# Diamond-like Heat Spreaders in the Form of Cheap Synthetic Graphite Tape for Cooling of Instrumentation in Radiation Intense Environments

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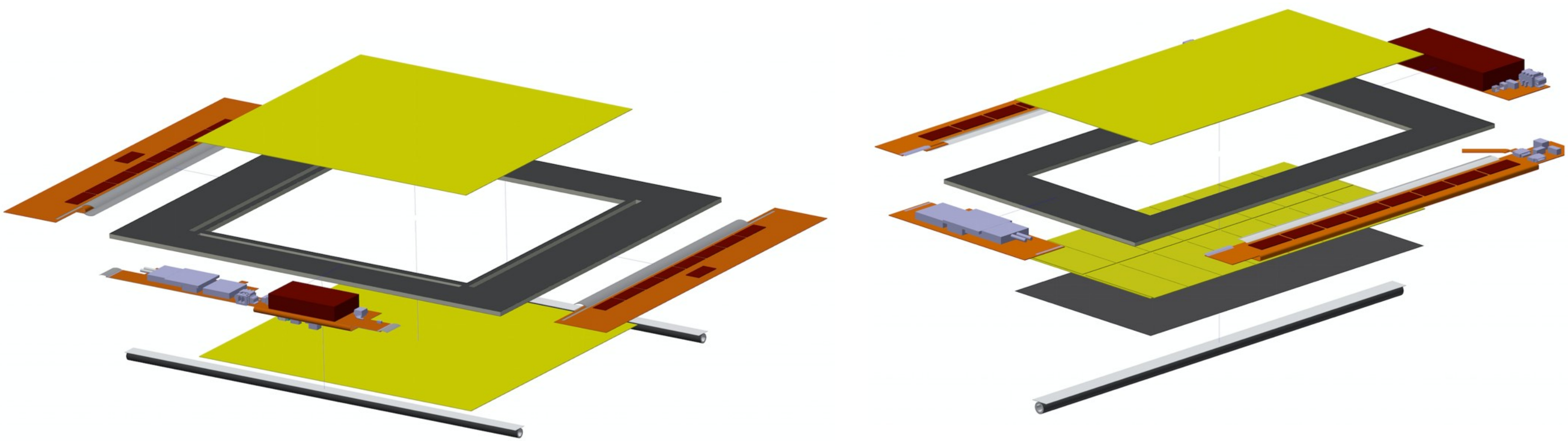
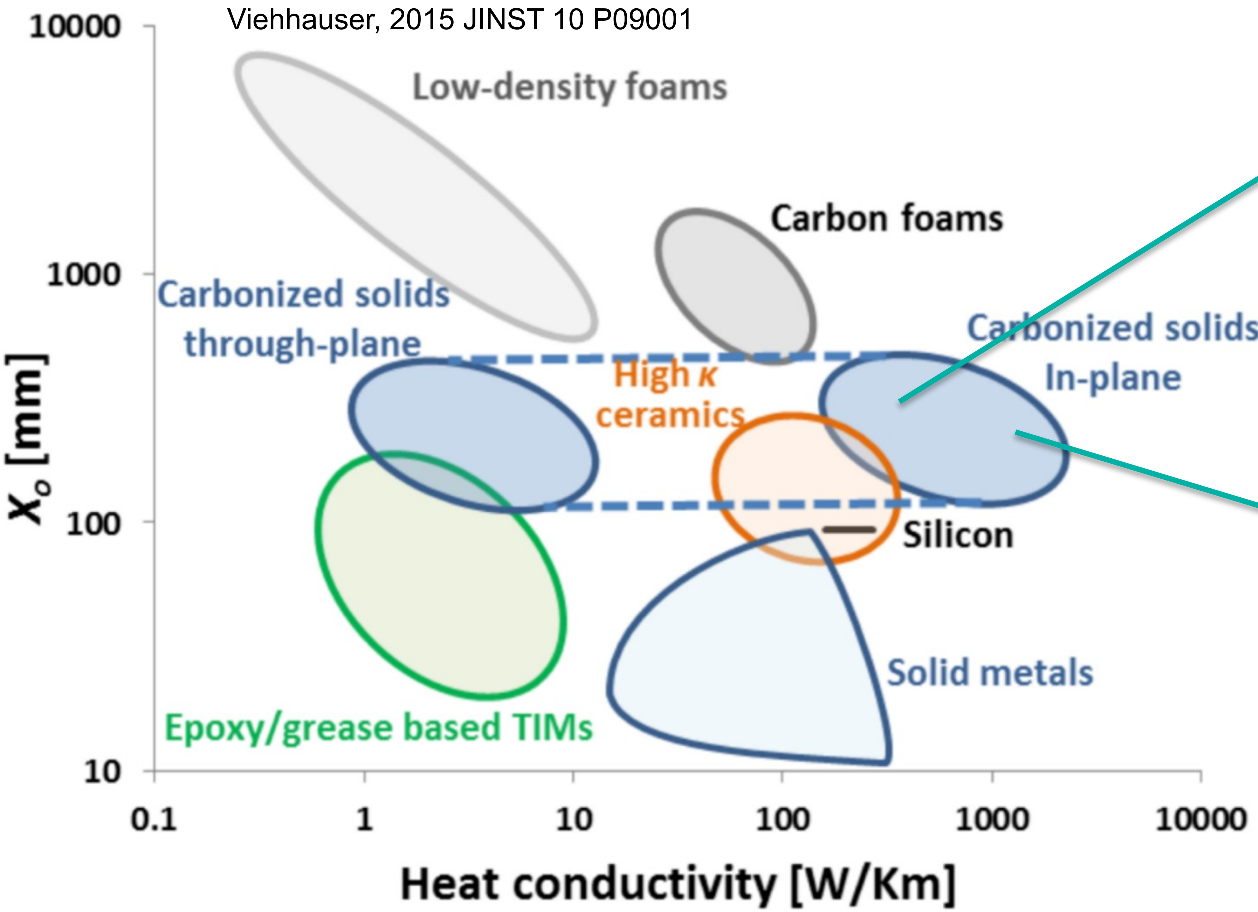
Institut für Experimentelle Kernphysik



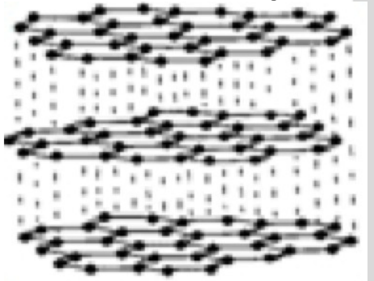
# Heat Conducting Materials




Carbon fiber (CF) in epoxy matrix (strong, medium heat conductivity, one-directional) expensive

Synthetic graphite: heat conductivity two-directional, double sided adhesives possible, cheap

# Synthetic Graphite (SG)



- **2004 first single layers of graphene fabricated by Geim, Novoselov. 2010 Nobel prize *"for groundbreaking experiments with the two-dimensional material graphene"***
- **Thin layers of graphene have a heat conductivity comparable to diamond**
- **Mass production methods by sintering polyimide tape above 3000°C (plasma oven) → carbon changes into liquid crystal phase and forms thermally conductive graphene layers in x,y directions**
- Graphene layer covered with pressure sensitive adhesive (PSA) layers on both sides: components can be glued to cooling structure with SG tape
- **Heat conducting tape with properties of diamond heat spreaders (but much cheaper) now used in mobile phones, LED screens, … → many manufacturers (providing customized tapes with customized shapes)**
- **Adhesive PET layers withstand HV of sensors**
- Other thermal transfer materials (carbon foam, phase changing tape, grease etc. phasing out → SG can replace „old" heat transfer materials)

# Can one use SGT in module construction?

- Many open questions
- Thermal conductivity good enough?
- Shear forces?
- Pull forces?
- Radiation hardness?
- How to build modules?

# Can one use SGT in module construction?

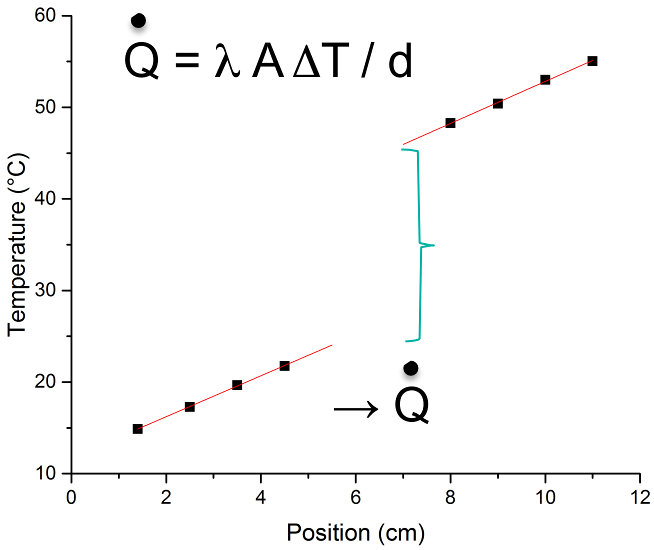
## Yes we can!

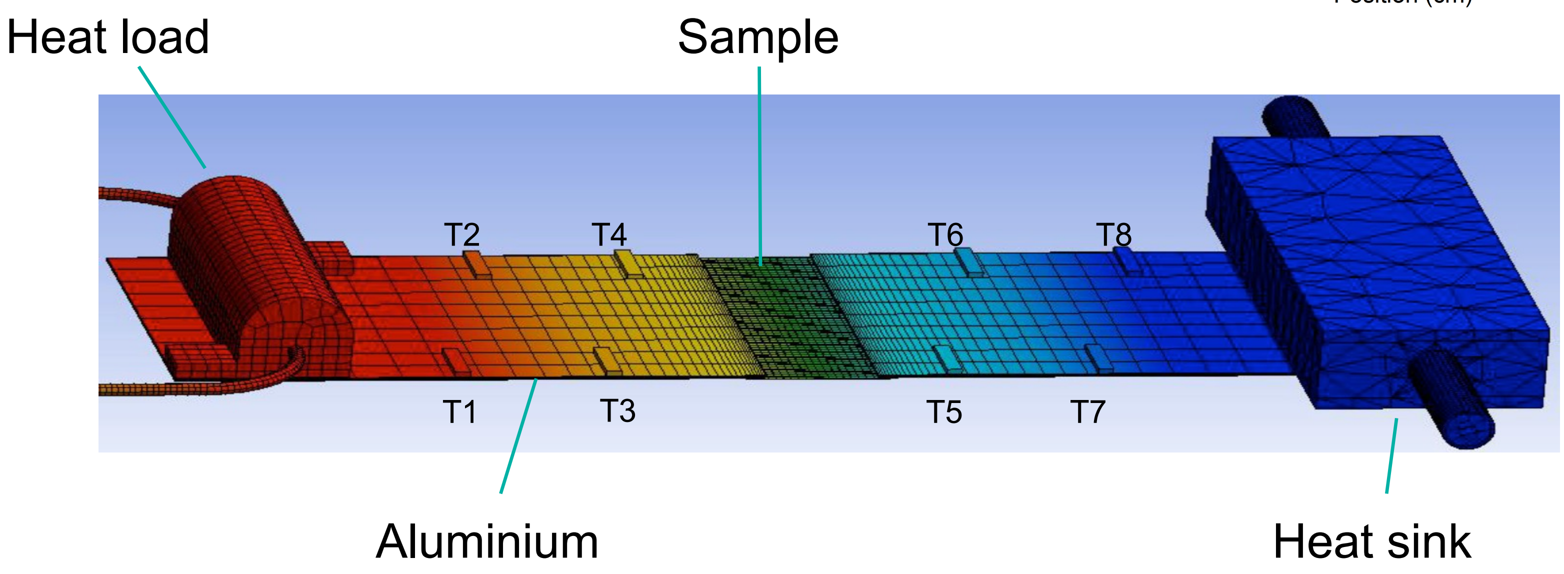
- Thermal conductivity ✓
- Shear forces ✓
- Pull forces ✓
- Radiation hardness ✓
- How to build modules ✓

Detailed measurements of SG properties and thermal performance of taped dummy module

# Thermal conductivity measurement

- **Problem** to measure heat conductivity in thin layer: how much heat goes through the layer?
- **Basic idea:** conduct heat via <u>known</u> conductor between heat source, sample and heat sink and determine heat flow from temperature drop in the known conductor and heat losses from change of slope



# Thermal conductivity of various SGTs

Table 4.3: **Thermal resistance measurements of different SGTs.** The thermal conductivity was calculated with the measured thermal resistance. Considering the tape as a one-layered object an effective thermal conductivity can be determined.

| SGT | Graphite (µm) | Total (µm) | $\lambda_{Gr.,man.}$ $\left(\frac{W}{mK}\right)$ | R $\left(\frac{K}{W}\right)$ | $\lambda_{Gr.}$ $\left(\frac{W}{mK}\right)$ | $\lambda_{eff.}$ $\left(\frac{W}{mK}\right)$ |
|---|---|---|---|---|---|---|
| FGS-020[1] | 200 | | 600 | 6.9 (±0.3) | 216 (±9) | |
| FGS-0125[1] | 125 | | 700 | 11.8 (±0.5) | 203 (±9) | |
| BM1000[2] | 150 | | 600 | 21.2 (±0.6) | 95 (±3) | |
| BM1000[2] | 70 | | 600 | 22.9 (±0.9) | 187 (±7) | |
| GS2000[2] | 45 | | 1200 | 14.6 (±0.8) | 455 (±25) | |
| TSM-1500D[3] | 25 | 49 | 1500 | 13.9 (±1.3) | 864 (±78) | 442 (±40) |
| DSN5025-05C05C[4] | 25 | 35 | 1500 | 14.5 (±1.3) | 824 (±74) | 593 (±53) |
| DSN5025-12C12C[4] | 25 | 49 | 1500 | 14.3 (±1.3) | 834 (±74) | 427 (±38) |
| DSN5040-12C12C[4] | 40 | 64 | 1200 ✓ | 12.4 (±0.8) | 602 (±37) | 379 (±23) |

[1] Amec Thermasol [The16b],[The16a]
[2] Shenzhen JRFT Electronic Technology Co., Ltd. [JRF16a],[JRF16b]
[3] Shenzhen Laimeisi Silicon Industry Co., Ltd [Lai16]
[4] Suzhou Dasen Electronics Material Co, Ltd. [szd14]

Master thesis
S. Maier, KIT 2016

# Comparison of synthetic graphite with carbon fiber

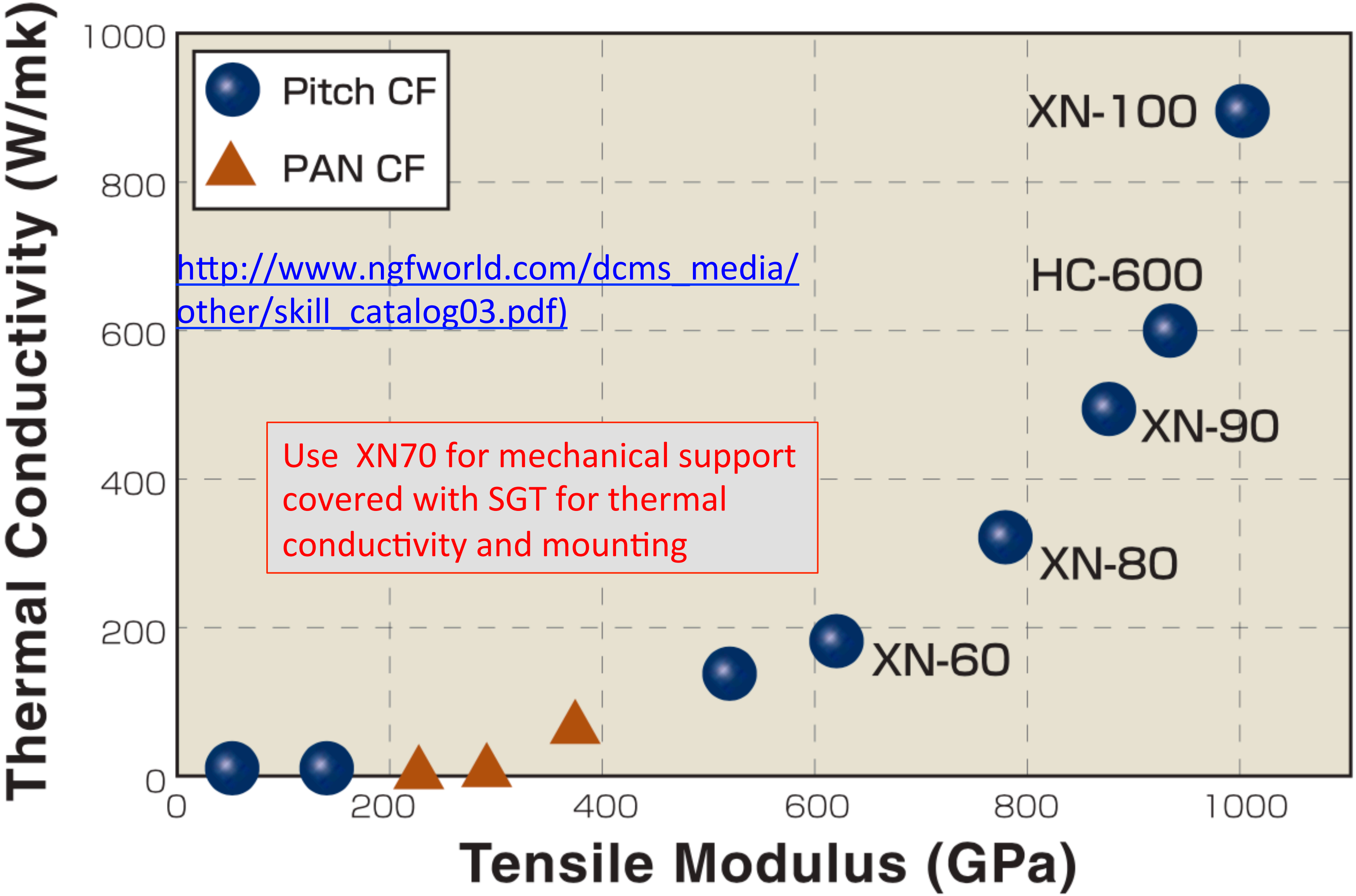
| | CF: Mitsubishi* 0° | CF: Mits. 0°/90°/0° | CF: Granoc[1] 0° | SG: DSN5040[2] |
|---|---|---|---|---|
| λx (W/mK) | 270 | 143 | 220 | 600 |
| λy (W/mK) | ~1.6 | 80 | ~1.6 | 600 |
| λz(W/mK) | ~1.6 | ~1.6 | ~1.6 | 20 |
| d (μm) | 78 | ~200 | 50 | 40+12+12(adhesive) |
| ρ ($g/cm^3$) | 2.38 | 2.38 | 2.38 | ~1.6 (average) |

**SGT DSN5040 far better thermal performance than CF sandwiches, but latter much stronger. So CF support covered with SGT yields mechanically strong, lightweight structures with a good thermal performance**

[2]from DSN: http://szdasen.en.alibaba.com

*K13D2U fiber from Mitsubishi Ten Cate prepreg

[1]E9026A-05S from Nippon Graphite Fiber (NGF) http://www.ngfworld.com/dcms_media/other/NGFPPHM2014.pdf




http://www.ngfworld.com/dcms_media/other/skill_catalog03.pdf)

Use XN70 for mechanical support covered with SGT for thermal conductivity and mounting

**One observes a factor 3 change in thermal conductivity if the tensile modulus changes by only 20% for high modulus fibers.** High modulus graphite expensive, XN70 and below cheap.

# Radiation resistance of different materials

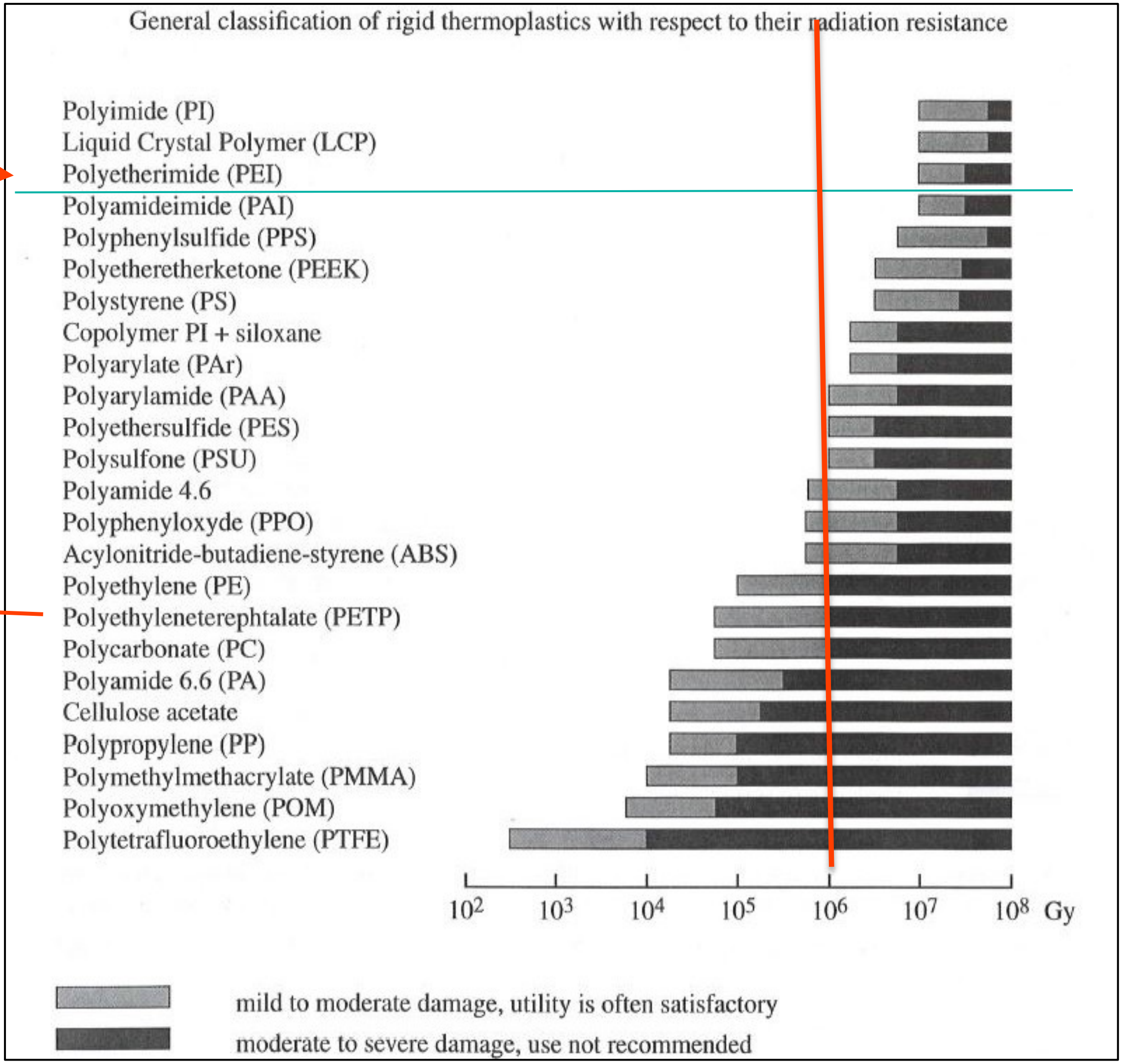
Airex R82

1 MGy is the expected highest dose level in the Phase 2 Upgrade Outer Tracker

Airex T92

From CERN yellow report

CERN 98–01
Technical Inspection and Safety Commission
18 May 1998

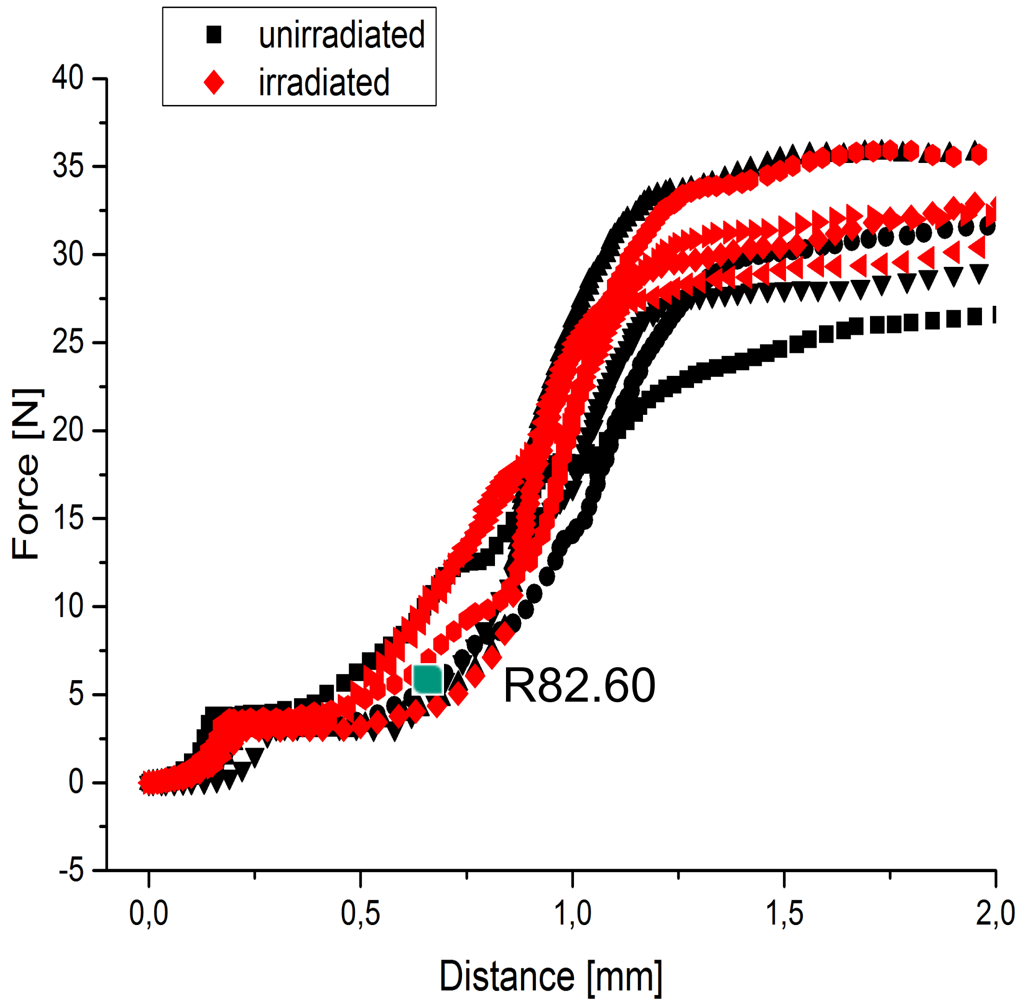


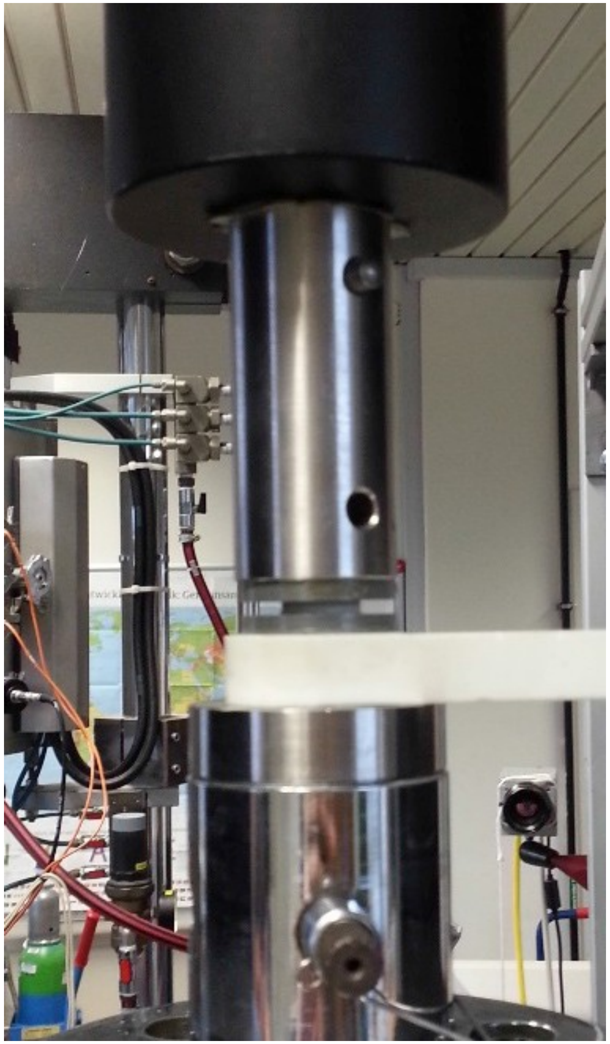
# Airex irradiation

- **Irradiation with 23 MeV protons at the Karlsruhe Cyclotron up to $5.10^{14}$ p/cm²**
- Cheaper foams, like Rohacell pulverized after irradiation
- All different Airex foams found to be radiation hard
- Checked how much pressure foam can withstand after irradiation
- Checked elasticity of CF sandwiches with irradiated foam

Samples: A=176,7 mm², d=10mm

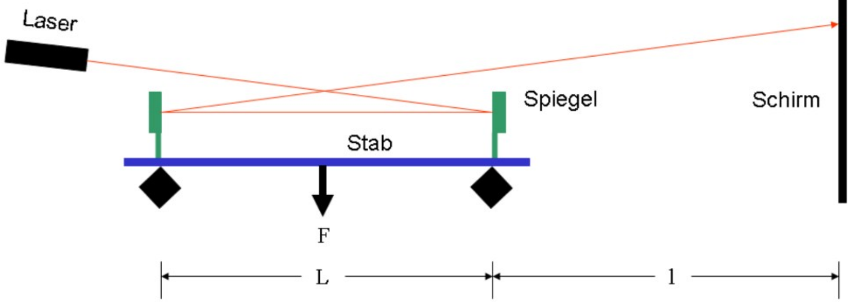
# Pressure tests

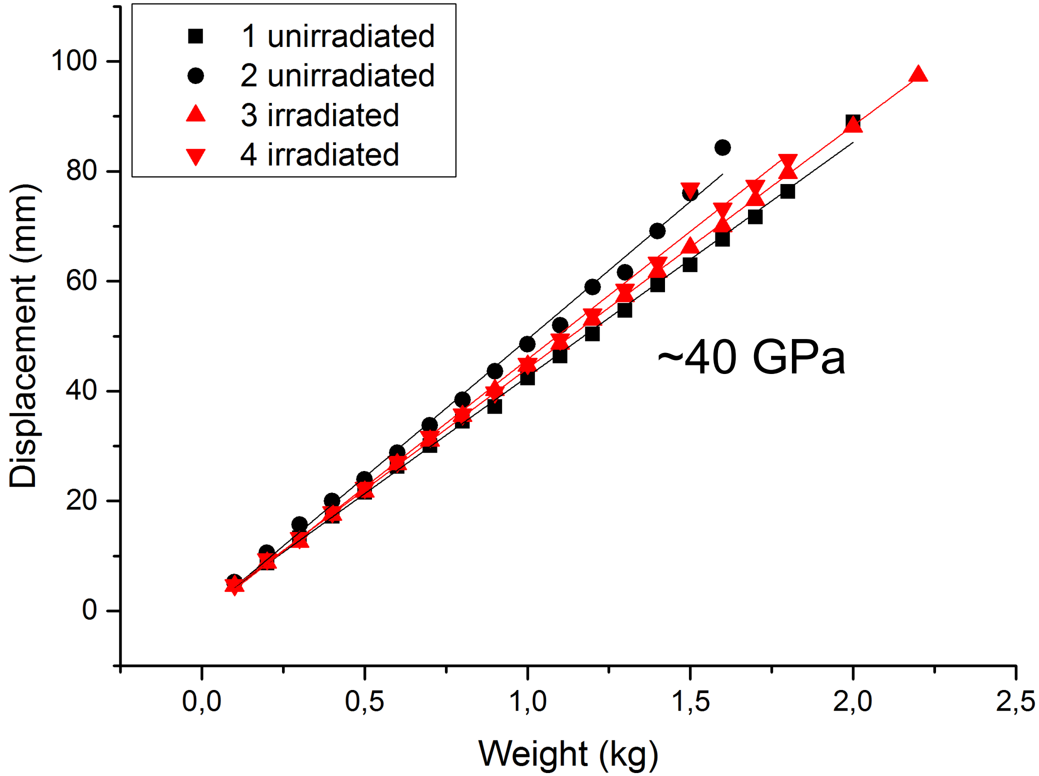


# E-modulus CF Airex sandwich

d=2.8mm ; b=25mm

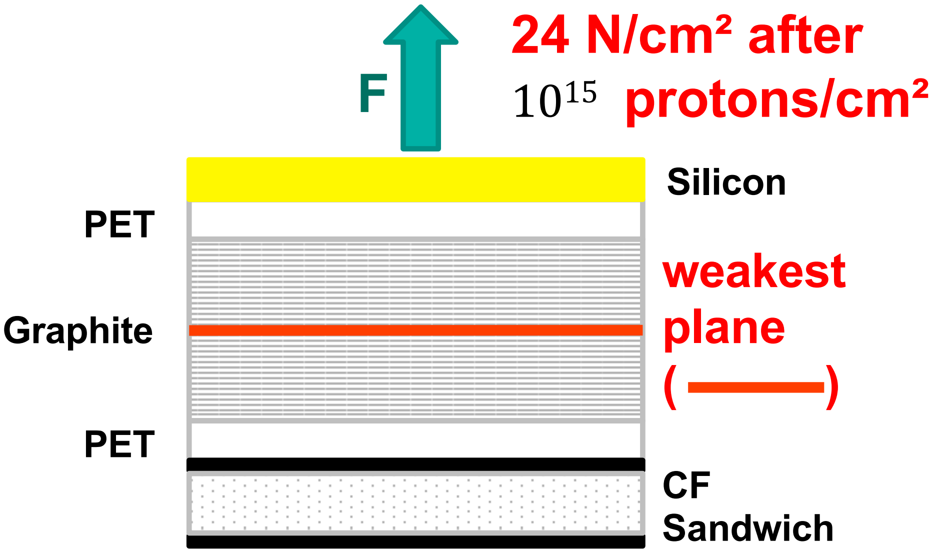



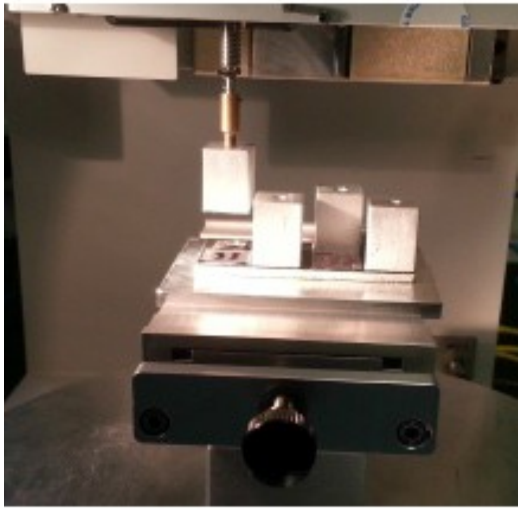




Same behaviour before and after irradiation

# Pull Forces

- Maximal force allowed on SGT, measured by pull test machine, was about 40 N/cm². Break at weakest point: graphene layers.

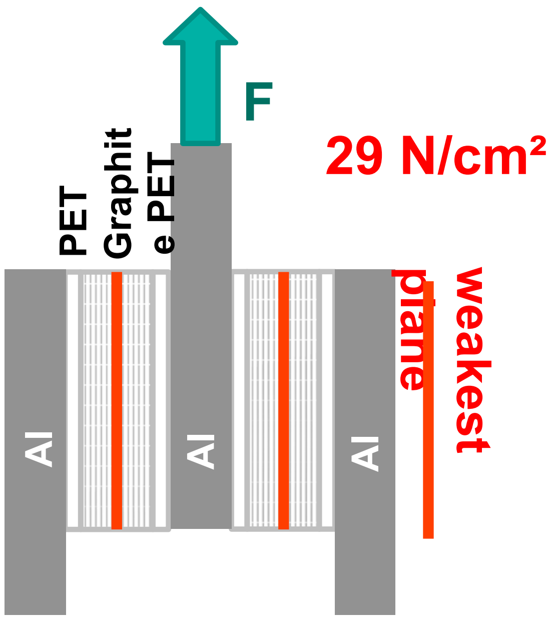


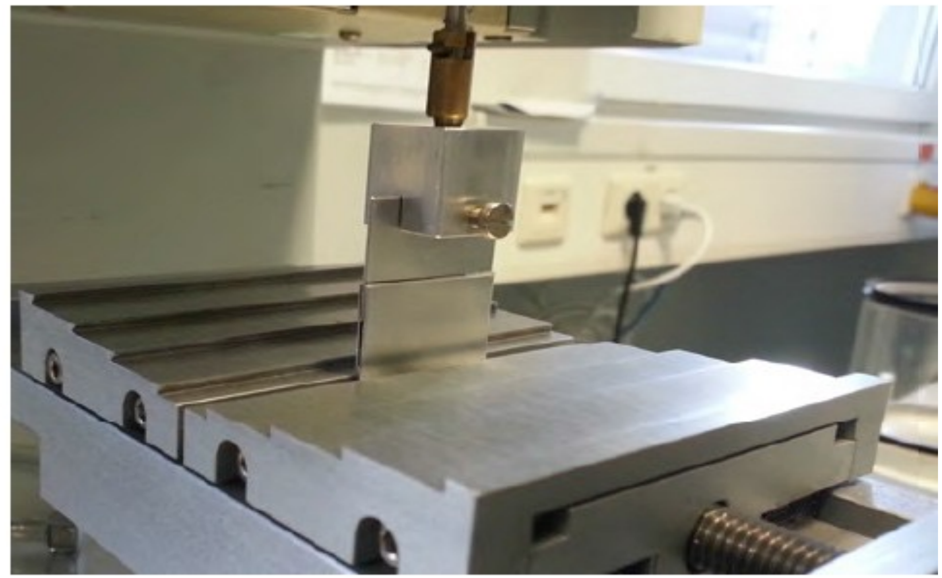



- Irradiation of $10^{15}$ protons/cm² reduces strength by about 40%
- Area of cooling pipe ~5cm² → max force of about 100 N or 10 kg

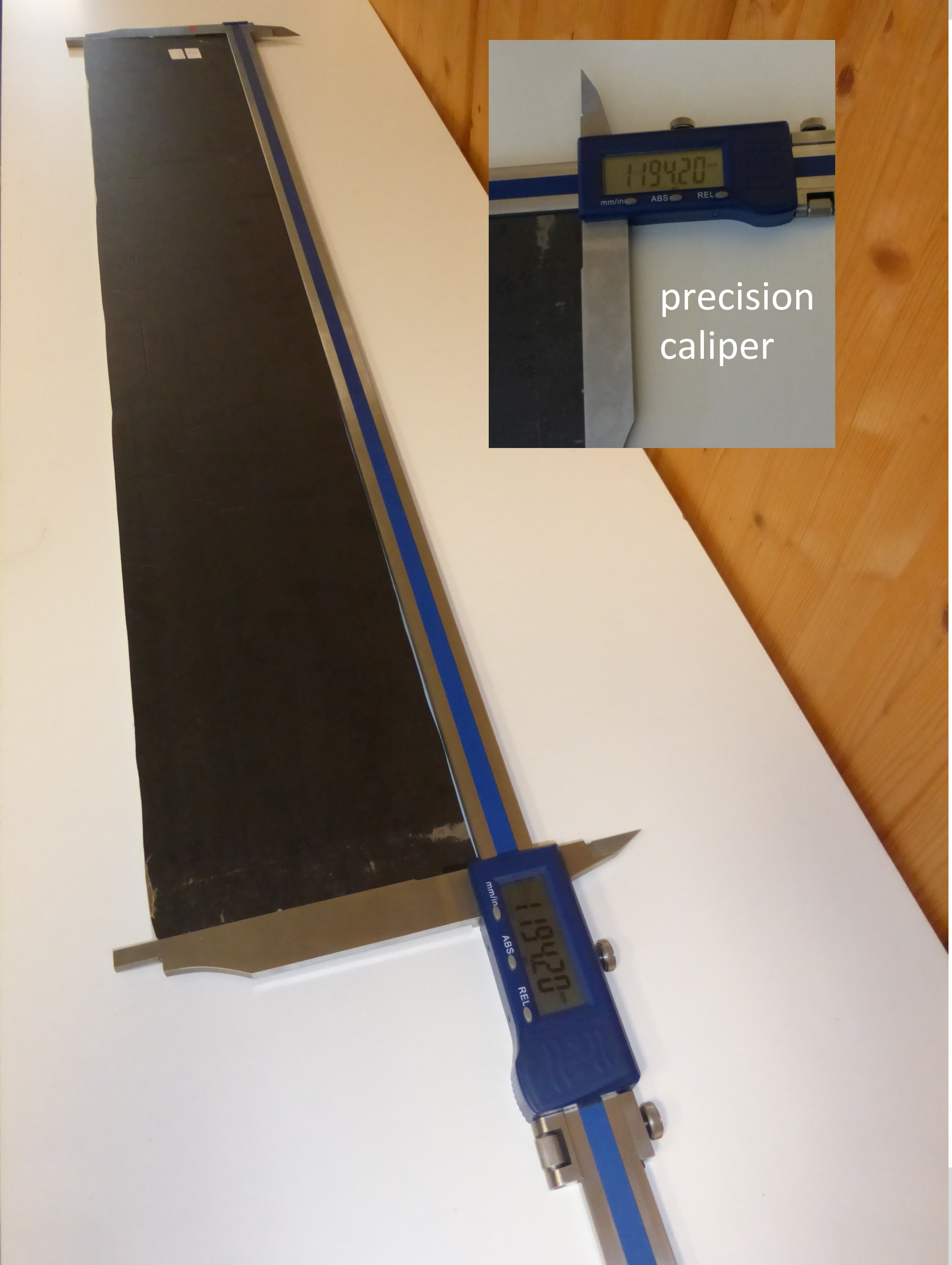
# Shear Forces

- The graphene layers in the SGT are only weakly connected by Van-der-Waals forces, so they easily slide over each other



- 29 N/cm² enough to withstand thermal stress due to different CTE between cooling pipe and module
- Thermal conductivity of SGT was not affected by many thermal cycles between 20ºC and -30ºC

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# CTE measurements (120 cm long pieces dT=22-(-18)=40 $^0$C)

**Sandwich:**

9 mm Airex T92.80
(T92=PET foam, 80=80 kg/m$^3$)

Carbon fiber skins (0-90$^o$)
2x50 µm Granoc E70

**CTE = (4 ± 1) 10$^{-6}$ /K**
**(matches very well silicon)**

Airex T92.80 alone
**CTE = (135 ± 10) 10$^{-6}$ /K**

Granoc alone (NFG info)
**CTE = (-0.2 ± 0.2) 10$^{-6}$ /K**

AIREX® T92 is a closed-cell, PET thermoplastic and recyclable polymer foam with very good mechanical properties and an outstanding price / performance ratio.
It has an extraordinary resistance to fatigue, is chemically stable and has negligible water absorption. (PET is an excellent water barrier material!) It is thermally stable during high temperature processing and post curing without after expansion or outgassing. T92 is designed for easy use with all resin systems and processing technologies.
AIREX® T92 is ideally suited as a core material for a wide variety of lightweight sandwich structures subjected to static and dynamic loads and/or exposed to elevated temperatures during manufacturing.

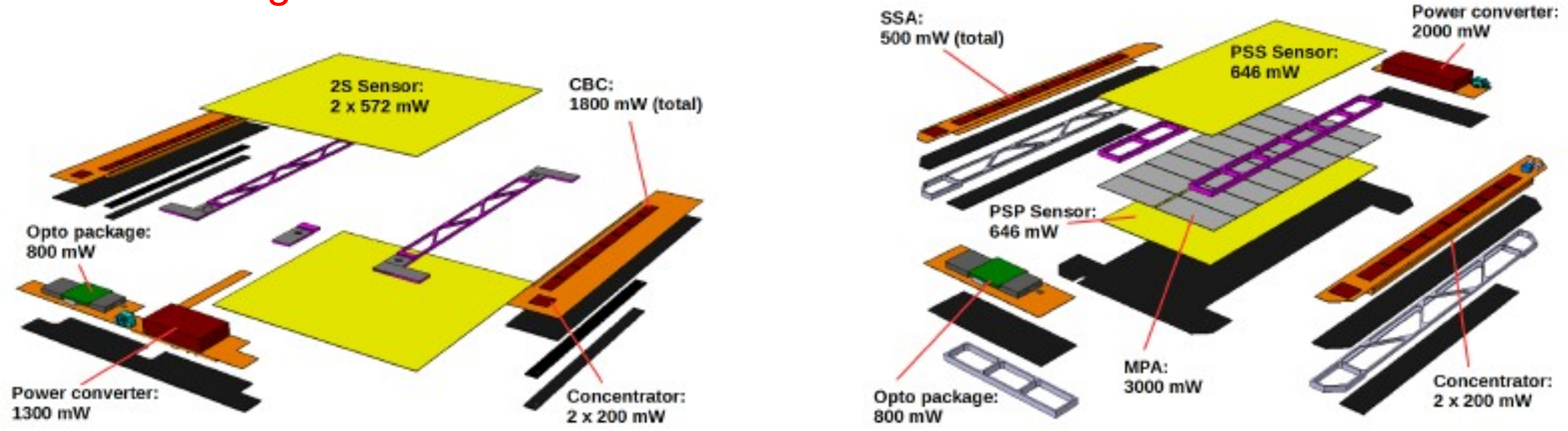


- Easy to process with all types of resin and lamination processes
- High process temperature up to 150 °C (302 °F)
- Outstanding fatigue strength
- Best-in-class resin uptake
- Very high chemical stability
- Good adhesion (skin-to-core bond)
- Excellent long term thermal stability up to 100 °C (212 °F)
- No water absorption, after expansion nor outgassing
- Recyclable and recycled material
- Highly consistent material properties
- Comprehensive material traceability (machine-readable batch information on each foam sheet)

**Verified that no after expansion or expansion by humidity occurred (max. 30 µm for 9 mm sandwich)**

# CMS Silicon tracker modules

## Baseline design




## Taped module design (No gluing, just pressing few parts together)

# Carbon Fiber Sandwich covered with SGT

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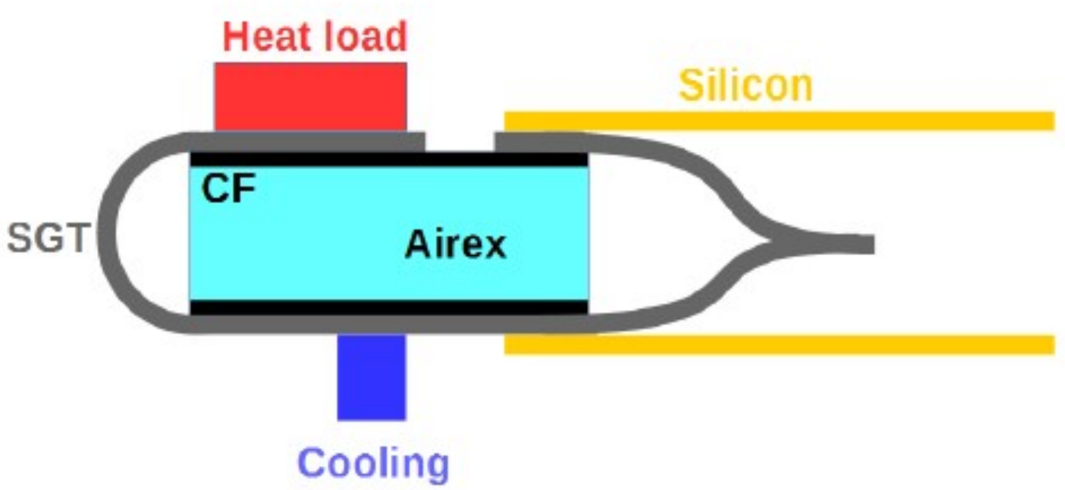
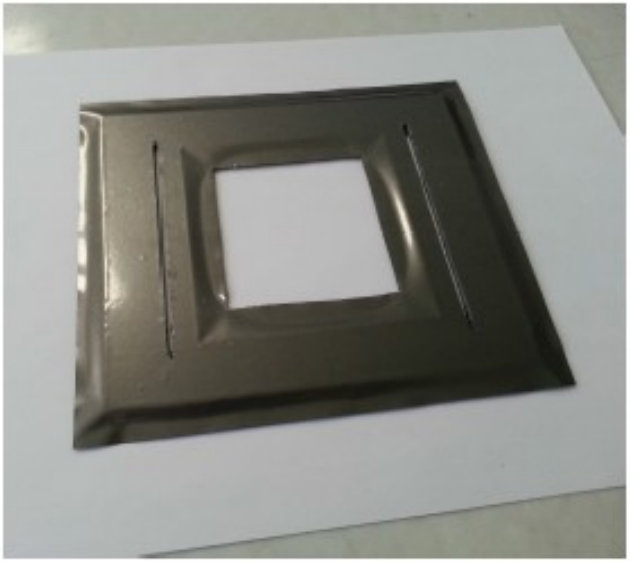
**Granoc-Airex sandwich has same CTE as silicon, so NO thermal stress on sensor**



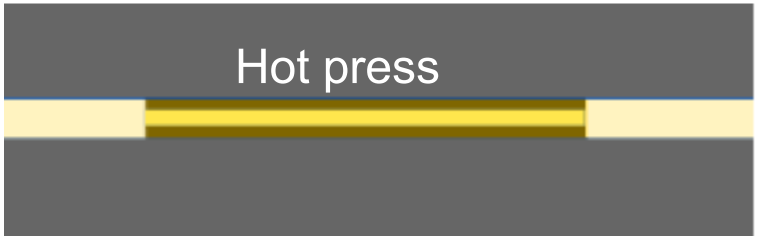



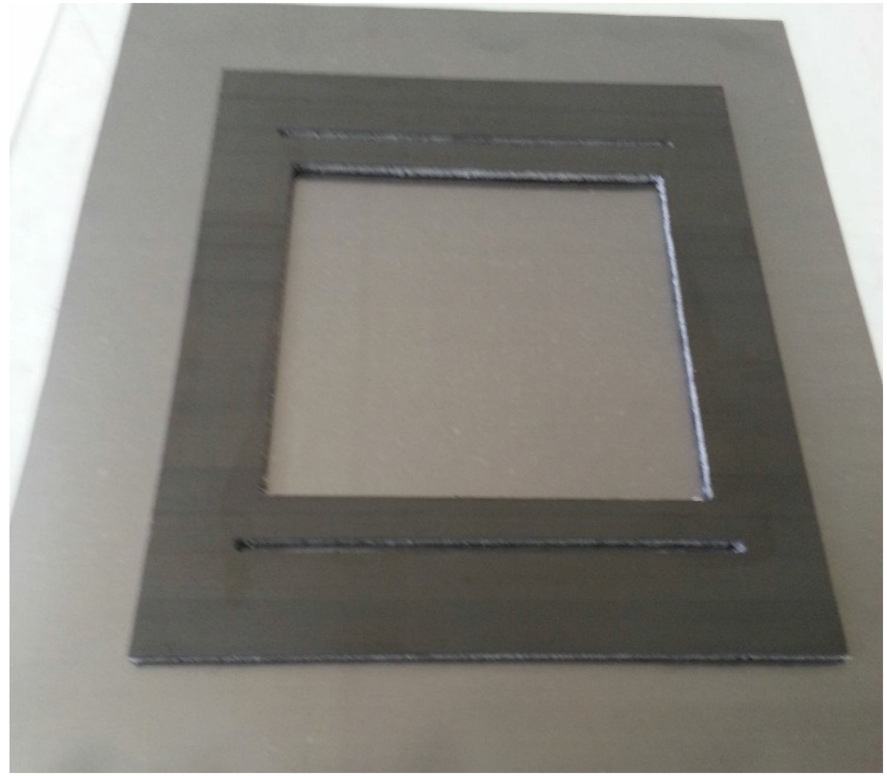
**Left:** **Cooling of the upper sensor by taping the SGTs of bottom and top together. The sensor can be thermally isolated from the electronics by a cut in the graphite layer of the SGT.**

**Right:** **The CF sandwich after gluing the SGT to it.**

# CF–Airex sandwich with synthetic graphite heat spreader





- Sandwich
  - Hot press process (4bar, 120°C, 2h)
  - 0°/90°/ Airex /90°/0°

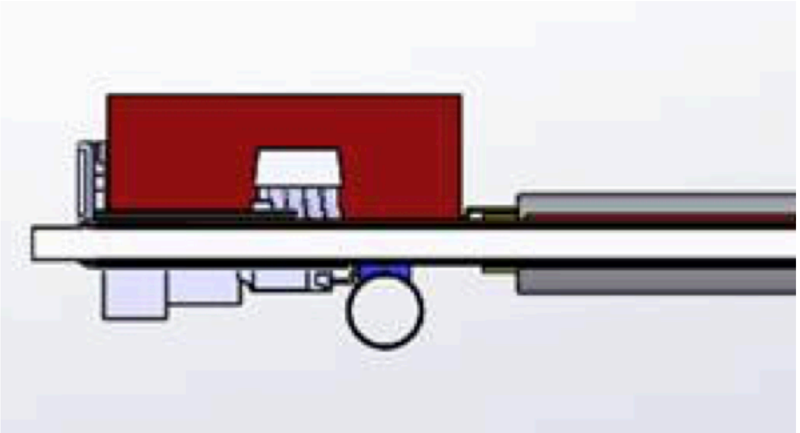
**Sandwiches made by co-curing foam with 2 layers of prepregs (0/90$^0$) on each side. Here 1.5 mm thick Airex R82.60 foam with 2x50 µm Granoc CF from Nippon Graphite Fiber (NGF) on top and covered on both sides with SG tape (DNS5040 40 µm graphite +12 µm adhesive layer (from** Suzhou Dasen Electronics Material Co.)

# Attachment of cooling pipes: pressed directly on SGT
# Optimal thermal contact

**Advantages of gluing instead of screwing:**

**large contact area ->**

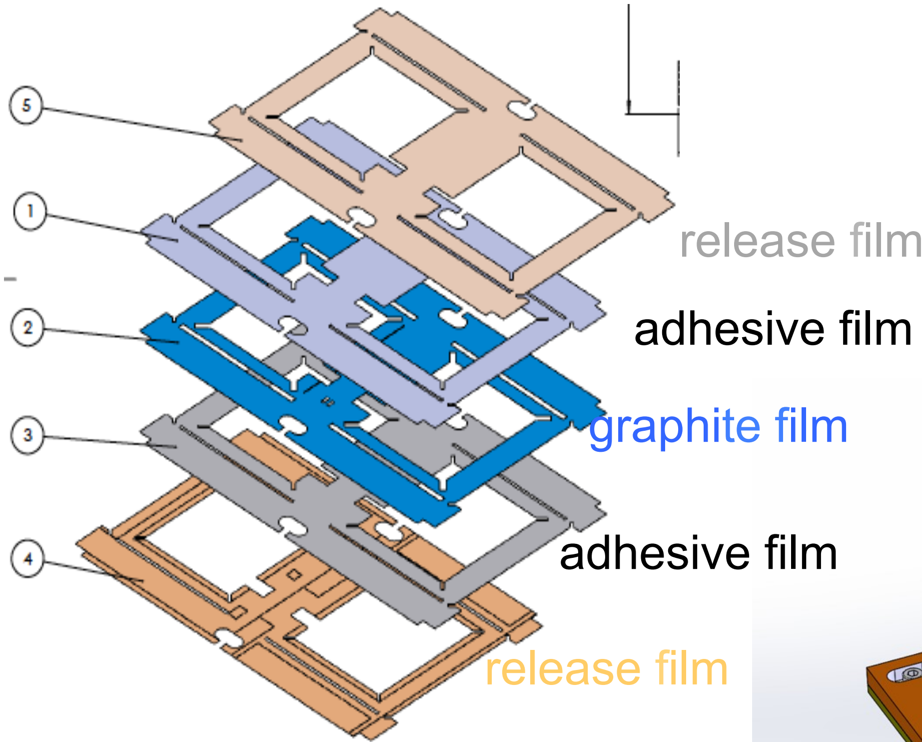
1) **better thermal performance**
2) **less weight**

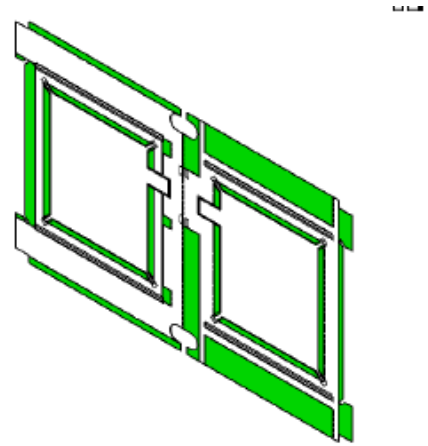


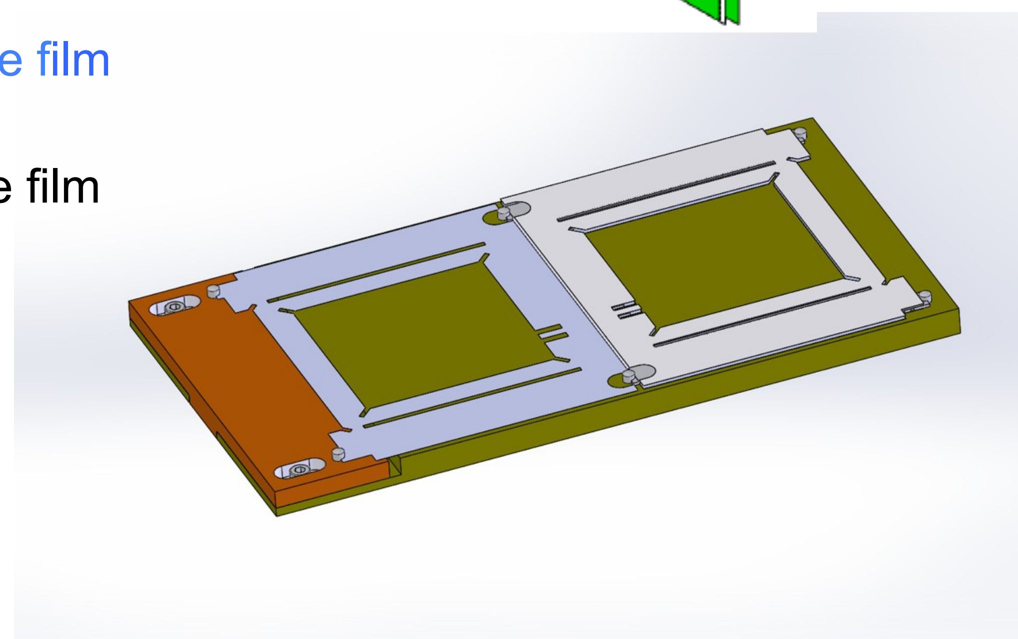
**Taped module: connect module with SGT to 0.3 x 2 mm thick Al cap = 2x0.3 g < 2% of module weight (order of magnitude better than screwing)**

$\Delta T$ =0.6 K for 9 $mW/mm^2$ (2S)
$\Delta T$ =1.8 K for 27 $mW/mm^2$ (PS)

# Tape Applicator





# Grounding SGT tapes

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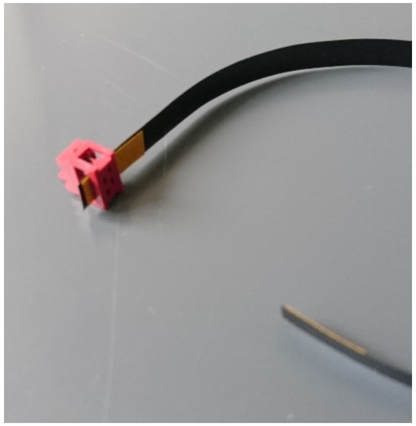
In the current module design each conductive part should be grounded
The graphite is conductive and covering the whole sandwich.

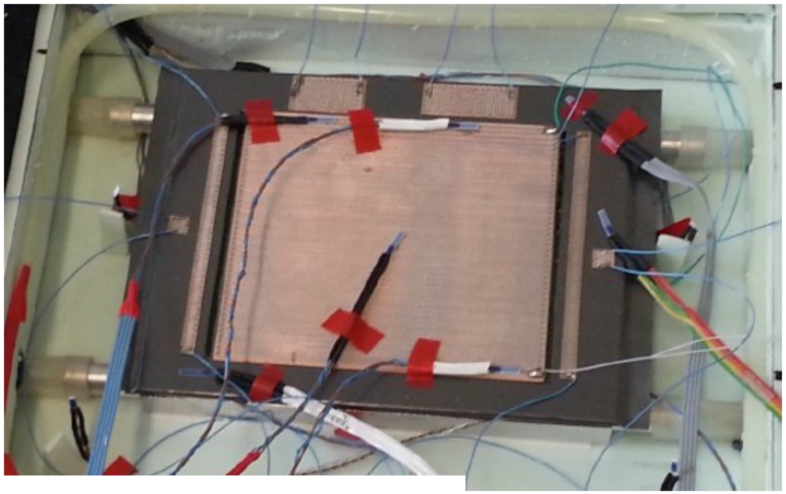
Grounding of whole sandwich by adding SGT tail with a solderable MicroMatch connector

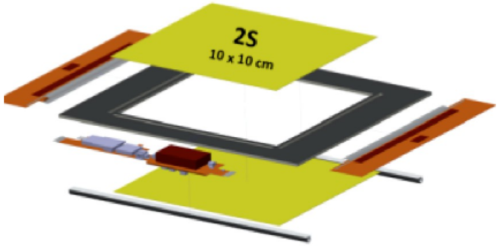


tested on many samples: $R_c<1\ \Omega$

# Dummy Module Thermal Measurements

## 2S

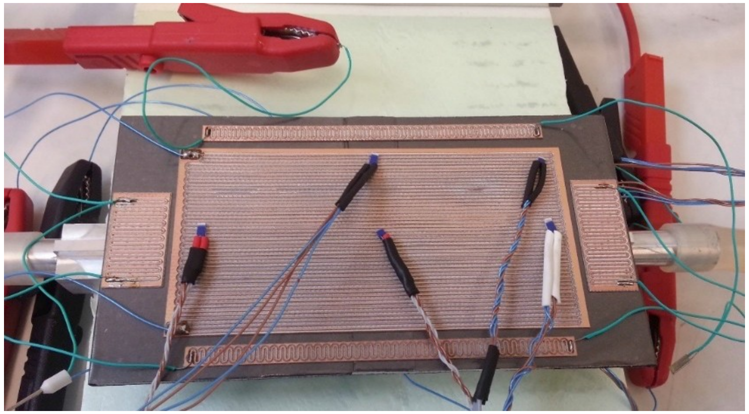


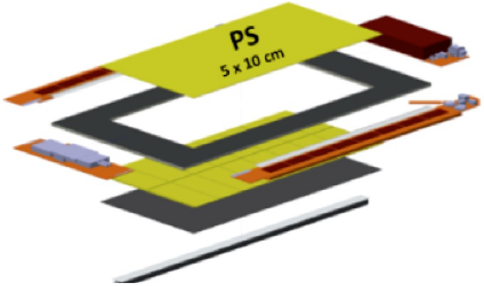



$P \approx 5W$

Measurement $\Delta T_{max} = 4.1$ºC
(in good agreement with
simulated $\Delta T_{max} \pm 1$ºC)

## PS



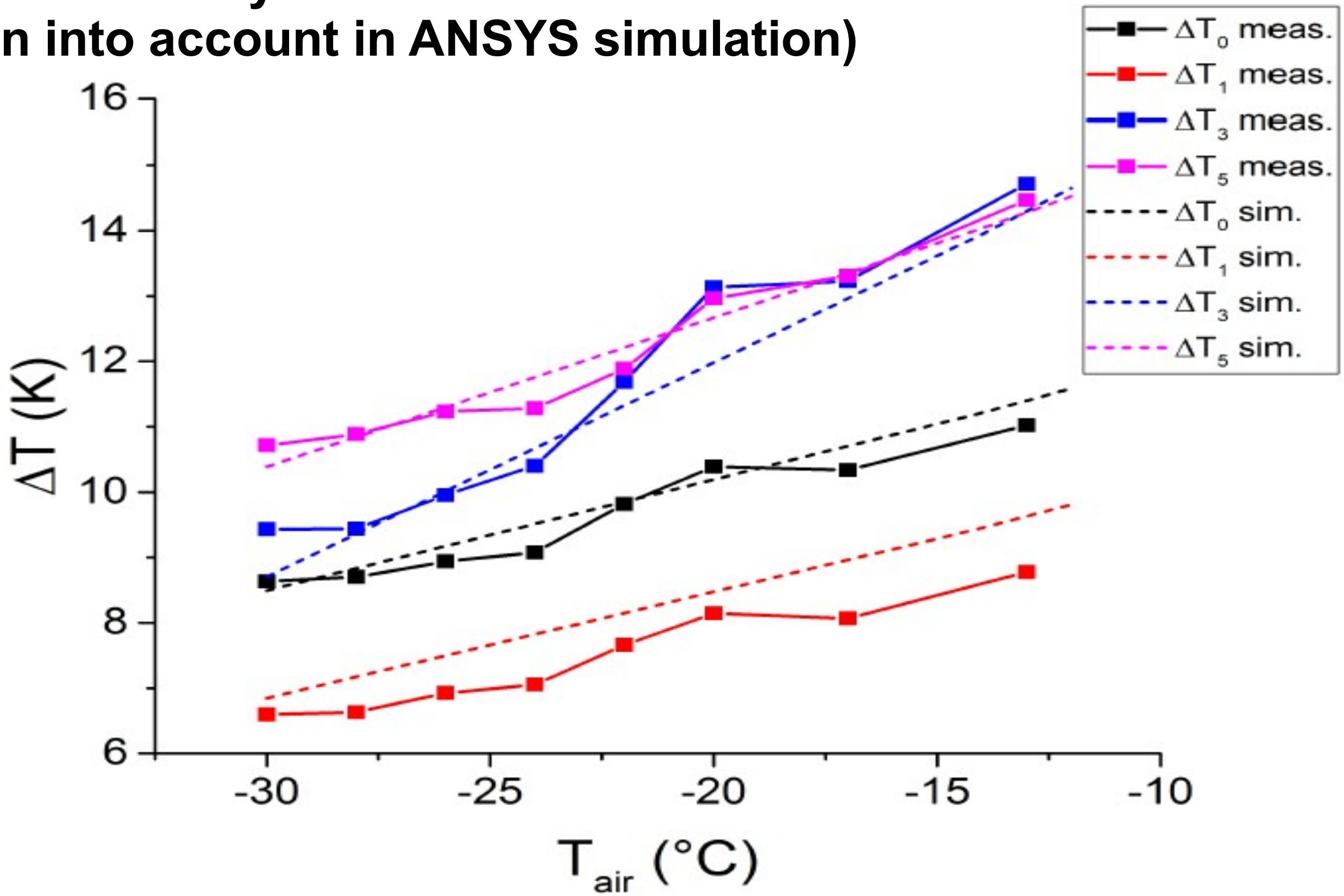



$P \approx 7.5W$

Measurement $\Delta T_{max} = 10.8$ºC
(in good agreement with
simulated $\Delta T \pm 1.5$ºC)

# Measurements as function of temperature in freezer

- **Simulation and measurements are in good agreement.**
- **Slope caused by convection and radiation (taken into account in ANSYS simulation)**



# GANTRY FOR SEMI-AUTOMATIC MODULE PRODUCTION

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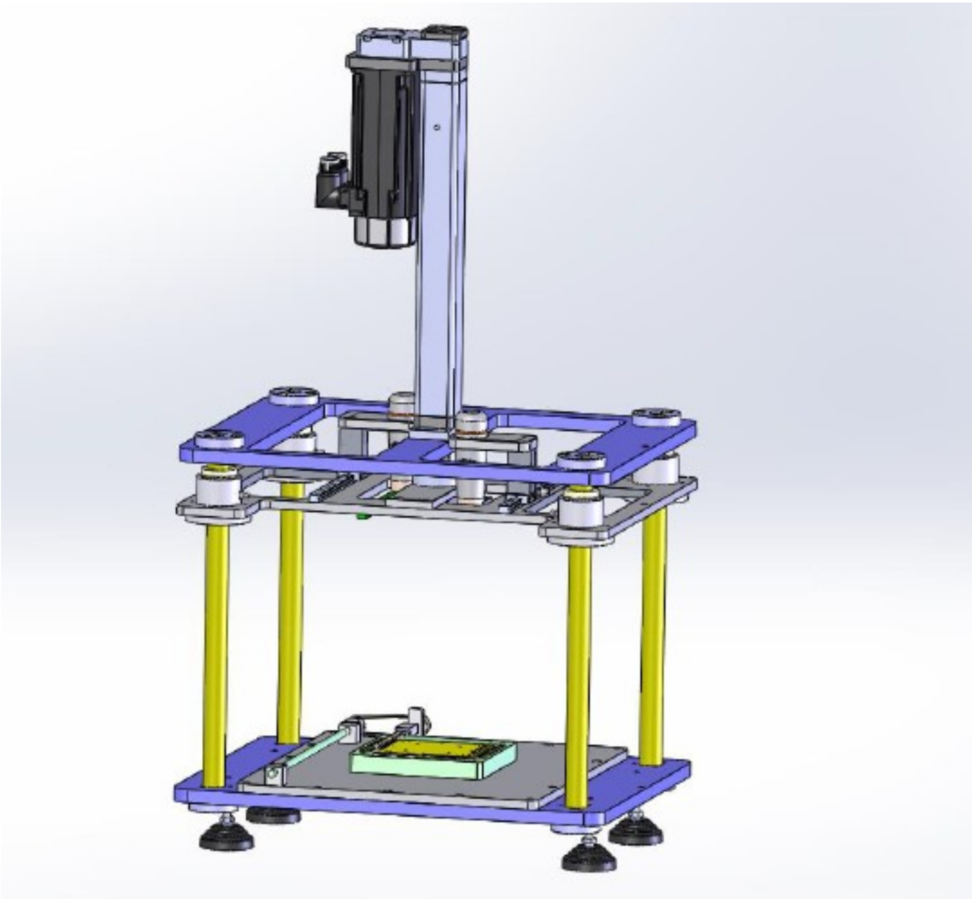
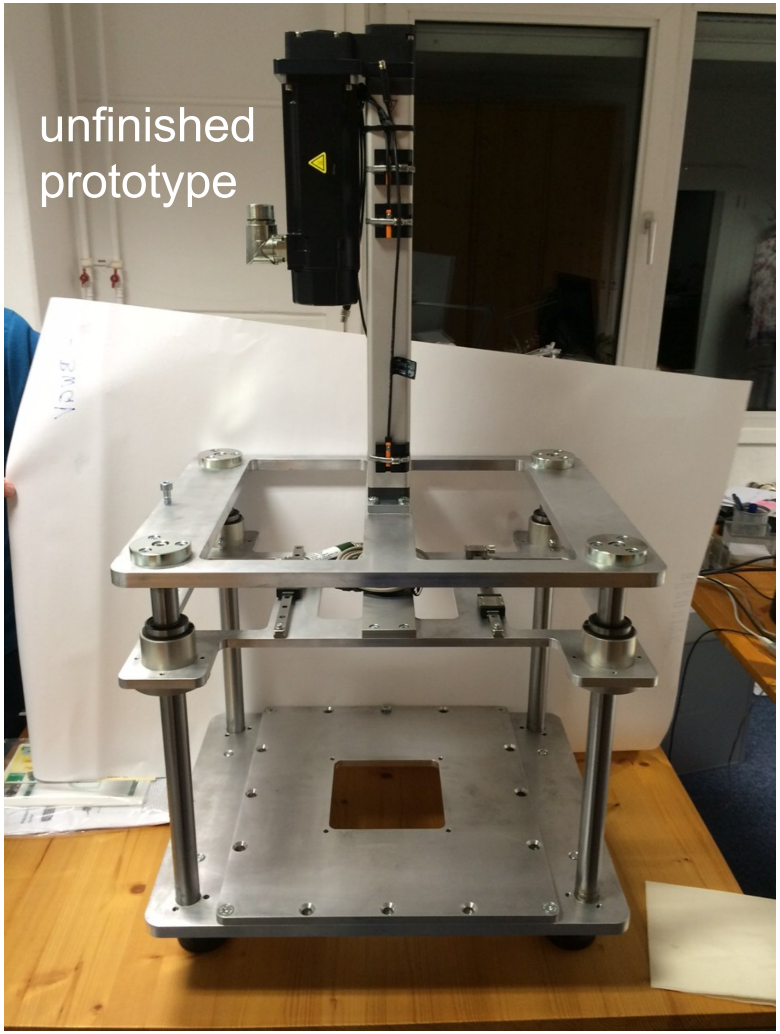
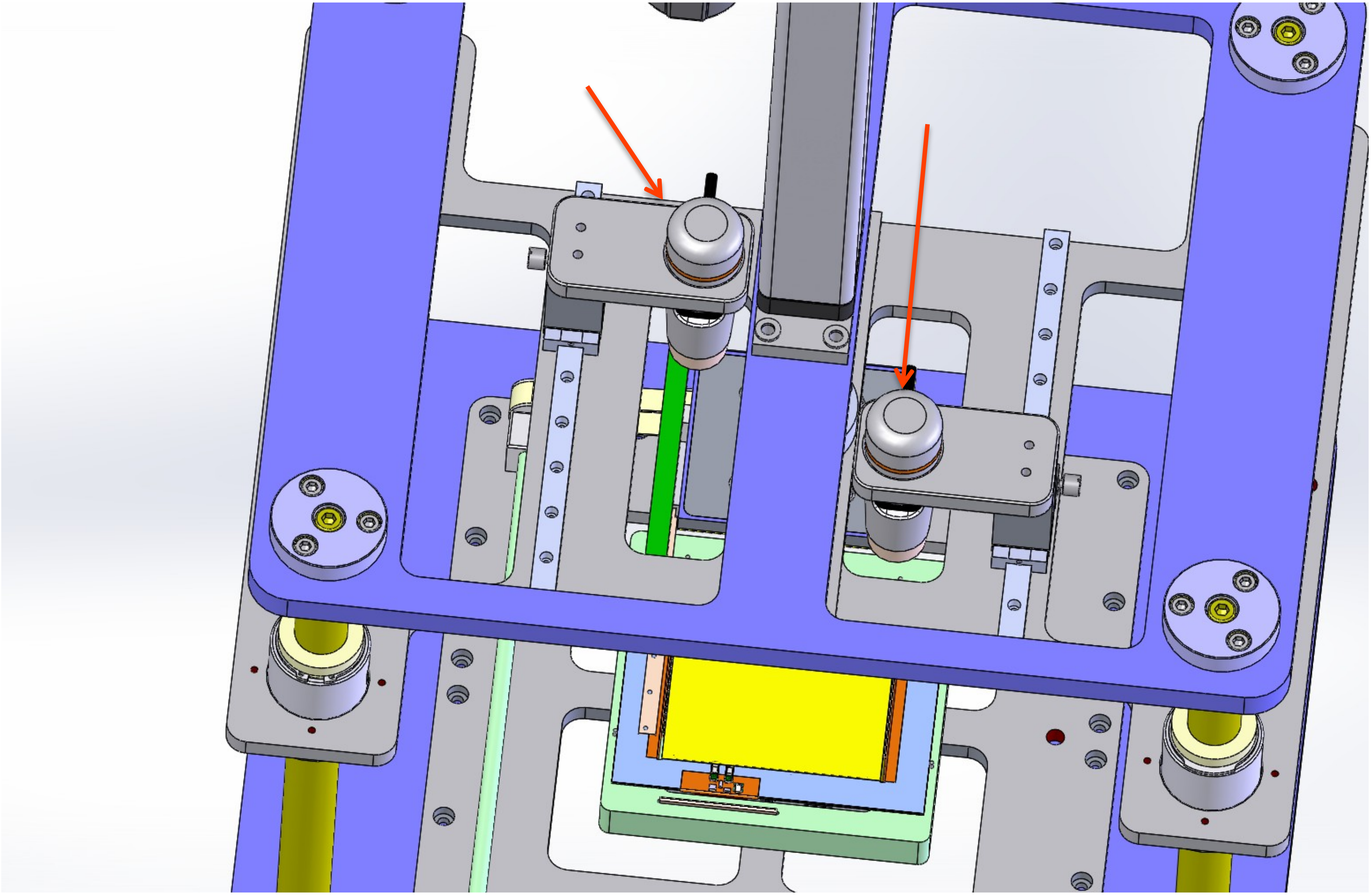
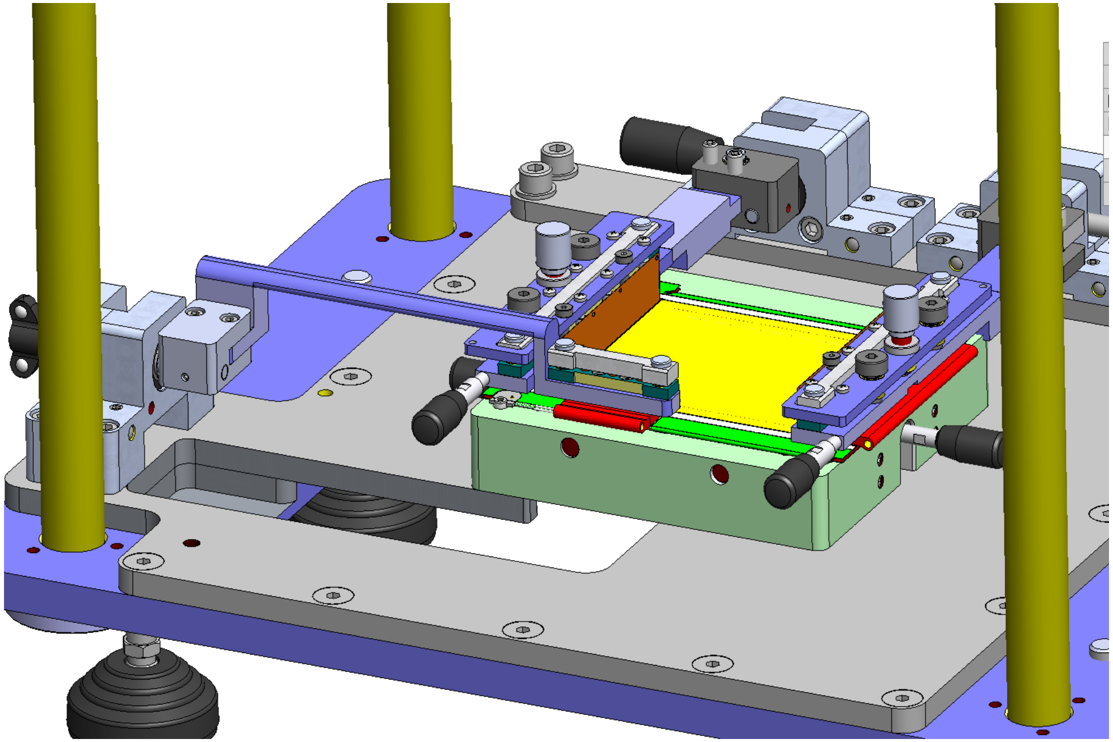




# USB microscopes to check alignment of upper and bottom sensor



# Bending dies to mount hybrids under high temperature and high pressure



**Hybrid assembly:**

**1) Mount empty flex on sandwich using 1 bar at 80 °C**

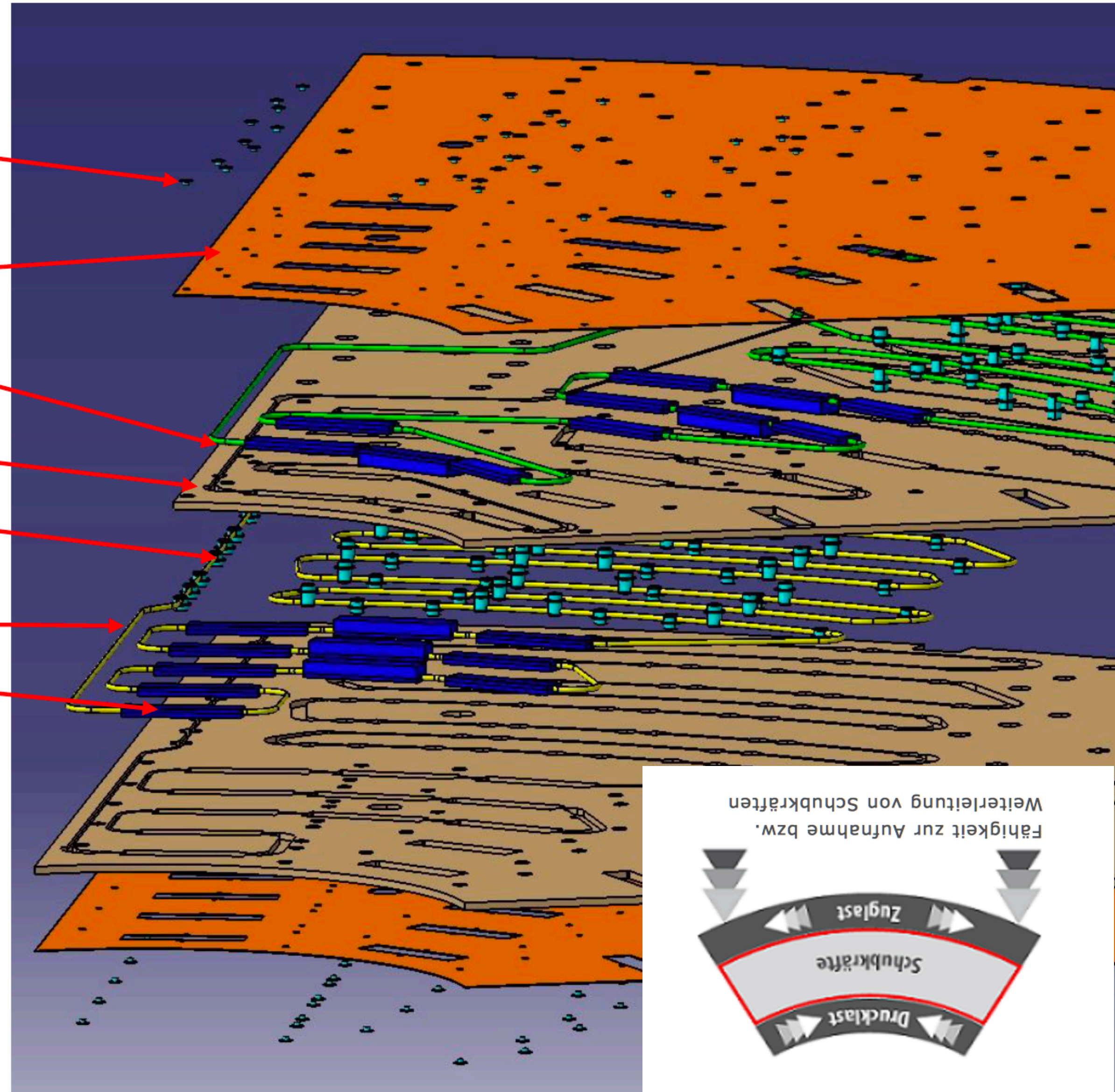
**2) Mount chips using pick and place machine**

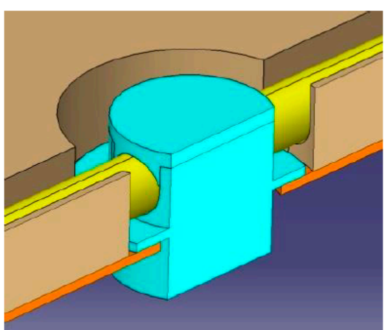
**3) Reflow at 280 °C**

**Note: mounting hybrids on sandwich allows to completely check readout before mounting sensors**
**Big question: can one replace single non-working hybrid?**
**Yes, by cutting tape around defective hybrid**

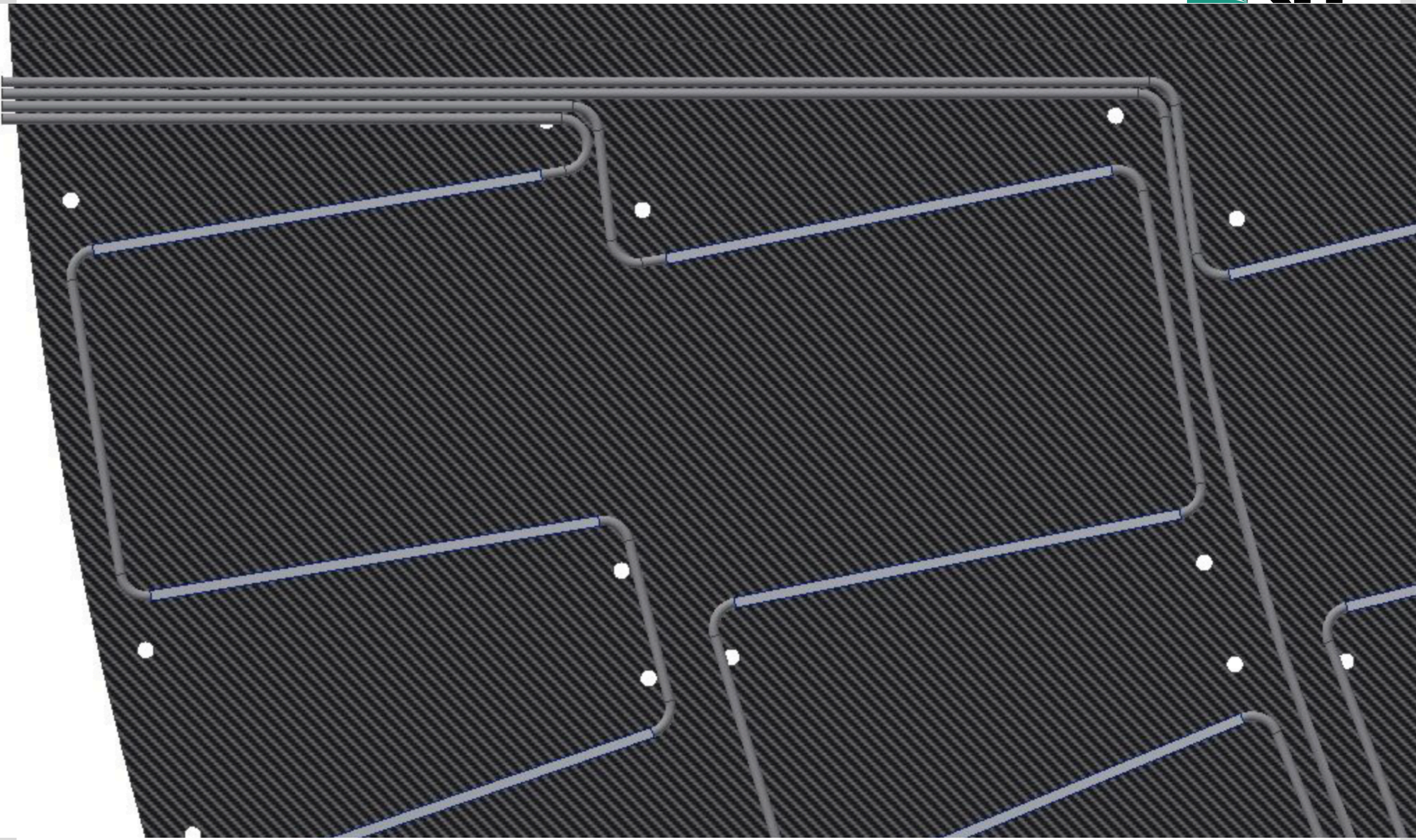
# Prototype layers

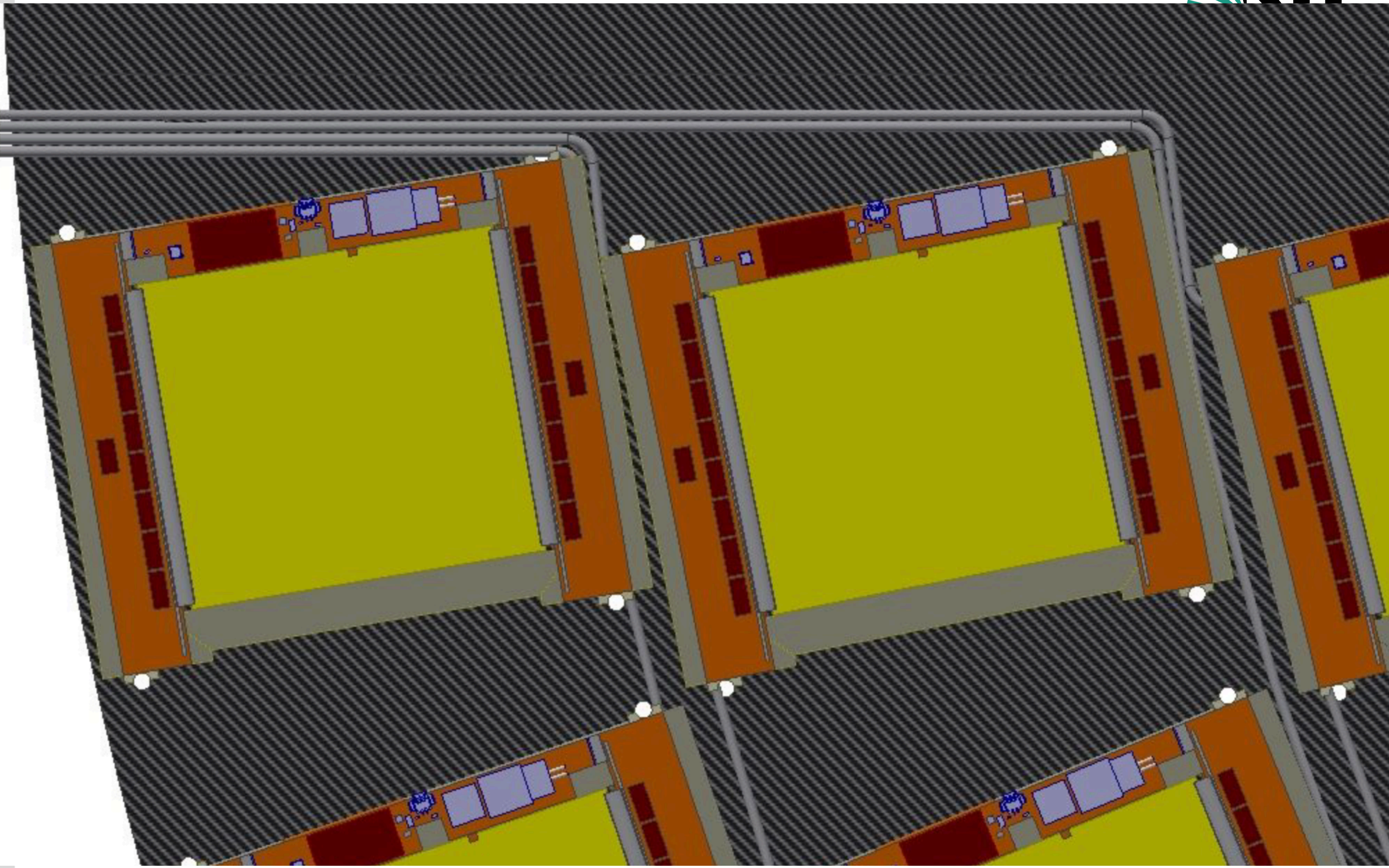
PS positioning inserts
CF skin, 0.5mm
Cooling sector 2
Airex R82 filler, 4.5mm
2S cooling insert
Cooling sector 1
C-foam pads

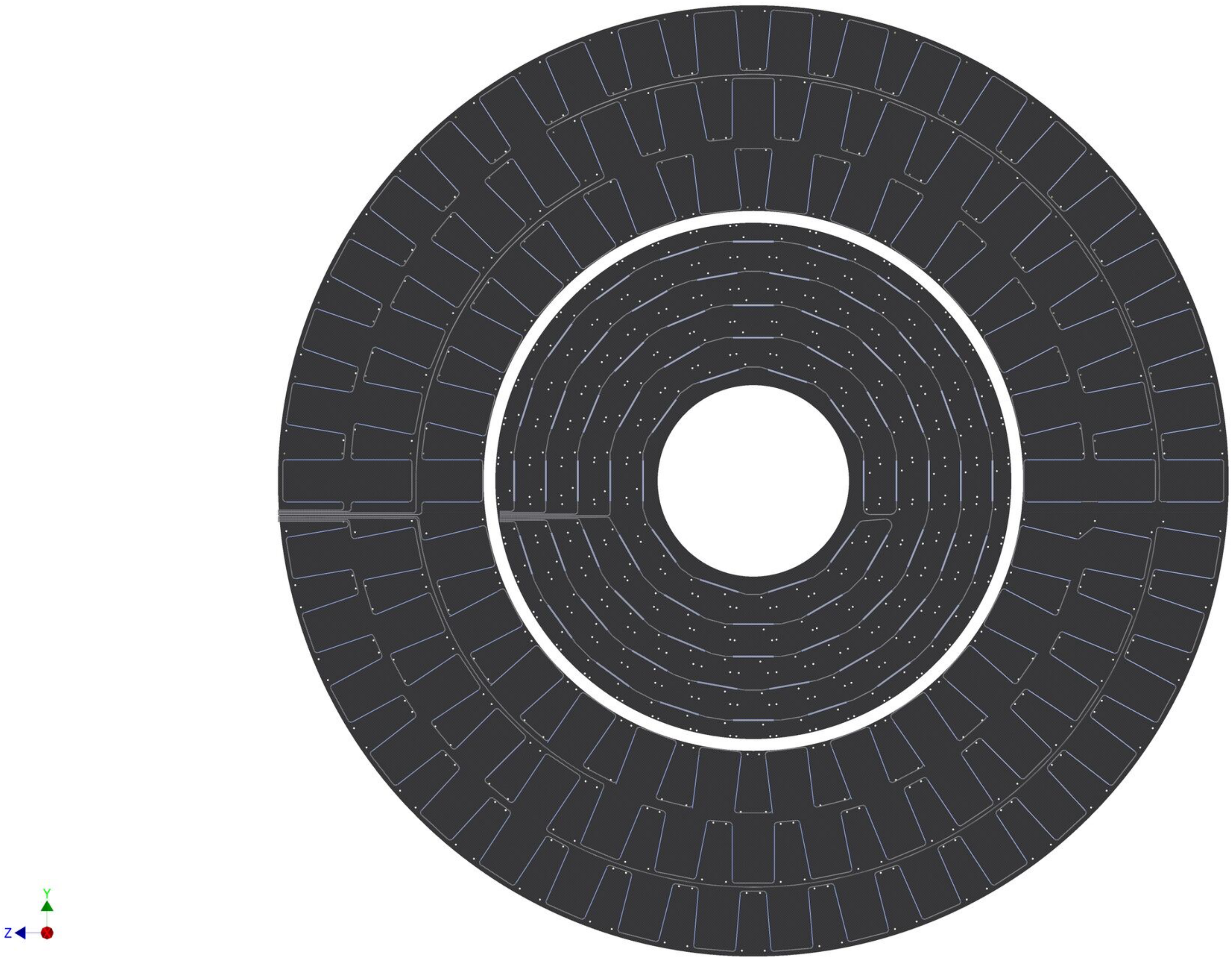


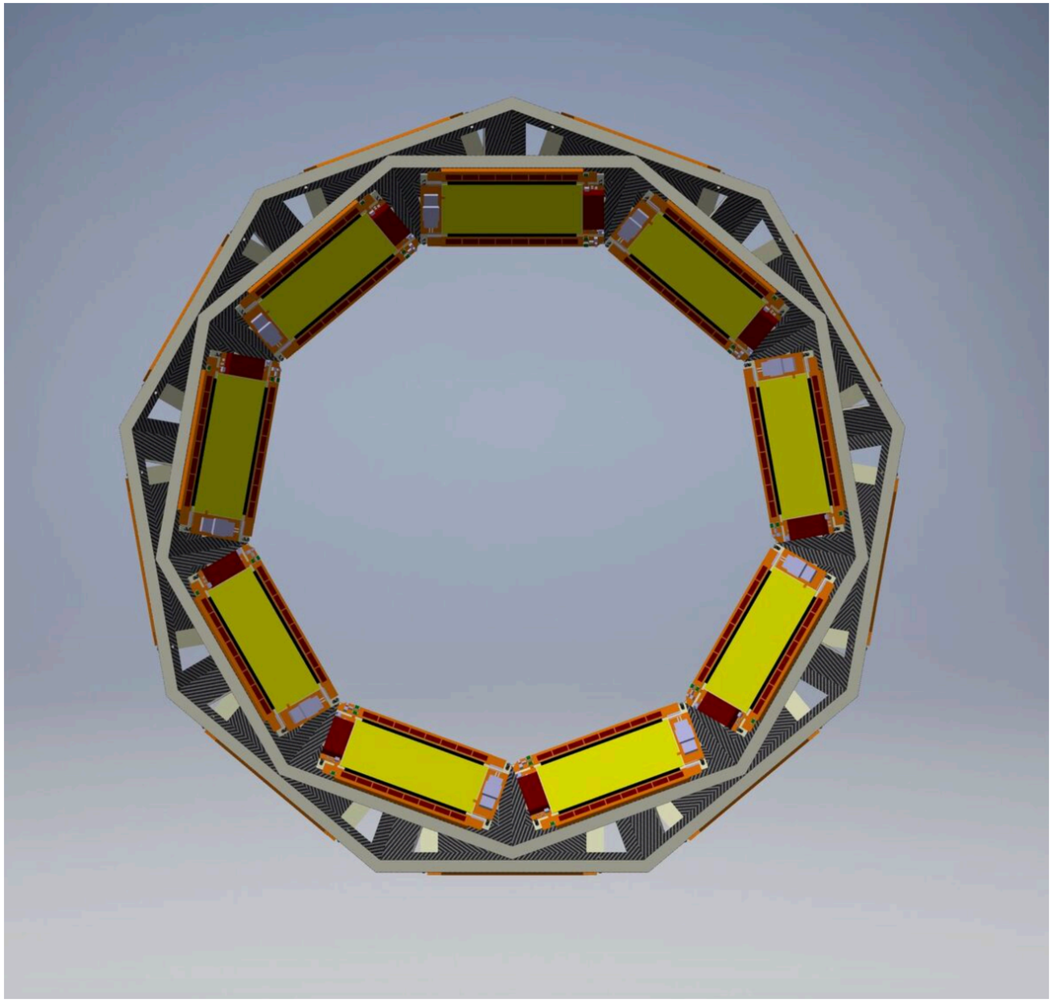



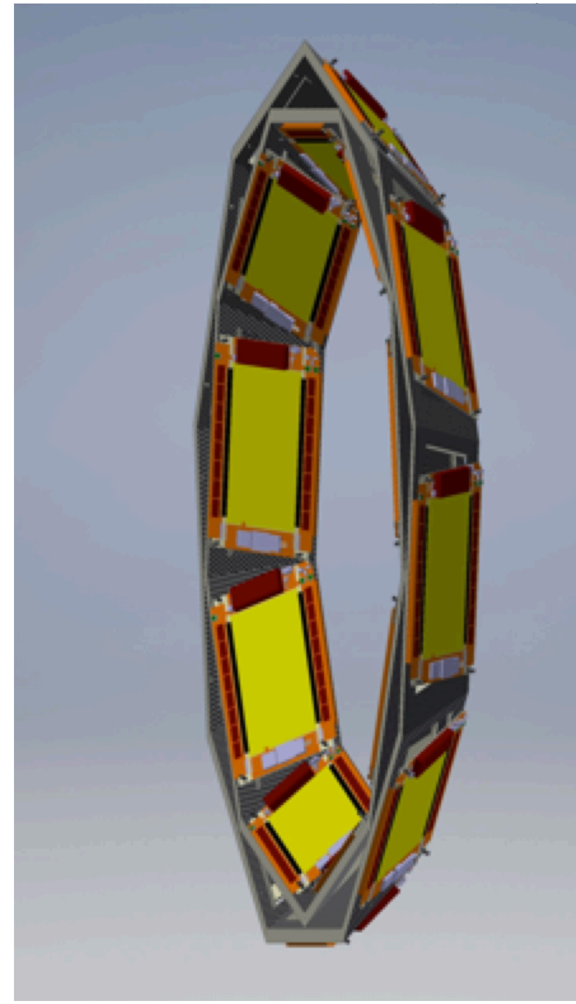
2S insert detail

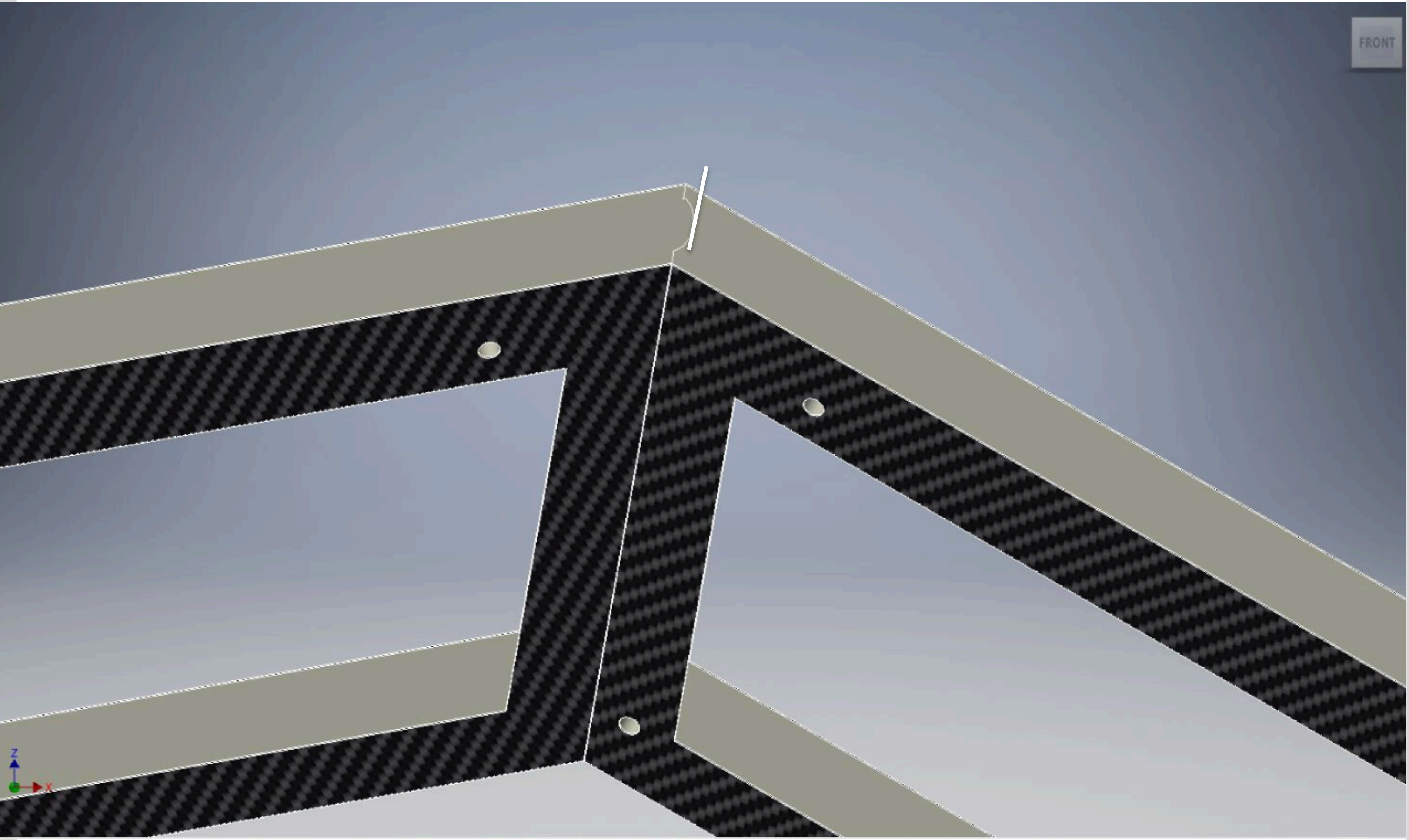





Y
Z






FRONT
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# How to make tilted CF structures?

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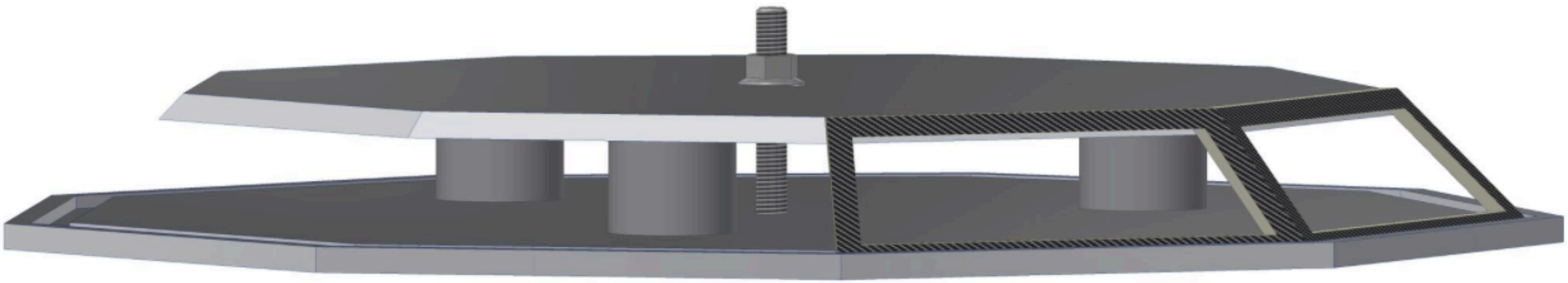

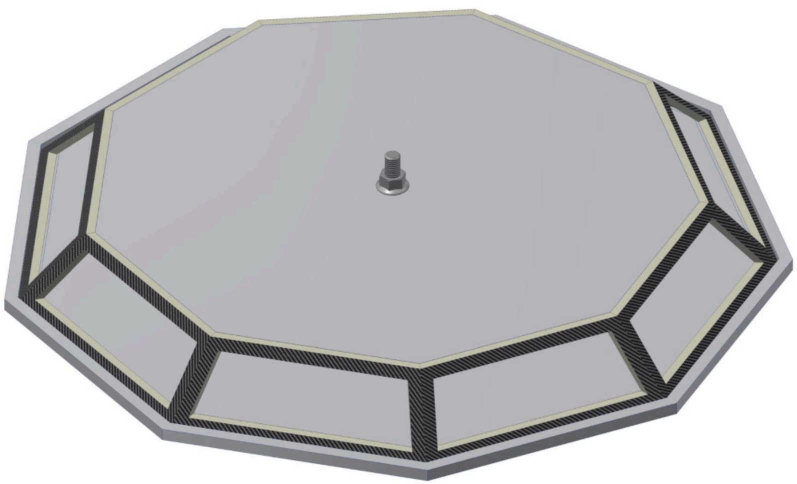

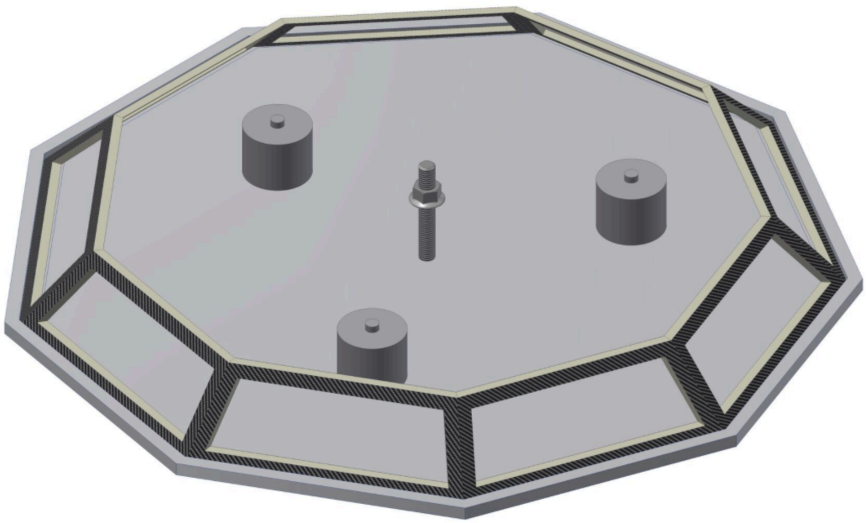

Need 6 baseplates for 3 radii with double rings and for each radius 3 top plates for 3 angles, so 6x4 =24 rather simple Al plates for the construction of all tilted rings

# Conclusion

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- **SG tape interesting material for future module construction**
- **Sticks well to metal and CF by pressure sensitive adhesives**
- **SG tape allows for easy module construction (no curing time, few parts, assembly with gantry) and excellent thermal performance**
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  **Proven to work with CMS-like dummy prototypes yielding mechanically robust and radiation hard modules with excellent thermal performance with standard materials**