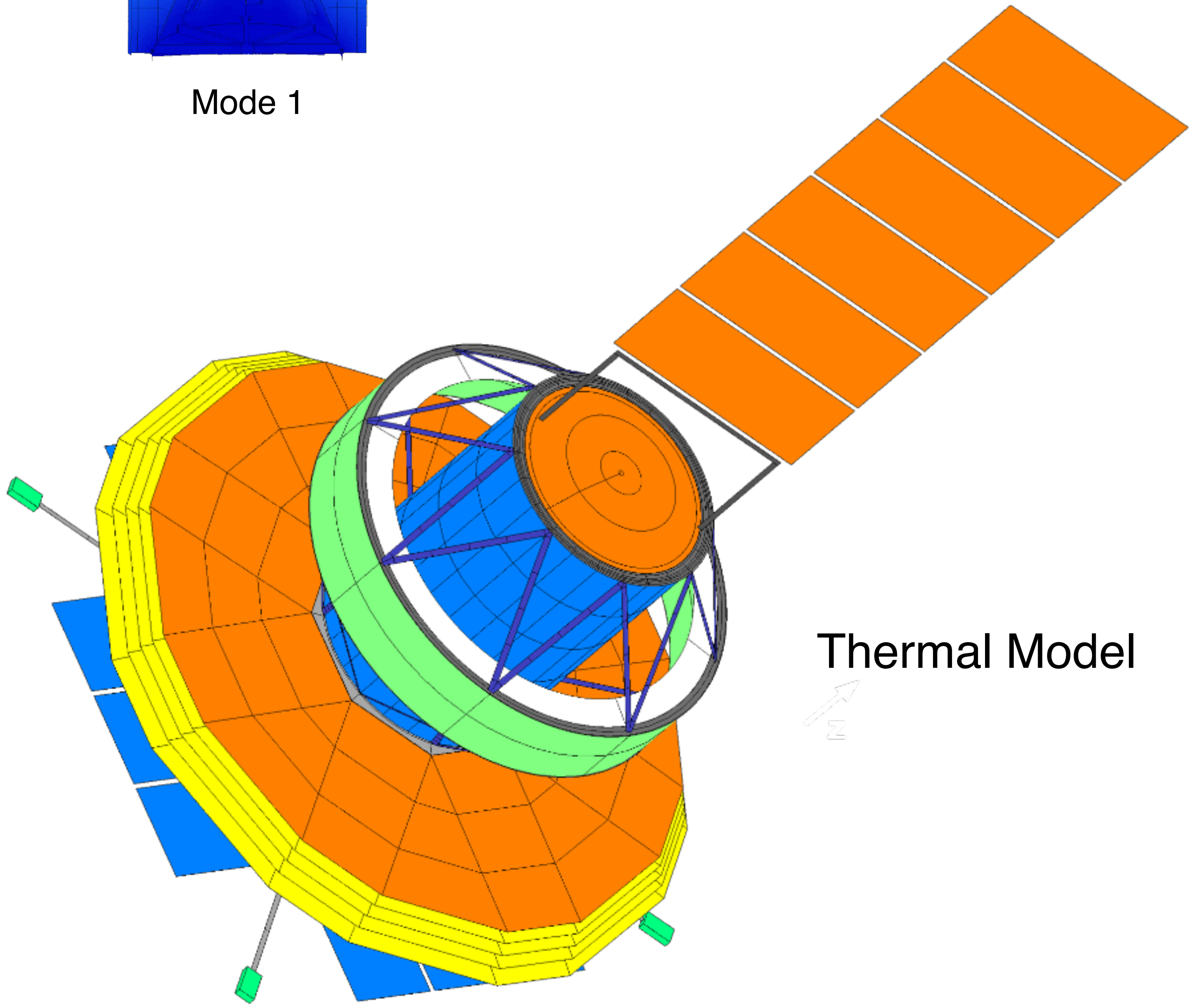


CAD Model



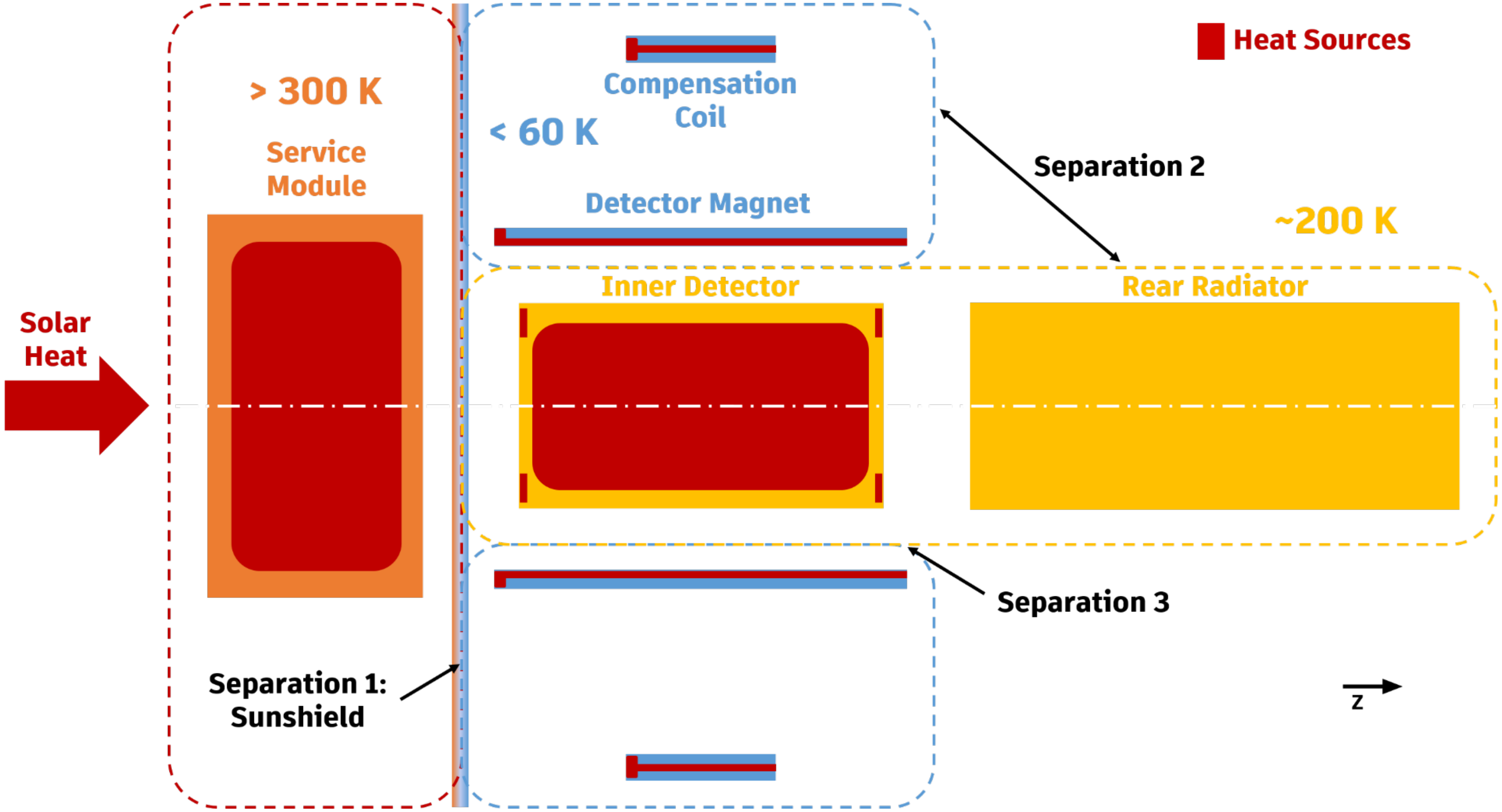
Structural Model

Mode 1



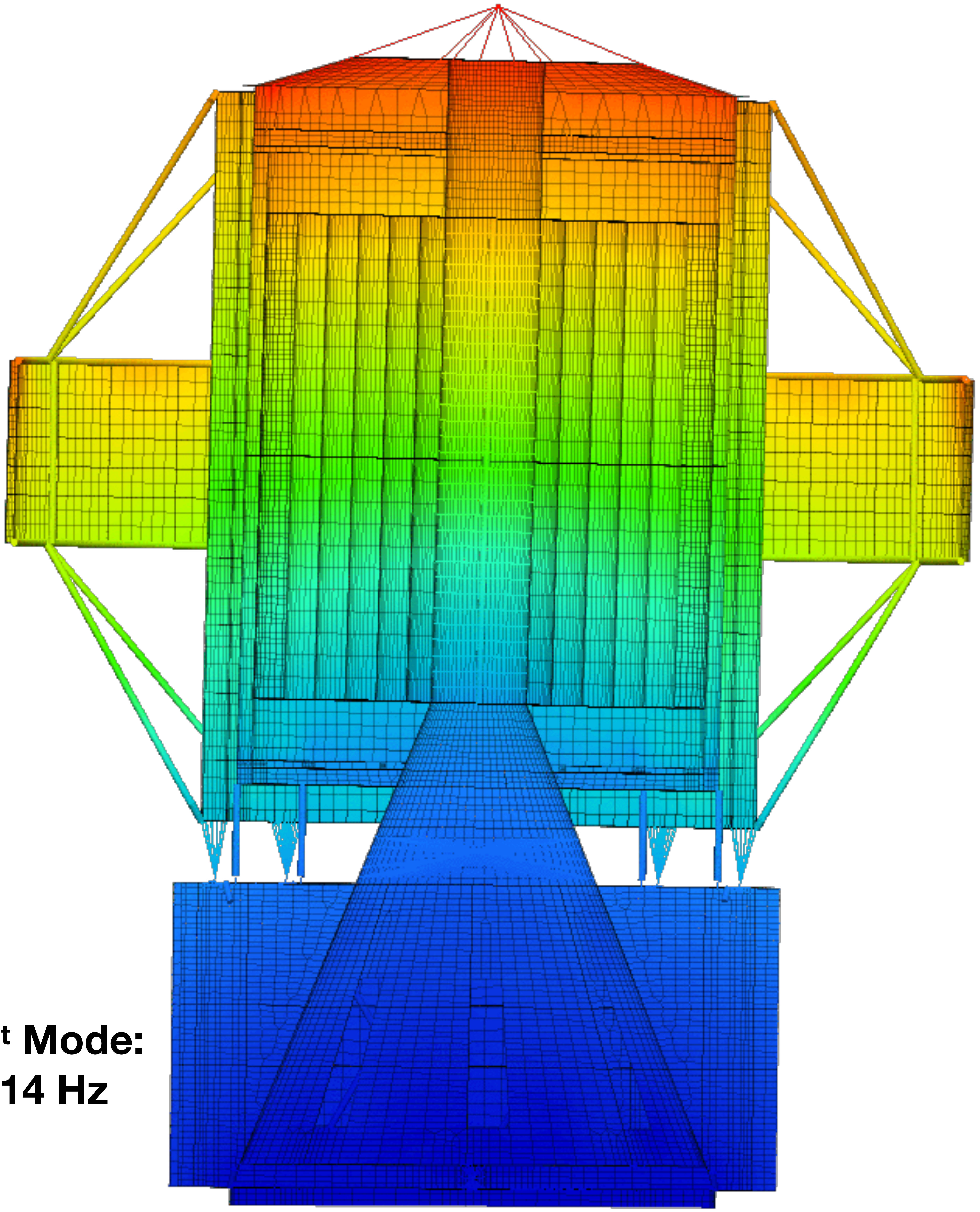
Thermal Model

THERMAL DESIGN | HEAT SOURCES



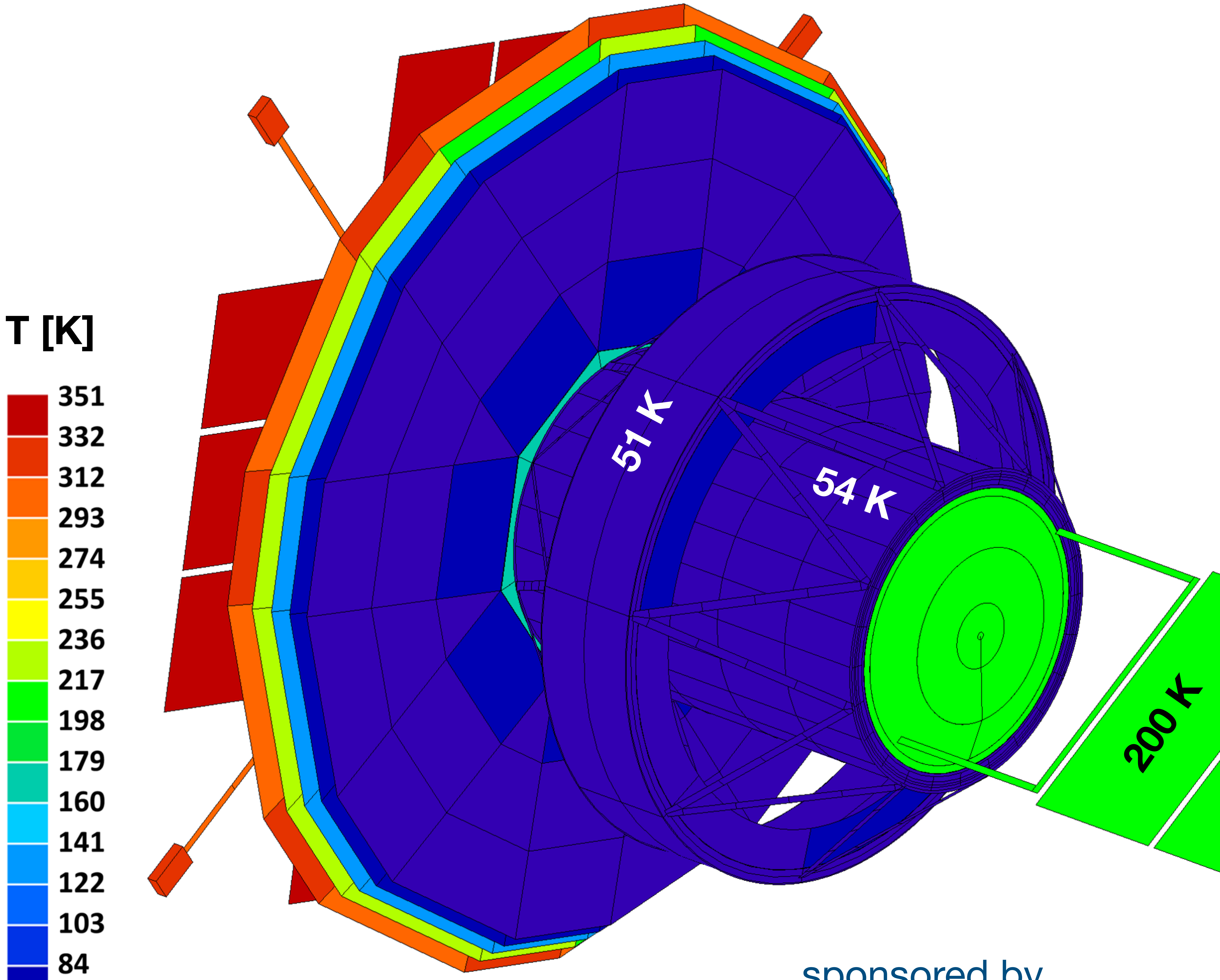
- Service module & payload data handling
  - ~8000 W
- Inner detector
  - ~8000 W
- Solenoids
  - ~15 W

AMS-100: Structural Model



1st Mode: 14 Hz

AMS-100: Thermal Model



sponsored by ESATAN-TMS thermal modelling suite

AMS-100

100 cm

Radiator & Debris shield: 0.5 mm Al 6110, 50 mm Al-Honeycomb, 0.5 mm Al 6110

outer-stringers, AL 6063
5 mm x 130 mm

h=8.6 cm

MLI

X_0=1.8%

SciFi-Tracker: 0.5 mm CFRP - 10 mm Nomex

GFRP

Magnet

inner-stringers,
AL 6063
10 mm x 25 mm

h=7.5 cm

MLI

Magnet Interfaces

10 cm

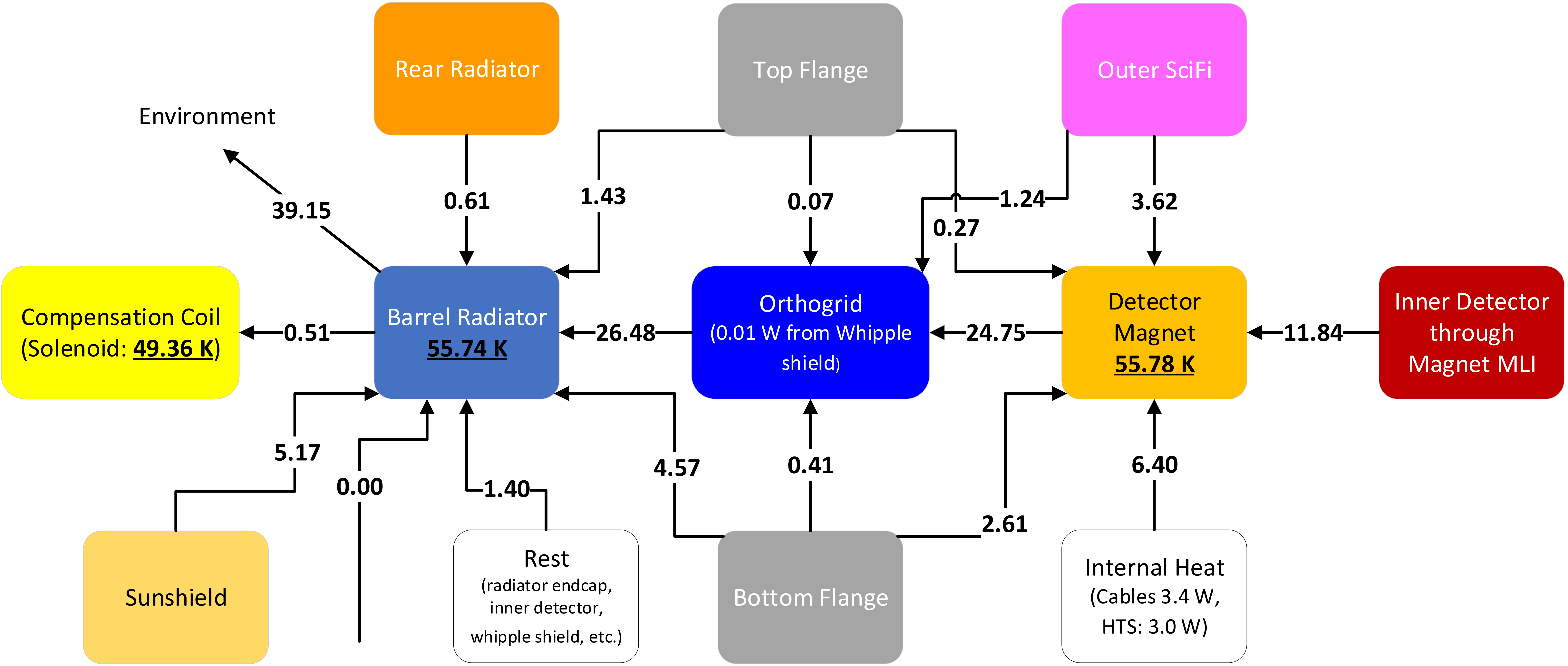
MLI

Main Support Cylinder
1.0 mm CFRP - 30 mm Al-Honeycomb - 1.0 mm CFRP

X_0=14.7%, NIL=2.8%
(without MLI)

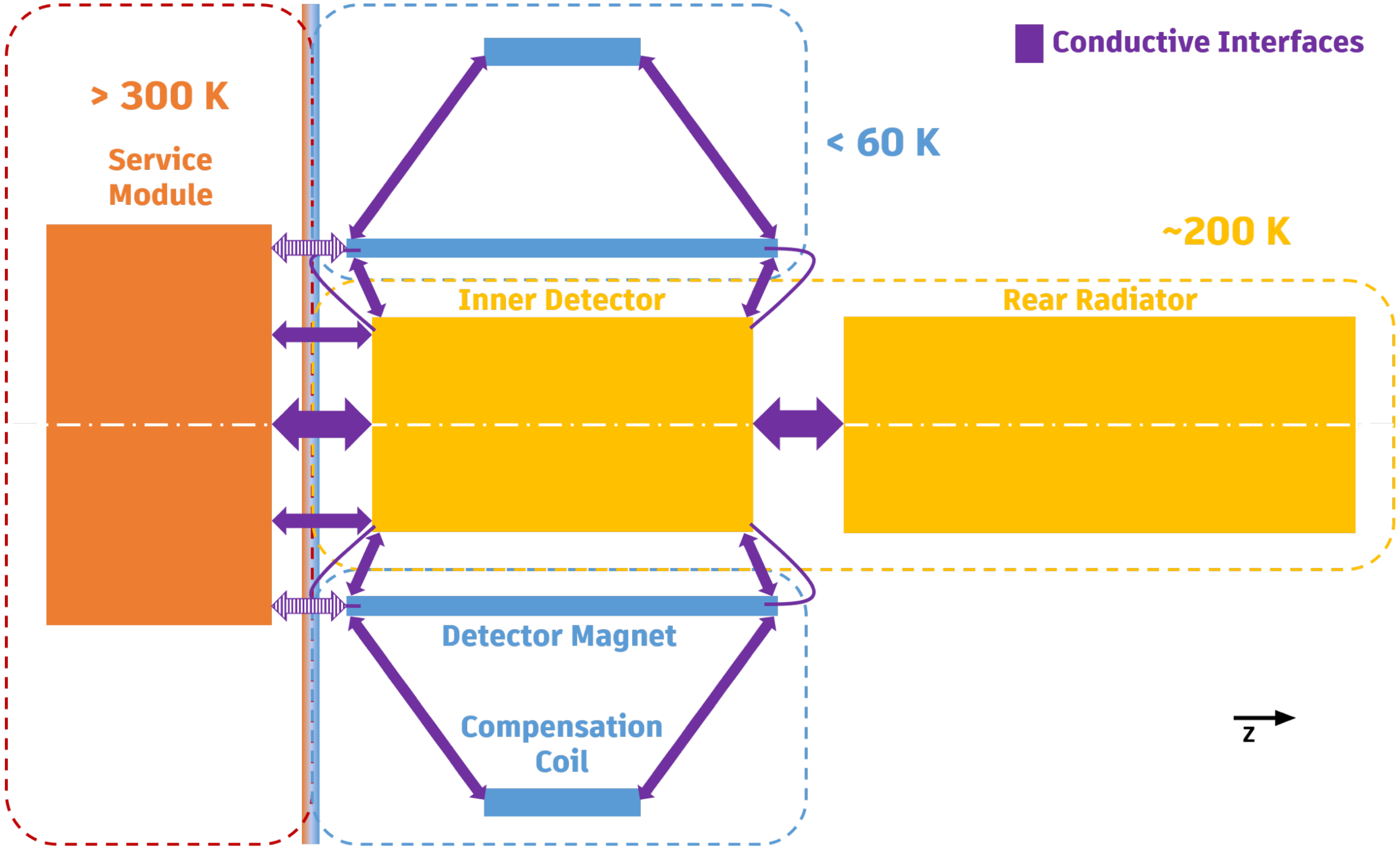
1mm =2 pt

THERMAL MODEL | PAYLOAD HEAT BALANCE

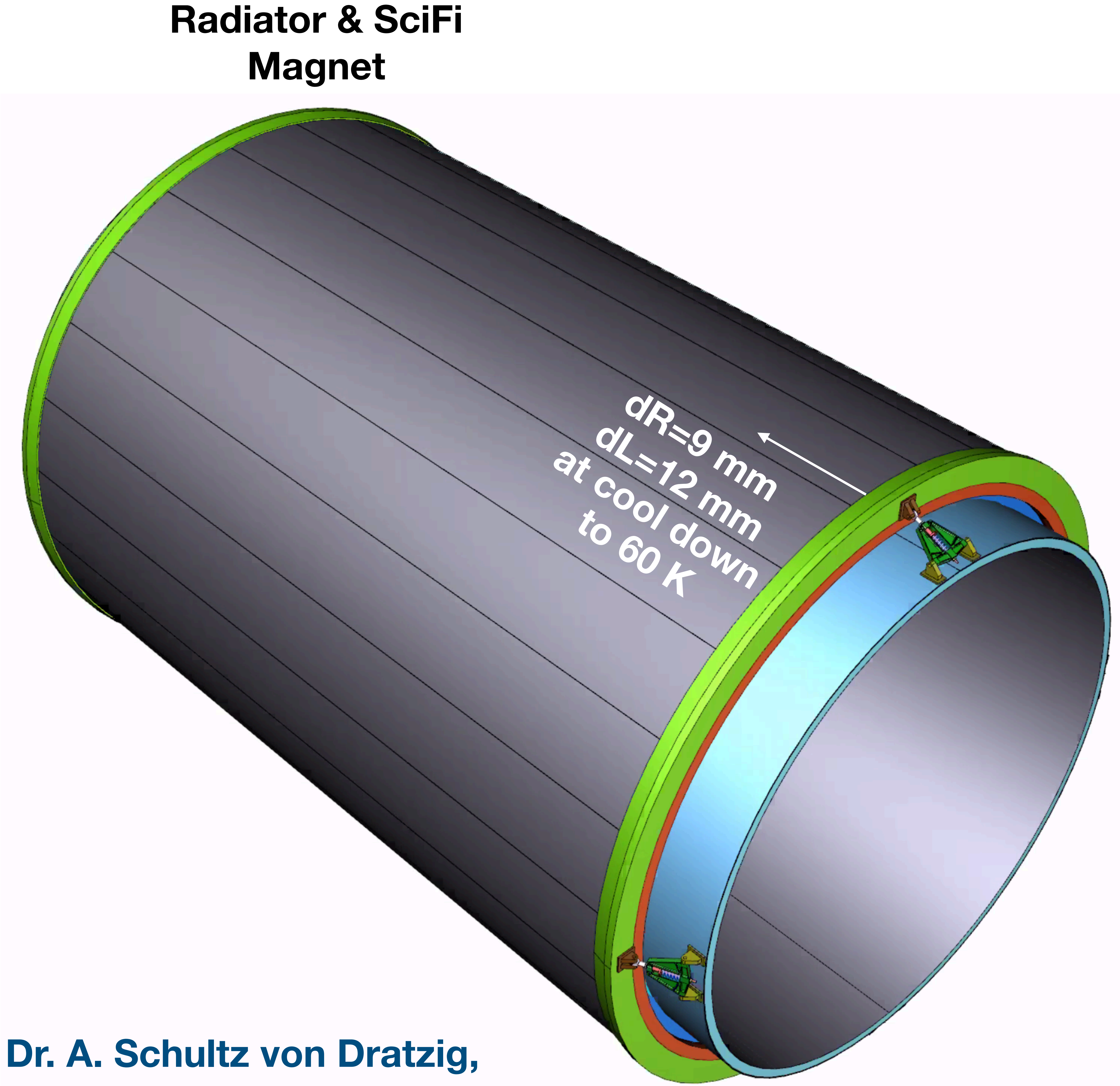


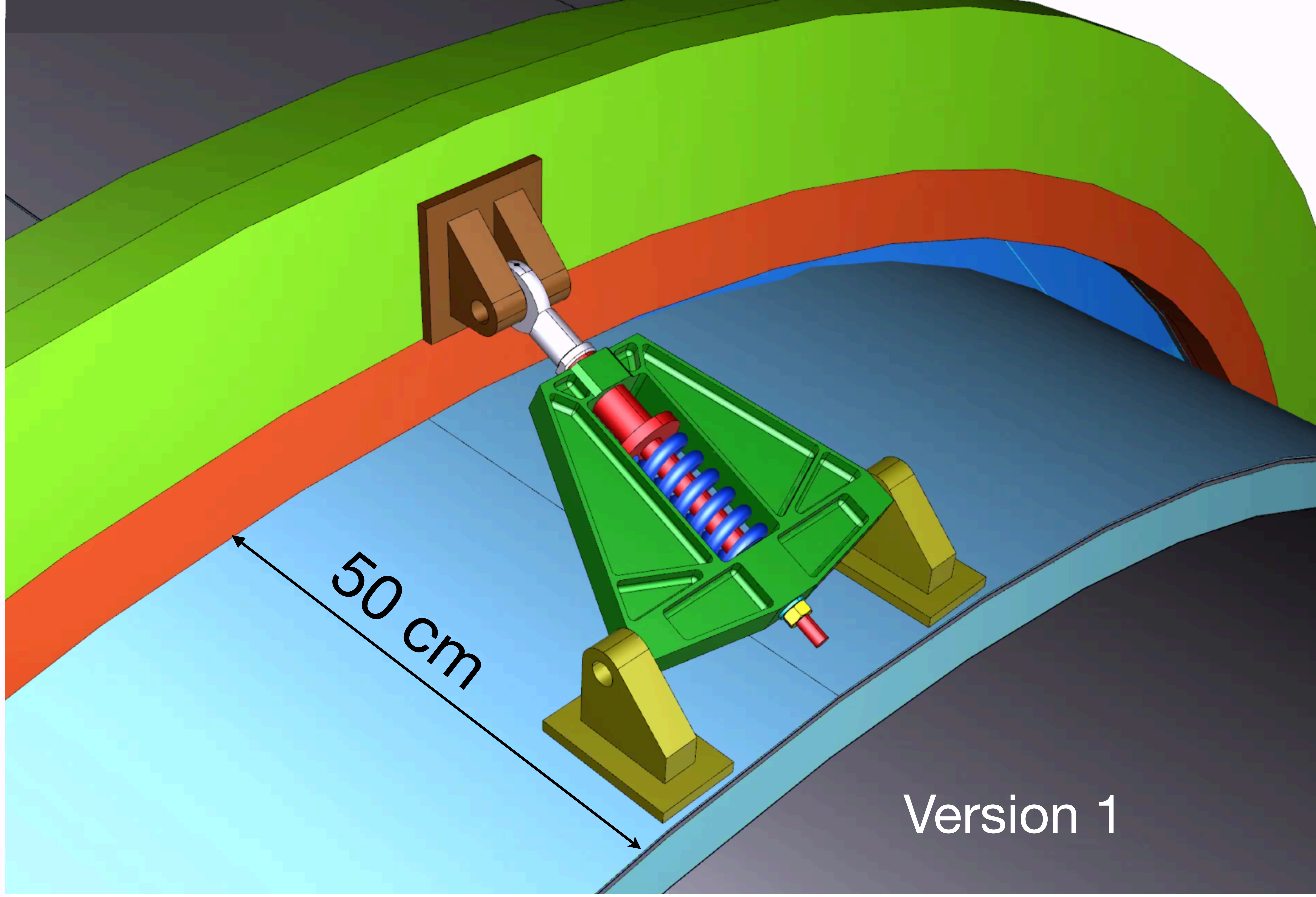
Unit not shown: [W]

THERMAL DESIGN | CONDUCTIVE CONNECTIONS



- Conductive interfaces between main elements
- Hatched connection
  - temporary interfaces



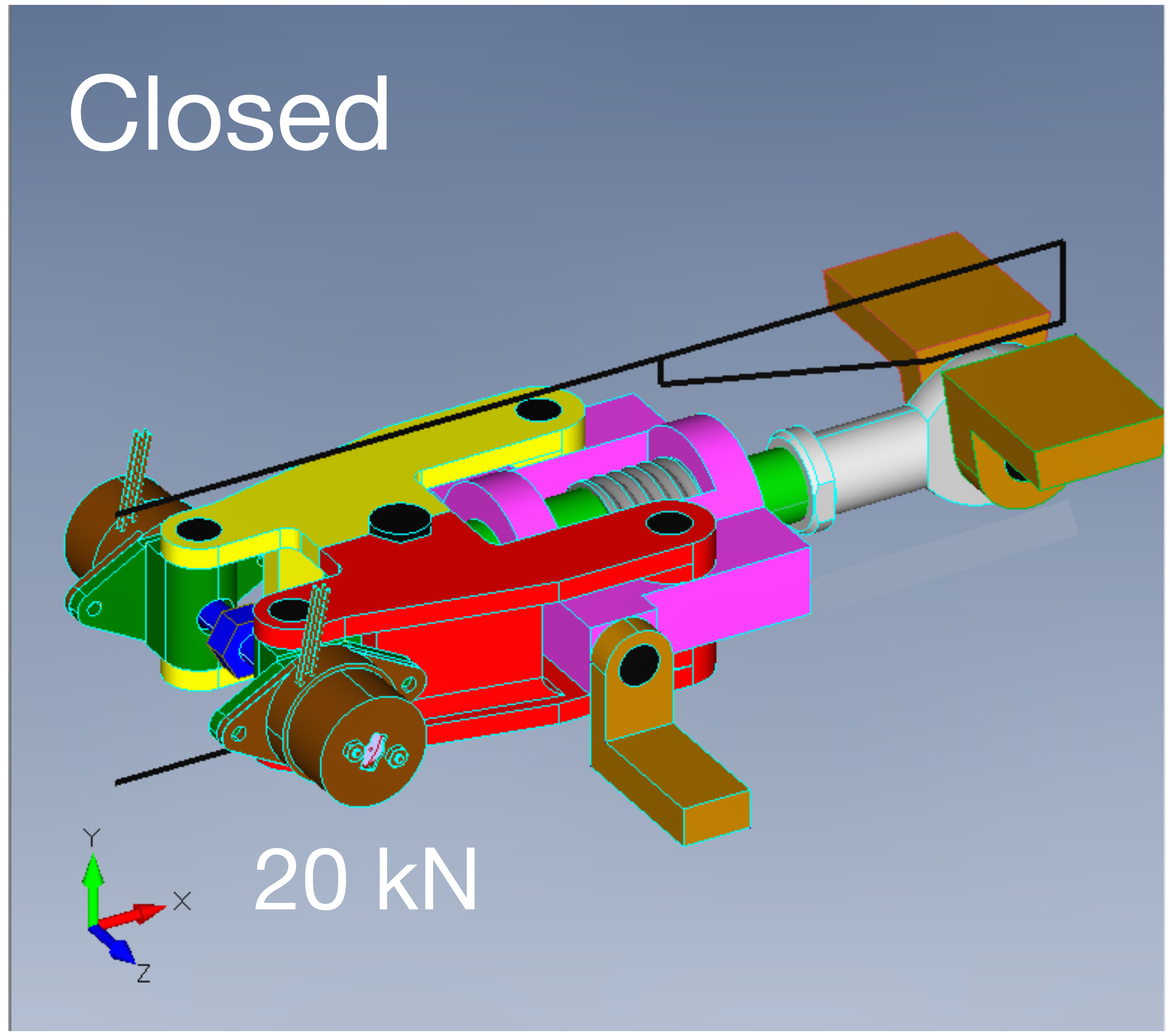


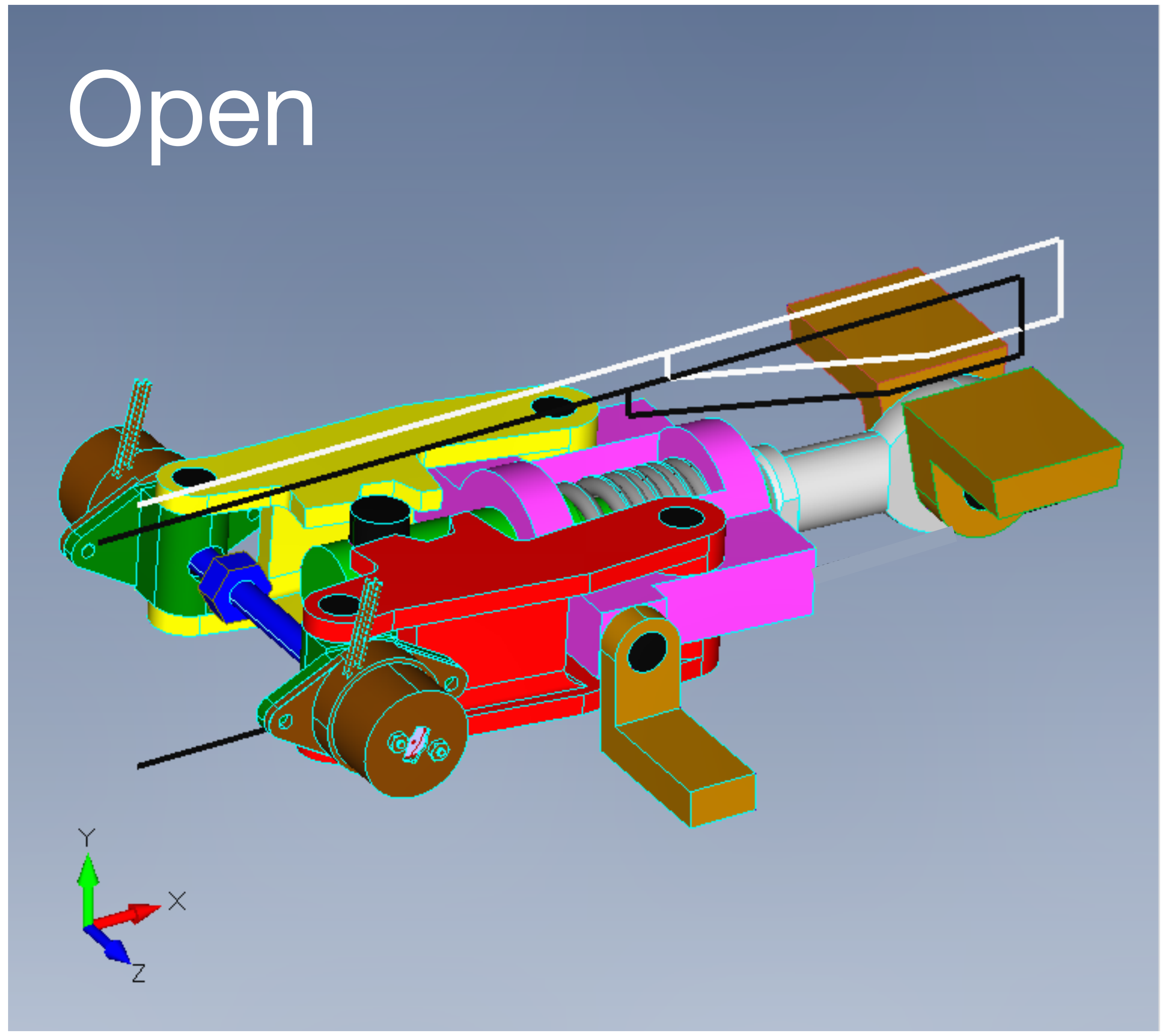
Connect the CFRP Support Cylinder to the Magnet End Flanges with four brackets at each end.

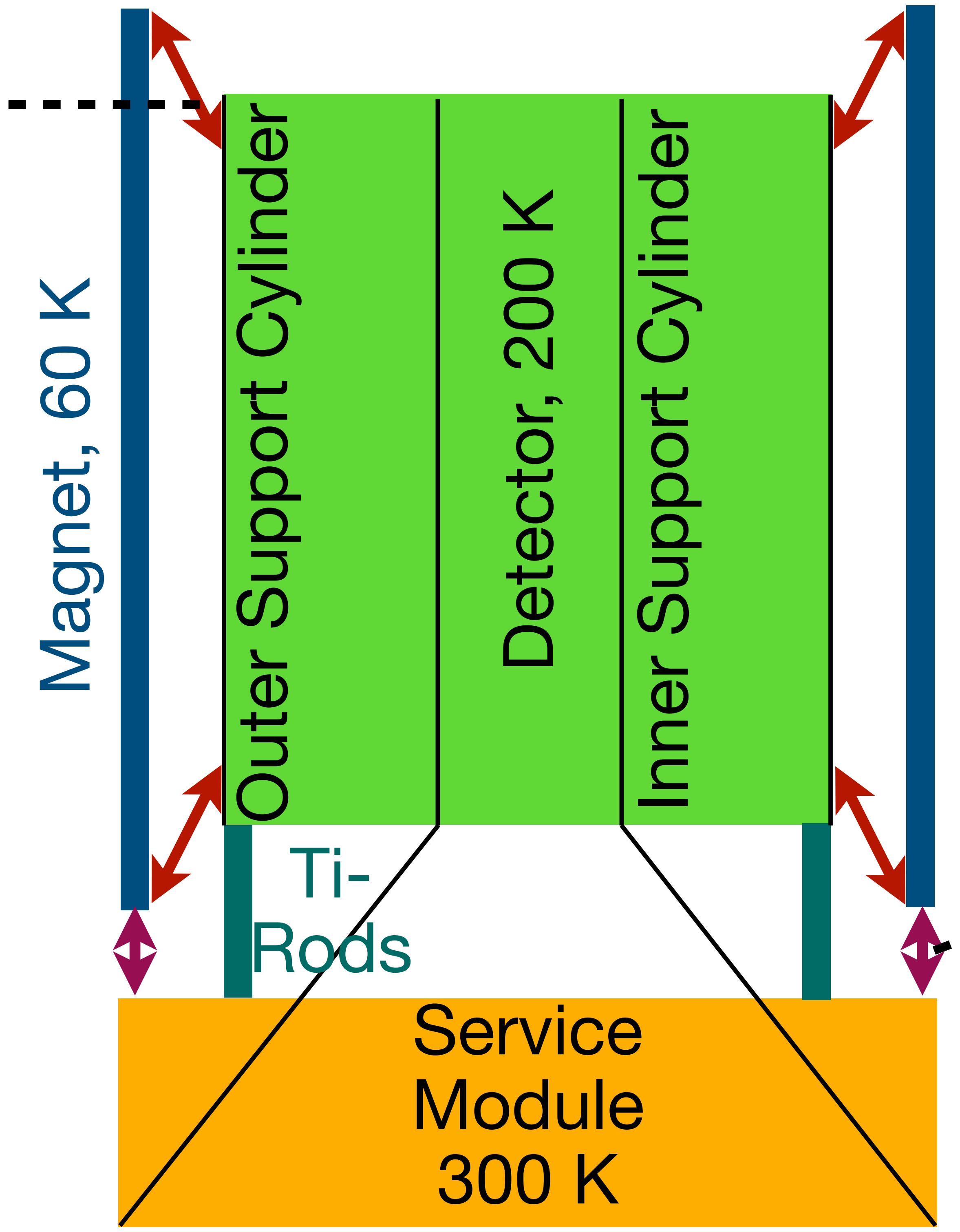
Dr. A. Schultz von Dratzig,
M. Wlochal, RWTH Aachen

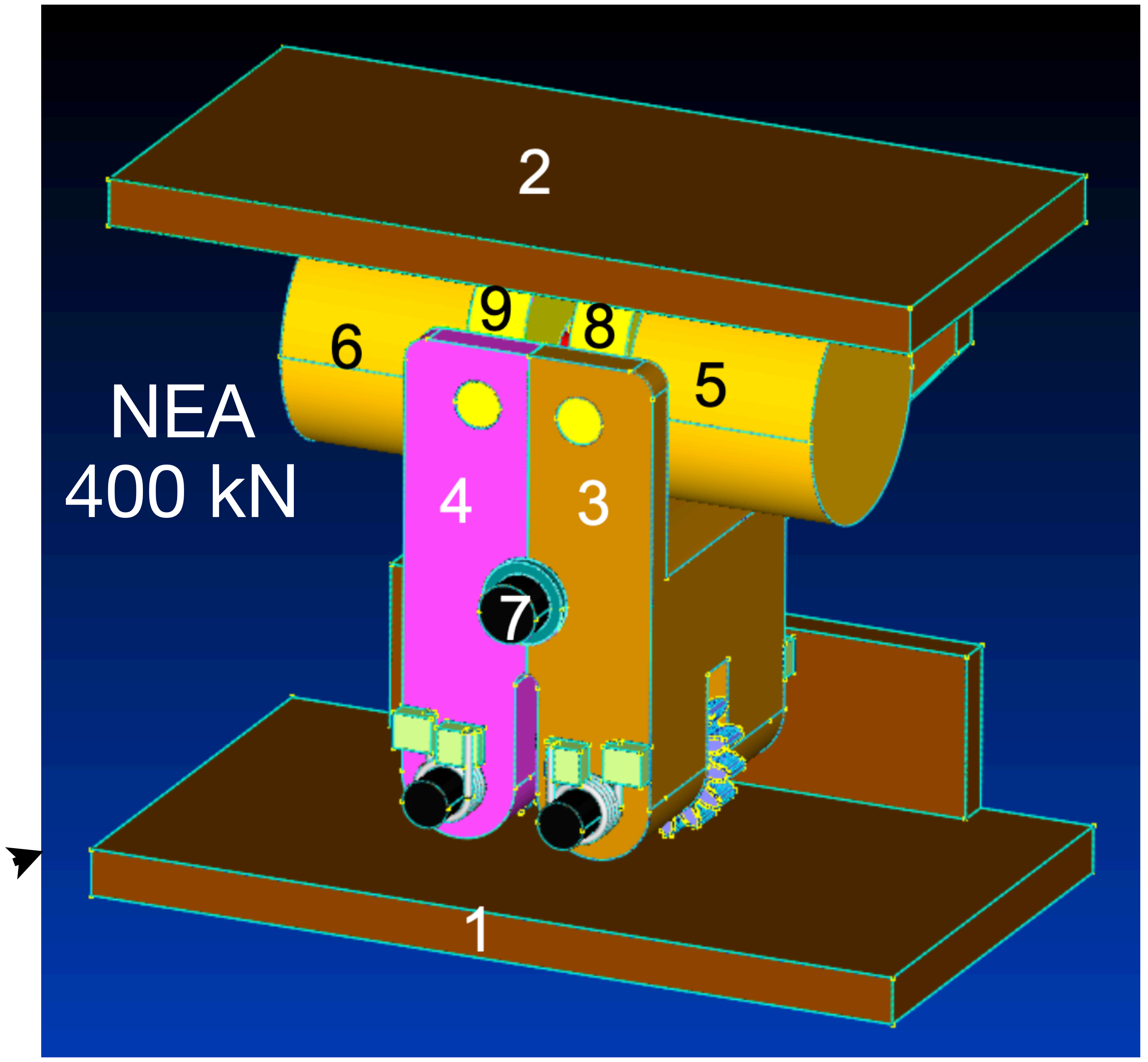
CFRP Support Cylinder

AMS-100: Hold- & Release Mechanisms





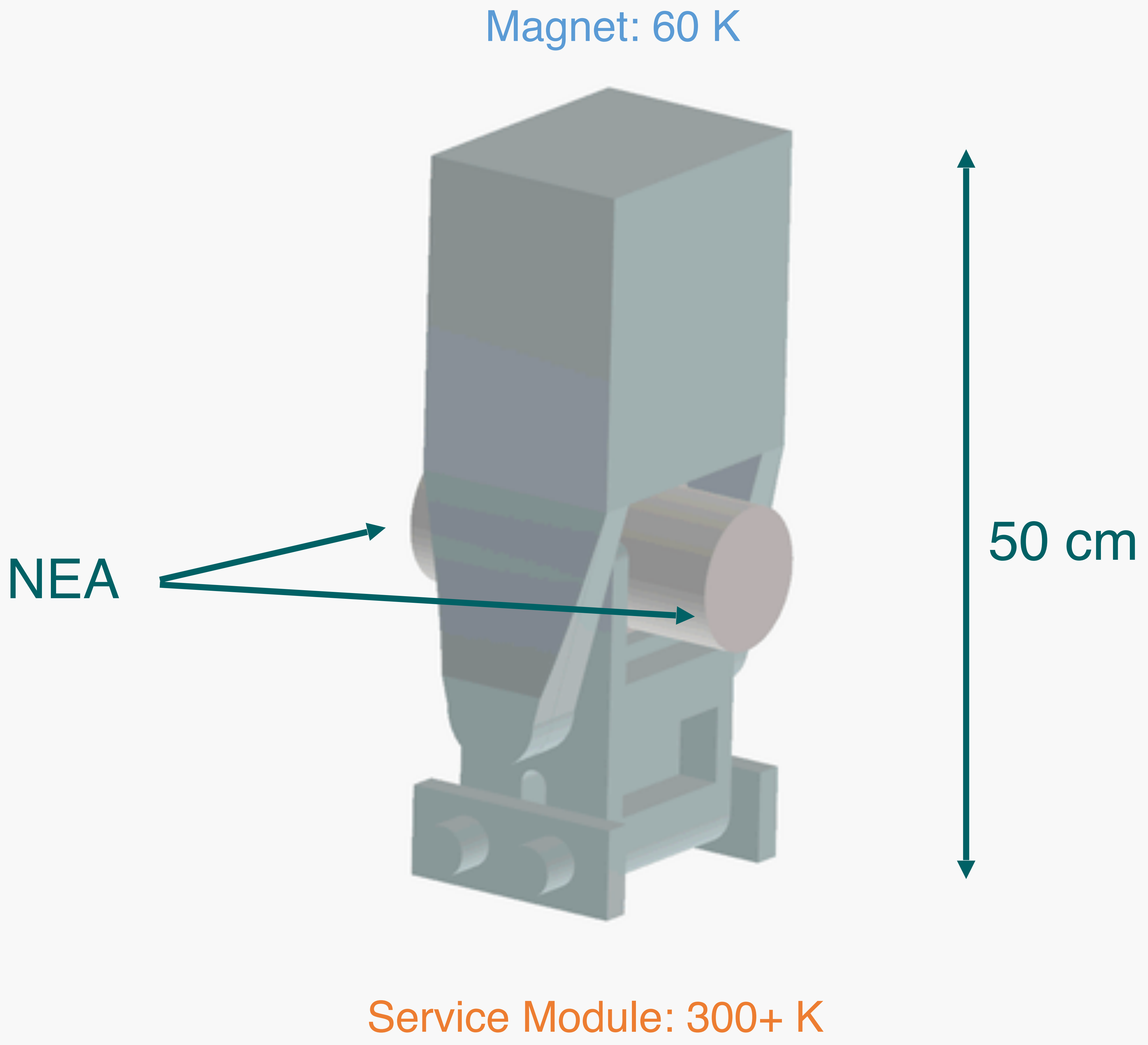




- Use Ti-Rods to connect the Service Module to the Outer Support Cylinder
- Hold - & Release Mechanisms (HRM):
  - 8 to connect the Magnet to the Outer Support Cylinder.
  - 8 to connect the Service Module to the Magnet.

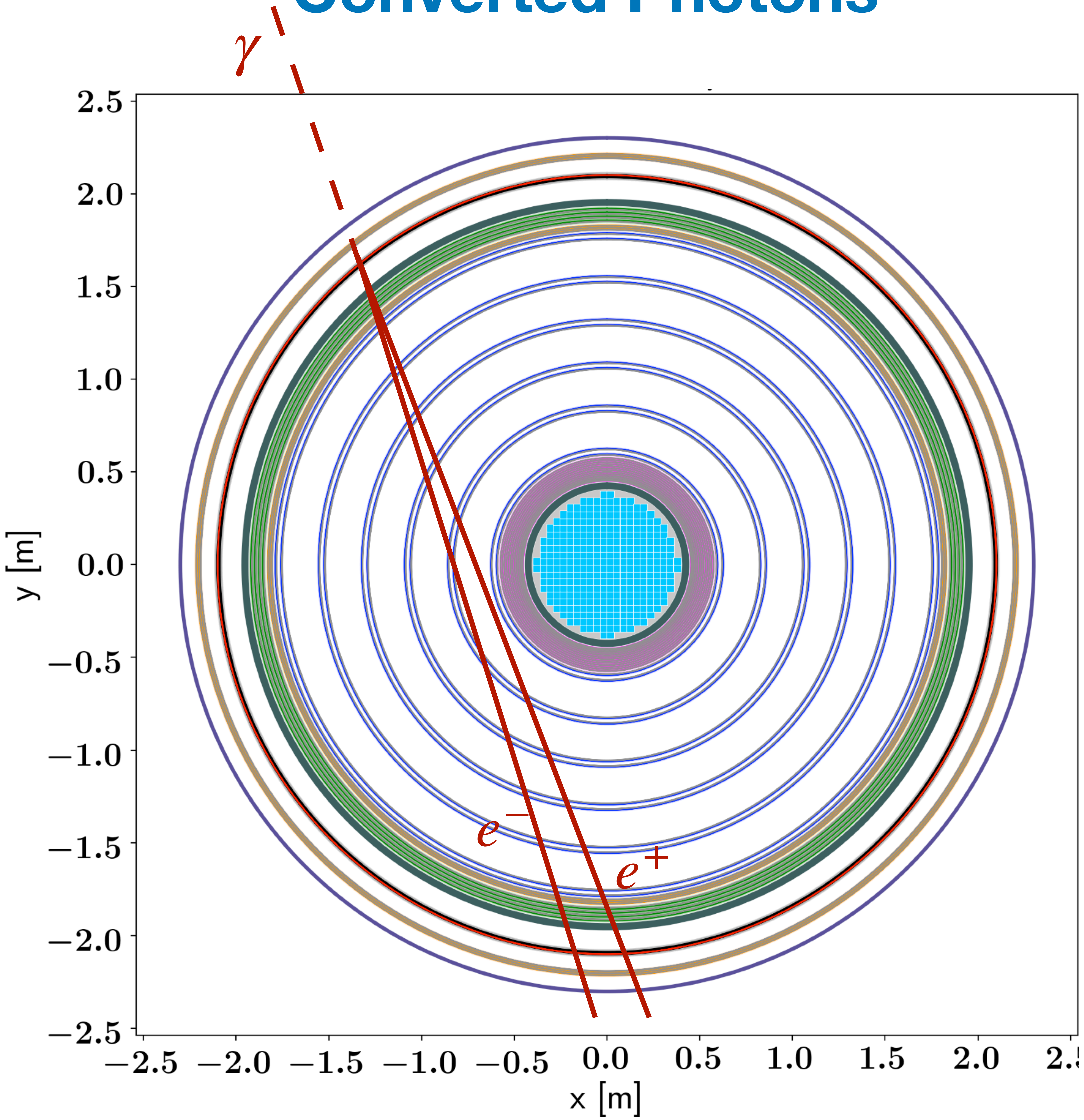
NEA: Non-Explosive Actuator

THERMAL DESIGN | CONDUCTIVE CONNECTIONS – SVM – MAGNETS



- Launch locked to prevent thermal bridge from 300+ K envelope to 60 K envelope by releasing connection during operation
    - Redundant Non Explosive Actuators (NEA)

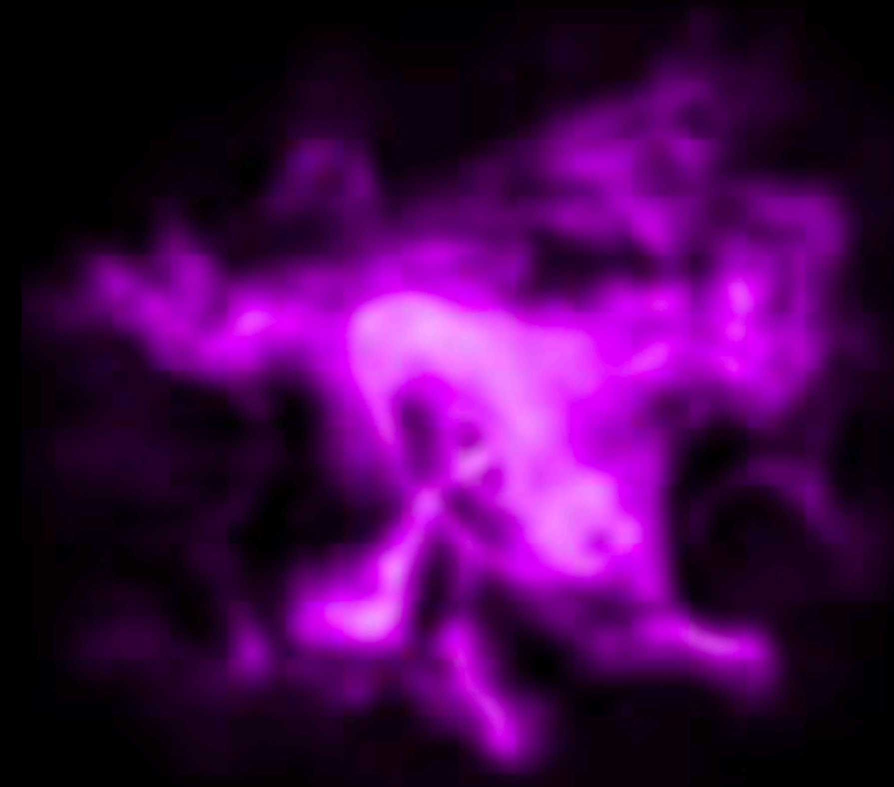
AMS-100
Converted Photons



Crab Nebula with Chandra (blue and white), Hubble (purple), and Spitzer (pink) data.

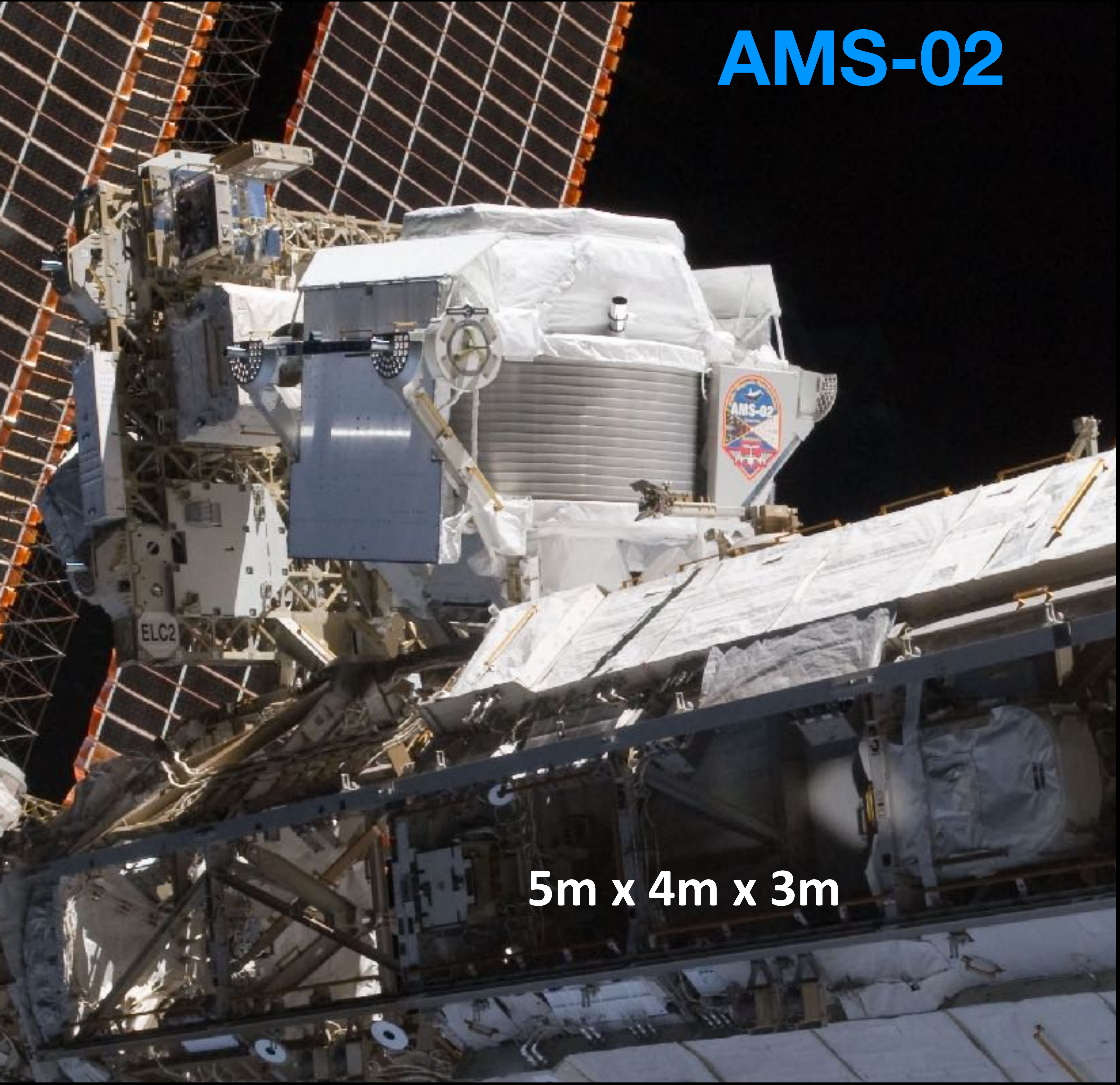
FERMI, CTA

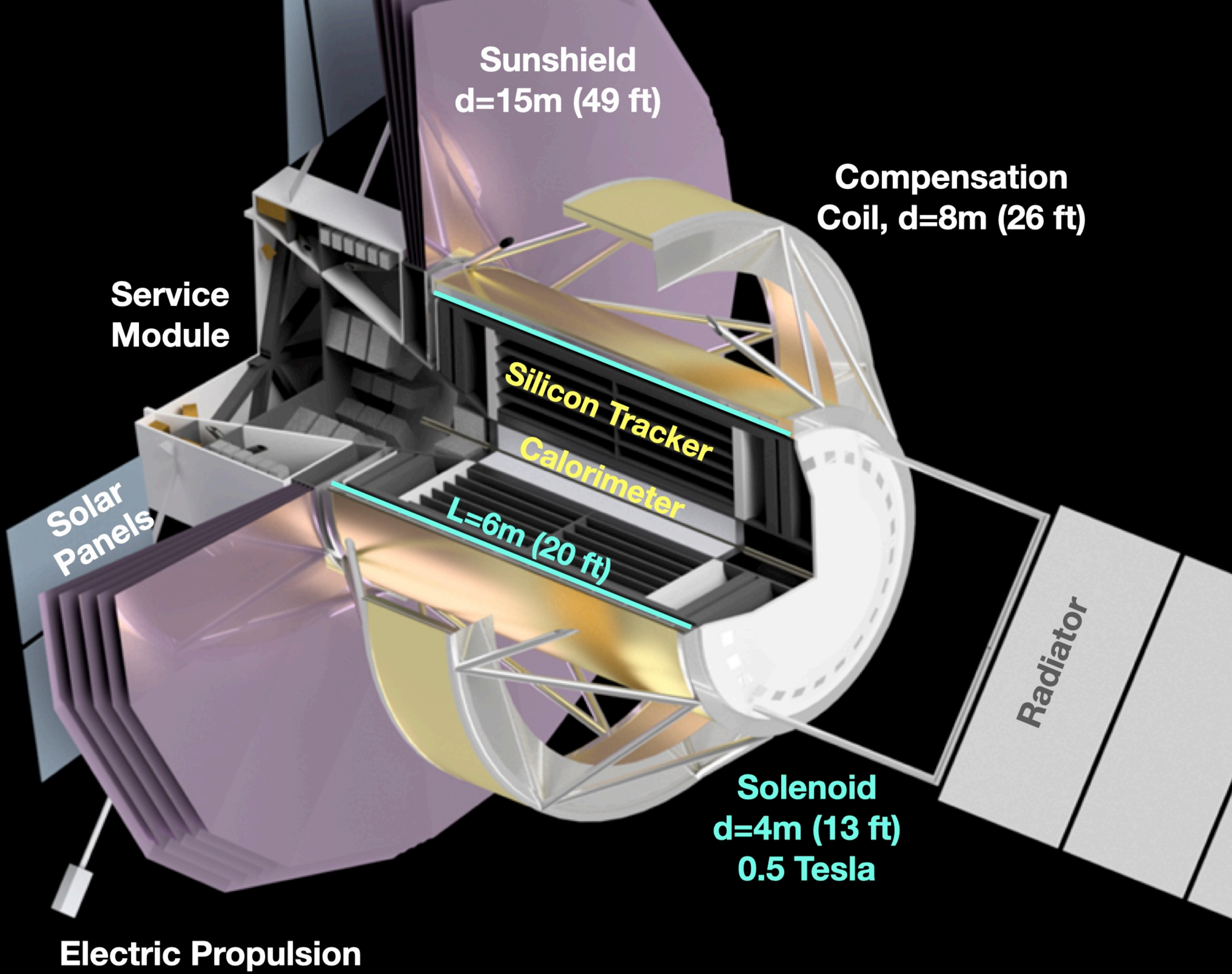
AMS-100



CRAB Nebula TeV - Photons

AMS-02





- **AMS-02 has collected more than 200 Billion cosmic rays since 2011 and will continue to take data for the lifetime of the ISS. It is a unique scientific instrument in Space.**
- **AMS-100 will improve the sensitivity of AMS-02 by a factor 1000 and will explore a completely new territory in precision cosmic ray physics.**