A thermal interface material for the PS modules of the CMS Outer Tracker upgrade.

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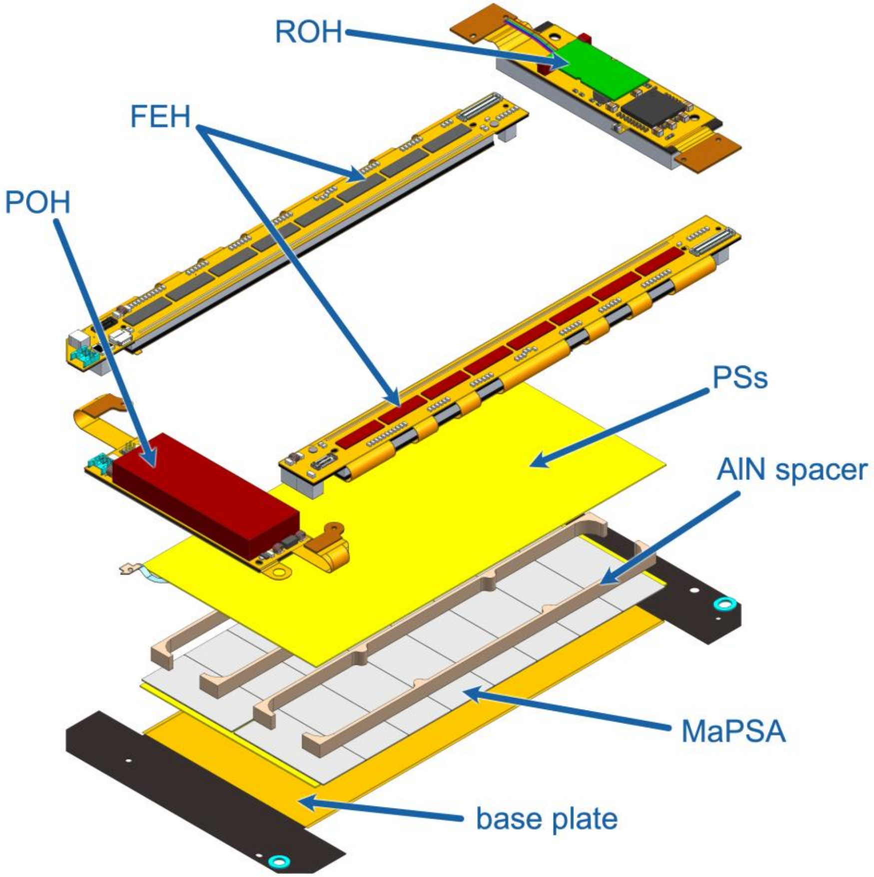
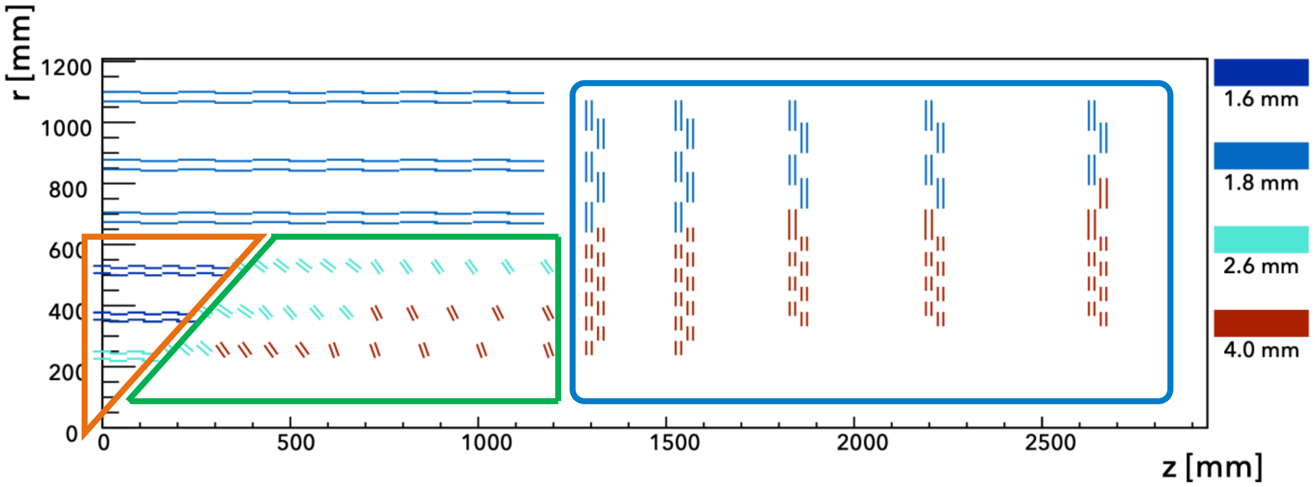
CMS outer tracker PS modules cooling

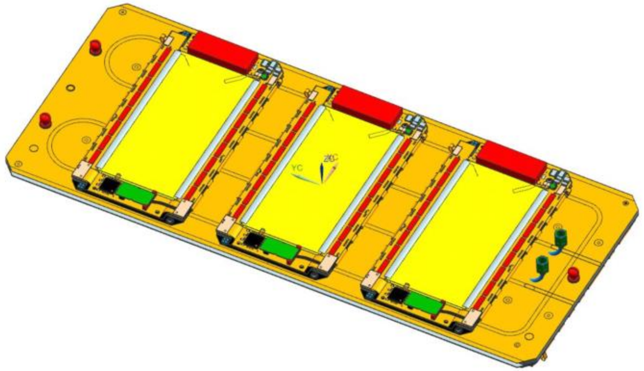
- Module is assembled on a thin CF base plate. Cooling is facilitated through the underside of the base plate.
- Pixel layer (MaPSA) is creating most of the heat and hence is cooled via the large area.
- Strip sensor (PSs) is cooled through AlN spacers and the MaPSA.
- The DC-DC converter (POH) is directly on the baseplate for efficient cooling.
- Readout hybdrids are cooled through small AlN blocks on the "ears" of the base plate.



PS cooling mechanics

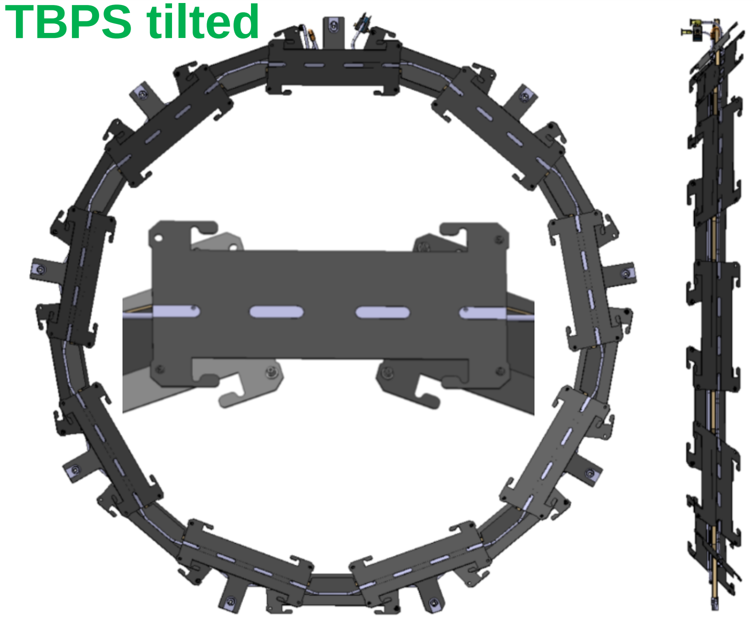


TBPS flat



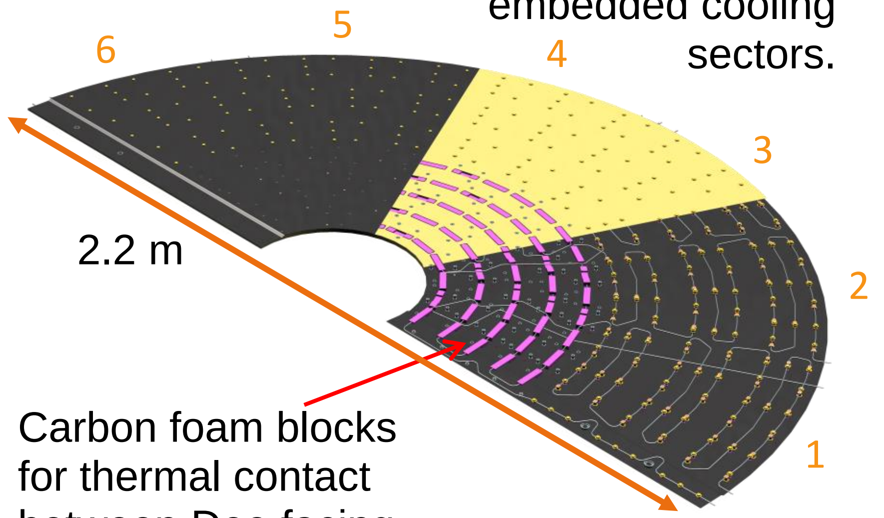
Carbon fiber / Carbon foam sandwich with embedded cooling pipes.

TBPS tilted

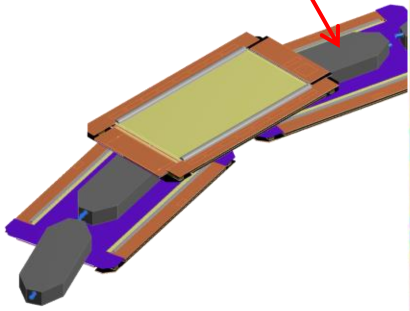


TEDD

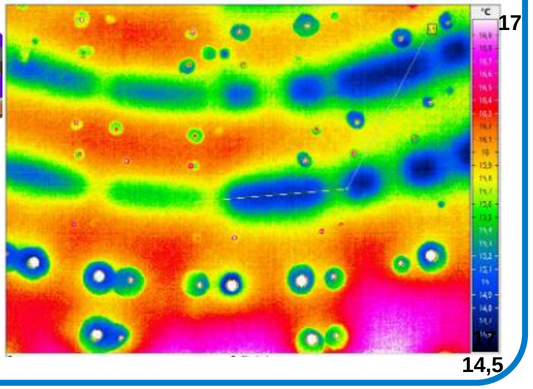
Endcap Dee with 6 embedded cooling sectors.



Carbon foam blocks for thermal contact between Dee facing and cooling pipe

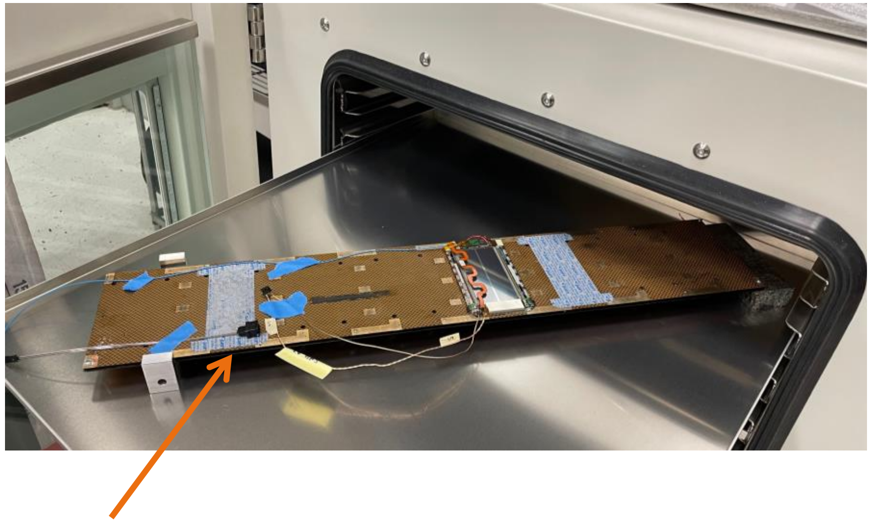


IR image of Dee surface



Key requirements for a Thermal Interface Material

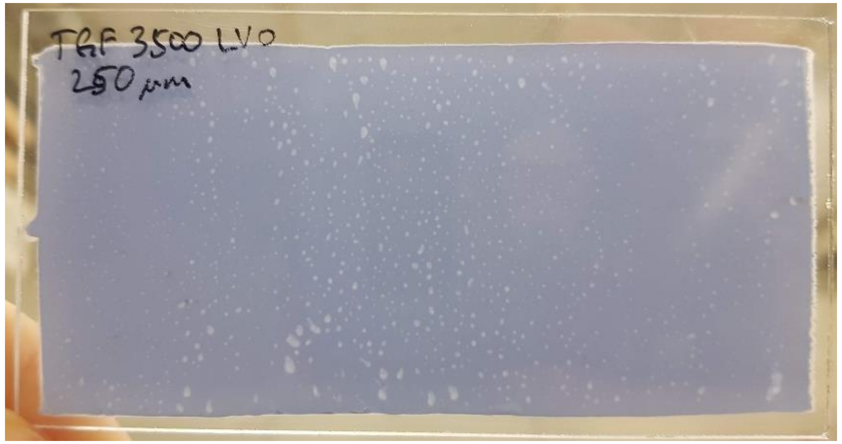
- Many different thermal interface materials (TIM) on the market: pastes, pads, phase change foils, gap fillers, ...
- Detector is in operation 10+ years and not accessible.
  - Should cure to maintain form over many years
- Should remain re-workable during integration.
  - Gluing the modules it is not an option.
- Reliable contact on an area of about 5 x 13 cm^2
- Needs to be radiation hard to about 800 kGy.
- Phase change foils make good contact if a force is applied (not possible), or the baking is done in vacuum.

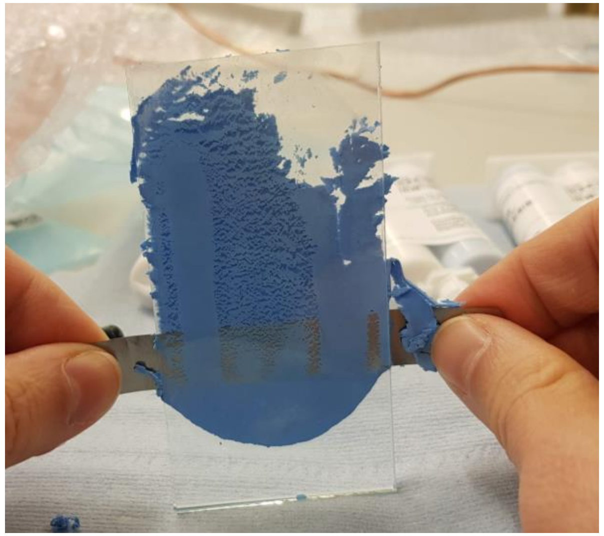


  - Baking in vacuum with a phase change foil is the baseline solution for the flat barrel planks.
  - Tilted rings and endcap Dees are too large for a vacuum oven.

Thermal Gap Filler as interface material

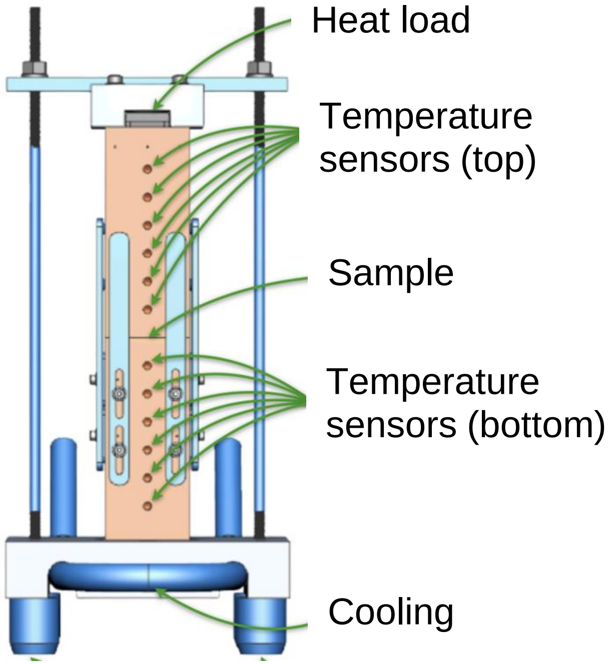
- Thermal Gap Filler: Typically silicone based two-component material with filler for thermal contact.
  - Self curing -> no heat treatment necessary.
  - Cured material is not a glue, but tacky. A thin layer between plates is fairly robust.
- Tests with glass plates showed that a thin layer can be produced.
  - Visually successful tests with 150 µm, 200 µm and 250 µm.
  - Separation without much force is possible.
- Materials under test here are from Bergquist/Henkel
  - TGF3500LVO: 3.5 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$, low silicone volatility (aka LVO)
  - TGF4500CVO: 4.5 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$, controlled silicone volatility (aka CVO)
  - TGF3000SF: 3.0 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$, silicone free (aka SF)

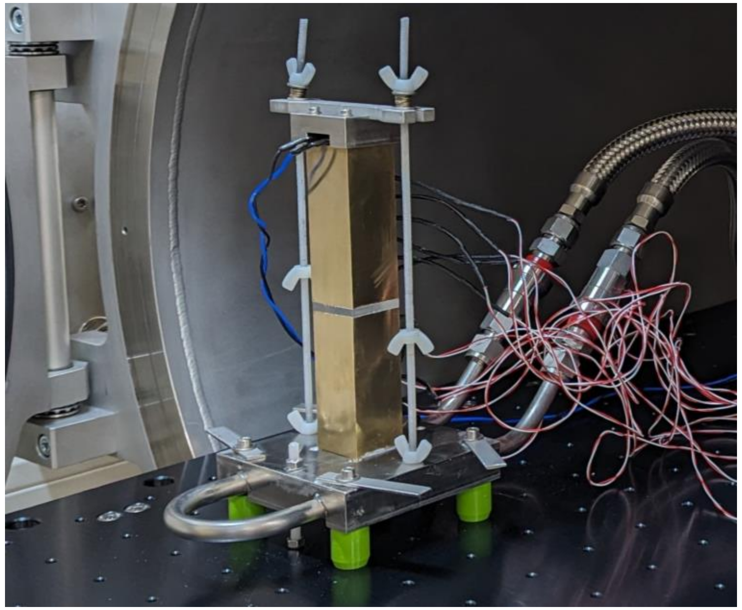




Thermal test setup at DESY

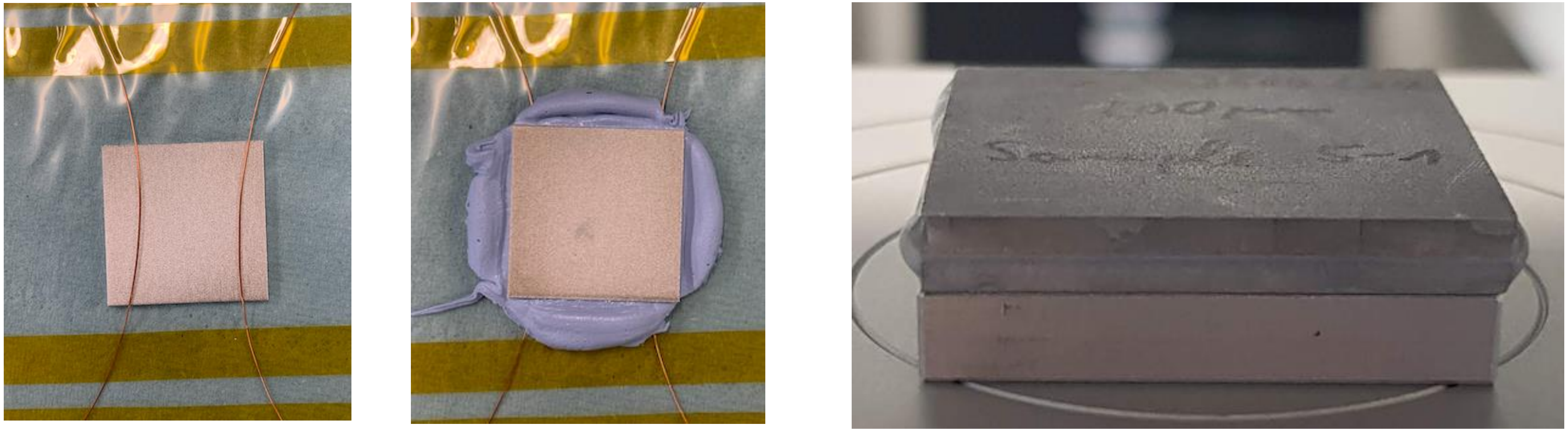
- Thermal conductivity setup using two brass blocks with 30 x 30 mm^2 cross section and 6 temperature sensors (NTCs) embedded in each.
- Thermal interface material Keraterm KP12 between blocks and sample.
  - Low viscosity allows to use a very thin layer.
  - Thermal conductivity: 10 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$
- To ensure the same conditions of the measurement, samples are compressed with compression spring. Resulting clamping force is ~70 N.
- Setup covered with radiation shield to reduce radiative heat exchange and placed in vacuum to remove convective heat exchange.





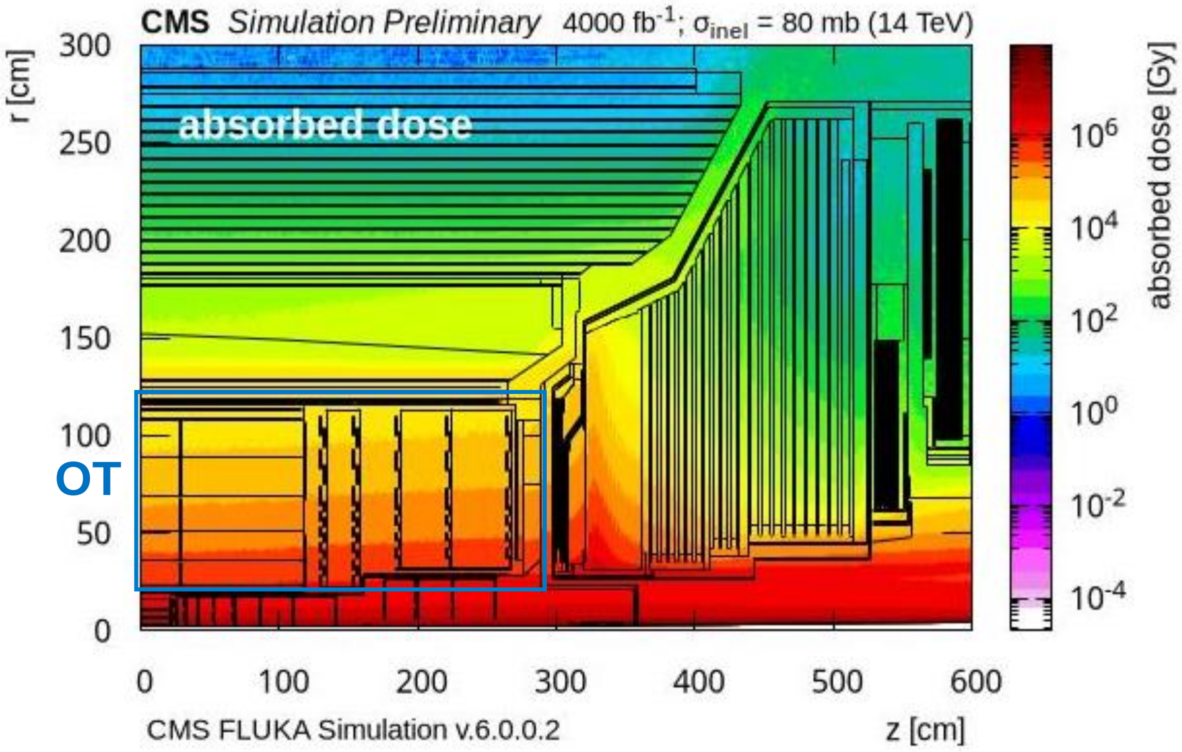
TIM thermal test samples

- Gap filler is sandwiched between 2 mm thick Aluminium plates.
- Spacer wires (off-the-shelve copper wire) to define different thicknesses (nominally: 0.2 mm, 0.3 mm, 0.4 mm) are removed after curing.
- Coating of the edges with epoxy for stability.
- Samples are pre-conditioned with 70 N force in our material test station.
- Measurement of final sample thickness with calipers.

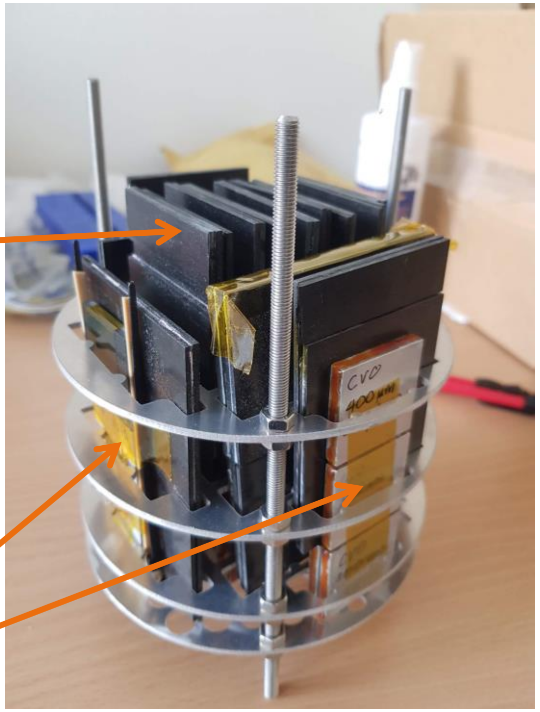


Irradiation

- Dose level increases significantly towards small radii.
  - Dose to ring 1 modules decrease from ~800 kGy to ~550 kGy after 4000 fb^{-1}.
  - Chose 600 kGy as first irradiation test. Roughly corresponds to center of ring 1.



- ^{60}Co irradiation at Ruder Boskovic Institute.
- Special sample holder designed to allow air flow for cooling and prevention of ozone build up.



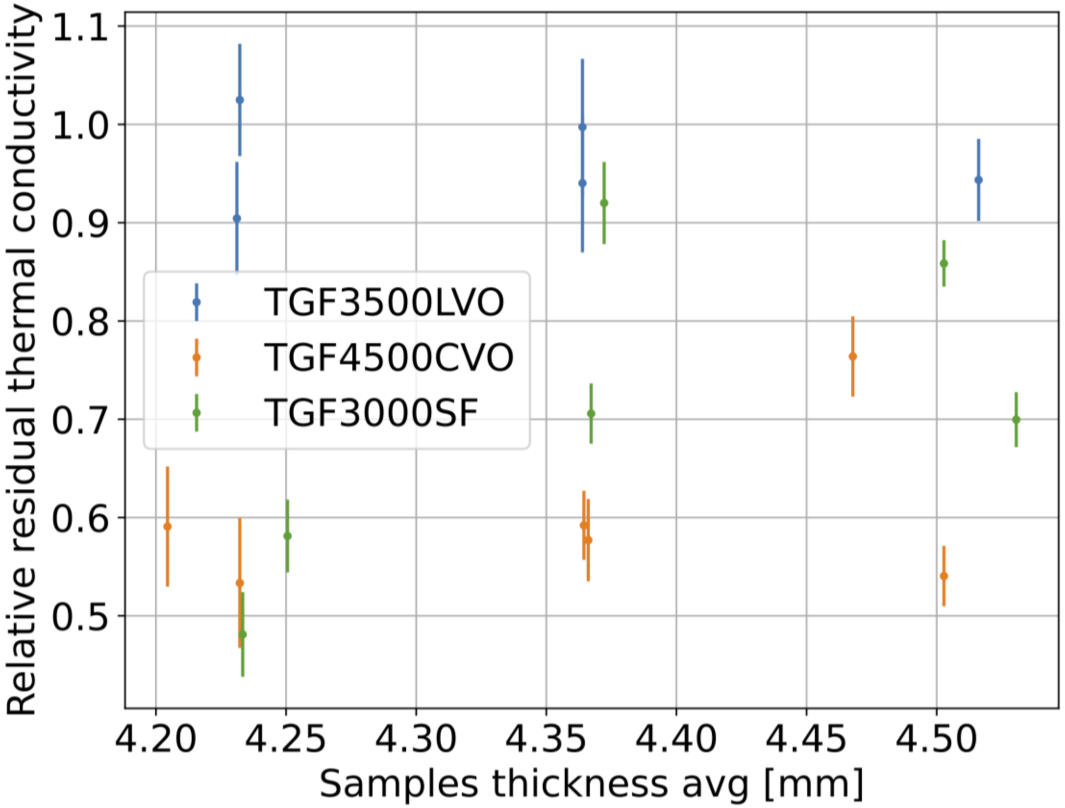
Mechanical samples

Thermal samples

Thermal tests - degradation

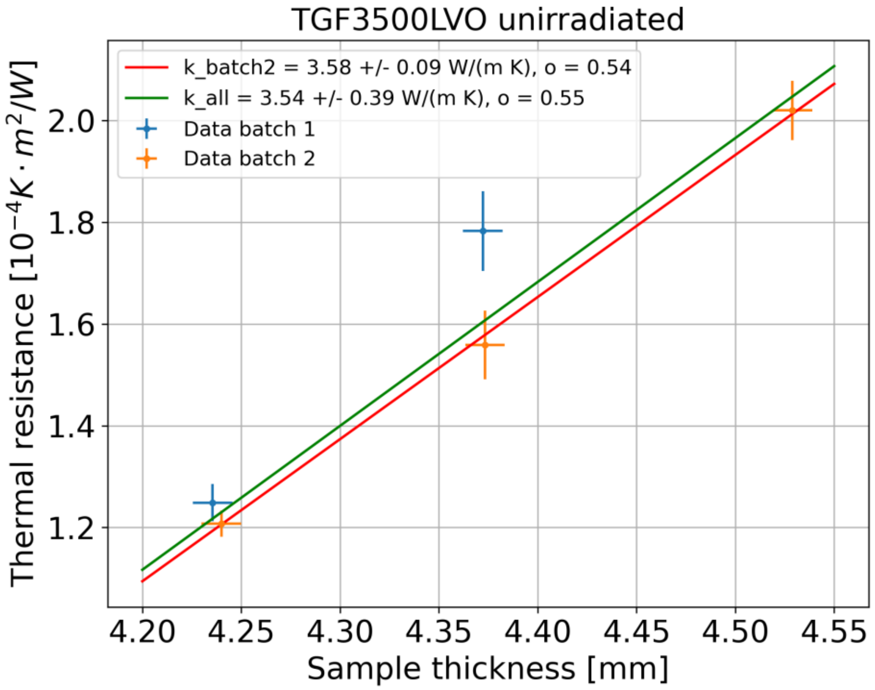
- Degradation d of a sample is defined as: $$d = \frac{resistance_{unirradiated} - offset}{resistance_{irradiated} - offset}$$

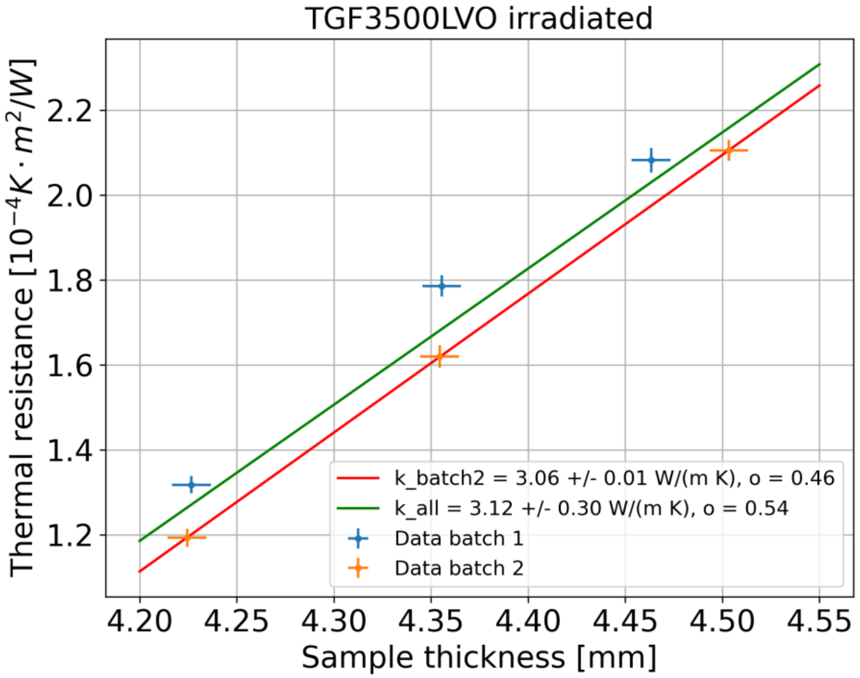
- An offset of $6 \times 10^{-5}\ \frac{\mathrm{K \cdot m^2}}{\mathrm{W}}$ is used, based on measurement of thermal grease and Aluminium plates.
- Degradation of LVO is between 0.9 and 1 which is within the errors of the measurement.
- CVO samples show a significant degradation (~ 0.6)
- SF samples of 0.2 mm thickness show a very strong degradation (~0.5), while 0.3 mm and 0.4 mm not as much (0.7-0.9).
- TGF3500LVO shows least amount of degradation and most consistent measurement result.



LVO thermal conductivity

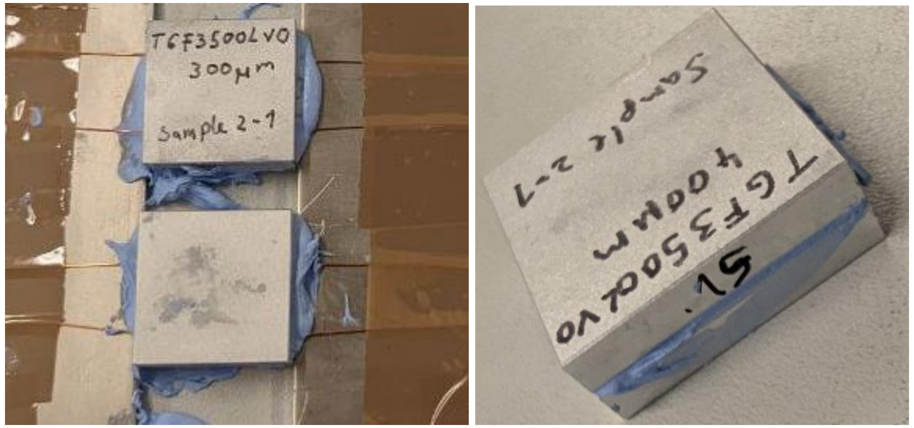
- Absolute thermal conductivity measurement result can be very sensitive to small errors in the thermal resistance. Not all samples gave consistent sets to calculate thermal conductivity.
- Unirradiated measurements of LVO are consistent with the specified 3.5 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$.
- After irradiation about 3 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$ is measured.

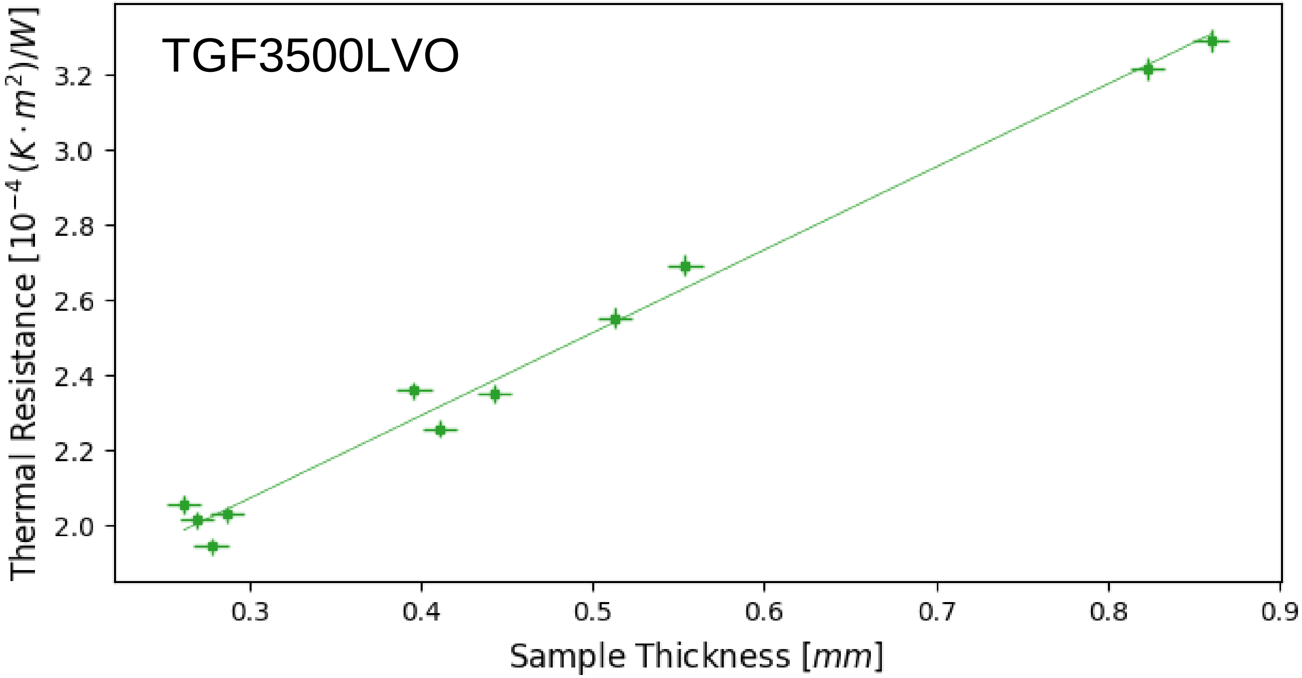




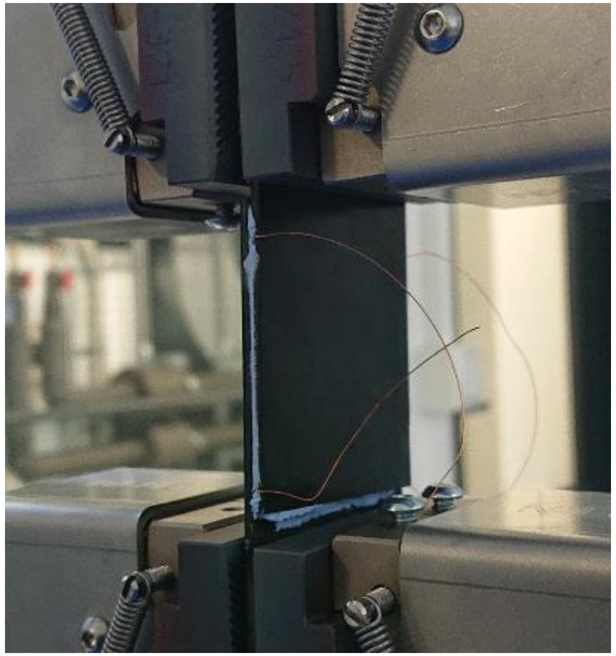
New geration of samples

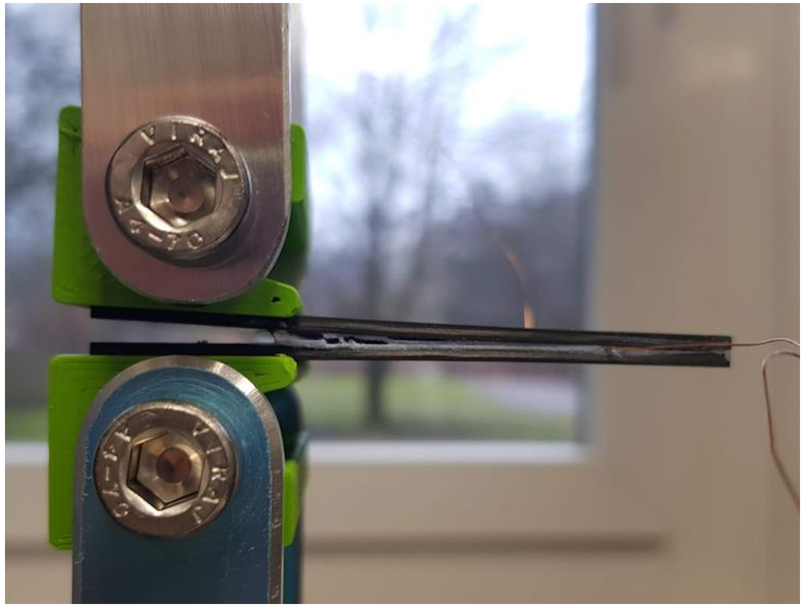
- Future tests focus on TGF3500LVO.
- Samples have been improved for better quantitative measurements.
  - 5 mm Al plates offer better flatness
  - Thickness of individual plates have been measured before sample production.
    - Improves estimation of TIM thickness in finished sample.
- More samples of different nominal thickness: 0.2, 0.3, 0.4, 0.7 mm
- Thermal resistance of all samples are very consistent.
- Thermal conductivity: 4.54 ± 0.09 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$
- Samples will be irradiatiated to 900 kGy.





Mechanical tests

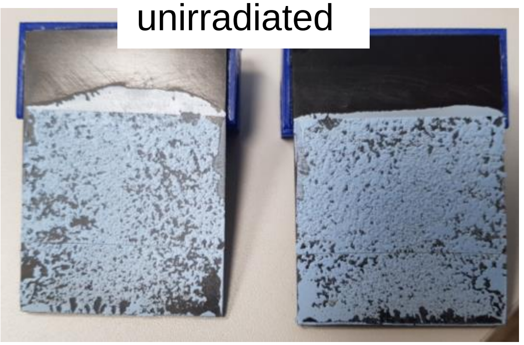


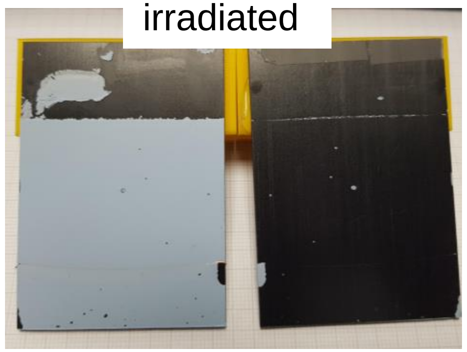


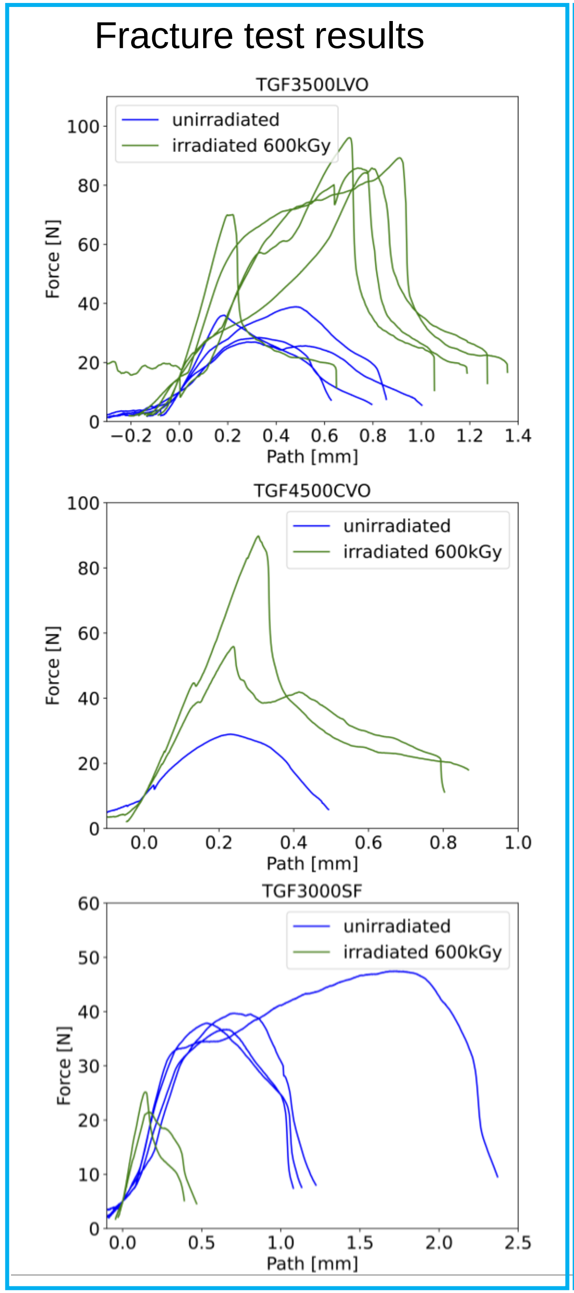
- Silicone is expected to harden under irradiation.
  - The main concern is the detachment from the surface due to the material becoming more brittle.
- TIMs are not adhesives. Adhesive properties are weak resulting in very low forces to be measured properly.
  - All samples use 50 x 50 mm^2 contact area to maximize forces with 0.2 mm TIM thickness.
- All test samples use He/O plasma cleaned carbon fibre plates to have a surface quality to the intended application.
- **Shear test** similar to ISO 4587 lap shear test with modified sample geometry.
  - Pull force parallel to the plane of the TIM material.
- **Fracture test** similar to ISO 25217 mode-1 fracture test.
  - Pull force orthogonally to the plane of the TIM material.

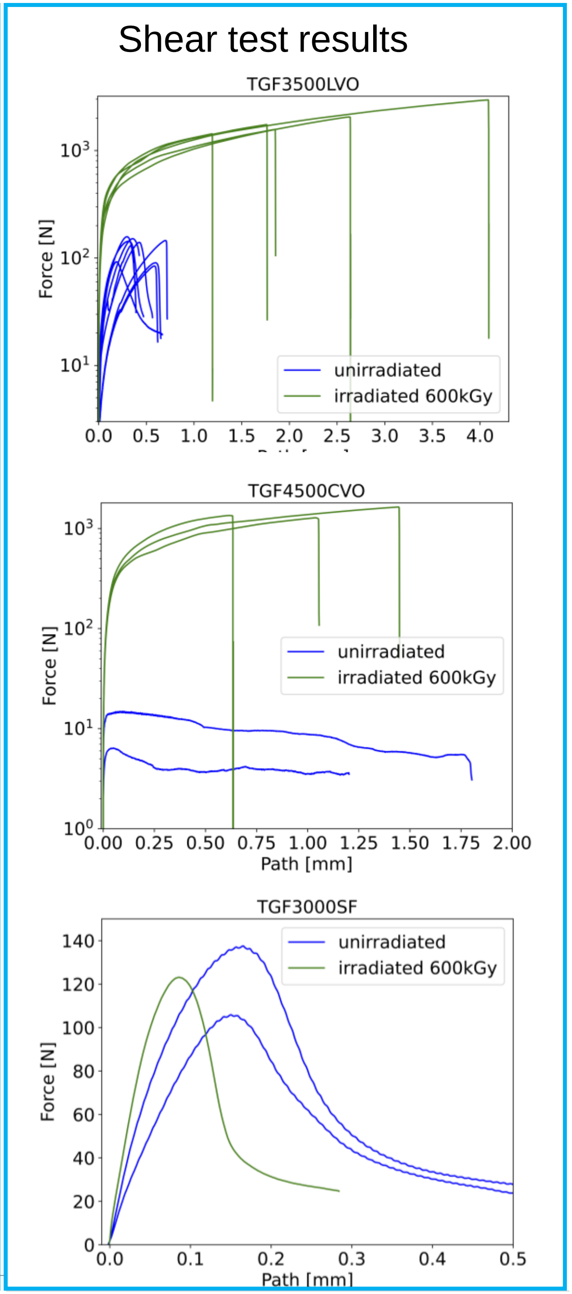
Mechanical test results

- Silicone based materials (LVO and CVO) harden significantly.
  - Significantly increased adhesive strength, mostly seen in shear test. (about x10 breaking force)
  - Fracture test after irradiation shows adhesion failure instead of cohesion failure.
  - No surface detachment
  - CVO and LVO could be used from the mechanical aspects.
- Silicone free material decreases in strength
  - Much lower breaking force in fracture tests, still showing cohesion failure.
  - Given potential CTE stress, SF is potentially unreliable after irradiation.



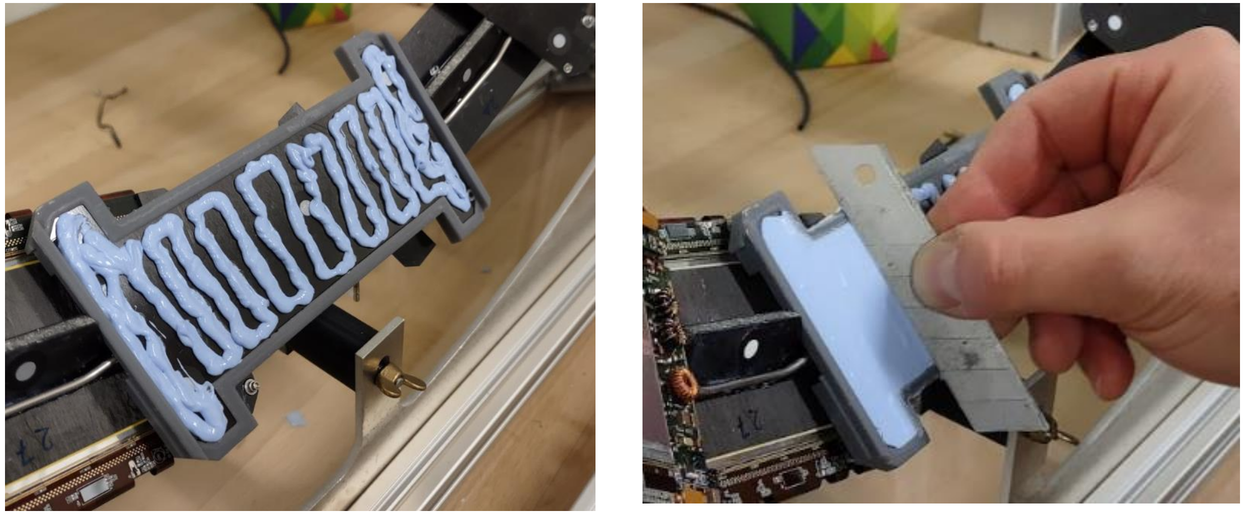



Fracture test results


Shear test results

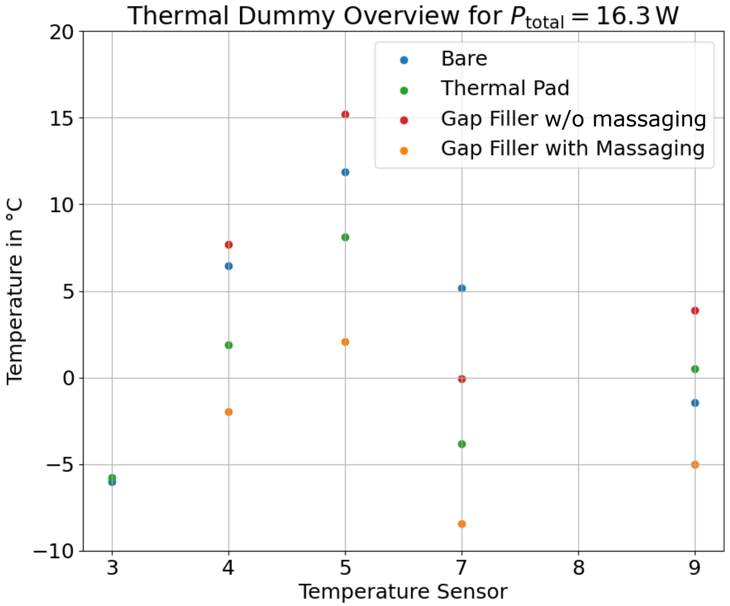
Application tests

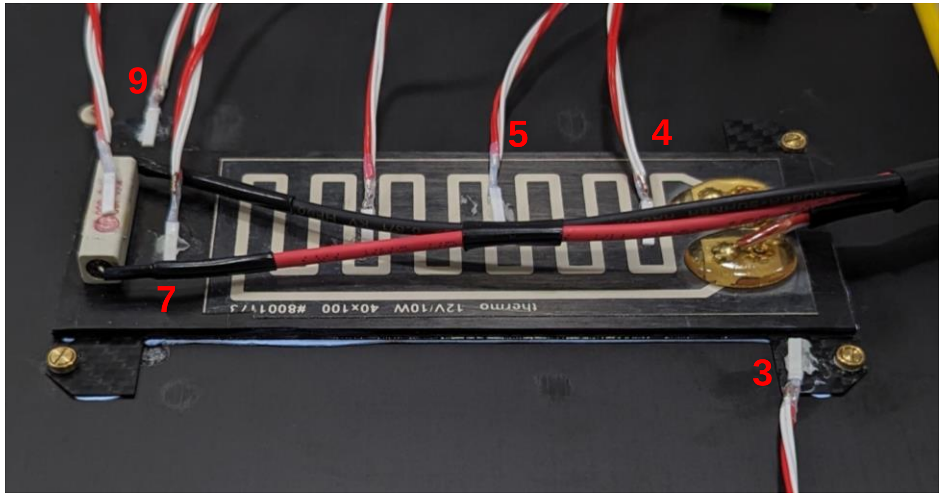
- Procedure (for endcaps Dees):
  - A stencil as large as the module real estate is positioned.
  - Gap Filler is applied on one side and a straight edge is used as squeegee to distribute the material evenly.
  - Place module and perform an in-plane circular motion many times to create a surface contact. Only very lille movement is necessary (~1 mm radius)
  - No way to verify good contact with a module during integration, only by learning how to apply reliably.
  - Tests with glass plate succesfull and reproducible.
- Similar tests are ongoing in Pisa for the TBPS rings.
  - Placing a mask is more difficult, as the module support plate is just as large as the module.

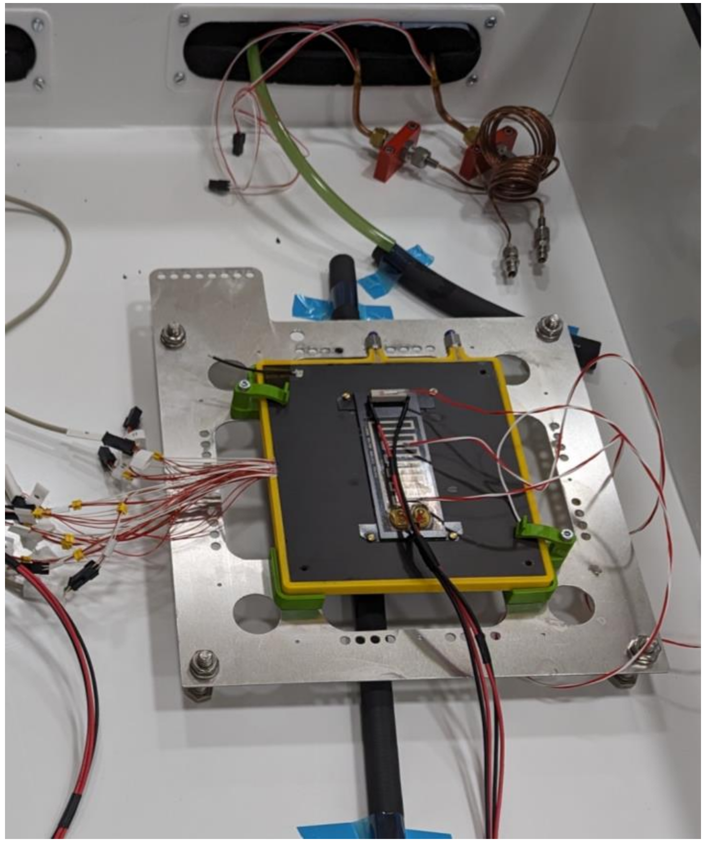


Thermal tests

- Currently ongoing thermal tests with realistic objects to optimize thermal contact.
  - A single PS module structure was built reflecting the geometry inside a Dee, including embedded temperature sensors.
  - A thermal dummy module was built as a heat load.
- Comparison of different thermal interfaces is ongoing.
- Tests with PS modules equipped with temperature sensors will follow.





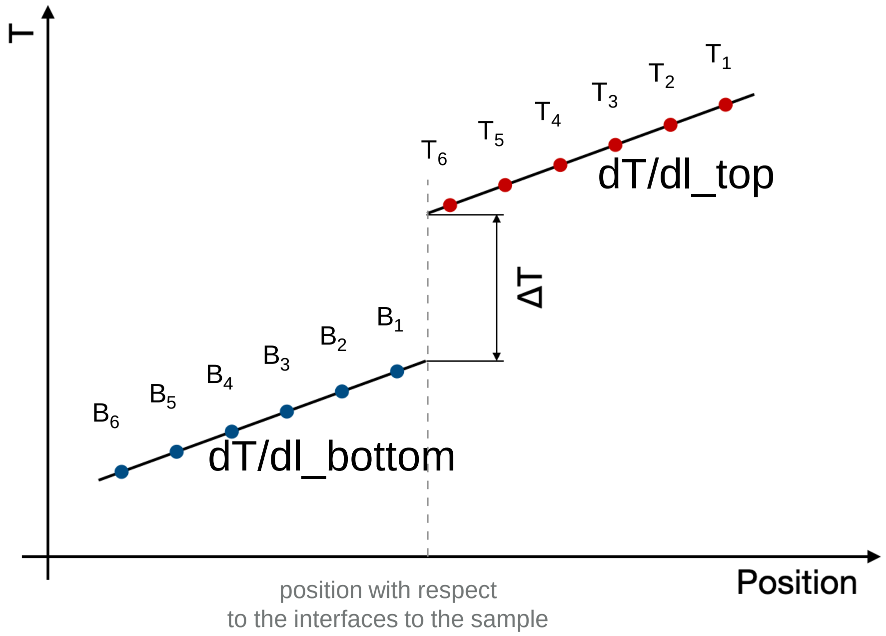


Summary & Outlook

- Thermal gap filler (TGF) materials have been studied for its thermal and mechanical performance before and after irradiation to 600 kGy.
  - Silicone based TGF harden as expected however the thermal coupling to the surface is maintained. The thermal conductivity of LVO is maintained better compared to the CVO variant.
  - Silicone free TGF does not harden and rather gets weaker with irradiation.
    - Thermal conductivity results are inconclusive, since different sample thicknesses showed different levels of degradation.
- Additional irradiations are planned, focusing on TGF3500LVO with improved sample design and to a higher dose level.
- Process of establishing a procedure to apply the material is underway. Tests of thermal performance comparing different thermal interfaces is ongoing.
  - Tests with an actual module would damage the module for other purposes when removing it.
    - Will be done as soon as we do not need prototype modules for other integration tests anymore.
    - A prototype module equipped with temperature sensors was prepared but not used for this test yet.

Backup

Thermal test setup – data processing



- Heat flux through the sample q is obtained from the temperature gradient: $\boldsymbol{q} = \frac{\boldsymbol{dT}}{\boldsymbol{dl}} \cdot \boldsymbol{k_{block}} \cdot \boldsymbol{A_{block}}$
- Temperature at the interfaces to the sample are obtained from a fit of the temperature measurements by extrapolation: $\boldsymbol{\Delta T} = \boldsymbol{T_{top}} - \boldsymbol{T_{bottom}}$ is measured.
- Thermal resistance is calculated: $\boldsymbol{R} = \frac{\boldsymbol{\Delta T}}{\boldsymbol{q}}$
- To remove the thermal resistance (R) of the contact, samples with different thicknesses (t) are measured.
  - The thermal conductivity is extracted from a linear fit: $\boldsymbol{k} = \frac{\boldsymbol{\Delta t}}{\boldsymbol{\Delta R}}$
- Reference measurements using brass blocks and sapphire glass are consistent with the nominal value within 0.5% in a combined fit.