Temperature and Strain Measurements With Optical Fibers in the Cryogenic Temperature Range

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Clemens Dittmar

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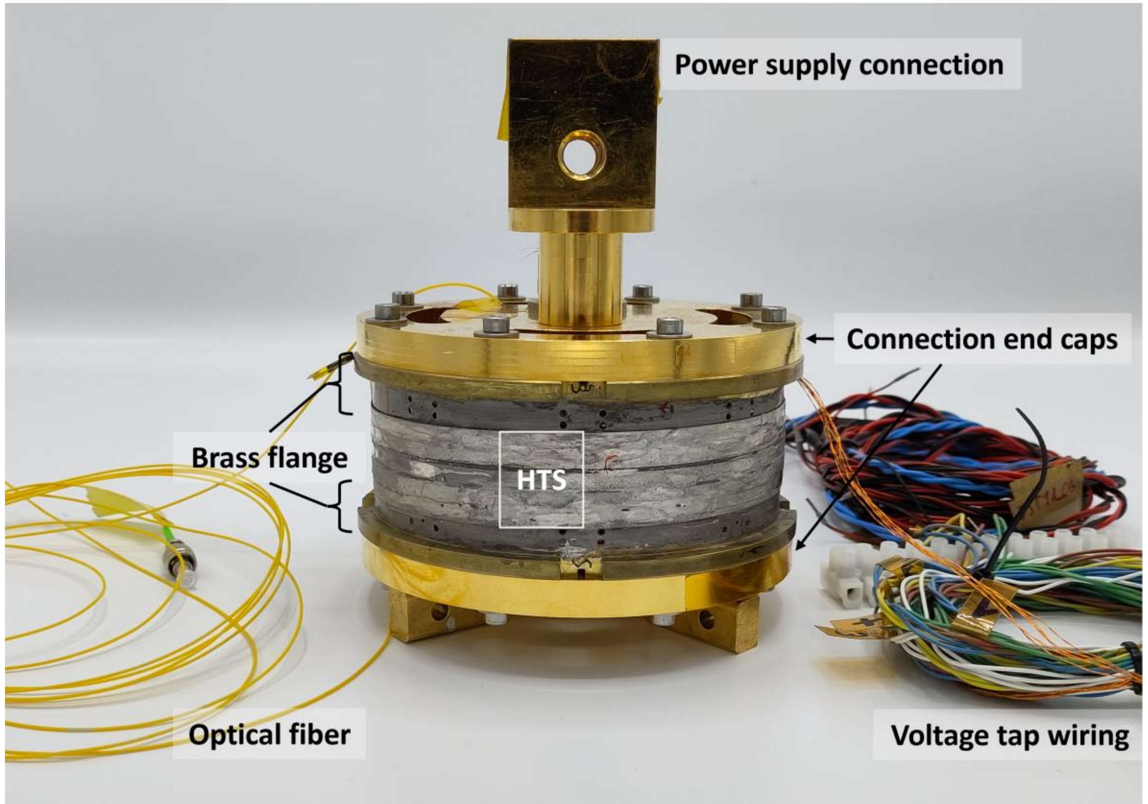
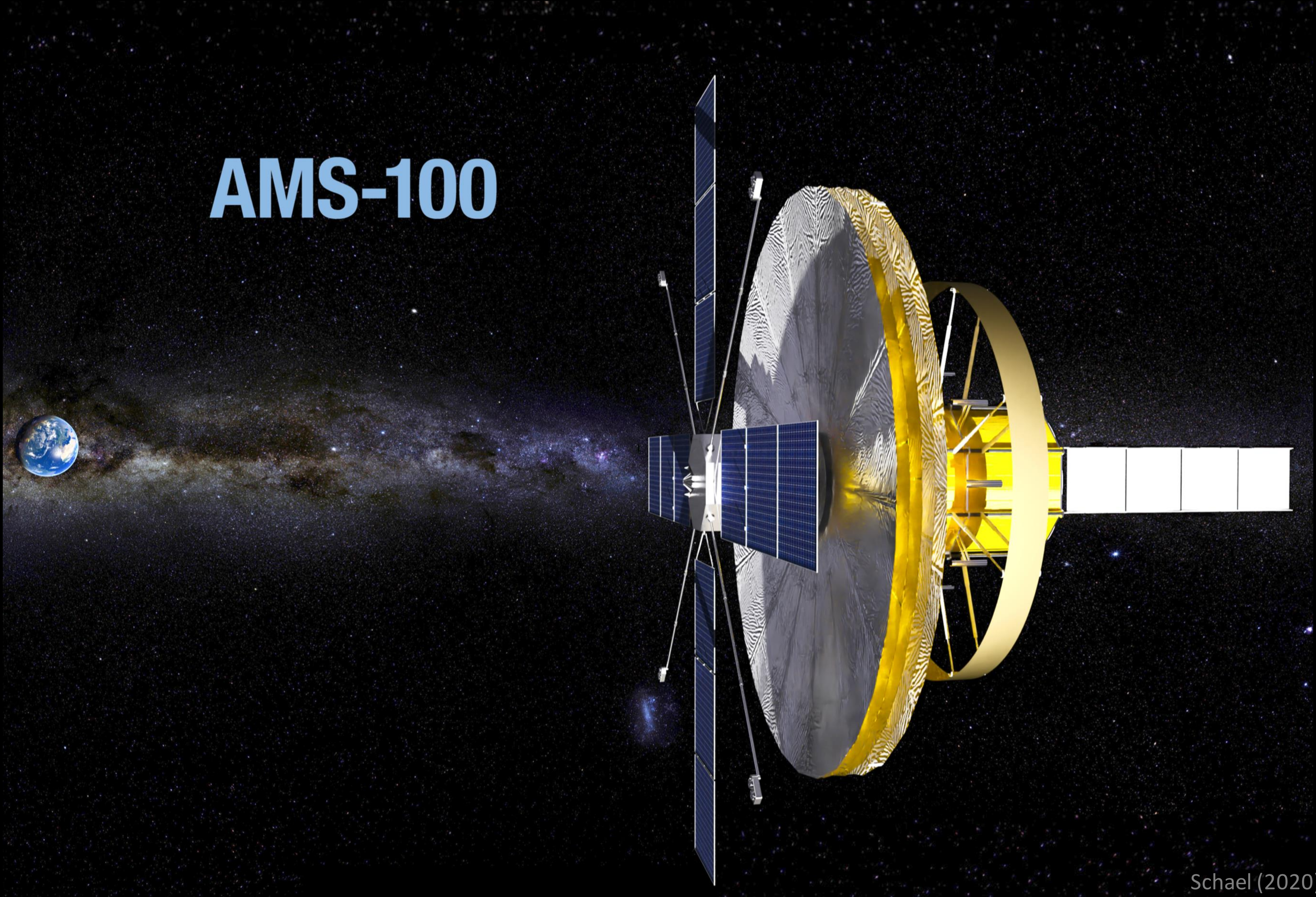
Contents

- Why do we need a fiber optic measurement system?
- How it works
- Calibration
- First measurements
- Measurement of a high temperature superconducting coil
- Summary and outlook





Schael (2020)[2]

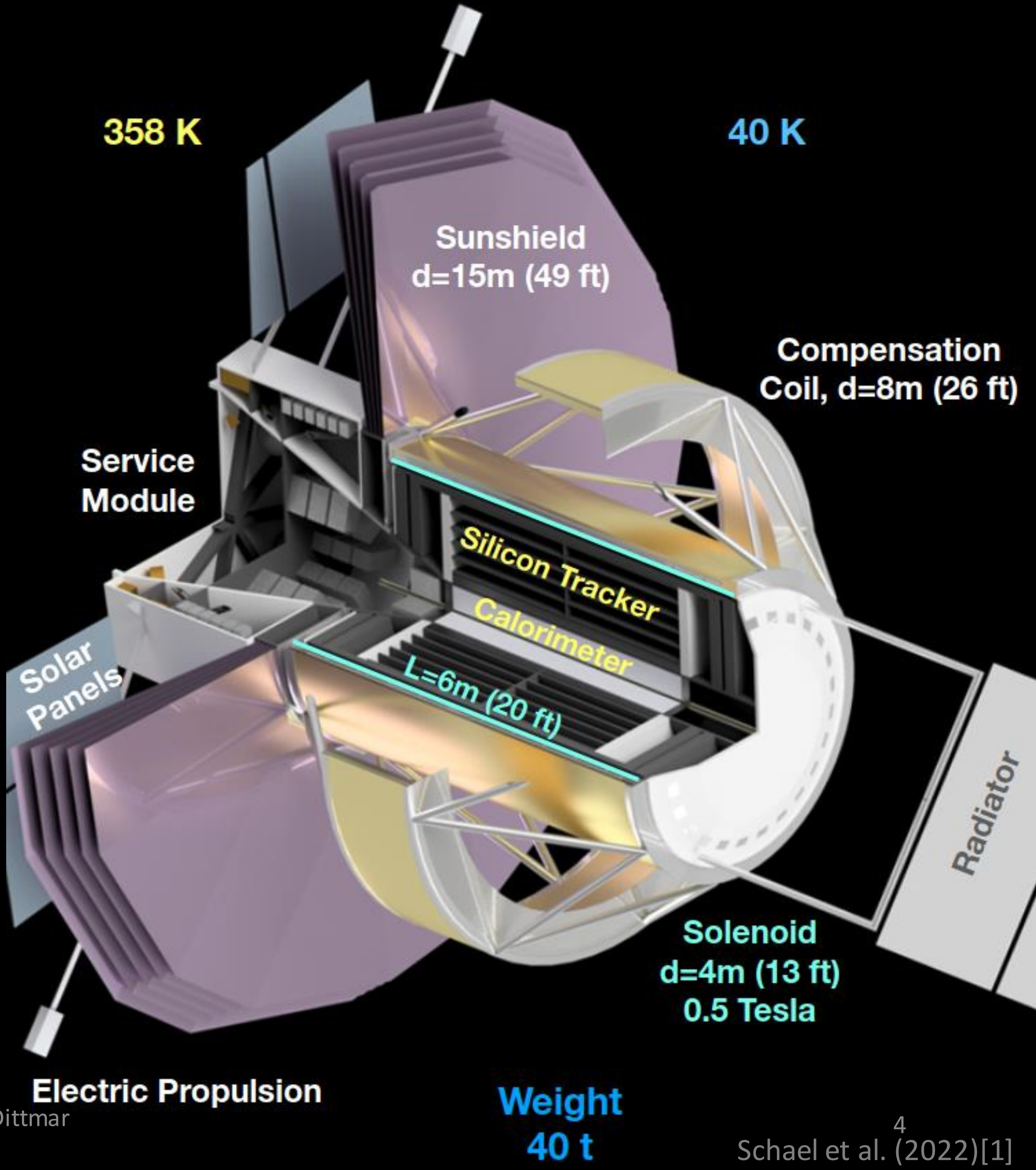
AMS-100

Design requirements

- Geometric acceptance of 100 m^2 sr
  → 1000 times the acceptance of AMS-02
- Max. detectable rigidity of 100 TV
- Measurement of cosmic nuclei with energies up to the cosmic-ray knee

Planned design

- 3mm high temperature superconducting solenoid
  → 0.5 T in a Volume of 75 m^3
- Compensation coil
- Sun Shield
- Electric propulsion
- Radiator
- SciFi tracker
- Silicon tracker
- Time of flight system
- Calorimetry



Schael et al. (2022)[1]

High Temperature Superconducting Tape

RWTH AACHEN UNIVERSITY
Fraunhofer

Coil Parameters

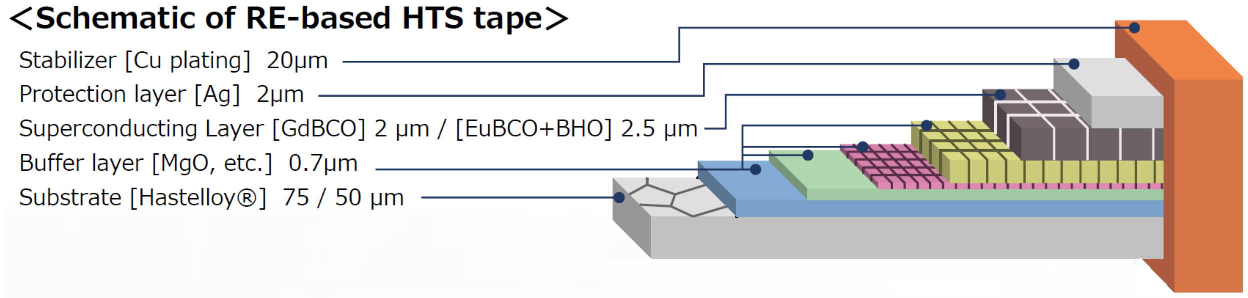
- Length of 6 m
- Diameter of 4 m
- Operating at 55 K
- Current 10 kA
- Layers of 12 mm HTS
- 5 km Kabel length
- 1 Layer Kabel
- <u>Non-Isolated</u>
- <u>Aluminium U-Profile</u>

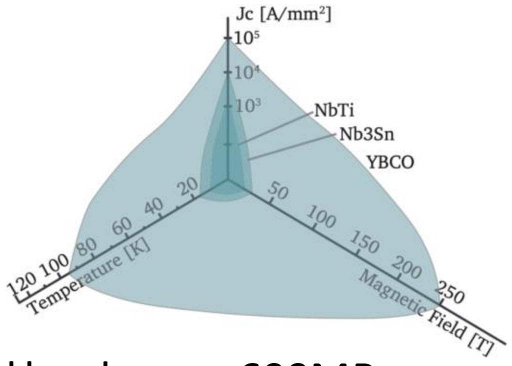
Highly protected against damage caused by quenching

HTS-Tape:

J. van Nugteren (2016) [7]

Fujikura Ltd. (2022) [6]

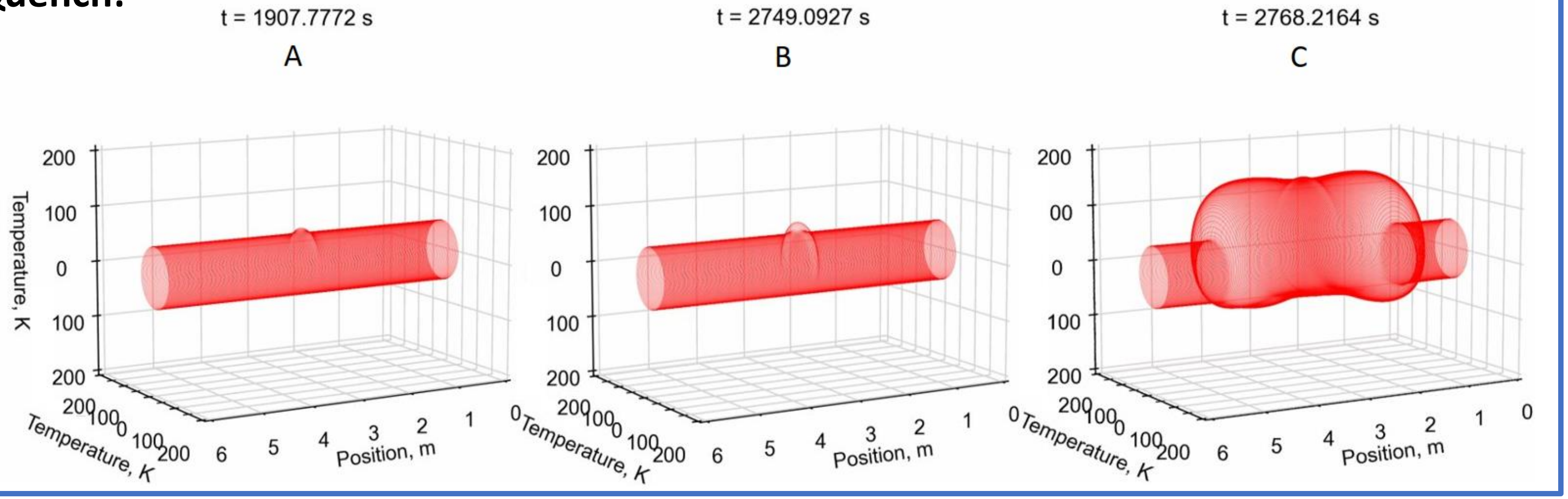




- <u>Will be damaged at temperatures above 473K and mechanical loads over 600MPa</u>

Quench:

Schael et al. (2022)[1]

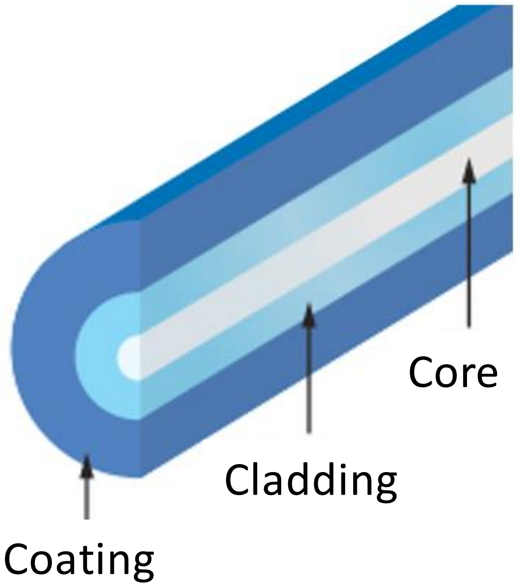


Sensors

Limited weight budget

- Platinum resistors or strain gauges unsuitable as additional wiring is required for each sensor

Distributed temperature and strain monitoring with Rayleigh scattering and optical fibers

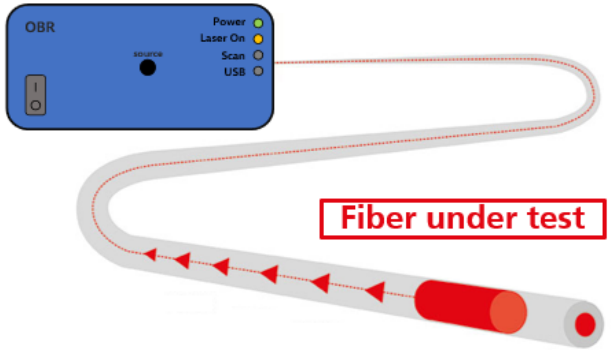


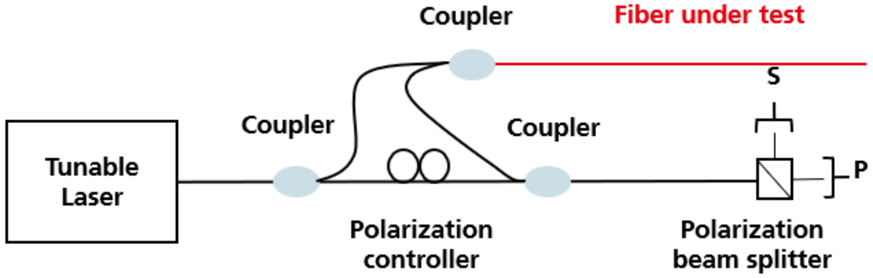
Fiber	Doping	Core/Cladding/Coating ⌀ [μm]	Coating material
SM1500(9/125)P	Germanium	9/125/157	Polyimide
PS1250/1500	Boron	9/125/145	Acrylate

ThorLabs [9]

Optical Frequency Domain Reflectometry (OFDR)

OBR-4613, Luna Innovations





- Light in an optical fiber can scatter at spectral index changes due to inhomogeneities ("Rayleigh Scattering")
- Each segment of an optical fiber has an individual Rayleigh scattering spectrum
- OFDR compares the changes between spectra for the same unloaded and loaded fiber segment

$$-\frac{\Delta\nu}{\hat{\nu}} = K_T \cdot \Delta T + K_\epsilon \cdot \epsilon$$

$$\Delta T = T_M - T_R \qquad \epsilon = \frac{\Delta L}{L}$$

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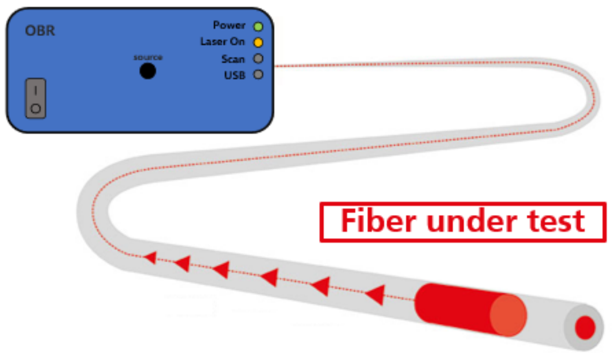

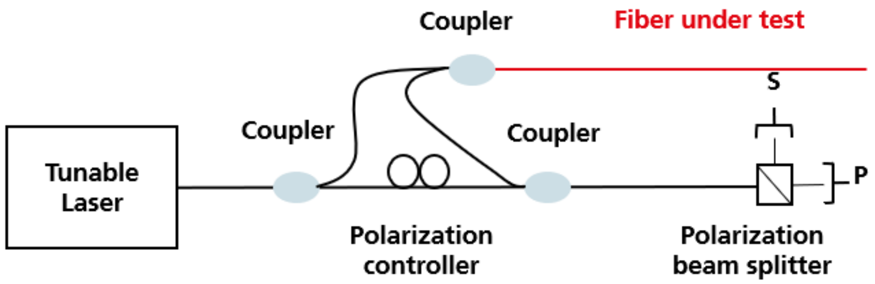

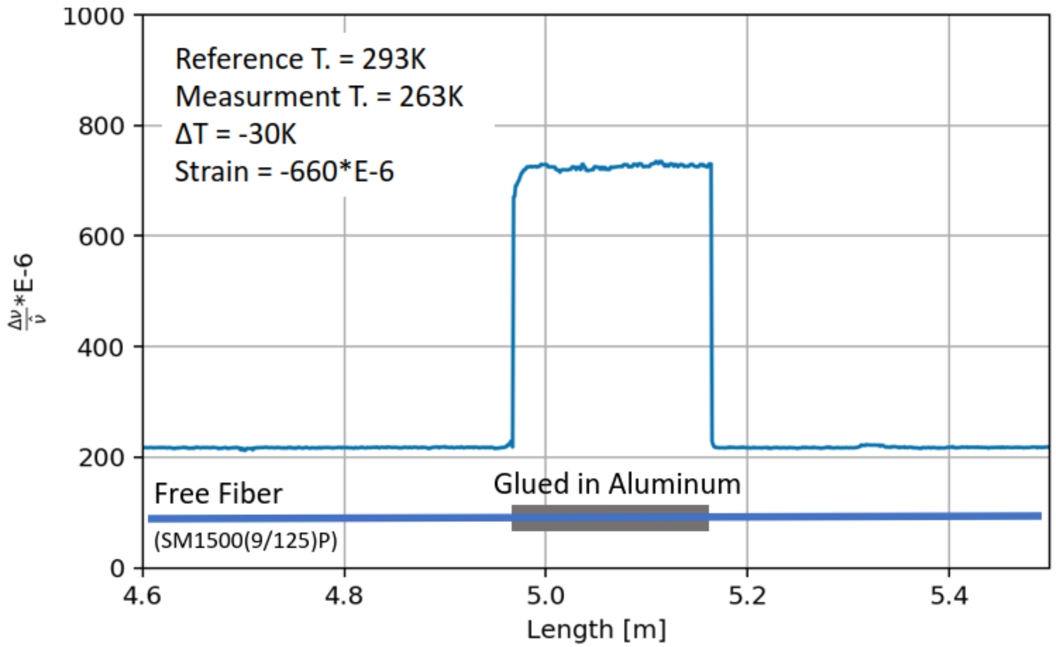

Non-Linear Model

What can be measured?

- Temperature changes
- Thermomechanical changes
- Mechanical changes

Linear standard model for minor temperature changes at room temperature

$$-\frac{\Delta\nu}{\hat{\nu}} = K_T \cdot \Delta T + K_\epsilon \cdot \epsilon$$

$$\Delta T = T_M - T_R$$

$$\epsilon = \frac{\Delta L}{L}$$

Temperature Sensitivity ($K_T \cdot \Delta T$)

Strain Sensitivity ($K_\epsilon \cdot \epsilon$)

Non-Linear Model

What can be measured?

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- Thermomechanical changes
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Linear standard model for minor temperature changes at room temperature

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Temperature Sensitivity — Strain Sensitivity

$$\Delta T = T_M - T_R$$

$$\epsilon = \frac{\Delta L}{L}$$

New non-linear model which considers all temperature influences:

$$-\frac{\Delta\nu}{\hat{\nu}} = F(T_R, T_M) + G(T_R, T_M) + K_\epsilon(T_M) \cdot \epsilon_{External}(T_M)$$

$$-\frac{\Delta\nu}{\hat{\nu}} = A \cdot (T_M - T_R) + \frac{B}{2} \cdot (T_M^2 - T_R^2) + \mathcal{O}(T^3)$$
$$+ \left(m \cdot \frac{T_M + T_R}{2} + b\right) \cdot \epsilon_{Sub.}(T_M, T_R)$$
$$+ (m \cdot T_M + b) \cdot \epsilon_{External}(T_M)$$

Theoretical prediction:

- Strain sensitivity is temperature dependent

$$K_\epsilon(T) = m \cdot T + b$$

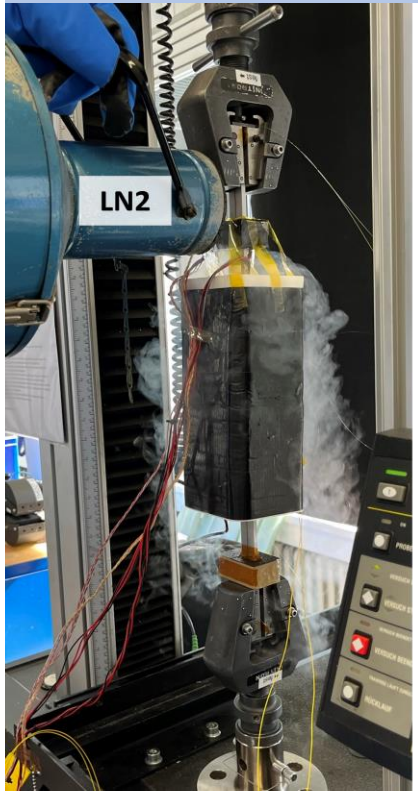
- Temperature sensitivity depends on doping and is also temperature dependent

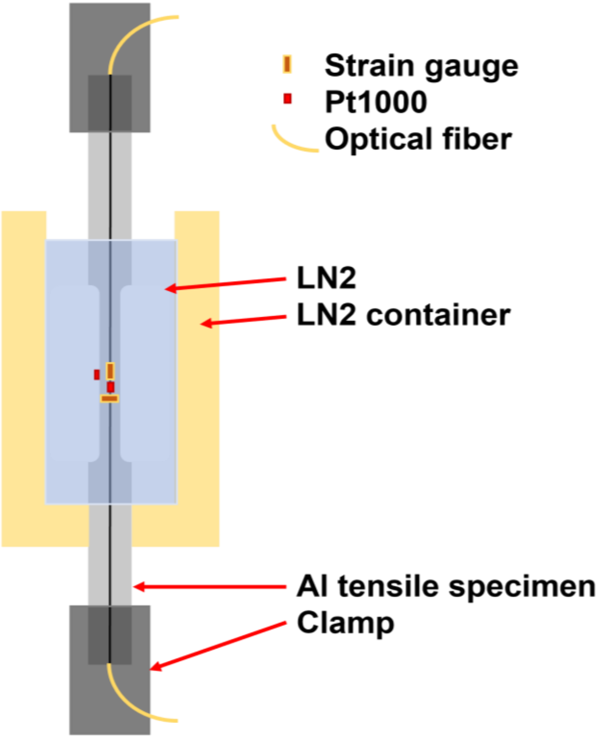
$$K_T(T) = \frac{1}{n}\frac{dn}{dT}(T)$$

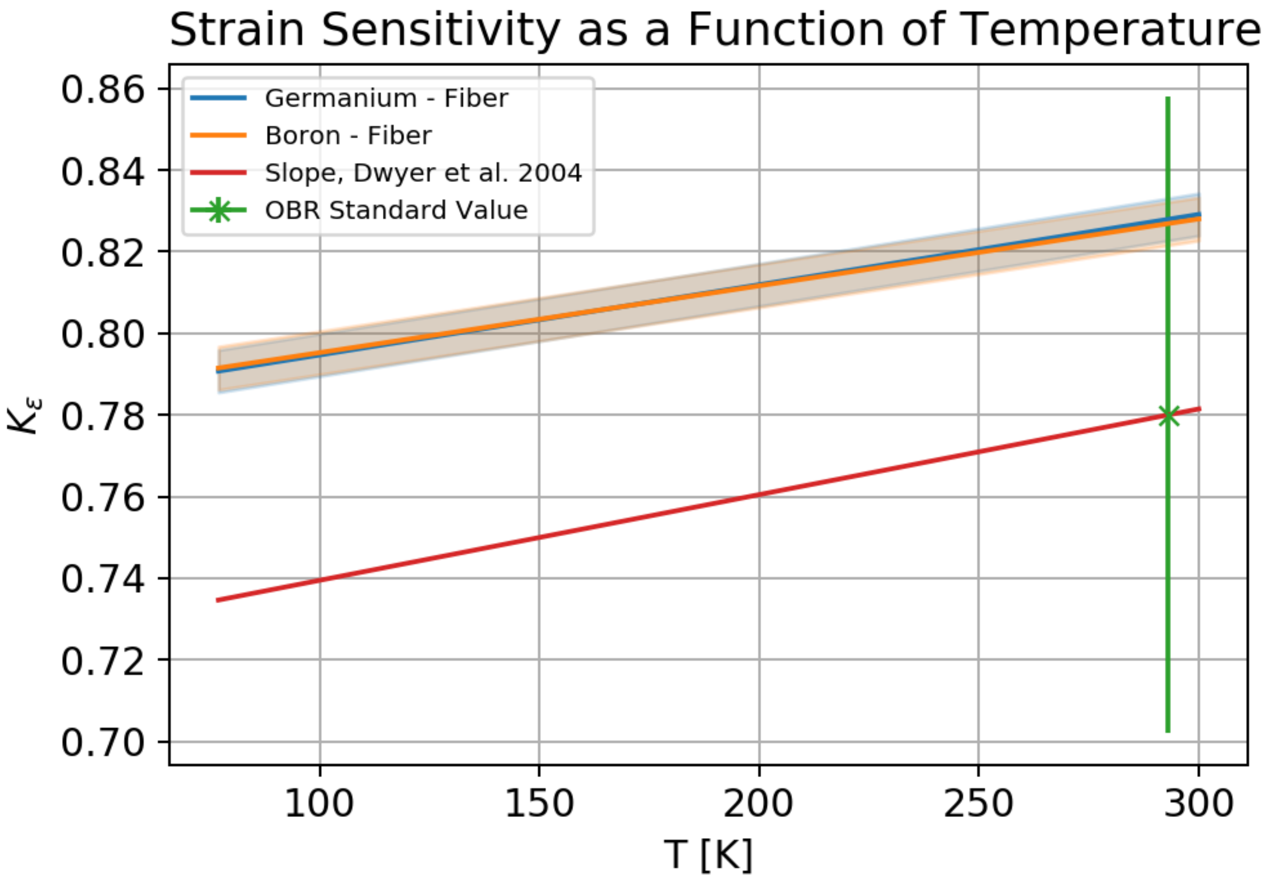
Strain Sensitivity

Test-Setup and conditions:

- Tensile test at 300 K and 77 K
- Two fibers glued in one groove







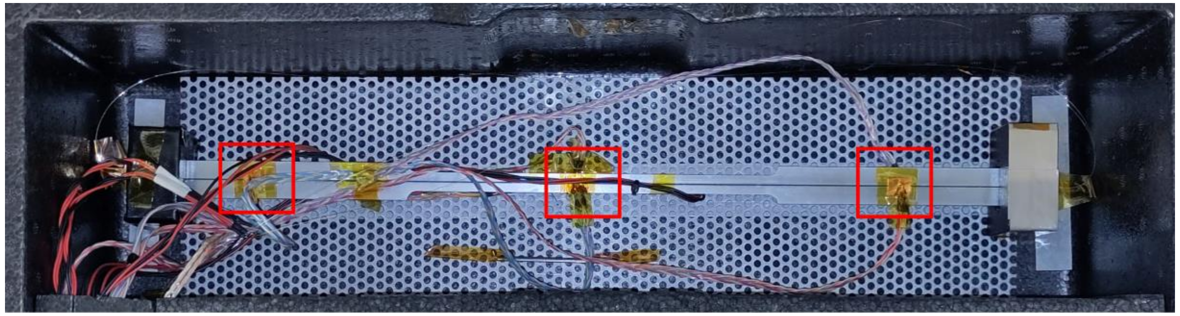
Results:

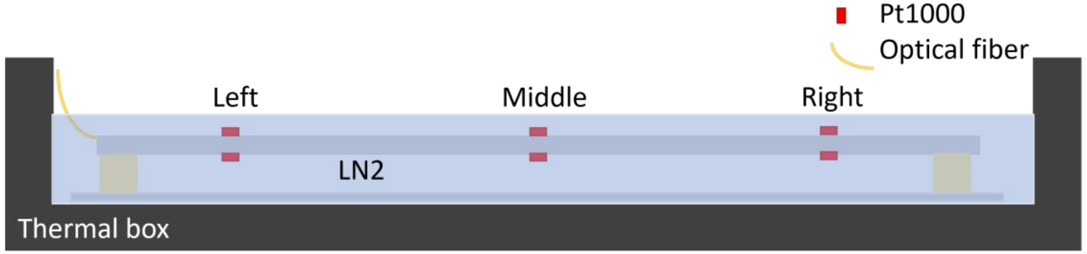
- Slope corresponds to the literature for FBGs
- Strain sensitivity is temperature dependent

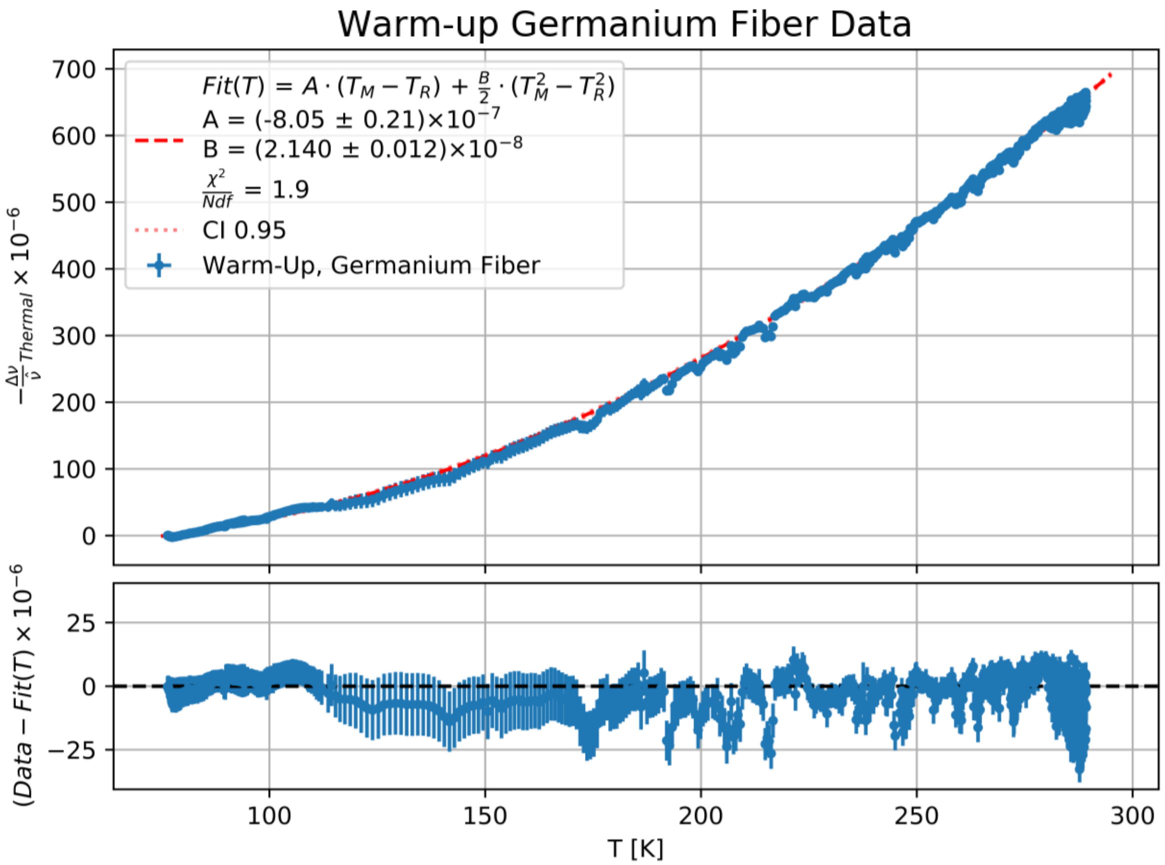
Temperature Sensitivity Germanium

Test-Setup and conditions

- Warm-up (77 – 290 K, 18h)
- Climate chamber, 6 steps (233 – 335 K)
- Mechanical part considered by determining the thermal expansion of Al-6060 with calibrated strain gauges and the determined strain sensitivity







Results

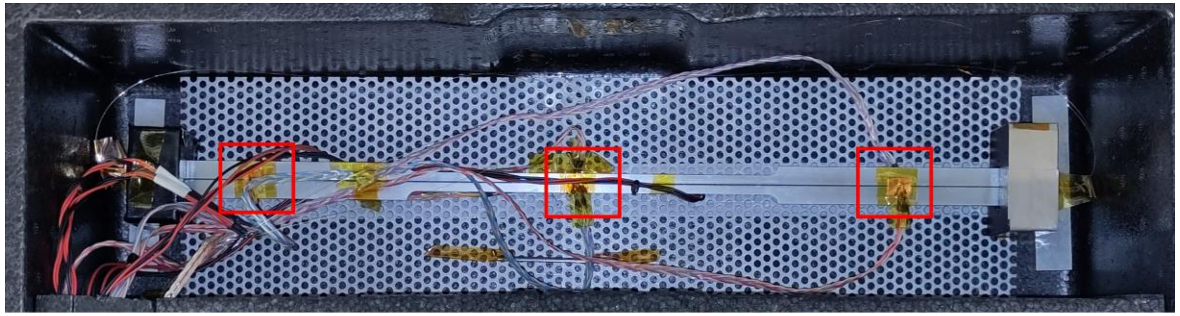
Germanium-doped fibers:

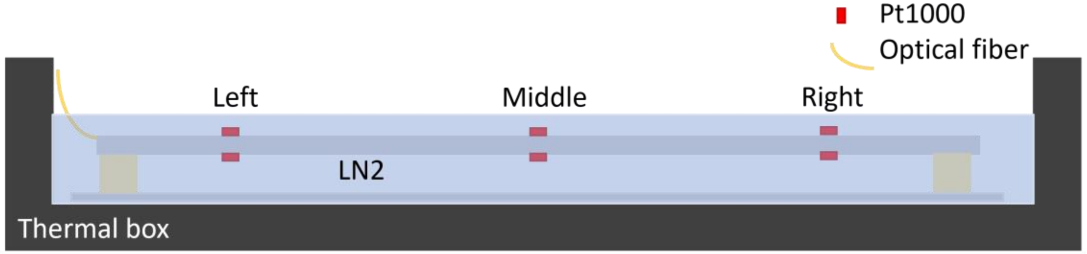
- Quadratic temperature dependence
- Signal also at 77K

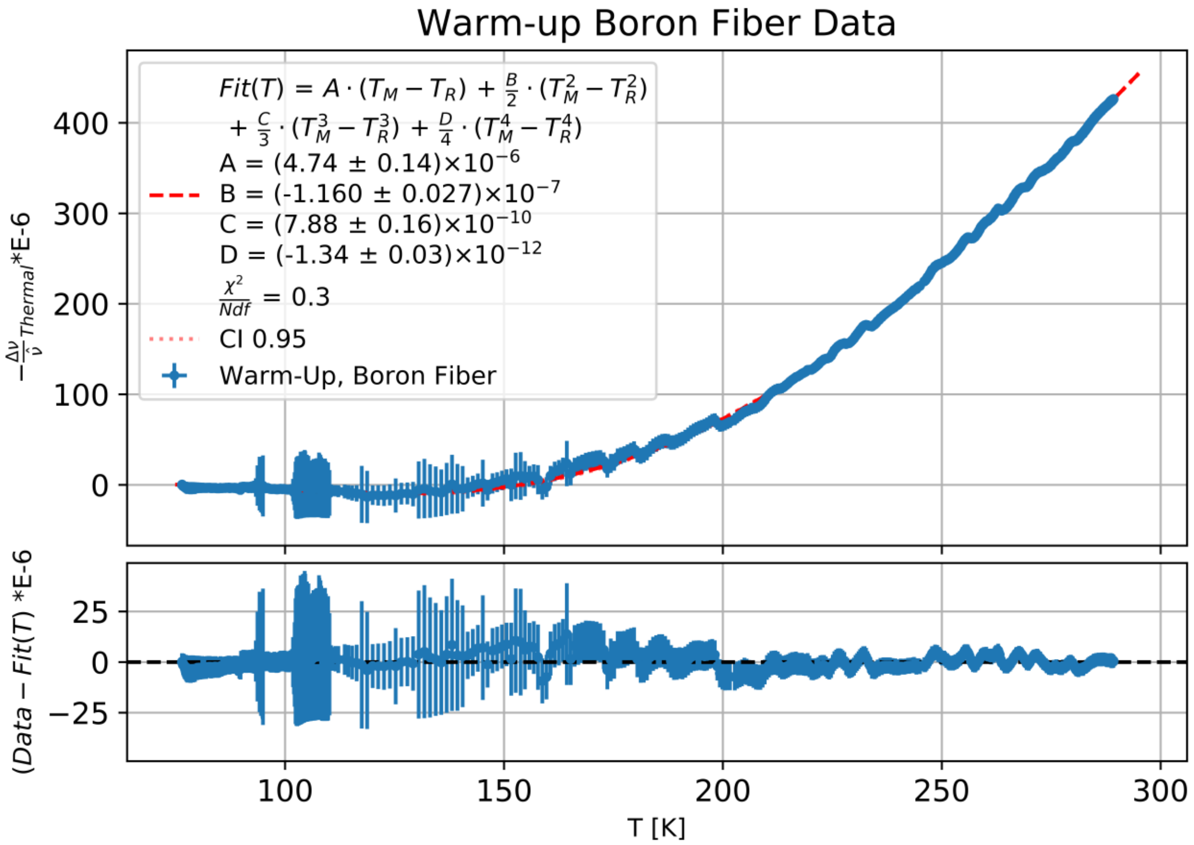
Temperature Sensitivity Boron

Test-Setup and conditions

- Warm-up (77 – 290 K, 18h)
- Climate chamber, 6 steps (233 – 335 K)
- Mechanical part considered by determining the thermal expansion of Al-6060 with calibrated strain gauges and the determined strain sensitivity







Results

Boron-doped fibers:

- Not sensitive to temperature < 150 K

Temperature Sensitivity

Test-Setup and conditions

- Warm-up (77 – 290 K, 18h)
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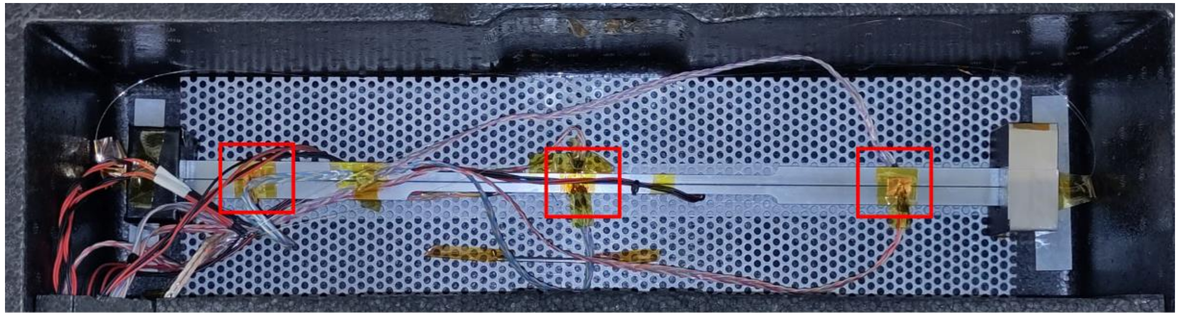
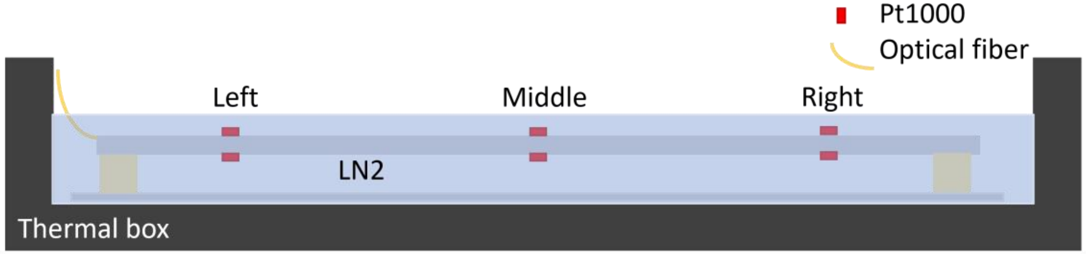
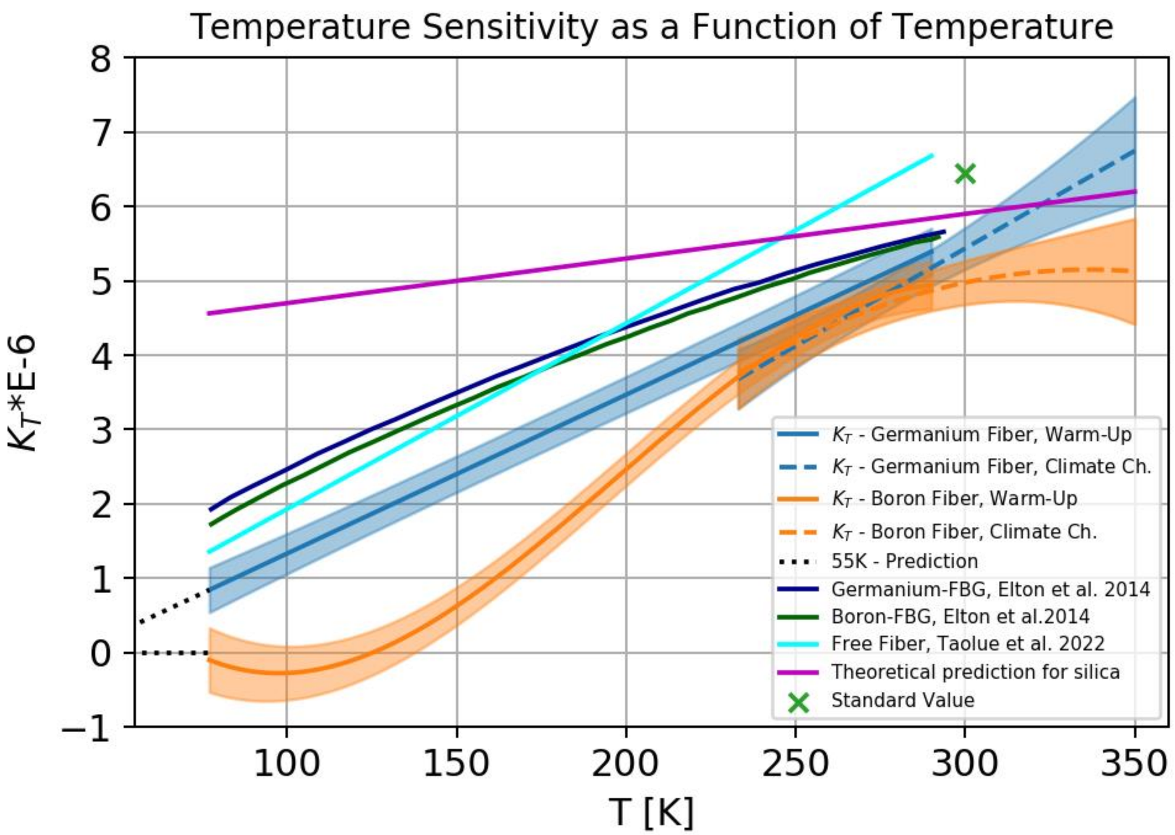






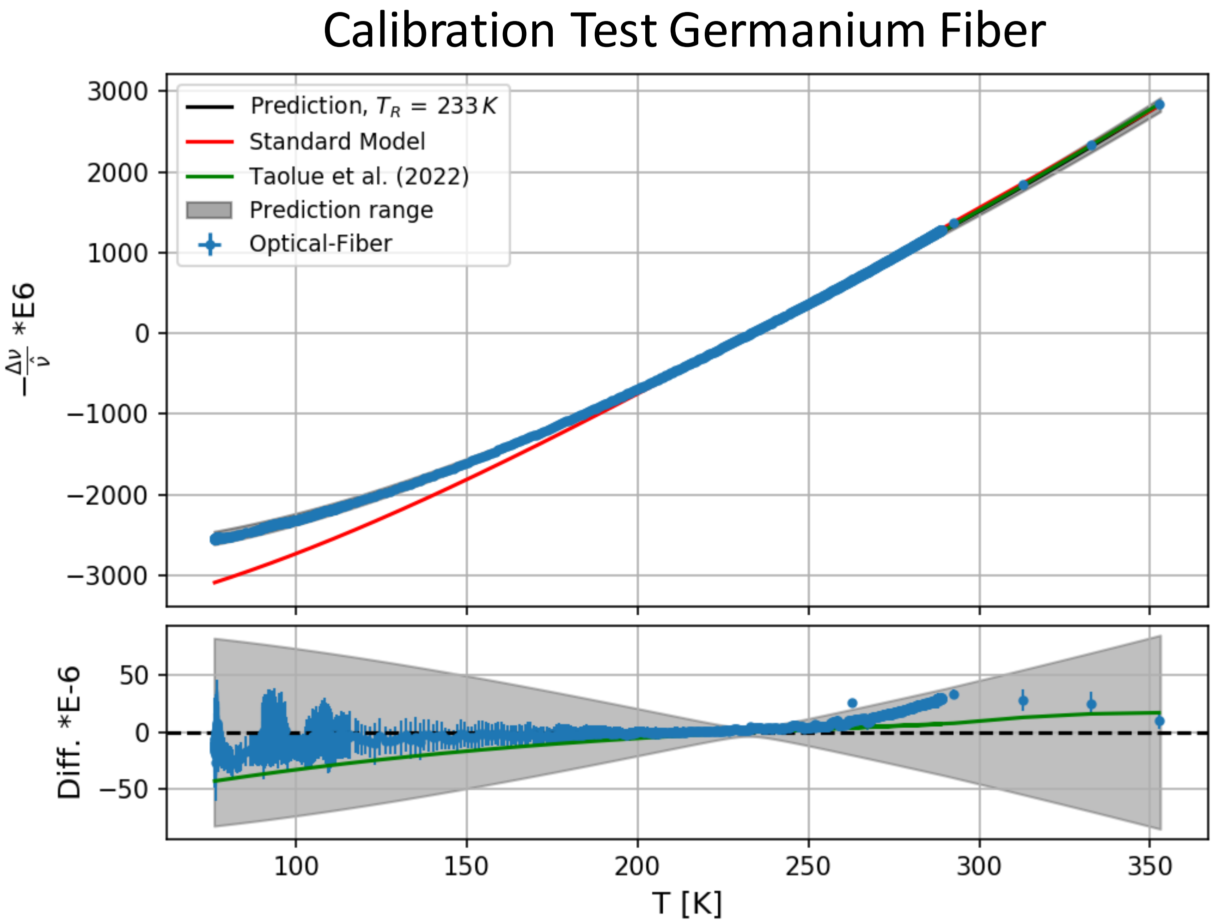
Results

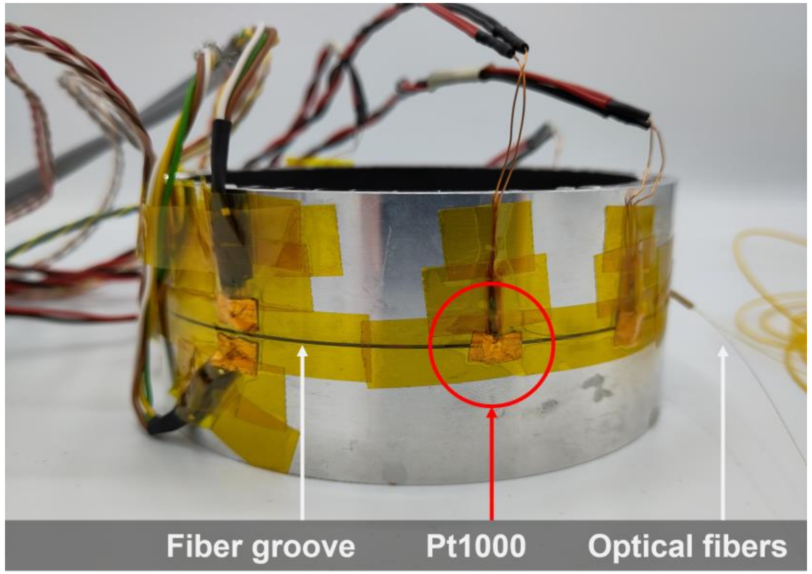
- Germanium-doped fibers: linear temperature sensitivity
- Expected temperature sensitivity at 55 K: 0.5E-6 [1/K]
- Boron-doped fibers: not sensitive to temperature < 150 K

Test of Calibration: Germanium-doped Fiber

Test-Setup and conditions:

- Ring shaped Aluminum body
- 5 cm high, 15 cm diameter
- Both fibers glued in one Aluminum groove
- Warm-up (77 – 300 K, 18 h)
- Climate chamber, 6 steps (233 – 353 K)
- Shape similar to AMS-100 test coils





Results:

- Well described across the total temperature range (77 K – 353 K)
- Consistent with literature parameterization

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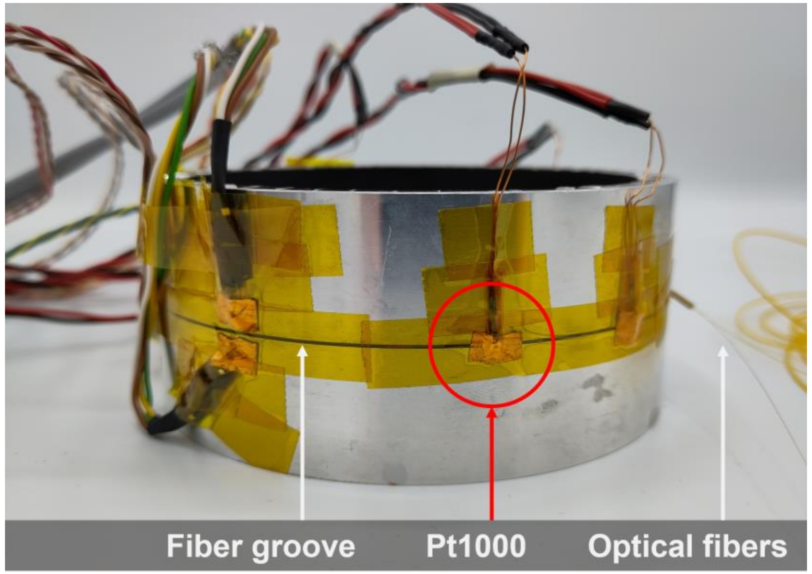
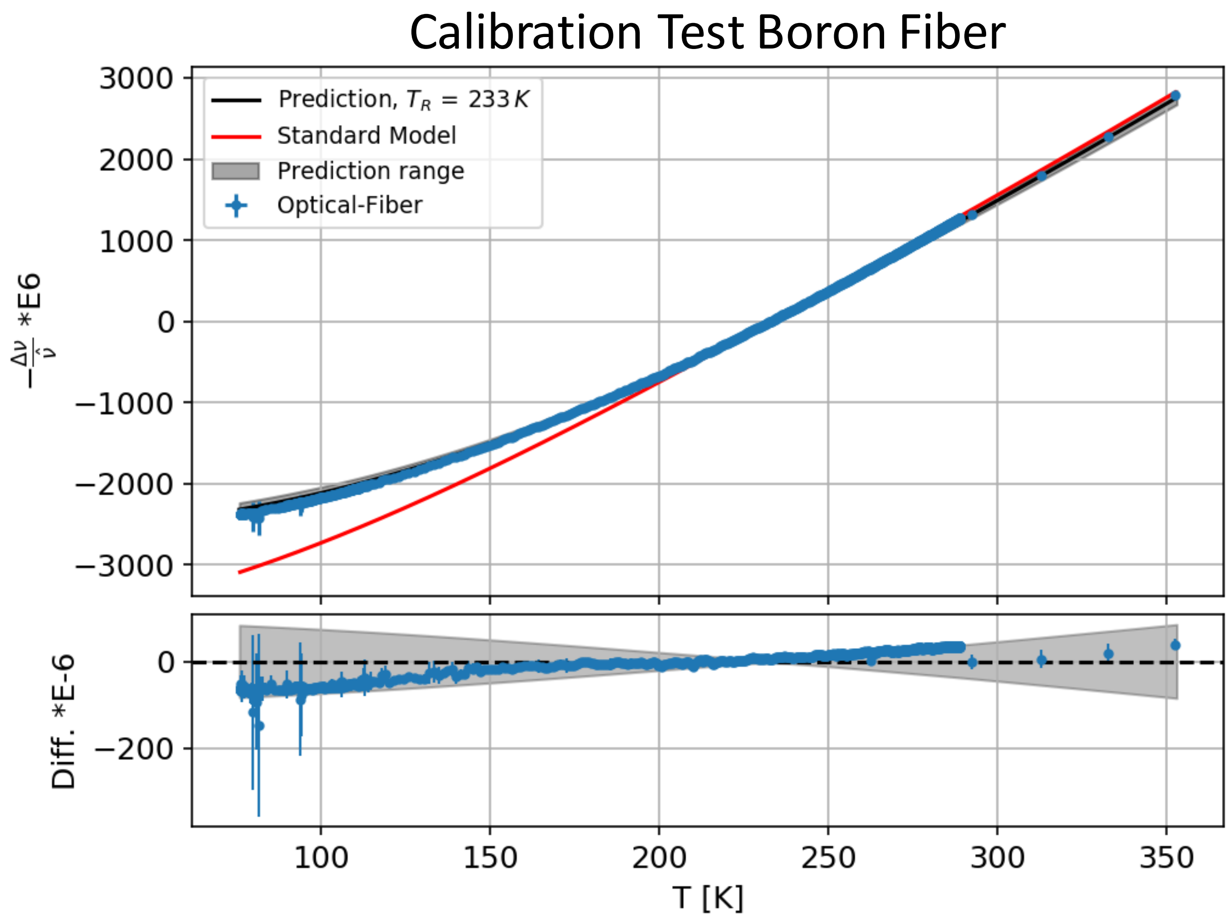




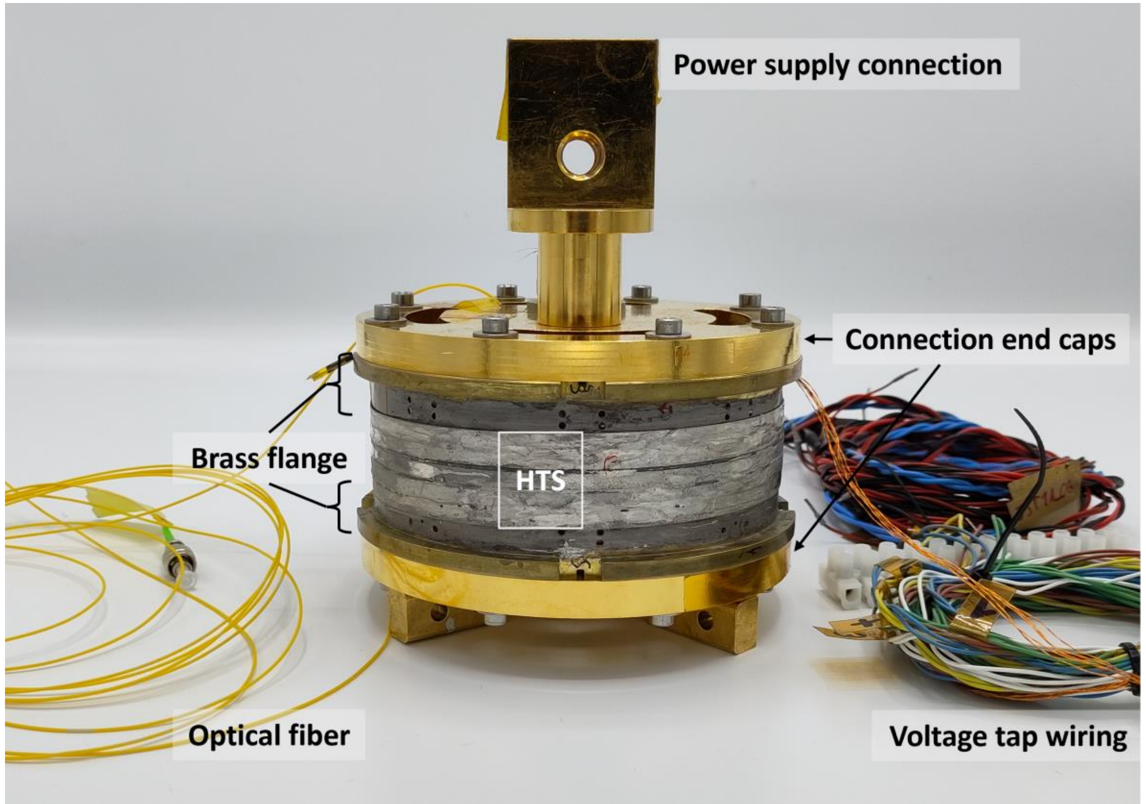
Results:

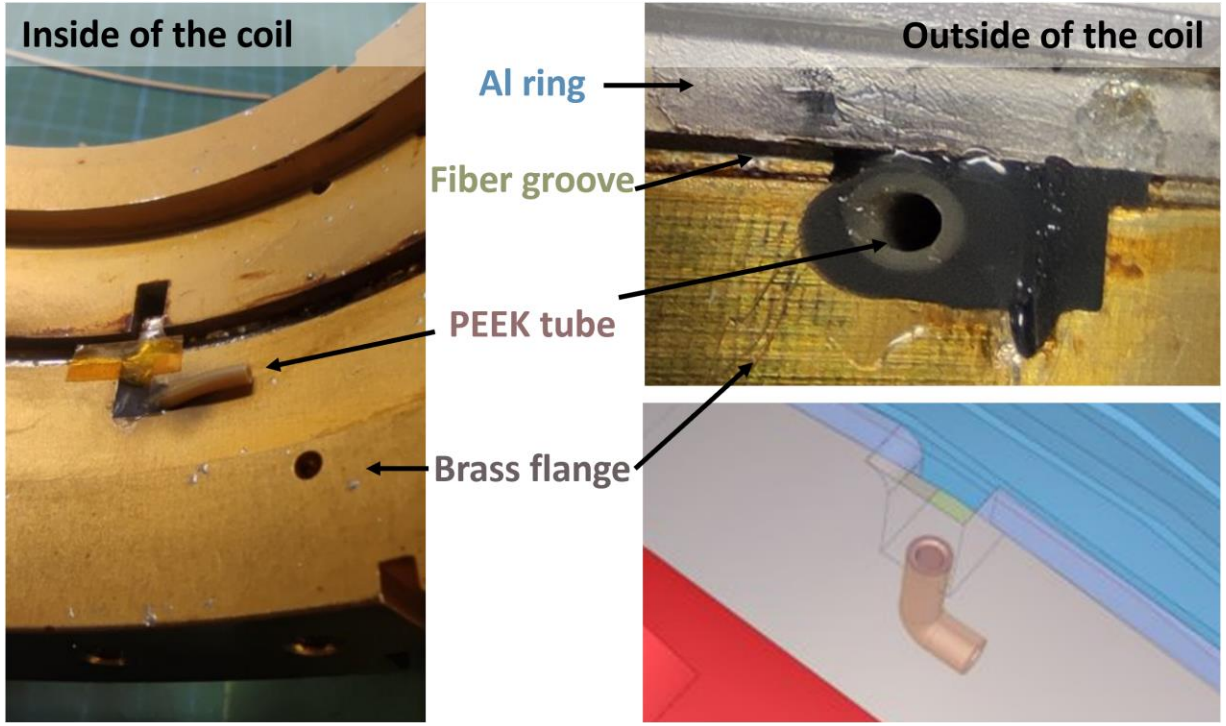
- Systematic drift at low temperatures
- Deviation within the prediction range

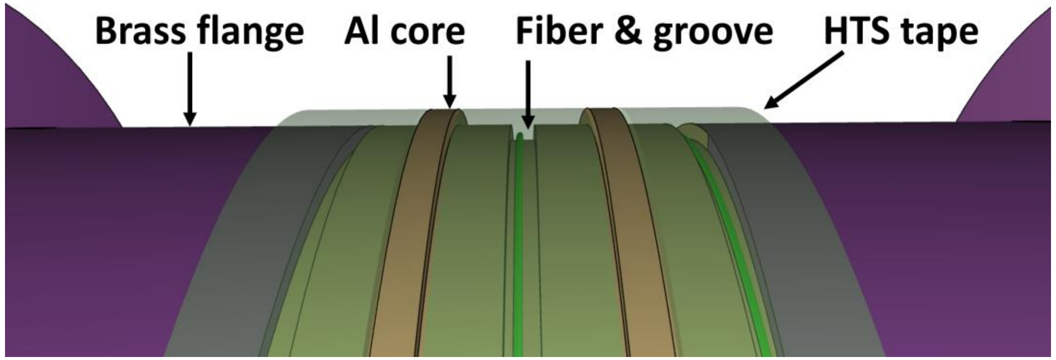
HTS – Test Coil

Test-Setup and conditions:

- HTS-Coil with 2.5 windings
- 10 cm high, 12 cm diameter
- 2 windings fiber under HTS-Tape glued in Aluminum
- Peek tubes for guiding the fibers into the structure







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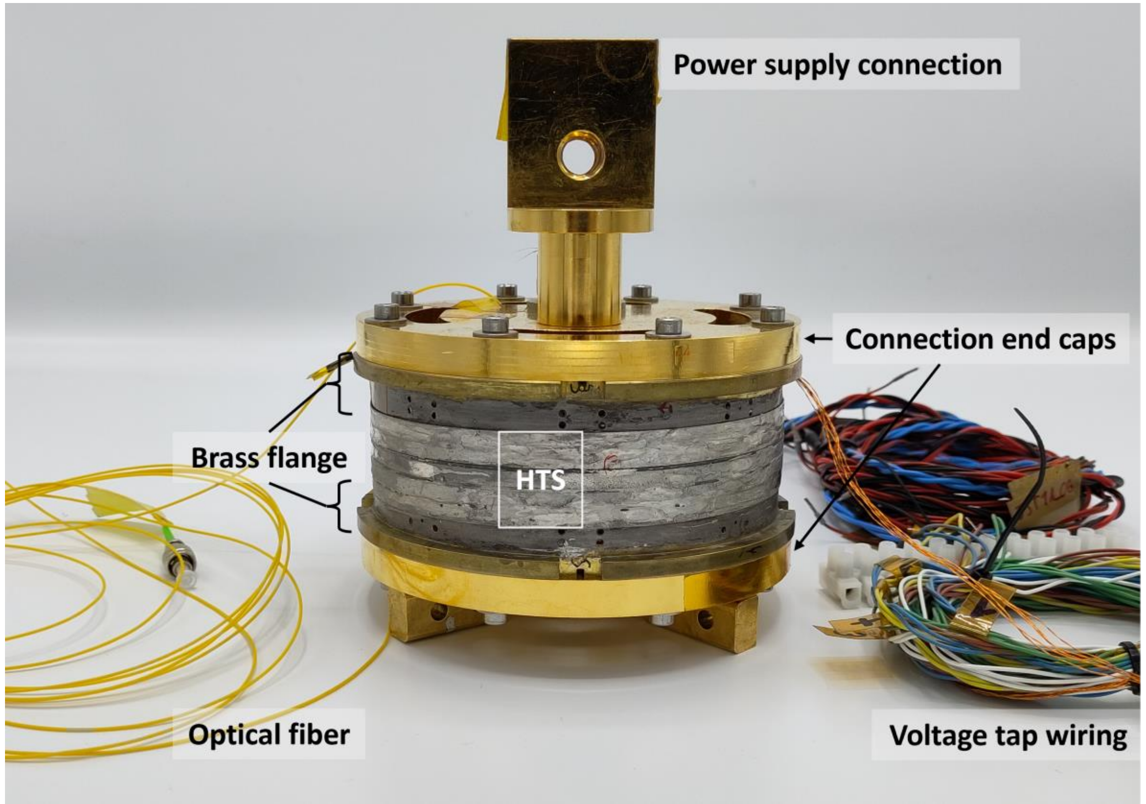
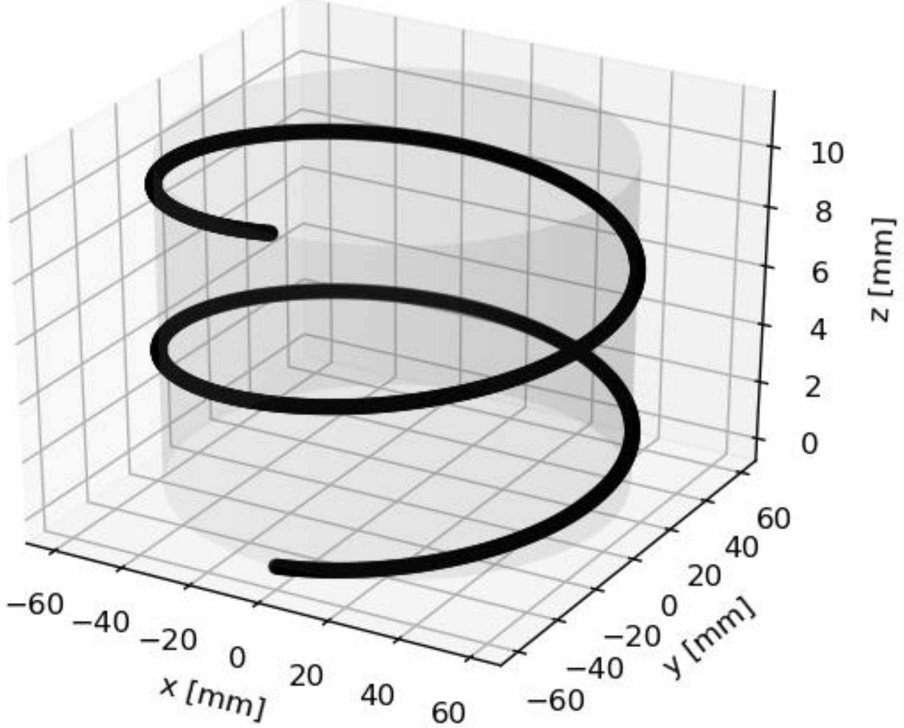


1200A applied current



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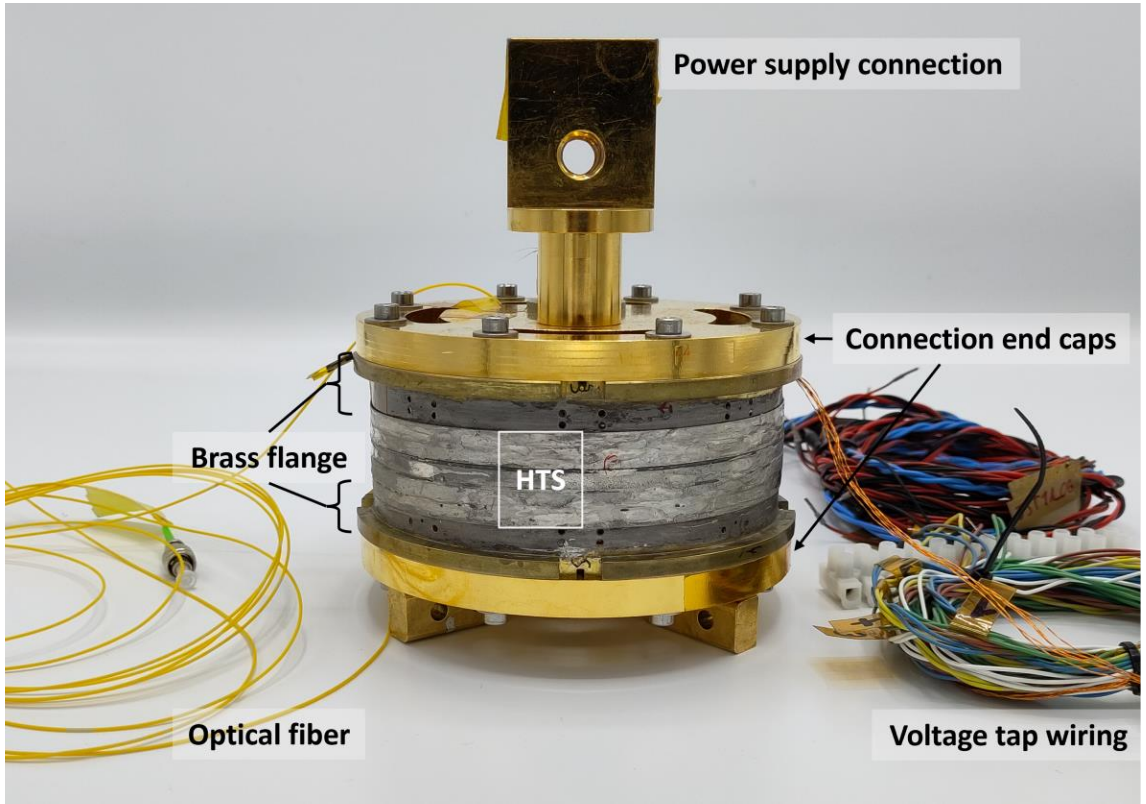

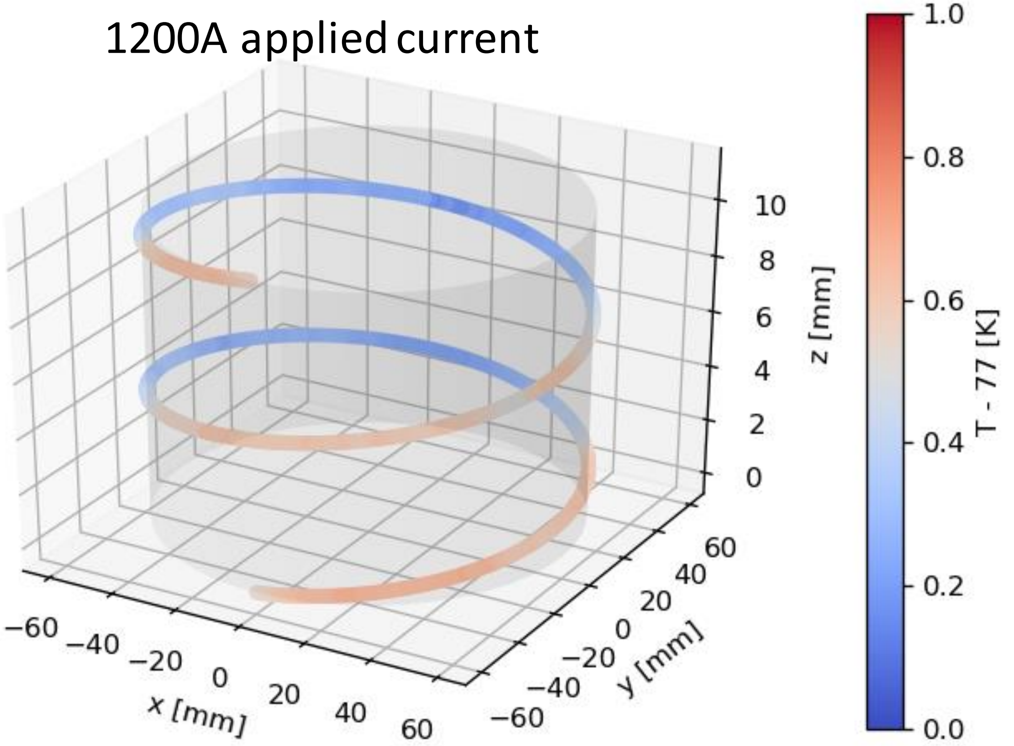

Results:
- Temperature profile with maximum of 0.7 K
  → Current flows through Aluminum structure
- Magnetic field measurements: current flow of 800 – 900 A through the Aluminum structure at 1200A applied current

HTS – Test Coil: Dynamic T. Measurement

Test-Setup and conditions:
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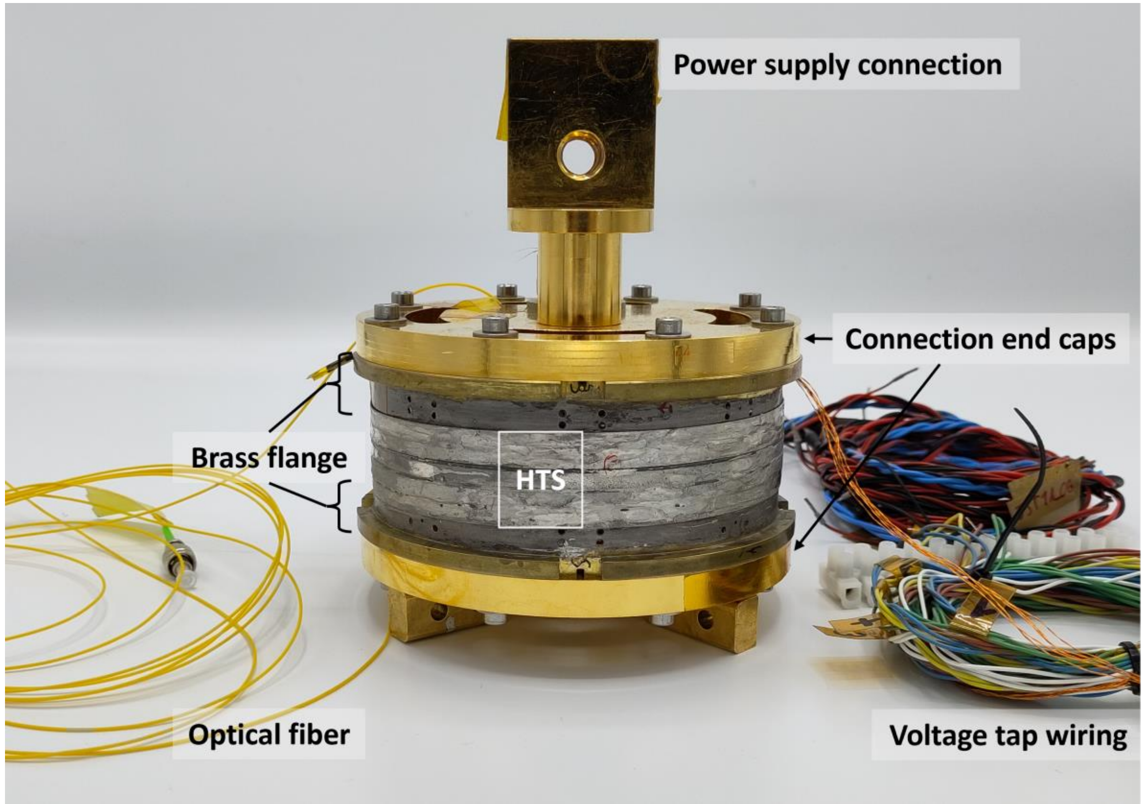

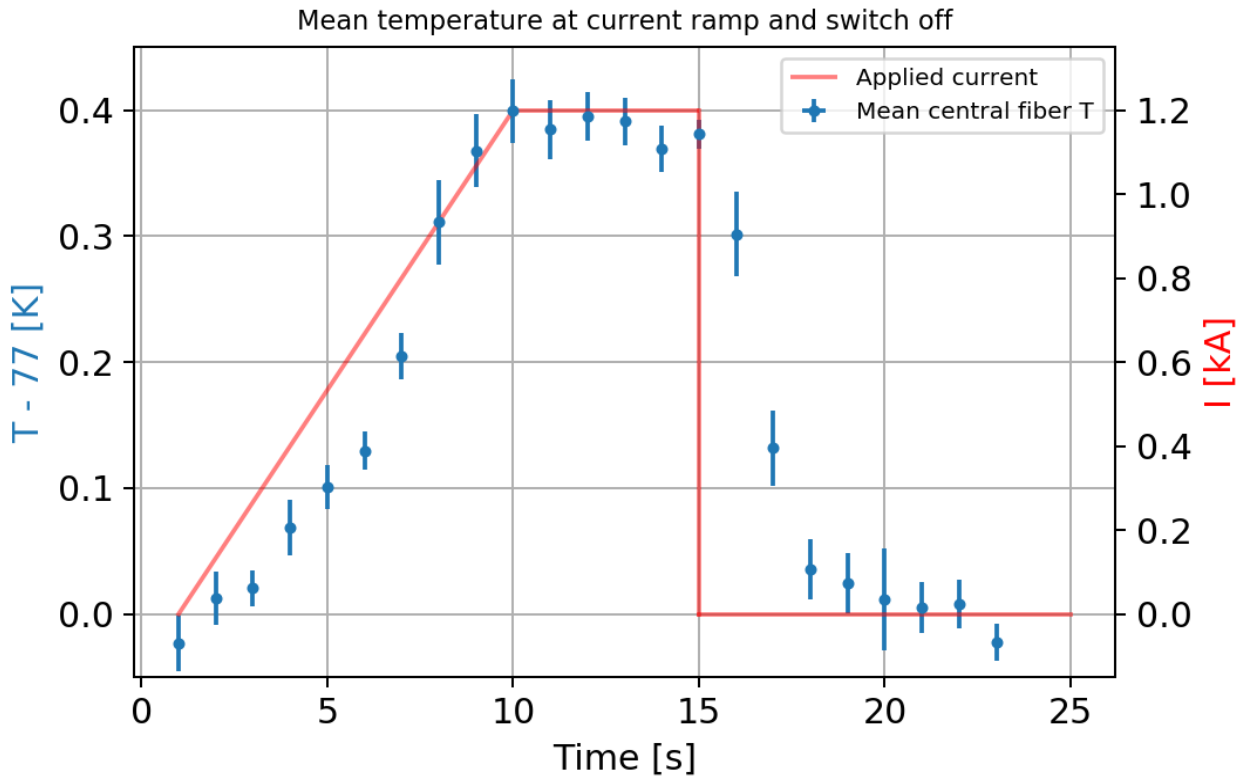

Results:
- Temperature curve follows the current curve
- Changing current flows can be measured

Decoupling of Thermal & Mechanical Load

- Combining two different fibers into one measurement
- Signal difference is due to the temperature sensitivity difference
- Newton method for function inversion

Test-Setup and conditions:

- Ring shaped Aluminum body
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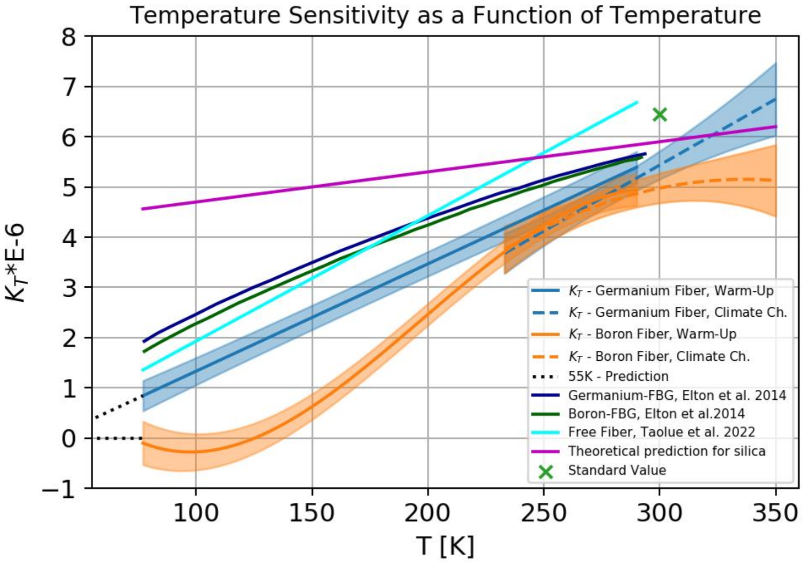
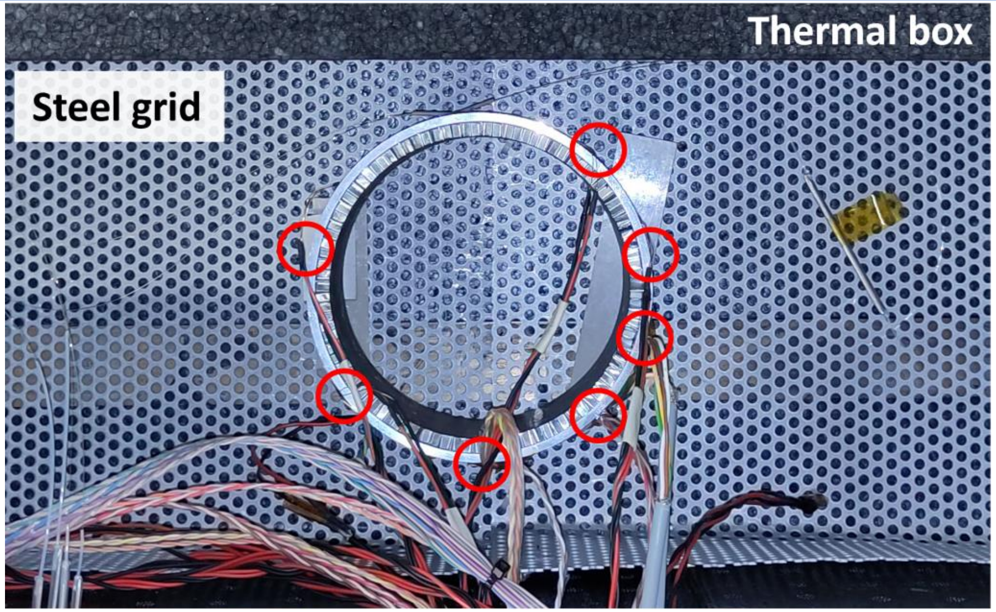
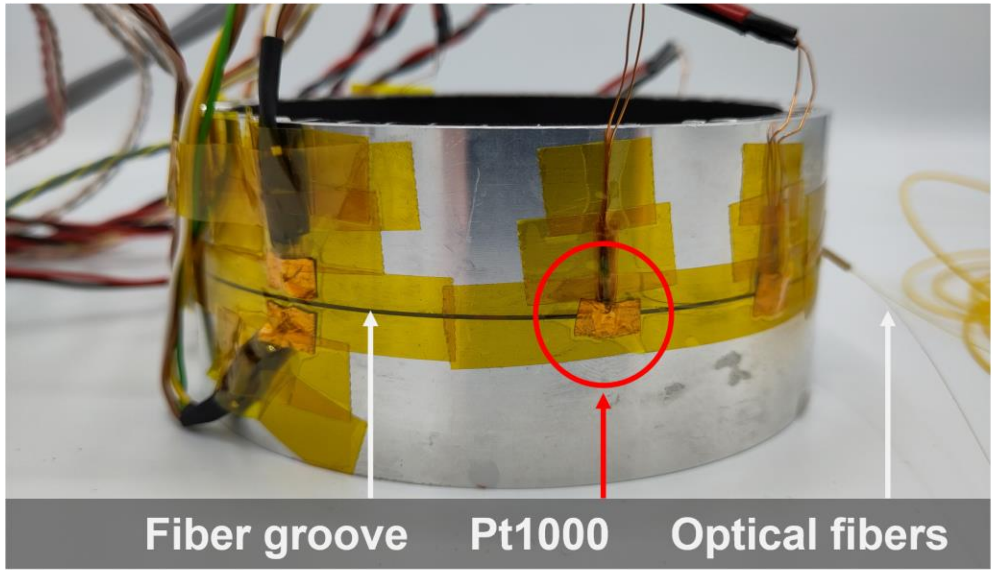
- Warm-up measurement (77 – 300 K, 18 h)







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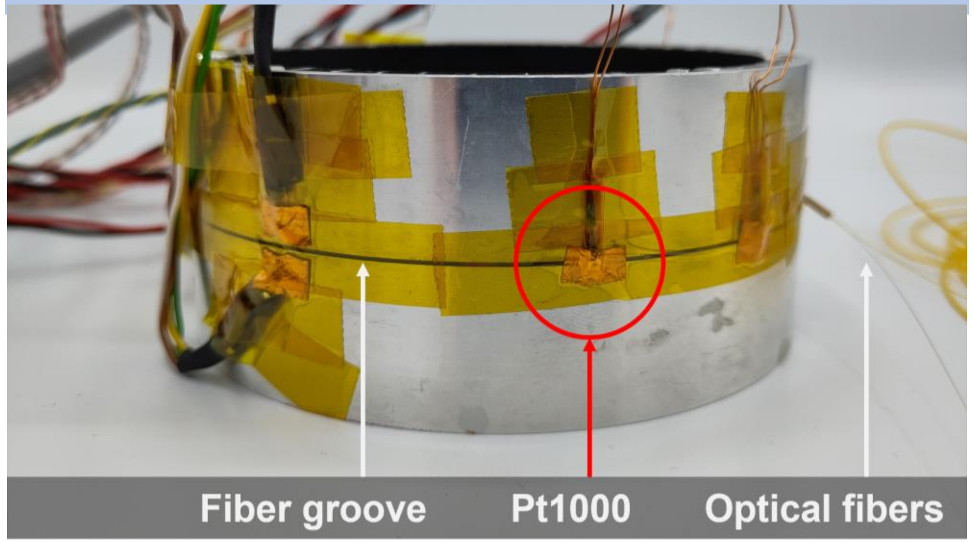
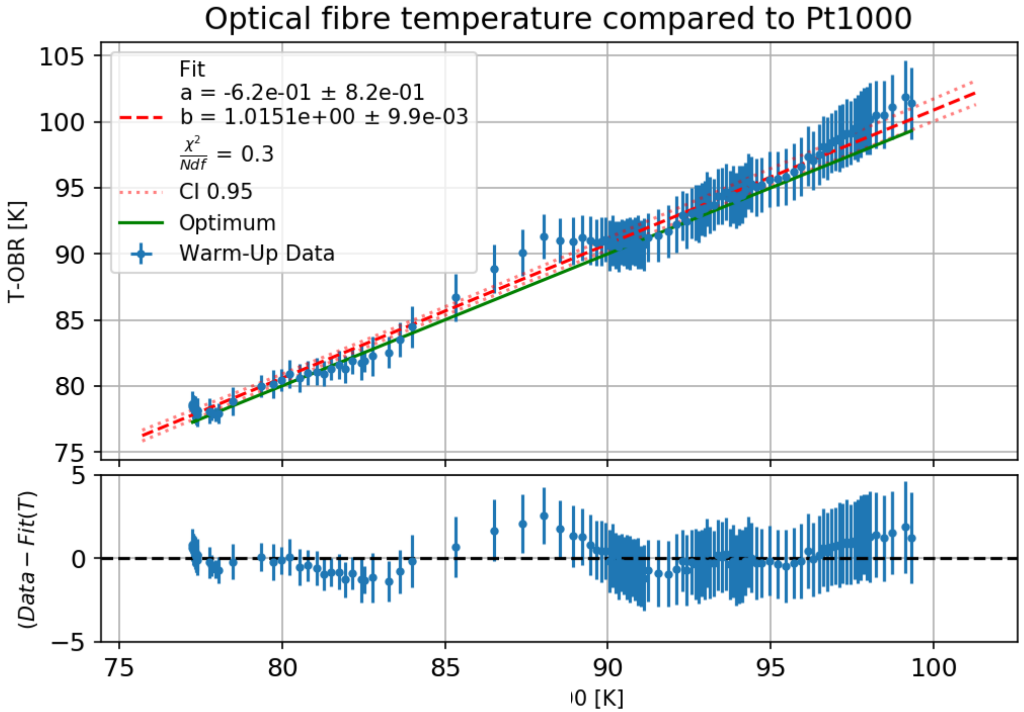
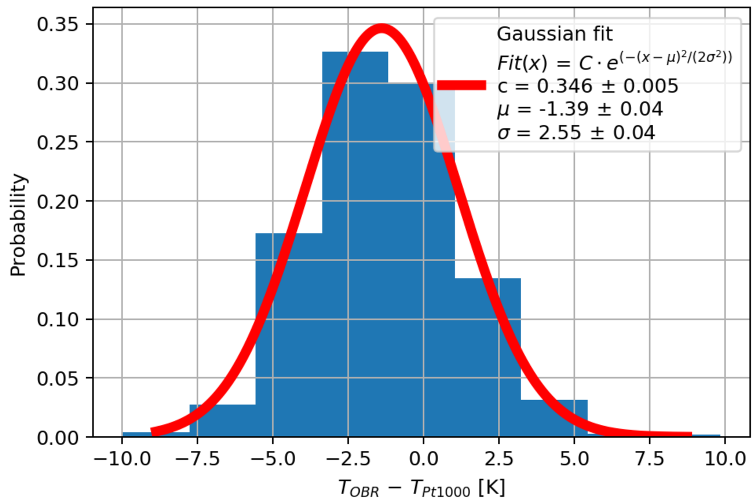






Result:
Temperature resolution:
2.6 K for 77 – 100 K

Summary

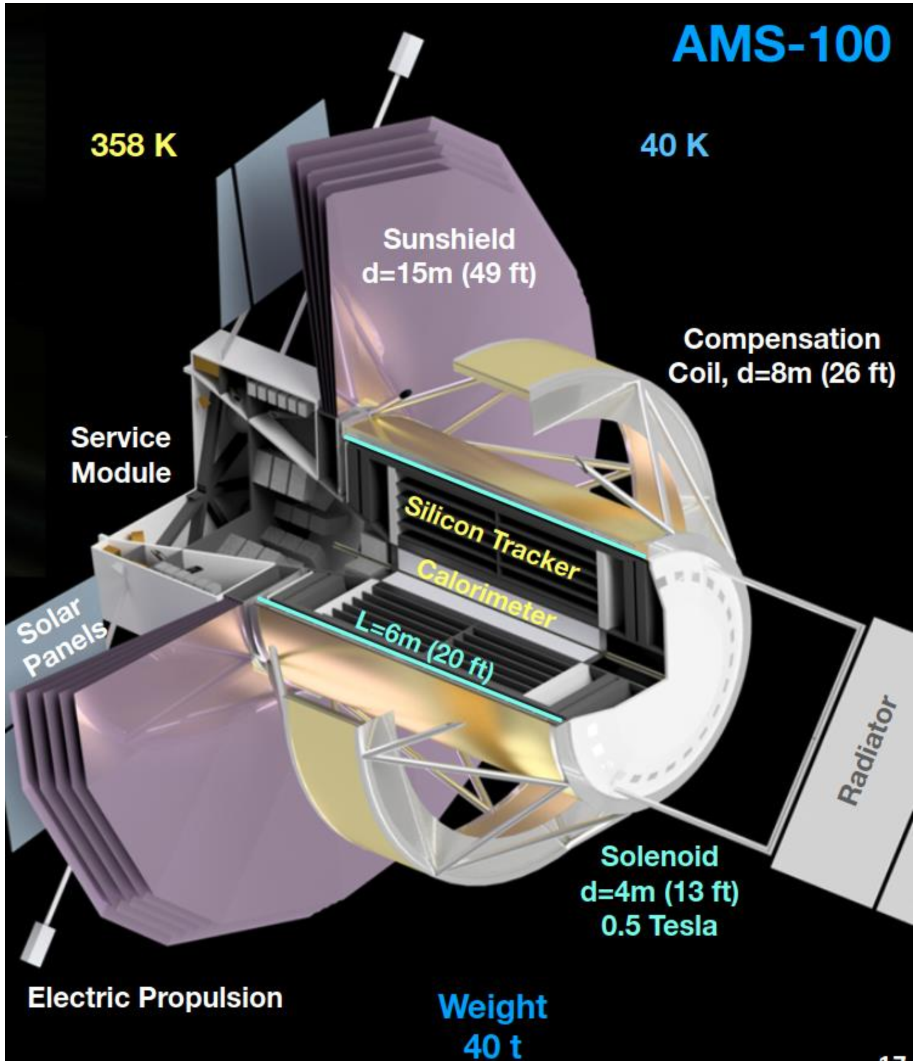
- OFDR works at 77 K with optical fibers integrated into a structure.
- Germanium-doped SM fibers are sensitive to temperature changes down to 77 K and probably down to 55 K.
- Local heat sources and temperature profiles can be measured, and the sensitivity is highly dependent on the substrate.
- Decoupling with two differently doped fibers is possible, allowing temperature measurement with 2.6 K uncertainty.

- Published paper:

  Girmen and Dittmar, 2023, "*Young's modulus independent determination of fibre-parameters for Rayleigh-based optical frequency domain reflectometry from cryogenic temperatures up to 353K*"

- Paper in preparation:

  "*New Measurement Principle for Decoupling Mechanical and Thermal Signals in OFDR Measurements for integrated Fibres*"



Thank you for listening!

Are there any questions?

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5. Figure based on information from https://lunainc.com/sites/default/assets/files/resource-library/OBR%20-%20Overview%20and%20Applications.pdf

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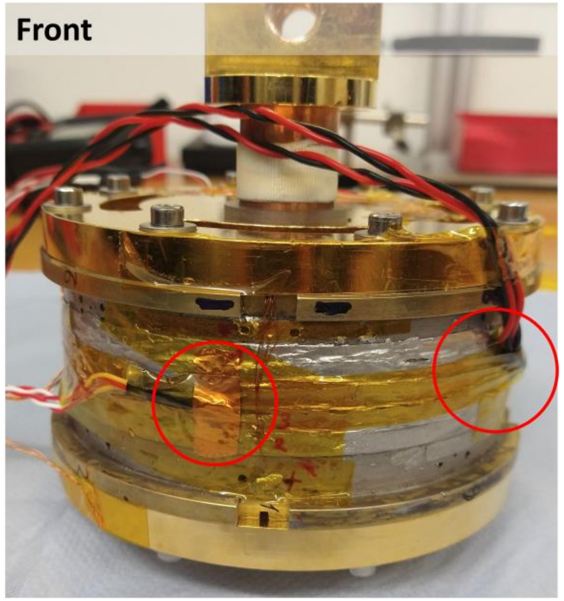
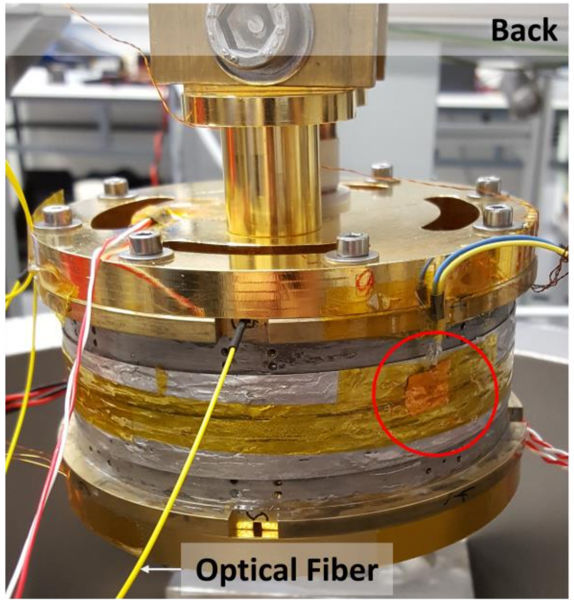
HTS – Test Coil: Measurement 2

Test-Setup and conditions:

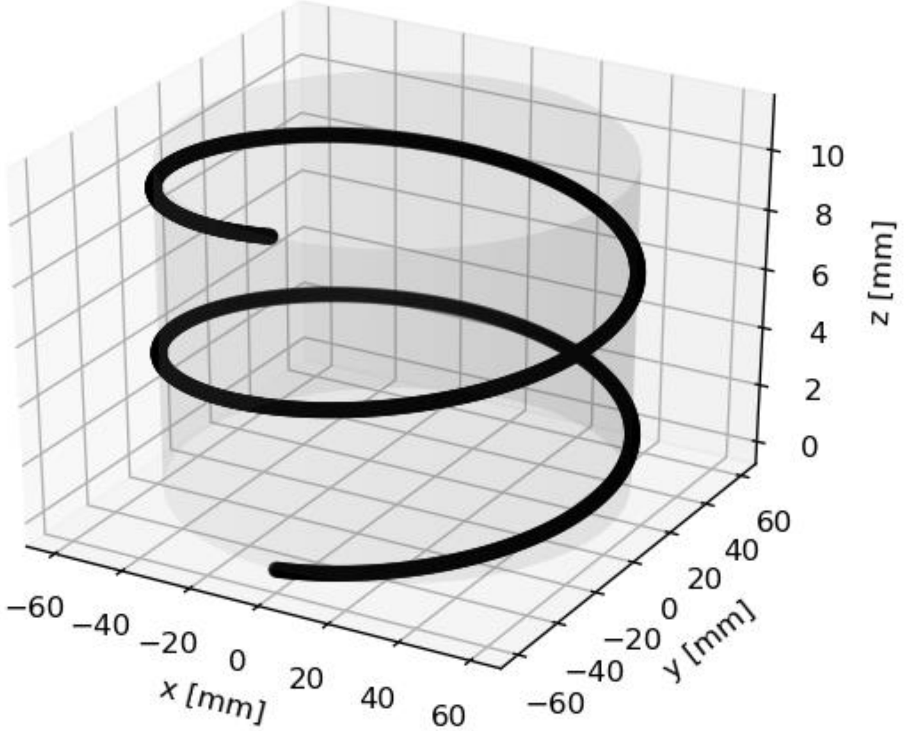
- HTS-Coil with 2.5 windings
- 10 cm high, 12 cm diameter
- 2 windings fiber under HTS-Tape glued in Aluminum
- Peek tubes for guiding the fibers into the structure





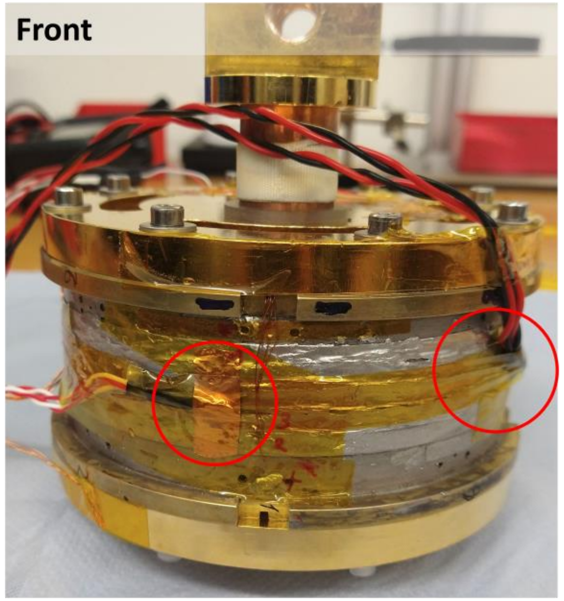
- 3 additional Pt1000 and Kapton tape

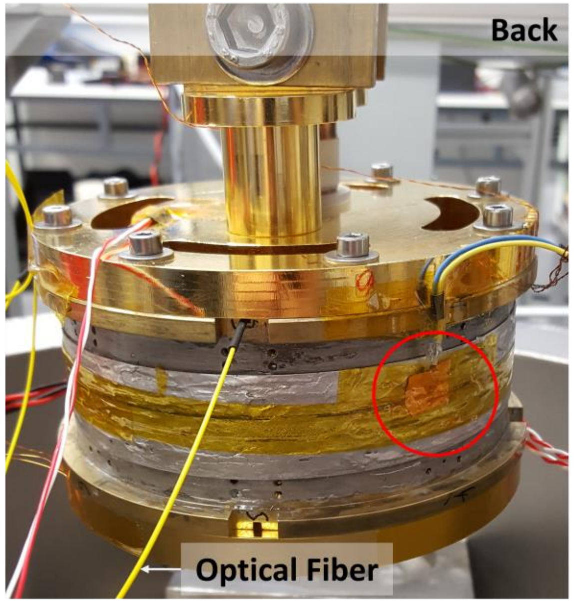
1200A applied current



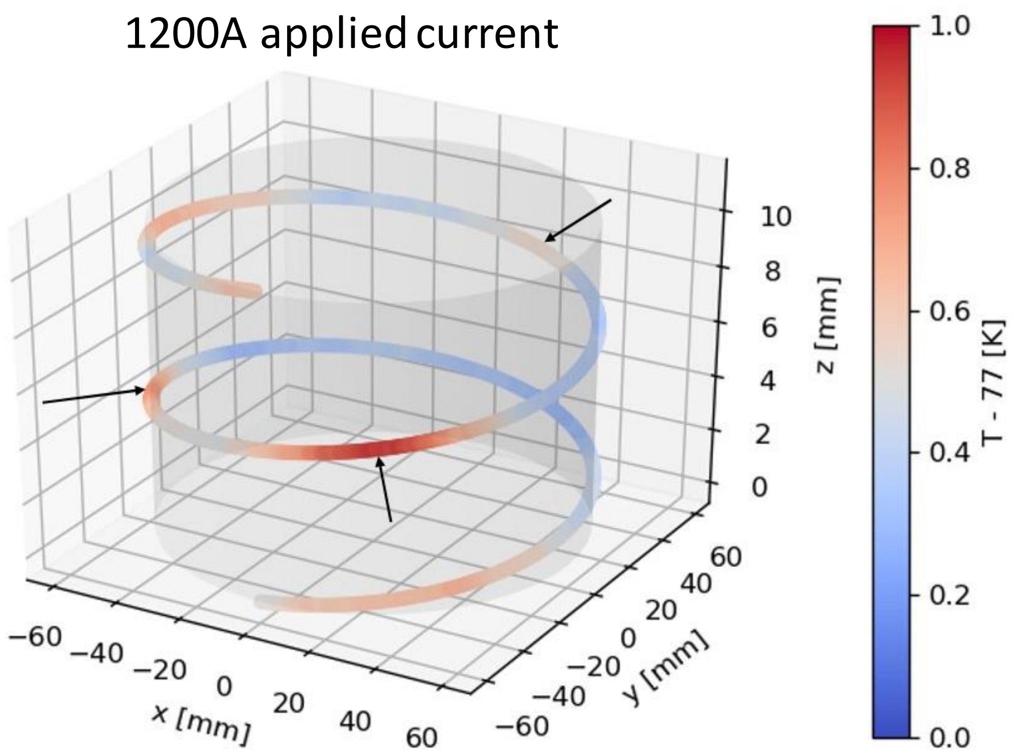
HTS – Test Coil: Measurement 2

Test-Setup and conditions:
- HTS-Coil with 2.5 windings
- 10 cm high, 12 cm diameter
- 2 windings fiber under HTS-Tape glued in Aluminum
- Peek tubes for guiding the fibers into the structure





- 3 additional Pt1000 and Kapton tape

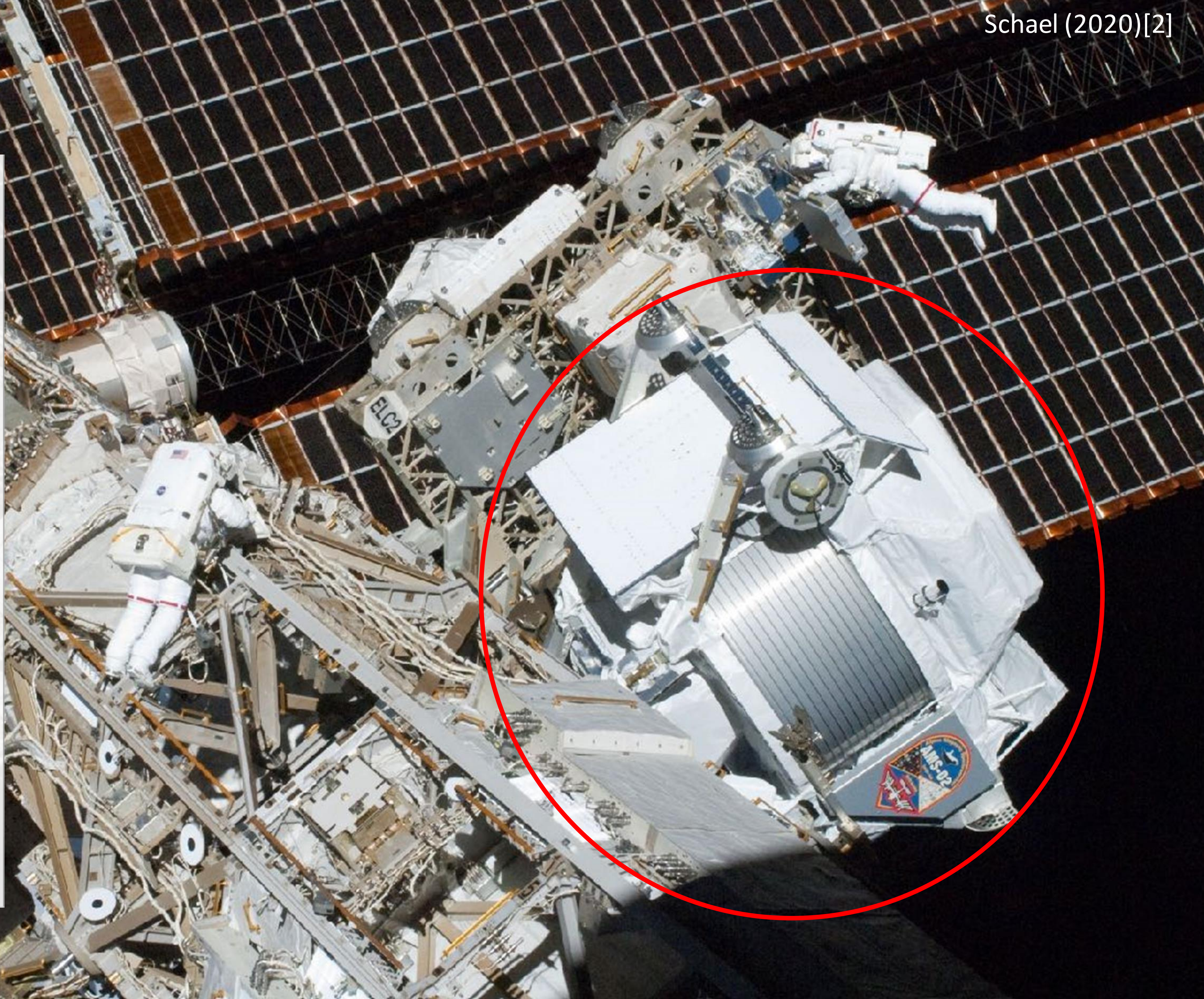


Results:
- Temperature profile with maximum of 0.8 K
  - Mean temperature higher as without Pt1000
- Pt1000 position detectable

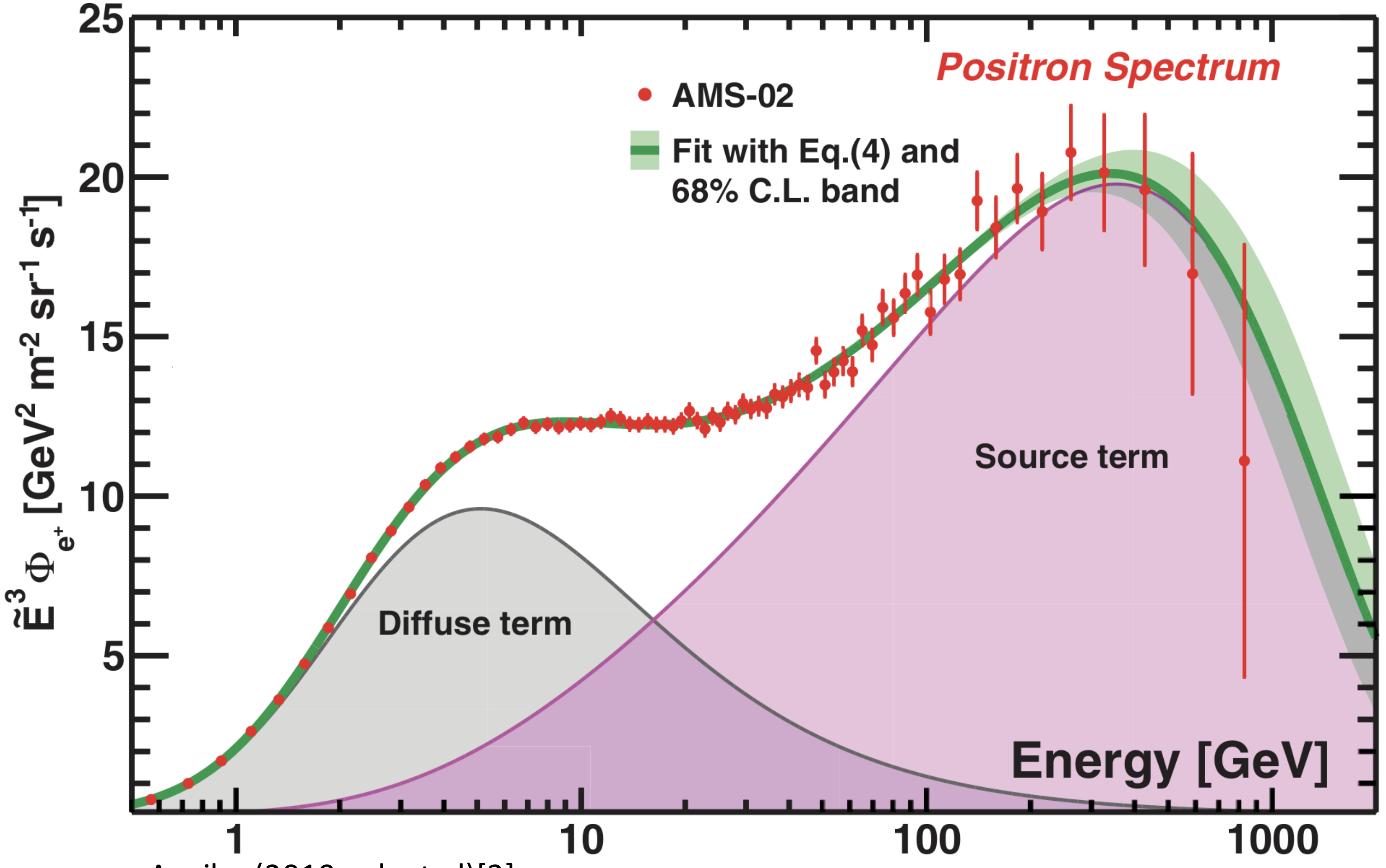
Schael (2020)[2]

AMS-02

- The only operating particle detector with a magnet in space
  - measure charge, mass and velocity of charged particles
    - *Rigidity (momentum per unit charge)*
  - Can therefore distinguish particles from antiparticles
  - Measures precisely cosmic ray fluxes with an accuracy of 2%-4% at 100 GV
- Installed on the ISS since 2011



Ex.: Positron Flux – Search for Dark Matter



Aguilar (2019, adapted)[3]

Diffuse term:
Low-energy part of the flux dominated by the positrons produced in the collisions of ordinary cosmic rays with the interstellar gas

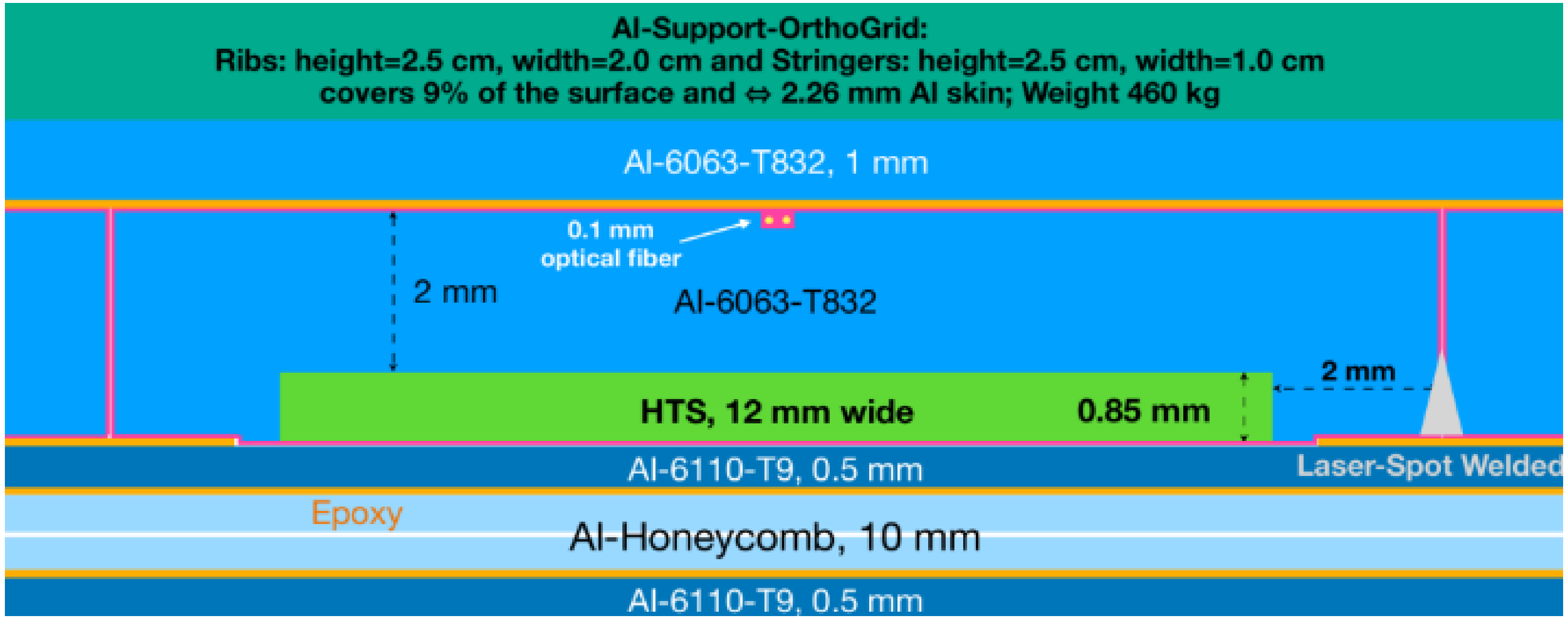
Source term:
Origin through pulsars or dark matter anihilation or an unknown source

High Temperature Superconducting Coil

Coil Parameters

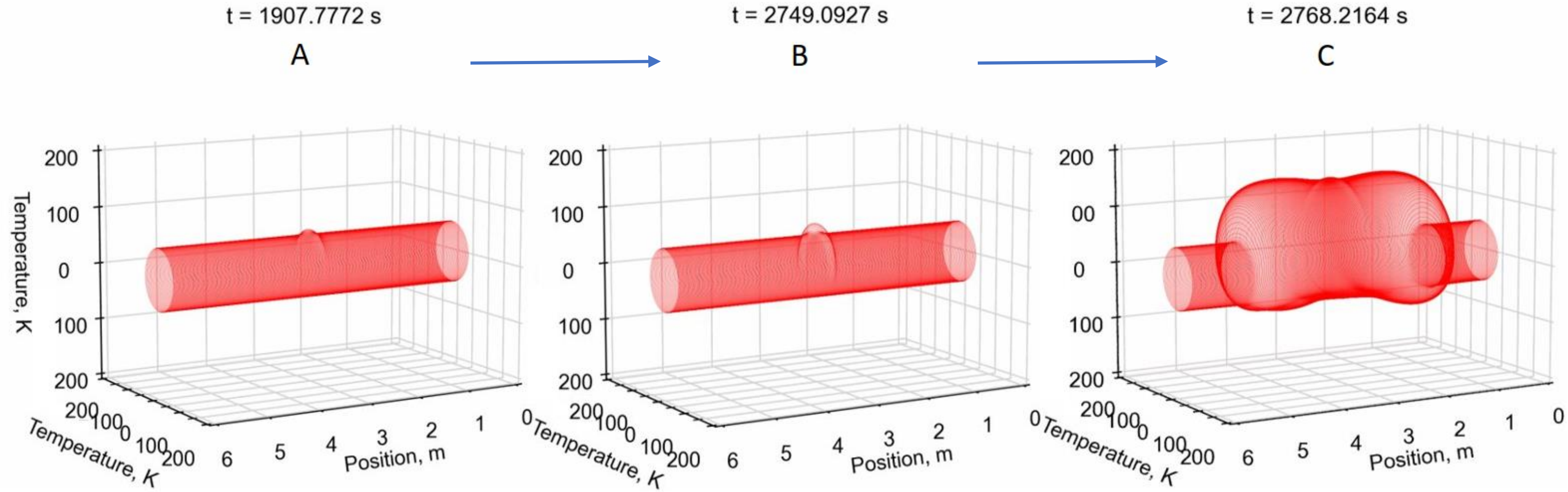
- Length of 6 m
- Diameter of 4 m
- Operating at 55 K
- Current 10 kA
- Layers of 12 mm HTS
- <u>Non-Isolated</u>
- <u>Aluminium U-Profile</u>

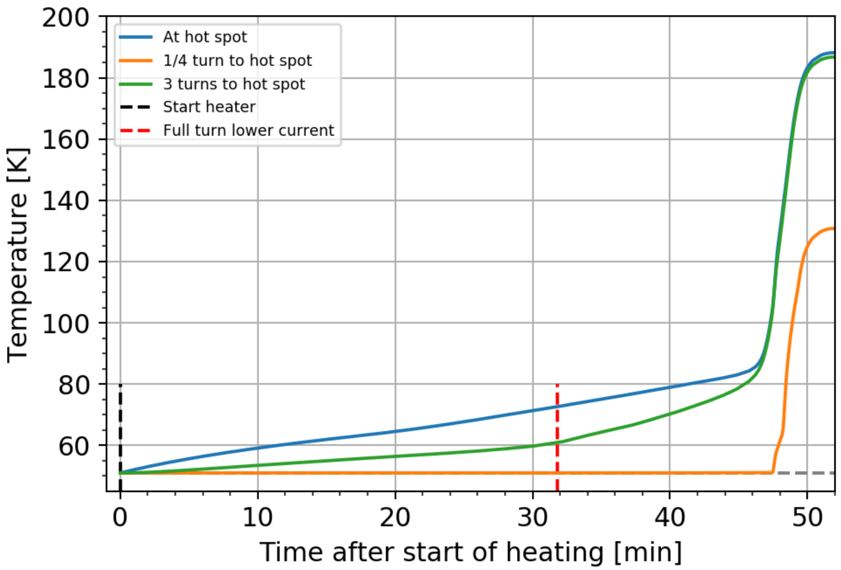
Highly protected against damage caused by quenching



Schael et al. (2022)[1]

HTS-Coil: Quench



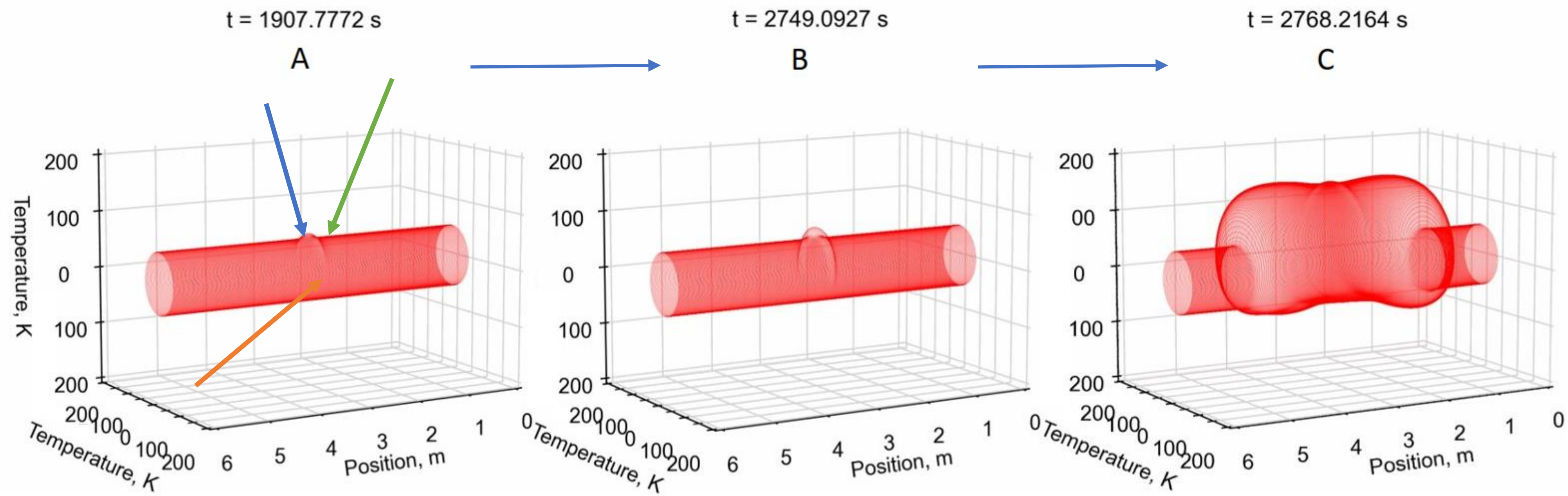


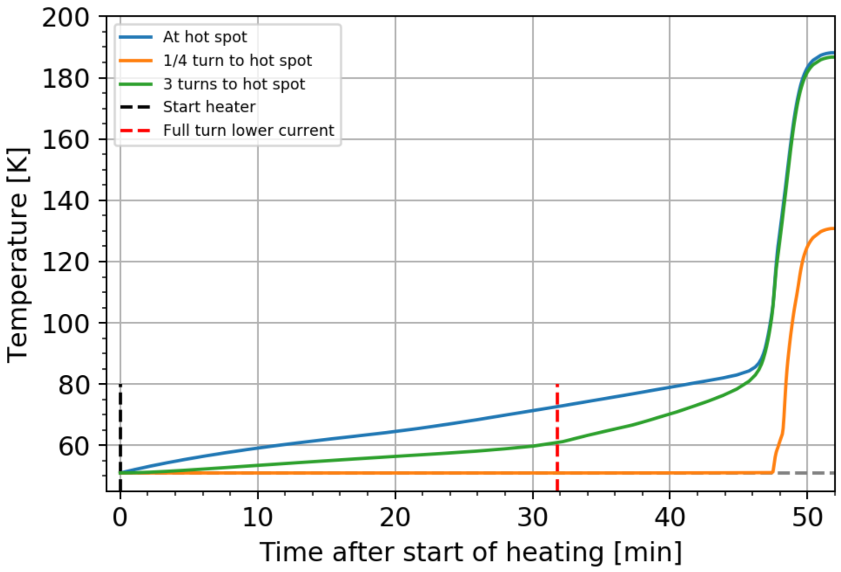
Thermal-electromagnetic quench simulation by Tim Mulder

Start Parameters:

- Current 10kA
- Windings: 376
- Layers: 18 layers HTS
- Temperature: 51K
- 200 W heater at three neighboring winding sections

HTS-Coil: Quench





Quench detection and structural monitoring are still required

- To prevent structural damage and thus damage to the HTS tapes
- For position stabilization (both coils have a dipole moment)

Schael et al. (2022)[1]

Quench of a non-isolated HTS-coil

Description:

Loss of superconductivity over the entire coil with conversion of the stored magnetic field energy into heat

Reasons:

Local or global heating:

- External source
  - Cooling failure, heat input due to damaged detectors or damaged sun shield
- Current passing through the aluminum structure
  - Due to an internal local failure of the superconductivity by e.g. mechanical damage

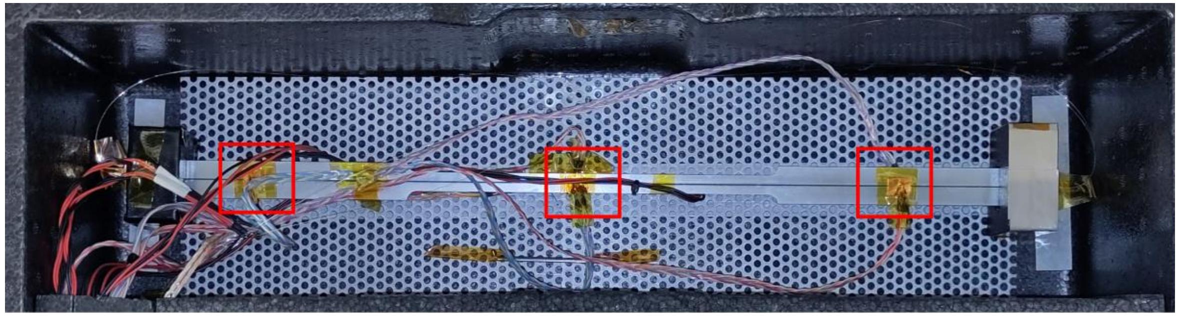
Process:

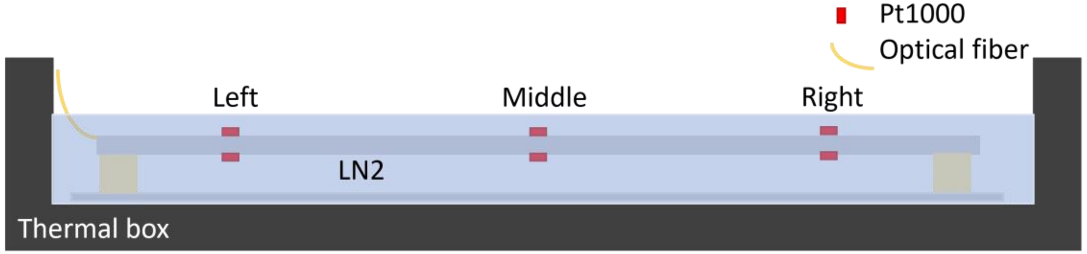
- High heat input or extensive damage to the superconductor
  - Quench within a few seconds
- Low heat input which is greater than the cooling can remove
  - If local, current can bypasses non-superconducting region through aluminium structure
  - Coil can remain stable
  - When the current skips a whole turn, the effective number of turns carrying current changes, which induces current and heat throughout the coil, causing the coil to quench.

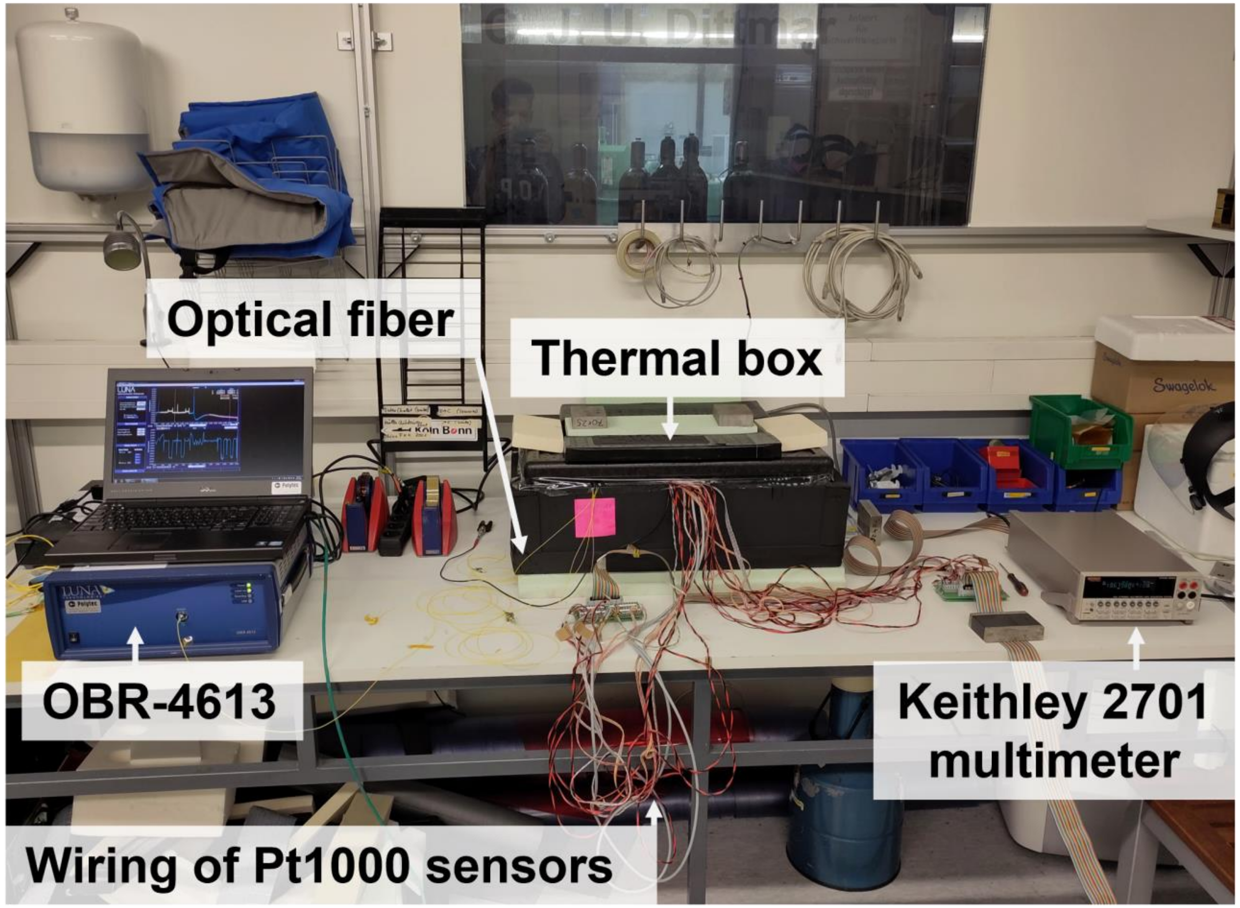
Temperature Sensitivity

Test-Setup and conditions

- Warm-up (77 – 290 K, 18h)
- Climate chamber, 6 steps (233 – 353 K)
- Mechanical part considered by determining the thermal expansion of Al-6060 with calibrated strain gauges and the determined strain sensitivity



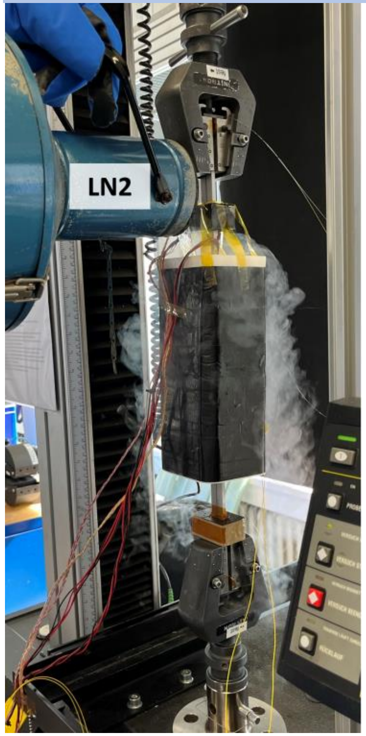


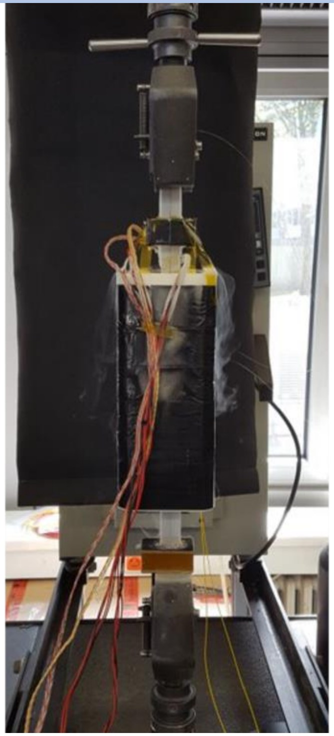


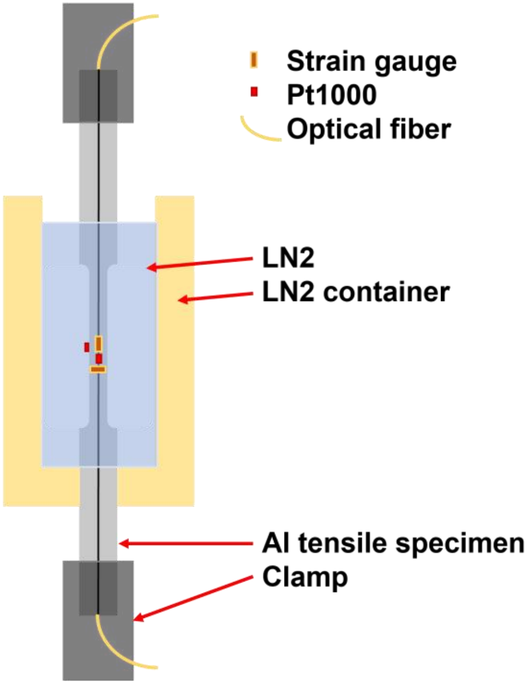
Strain Sensitivity

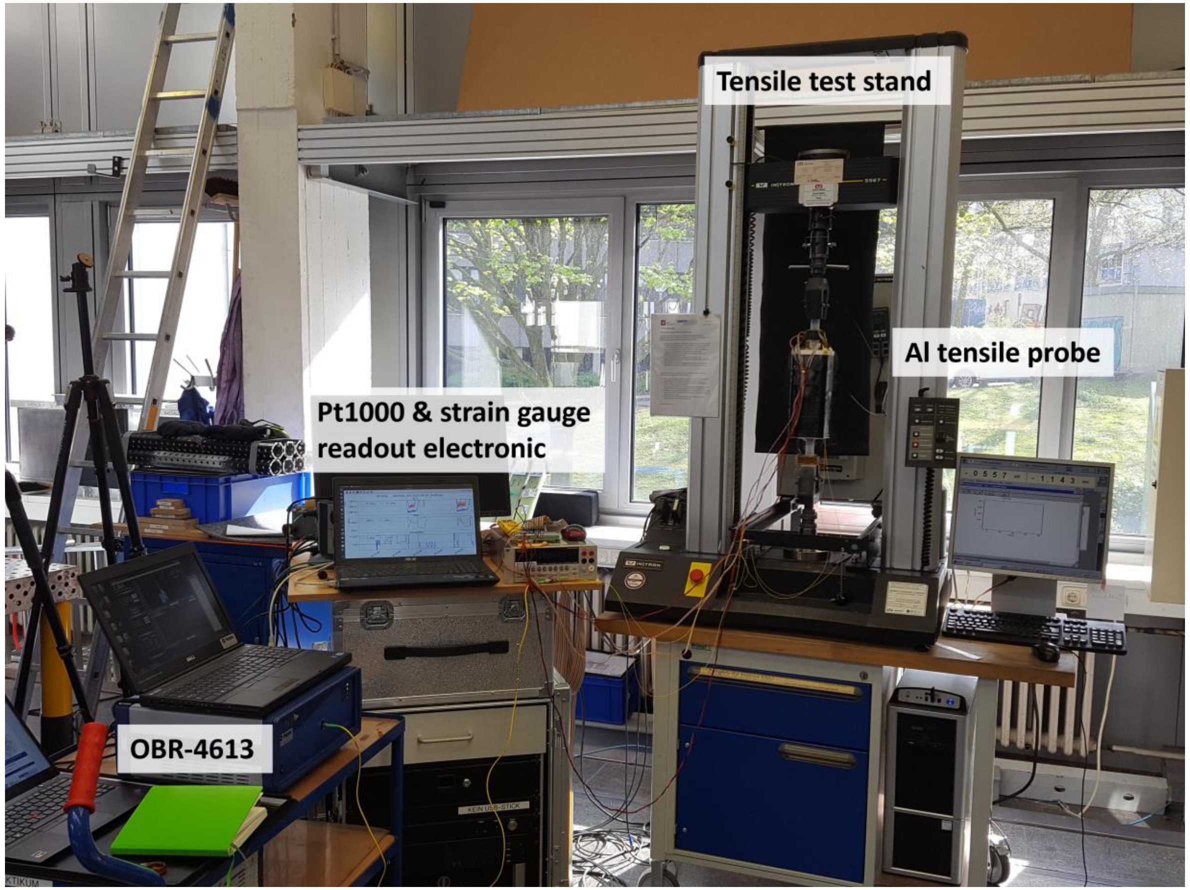
Test-Setup and conditions:

- Tensile test at 300 K and 77 K
- Two fibers glued in one groove





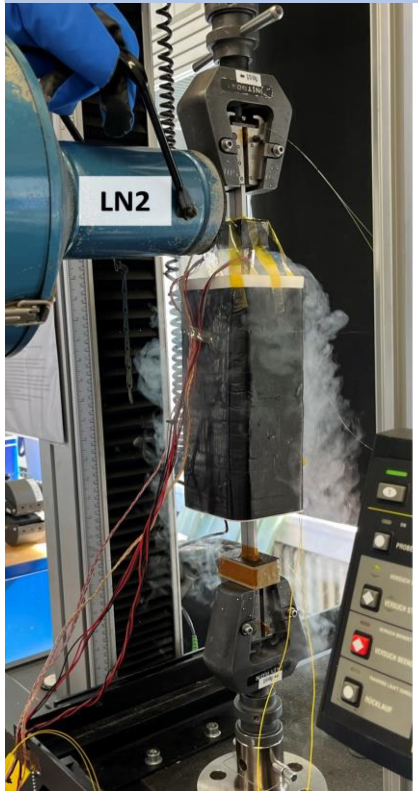


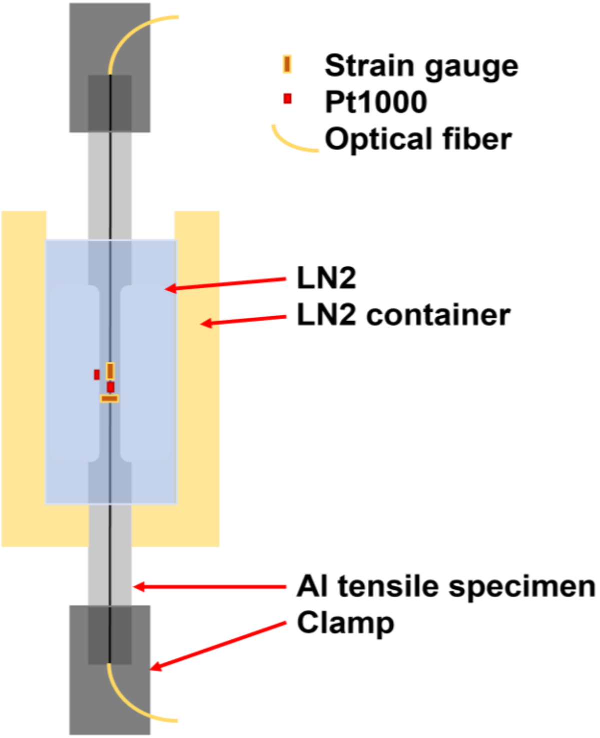


Strain Sensitivity

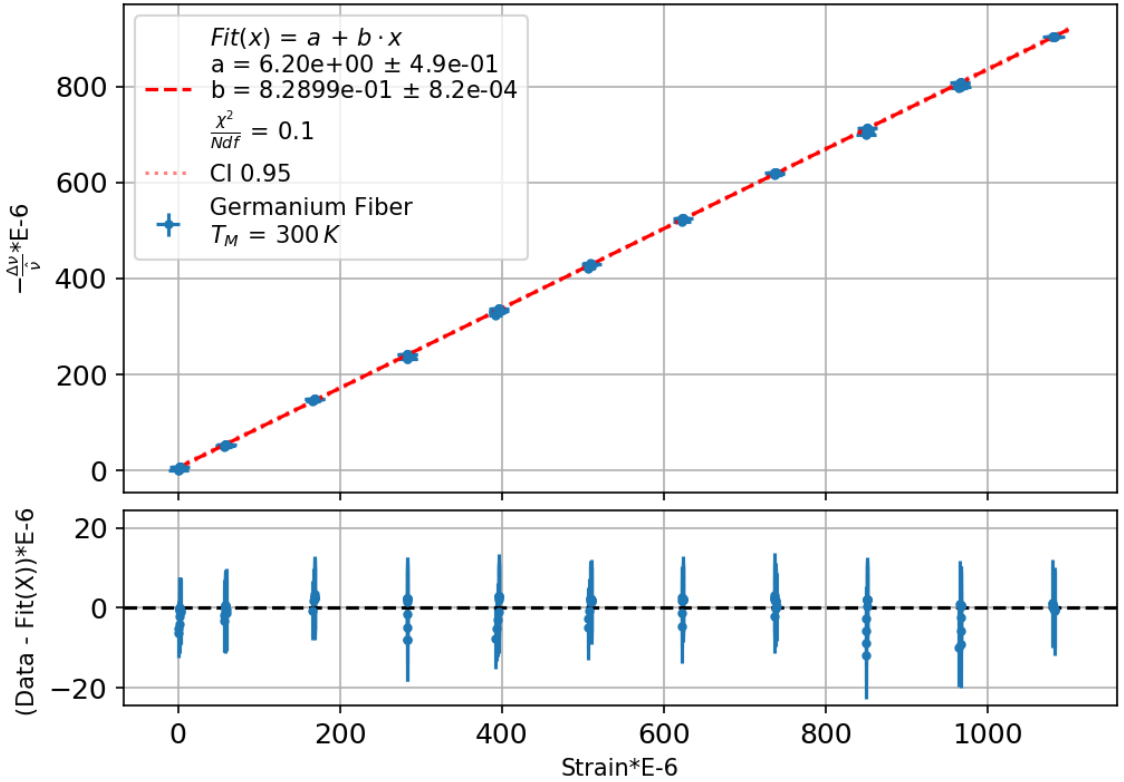
Test-Setup and conditions:

- Tensile test at 300 K and 77 K
- Two fibers glued in one groove





Tensile Test Germanium Fiber Data

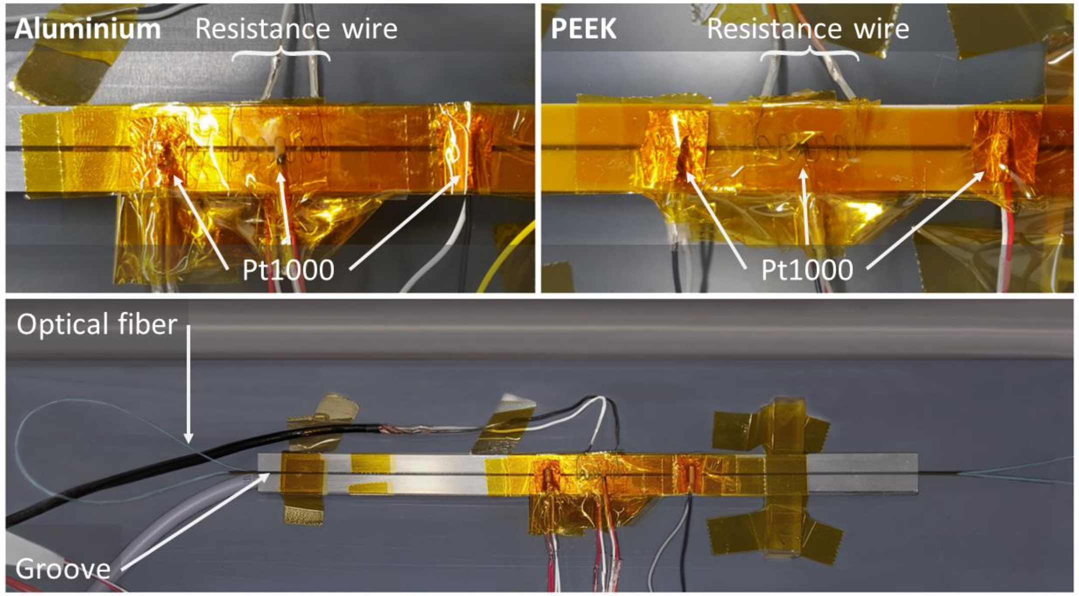


Fiber	T [K]	$K_\epsilon(T)$
Germanium	300	$0.8290 \pm 0.8 \cdot 10^{-3}$ (stat) $\pm 5.0 \cdot 10^{-3}$ (sys)
Germanium	77	$0.7907 \pm 0.7 \cdot 10^{-3}$ (stat) $\pm 4.7 \cdot 10^{-3}$ (sys)
Boron	300	$0.8279 \pm 0.8 \cdot 10^{-3}$ (stat) $\pm 5.0 \cdot 10^{-3}$ (sys)
Boron	77	$0.7915 \pm 1.2 \cdot 10^{-3}$ (stat) $\pm 4.7 \cdot 10^{-3}$ (sys)

Tests with local thermal signals

Test-Setup and conditions:

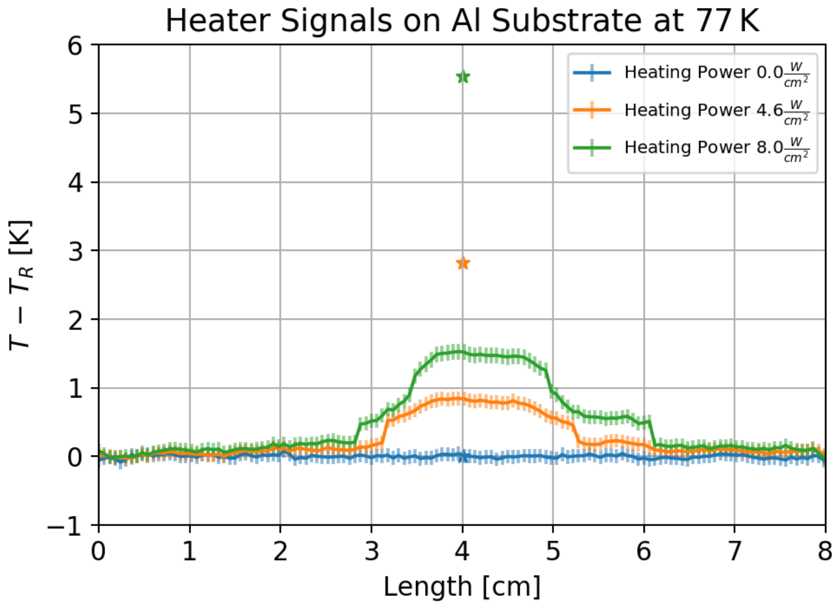
- Heater on linear Aluminum and Peek structure in LN2

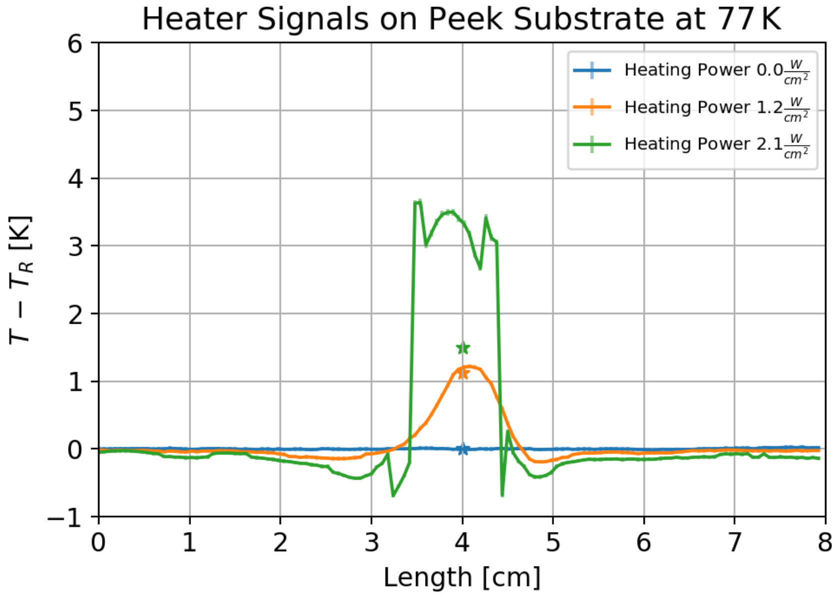


$$(T_M - T_R) = -\frac{\Delta\nu}{\hat{\nu}} \cdot \frac{1}{K_T(T_R) + K_\epsilon(T_R) \cdot CTE_{Substrate}}$$

Results:

- 1 cm external heating signals in LN2 can be measured
- Fiber temperature sensitivity depends on the CTE of the carrier material [CTE(PEEK) ≥ 2*CTE(Al)]

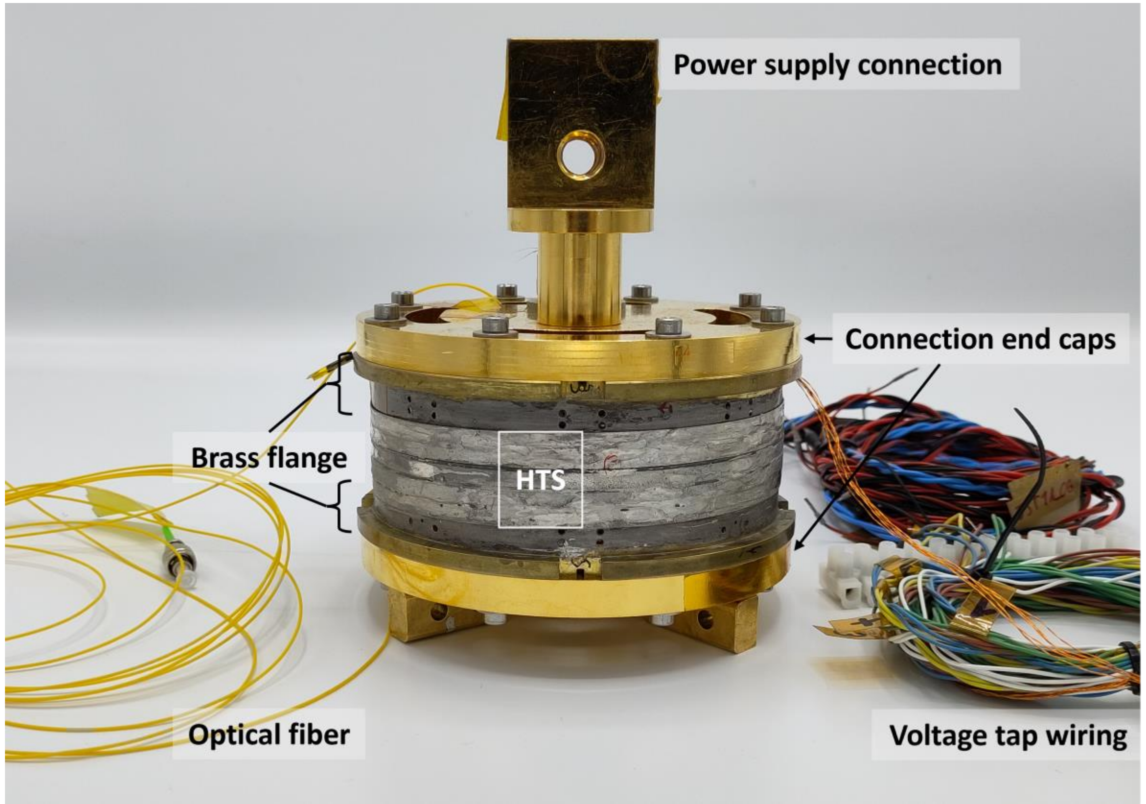


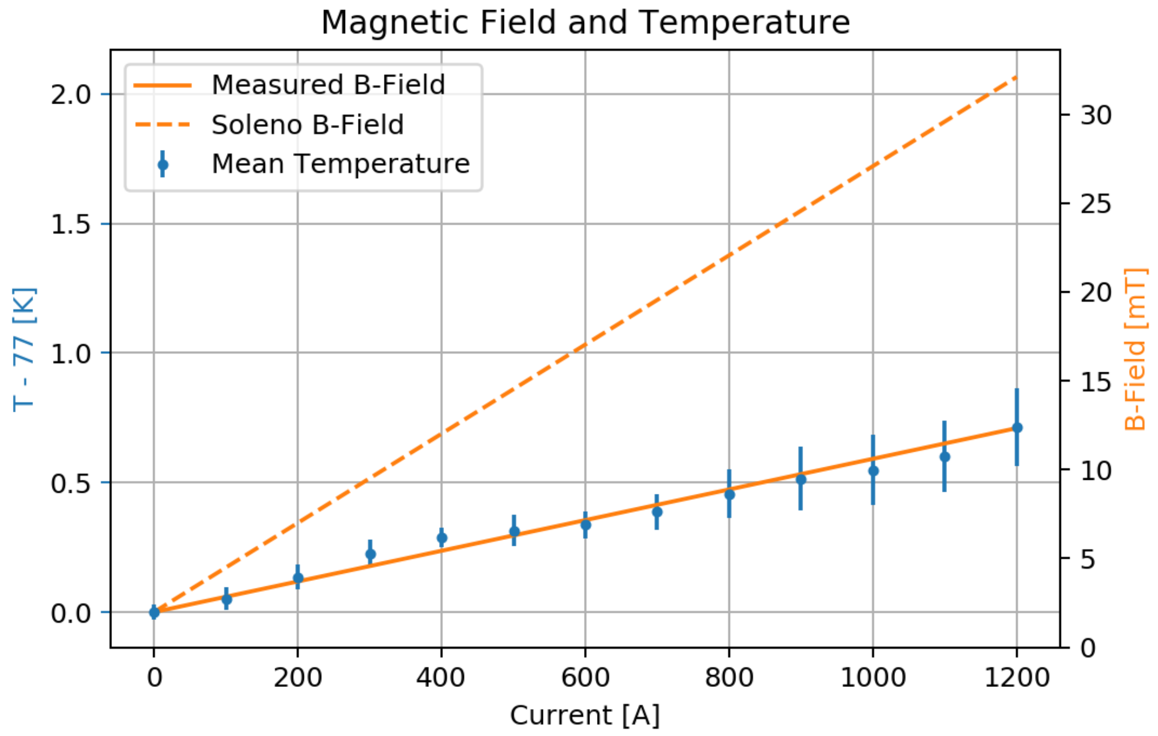


HTS – Test Coil

Test-Setup and conditions:

- HTS-Coil with 2.5 windings
- 10 cm high, 12 cm diameter
- 2 windings fiber under HTS-Tape glued in Aluminum
- Peek tubes for guiding the fibers into the structure

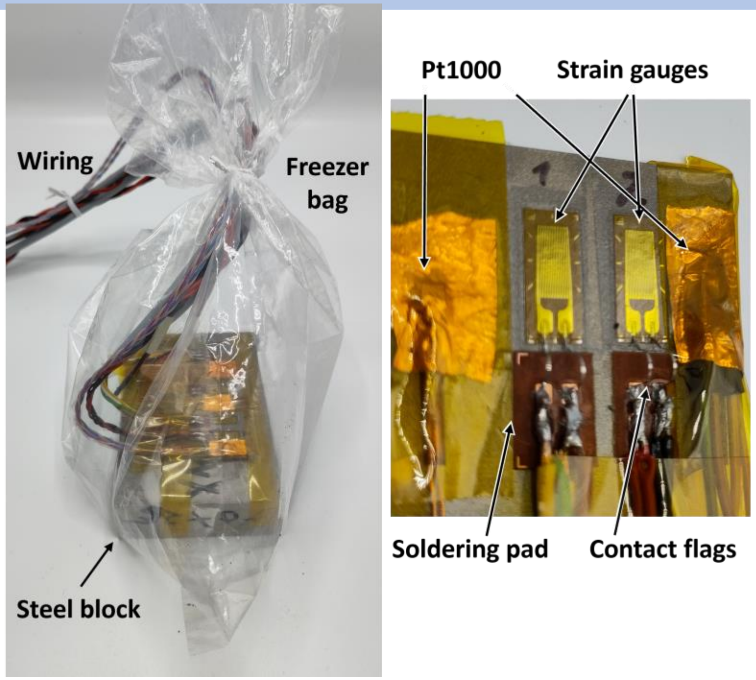


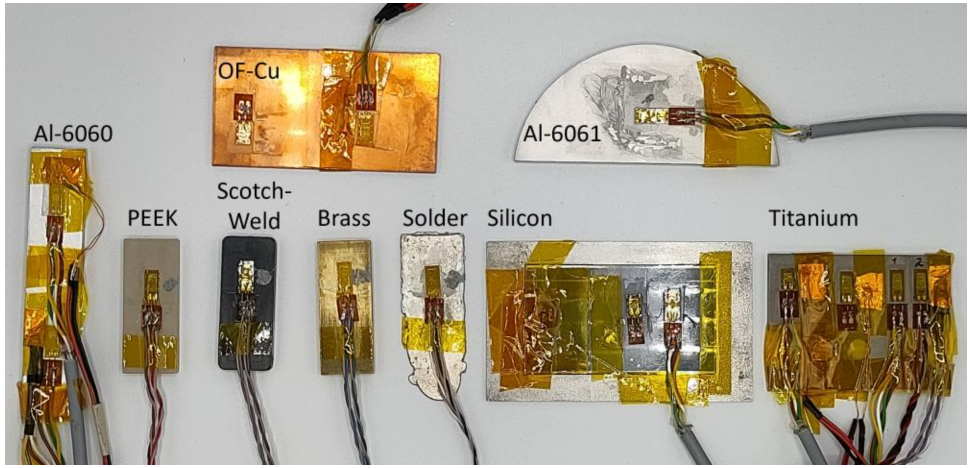


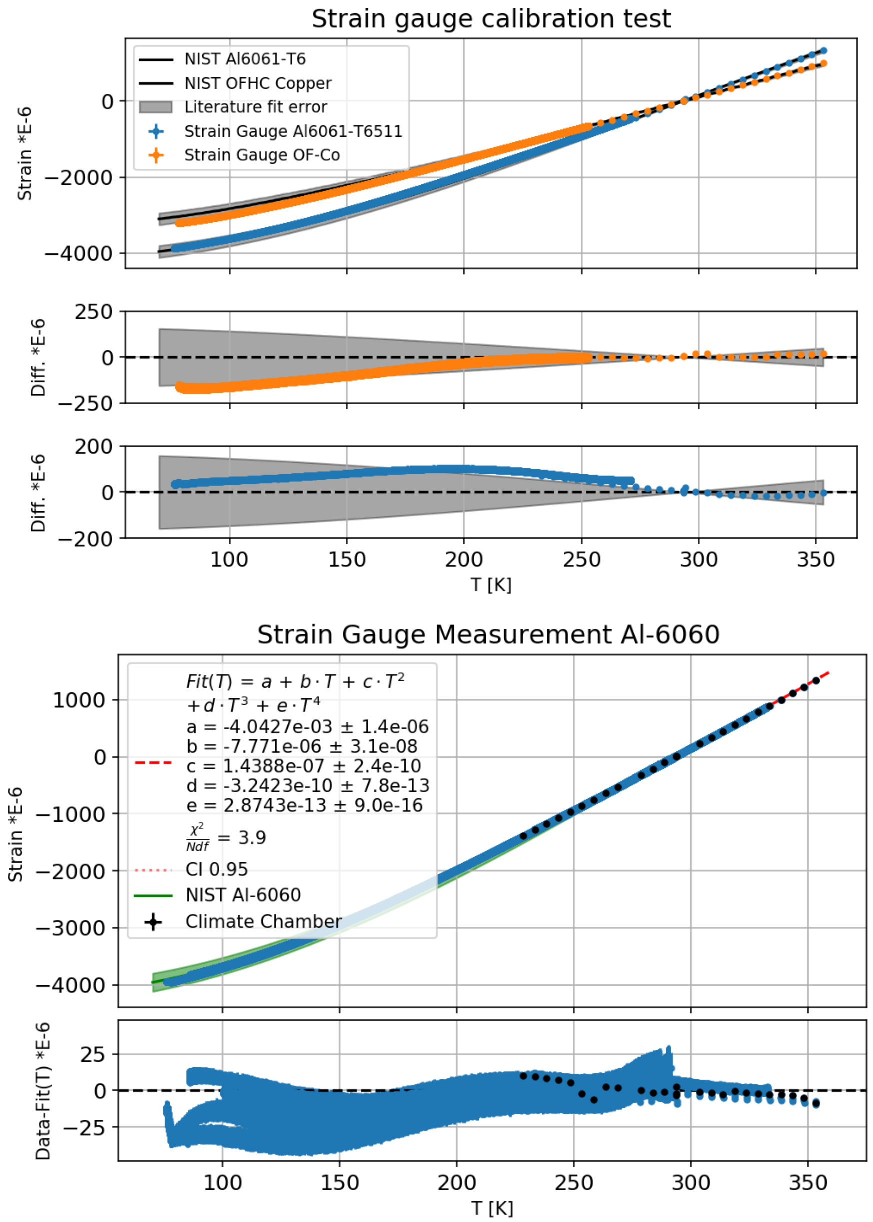
Results:

- Temperature profile with maximum of 0.7 K
  → Current flows through Aluminum structure
- Magnetic field measurements: current flow of 800 – 900 A through the Aluminum structure at 1200A applied current

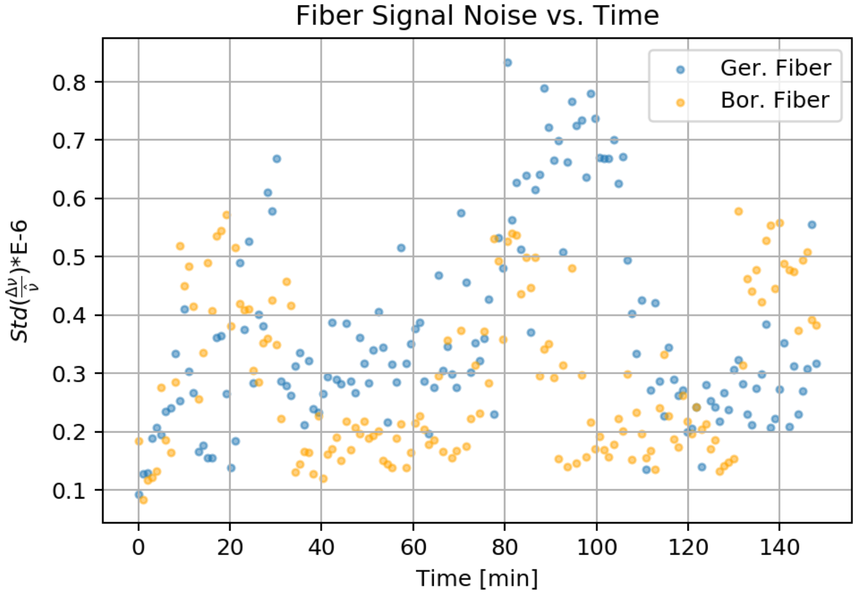
Strain Gauge Measurements



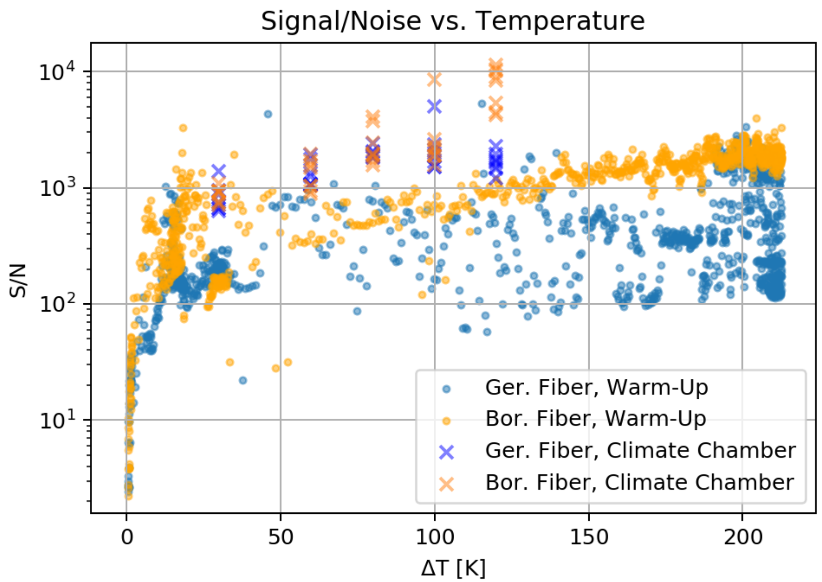


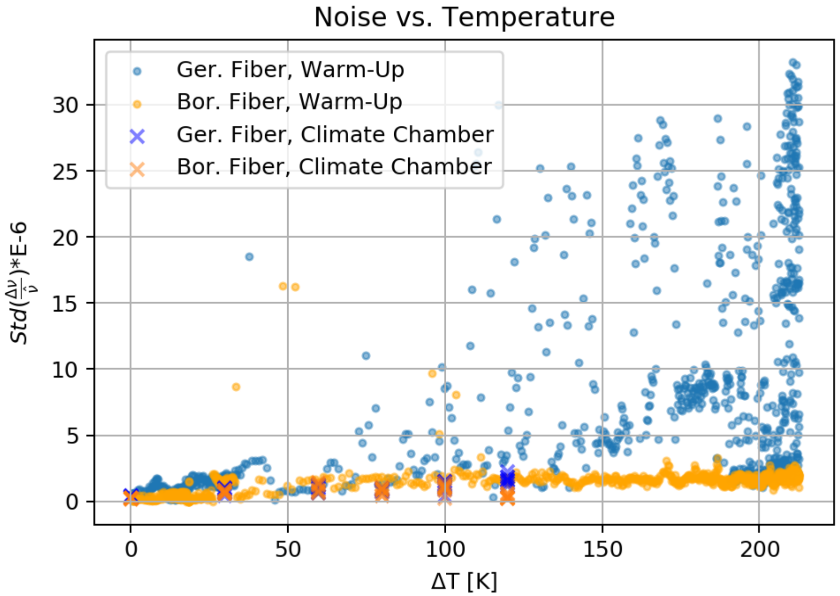


Resolution

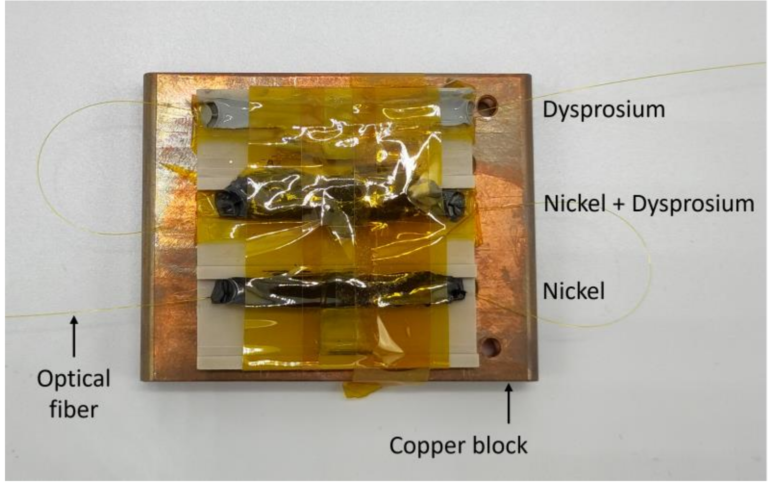


	Germanium	Boron
Noise	0.8	0.6



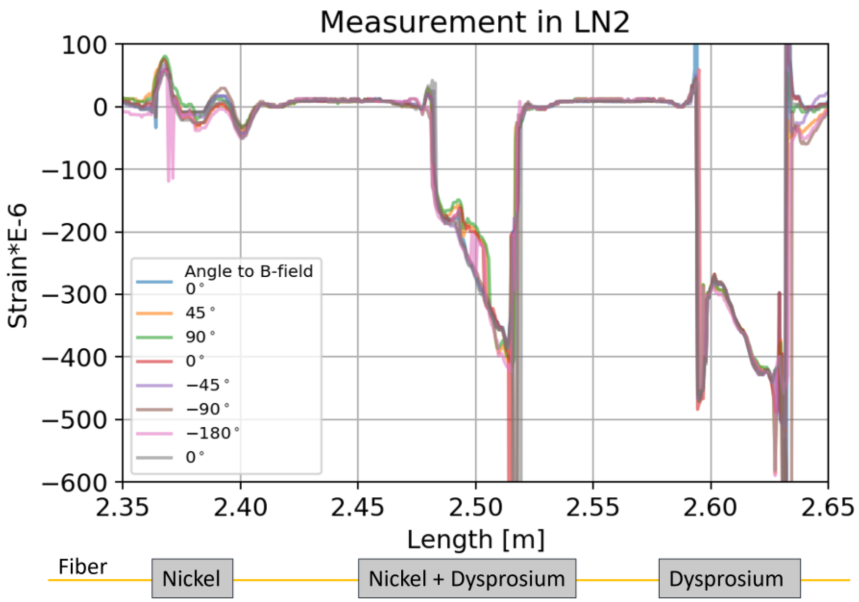


Magnetic Field Measurement

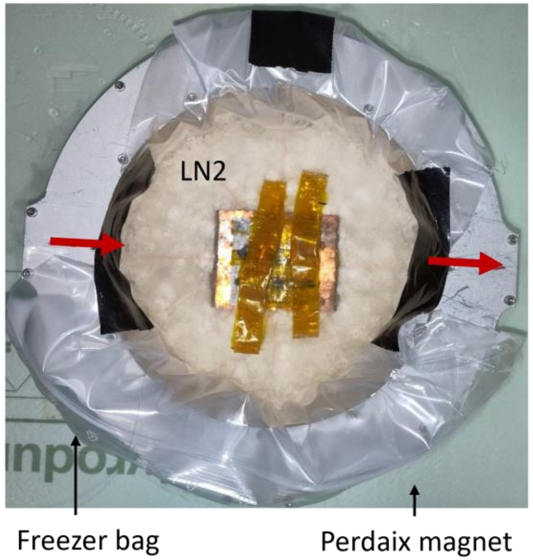


Magnetostriction

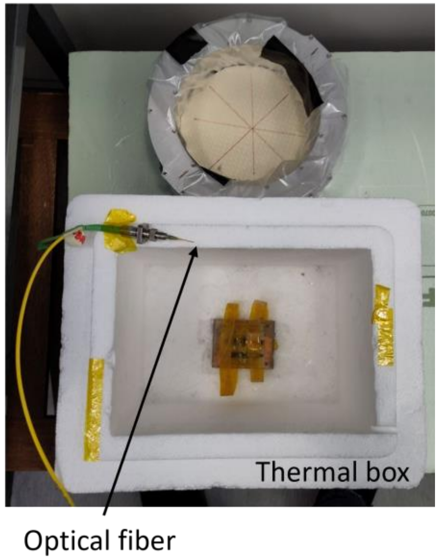
- Mechanical deformation in external magnetic field
- Dysprosium has a high mechanical deformation below 180K
- Epoxy dysprosium-powder mixture should have similar properties
- A bonded fiber should therefore be sensitive to magnetic fields at 77K
- 3 samples with nickel powder (test powder), dysprosium + nickel and dysprosium
- Measurement with and without homogeneous magnetic field
- Rotation in the magnetic field

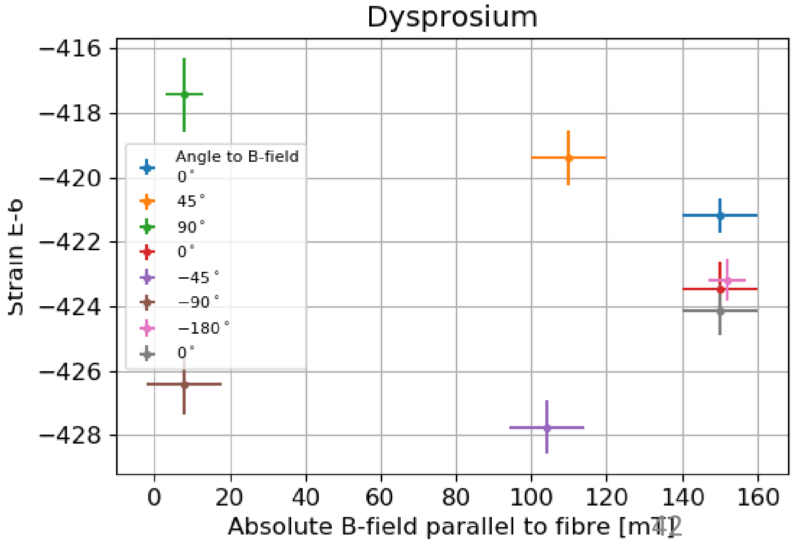


Measurement with 150 mT B Field in LN2

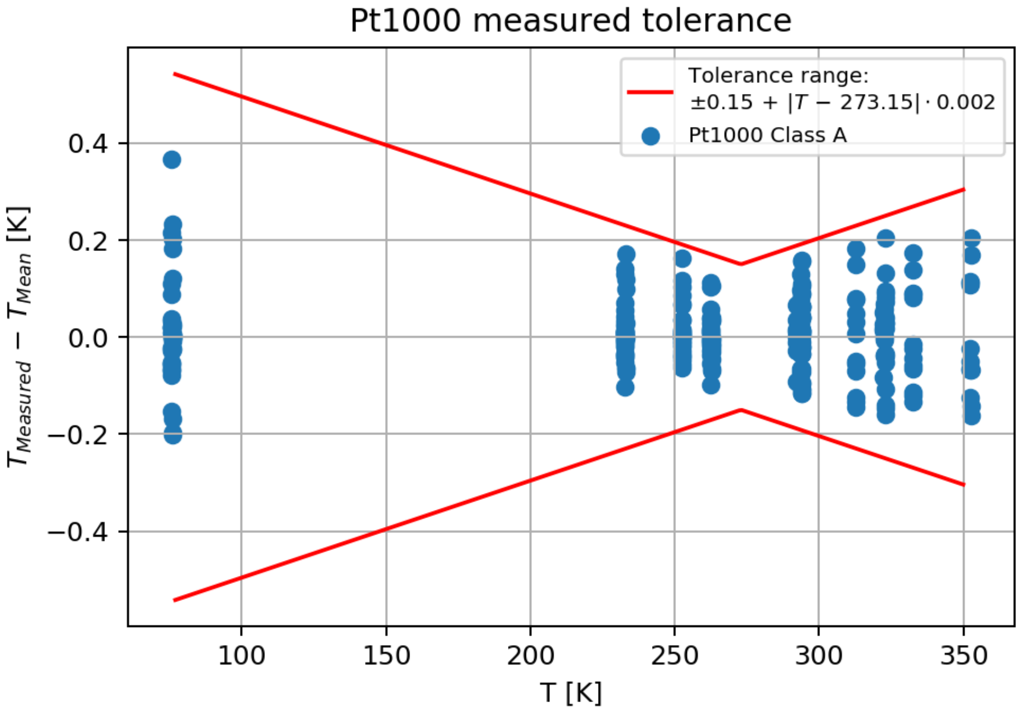


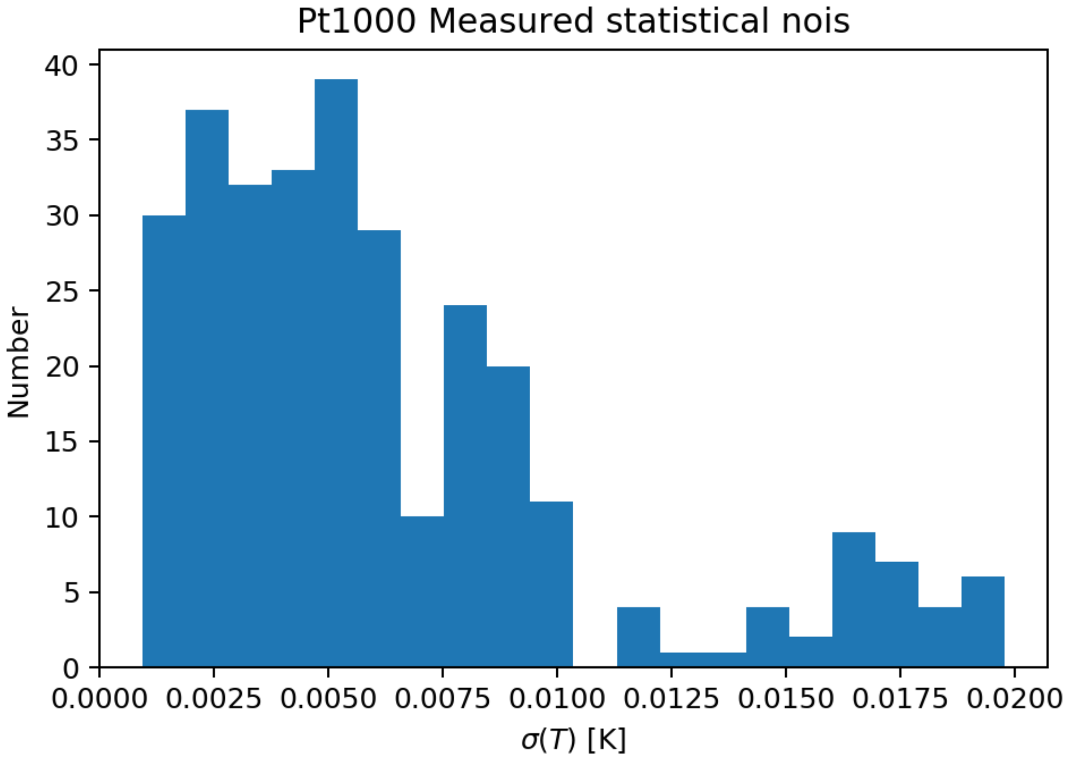
Measurement in LN2



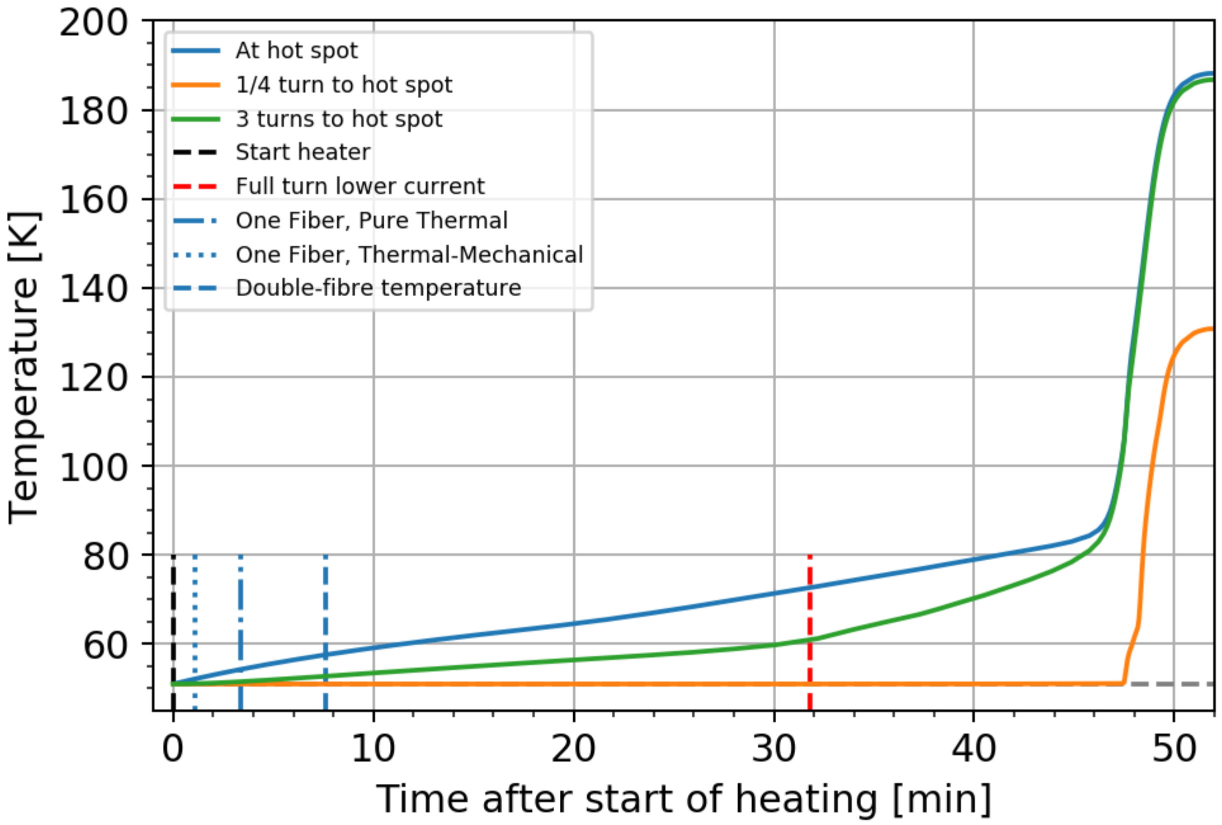


Pt1000 Temperature Sensor





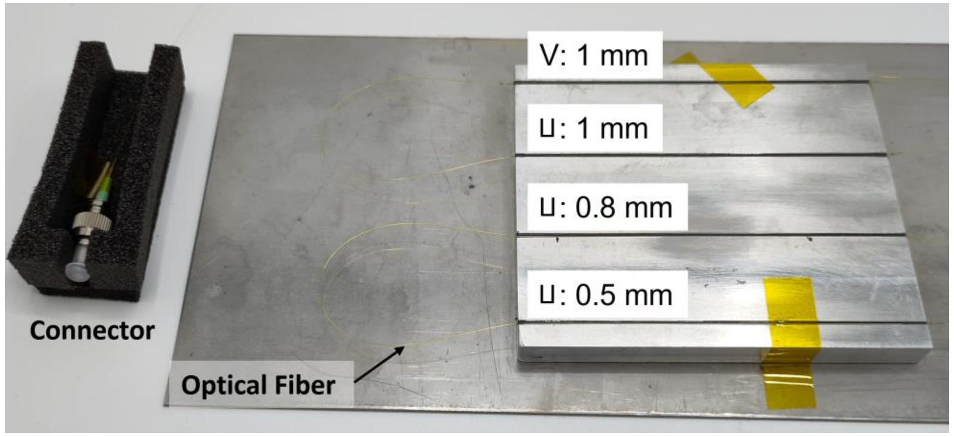
Back to the application

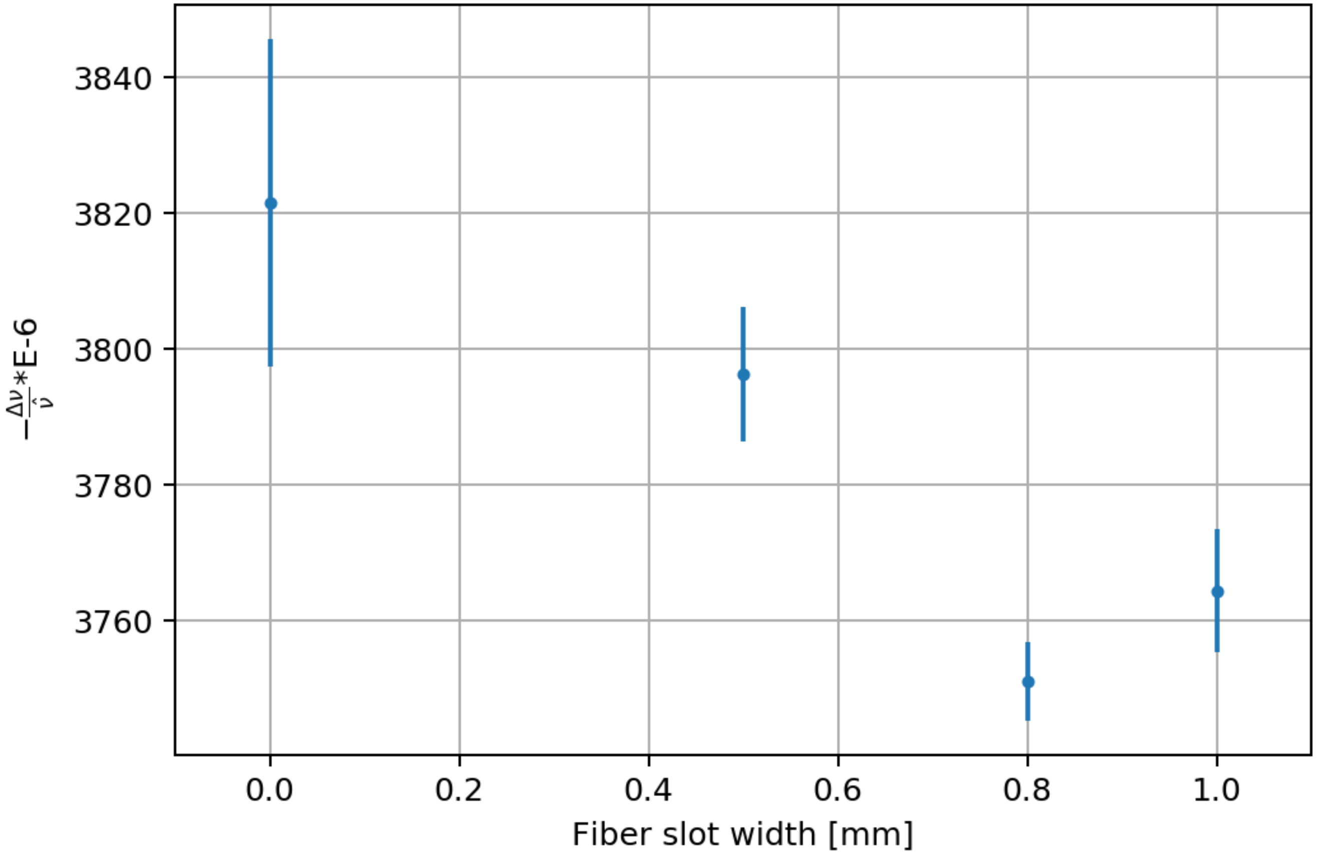


Conclusion:

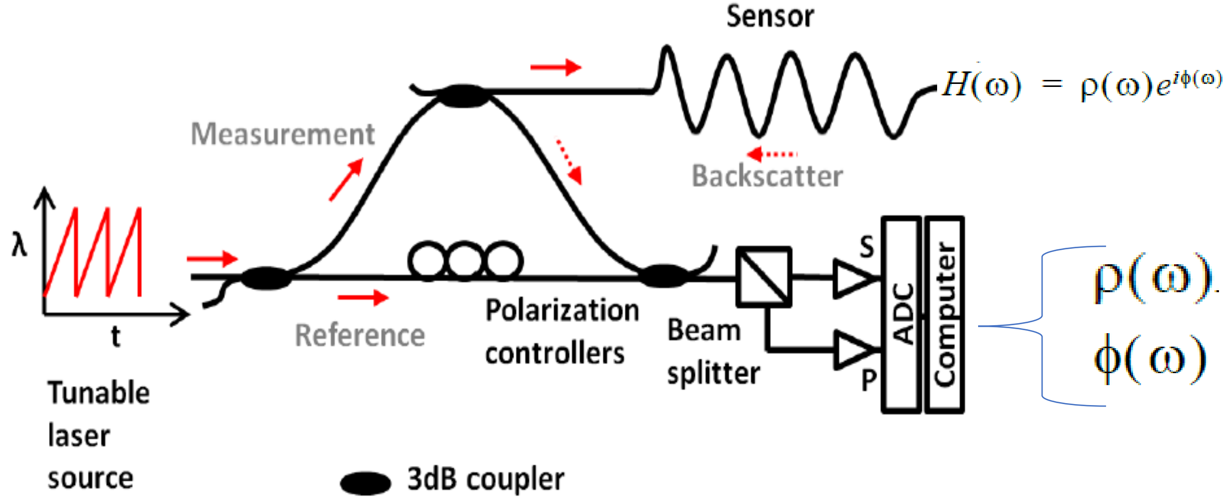
Structure monitoring and quench protection is possible with the OFDR and multiple fibers.

Groove Width





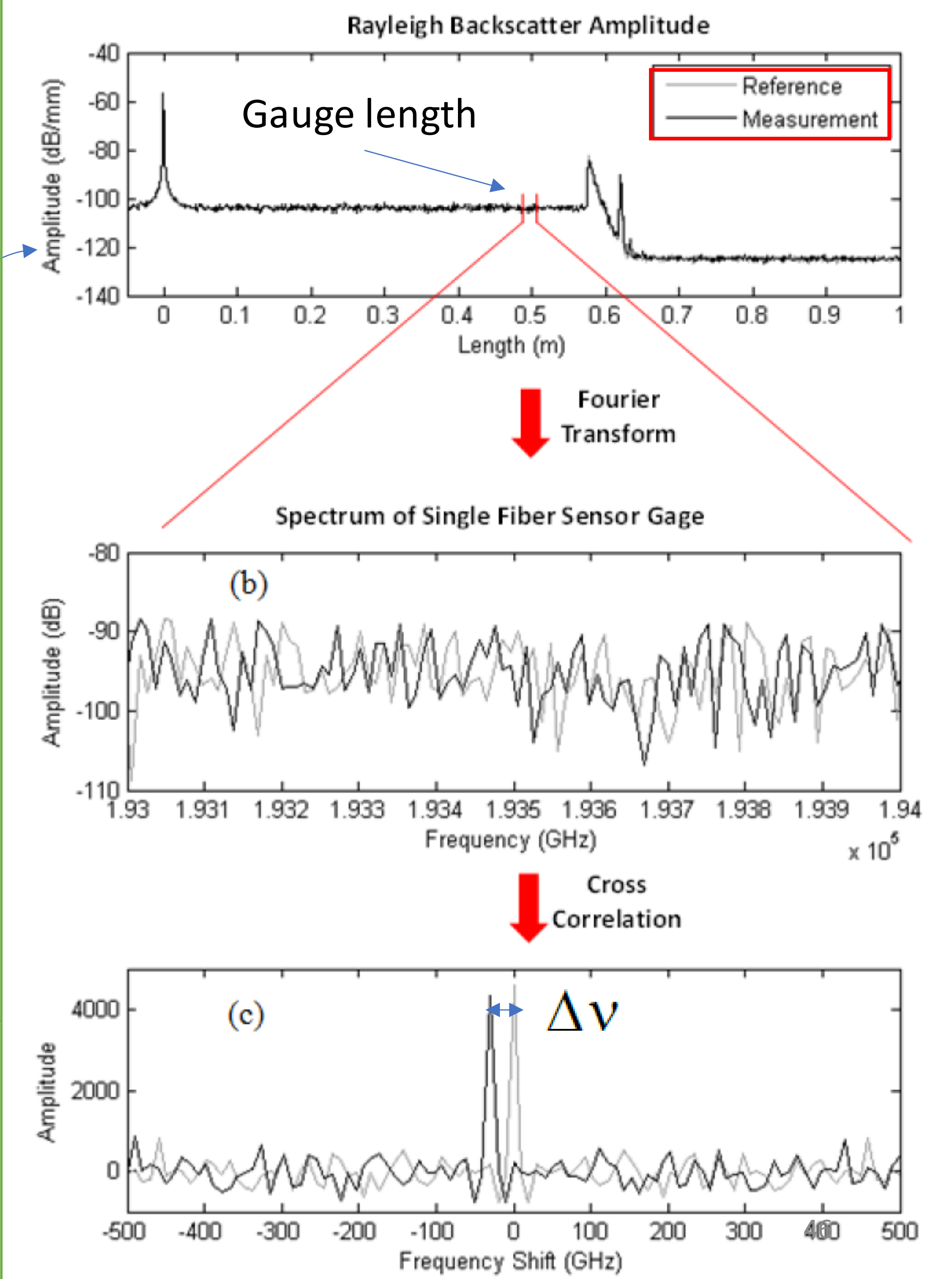
OFDR Analysis



$$\tilde{h}_j = FFT\{H(\omega)\}_j$$

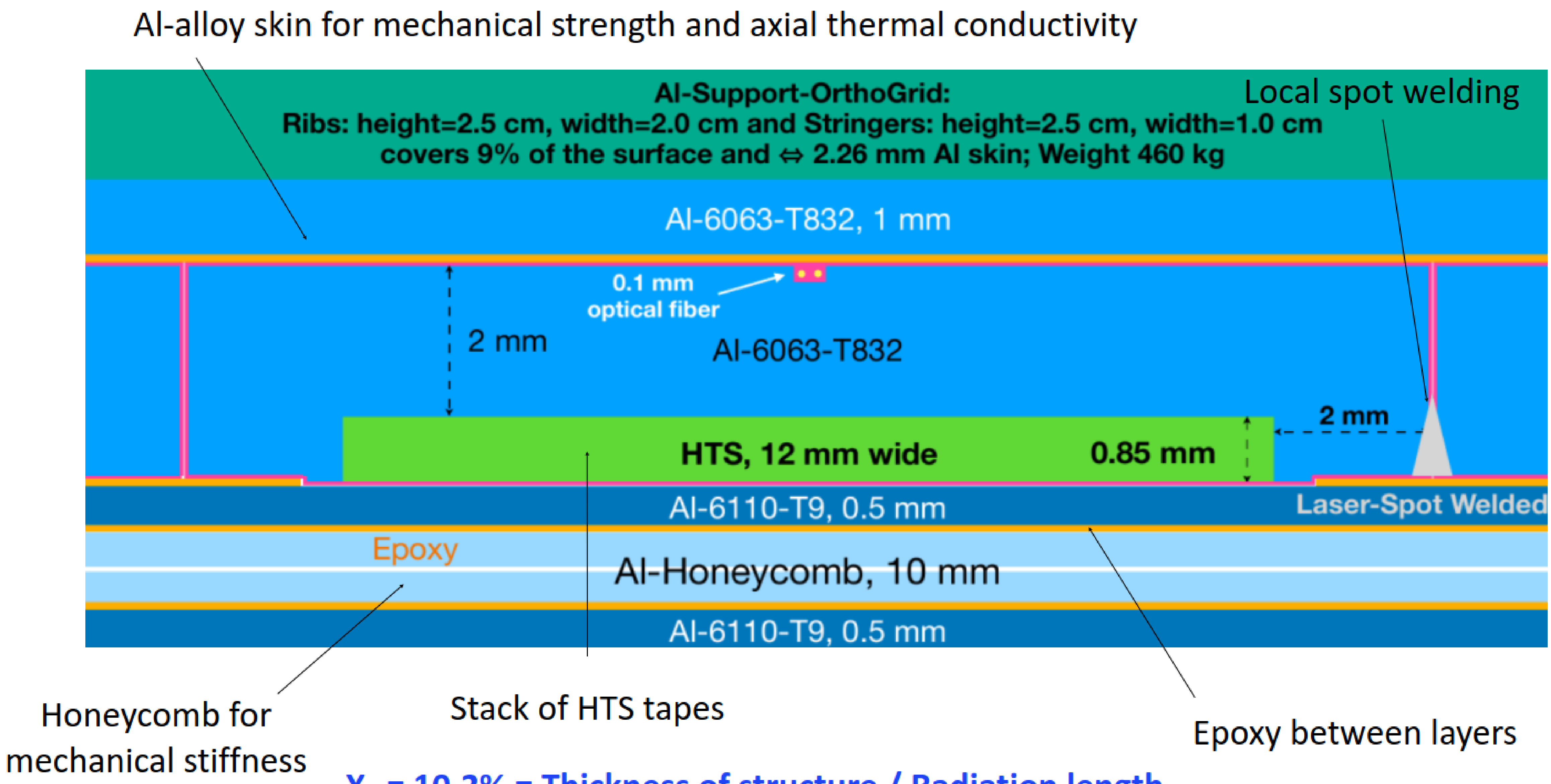
$$Amp[dB]_j = 10\log[|h_j|]$$

OBR-4613



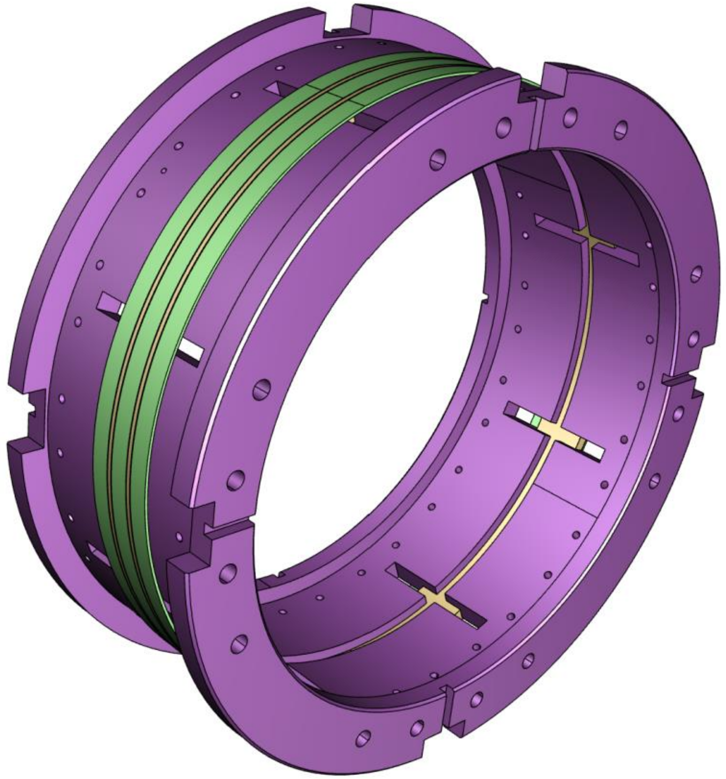
Fiber constants

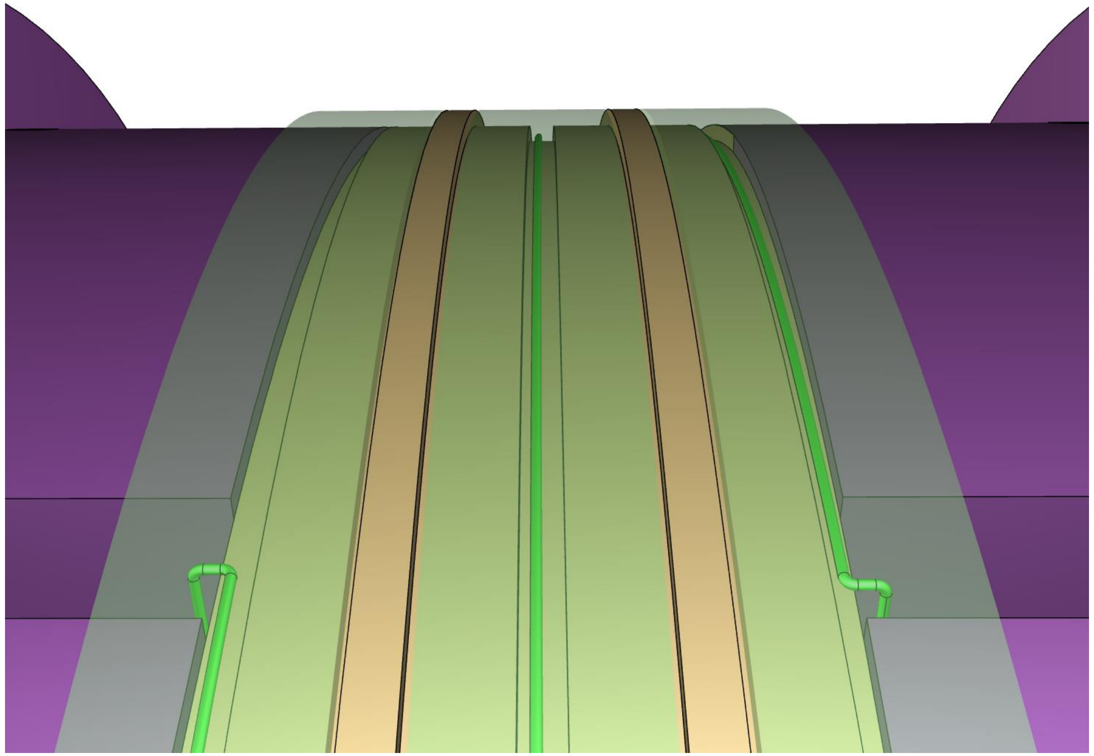
$$-\frac{\Delta\nu}{\nu} = K_T\Delta T + K_\varepsilon \varepsilon$$



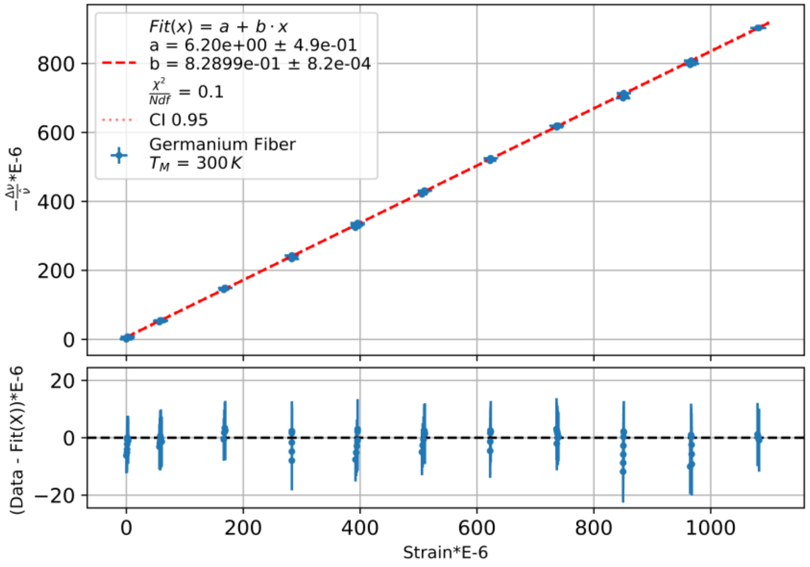
X_0 = 10.2% = Thickness of structure / Radiation length

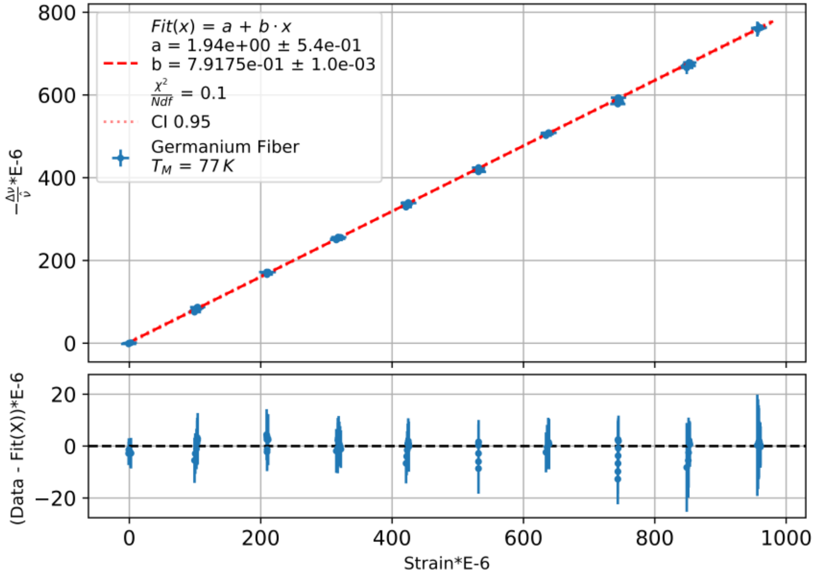
Coil Model

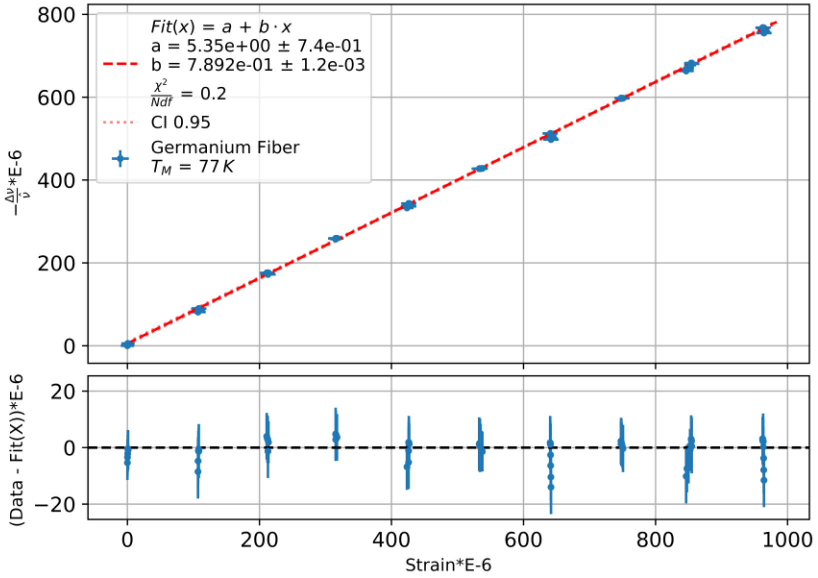




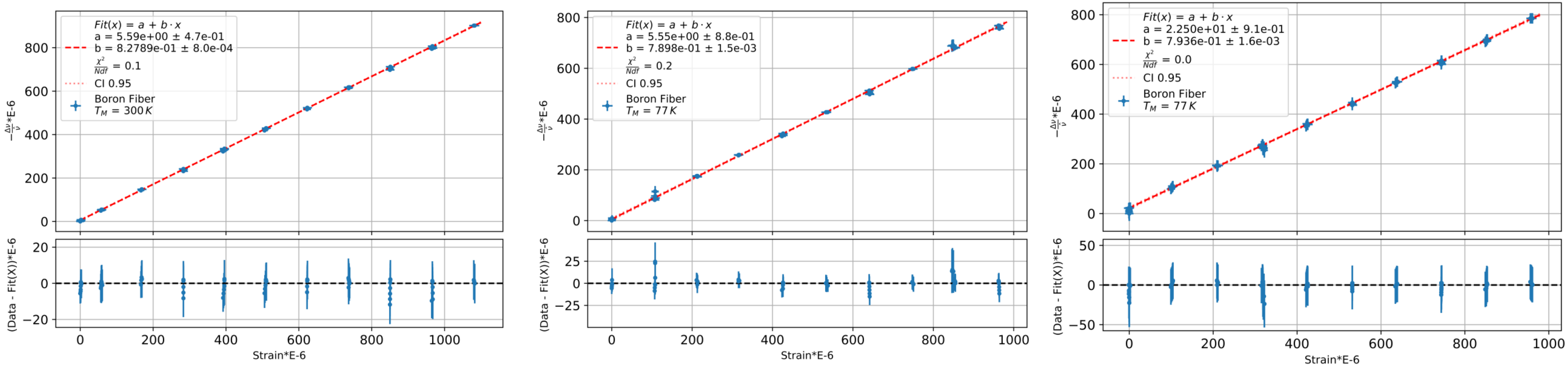
Strain Sensitivity: Germanium doped fiber



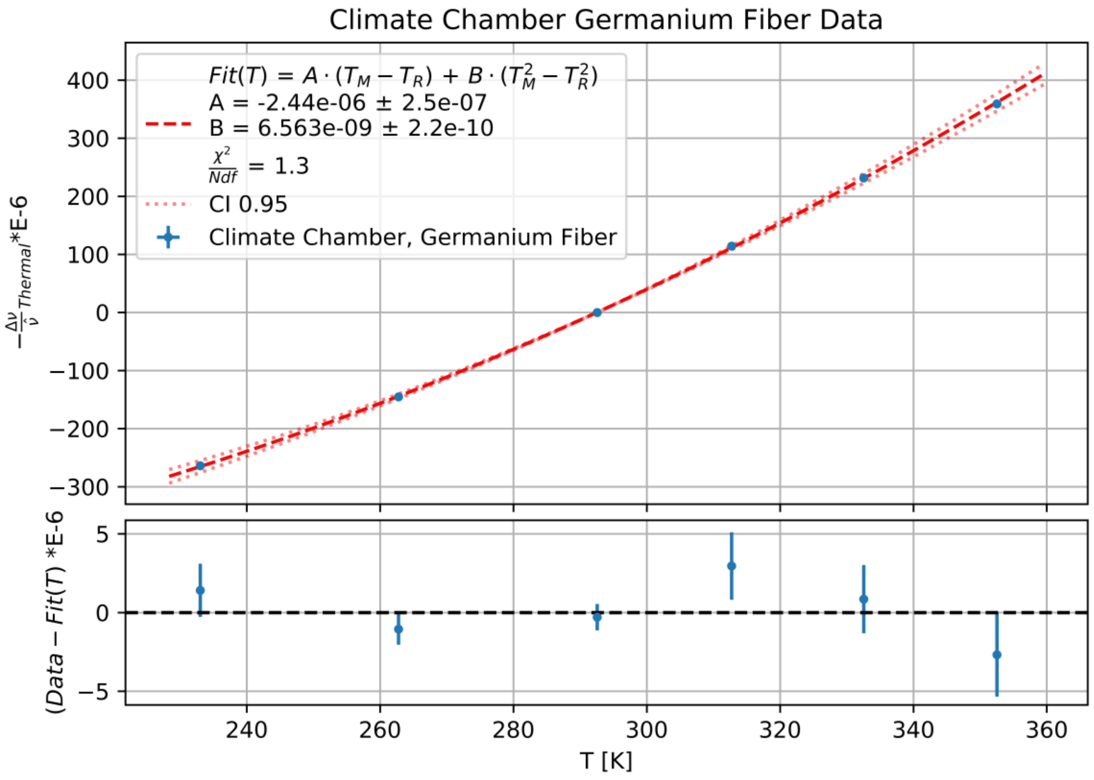


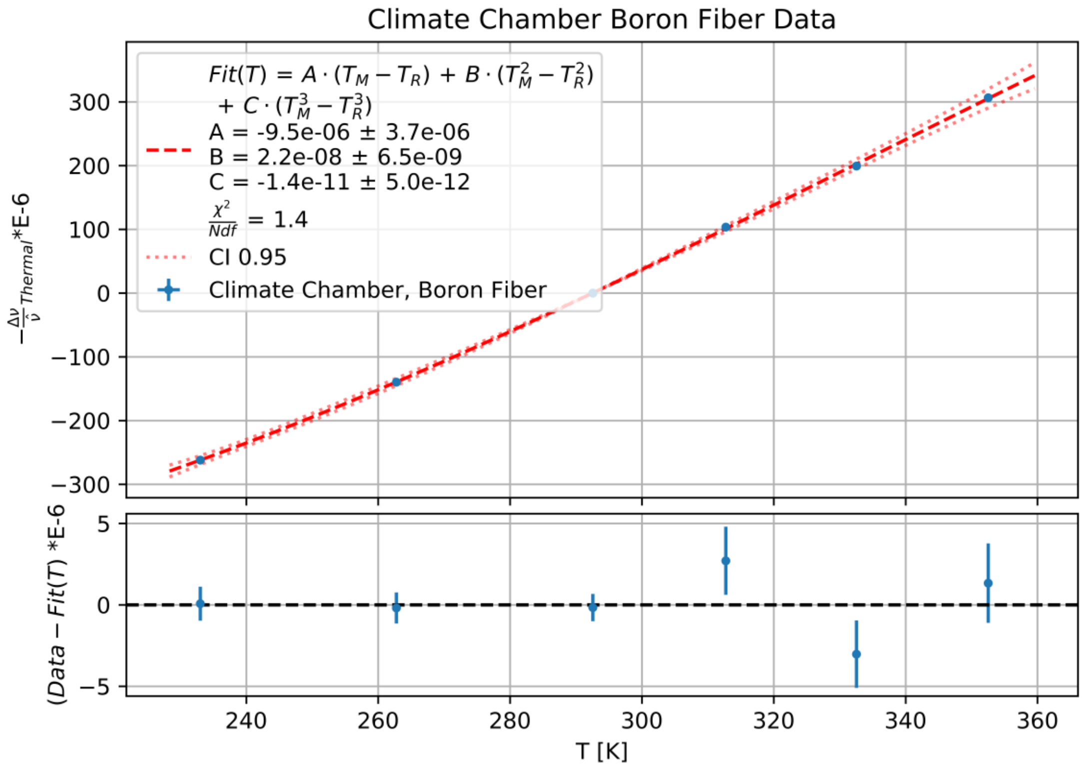


Strain Sensitivity: Boron doped fiber

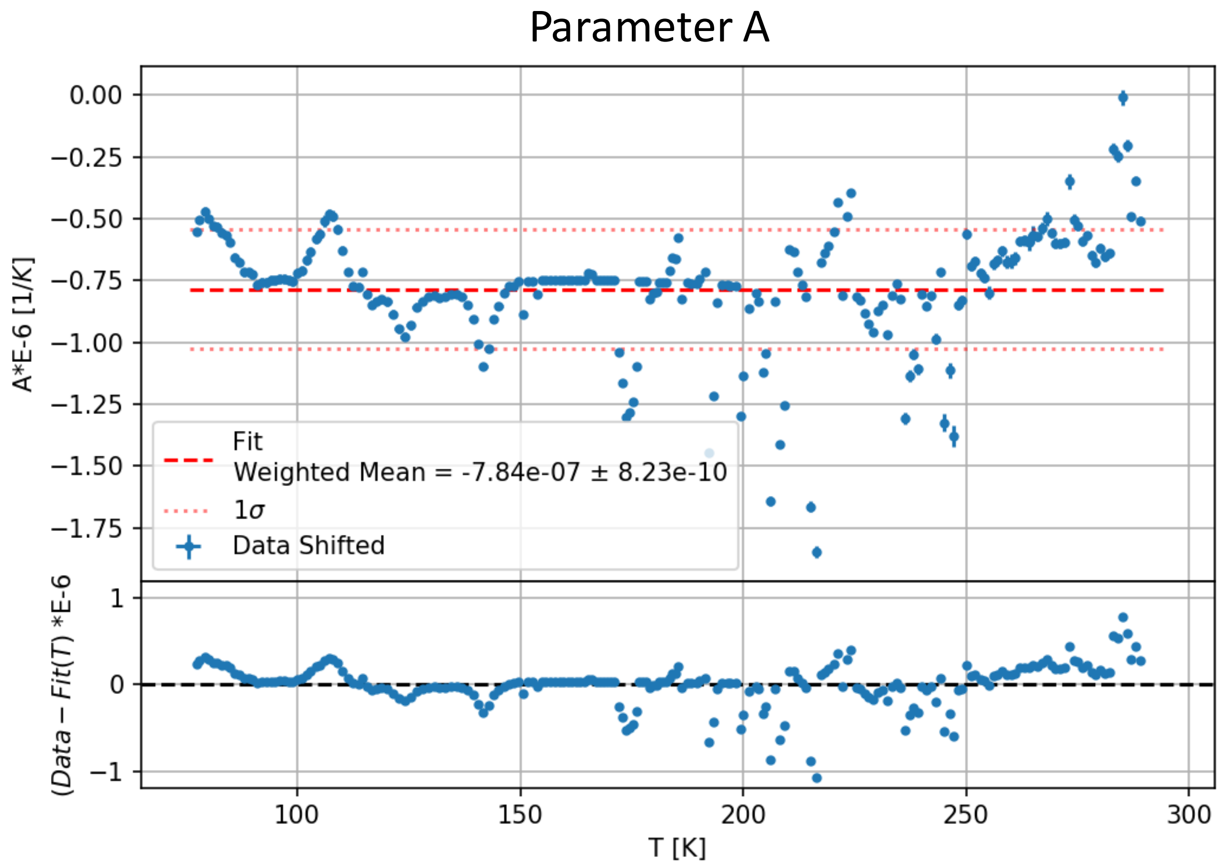


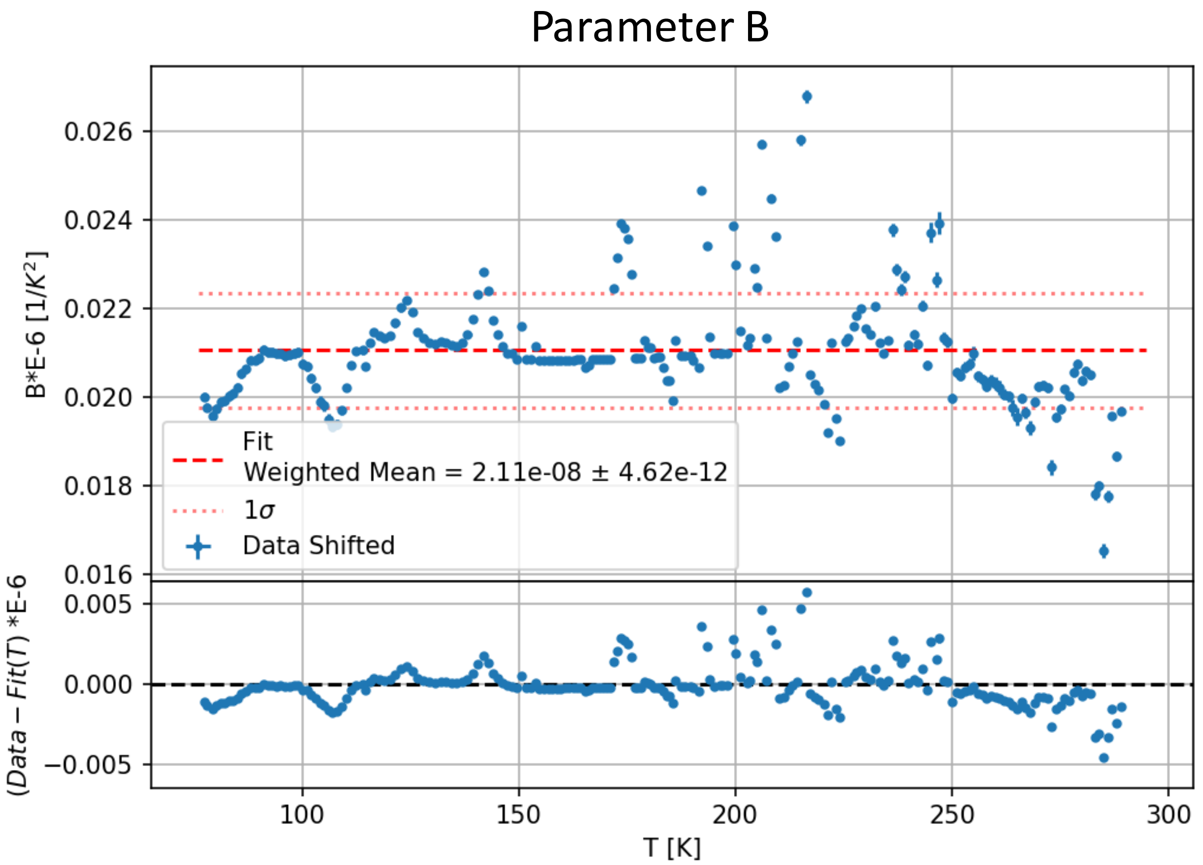
Temperature Sensitivity: 233 K – 353 K





Reference Temperature check Germanium Fiber





Reference Temperature check Boron Fiber