STS Cooling
Concept And Design

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- for the CBM-STS Team -

37th CBM Collaboration Meeting
Virtual Meeting
05/03/2021

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut

GSI

CBM

FAIR

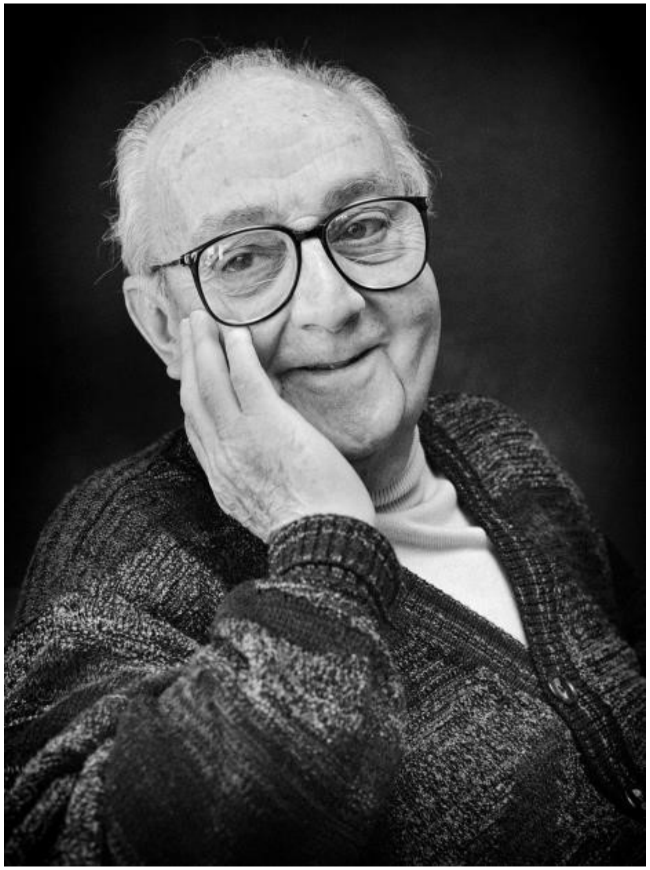
Honest Confession

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful."

G.E.P. Box; N.R. Draper, *Empirical Model-Building and Response Surfaces*, John Wiley & Sons, pg. 74 (1987)

George Edward Pelham Box
1919 – 2013
FRS; Statistician

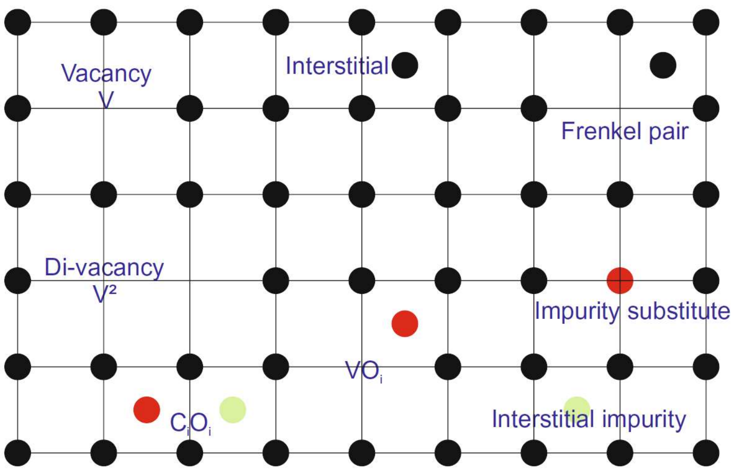
The contents shown in this presentation are just simulations/approximations/expectations.
Reality could be, and probably would be different.

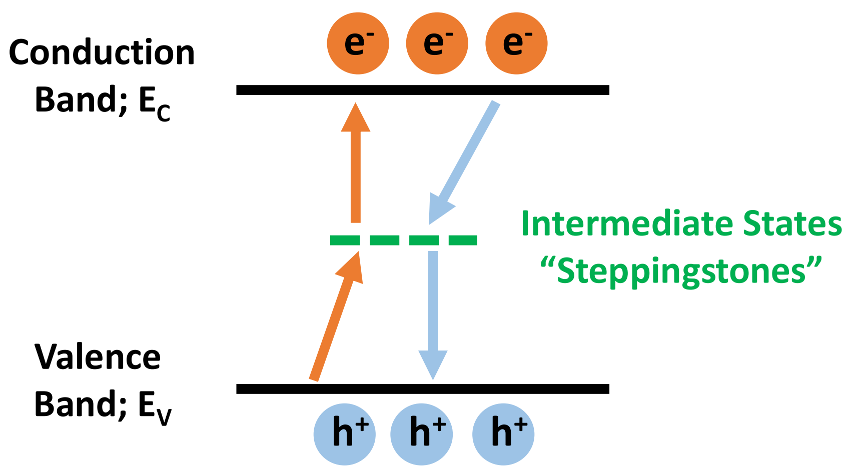


A. F. M. Smith, *George Edward Pelham Box*, Biogr. Mems Fell. R. Soc. 61, 23–37 (2015)

Motivation To Cool Silicon Sensors

Non-Ionizing Radiation Damage ∝ Defects in Si-Lattice ∝ Intermediate Energy States ∝ (Higher) Leakage Current





Frank Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics* (2nd Edition) - Springer Tracts in Modern Physics, Volume 275 (2017)

Motivation To Cool Silicon Sensors

Leakage Current varies linearly with fluence:

$$\Delta I = \Phi \cdot \alpha \cdot (A \cdot d)$$

This also increases the detector shot noise and degrades the S/N ratio:

$$ENC_{I_{Leakage}} = \frac{e}{2}\sqrt{\frac{I_{Leakage} \cdot t_p}{q_e}}$$

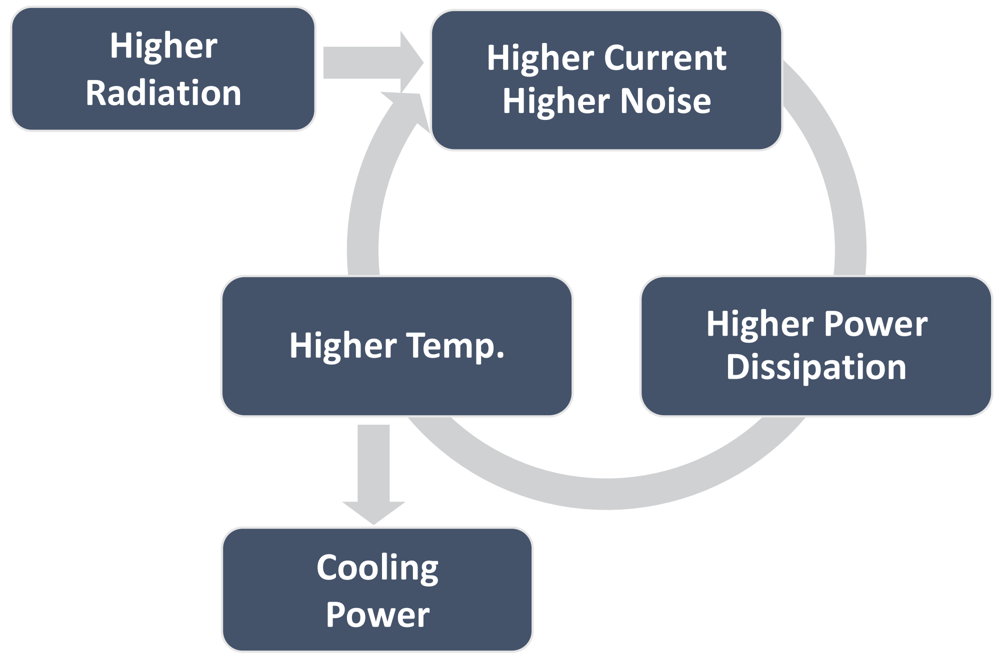
Power Dissipation in a silicon sensor is described as:

$$P_{Silicon} = V_{Bias} \cdot I_{Leakage}$$

$$P_{Silicon} \sim V_{Bias} \cdot T_{Silicon}^{\;2} \cdot e^{-\frac{E_{eff}}{2 \cdot k_B \cdot T_{Silicon}}}$$

Power Dissipation (or leakage current) doubles whenever the silicon temperature is increased by 10°C

Non-Ionizing Radiation Damage ∝ Defects in Si-Lattice ∝ Intermediate Energy States ∝ (Higher) Leakage Current

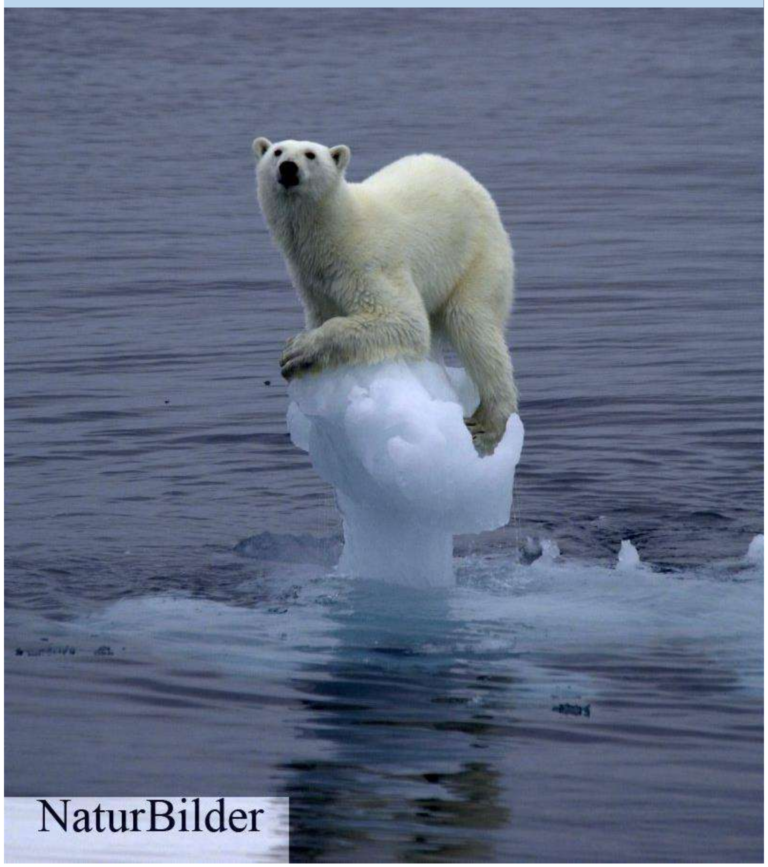


If the Cooling Power can't neutralise the Heating Power caused due to high STS irradiation environment, then this self feeding system goes into '<u>Thermal Runaway</u>'

Frank Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics* (2nd Edition) - Springer Tracts in Modern Physics, Volume 275 (2017)

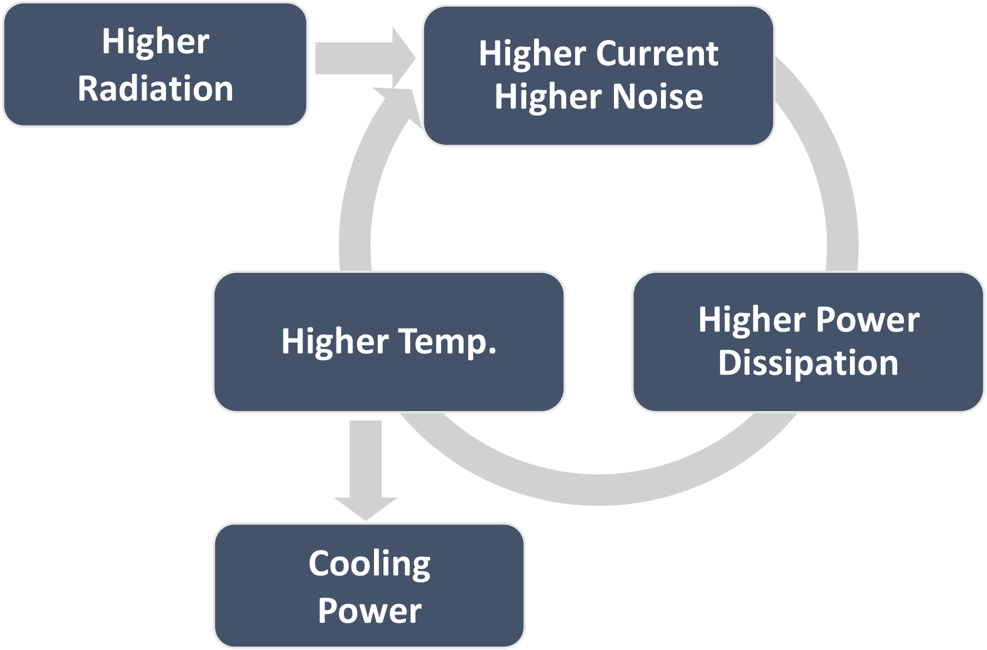
Motivation To Cool Silicon Sensors (& Planet Earth)

Planet Earth is also in a 'Thermal Runaway'

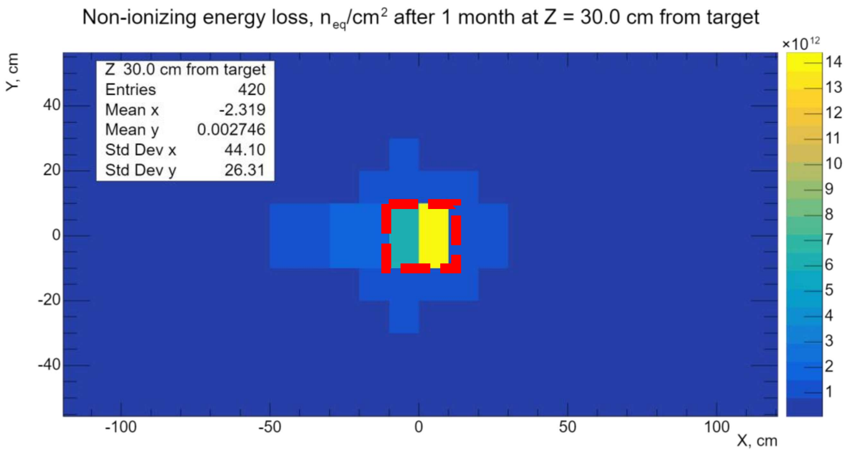


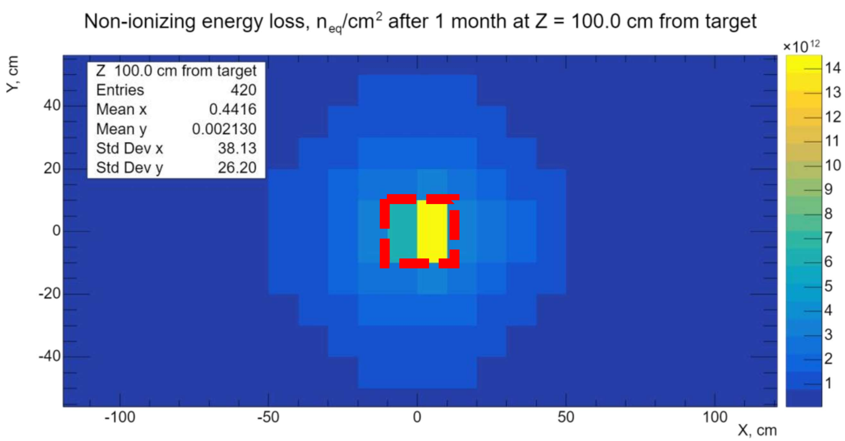
Arne Navra, www.NaturBilder.no

Non-Ionizing Radiation Damage ∝ Defects in Si-Lattice ∝ Intermediate Energy States ∝ (Higher) Leakage Current

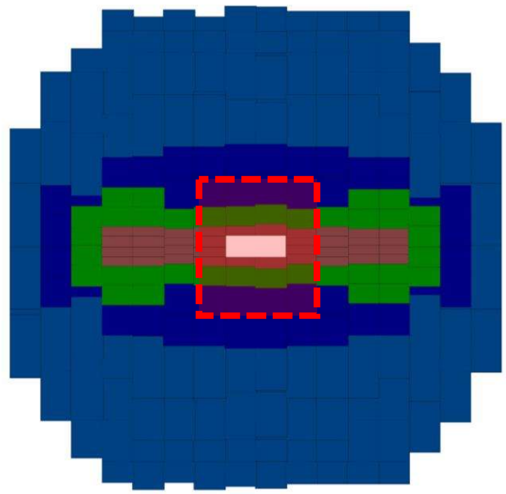


If the Cooling Power can't neutralise the Heating Power caused due to high STS irradiation environment, then this self feeding system goes into '<u>Thermal Runaway</u>'

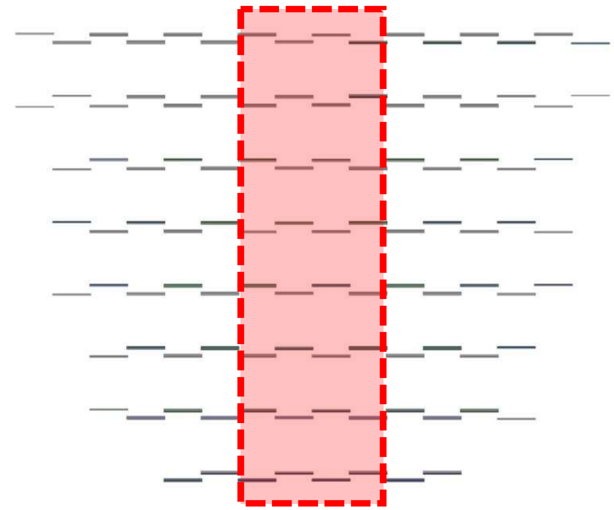




Online Tool: *https://fair-center.eu/fileadmin/fair/experiments/CBM/tmp/CBM_FLUKA.htm*



STS Front View



STS Top View

- **Only the innermost sensors of the central ladders (x,y ≤ ± 10 cm) of all stations, where power dissipation is less than 3mW/cm² (@-10°C, EOL) requires active cooling †**
- **The peripheral sensors of the central and peripheral ladders can be cooled by natural convection (-10°C)**

† Detailed power dissipation numbers for inner ladders of Station #1 and #8 are tabulated in the backup slides (#26)

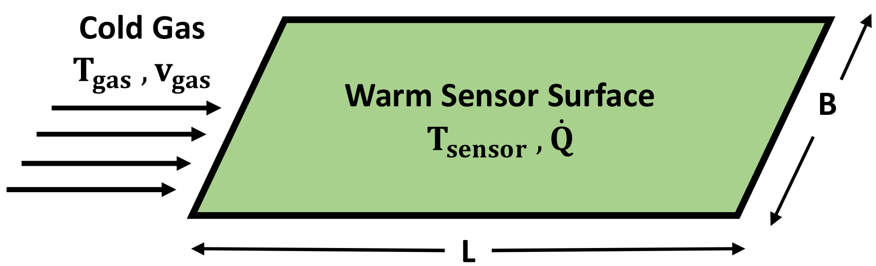
Boundary Conditions And Potential Solution

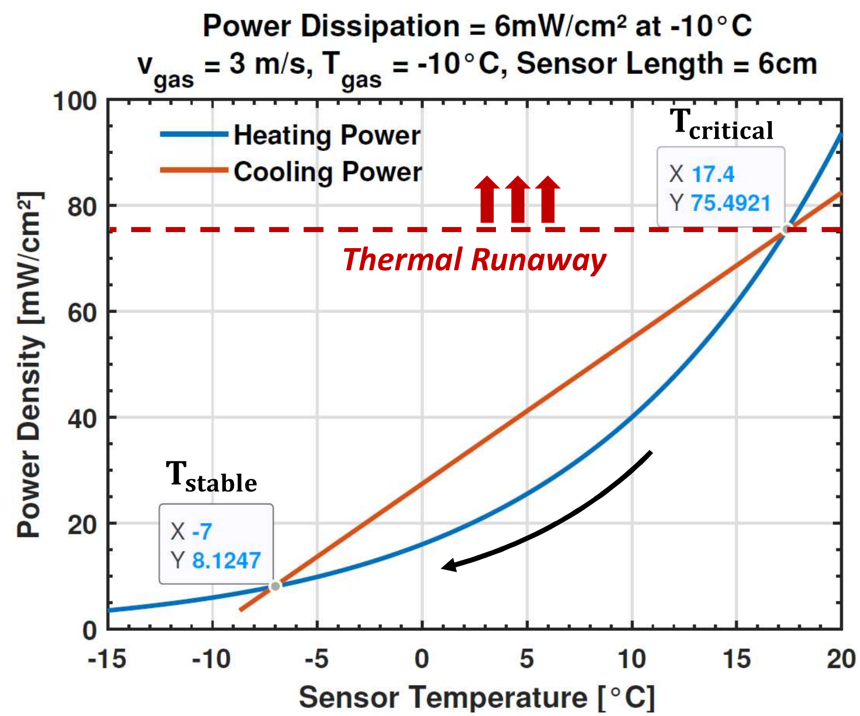
BOUNDARY CONDITIONS -

- **Power dissipation for innermost sensors ~ 6 mW/cm² (at -10°C at EOL fluence 10^{14} n_{eq}(1 MeV)/cm²)**
- **Target sensor temp. -10 … -5°C to achieve S/N ≥ 10**
- **To be done by adding minimum additional material budget in active detector geometry**

COOLING IDEA -

- **Forced convective air cooling**



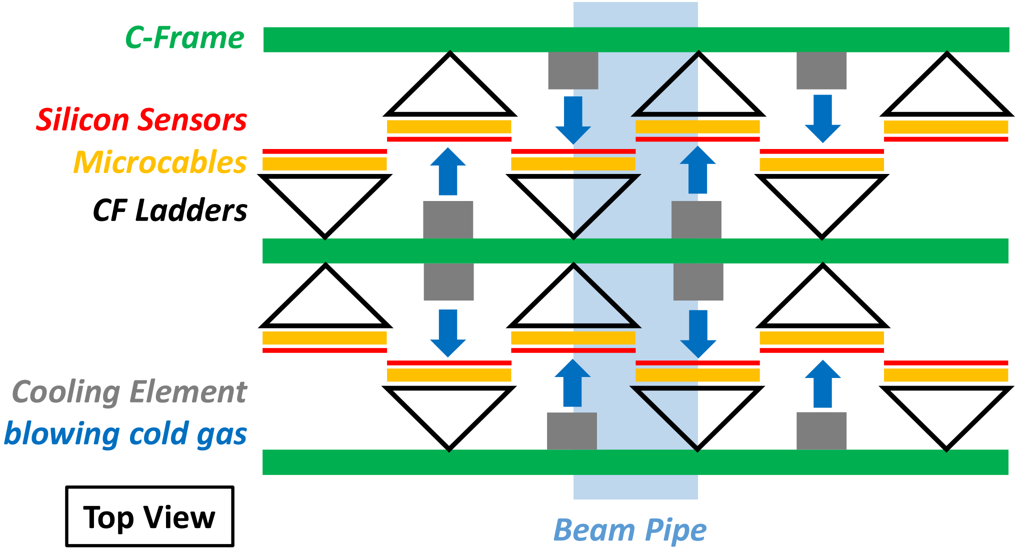


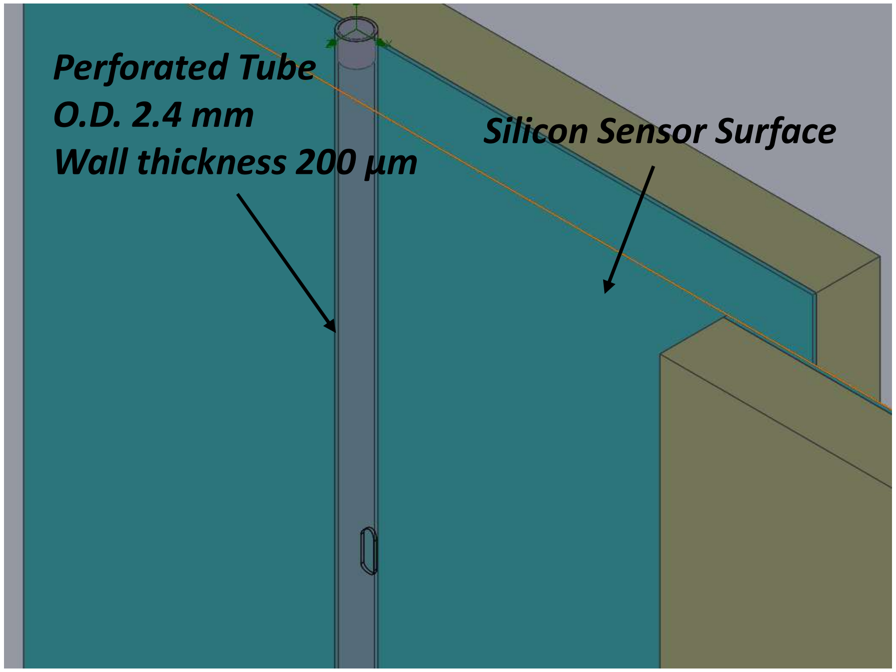
- **If $T_{stable} < T_{sensor} < T_{critical}$ ⇒ Stable operation at T_{stable}**
- **If $T_{sensor} \geq T_{critical}$ ⇒ Thermal Runaway**

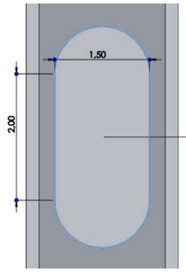
Detailed Calculations: K. Agarwal, *Thermal Runaway Analysis for STS Sensors*, STS Coordination Meeting, 25.01.2021 | Link

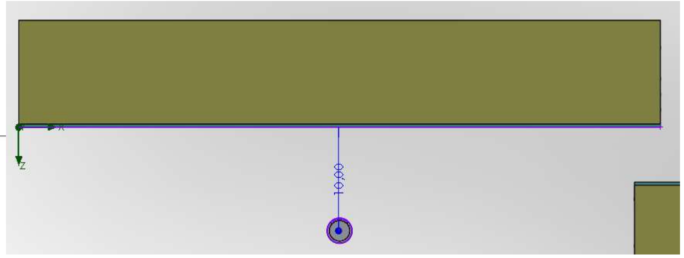
Theoretically, it's possible to stably operate the innermost STS sensors at -7°C with sufficient margin from thermal runaway (by assuming that one can achieve an infinite heat sink around at -10°C at 3 m/s)

Practicalities



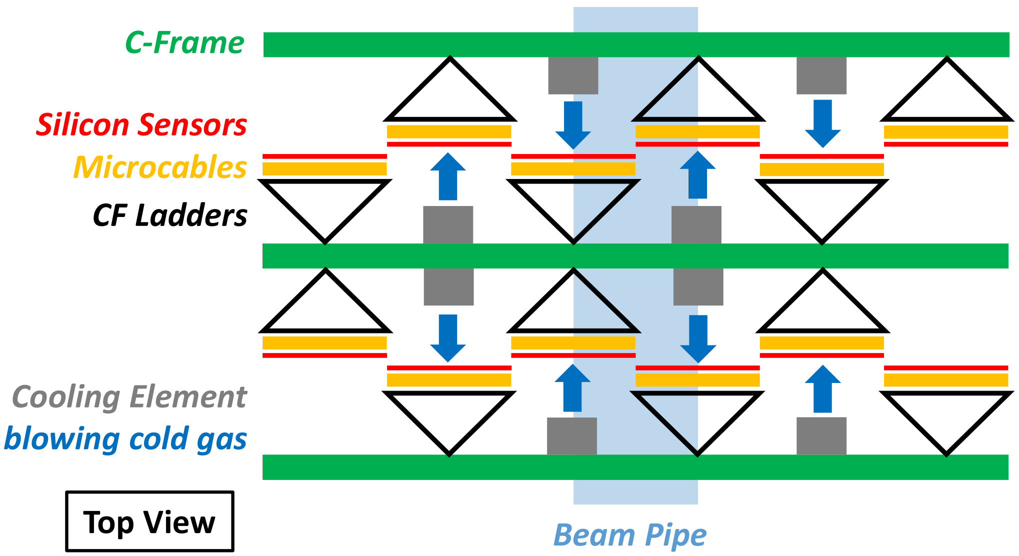




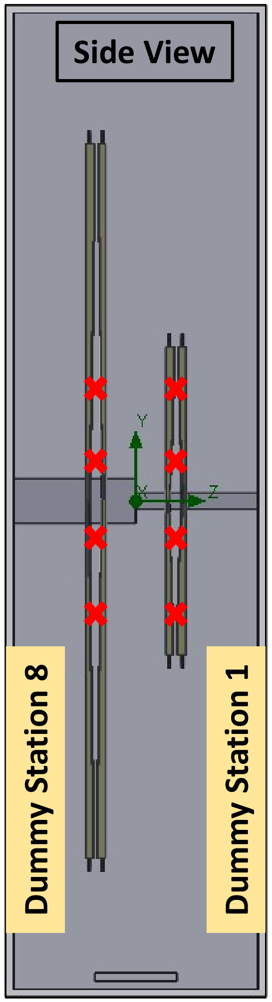


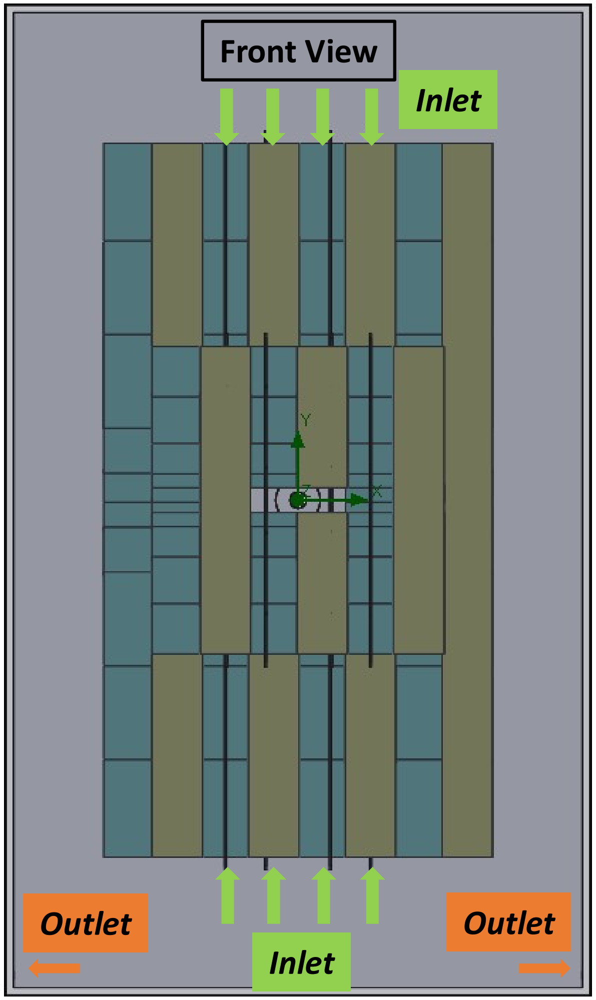
- **<u>Cooling Element:</u> Perforated Tube running along the sensors**

Toy Model – Setup

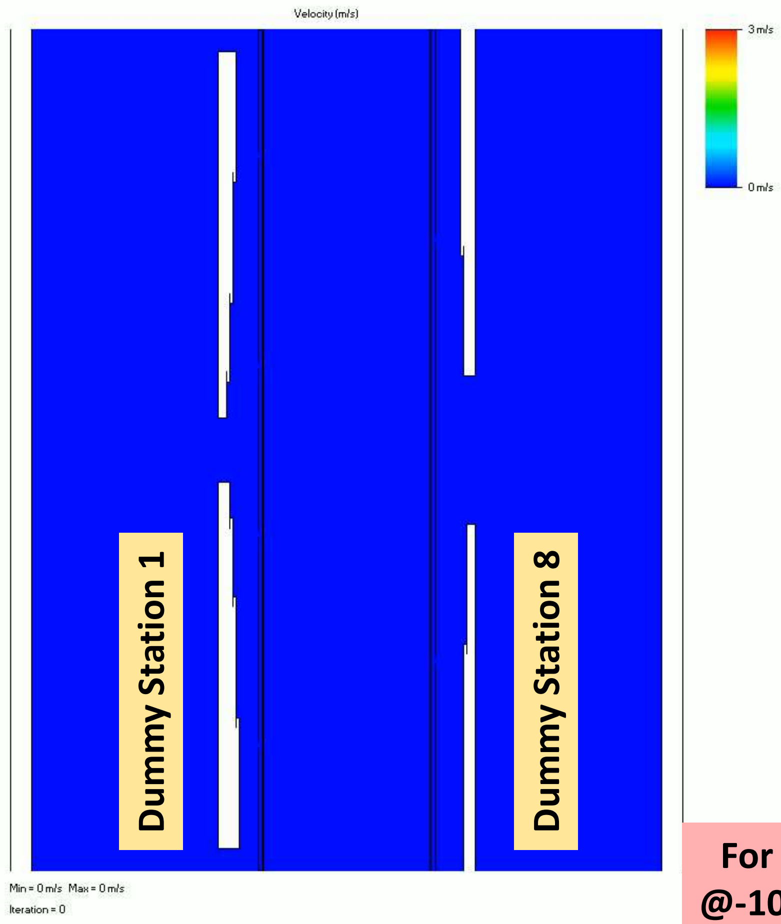


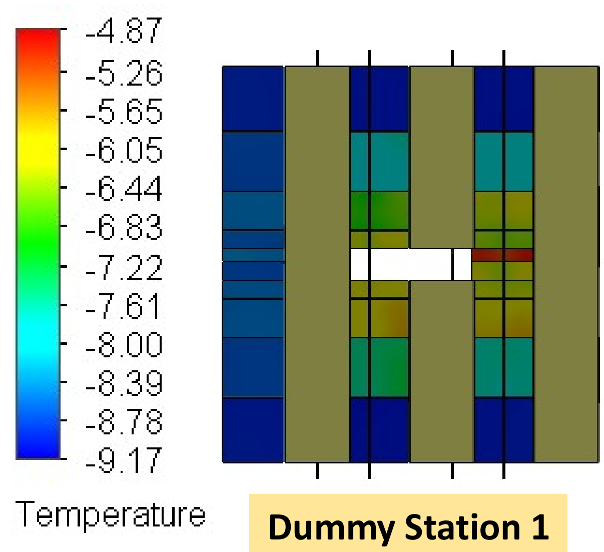
- **Cooling Element: Perforated Tube running along the sensors**
- **Toy Model developed in SolidWorks for CFD Simulations with 2 dummy stations resembling the STS stations no. 1 and 8 in an enclosure (only active volume of the detector)**
- **20 lt/min of cold air flow at -10°C in every tube to cool only the innermost sensors**

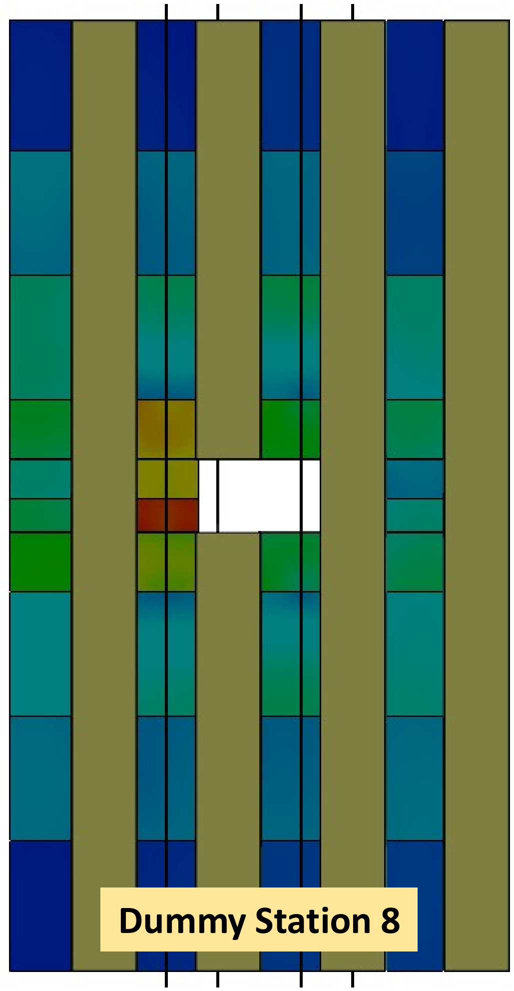




Toy Model – Flow And Temp. Distribution



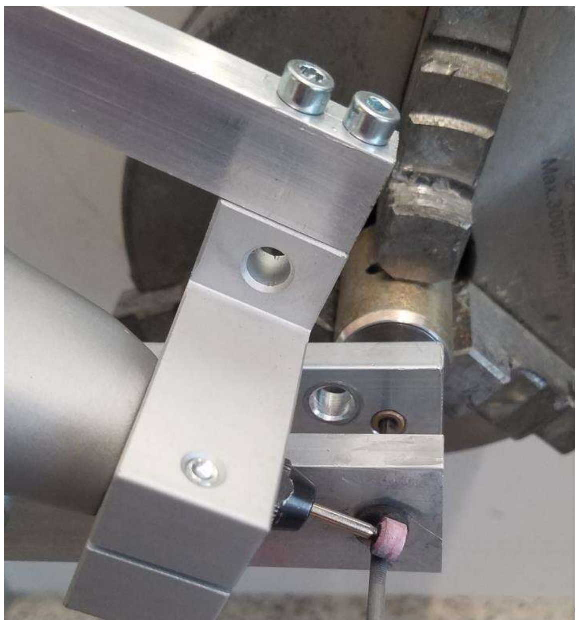




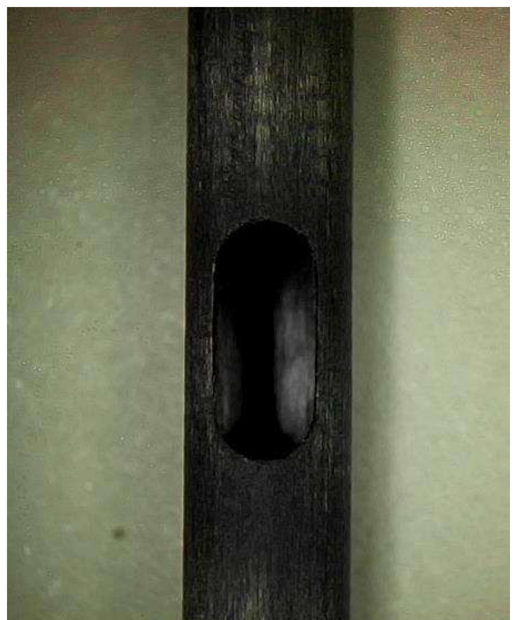
For an ambient temperature of -10°C, with flow @-10°C and 20 lt/min per tube, a stable operation with max. temp. at -4.9°C is possible!

PERFORATED TUBE – MATERIAL & MANUFACTURABILITY

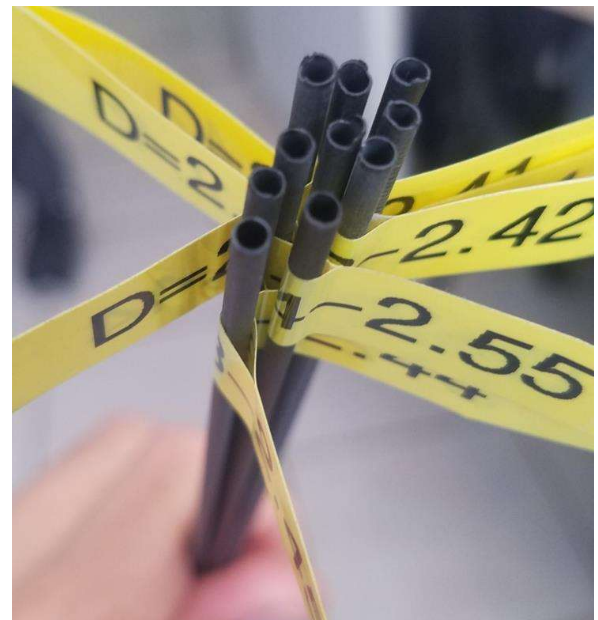
- **Perforated tubes made from carbon fibre (CF); Outer Diameter = 2.4 mm, Thickness = 200 µm**
- **Local addition of x/X_0^{tube} = 0.14% radiation length to its location of mounting. So, the average material budget is only increased very marginally and will soon be added in the STS GEANT geometry.**
- **Manufacturability tested by ICM-Composites (DE)**



Milling down of thicker CF-tube



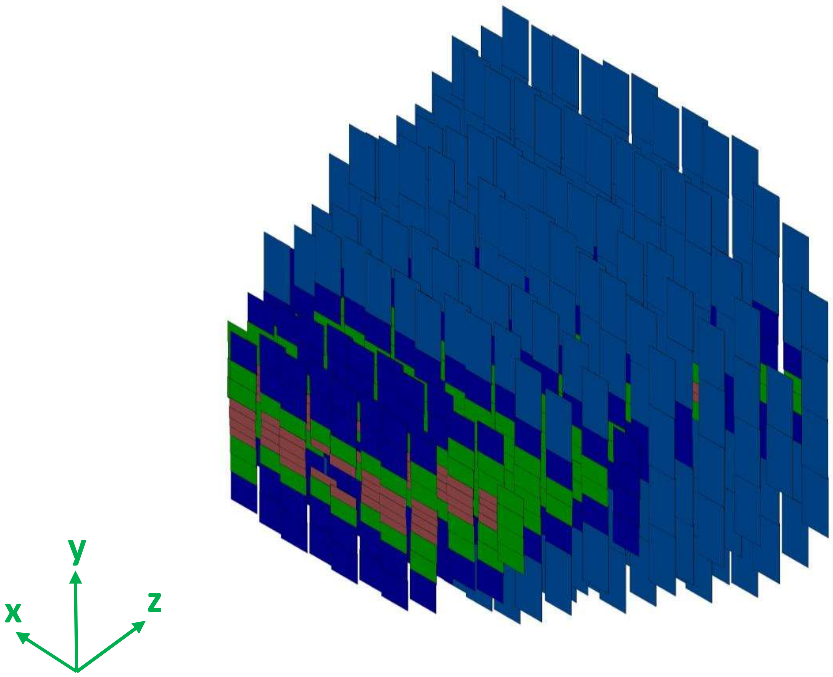
Perforated CF-tube

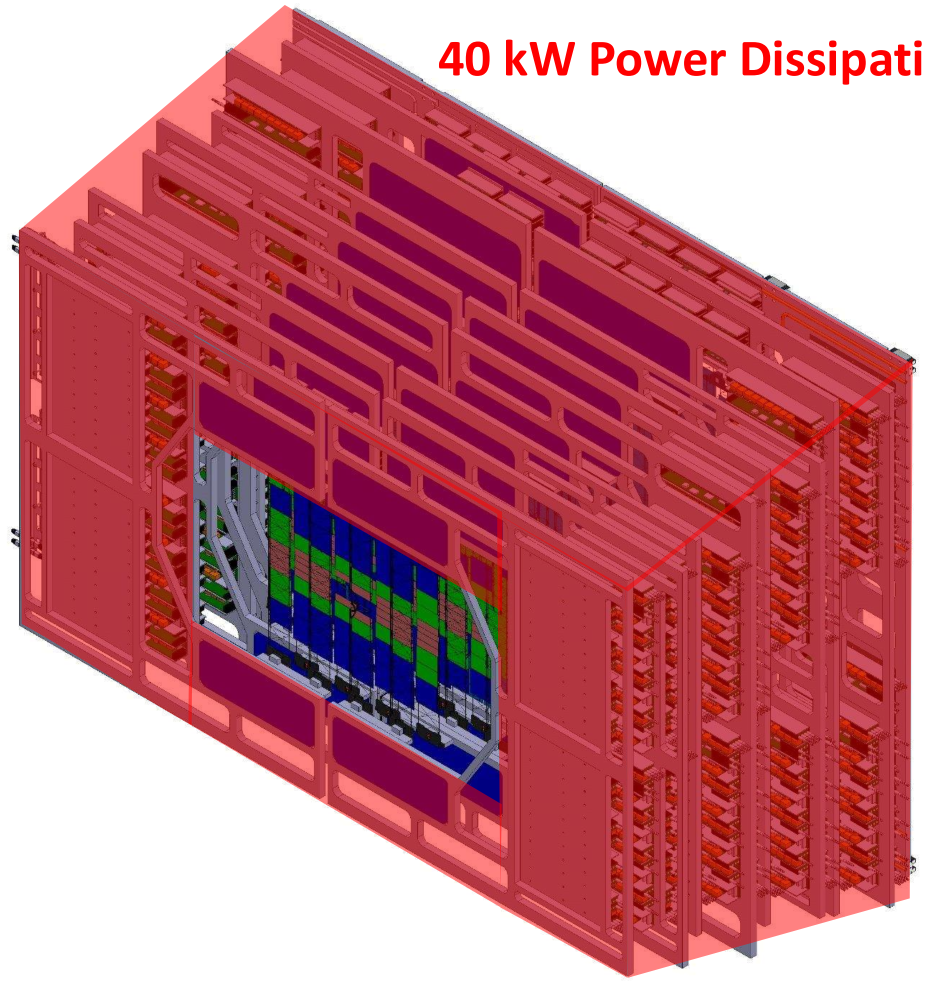


10 samples delivered at GSI

Material Budget Estimates: J.M. Heuser, U. Frankenfeld, *Production Readiness Review for the STS Carbon Fiber Ladders*, CBM-TN-19006 (2019) | Link

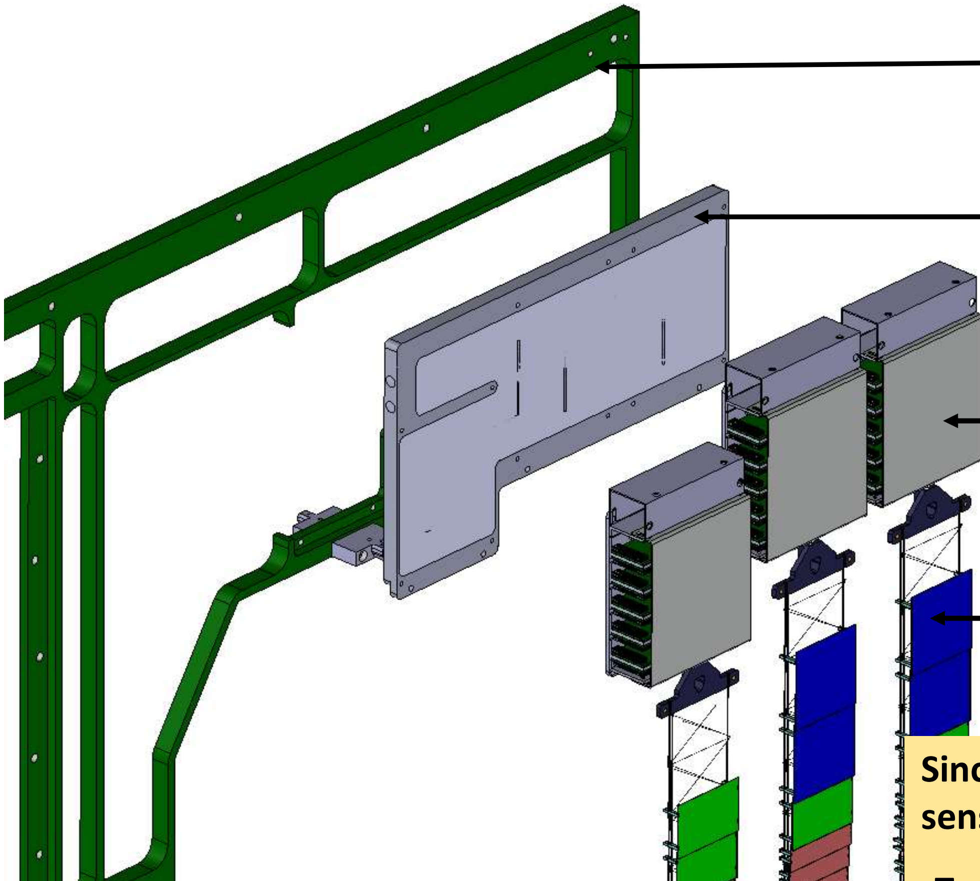
STS W/O AND W/ PERIPHERAL INFRASTRUCTURE





40 kW Power Dissipation!

REQUIREMENTS ON ELECTRONICS COOLING



C-Frame (support structure)

Cooling Plate carrying the coolant

Front-End Electronics Board (FEB) Boxes
P_{FEB} = 10 W (approx.)
$P_{FEB\ Box}$ = 100 W

Silicon Sensor mounted on the CF ladder (microcables hidden)

Since the electronics are 25…50 cm away from the innermost sensors, one must neutralise the electronics power dissipation

Temp. exposed by the FEB Boxes ≈ Temp. on the sensors ≈ -10°C

Transition From Bi-Phase CO_2 To Mono-Phase 3M Novec 649

58 μm, strip lengths between 20 and 60 mm, and a thickness of 300 μm of silicon. According to the CBM running scenario the maximum non-ionizing dose for the sensors closest to the beam line does not exceed 1×10^{14} n_{eq} cm^{-2}. The STS is operated in a thermal enclosure that keeps the sensors at a temperature of about -5° C. The heat dissipated in the read-out electronics is removed by a CO_2 cooling system. The mechanical structure of the detector system including

J.M. Heuser (eds.) *et al.*, *Technical Design Report for the CBM Silicon Tracking System (STS)* – GSI Report 2013-4 (2013)

Biphase CO_2 (GWP = 1)

- ✓ Operational in various trackers at (HL-)LHC, ISS
- ✓ Great performance
  - less mass flow; H = 150 kJ/kg (at -20°C)
  - low pressure drop; ν = 0.14 cSt (at -23°C)
  - smaller tubes; h_{vol} = 10 kW/m².K
  - uniform temperature
- ✗ Higher system pressures i.e., safety regulations
- ✗ Potentially difficult for commercial manufacturing (2PACL-type system)

CBM-STS FEE Cooling Conceptual Design Review, 10.12.2019 | Link

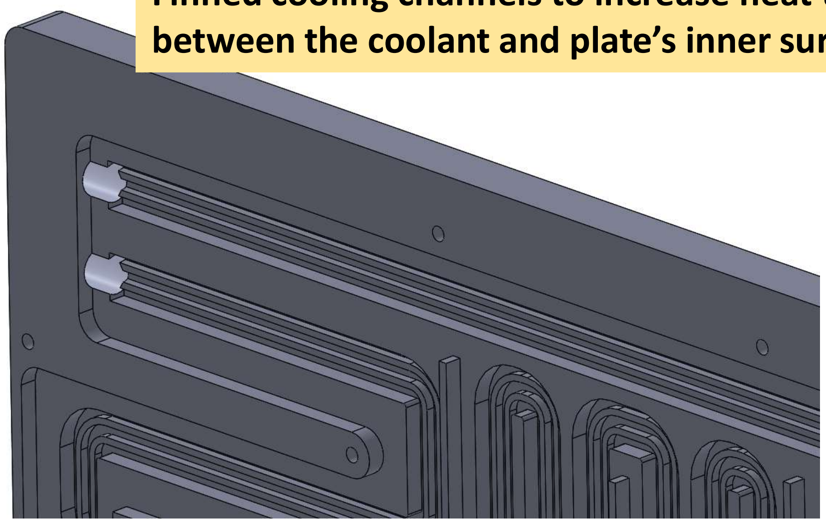
Monophase 3M™ NOVEC™ 649 (GWP = 1)

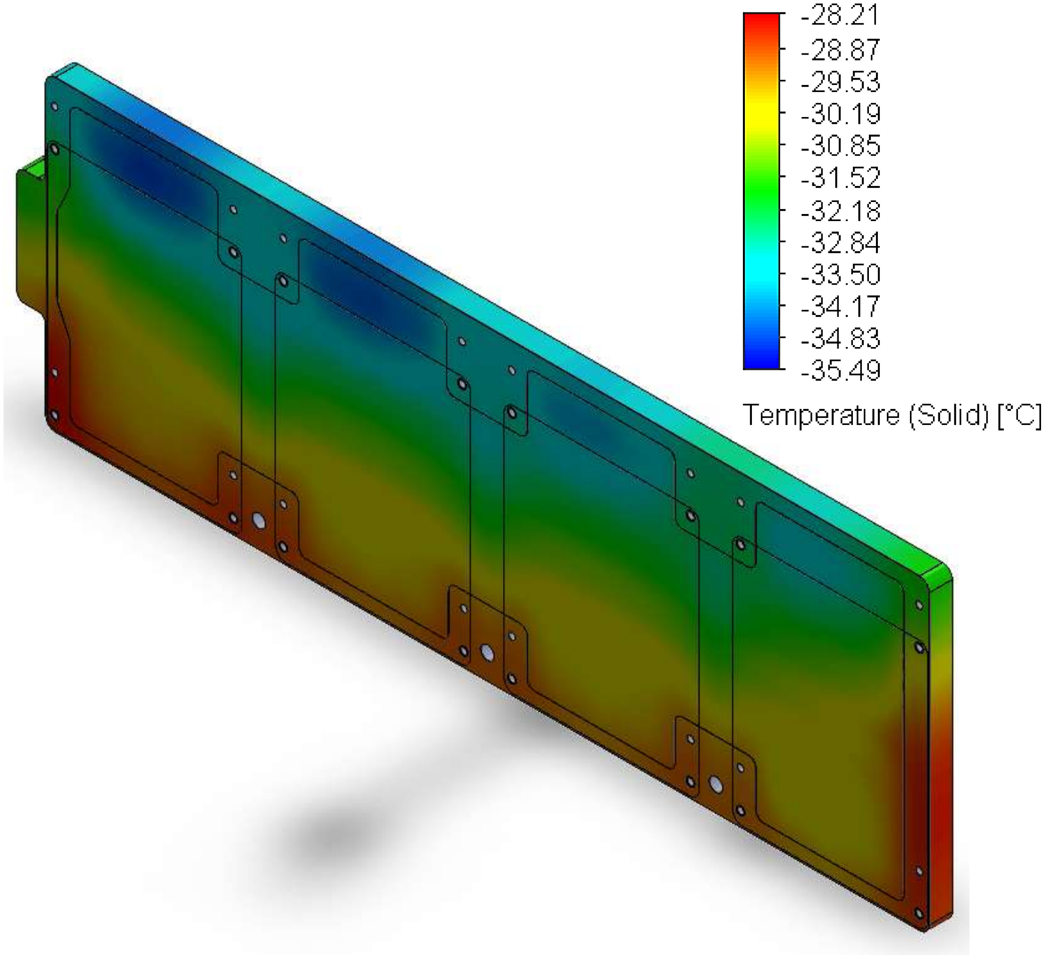
- ✓ To be used in LHCb Sci-Fi Tracker. Considered for more...
- ✗ Relatively lower performance
  - higher mass flow; c_p = 1.1 kJ/kg.K
  - higher pressure drop; ν = 0.70 cSt (at -40°C)
  - larger tubes; h_{vol} = 2 kW/m².K
  - non-uniform temperature
- ✓ Lower system pressures i.e., safe to use
- ✓ Easier commercial manufacturing

Based on recommendations from CERN, CBM and industrial experts, the coolant for STS-FEE is NOVEC™ 649

CFD Simulations – Cooling Plate

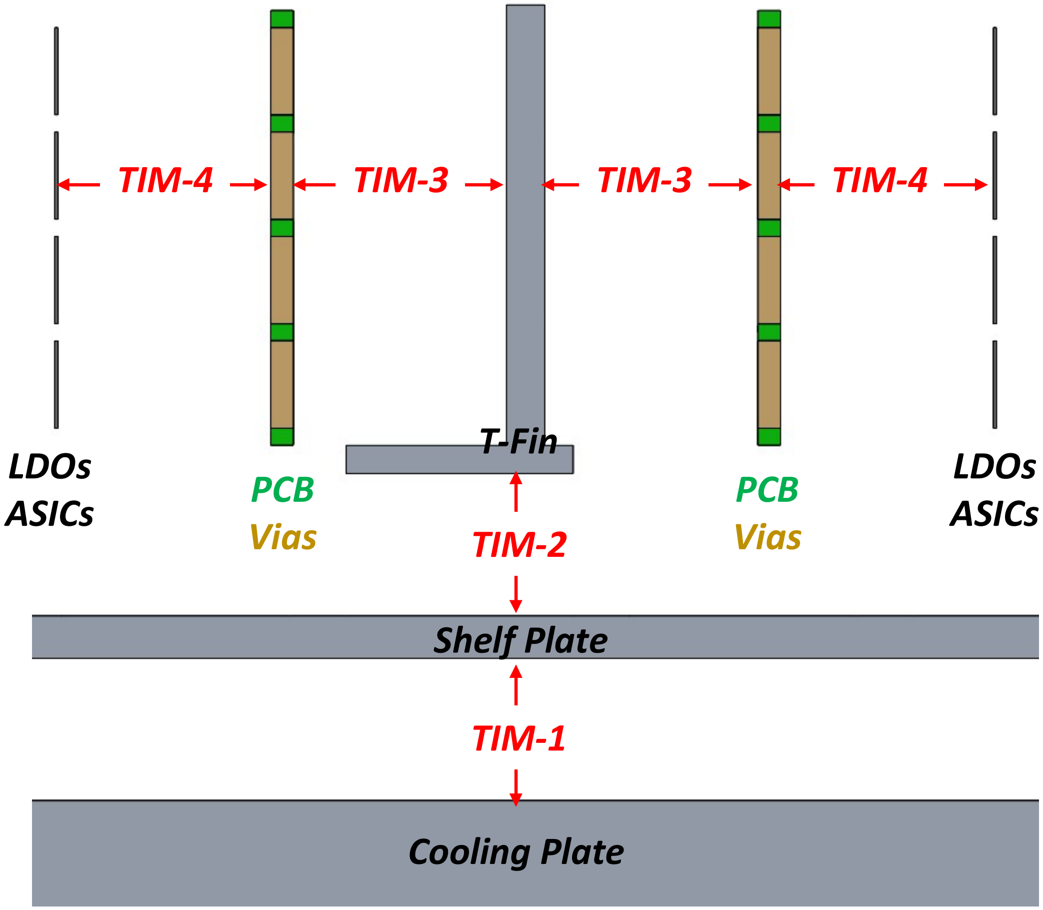
Finned cooling channels to increase heat transfer between the coolant and plate's inner surface



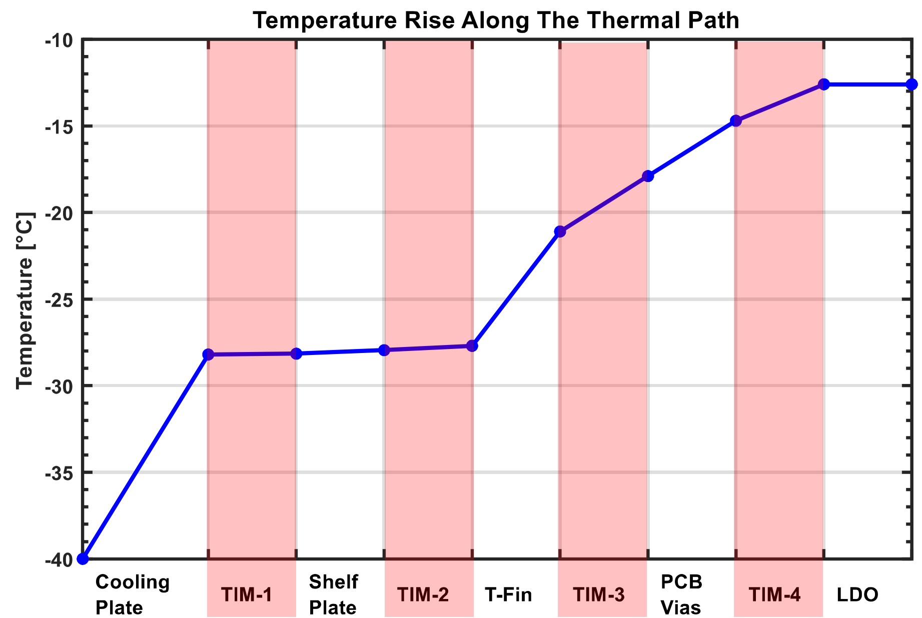


Material:	**Aluminium**
Inlet:	**3M Novec 649** (TM, TM)
	-40°C at 3 litre/min
Total power dissipation:	**800 W**
Temperature outlet:	**-33.8 °C**
Max. temp. of cooling plate:	**-28.2 °C**
Pressure loss:	**1.32 bar**

THERMAL FEA SIMULATIONS – FEB BOX

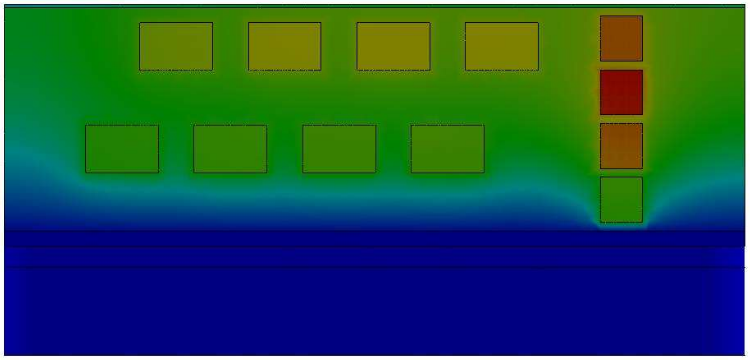


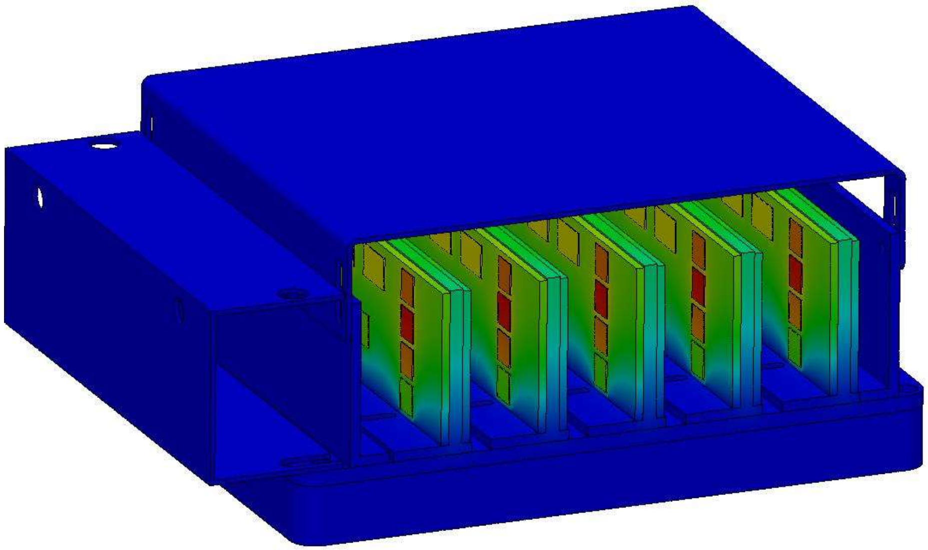
TIM: Thermal Interface Material

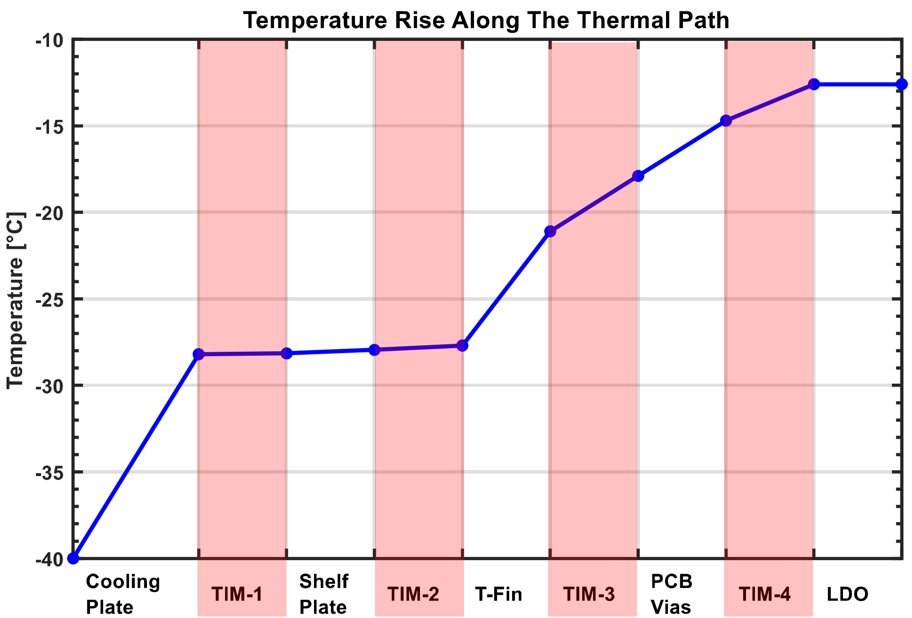


	Product	Thermal Conductivity (along z-) [W/m.K]	Thickness [µm]
TIM-1	DSN5040-10DC10DC	20	40
TIM-2	DSN5040-10DC10DC	20	40
TIM-3	Stycast 2850FT (+23LV)	1.02	150
TIM-4	EPO-TEK E4110	1.37	100

Thermal FEA Simulations – FEB Box

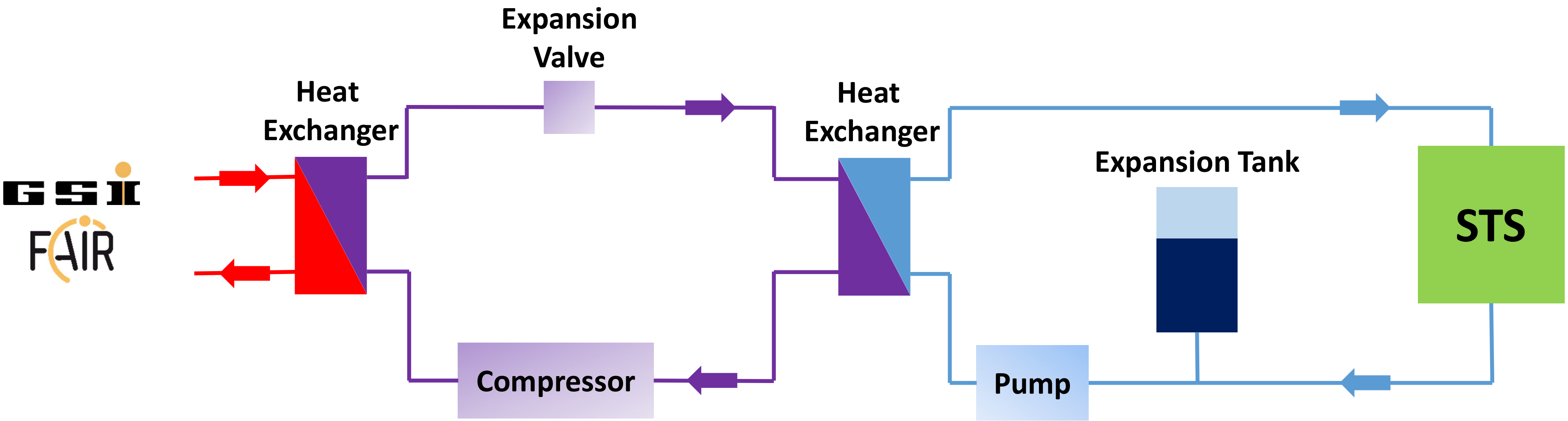






Since the temp. exposed to the environment (i.e., temp. 'seen' by the silicon sensors) is ~ -20°C which is much lower than -10°C, there is substantial headroom for increasing the coolant temp. from -40°C

Baby Cooling Plant – Simplified P&ID



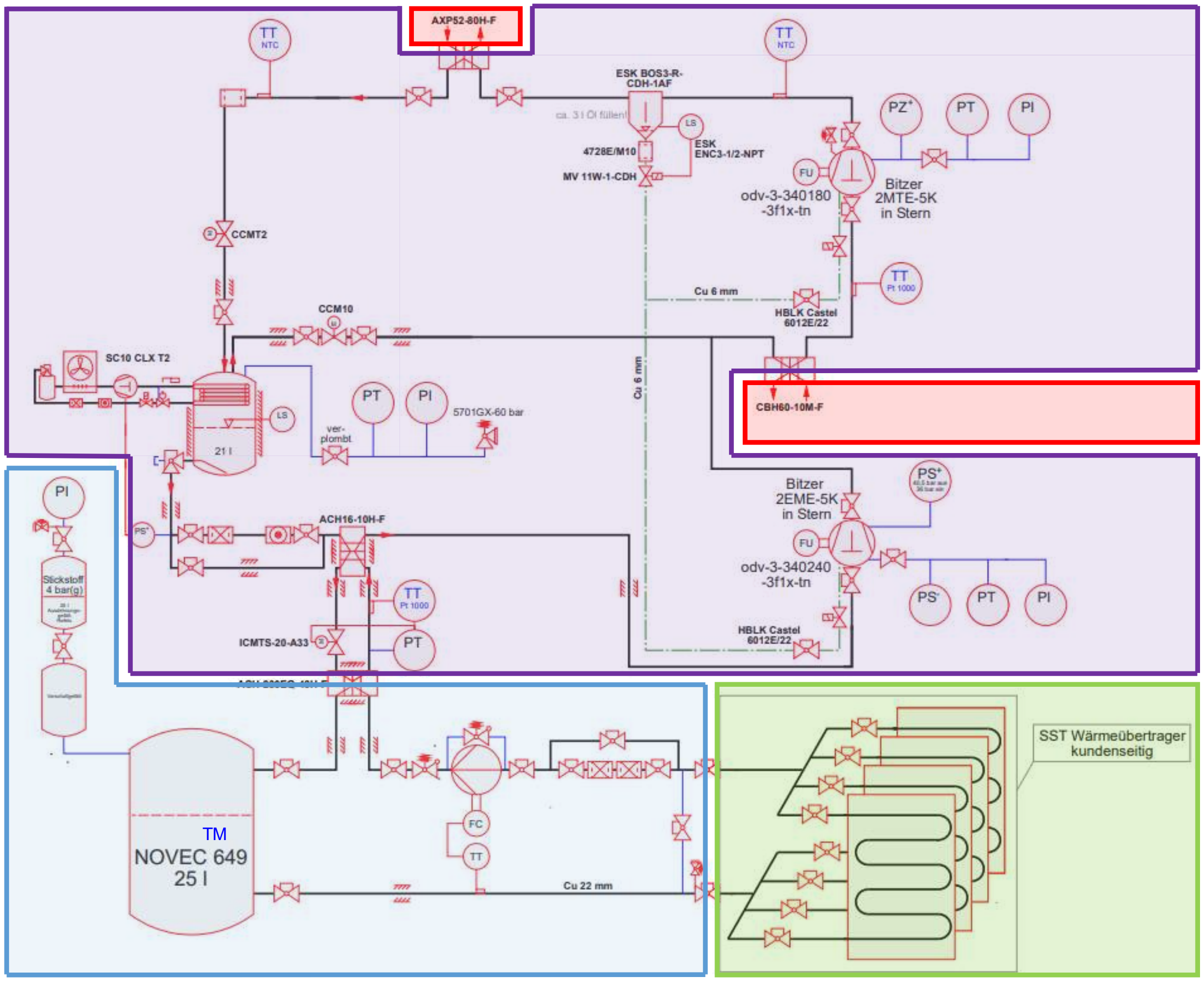
Water Cooling	Biphase CO_2 Vapor Compression Cycle (Primary Circuit)	3M™ NOVEC™ 649 Monophase Cycle (Secondary Circuit)

- All coolants used in this concept are GWP = 1, which makes this cooling plant usable for coming decades
- 'Simple' to manufacture commercially by using established technology and industrial practices
- To be used by STS for the Thermal Demonstrator and detector assembly procedure & testing

Baby Cooling Plant – Complete P&ID

Biphase CO_2 Vapor Compression Cycle

3M™ NOVEC™ 649 Monophase Cycle



Water Cooling

STS

BABY COOLING PLANT – DELIVERED & UNDER COMMISSIONING

(pilot refrigeration plant for the pilot refrigeration system of the detector)

- **Baby Cooling Plant delivered at GSI on 18.12.2020**
  (Pilot refrigeration/cooling plant for the pilot refrigeration system of the detector)
- **7.5 kW cooling capacity at -40°C**
- **Commissioning to be done within 2 months**

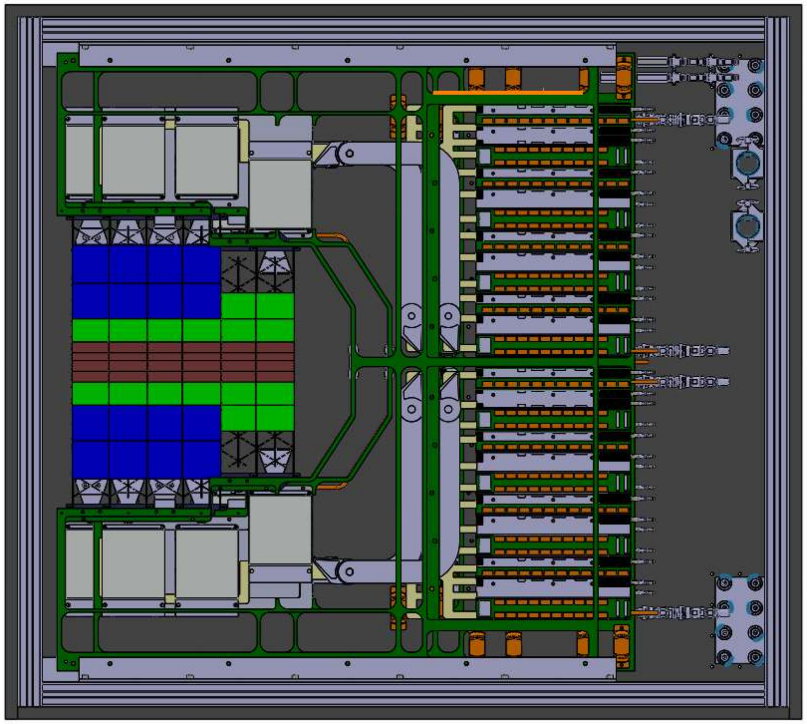
SUMMARY AND OUTLOOK

SENSOR COOLING

- **Based on CFD Flow Simulations, a cooling concept to avoid thermal runaway of the STS sensors at their end-of-lifetime has been established**
- **Manufacturability of low material budget CF-perforated tubes, which are the active sensor cooling elements, has been demonstrated**

ELECTRONICS COOLING

- **3M[tm] NOVEC[tm] 649 has been chosen as the coolant to neutralise the electronics power dissipation of 40 kW**
- **Combination of CFD and Thermal FEA Simulations shows that sufficient margin is available if one uses the coolant at -40°C**
- **A Baby Cooling Plant, with 7.5kW cooling capacity at -40°C, was delivered in 12/2020 which will be used for STS assembly and any intermediate tests**



BUSY ROAD AHEAD (2021)

To experimentally demonstrate the feasibility of STS concepts in realistic boundary conditions, the construction of a thermal demonstrator is ongoing!

STS Thermal Demonstrator – A 'Cool' Mock-Up

CBM

ATLAS EXPERIMENT

Exploring the "coolest" mock-up

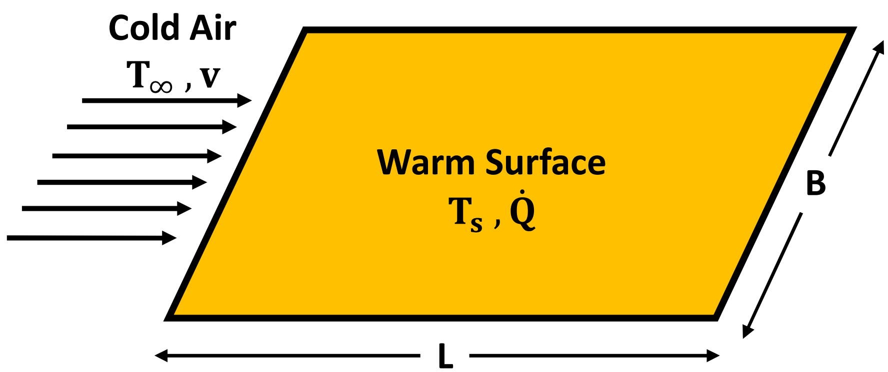
10th September 2020 | By Claudio Bortolin

https://atlas.cern/updates/blog/exploring-coolest-mockup

A lot to look forward with the STS Thermal Demo ☺

Thanks A Lot…
Questions? Comments?

(Rough) Estimation Of Cooling & Heating Power



$$\dot{Q} = [h \cdot A_s \cdot (T_s - T_\infty)]$$

$$T_s = T_\infty + \frac{\dot{Q}}{h \cdot A_s}$$

$$\Rightarrow h = \frac{k}{L} \cdot Nu$$

$$\Rightarrow Nu = 0.664 \cdot Re_L^{0.5} \cdot Pr^{\frac{1}{3}} \quad \text{(Laminar Flow)}$$

$$\Rightarrow Re_L = \frac{v \cdot L}{\mathcal{V}}$$

Simplification of Sensor Cooling Concept

Formulas: Yunus, Cengel, Turner, ***Fundamentals Of Thermal-fluid Sciences*** **(2004), McGraw-Hill**

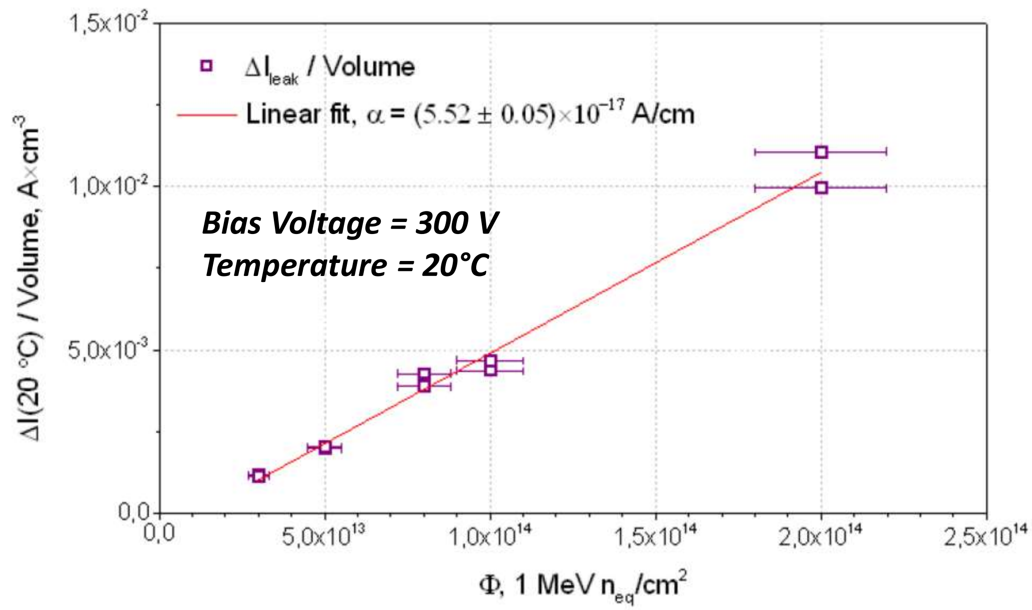


Figure 3.14: Fluence dependence of the leakage current density for neutron irradiated STS miniature sensors. The data points are scaled to 20 °C.

Assuming that the sensor thickness is 320µm and $I \propto \sqrt{V}$,

- **Leakage Current = 206.56 µA/cm² (+20°C, 500V, 10^{14} n_{eq}/cm^2)**
- **Power Density = 103.28 mW/cm² (+20°C, 500V, 10^{14} n_{eq}/cm^2)**

Pavel Larionov (Uni. Frankfurt), PhD Thesis (2016)

…. with particle fluence: …. with time (annealing):

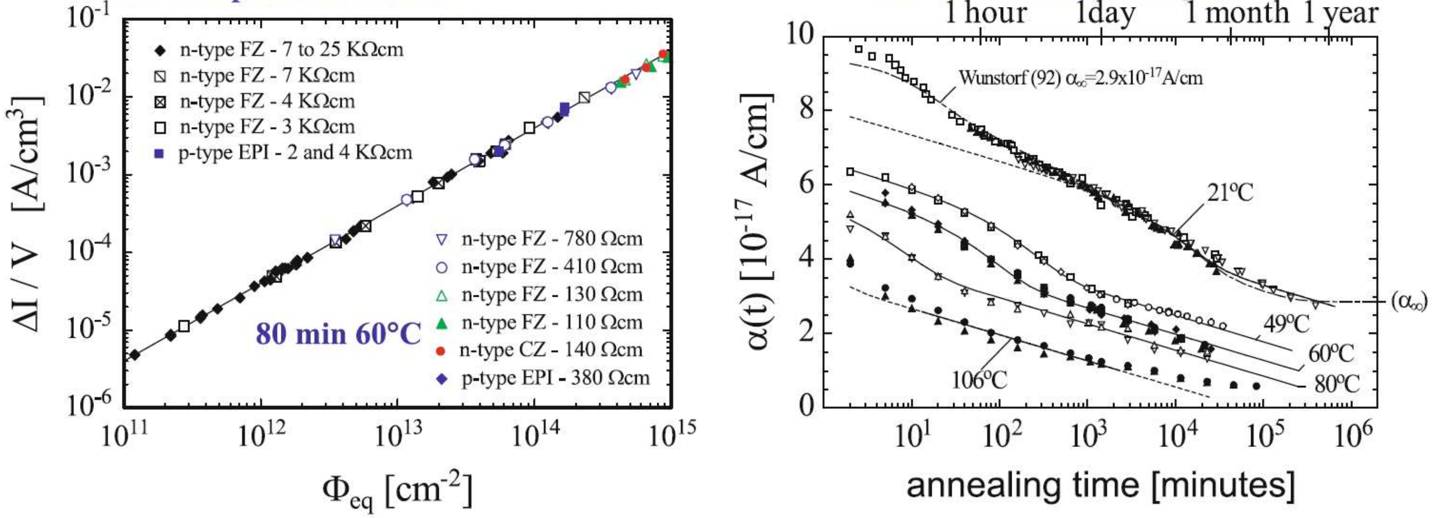


Fig. 2.5 Leakage current versus fluence and annealing time [219, 356]

Table 2.4 α and τ_I for different temperatures

Annealing temperature in °C	21	40	60	80
α_0 in 10^{-17} A/cm	7	6	5	4
τ_I in min	140000	260	94	9

The table shows the α parameter and the time constants τ_I for the current annealing for different temperatures. Below room temperature the time constants are longer than 100 days and annealing is almost frozen out

Estimates For STS Sensor Heating From The Hamburg Model

Olga Bertini, Results from mass QA inspection from HPK sensors
Michael Moll - DESY THESIS-1999-040

Theoretical estimate of Leakage Current after EOL Neutron Irradiation at 20°C at 500V:

$$\because \frac{(\Delta I)_V}{A\cdot d} = \Phi\cdot\alpha \Rightarrow \frac{(I)_V}{A} = \frac{(I_0)_V}{A} + (\Phi\cdot\alpha\cdot d)$$

Assuming the following values:

$$\frac{(I_0)_{500}}{A} < 0.04\left[\frac{\mu A}{cm^2}\right] at\ 20°C$$

$$\Phi = 10^{14}\left[\frac{n_{eq}}{cm^2}\right]$$

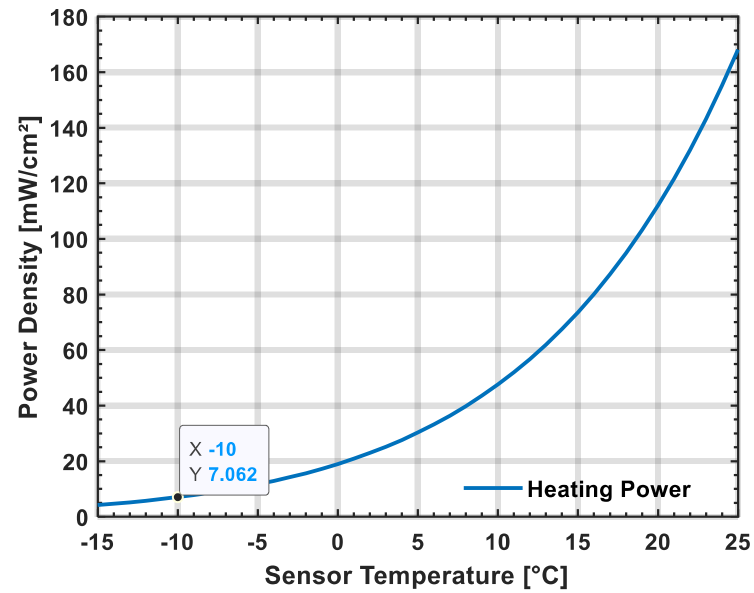
$$\alpha < 7\times10^{-17}\left[\frac{A}{cm}\right] = 7\times10^{-1}\left[\frac{\mu A}{cm}\right]$$

$$d = 320\ [\mu m] = 320\ \times10^{-4}\ [cm]$$

$$\Rightarrow \frac{(I)_{500}}{A} = [0.04 + 224] = 224.04\left[\frac{\mu A}{cm^2}\right]$$

Theoretical estimate of Power Dissipation after EOL Neutron Irradiation at 20°C at 500V:

$$\Rightarrow \frac{(P)_{500}}{A} = 224.04\left[\frac{\mu A}{cm^2}\right]\times 500\ [V] = 112.02\left[\frac{mW}{cm^2}\right]$$



Power Dissipation from the Hamburg Model is < 7.06 mW/cm² (-10°C, 500V, 10^{14} n_{eq}/cm²)

Power Dissipation Chart For This Anaylsis

With Active Cooling

Without Active Cooling

CBM

Power Dissipation for Station 1 (@-10°C, EOL)
Inner Ladders (Left), Peripheral Ladders (Right)

Sensor #	y-Length [cm]	EOL Power [mW/cm²]	Total Power [W]
(±) 1	2,2	6,00	0,08
(±) 2	2,2	6,00	0,08
(±) 3	4,2	6,00	0,16
(±) 4	6,2	3,16	0,12
(±) 5	6,2	0,49	0,02
Total Power Dissipation per Ladder = 0.92 W			

Sensor #	y-Length [cm]	EOL Power [mW/cm²]	Total Power [W]
(±) 1	2,2	0,70	0,01
(±) 2	2,2	0,70	0,01
(±) 3	4,2	0,70	0,02
(±) 4	6,2	0,51	0,02
(±) 5	6,2	0,37	0,01
Total Power Dissipation per Ladder = 0.14 W			

Power Dissipation for Station 8 (@-10°C, EOL)
Inner Ladders (Left), Peripheral Ladders (Right)

Sensor #	y-Length [cm]	EOL Power [mW/cm²]	Total Power [W]
(±) 1	4.2	6.00	0.16
(±) 2	6.2	6.00	0.23
(±) 3	12.4	1.46	0.11
(±) 4	12.4	0.73	0.06
(±) 5	12.4	0.45	0.03
Total Power Dissipation per Ladder = 1.18 W			

Sensor #	y-Length [cm]	EOL Power [mW/cm²]	Total Power [W]
(±) 1	4,2	1,37	0,04
(±) 2	6,2	1,37	0,05
(±) 3	12,4	1,00	0,08
(±) 4	12,4	0,64	0,05
(±) 5	12,4	0,42	0,03
Total Power Dissipation per Ladder = 0.50 W			

WHAT'S A REASONABLE FLOW VELOCITY ?

Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems

API RECOMMENDED PRACTICE 14E (RP 14E)
FIFTH EDITION, OCTOBER 1, 1991

Reaffirmed June 2000

Fluid	Density		Erosional Velocity	
	[lbs/ft³]	[kg/m³]	[ft/sec]	[m/sec]
NOVEC 649	100	1600	10	2.5
Nitrogen	0.0725	1.1606	371.4	92.8

- **Result for Novec 649 is in agreement with CERN recommendations**
- **This means that ≈ 100 m/s flow velocities could be O.K. for gases**
  - **I.D. 4 mm → 80 litre/min**

2.5 Sizing Criteria for Gas/Liquid Two-Phase Lines.

a. **Erosional Velocity.** Flowlines, production manifolds, process headers and other lines transporting gas and liquid in two-phase flow should be sized primarily on the basis of flow velocity. Experience has shown that loss of wall thickness occurs by a process of erosion/corrosion. This process is accelerated by high fluid velocities, presence of sand, corrosive contaminants such as CO_2 and H_2S, and fittings which disturb the flow path such as elbows.

The following procedure for establishing an "erosional velocity" can be used where no specific information as to the erosive/corrosive properties of the fluid is available.

(1) The velocity above which erosion may occur can be determined by the following empirical equation:

$$V_e = \frac{c}{\sqrt{\rho_m}} \qquad \text{Eq. 2.14}$$

where:

V_e = fluid erosional velocity, feet/second

c = empirical constant

ρ_m = gas/liquid mixture density at flowing pressure and temperature, lbs/ft³

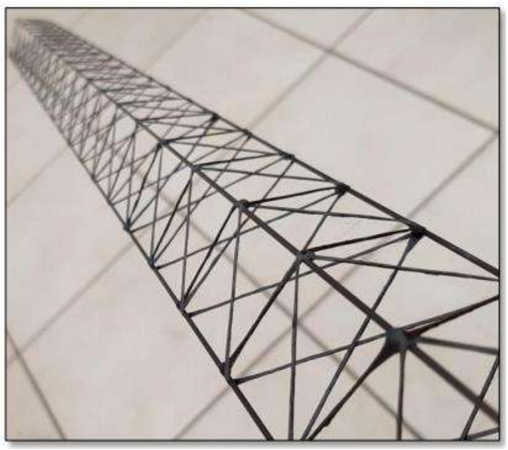
Industry experience to date indicates that for solids-free fluids values of c = 100 for continuous service and c = 125 for intermittent service are conservative. For solids-free fluids where corrosion is not anticipated or when corrosion is controlled by inhibition or by employing corrosion resistant alloys, values of c = 150 to 200 may be used for continuous service; values up to 250 have been used successfully for intermittent service. If solids

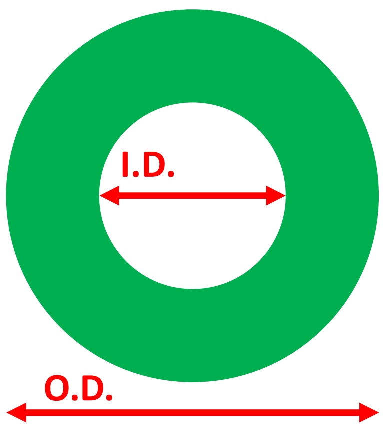
QUESTION ABOUT THE ADDED MATERIAL BUDGET

parameter		value
carbon density	ρ	1.5 g/cm^3
carbon radiation length	X_0	42.7 g/cm^2
ladder mass	m	14.8 g
ladder length	l	120 cm
ladder width	w	6.15 cm
base side area	A	$l \cdot w$
trajectory length	L	0.1 cm (carbon fiber twist)
		0.17 cm (knots on carbon tube)
maximum material budget	x/X_0^{max}	$L \cdot \rho/X_0$
average material budget	x/X_0^{av}	$m/(A \cdot X_0)$

- **CF pipes aren't the dominant contributor to the material budget**
- **Material budget worth 1 additional pipe shouldn't be a big problem**
- **Must be proven with updated material budget simulations**

The maximum material budget crossed is $x/X_0^{max} = 0.35\%$ for the carbon fiber twist and 0.60% for the knots on the tubes. The average material budget from the carbon fibers on the sensors is $x/X_0^{av} = 0.047\%$.





These scenarios are same from material budget point-of-view			
O.D. [mm]	**I.D. [mm]**	**Thickness [mm]**	**Shell Area [mm²]**
1.50	0.70	0.40	1.38
1.60	0.90	0.35	1.37
1.75	1.15	0.30	1.37
2.00	1.50	0.25	⬅ **Currently** 1.37
2.40	2.00	0.20	1.38
3.10	2.80	0.15	1.39

STS Sensor Module

- To obtain high momentum resolution (which is imperative for tracking, especially at low momentum), its important to reduce any unnecessary material inside the detector acceptance:

$$\Theta_m = \frac{13.6\ MeV}{\beta.c.p} \cdot \sqrt{\frac{X}{X_0}}$$

- Therefore, design of STS sensors are a 'bit' different than conventional silicon sensors (e.g., at LHC exp.)
  - Ideally, electronics should be immediately behind the sensors to reduce any in-line capacitance/noise
  - But given that electronics would have added too much to the material budget, ultrathin microcables are used in-between

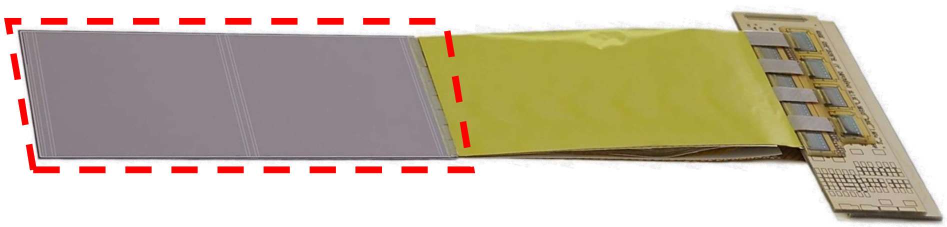
6 mW/cm² @ -10°C
Non-ionising damage 10^{14} n_{eq}/cm^2

Nominal FEE Power Dissipation per STS Module ≤ 27 W

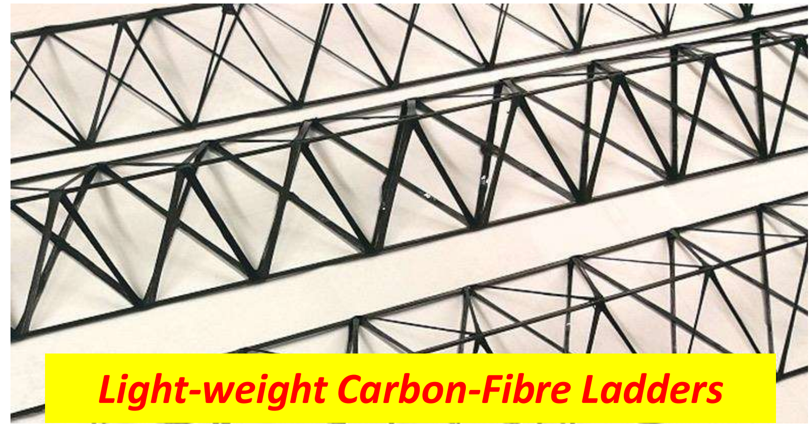
For whole STS, ~ 40 kW

Silicon Sensor (inside detector acceptance)	Microcables; ≤ 55 cm in length (inside detector acceptance)	Front-End Electronics (outside detector acceptance)

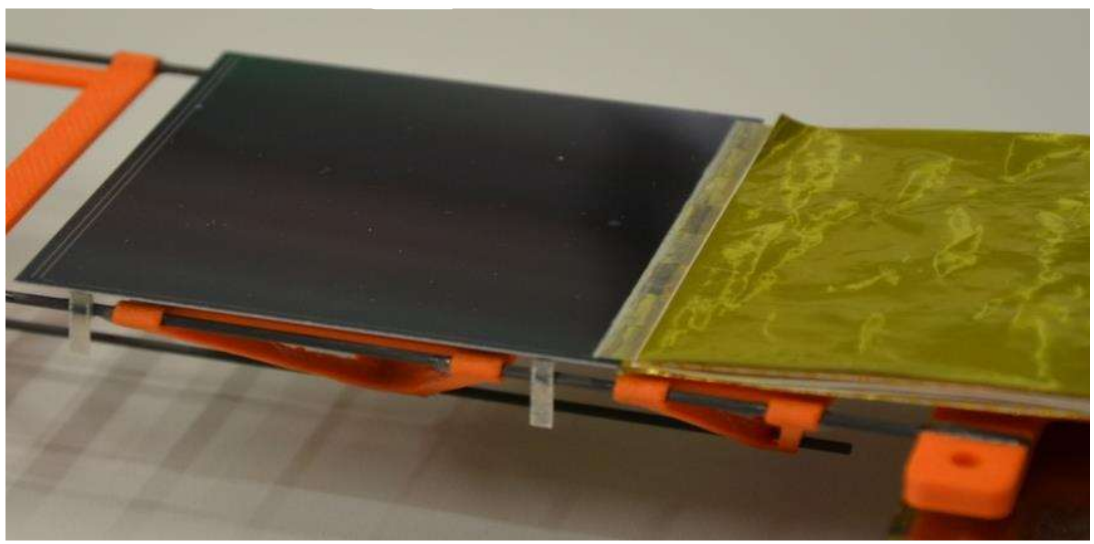
Carbon Fibre Ladder



***STS Module:** Silicon Sensors + Microcables + FEE Boards*



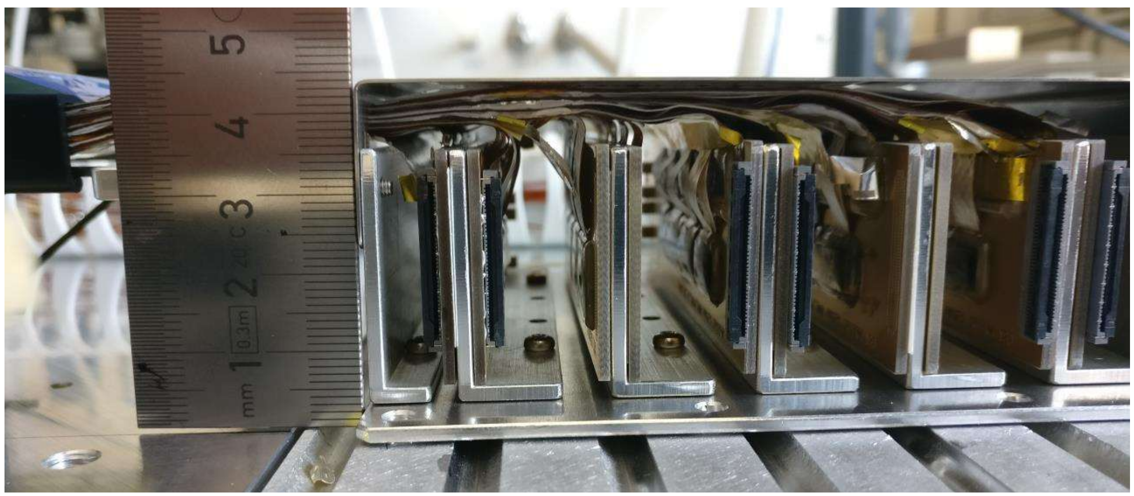
Light-weight Carbon-Fibre Ladders



FEB Box

STS Module: Silicon Sensors + Microcables + FEE Boards

Front-End Electronic Board (FEB) Box



WHY 3M NOVEC 649 ?

Novec and 3M are trademark of 3M (TM) Corporation

Radiation hard (resistant to gamma radiation > 10 kGy). So minimal production of radiation byproducts, which otherwise could block cooling lines or cause corrosion!

Usable down to -108°C

Unfortunately higher pressure drops, but could be compensated by higher tube diameters (for STS, ID = 6 mm)

Green and possible long-term availability

Properties Description

Composition of 3M™ Novec™ 649 Fluid	
Dodecafluoro-2-methylpentan-3-one	99.0 mole %, minimum
Chemical Formula	$CF_3CF_2C(O)CF(CF_3)_2$

Typical Physical Properties

	3M™ Novec™ 649 Fluid
Boiling Point(°C)	49
Pour Point (°C)	-108
Molecular Weight (g/mol)	316
Critical Temperature (°C)	169
Critical Pressure (MPa)	1.88
Vapor Pressure (kPa)	40
Heat of Vaporization (kJ/kg)	88
Liquid Density (kg/m³)	1600
Coefficient of Expansion (K^{-1})	0.0018
Kinematic Viscosity (cSt)	0.40
Absolute Viscosity (cP)	0.64
Specific Heat (J/kg-K)	1103
Thermal Conductivity (W/m-K)	0.059
Surface Tension (mN/m)	10.8
Solubility of Water in Fluid (ppm by wt)	20
Dielectric Strength, 0.1" gap (kV)	>40
Dielectric Constant @ 1kHz	1.8
Volume Resistivity (Ohm-cm)	10^{12}
Global Warming Potential (GWP)	1

3M Novec 649 Commercial Availability

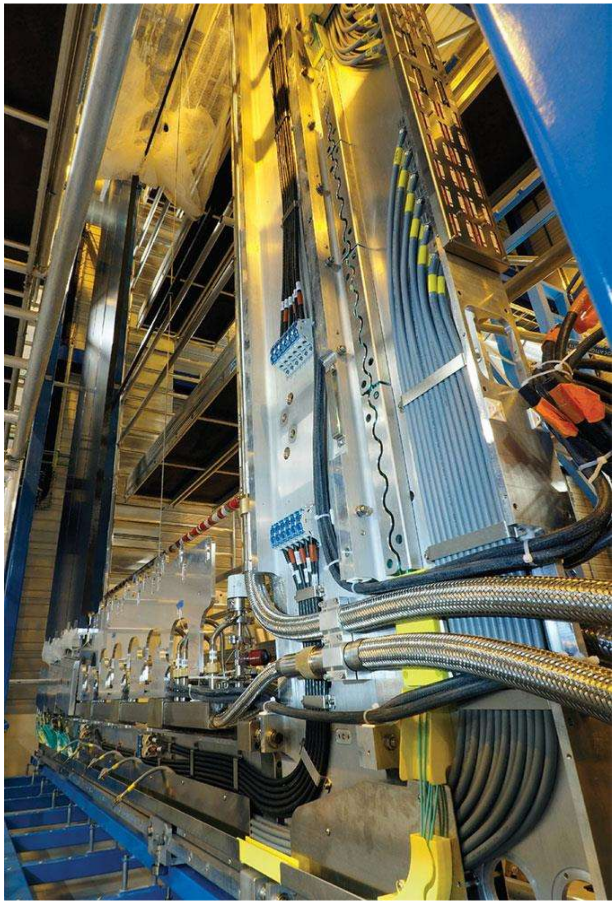
Novec and 3M are trademark of 3M (TM) Corporation

Offer for litres	Packaging Net weight kg	**Price per kg CHF/kg**	Package price CHF
100	5.0	**95.2**	475
100	17.2	**144.2**	2485
100	160.1	**132.9**	21272
1200	5.0	**64.7**	323
1200	17.2	**61.3**	1056
1200	160.1	**57.0**	9132
2000	160.1	**51.8**	8289
2000	300.1	**50.7**	15215

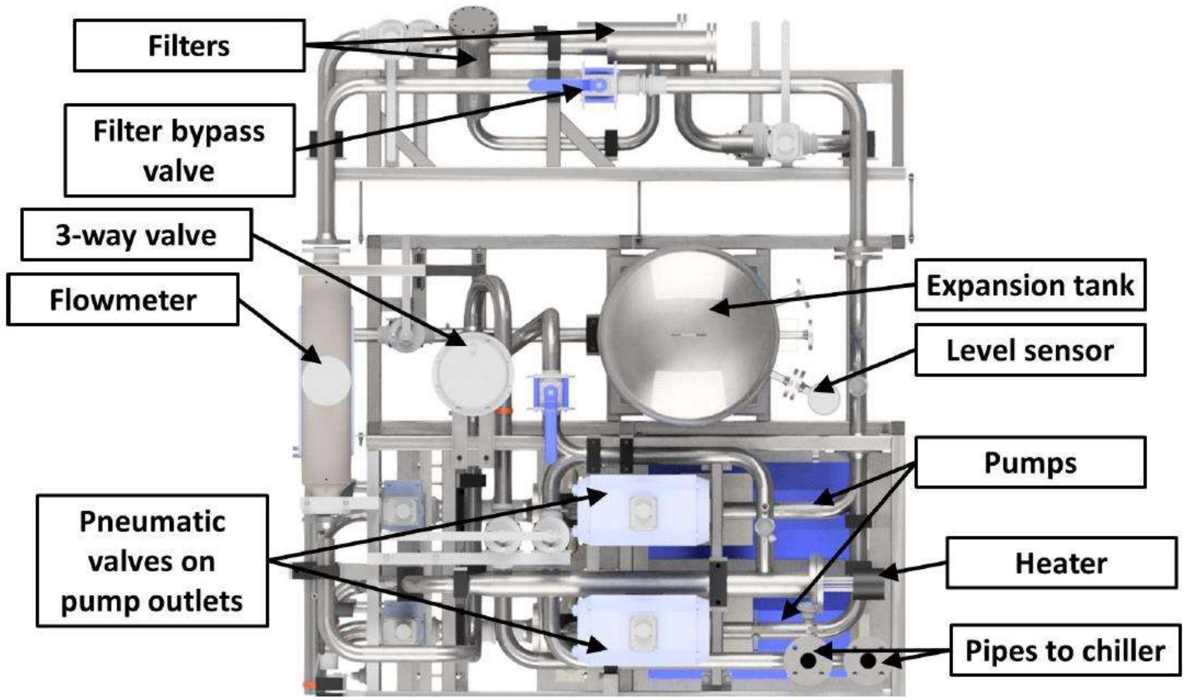
- **Higher quantities could be purchased directly from 3M**TM
- **Lower quantities are readily available from Ionic**

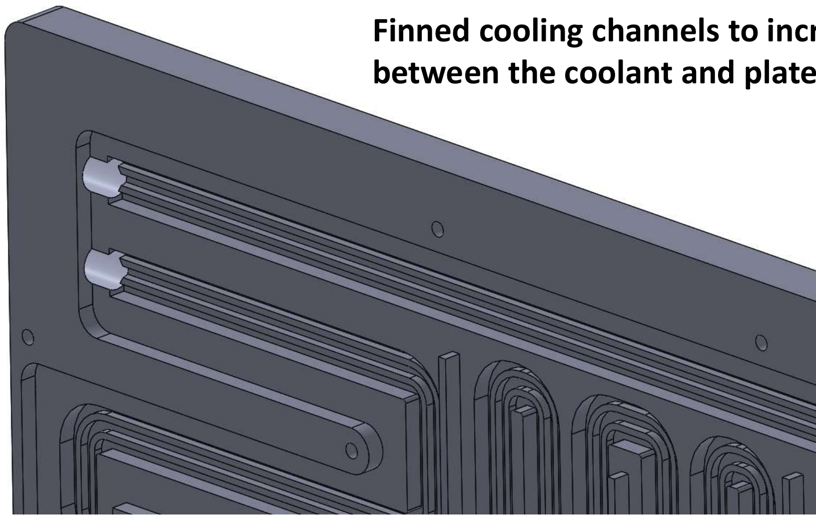
3M Novec 649 – Where In Use So Far?

Novec and 3M are trademark of 3M (TM) Corporation

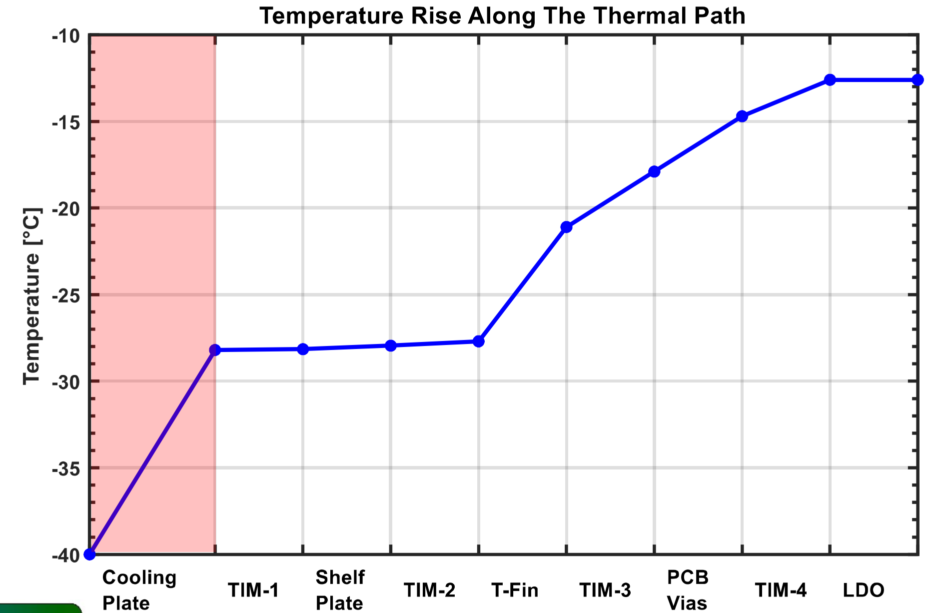


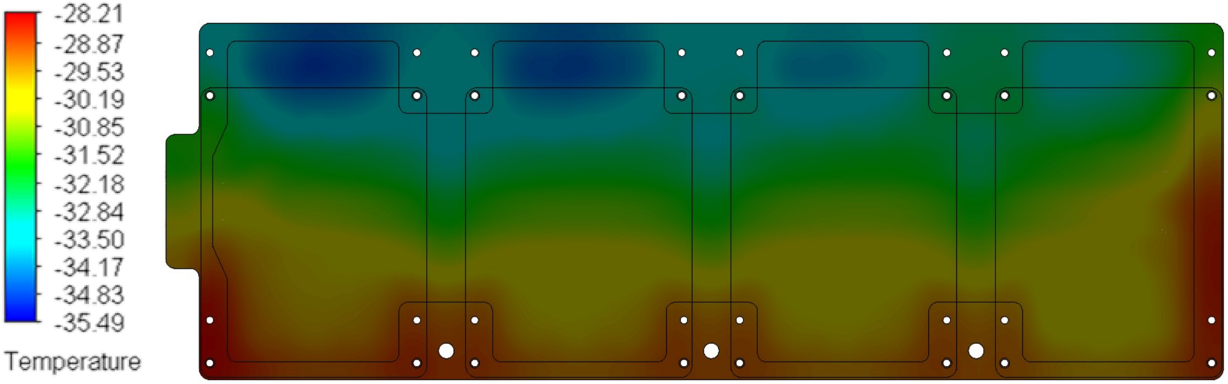
LHCb SciFi Tracker



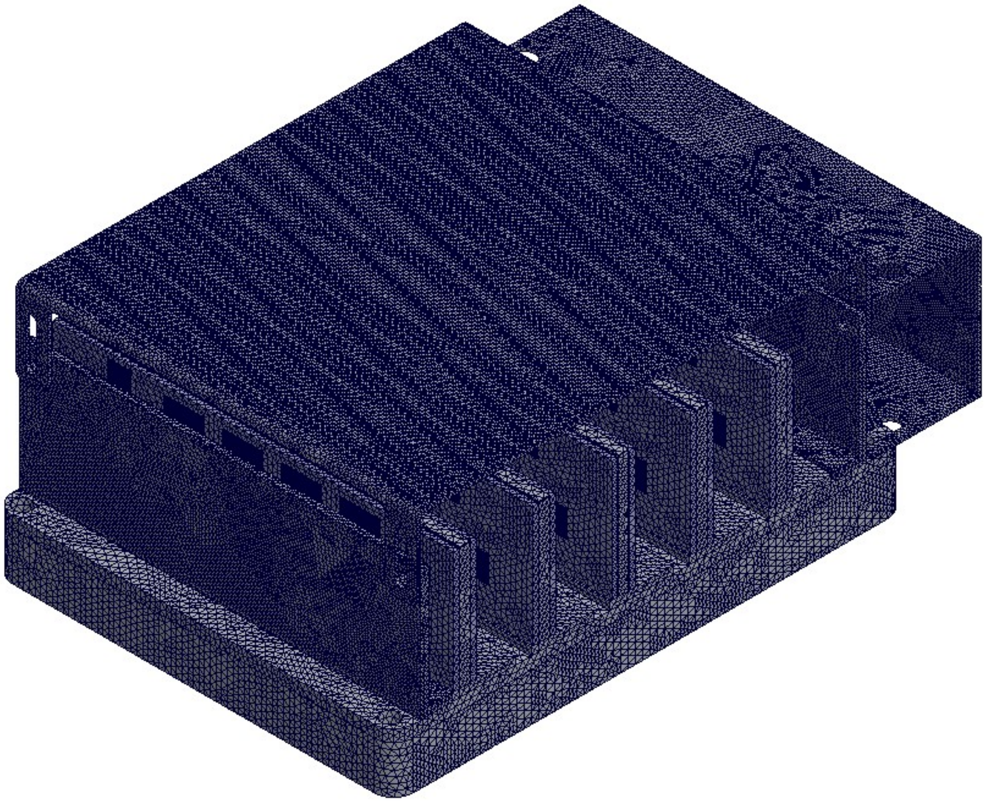


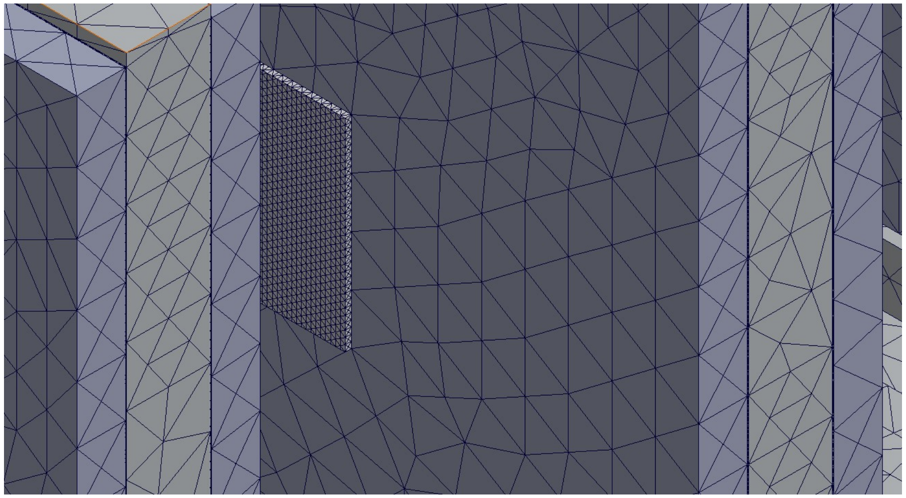
Finned cooling channels to increase heat transfer between the coolant and plate's inner surface



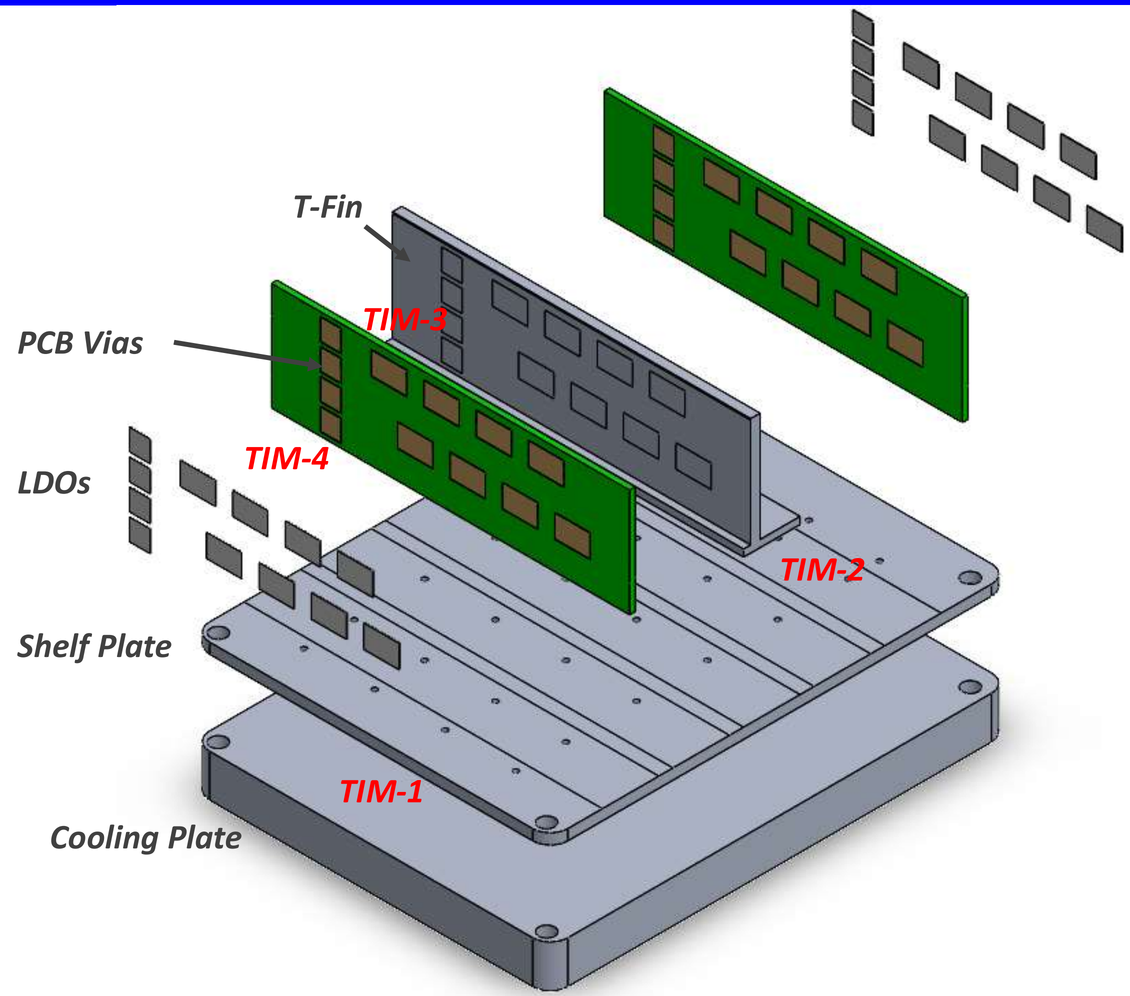


Material:	**Aluminium**
Inlet:	**3M™ Novec™ 649**
	-40°C at 3 litre/min
Total power dissipation:	**800 W**
Temperature outlet:	**-33.8 °C**
Max. temp. of cooling plate:	**-28.2 °C**
Pressure loss:	**1.32 bar**





Thermal FEA Simulations For FEB Box



Baby Cooling Plant – CAD Snapshots