News from the optical fibers on MQXFB02…

100% of the mechanical instrumentation (Optical for coils and Electrical for rods) is working well at 1.9 K and during the powering phases!
MQXFB magnet coils
CTE characterization down to 1.9 K

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Outline

• Experimental set-up
• Validation campaign
• Results

Special acknowledgement to Stefan Hoell!!
Our approach to thermal contraction measurements at 1.9 K

Look first into existing commercial solutions

- **Main system requirements**
  - Cryogenic environment with controllable temperature
  - CTE test set-up (large spectrum of sample sizes and properties)

- **Further requirements**
  - Low vibration environment
  - Superconducting magnet for material and sensor studies
  - Sufficiently big bore diameter (sample size, sensors, etc.)

**Solution**
- Off the shelf closed-cycle cryostat from attoCUBE company
- Joint development of CTE measurement insert
Cryogenic testing environment
attoDRY2100 cryostat

- Temperature controllable in a range from 300 K down to 1.8 K
  - Dynamic and steady-state measurements
  - High temperature stability in steady-state conditions ($\Delta T \leq 10$ mK for $T < 10$ K)

- Cooling without liquid Helium supply by using a closed-cycle cryocooler
  - Operational cost efficiency
  - Reduced safety requirements

- 9 T Magnet
  - Magnetostriction, own sensors development, etc.
CTE Measurements Setup

Thermal contraction determination

- Each optical head detects **absolute displacement** $\Delta d$

\[
\frac{\Delta L}{L_0}(T) = \frac{\Delta L_{\text{Sample}}(T)}{L_0(T_{\text{Ref}})} = \frac{\Delta d_{\text{Ref side}}(T) - \Delta d_{\text{Sample side}}(T)}{L_0(T_{\text{Ref}})}
\]

$\rightarrow$ **Contraction of sample housing** requires **reference**

IDS3010 – Fiber-Optic Fabry-Pérot interferometer

- **Highly compact interferometer** with an accuracy in **nanometer range**
- Suitable for **harsh environments**
- **Working principle**
  - Reflected beam interferes with a reference beam inside the optical fiber
  - Change in **absolute distance** leads to **proportional change** in **interferometric pattern** due to **phase shift**
Test protocol

Two measurement conditions

• **Dynamic cool-down**
  • Cooling rate generally below 2 K/min
  • Constantly below 1 K/min for T < 100 K
  • Cool-down time of 6-7 h

• **Steady-state conditions**
  • Several temperatures: ~1.8, 4, 10, 20, 50, 100, 150, 200, and 293 K
  • Stability criteria:
    • $|T - T_{\text{set}}| < 0.05 \, K$
    • $\Delta L (\Delta t = 10 \, \text{min}) < 20 \, \text{nm}$
    • Criteria maintained for 30 min

• Reference temperature: 293 K
Validation campaign

- Dynamic cool-down and steady-state heat-up measurements
  - Invar (Fe64Ni36)
  - Ti grade 5 (TiAl6V4)
  - SS304
  - OFE Copper
  - Al 6082 (AlSi1MgMn)

- Reference data
  1. Comparison to NIST reference data
     → Difference < 4 % (except for Invar)
  2. Measurement results with the pushrod DIL
     → Difference < 2.5 %
Uncertainty Determination

- **Single crystal silicon reference**
  - High material consistency → independent of supplier
  - Very low thermal contraction

- **Reference data from German National Metrology Institute (PTB) [1]**
  - Uncertainty in ppb range for differential CTE
  - Thermal contraction determined from RT to 8 K

- **Expanded uncertainty for dynamic and steady-state conditions**
  - Calculation considers random error $u_r$ and absolute difference between mean and reference data $u_{\Delta L/L_0}$
  - Coverage factor $k = 2$ (≈ 95 %)
  - Relative uncertainty of 0.31 % at 1.9 K when related to copper ($-3.25 \cdot 10^{-3}$)

- **Optical setup → some materials require coating with aluminum foil**
  - Increased uncertainty to 0.03 $\cdot 10^{-3}$
  - → still less than 1 % for copper, SS304, aluminum

Incipient collaboration with the European Space Agency for subsequent developments
Practice coil CR120 (EDMS 2670844)

- **Critical non-conformity during winding of outer coil layer**
  - Thus, coil used as practice coil for fabrication process
  - Major modification: *no application of ceramic binder CTD 1202 on outer layer* in order to investigate feasibility of coil production without the binder

- **First observations during sample preparation**
  - Cutting induced distortion due to residual stresses in the coil
  - Detachment of layers due to poor bonding
Sample preparation

- Requirements
  - Sample height = 15 mm
  - Sufficient surface reflectivity
- Sample cutting with diamond wire saw
  - Azimuthal and longitudinal direction
    - Cutting along resin + subsequent polishing to obtain parallel faces
  - Radial direction
    - Cutting through cables as only a few layers necessary
- Coating of sample surface with aluminum foil (~16 µm thickness)
  - Foil bonded with Araldite standard two-component glue
  - Increased but still acceptable uncertainty
- Thermal cycling in LN2 bath to improve time efficiency
  - Avoiding cyclic behavior

Test matrix

<table>
<thead>
<tr>
<th>Direction</th>
<th>Samples</th>
<th>Geometry (L x A x R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>Inner S1 + S2</td>
<td>15x15x18 mm</td>
</tr>
<tr>
<td></td>
<td>Outer S1</td>
<td></td>
</tr>
<tr>
<td>Radial</td>
<td>Inner S3</td>
<td>15x9x15 mm</td>
</tr>
<tr>
<td></td>
<td>Outer S3</td>
<td>15x7x15 mm</td>
</tr>
<tr>
<td>Azimuthal</td>
<td>Inner S1 + S2</td>
<td>15x15x18 mm</td>
</tr>
<tr>
<td></td>
<td>Outer S1 + S2</td>
<td></td>
</tr>
</tbody>
</table>

MQXF – CTE characterization to 1.9 K
Results – Longitudinal

• Measurement labelling
  - Outer S1 (C1)
  - Series of consecutive measurements
  - Dynamic cool-down (C) or steady-state heat-up (H)
  - Sample number
  - Coil layer (Inner/Outer)

• Longitudinal direction tested for three samples
  - Several dynamic plus one steady-state measurement
  - Total contraction at 1.9 K between -2.9 and -3.1 \cdot 10^{-3}
  \[
  \left( \frac{\Delta L}{L_0} \right) (1.9 \text{ K}) = -2.97 \cdot 10^{-3}
  \]
  \[
  \sigma(1.9 \text{ K}) = 0.065 \cdot 10^{-3} = 2.2 \%
  \]
Results – Longitudinal

Cyclic behavior

• Lower contraction in first cooling cycle (no prior LN thermal cycle)
• Sample height reduced by 10 µm after first cycle
• Also observed for other coil axes

11T Cable Stack Comparison

• Total contraction a bit lower than for MQXF coil samples

MQXF – CTE characterization to 1.9 K

11T cable stack according to EDMS 2088807
Results – Radial

\[
\left( \frac{\Delta L}{L_0} \right)_{\text{inner layer}} (1.9 \text{ K}) = -1.61 \times 10^{-3}
\]

\[
\left( \frac{\Delta L}{L_0} \right)_{\text{outer layer}} (1.9 \text{ K}) = -1.75 \times 10^{-3}
\]

\[\rightarrow \text{ Inner layer contracts less than outer layer}\]
\[\rightarrow \text{ Both comparable to the behavior of } \text{Nb}_3\text{Sn} \ (1.6 \times 10^{-3})\]
Measurements in azimuthal direction at three different positions along radial axis

- Strong deviations along axis and also high variability of contraction at similar positions
- But evidence that **inner coil contracts less than outer coil**
Results – Azimuthal

Thermal contraction at 1.9 K over the entire campaign in azimuthal direction

- Contraction at cold indicates an apparent trend
  - Contraction increases with the radius

- However, important scatter
  - Low consistency in contraction
  - Interfaces between layers?
  - Link to weak bonding?
Conclusions

- Measurement technique has been validated, and is deemed appropriate for these measurements.
- Challenging sample preparation due to poor interlayer adhesion and internal stresses.
- Cyclic behavior observed in the three directions. More complex to evaluate in azimuthal direction.

Next steps

- Measurements on samples from state-of-the-art coil.
- Focus on contraction dependence on resin/conductor fraction.
- Open to further relevant requests (magnetostriction, …)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Layer</th>
<th>$\Delta L/L_0$ at 1.9 K</th>
<th>$\sigma(\Delta L/L_0)$ at 1.9 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>Inner</td>
<td>$-2.98 \cdot 10^{-3}$</td>
<td>$0.06 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Outer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial</td>
<td>Inner</td>
<td>$-1.61 \cdot 10^{-3}$</td>
<td>$0.04 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Outer</td>
<td>$-1.75 \cdot 10^{-3}$</td>
<td>$0.03 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Azimuthal</td>
<td>Inner</td>
<td>$-2.55 \cdot 10^{-3}$</td>
<td>$0.38 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Outer</td>
<td>$-3.77 \cdot 10^{-3}$</td>
<td>$0.47 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Uncertainty of $U_{coated} = 0.03 \cdot 10^{-3}$
MQXF - CTE characterization to 1.8 K
Validation campaign

Expanded uncertainty based on GUM

- Combined uncertainty estimated as the maximum of two methods
  - Uncertainty based on individual error sources (Ti)
  - Uncertainty based on reference data (single crystal silicon, SCS)

- Coverage factor of $k = 2$
  - Coverage probability of more than 95 %
  - Expanded uncertainty corresponds to 0.31 % in respect to the total contraction of copper at 1.9 K

- Optical setup → some materials require coating with aluminum foil
  - Increased uncertainty to $0.03 \cdot 10^{-3}$
  - still less than 1 % for copper, SS304, aluminum
MQXF – CTE characterization to 1.8 K
Samples

- **Two kind of cuttings**
  
  \( v1 = 15 \times 15 \times 15 \text{ mm with} \)
  
  “resin only on one radial face”

  \( v2 = 15 \times 15 \times 19 \text{ mm with} \)
  
  “resin on both radial faces”

- **Problem with v1**
  
  - Internal stresses in azimuthal direction
  - Layers are not sufficiently sticking together
  
  \( \rightarrow \) Often loosening of layers
  
  \( \rightarrow \) Switching to v2
Results – Azimuthal

Steady-state measurements?
Ten stack – longitudinal
Thermal contraction of S2 C2.1 initially higher, but equal below 200 K
Samples v2 – longitudinal

Thermal cycling of S8
Azimuthal direction – steady-state and dynamic

• **At minimum temperature**
  • Deviations are rather small and induces by the cyclic trends

• **At elevated temperature (100, 150, and 200 K)**
  • Significant lowered contraction for steady-state conditions
  • Temperature error should result in the opposite
  • Cause? Stresses that build up and release?
Azimuthal direction – bottom coil layer
Azimuthal direction – bottom coil layer

![Graph showing the relationship between temperature and ΔL/L₀. The graph plots different samples labeled as S11 inner side C3.3, S8 inner side C4.2, S8 inner side C6.3, S11 center C1.3, S8 center C1.3, S11 outer side C2.4, S8 outer side C2.3, and S8 outer side C5.3. The temperature is in Kelvin, and the ΔL/L₀ is in 10⁻³.]
Azimuthal direction – bottom coil layer

\[ \Delta L/L_0 \left[ 10^{-3} \right] \]

Temperature [K]

- S11 inner side C3.3
- S8 inner side C4.2
- S8 inner side C6.3
- S11 center C1.3
- S8 center C1.3
- S11 outer side C2.4
- S8 outer side C2.3
- S8 outer side C5.3
Azimuthal direction – top coil layer
Azimuthal direction – top coil layer

**MQXF S5**

**MQXF S7**

- Inner side C5.3
- Inner side C7.2
- Center C3.3
- Outer side C4.3
- Outer side C6.3

![Graphs showing temperature vs. ∆L/L0 for MQXF S5 and S7, with different coil layers plotted.](image-url)
Azimuthal direction – bottom coil layer
Azimuthal direction – bottom coil layer
Azimuthal direction – bottom coil layer

MQXF S8

MQXF S11

Temperature [K]

$\Delta M(L_0) [10^{-5}]$

-4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0

-4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0

Inner side C4.2
Inner side C6.3
Center C1.3
Outer side C2.3
Outer side C5.3

Inner side C3.3
Center C1.3
Outer side C2.4
Azimuthal direction – bottom coil layer

![Graph](image_url)

- **ΔL/L₀ [10⁻³]**
- **Temperature [K]**

Legend:
- S11 inner side
- S11 center
- S11 outer side
- S7 inner side
- S7 center
- S7 outer side
Radial direction – cyclic trend

C1.1 was first thermal cycle (no LN2 bath beforehand) → Sample maintained contraction of 10 µm
Radial direction

- **S12 = outer layer**
  - Higher contraction
  - C2 equals C1.1 (but cyclic trend)

- **S13 = inner layer**
  - Lower contraction
  - Steady-state is running currently

- **Similar contraction for Nb3Sn in literature (Xu1995)**

![Graph showing contraction vs. temperature for different samples](image)
Differences between inner and outer coil layer

• Ceramic binder only on inner coil layer
  • Leads to increased brittleness of the fiberglass insulation
  • Also adhesion can suffer of improper impregnation
  • Overall lower contraction for inner layer than for outer layer
  → Connection to ceramic binder? However, also no binder on the first four layers close to the titanium pole

• Removed binder on outer layer led to

Then, after the high temperature heat treatment to form Nb-Sn, ceramic binder makes the fiberglass around the cable very brittle. In fact, during the preparation for impregnation, we always see parts of the fiberglass insulation that come off from the cable and the wedges, especially during the cleaning of the poles and the light vacuuming of the coil for the mica flakes.

As the fiberglass around the cable is the mechanical support of the coil once impregnated, the more the fiberglass is fragile the more the mechanical strength of the coil will suffer. Similarly if the fiberglass is polluted by a not proper treatment of the ceramic binder (in fact the product does not pyrolyze in a closed mold as in Annex 1), the adhesion of the resin injected during impregnation will be weaker.