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

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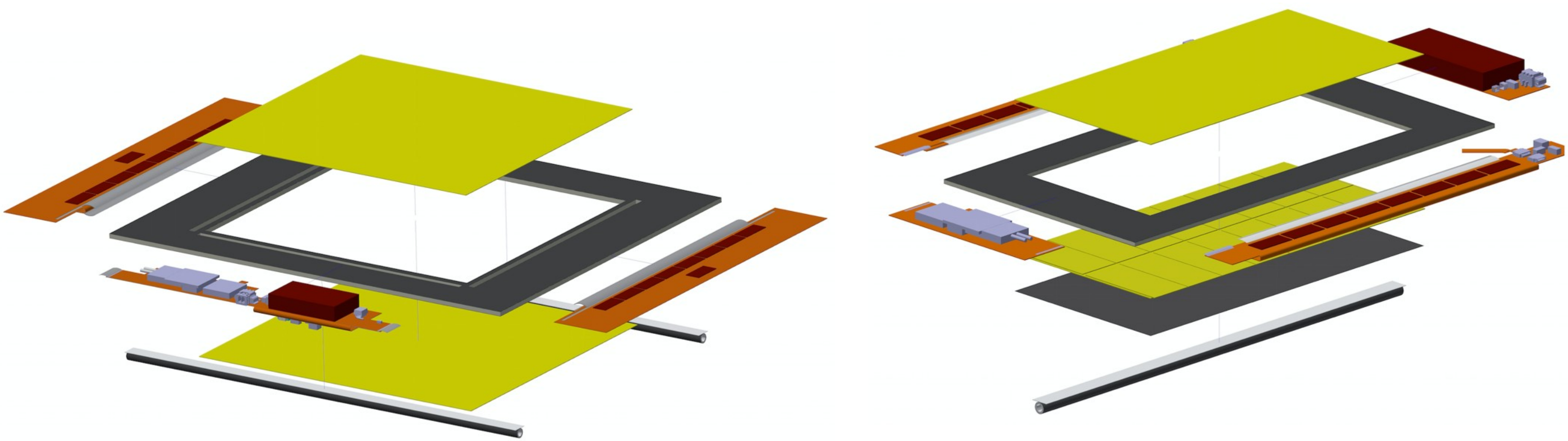
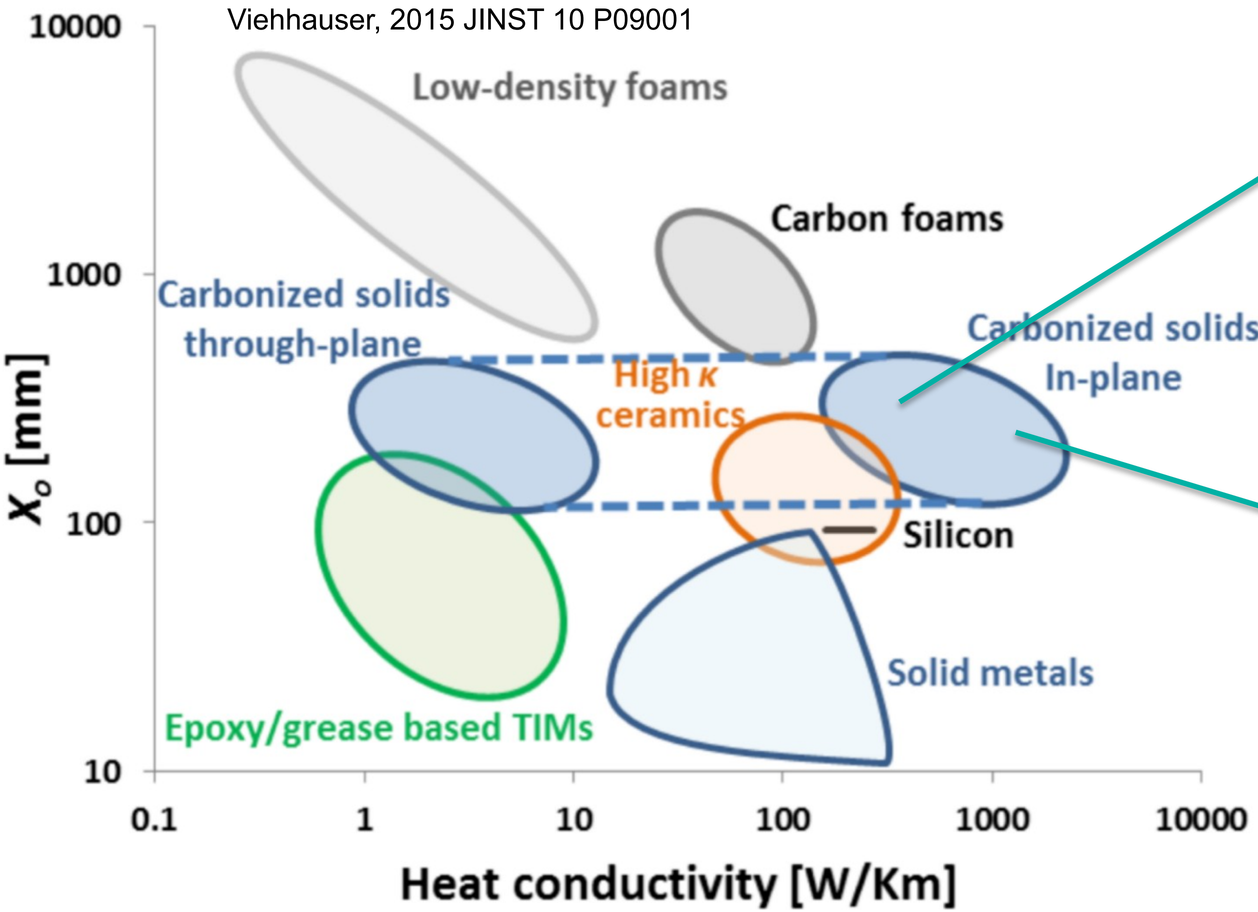
Institut für Experimentelle Kernphysik



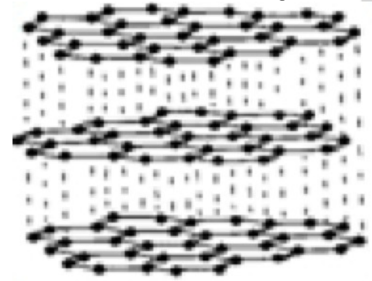
Heat Conducting Materials



Carbon fiber (CF) in epoxy matrix (strong, medium heat conductivity)

Synthetic graphite (SG), double sided adhesive

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 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

Typical cross section of SGT

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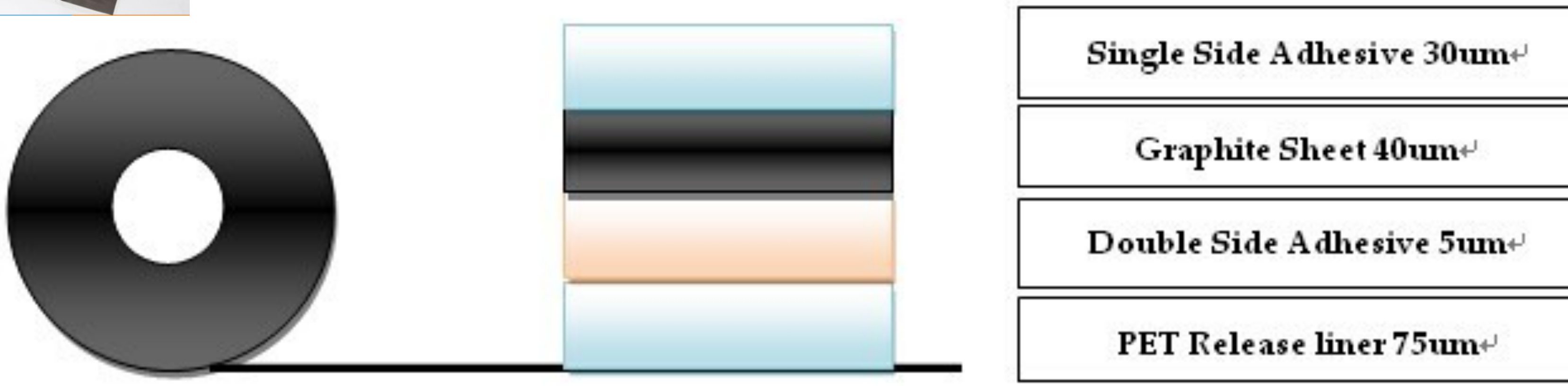
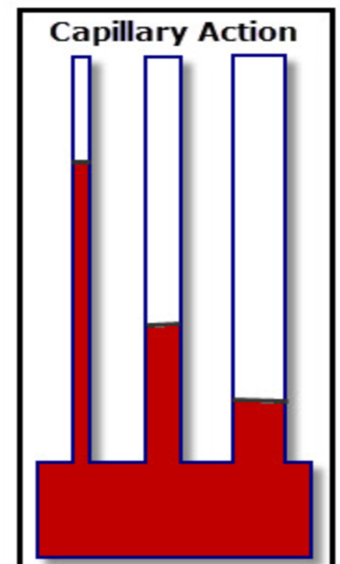


PRESSURE SENSITIVE ADHESIVES (BY VAN DER WAALS FORCES)

Wetability	Surface Tension
Poor (PSA on Substrate)	Adhesive > Substrate
Good (PSA on Substrate)	Adhesive = Substrate
Very Good (PSA on Substrate)	Adhesive < Substrate

High Surface Tension/Energy POLAR	Low Surface Tension/Energy NON-POLAR
Steel	Rubber
Aluminum	PE = Polyethylene
Copper	PP = Polypropylene
Polycarbonate	Powder Coating
ABS = Acryinitril-Butadien-Styrene	Silicone
PVC = Polyvinyl Chloride	Teflon®
Easy to Mount	Critical to Mount



Can one use SGT in module construction?

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

Can one use SGT in module construction?

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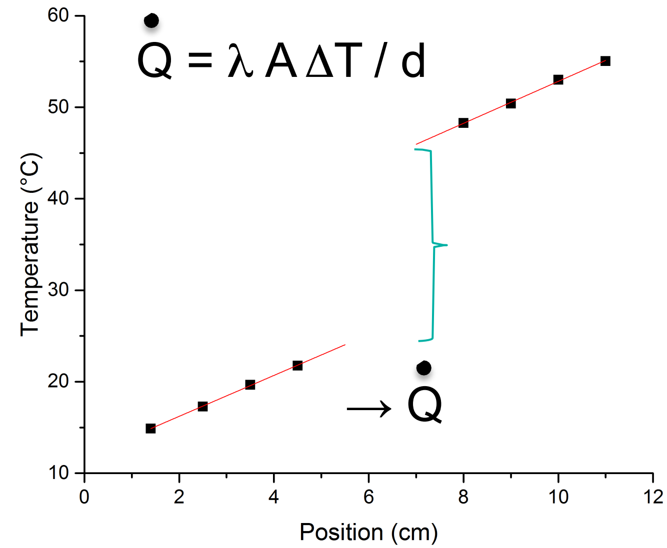
Yes we can!

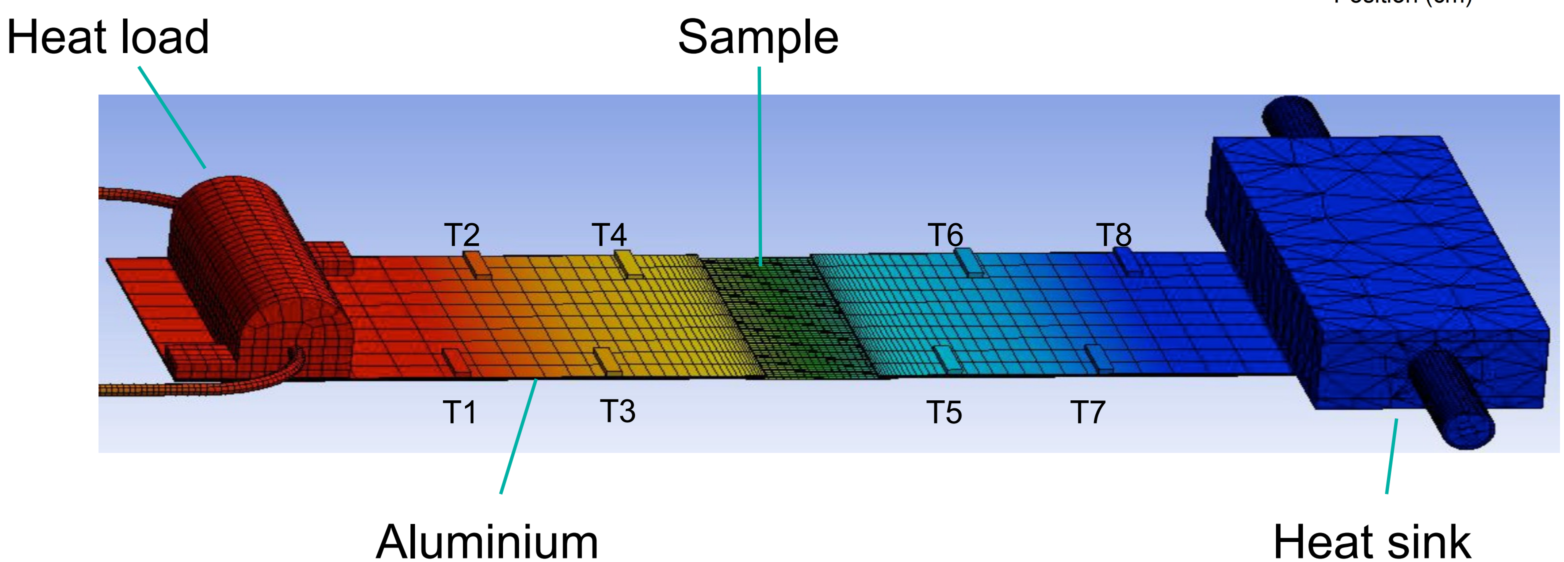
- Thermal conductivity ✓
- Shear forces ✓
- Pull forces ✓
- Radiation hardness ✓
- How to build modules ✓

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.**





Thermal conductivity of various SGTs

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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)	$\lambda_{\mathrm{Gr.,man.}}$ $\left(\frac{\mathrm{W}}{\mathrm{mK}}\right)$	R $\left(\frac{\mathrm{K}}{\mathrm{W}}\right)$	$\lambda_{\mathrm{Gr.}}$ $\left(\frac{\mathrm{W}}{\mathrm{mK}}\right)$	$\lambda_{\mathrm{eff.}}$ $\left(\frac{\mathrm{W}}{\mathrm{mK}}\right)$
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

	Mitsubishi* 0°	Mits. 0°/90°/0°	Granoc° 0°	DSN5040x
	CF	CF	CF	SG
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

*from DSN: http://szdasen.en.alibaba.com

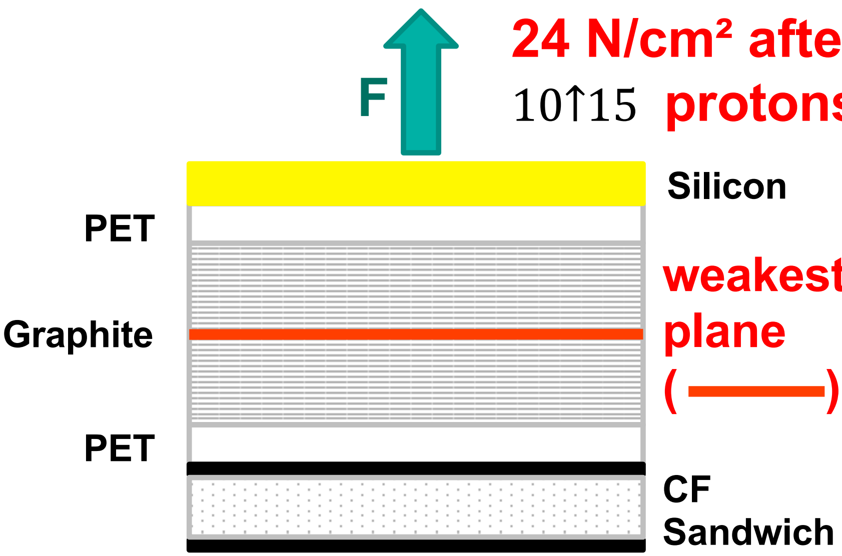
*K13D2U fiber from Mitsubishi Ten Cate prepreg

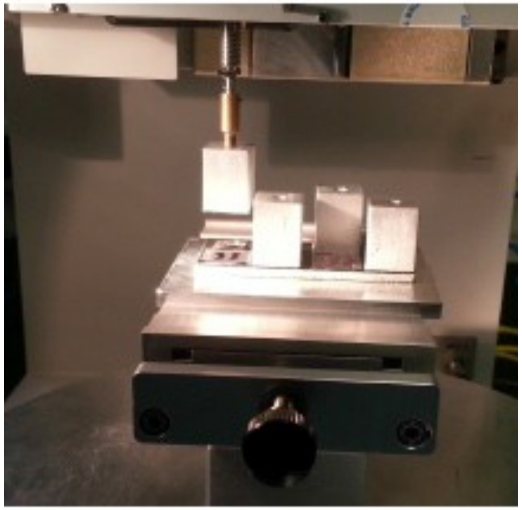
*E9026A-05S from Nippon Graphite Fiber (NGF) http://www.ngfworld.com/dcms_media/other/NGFPPHM2014.pdf

Pull Forces

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

24 N/cm² after 10^{15} protons/cm²

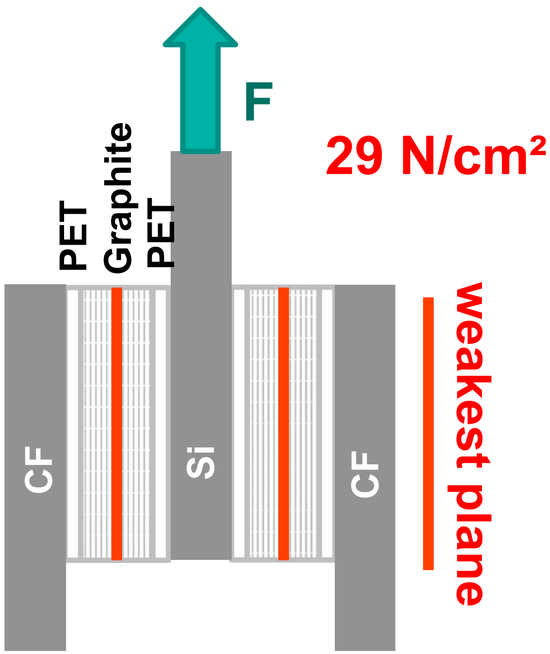


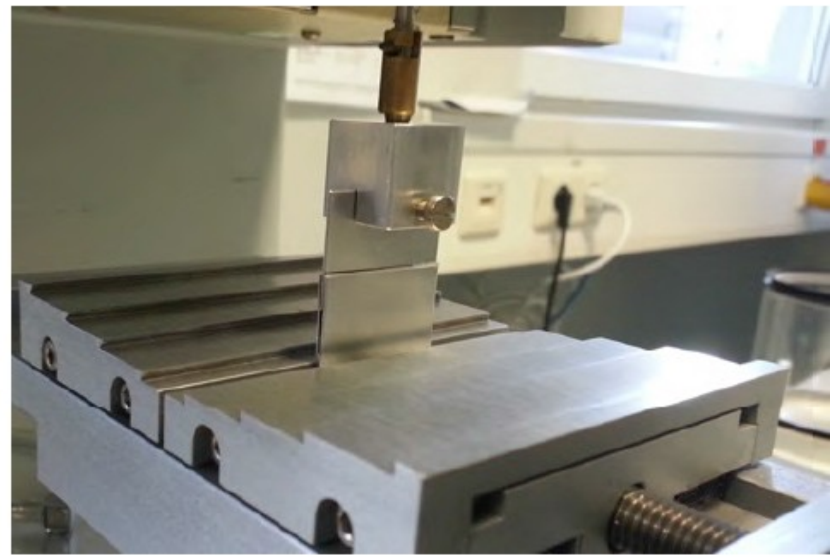


- Irradiation of 10^{15} protons/cm² reduces strength by about 40%
- Area of cooling pipe ~5cm² → max force of about 100 N or 10 kg

Shear Forces

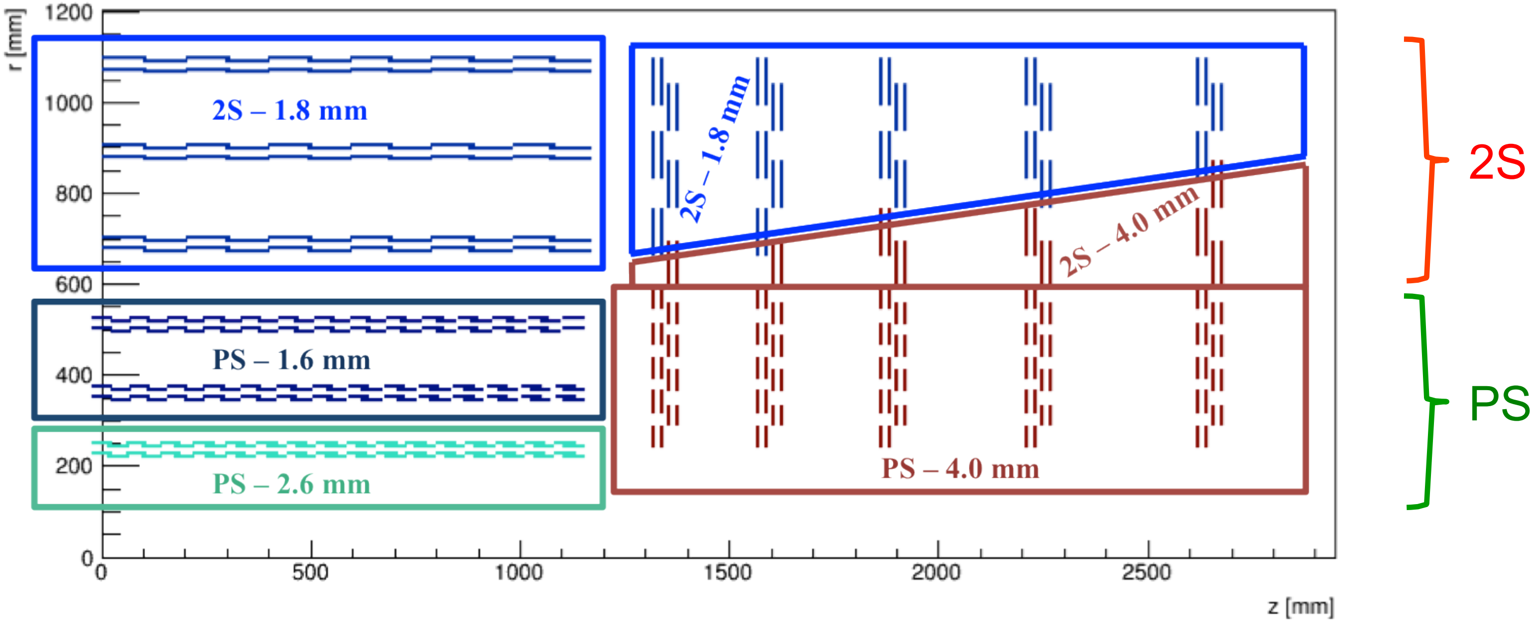
- The graphene layers in the SGT are only weakly connected by Van-der-Waals forces, so they easily slide over each other





- 29 N/cm² enough to withstand thermal stress due to different CTE between cooling pipe and module
- Thermal connection was not affected by many thermal cycles between 20°C and -30°C

CMS Tracker Layout for HL-LHC



	2S Modules		PS Modules		
	1.8mm	4.0mm	1.6mm	2.6mm	4.0mm
Inner	.	.	888	1516	504
Outer	4464	.	.	.	.
Endcap	2976	984	.	.	2800

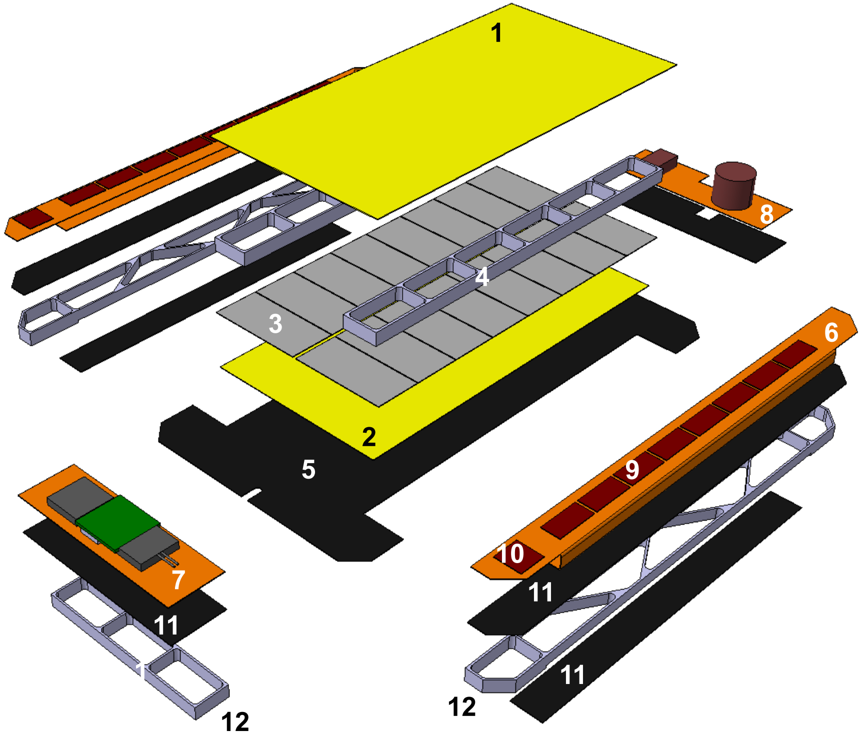
Total 2S Modules **8424**

Total PS Modules **5708**

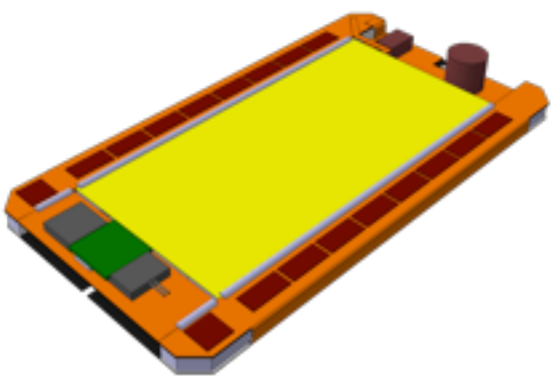
Total Modules **14132**

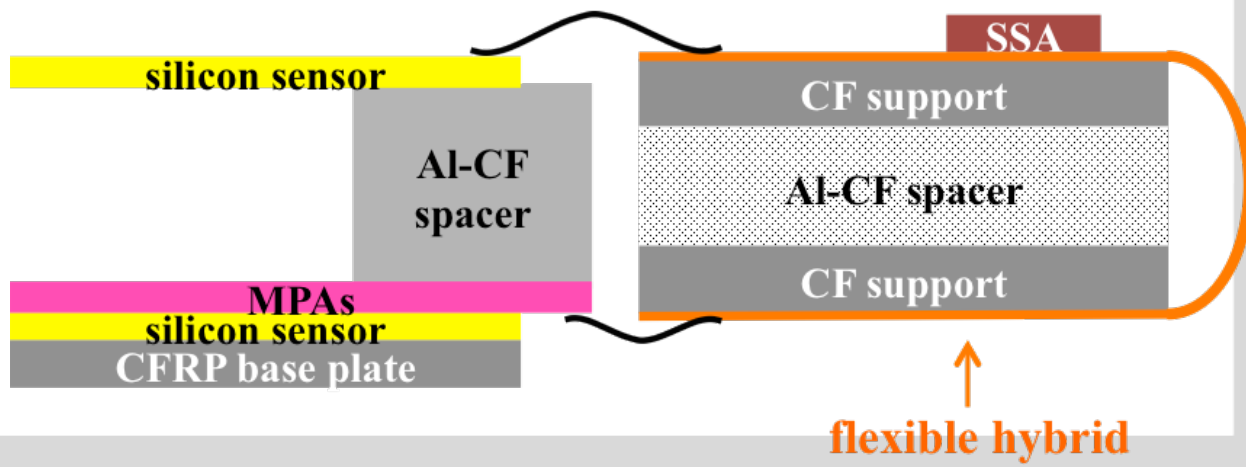
2S=strip+strip sensor (pair to allow trigger capability)

PS=pixel+strip sensor ("pixel"=x mm for higher granularity in z)



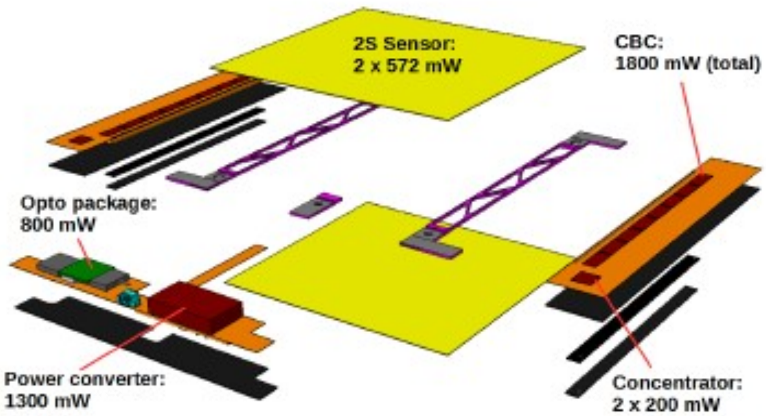
1. Silicon strip sensor
2. Silicon pixel sensor
3. Macro-Pixel ASIC (MPA)
4. Al-CF sensor spacer
5. CFRP base plate
6. FE Hybrid
7. Opto-Link Hybrid
8. Power Hybrid
9. Short-strip ASIC (SSA)
10. Concentrator IC (CIC)
11. Hybrid CF support
12. Al-CF Hybrid spacer

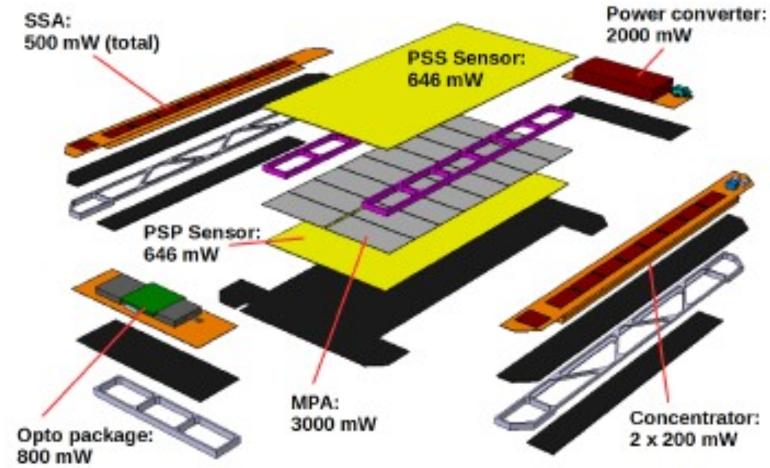




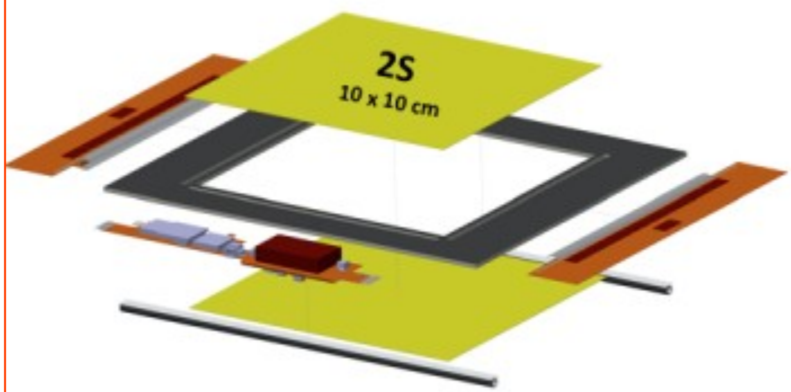
CMS Silicon tracker modules

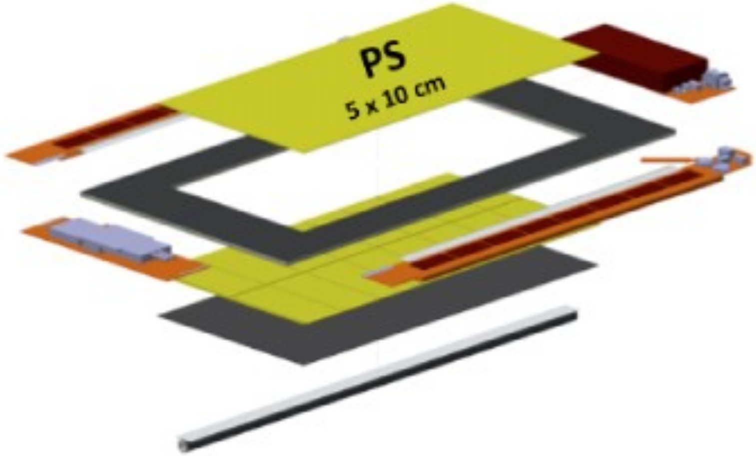
Baseline design





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





Carbon Fiber Sandwich covered with SGT

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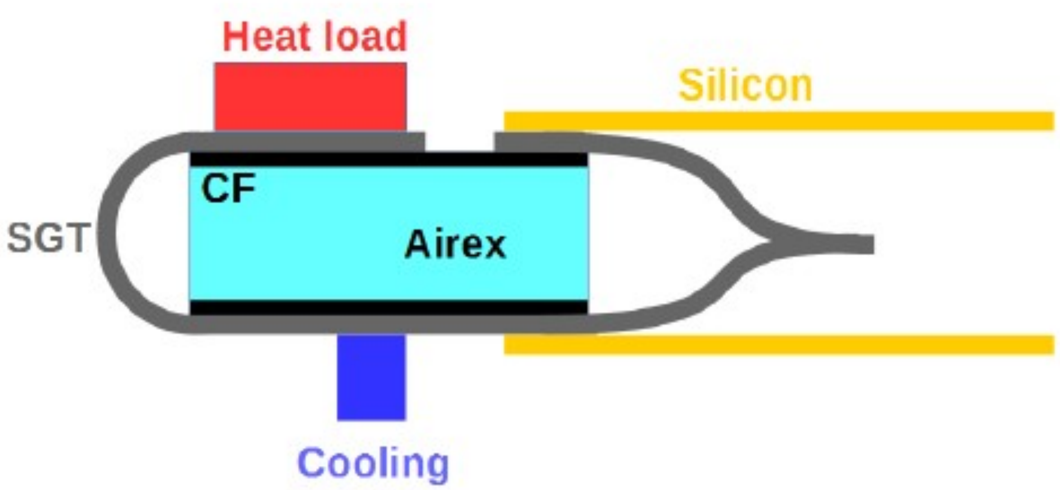
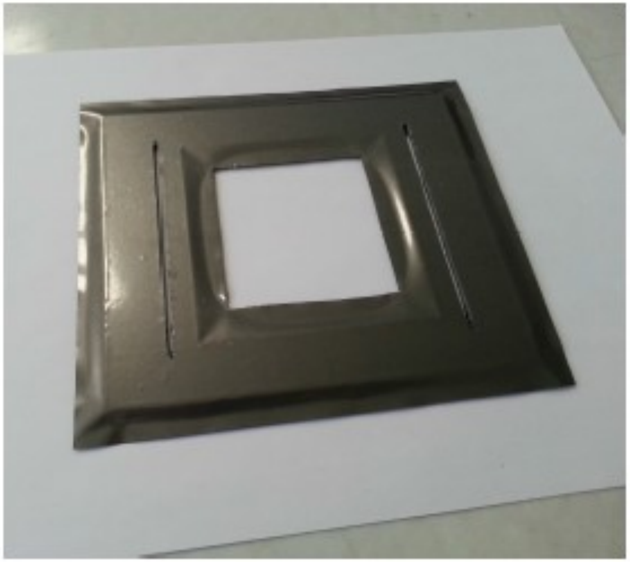
Granoc-Airex sandwich has same CTE as silicon, so NO thermal stress on sensor





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

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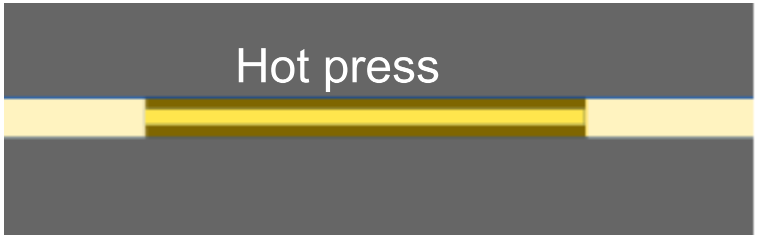
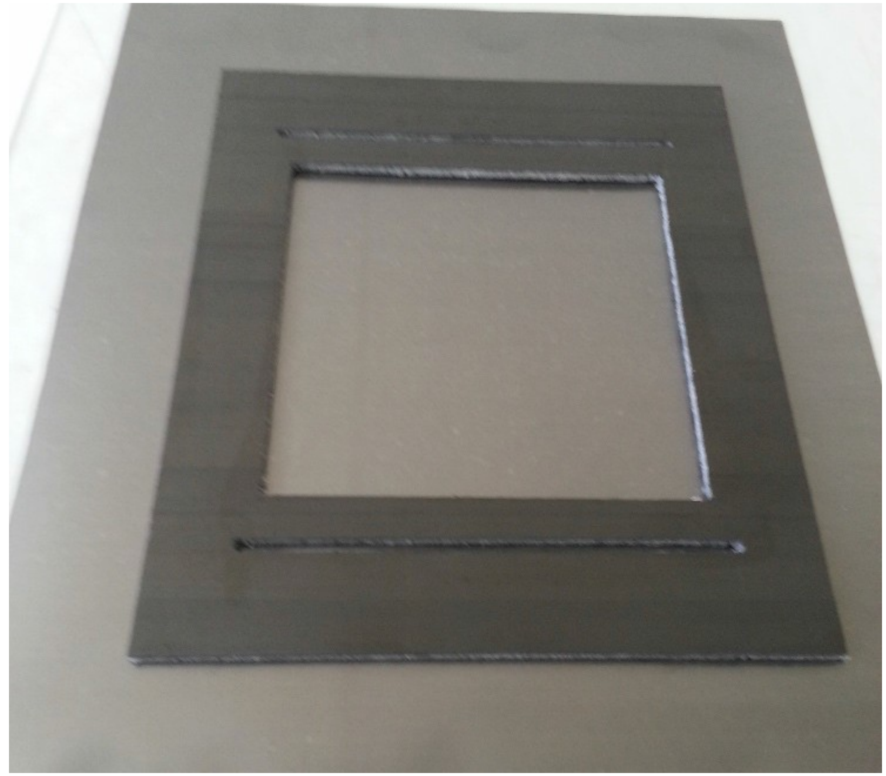




- Sandwich
  - Hot press process (4bar, 120°C, 2h)
  - 0°/90°/ Airex /90°/0°

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 (Dasen DNS5040 40 μm graphite +12 μm adhesive layer (from Suzhou Dasen Electronics Material Co.)

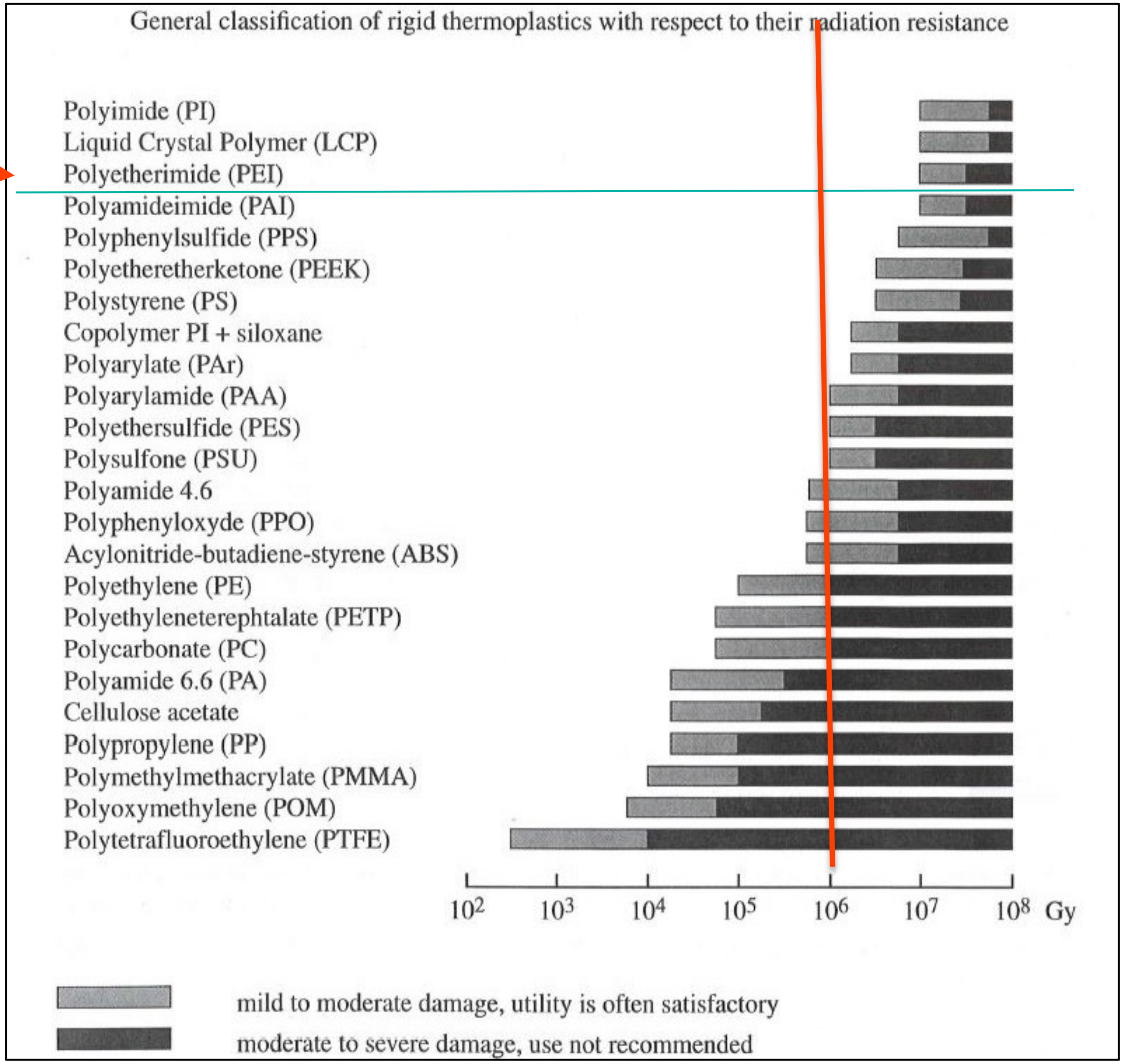
Radiation resistance of different materials

Airex R82

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

From CERN yellow report

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

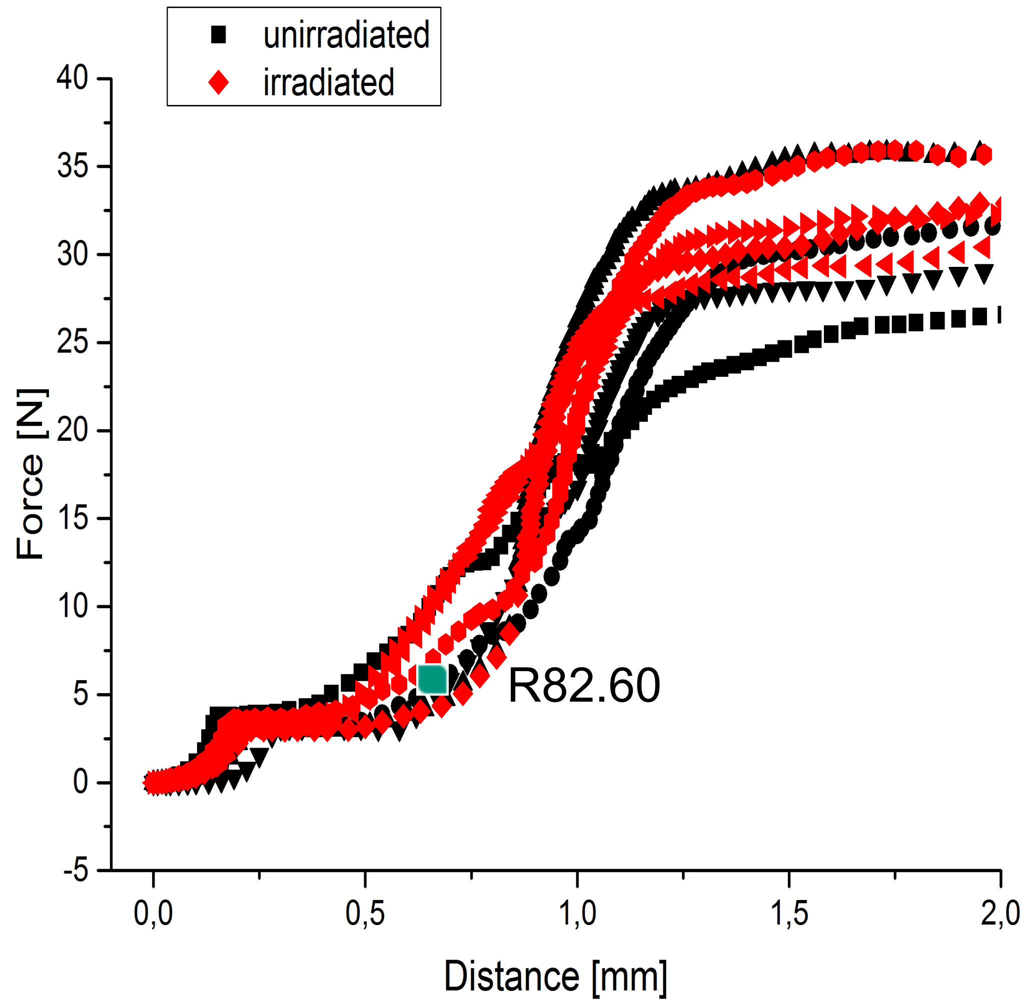


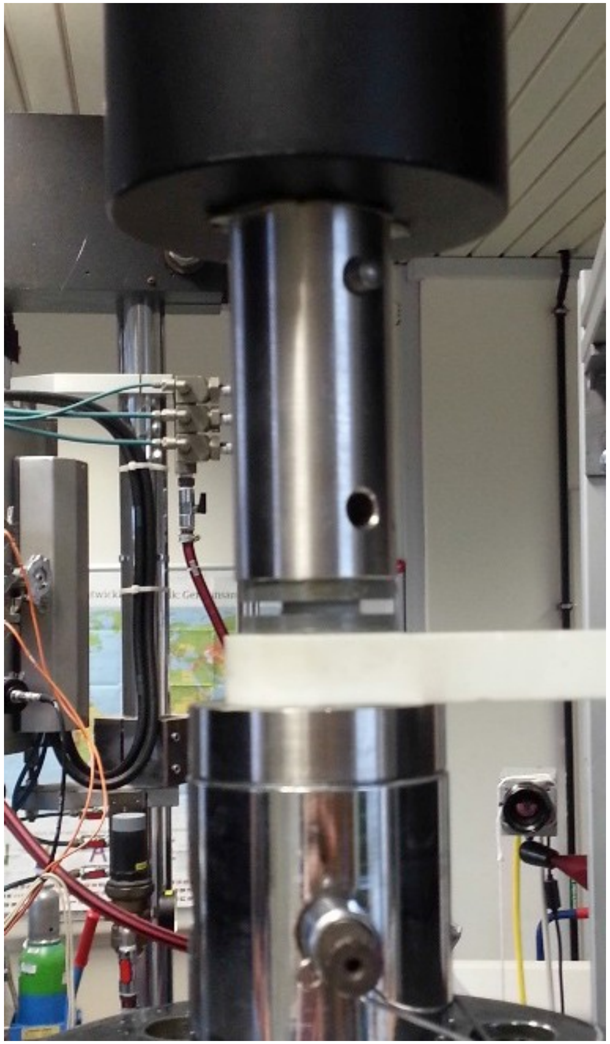
Airex irradiation

- **Irradiation with 23 MeV protons at the Karlsruhe Cyclotron up to 10^{15} p/cm^2**
- 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

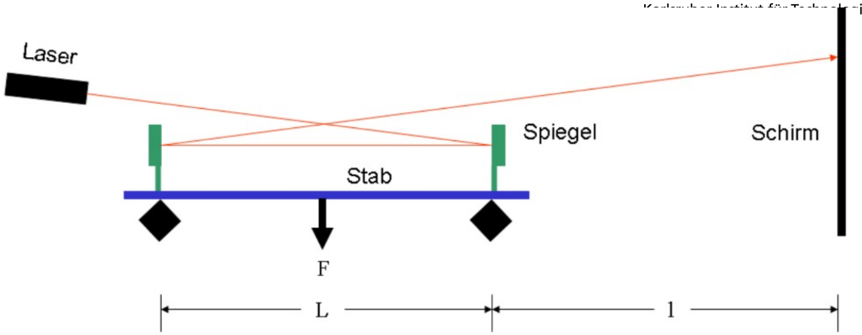
Pressure tests

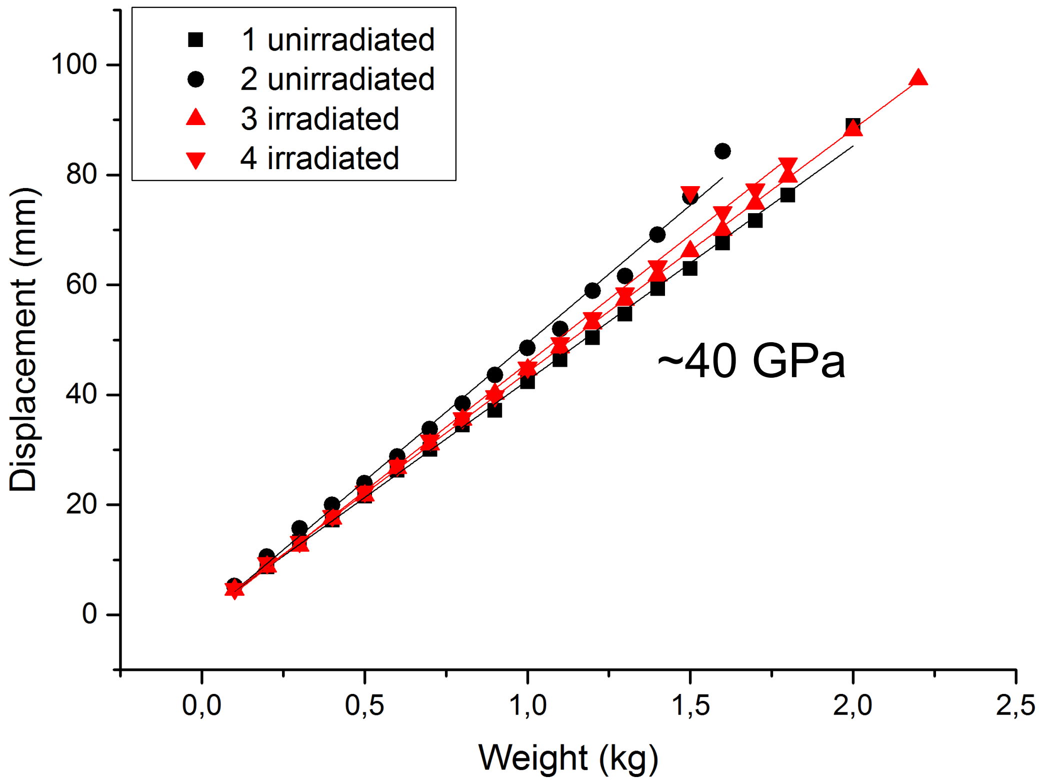




E-modulus CF Airex sandwich

d=2.8mm ; b=25mm

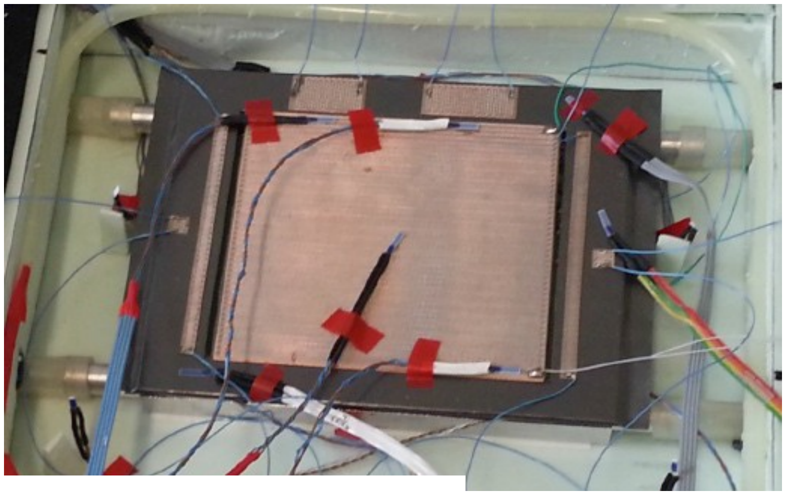


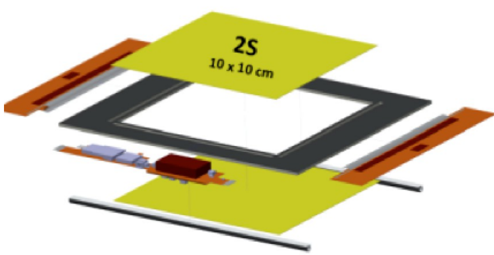


Same behaviour before and after irradiation

Dummy Module Thermal Measurements

2S

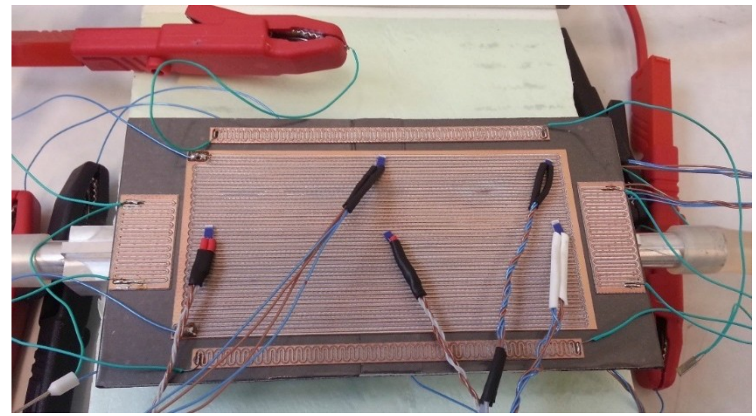


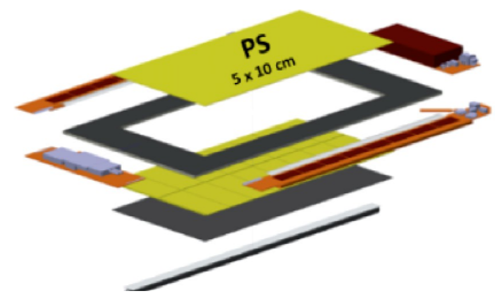


$P \approx 5W$

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

PS

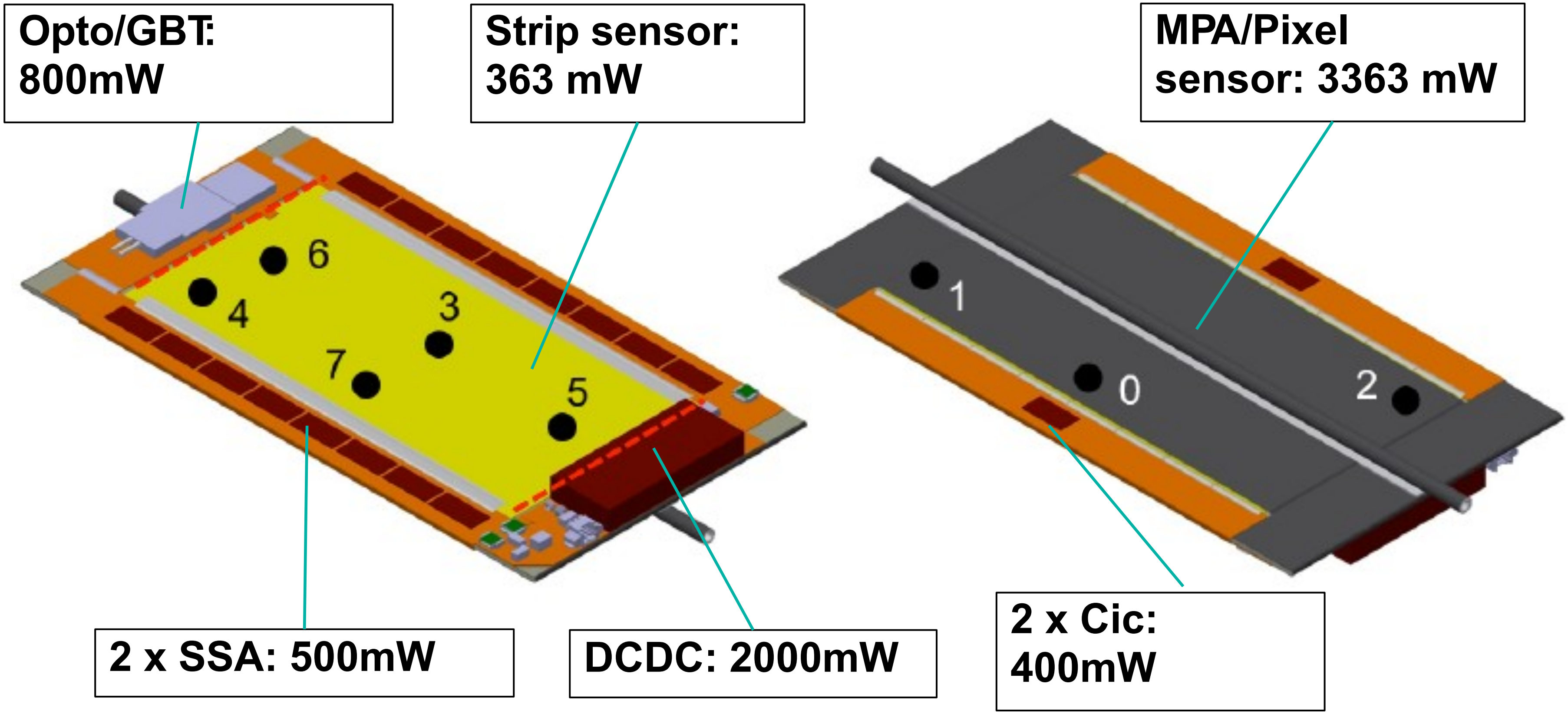




$P \approx 7.5W$

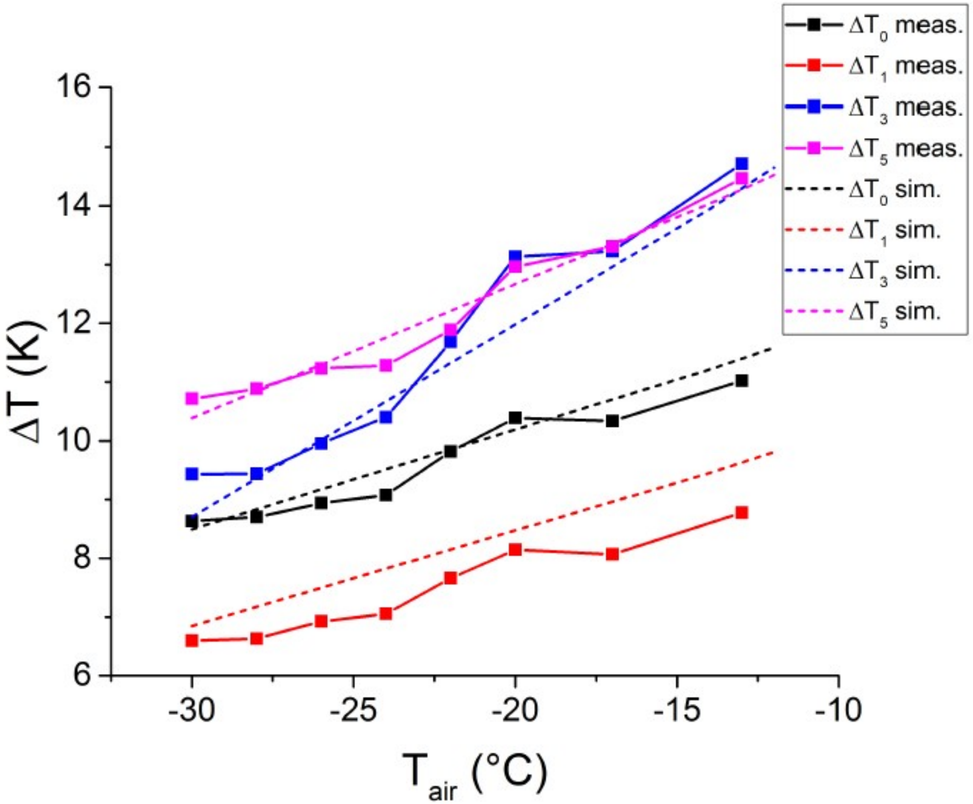
Measurement $\Delta T_{max} = 10.8$ºC (in good agreement with simulation $\Delta T \pm 1.5$ºC)

Dummy PS Module – ΔT Measurements



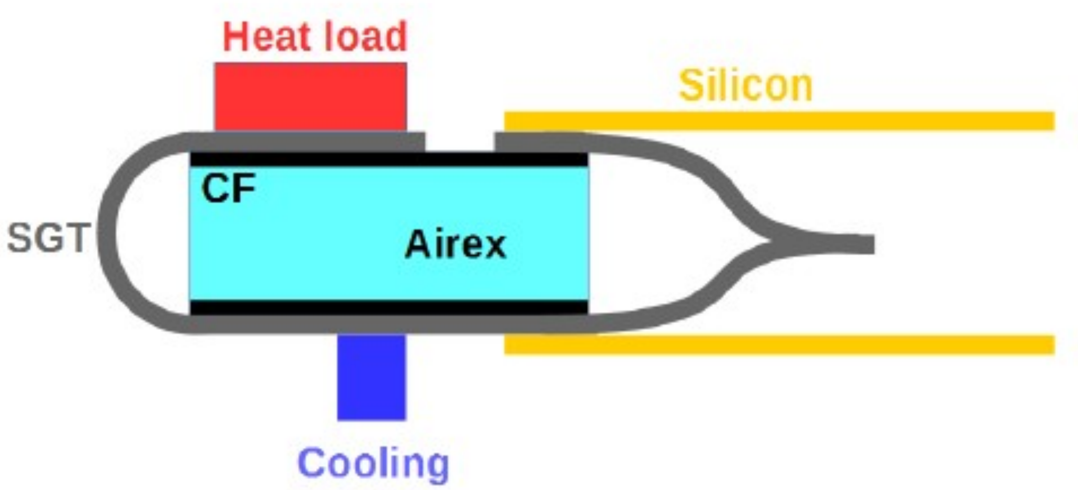
Measurements as function of temperature of climate chamber

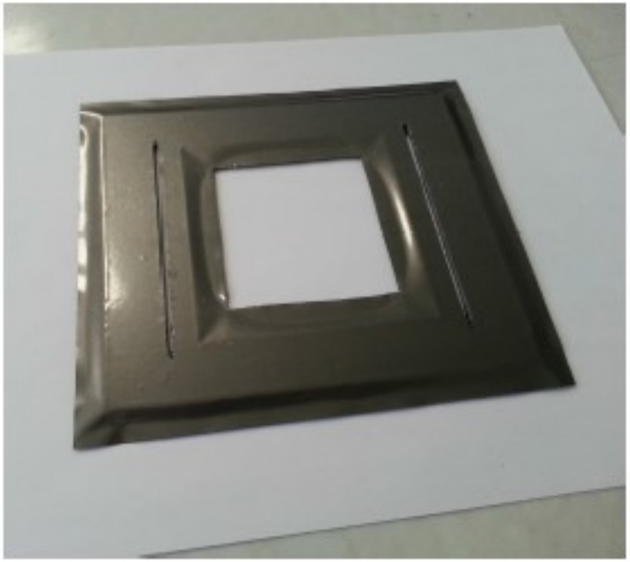
- **Simulation and measurements are in good agreement.**
- **Slope caused by convection and radiation (taken into account in ANSYS simulation)**



Carbon Fiber Sandwich covered with SGT

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

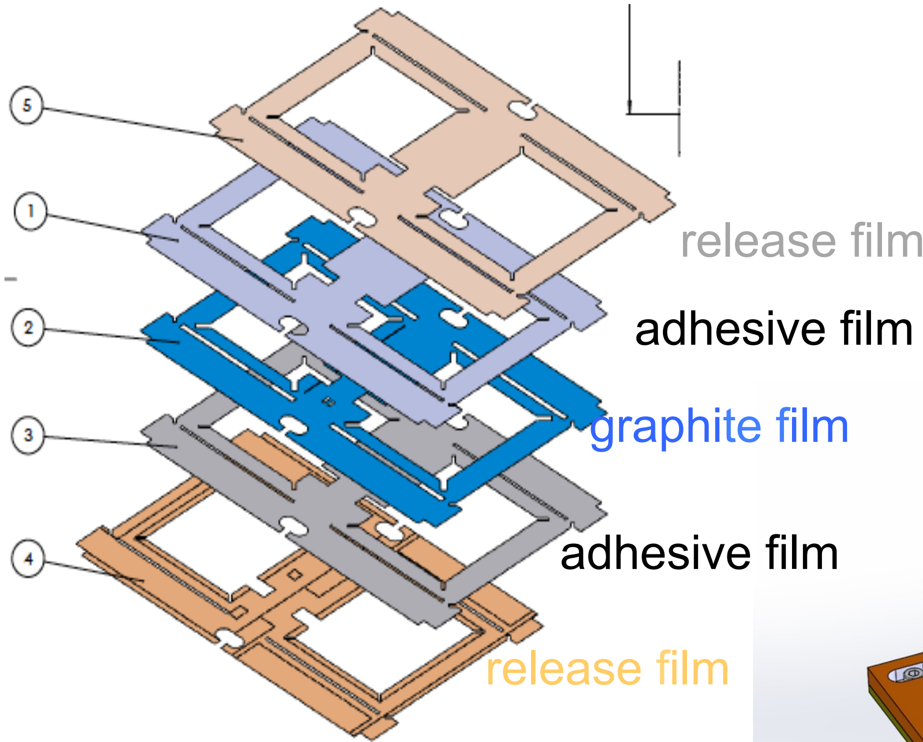


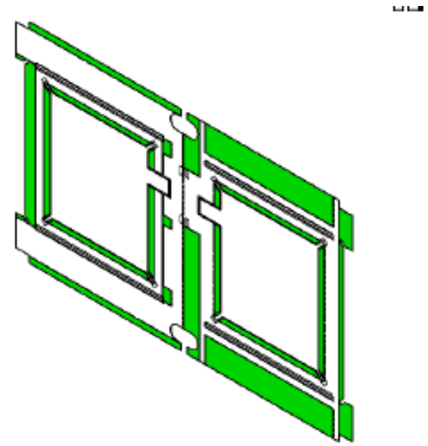


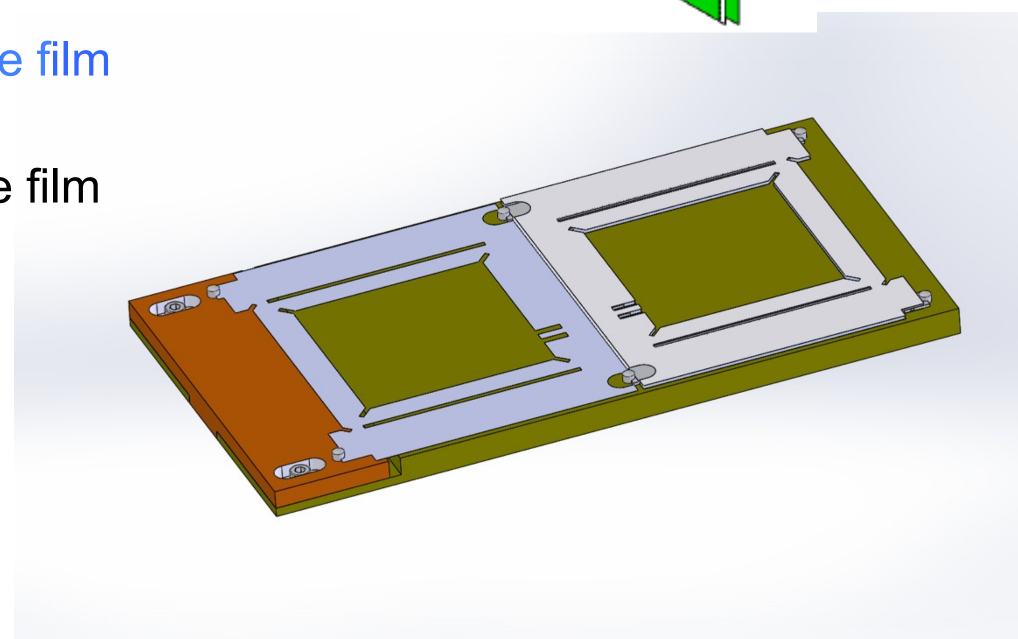
Left: Cooling of the upper sensor by taping the SGTs of bottom and top together. The sensor can be thermally isolated from the electronics by a cut in the graphite layer of the SGT.

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

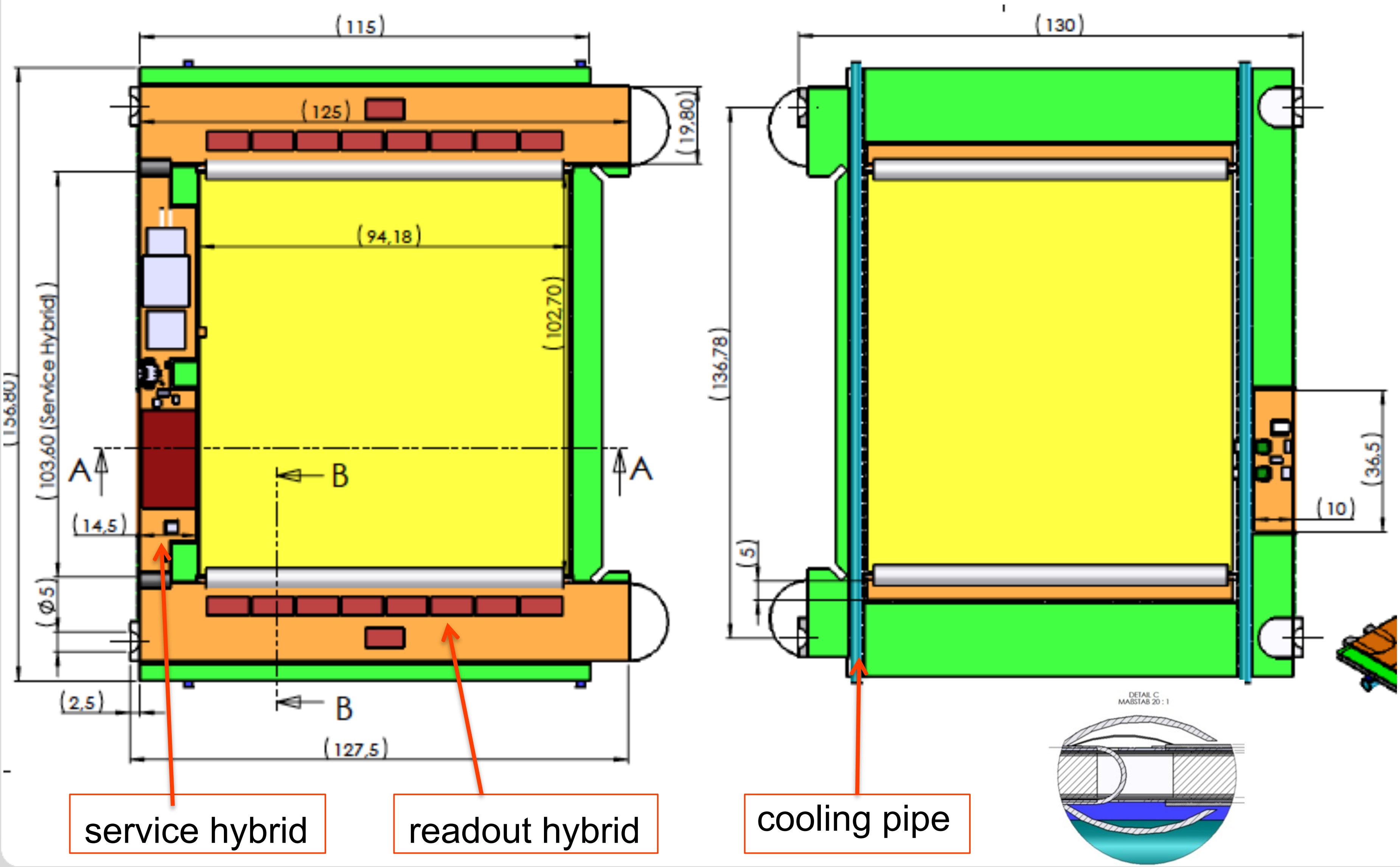
Tape Applicator



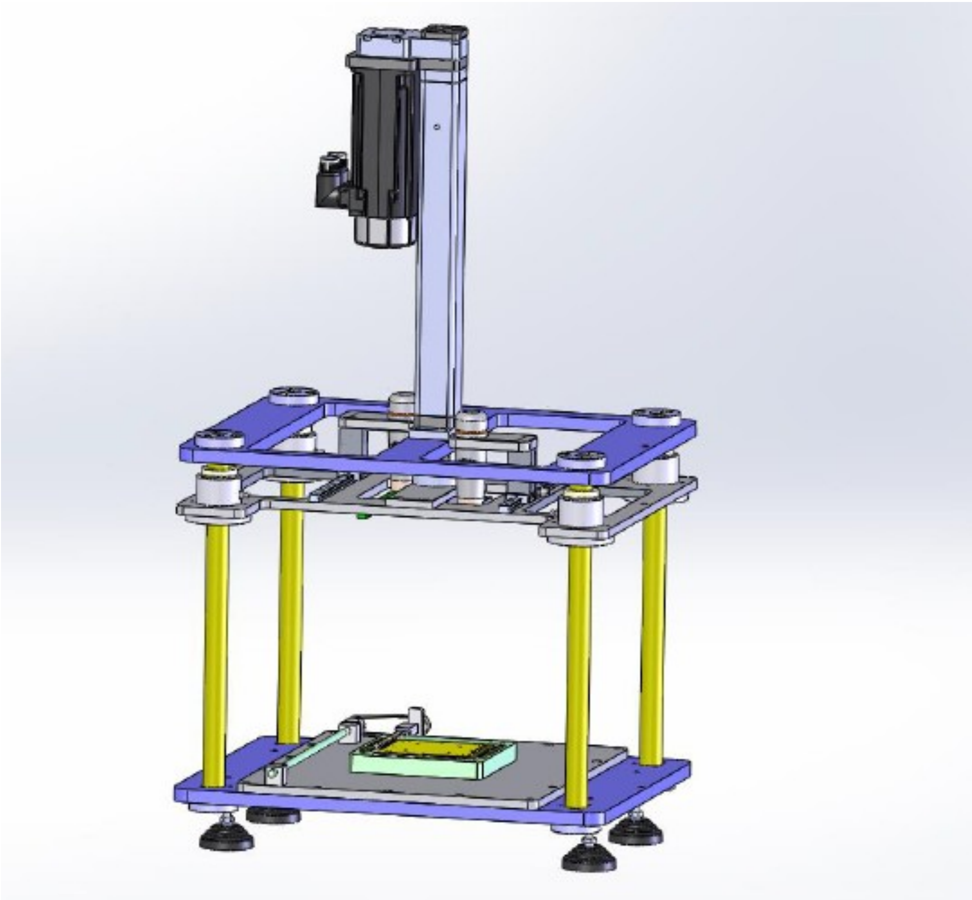


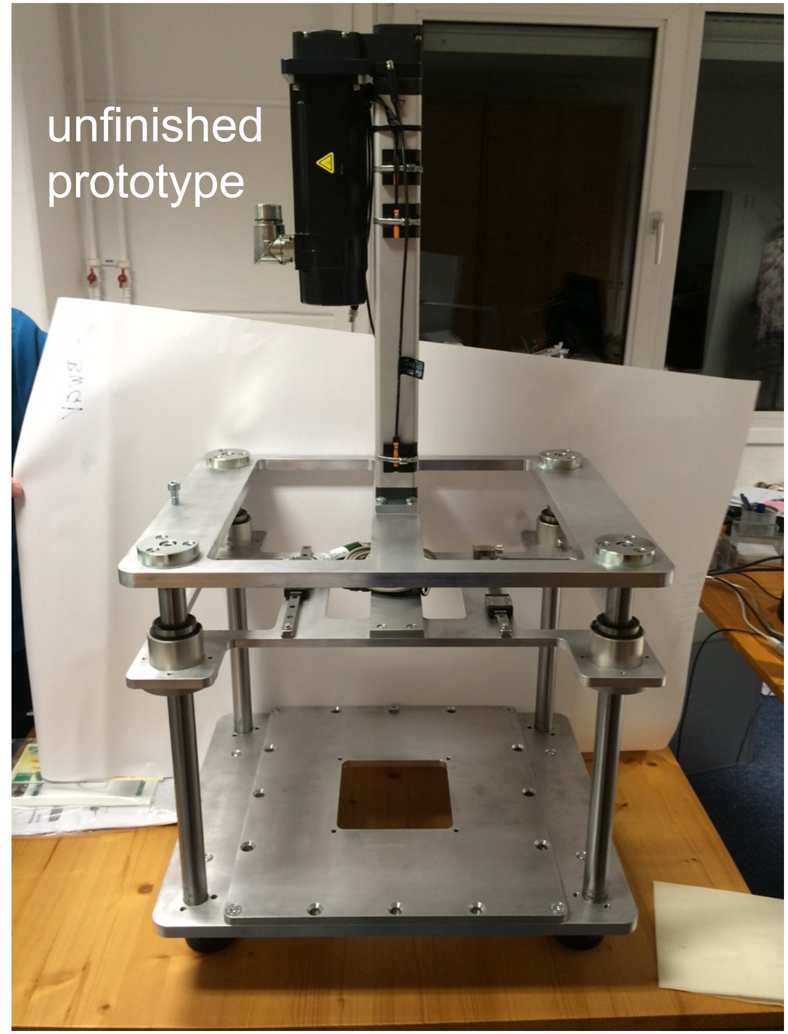


Front and backside of taped 2S module

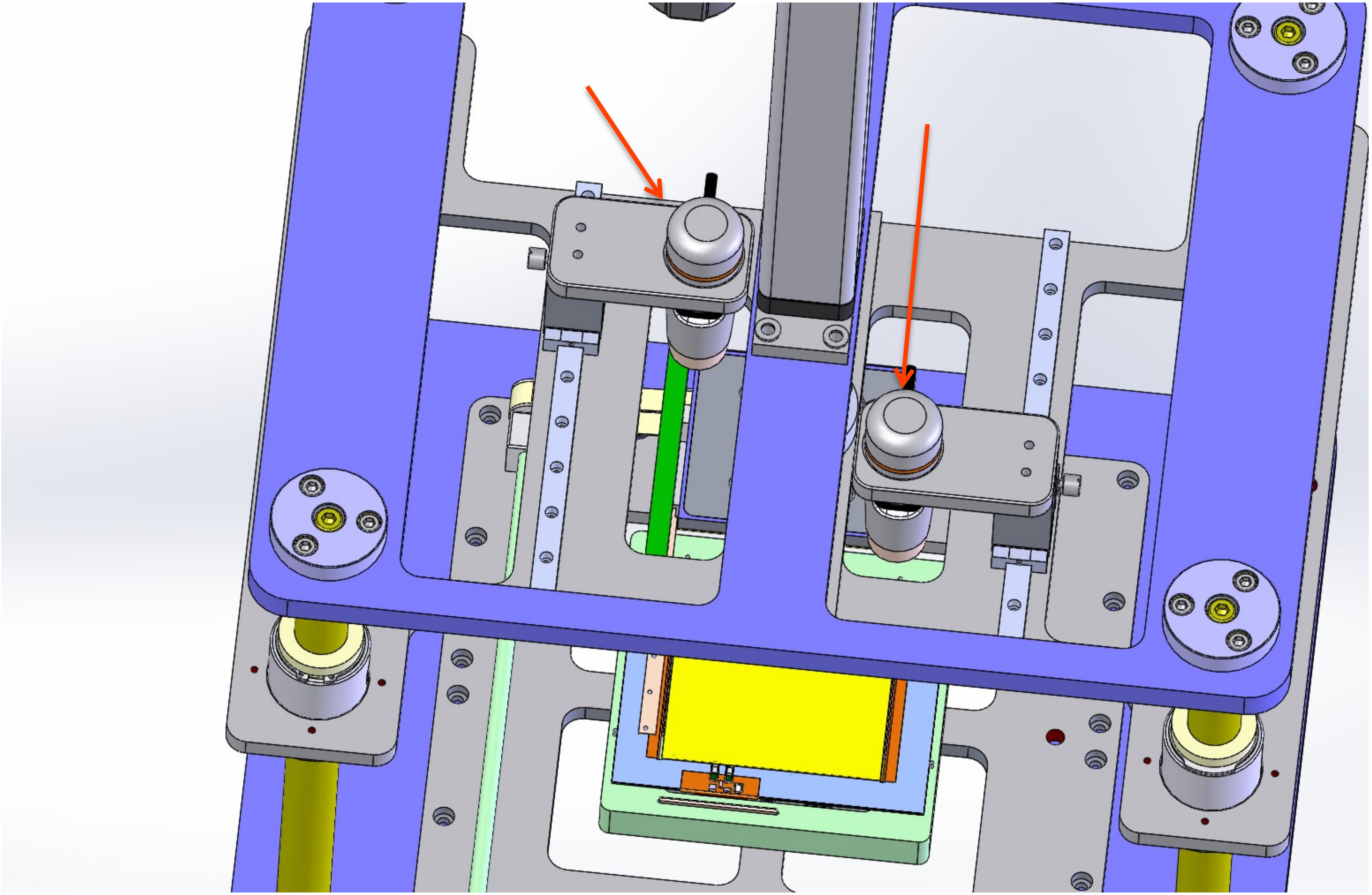


GANTRY FOR SEMI-AUTOMATIC MODULE PRODUCTION





USB microscopes to check alignment of upper and bottom sensor



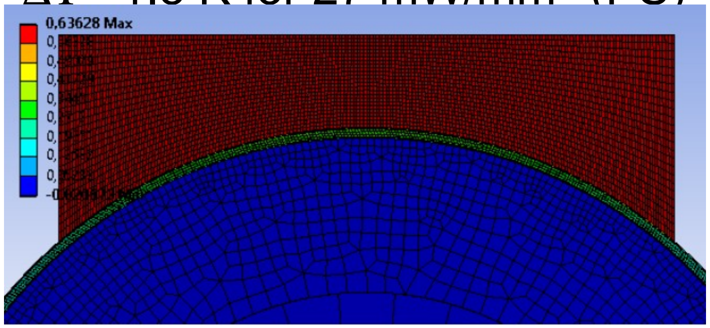
Attachment of cooling pipes: pressed directly on SGT
Optimal thermal contact

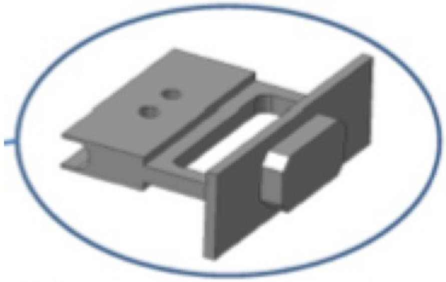
Advantages of gluing instead of screwing:

large contact area ->

1) better thermal performance
2) less weight

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



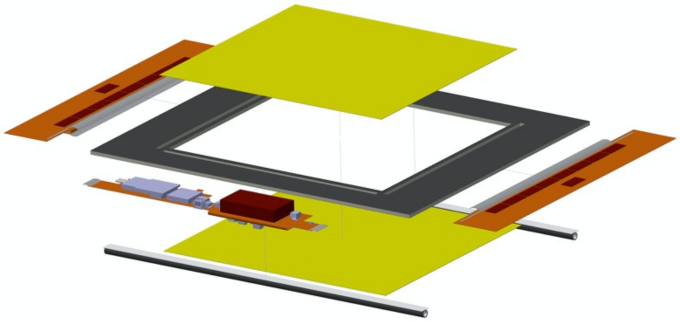


Weight of cooling inserts:
-> 5x2 g/module or ca. 25% of total weight of module

Taped module: connect module with SGT to 0.3 x 2 mm thick Al cap
= 2x0.3 g < 2% of module weight

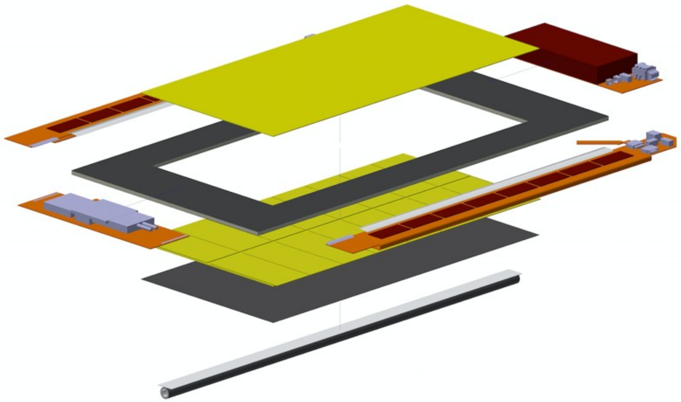
Conclusion

- **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) and excellent thermal performance**



- **Proven to work with CMS-like dummy prototypes yielding**
  mechanically robust and radiation hard modules with excellent thermal performance with standard materials