Progress Towards The Thermal Management Of The CBM Silicon Tracking System (STS)

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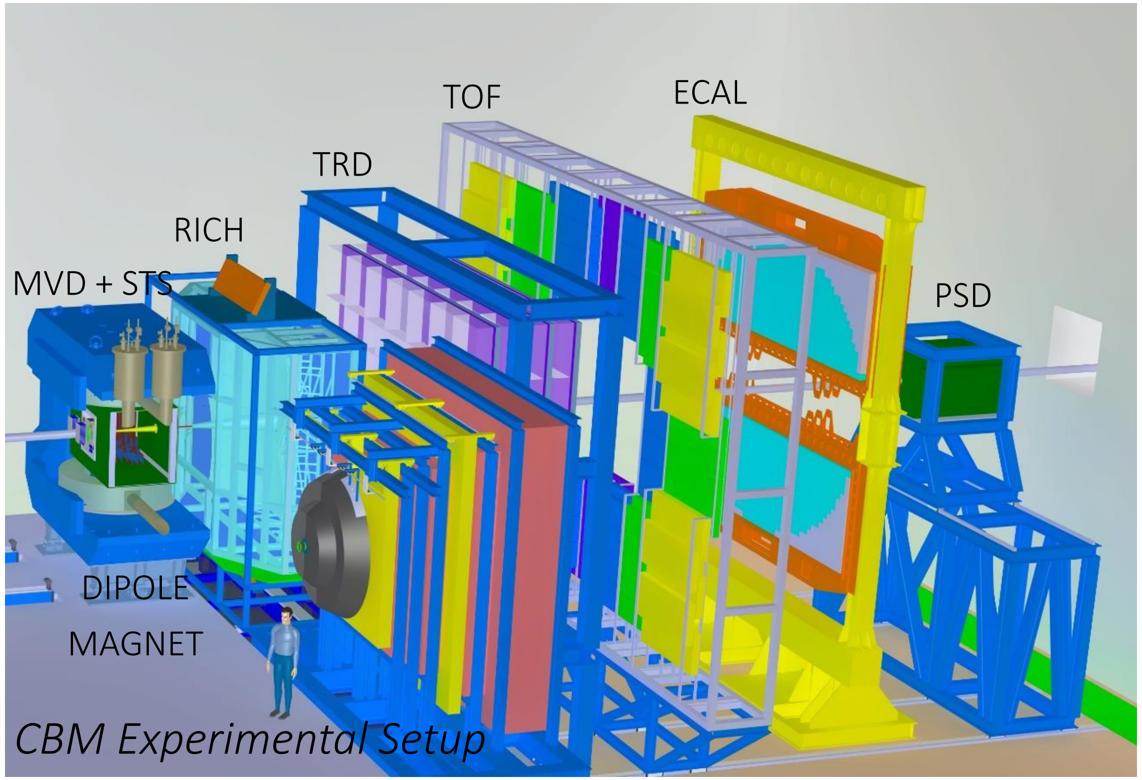
Forum on Tracking Detector Mechanics – 2018
25/06/2018

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

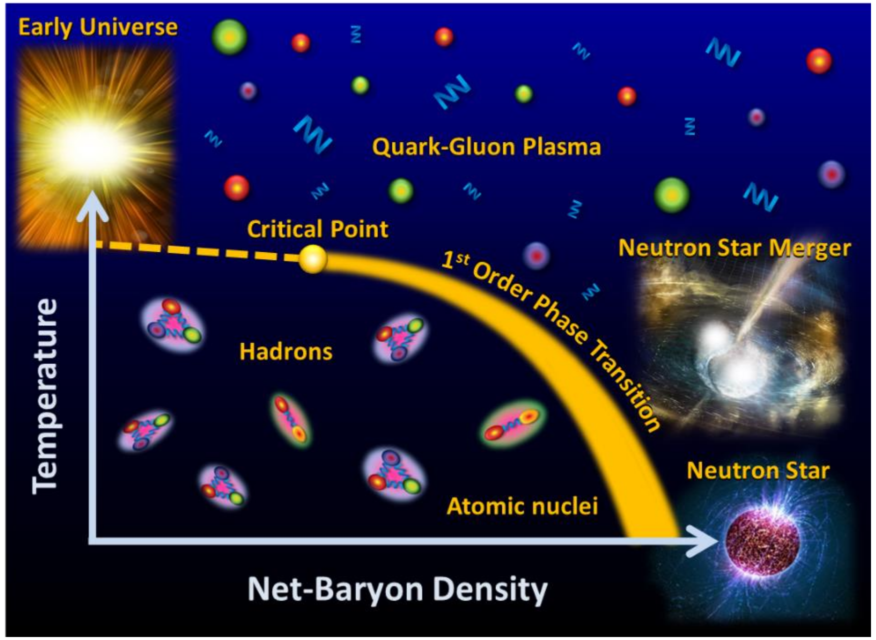
MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut

UNDERSTANDING THE PROBLEM – CBM PHYSICS

- CBM aims to explore regions of high-baryonic densities of QCD phase diagram
- Requires detection of rare probes
  - → $10^5 – 10^7$ collisions/sec (Au-Au)
  - → Momentum Resolution $\Delta p/p \approx$ 1-2%
  - → High track reconstruction efficiency with pile-up free track point determination



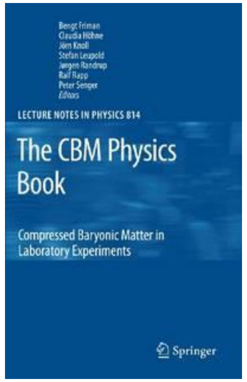
CBM Experimental Setup



QCD Phase Diagram

<u>More Info on CBM Physics:-</u>
The CBM physics book: Compressed baryonic matter in laboratory experiments
Lect.Notes Phys. 814 (2011) pp.1-980
(DOI: 10.1007/978-3-642-13293-3)

Challenges in QCD matter physics -The scientific programme of the Compressed Baryonic Matter experiment at FAIR
Eur.Phys.J. A53 (2017) no.3, 60
(DOI: 10.1140/epja/i2017-12248-y)



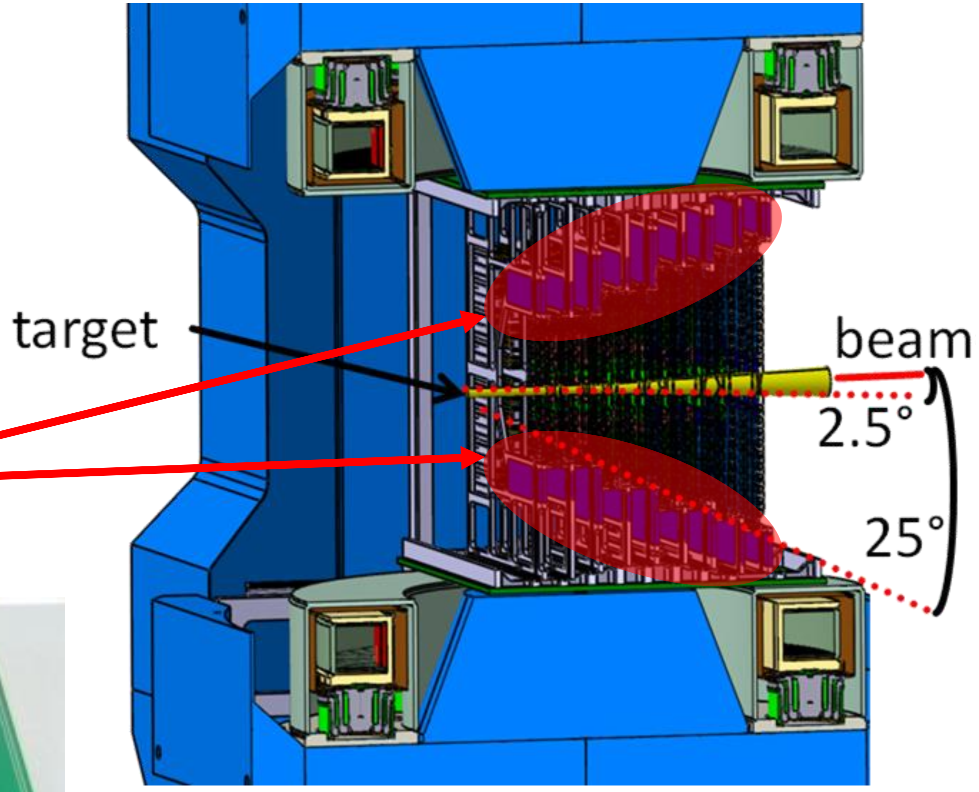
UNDERSTANDING THE PROBLEM – STS REQUIREMENTS

- Silicon Tracking Station: Key to CBM Physics
  - → 8 Tracking Stations inside 1Tm field
  - → 896 double-sided micro-strip sensors
  - → Low Material Budget: 0.3% - 1.5% X_0/station

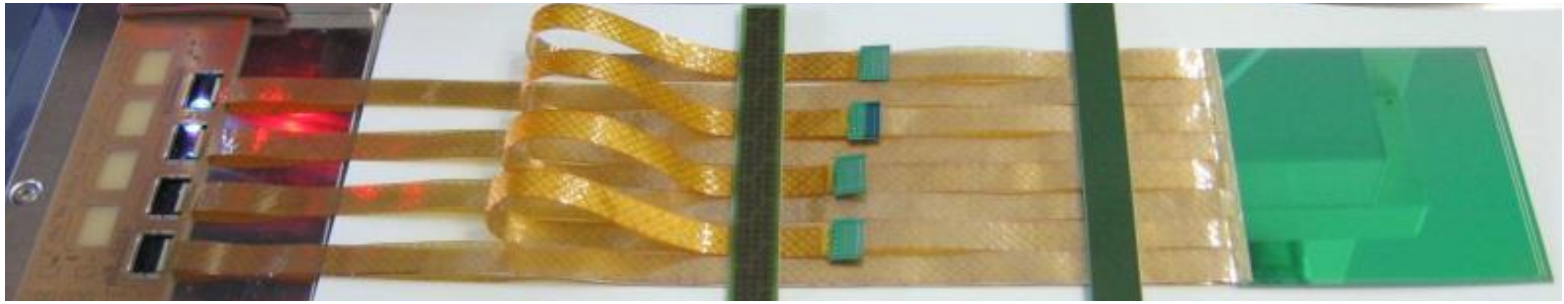
↓

  - → Self-triggering front-end electronics located outside acceptance
  - → ~1.8 million r/o channels + ~16000 r/o ASICs "STS-XYTER"

40kW Electronic Power Dissipation



Silicon Tracking System in Dipole Magnet



FEE with r/o ASICs — *Outside Acceptance*

Ultra-thin Microcables *Silicon Sensor* — *Inside Acceptance*

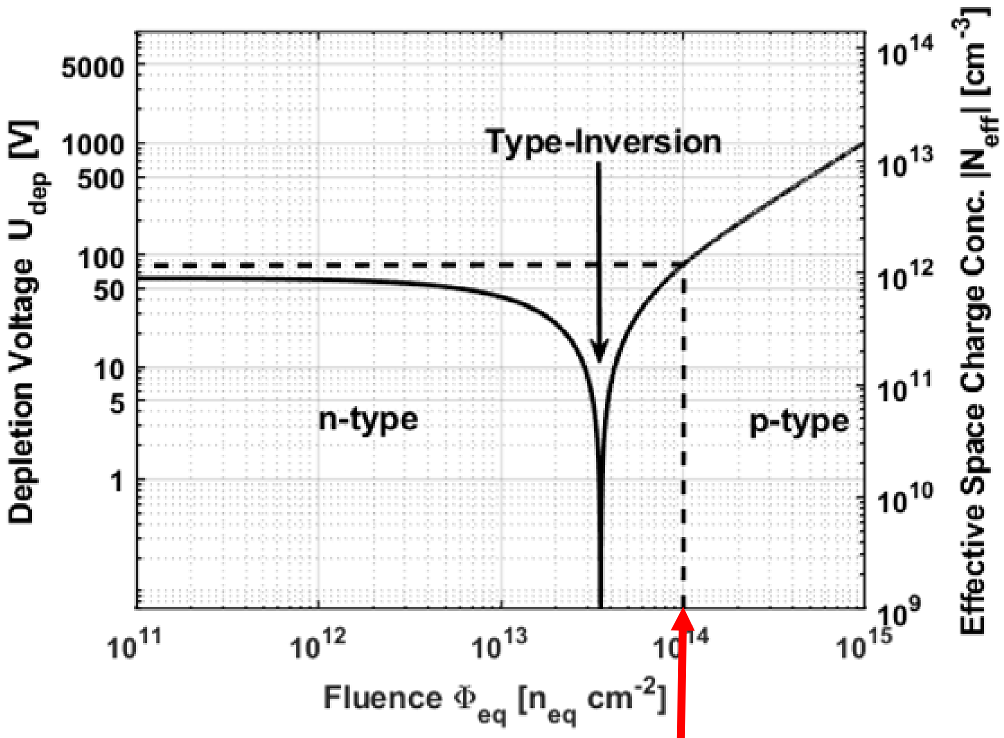
More Info on STS Geometry and Integration:-
Oleg Vasylyev – Mechanical concept, design and prototyping of the Silicon Tracking System for the CBM Experiment at FAIR
Forum on Tracking Detector Mechanics, Marseilles – 2017

UNDERSTANDING THE PROBLEM – STS REQUIREMENTS

- Silicon Tracking Station: Key to CBM Physics
  - → Non-ionising Radiation tolerance: ≤ 10^{14} n_{eq} cm^{-2} (5-10 months operation @10MHz Au-Au)
    - Sensor leakage current increases with fluence
      $$\Delta I = \alpha \cdot \Phi_{eq} \cdot (A \cdot d)$$
    - Sensor leakage current increases with temperature
      $$I_L(T) \propto T^2 exp(-1/T)$$
  - → Signal-to-noise ≥ 10
    $$\text{Shot Noise} \propto \sqrt{I_L}$$

- Sensor cooling mandatory to:
  - → Maintain S/N
  - → Avoid thermal runaway
  - → Suppress reverse annealing

Keeping the sensors at -10°C at all times

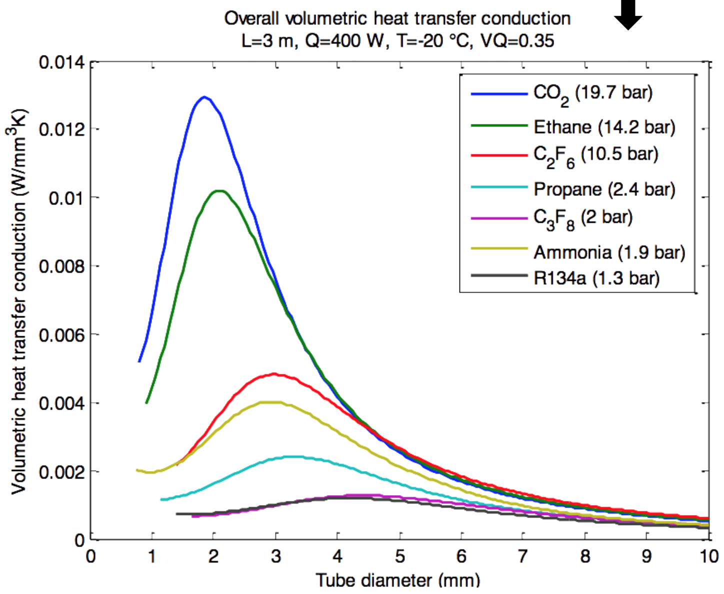


6mW/cm² at end of life (ϕ_{eq} = 10^{14} n_{eq} cm^{-2})

More Info on STS Radiation Environment:-
J. Heuser et al. – Technical Design Report for the CBM Silicon Tracking System (2013) [GSI Report 2013-4]

Cooling Requirements

- Total Electronics Power ~ 40kW
- FEE temp. < -10°C to avoid any heat transfer to sensors
- Less space available for respective cooling plates → Small tubes needed



Fluid Requirments:-

→ High Vol. Heat Transfer Co-efficient

→ Long operational lifetime (~ 10 years)

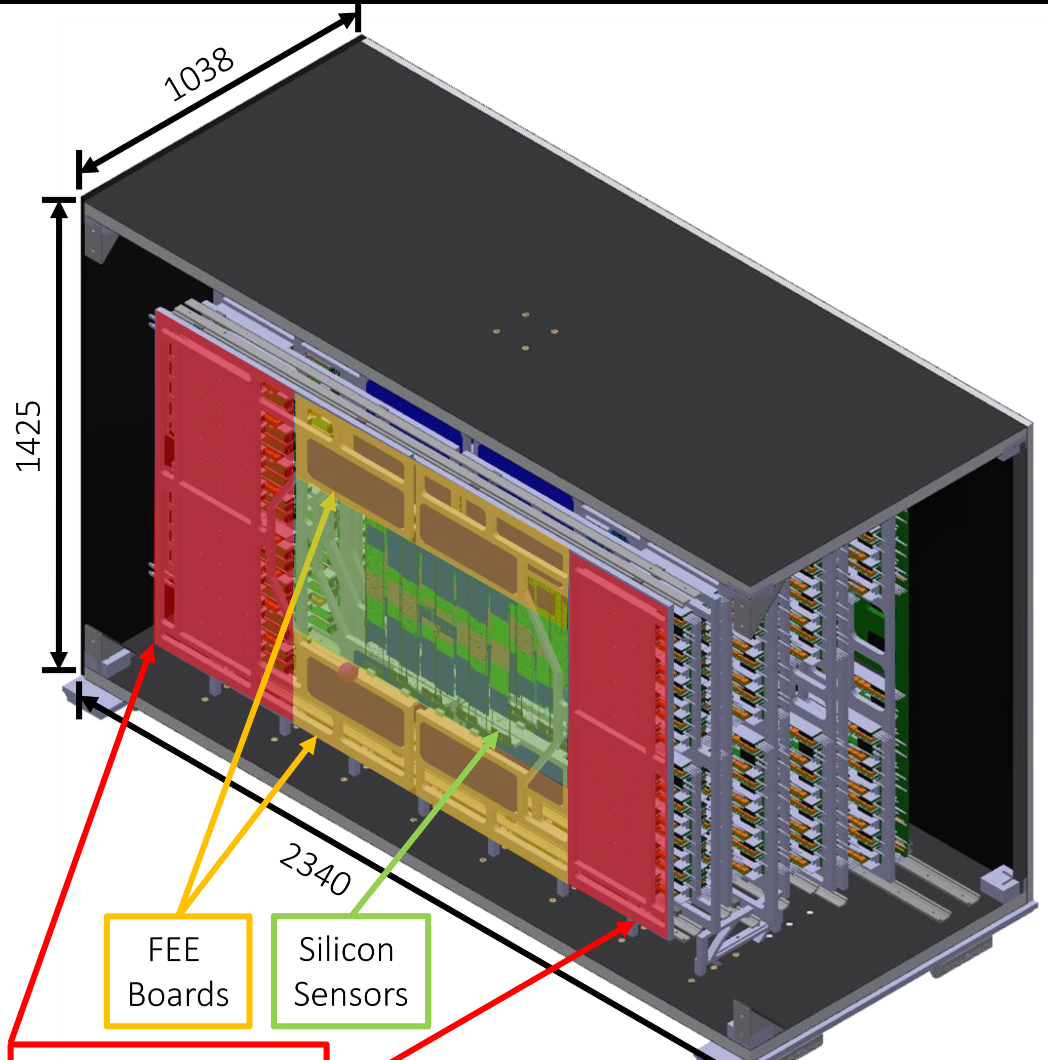
→ Radiation hardness

(NI dose outside detector acceptance < 10^{12} n_{eq} cm^{-2} @10MHz for 1month)

Bi-Phase CO_2 Cooling

- Sensor power dissipation upto ~ 6mW/cm² (at end-of-life $\phi_{eq} = 10^{14}$ n_{eq} cm^{-2})
- Sensor temp. ~ -10°C
- Cooling with minimal additional X_0/station

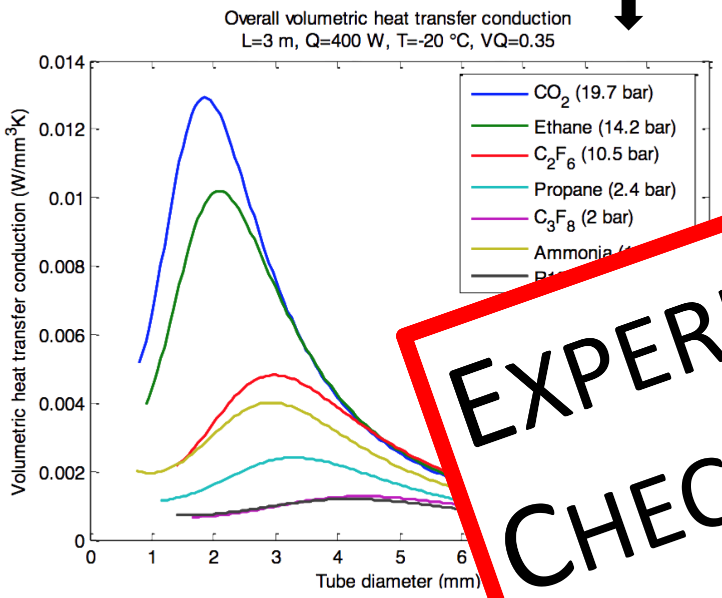
Forced N_2 convection directly on sensors



Silicon Tracking System in a thermal enclosure

COOLING REQUIREMENTS

- Total Electronics Power ~ 40kW
- FEE temp. < -10°C to avoid any heat transfer to sensors
- Less space available for respective cooling plates → Small tubes needed



Fluid Requirments:-

→ High Vol. He

→ L

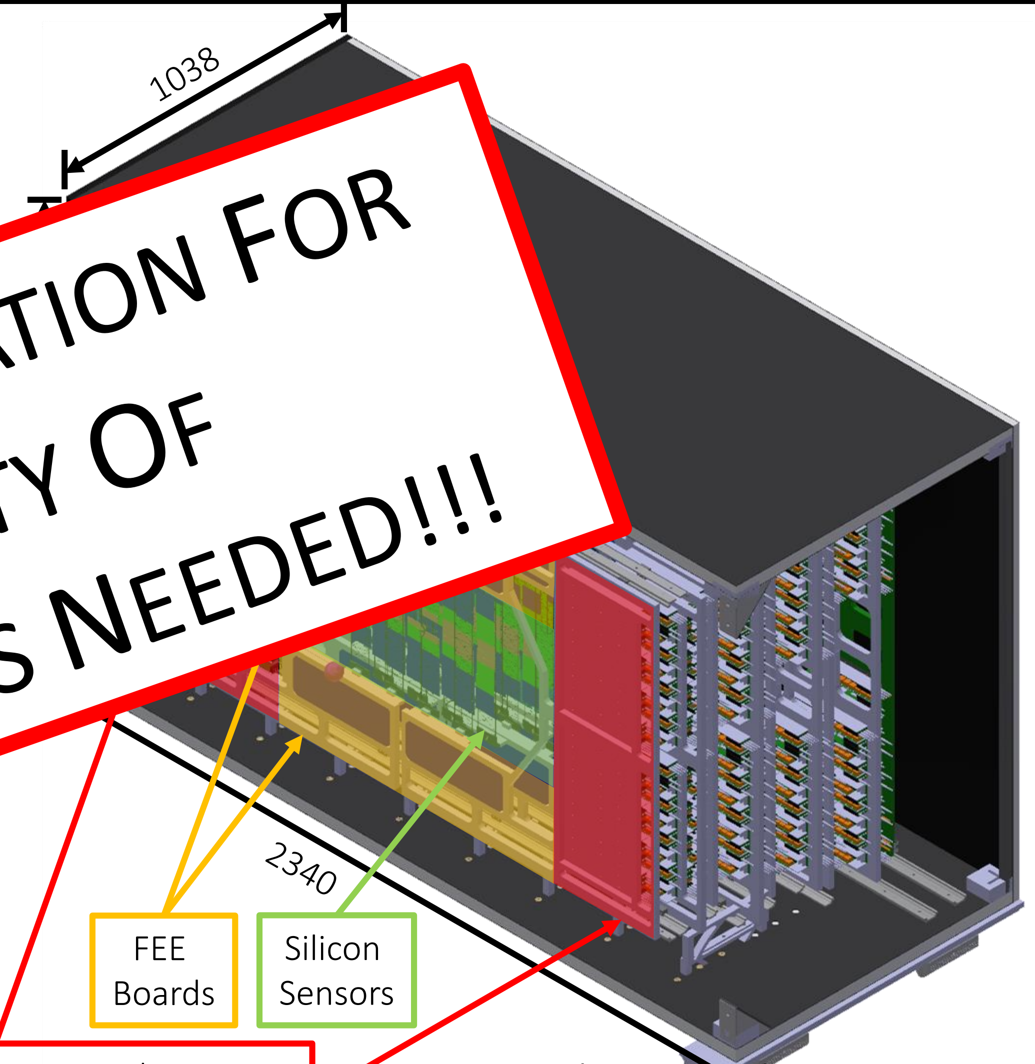
EXPERIMENTAL VERIFICATION FOR CHECKING THE VIABILITY OF COOLING CONCEPTS IS NEEDED!!!

- Sensor power dissipat

  (at end-of-life ϕ_{eq} = 10^{1}

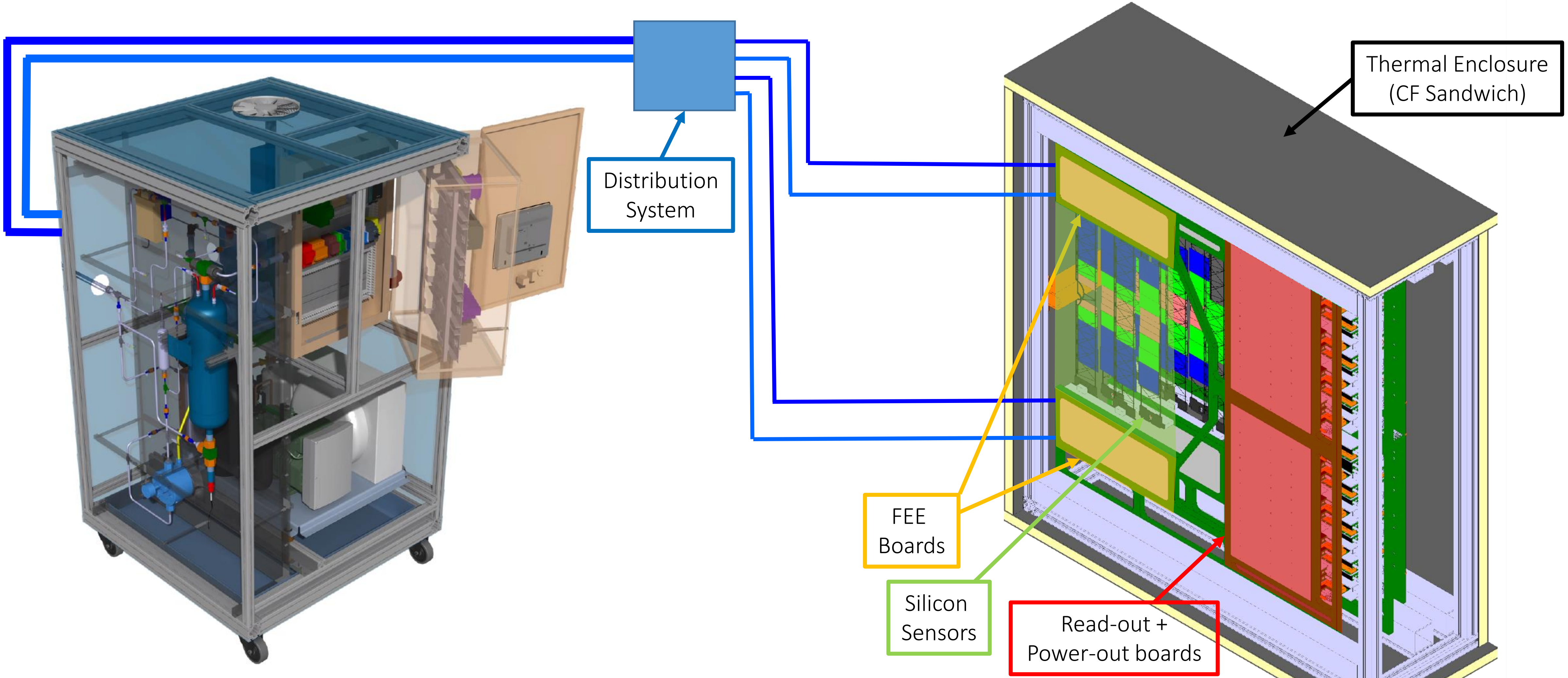
- Sensor temp. ~ -10°C
- Cooling with minimal additional X_0/station

→ Forced N_2 convection directly on sensors



Silicon Tracking System in a thermal enclosure

STS Cooling Demonstrator



CO_2 Cooling Plant
(1kW TRACI-XL @GSI-Darmstadt)

STS Cooling Demonstrator
(2 Half-Stations)

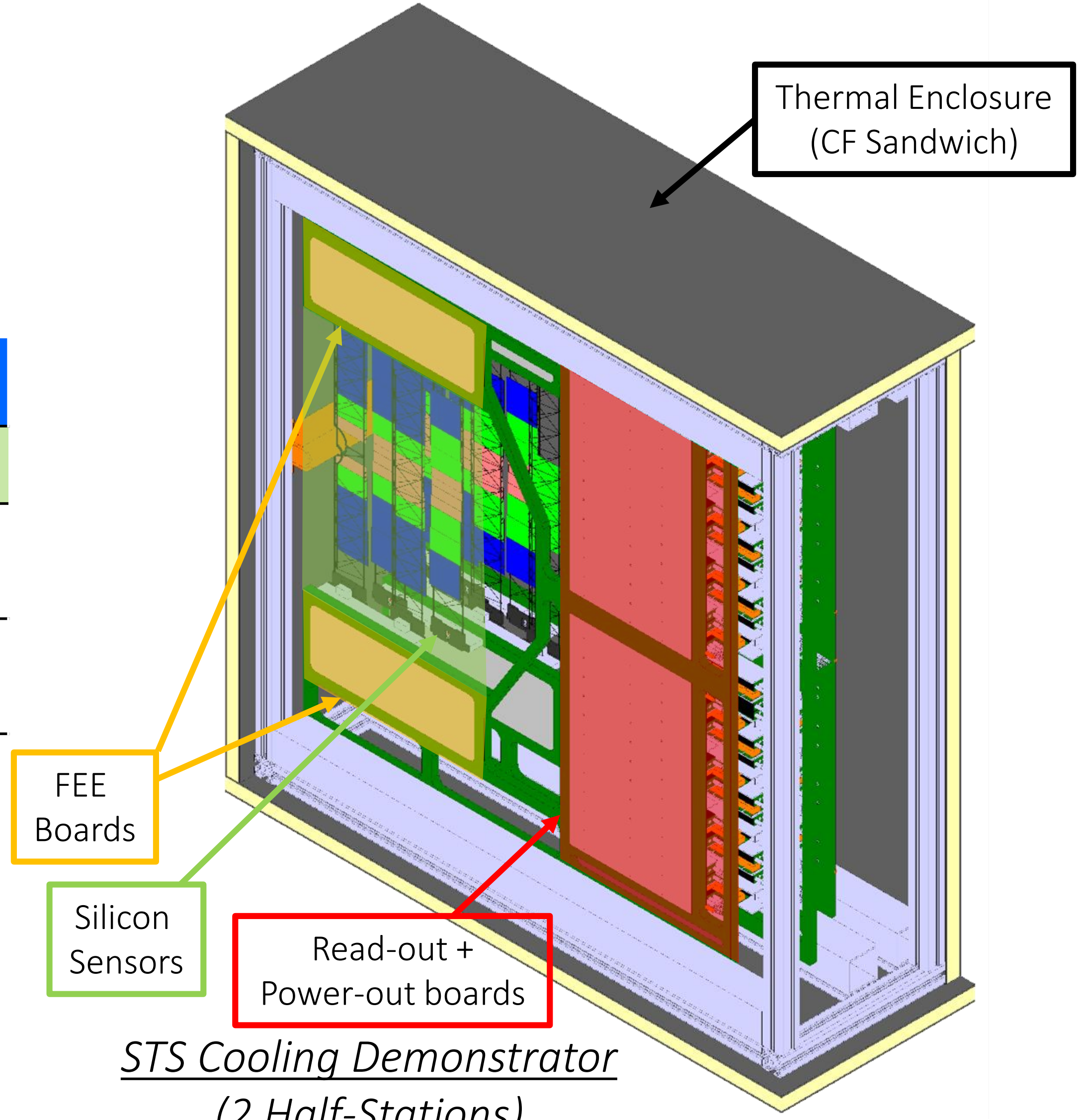
STS Cooling Demonstrator

- 2 STS Half-Stations (1-2) in realistic thermal conditions
  → Highest radiation damage ➔ Most sensor power dissipation
  → Closest vicinity to electronics ➔ Most heat transfer from elec.
- Could serve a dual purpose of integration demonstrator

Cooling Demonstrator Power Dissipation Estimates *				
Quarter-Station #		P_{FEE} (W)	$P_{POB-ROB}$ (W)	$P_{SENSORS}$ (mW/cm²)
1	Unit 0	265.0	346.25	0.22
	Unit 1	609.5	780.125	
2	Unit 2	344.5	400.50	0.19
$TOTAL_{1/4\ STATION}$		1219.0	1526.875	
$TOTAL_{1/2\ STATION}$		2438.0	3053.75	
$TOTAL_{DEMONSTRATOR}$		5401.75		

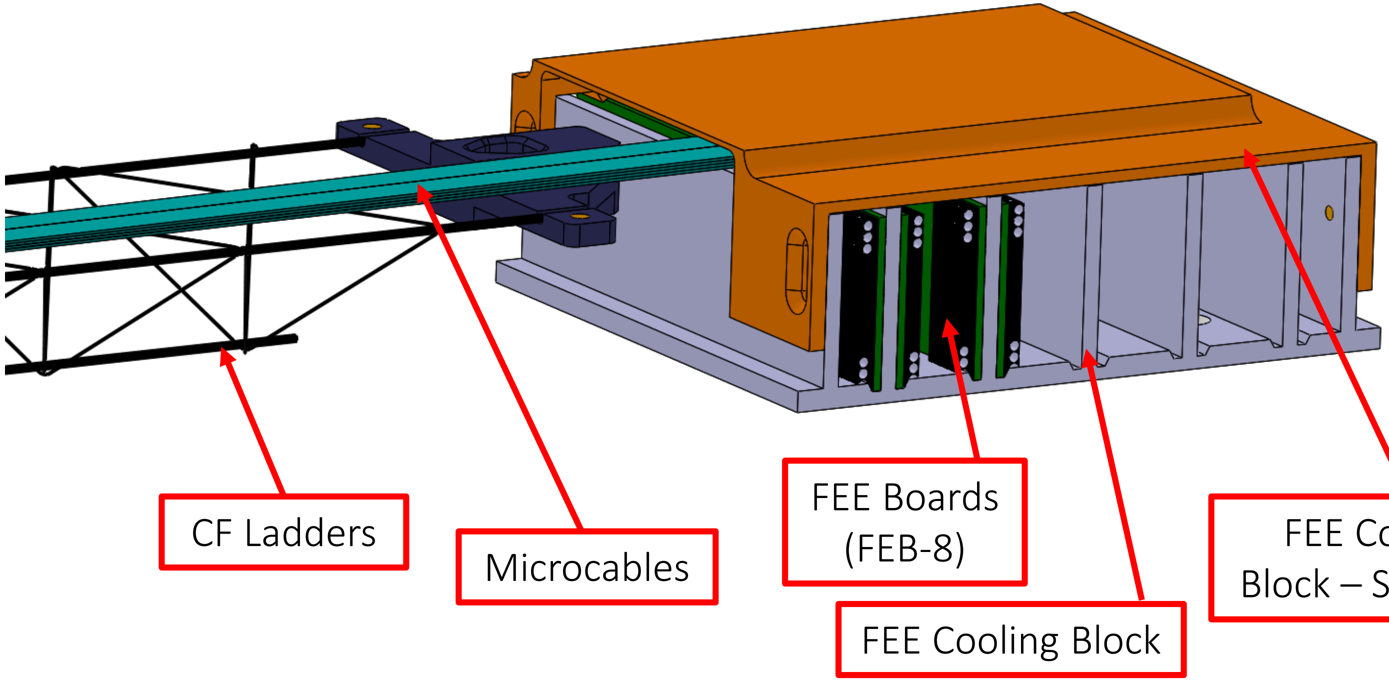
* Including 25% margin

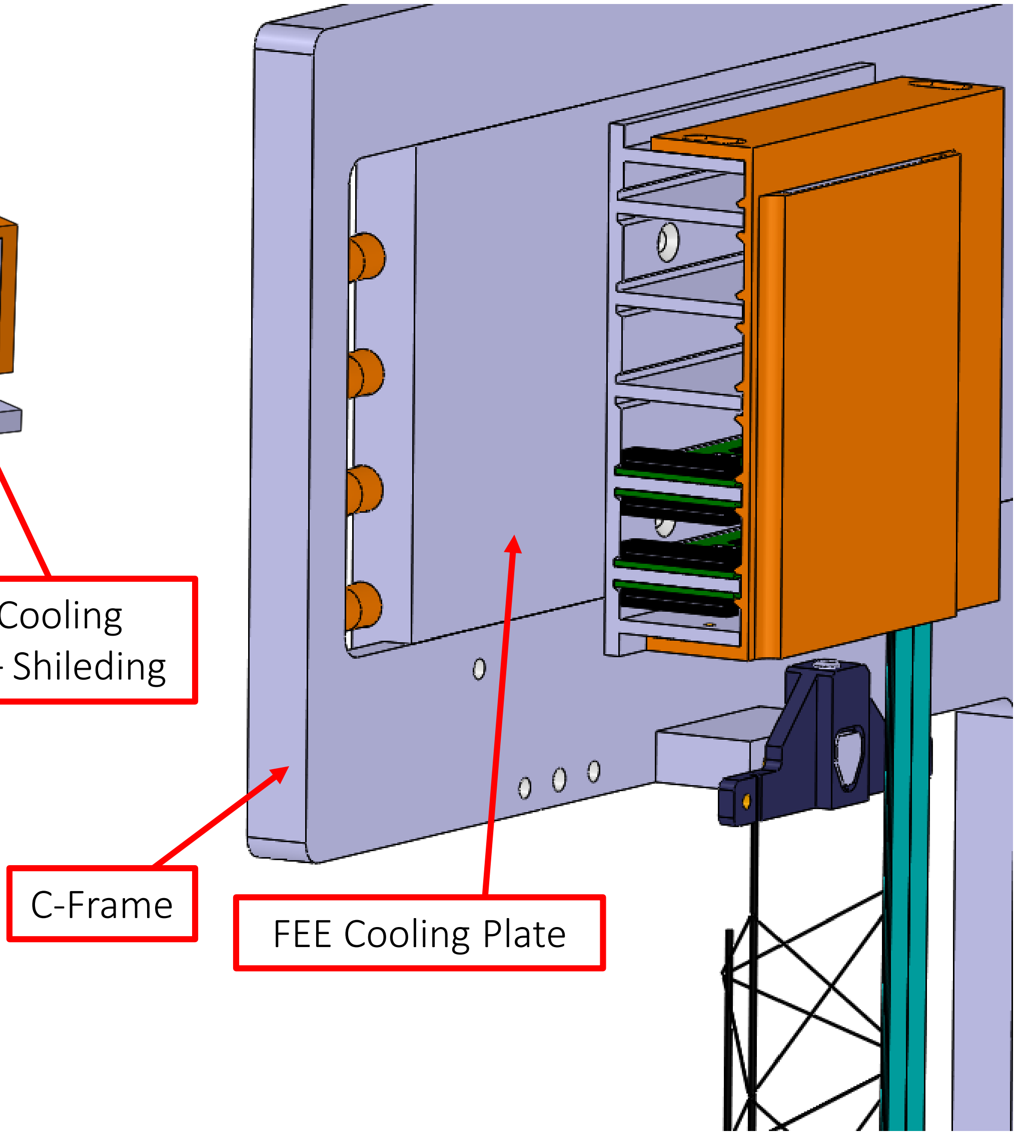
5.4kW Electronics Power Dissipation



STS Cooling Demonstrator
(2 Half-Stations)

FEE Cooling – Concept





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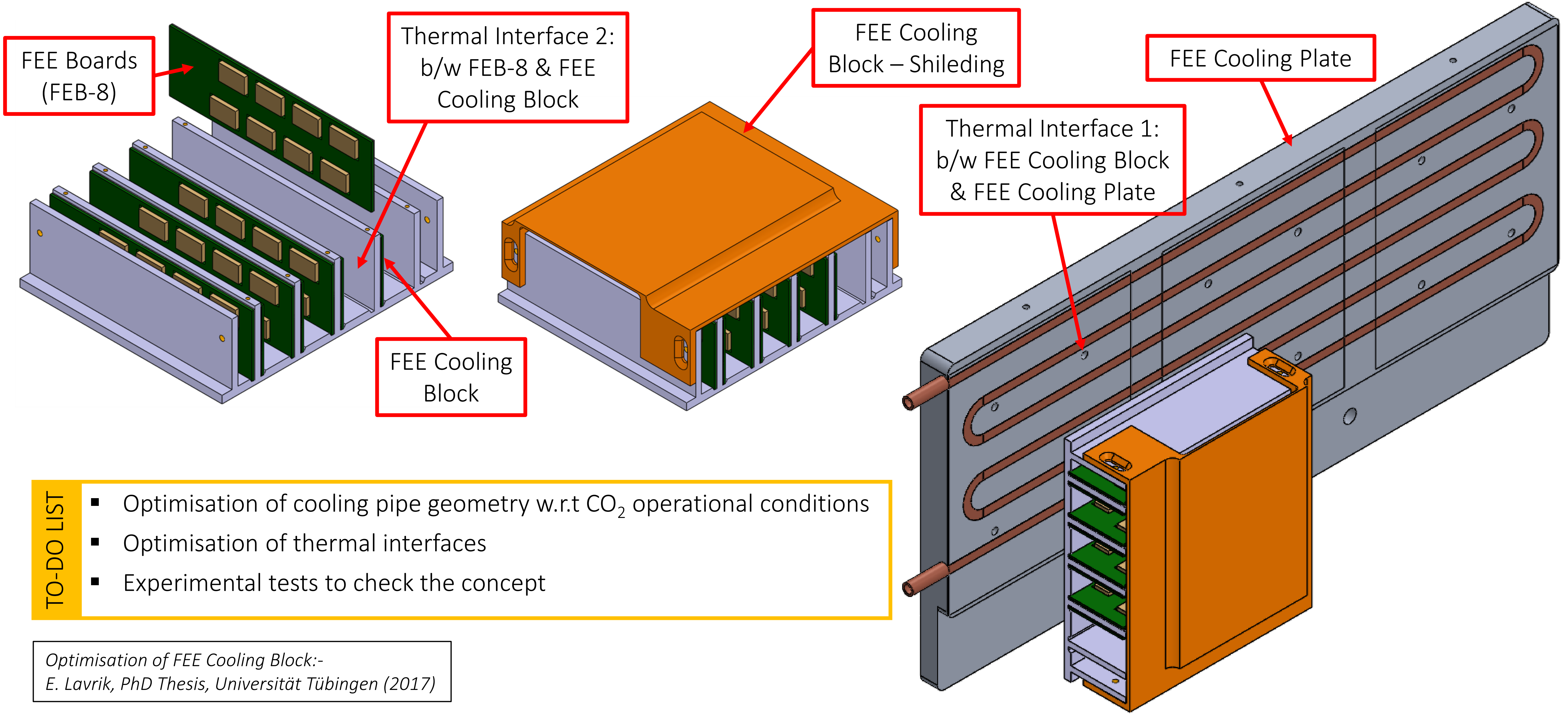
FEE Cooling – Concept



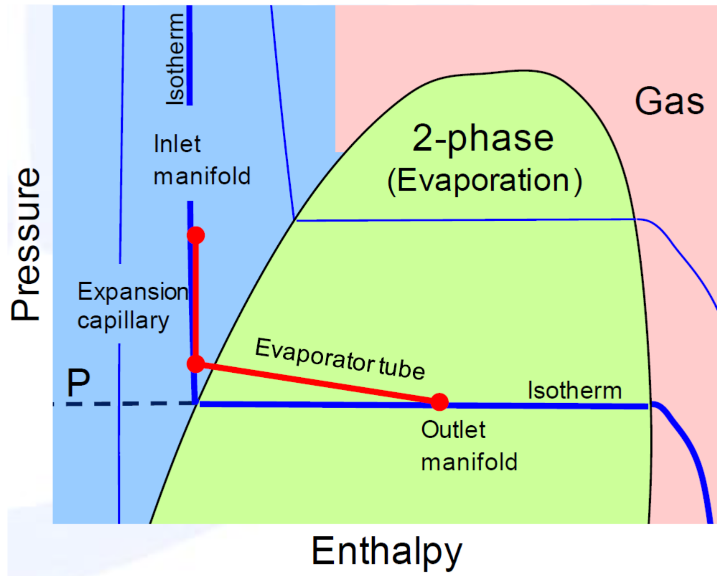
TO-DO LIST

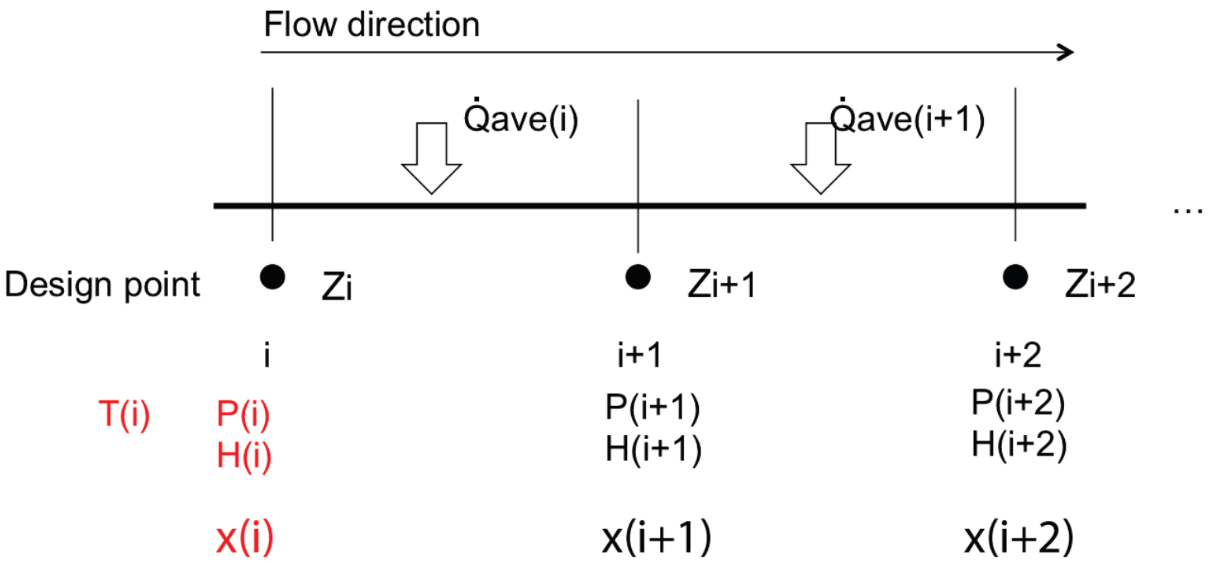
- Optimisation of cooling pipe geometry w.r.t CO_2 operational conditions
- Optimisation of thermal interfaces
- Experimental tests to check the concept

Optimisation of FEE Cooling Block:-
E. Lavrik, PhD Thesis, Universität Tübingen (2017)

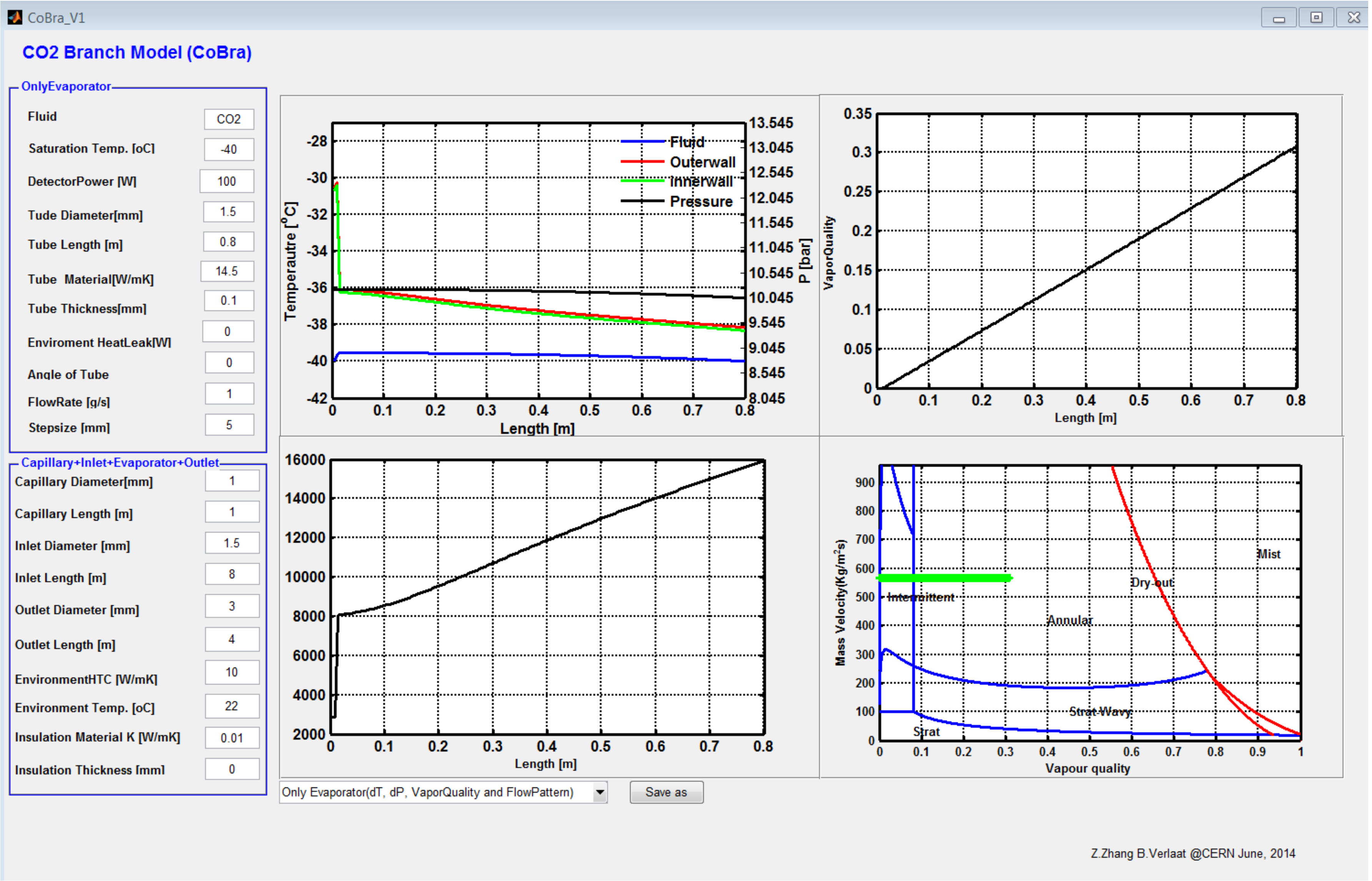
Optimisation Of Operational Parameters

- Important to predict pressure drop and local HTC along the tube length in 2-phase CO_2 flow
  → Flow Pattern Maps (FPMs) derived by Cheng, Thome et al. at EPFL Lausanne
  → Long tube divided in small elements (~1mm) to compute flow properties
- Calculations performed based on CO_2 Branch Calculator (CoBra) by Verlaat, Zhang et al.
  → Model developed in MATLAB
  → State properties derived from REFPROP – NIST
- Current measurements done with 2PACL boundary conditions i.e.,
  → Fixed outlet pressure
  → Fixed inlet temperature (enthalpy)
- Could be varied for different setups (eg. Vapor compression cycles, liquid overflow cycles etc.)
- In principle, could be developed for other coolants with respective FPMs





OPTIMISATION OF OPERATIONAL PARAMETERS – COBRA



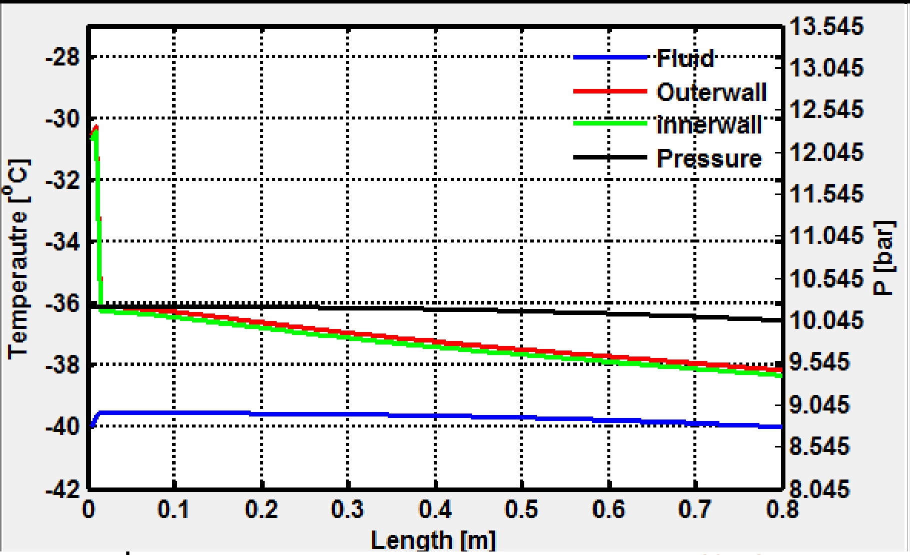
→ Complex bi-phase CO_2 calculations could be done by this approach

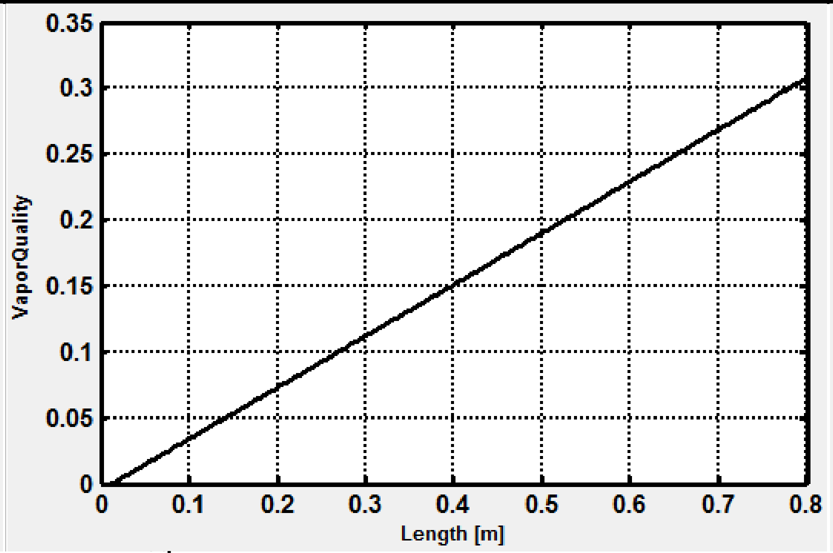
→ Used extensively for designing and analysing cooling systems for ATLAS, CMS, LHCb

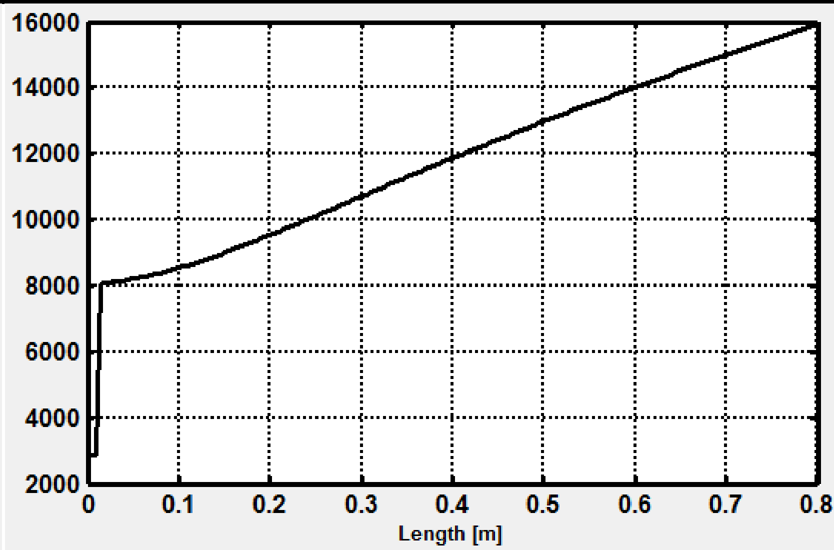
More info on CoBra:-

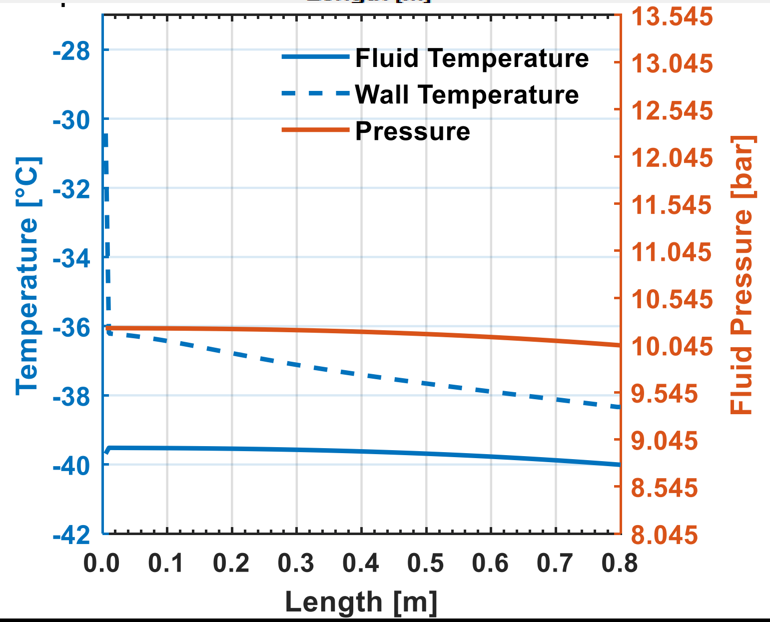
- *B. Verlaat et al., Proceedings of 10th IIR Gustav Lorentzen Conference on Natural Refrigerants (2012), GL-209*
- *Z. Zhang, CERN-THESIS-2015-320 (2015)*

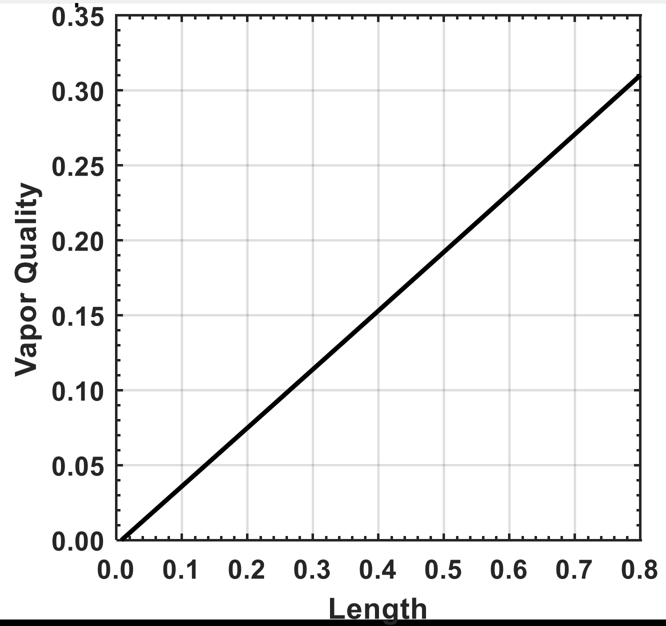
Optimisation Of Operational Parameters – Comparision

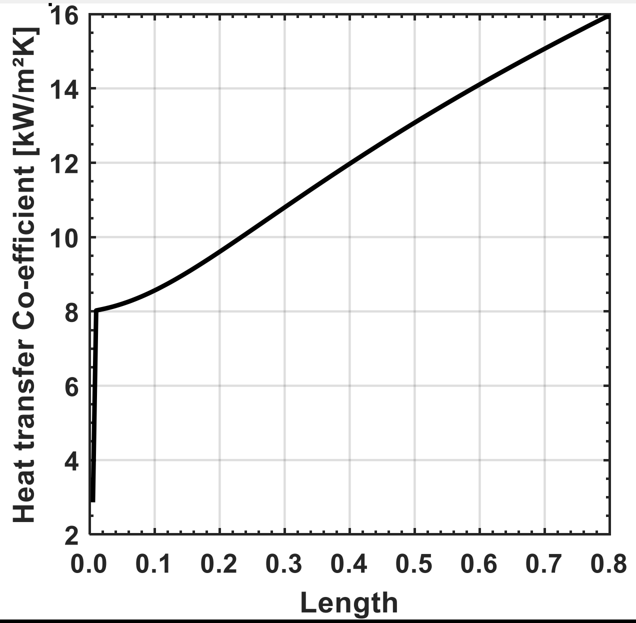








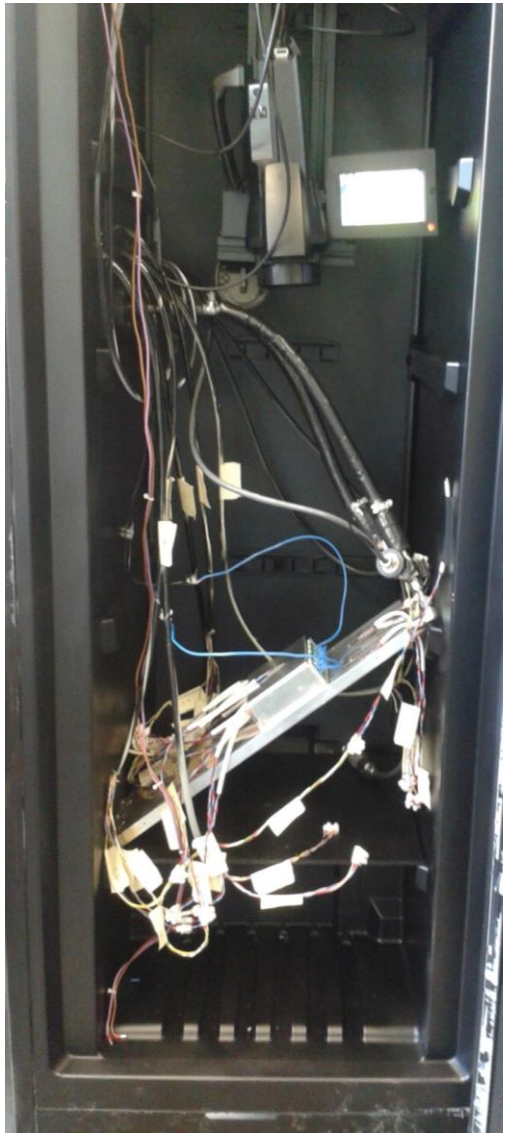




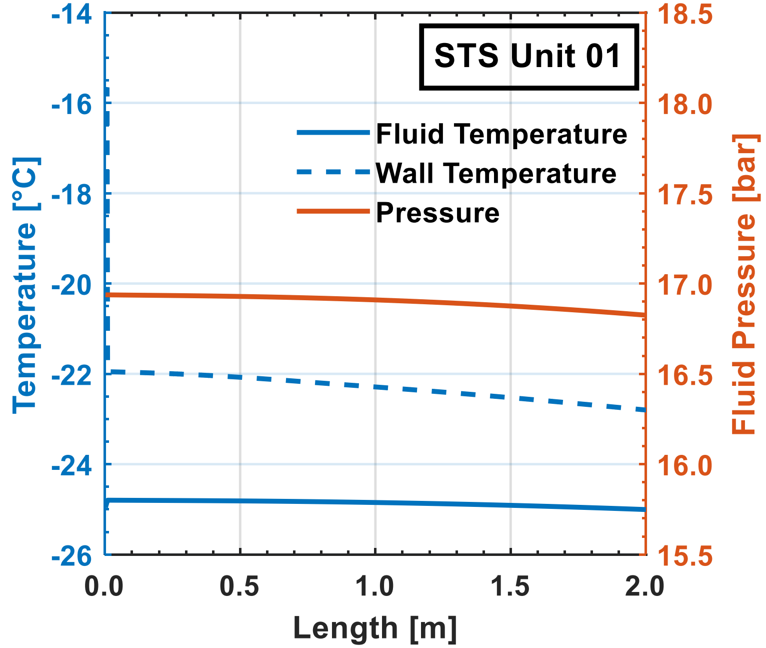
COOLING PLATE (HEAT EXCHANGER)

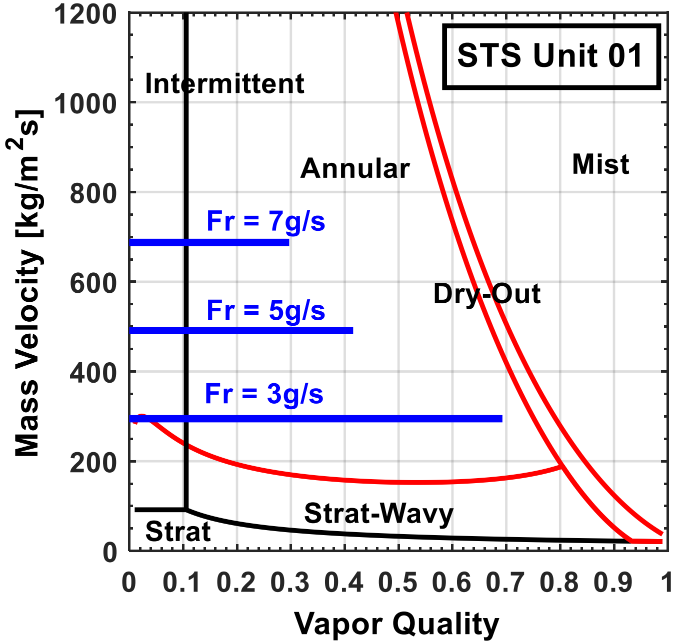
Cool Tec Electronic GmbH

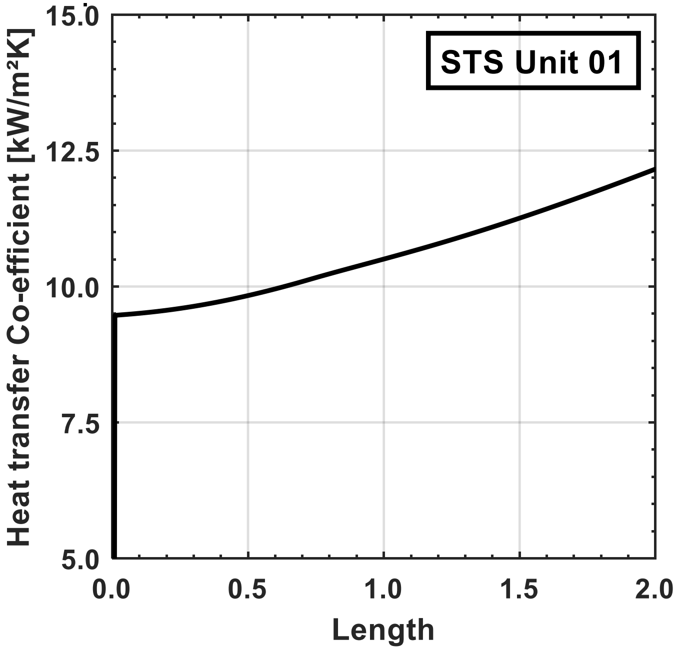
- Press-fitted tube channel plates
- Copper tubes (O.D. 6mm) press-fitted in Aluminium base
- Widely available commercially ➔ Relatively cheap (~3k€)
- Dimensions: 460mm (L) x 160mm (H) x 15mm (W)
- Tested upto 100 bars without issues at GSI – Darmstadt
- Limited tube lengths (~3m) due to large bending radius
- Used for thermal interface measurements with H_2O were done at EKU – Tübingen



Optimisation Of Operational Parameters – Demonstrator







Cooling Demonstrator – FEE Operational Parameters							
T_{CO2} = -25°C, Tube D_{eq} = 3.6mm (O.D. 6mm), L = 2m							
Quarter-Station #		P_{FEE} (W)	Fr (g/s)	D.O. Margin (%)	ΔP (bar)	ΔT_{2PHASE} (°C)	L_{1PHASE} (mm)
1	Unit 0	265	4	70.14	0.0376	0.43	6
	Unit 1	609.5	7	51.53	0.1120	0.84	12
2	Unit 2	344.5	4	60.45	0.0496	0.47	6

Figures for Unit00 and 02 are in backup slides

Optimisation Of Operational Parameters – Demonstrator

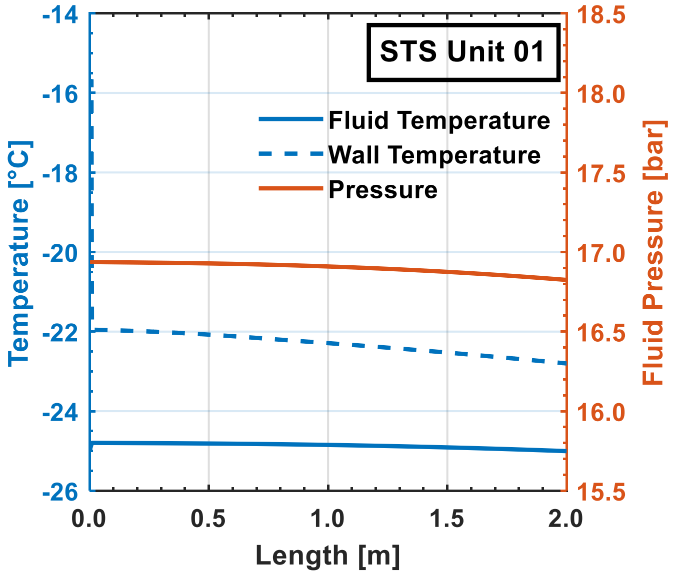
T-p-HTC v/s L Analysis
Flow Pattern Map
(MATLAB + REFPROP)

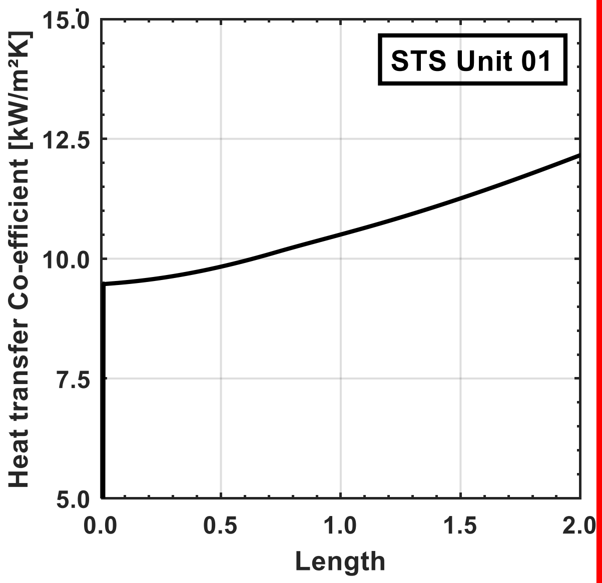
Input: Average Fluid Temp.
Average Local HTC

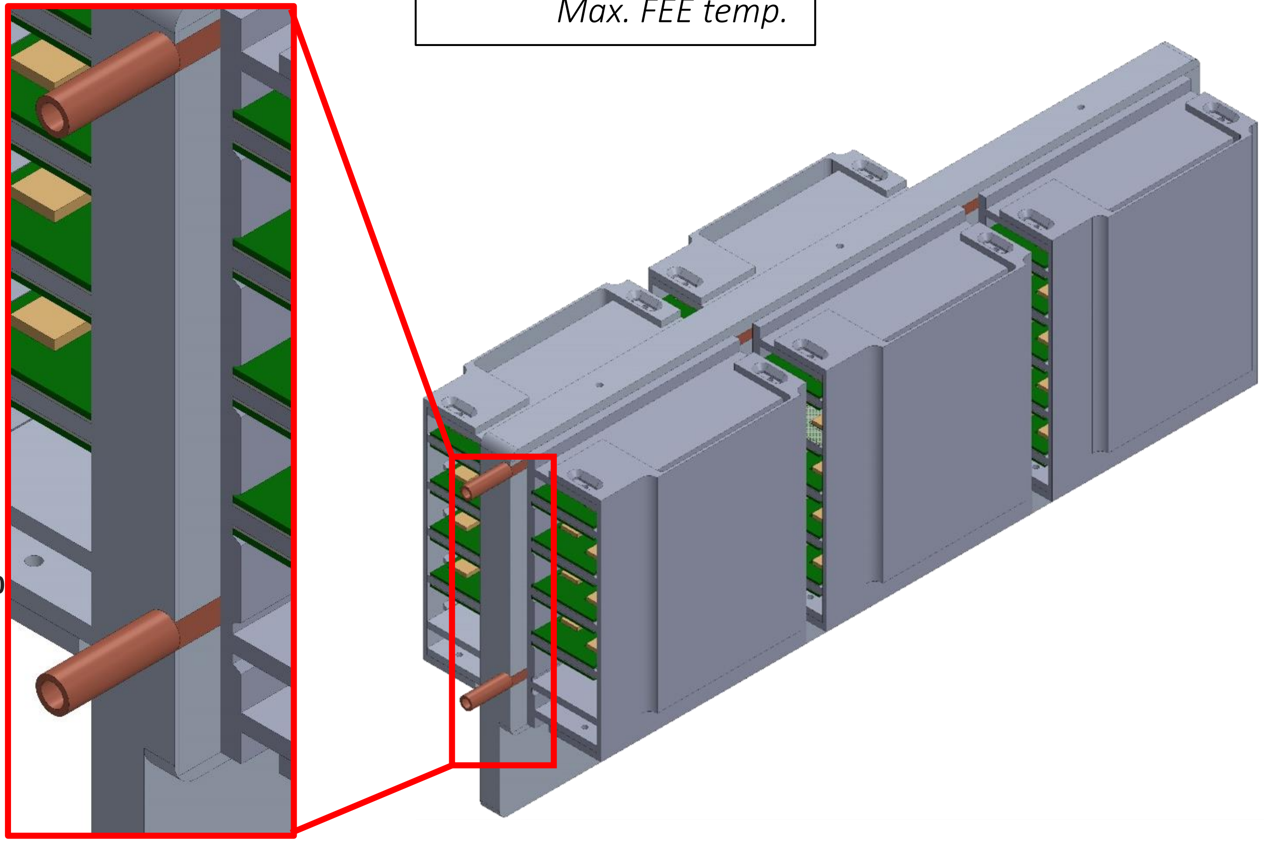
✚

Thermal FEA
(SolidWorks)

Output: Temp. Profile
Max. FEE temp.

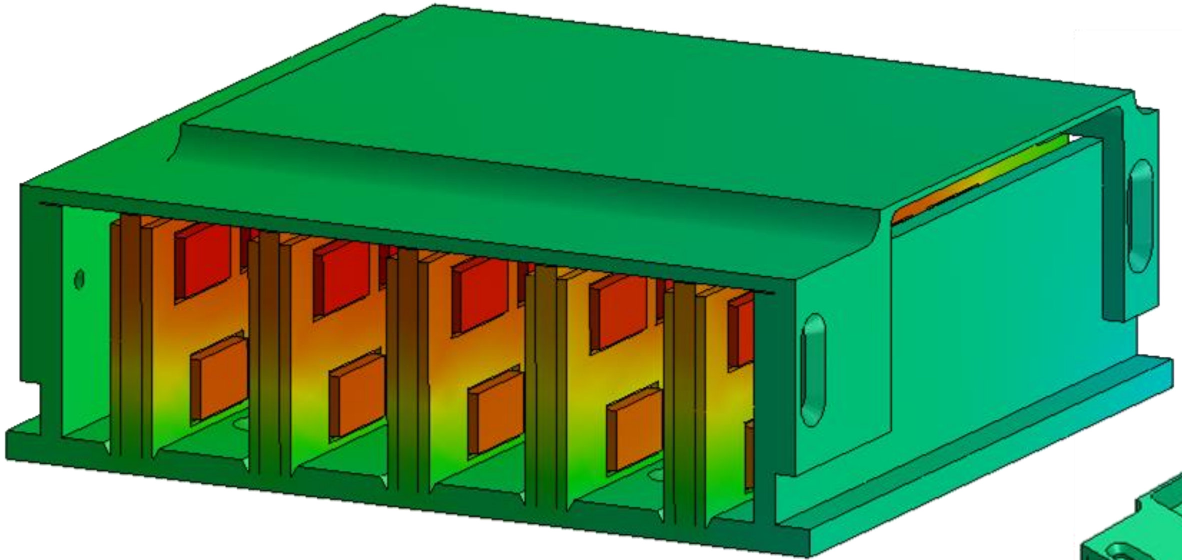


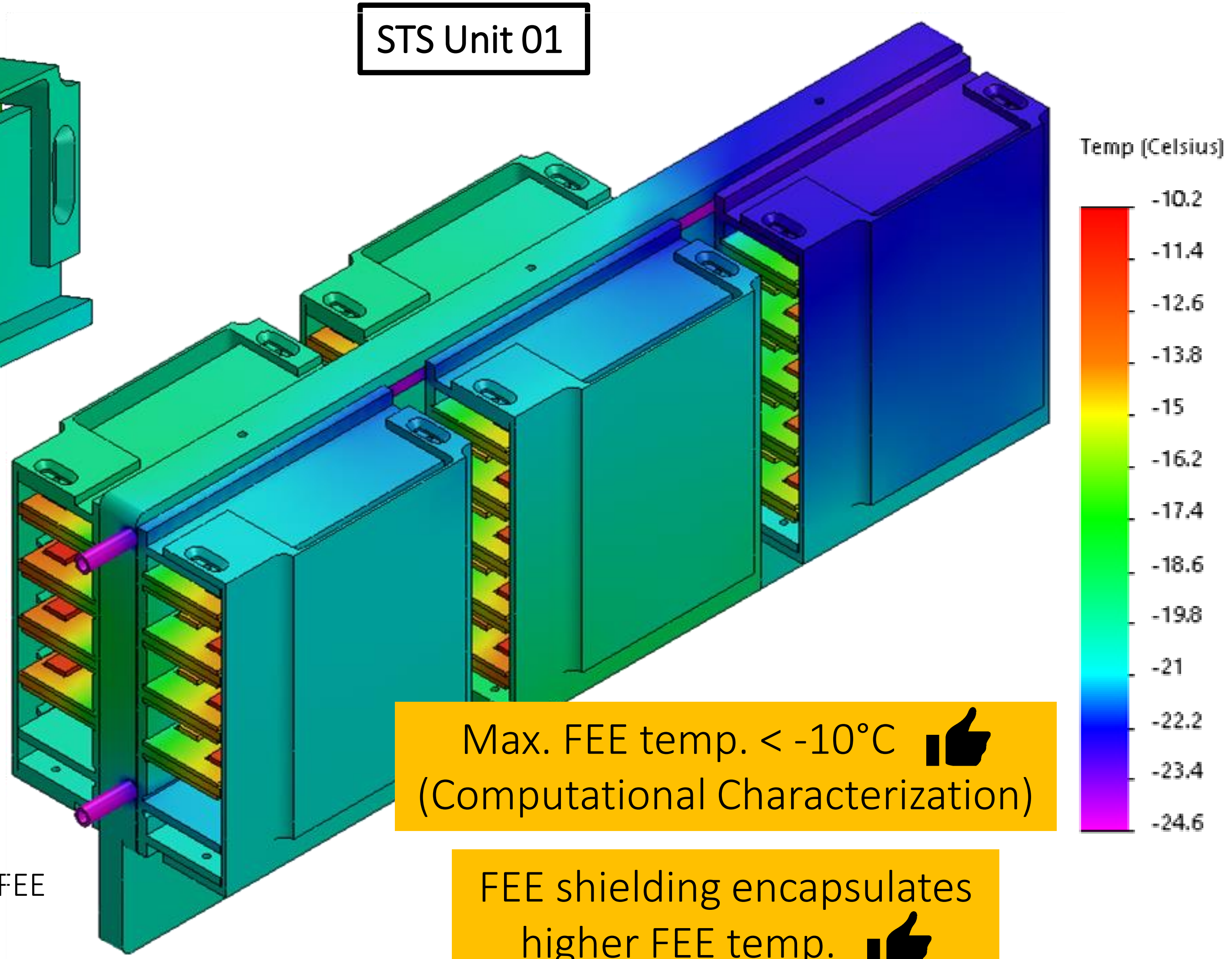




Idea based on:
Max Philip Rauch – Thermal Measurements and FEA of the 2S Module for the CMS Phase-2 Tracker Upgrade
Forum on Tracking Detector Mechanics, Marseilles – 2017

Optimisation Of Operational Parameters – Demonstrator





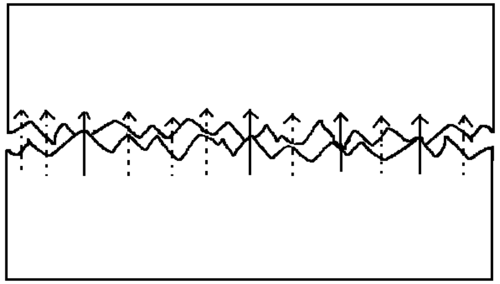
- Thermal FEA performed in SolidWorks 2016
- Boundary Conditions for STS Unit 01 calculations:
  - Total Power: 609.5W
  - Avg. HTC: 10553.85 W/m²K
  - Avg. Fluid Temp.: -24.87°C
- No convection and radiation included (yet!)
- Grease used as TIM for interface 1-2 (Ref. Slide 9)
- Provides good 1st order estimation
- Similar compuational characterization to be done for other FEE and ROB-POB plates
- More accuracy expected with component freeze of electronics

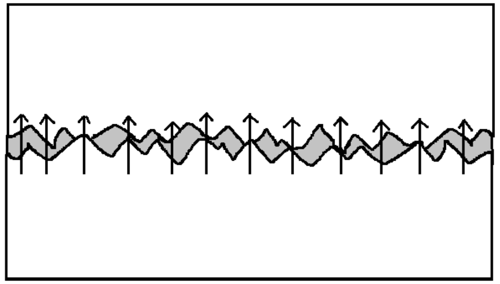
Max. FEE temp. < -10°C (Computational Characterization)

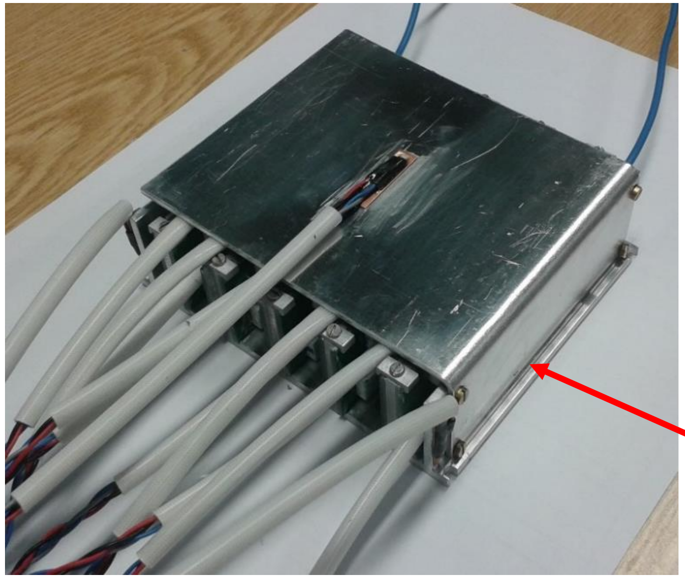
FEE shielding encapsulates higher FEE temp.

Optimisation Of Thermal Interfaces

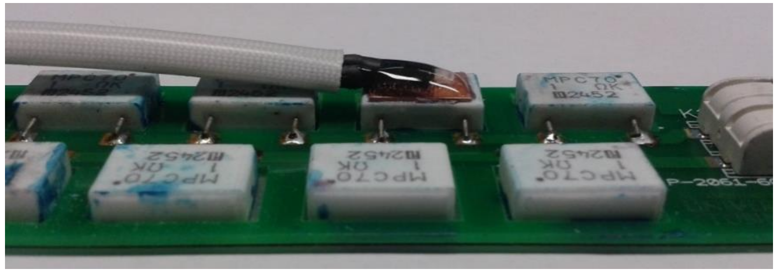
- Thermal Interface Materials (TIMs)
  - → Increase area of contact at microscopic level
  - → Increase overall thermal conductivity (k_{air} = 0.026 W/(m·K))
- Relative measurements done with H_2O at 15°C



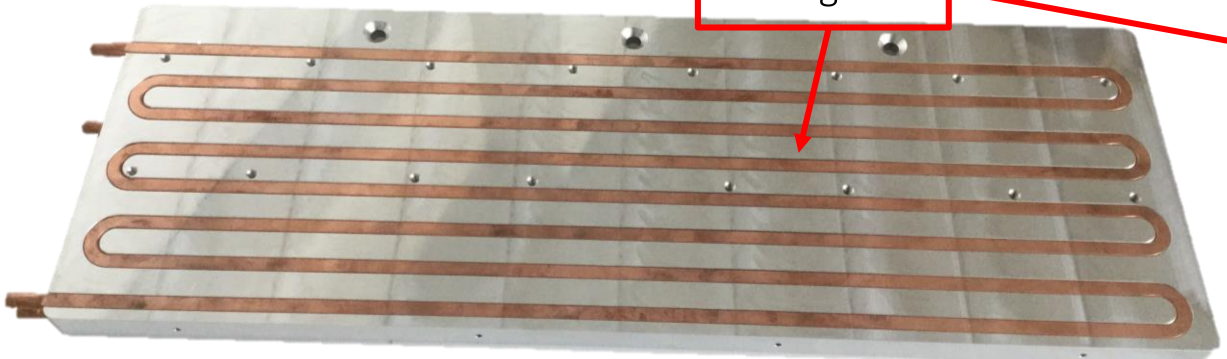




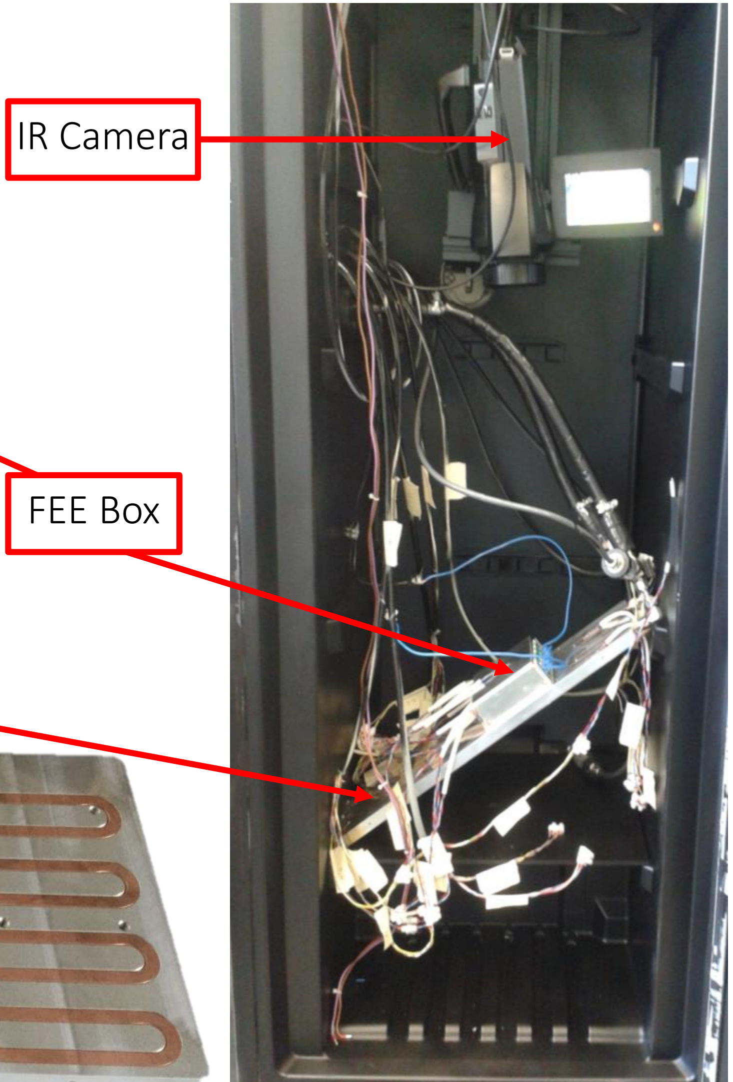
Assembled FEE Cooling Block



FEB-8 with ceramic resistors and PT100 sensors

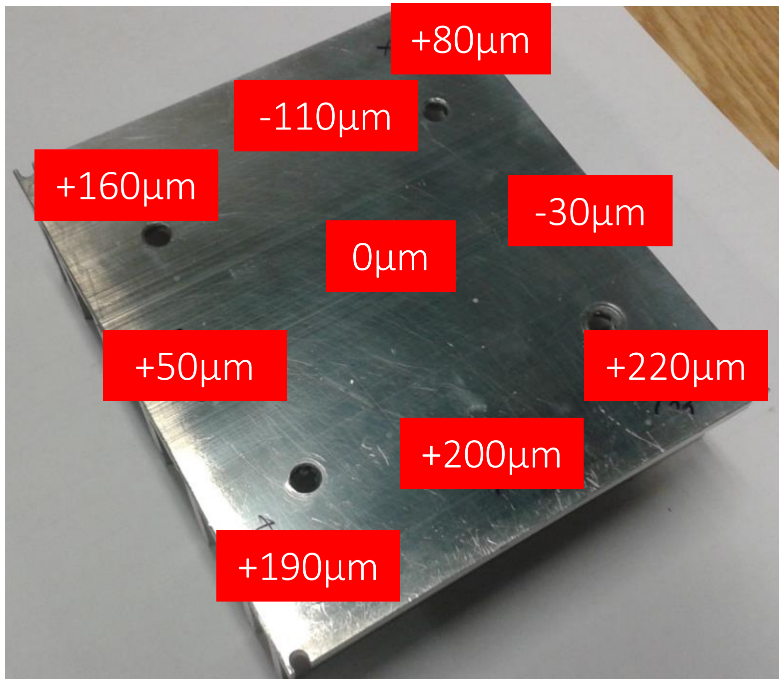


CoolTec Cooling Plate

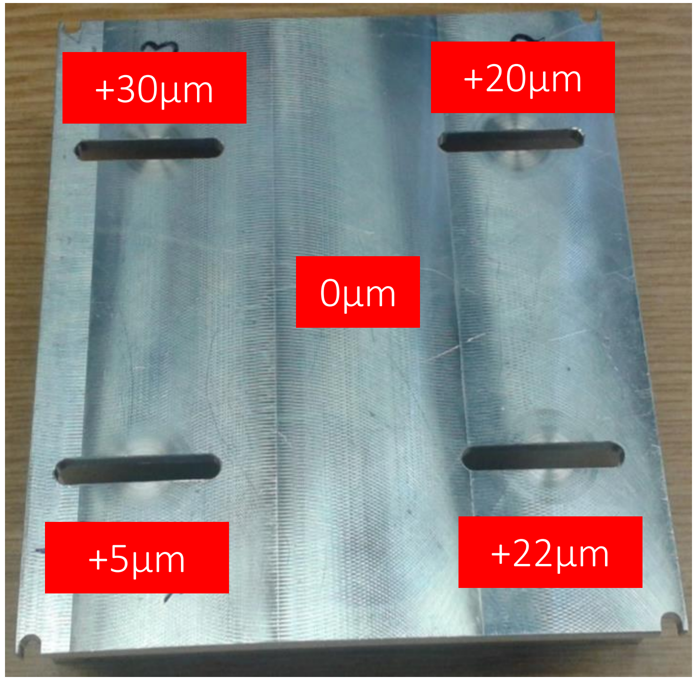


Experimental Setup

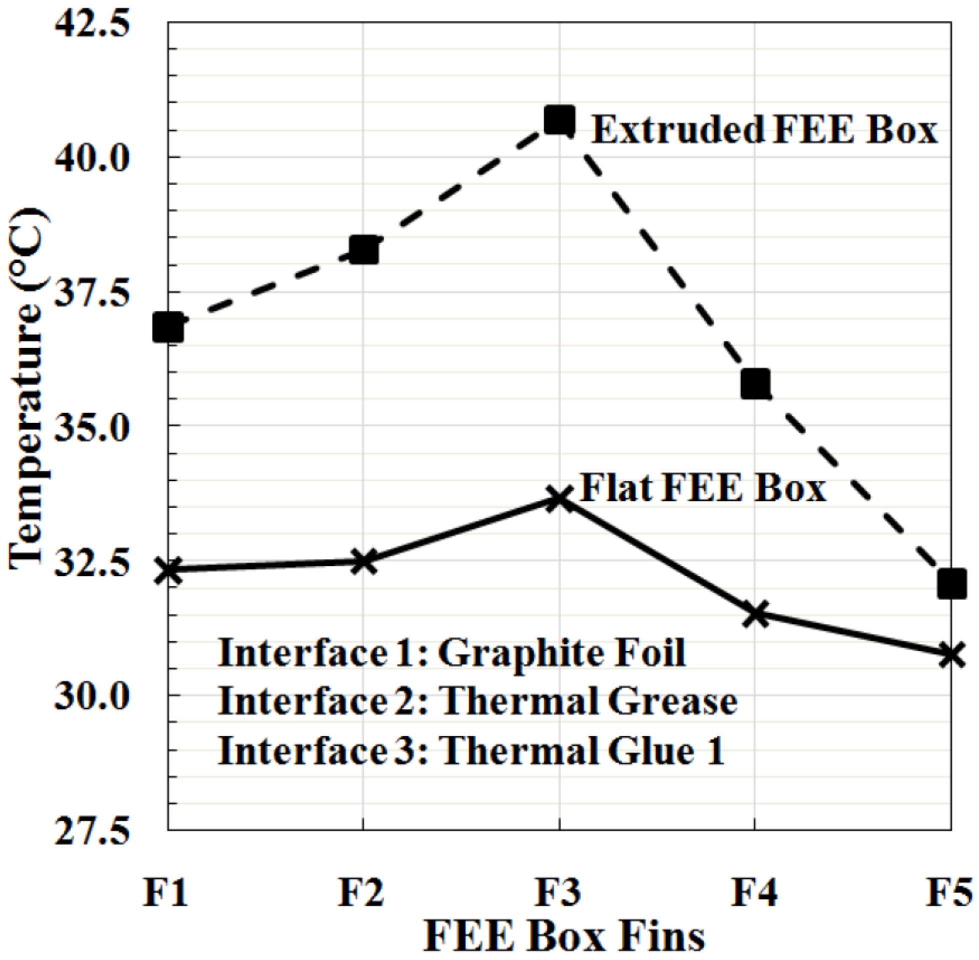
Optimisation Of Thermal Interfaces – Takeaways



Extruded FEE Box
(Variation w.r.t. center = -110 to 220µm)

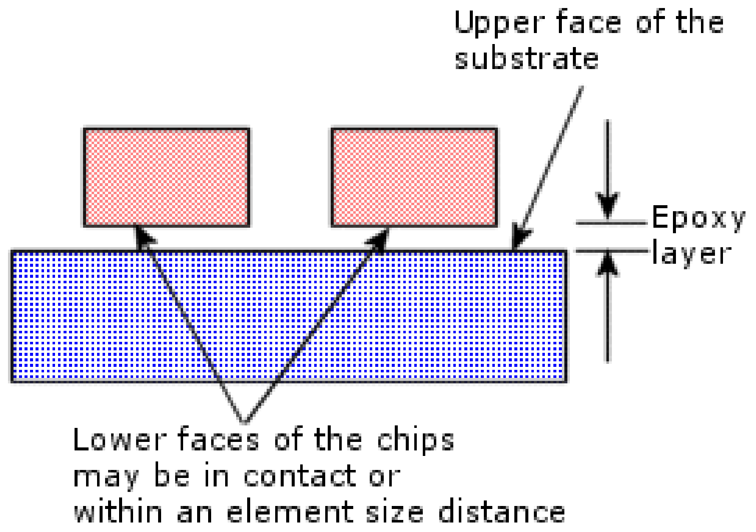


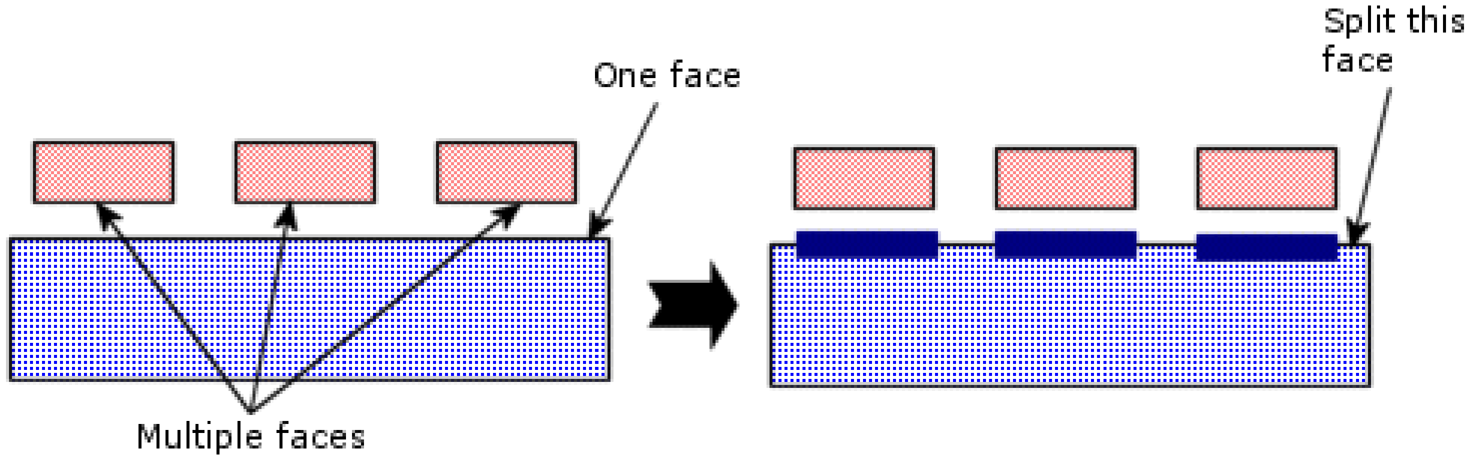
Flat FEE Box
(Variation w.r.t. center = 5 to 30µm)



Flattening interfaces improves the results substantially (~°5C)

DENFINING THERMAL INTERFACES IN SOLIDWORKS





Modeling thermal contact resistance

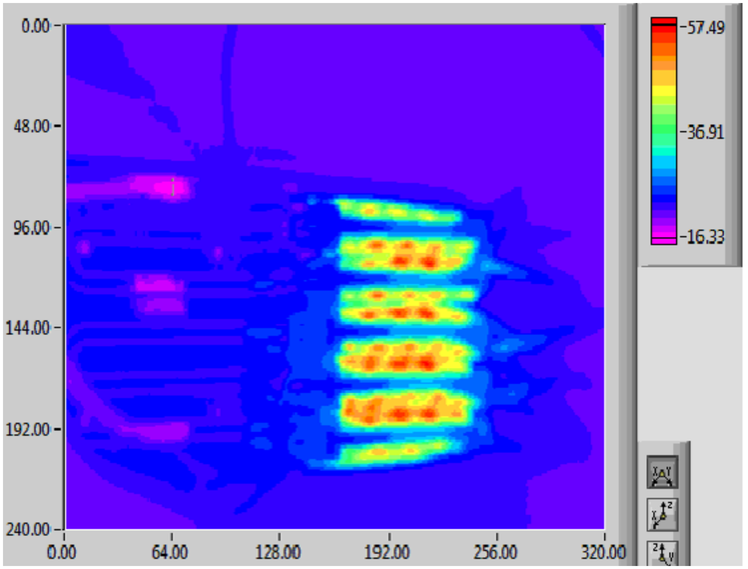
- Modelling the epoxy layer as a separate component requires the use of a very small element size
- Could possibly result in meshing failure or an unnecessarily large number of elements → More computation time
- Better to use thermal resistance as surface-to-surface contact condition caused by the epoxy layer
- Careful splitting of surfaces is required for accurate thermal resistance modelling

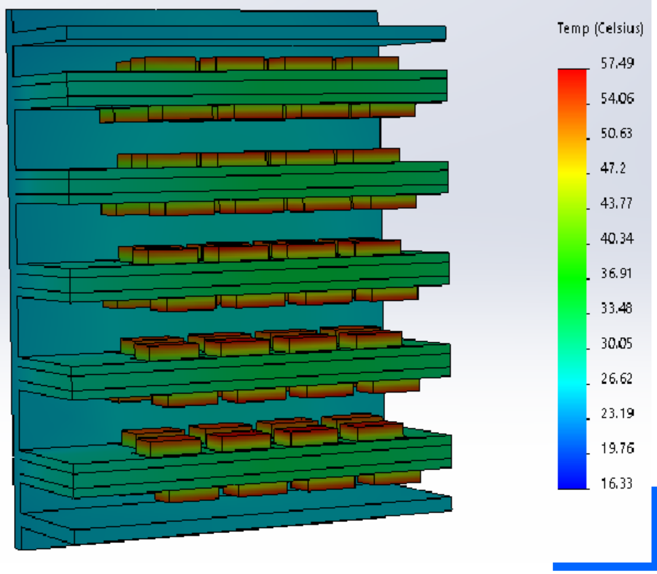
TIM Properties for this study

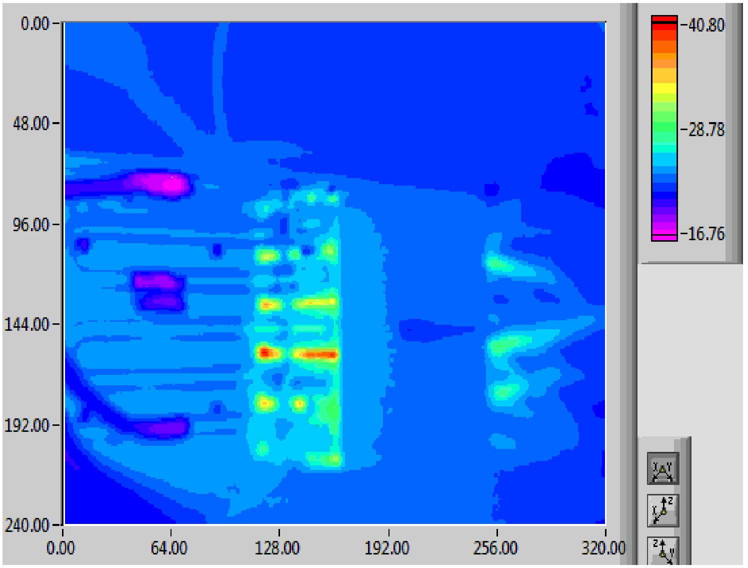
	k (W/m·K)	d (µm)	R_Θ (=d/k; m²·K/W)
Grease (KP97)	5.0	30	6.0×10^{-6}
C-Foil (QGF-G03)	16.0	125	7.8×10^{-6}

More Info: http://help.solidworks.com/2017/english/SolidWorks/cworks/c_Thermal_Contact_Resistance_contact_analysis.htm

Optimisation Of Thermal Interfaces – Takeaways







Viscous TIM (grease) is better

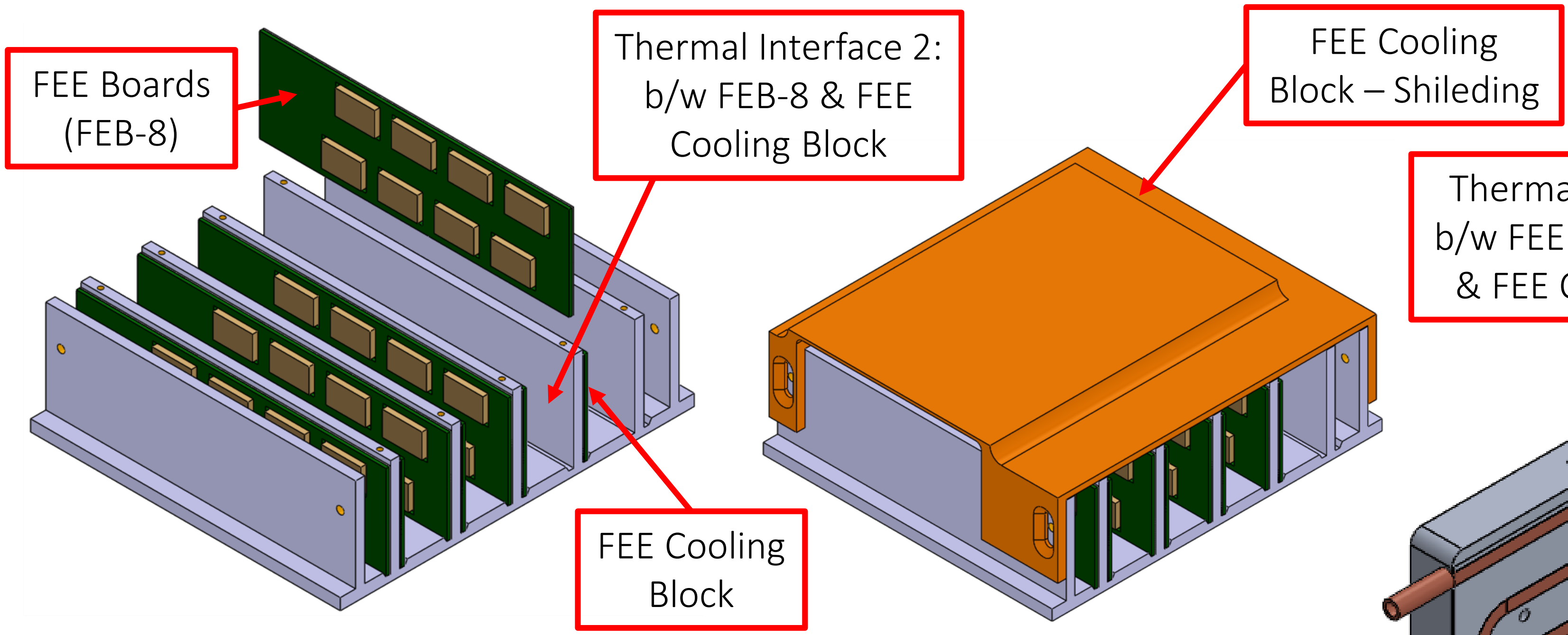
FEE shielding works

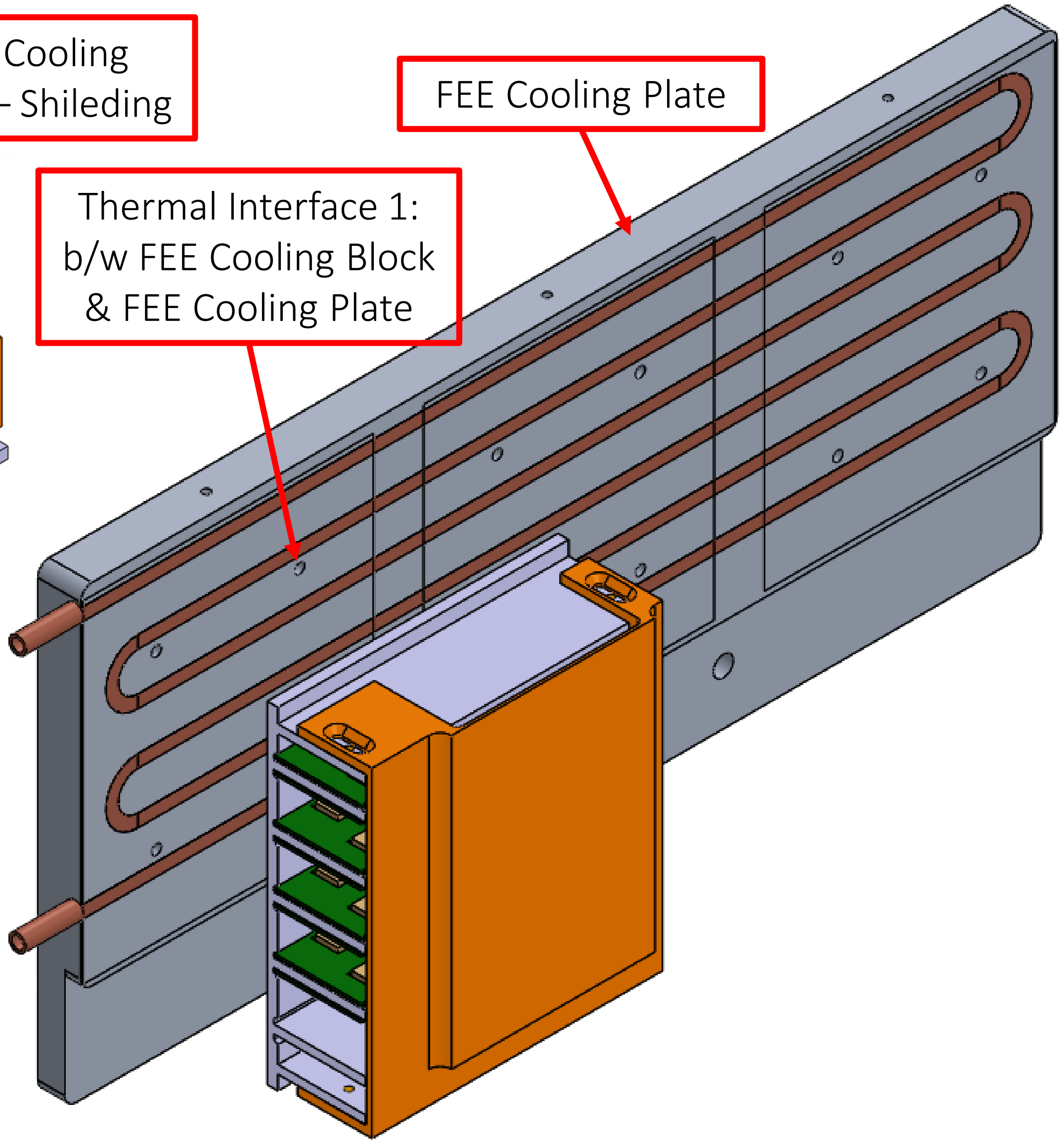
TIM Optimisation

T_{H2O} = 15°C, $\dot{Q}$ = 160W, Fr = 11.1g/s

Interface #1	Interface #2	Maximum Fin Temp. (°C)	
		Exp. (PT100)	Thermal FEA
Grease	Grease	29.7	32.0
	C-Foil	29.6	32.0
C-Foil	Grease	33.7	32.1
	C-Foil	33.9	32.1

FEE COOLING – CONCEPT



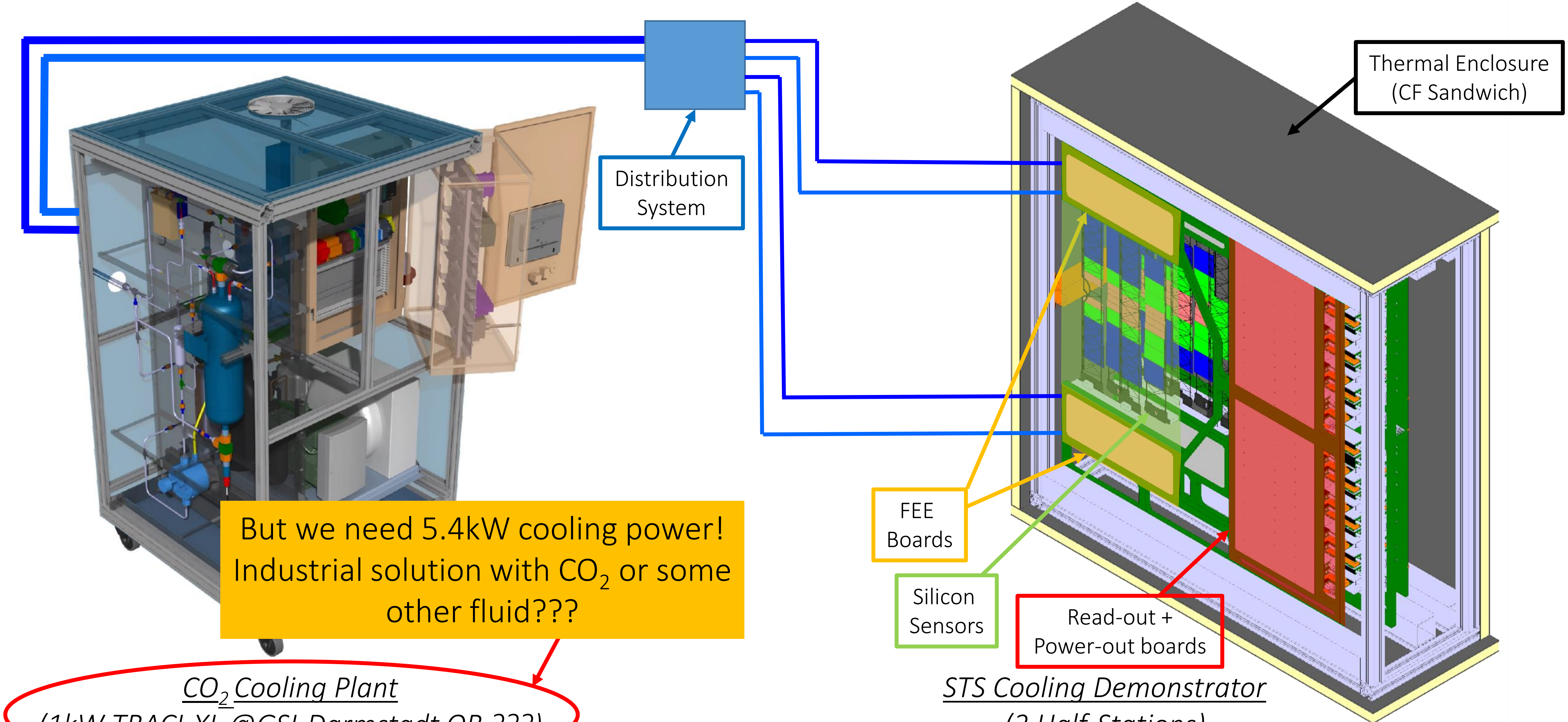


TO-DO LIST

- ✓ ~~Optimisation of cooling pipe geometry w.r.t CO_2 operational conditions~~
- ✓ ~~Optimisation of thermal interfaces~~
- X Experimental tests to check the concept

Optimisation of FEE Cooling Block:-
E. Lavrik, PhD Thesis, Universität Tübingen (2017)

OPEN QUESTIONS – COOLING PLANT



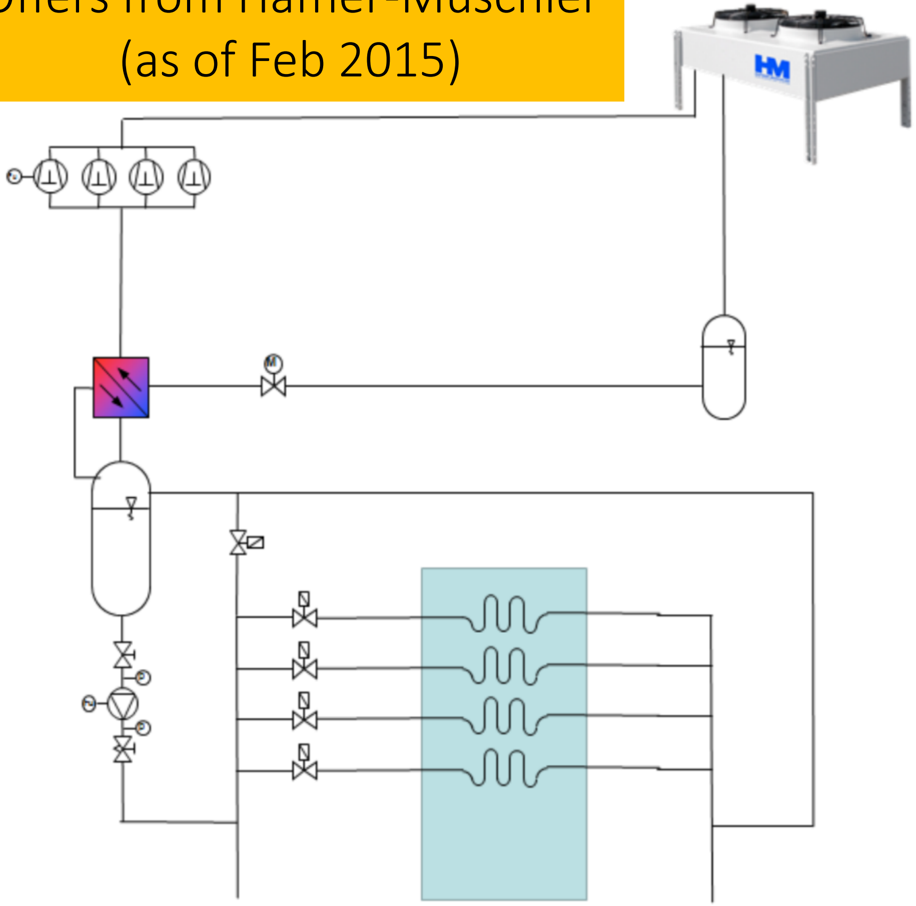
But we need 5.4kW cooling power! Industrial solution with CO_2 or some other fluid???

CO_2 Cooling Plant
(1kW TRACI-XL @GSI-Darmstadt OR ???)

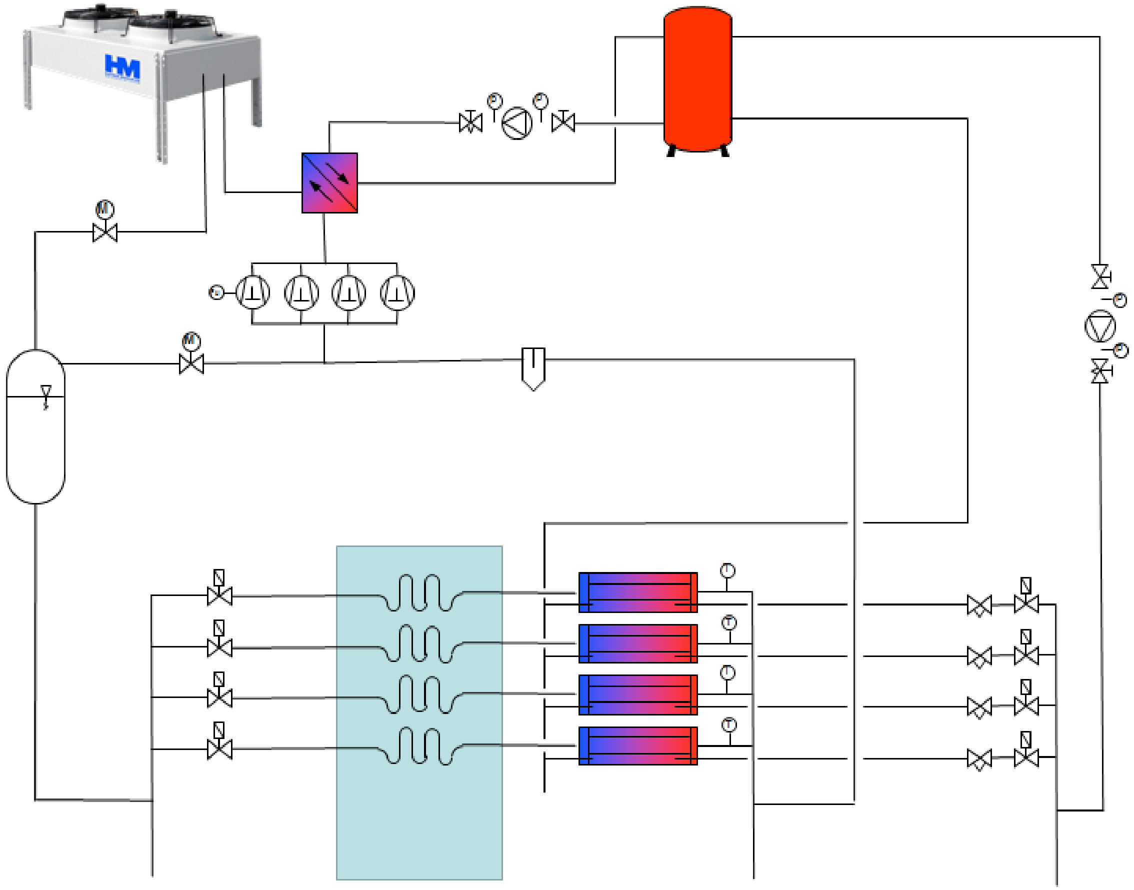
STS Cooling Demonstrator
(2 Half-Stations)

OPEN QUESTIONS – COOLING PLANT

Offers from Hafner-Muschler
(as of Feb 2015)



Liquid Overflow Cycle
(Similar to 2PACL)



Vapor Compression Cycle
(Suitable for radiation environment?)
Commercially available with HM!

Open Questions – Cooling Plant

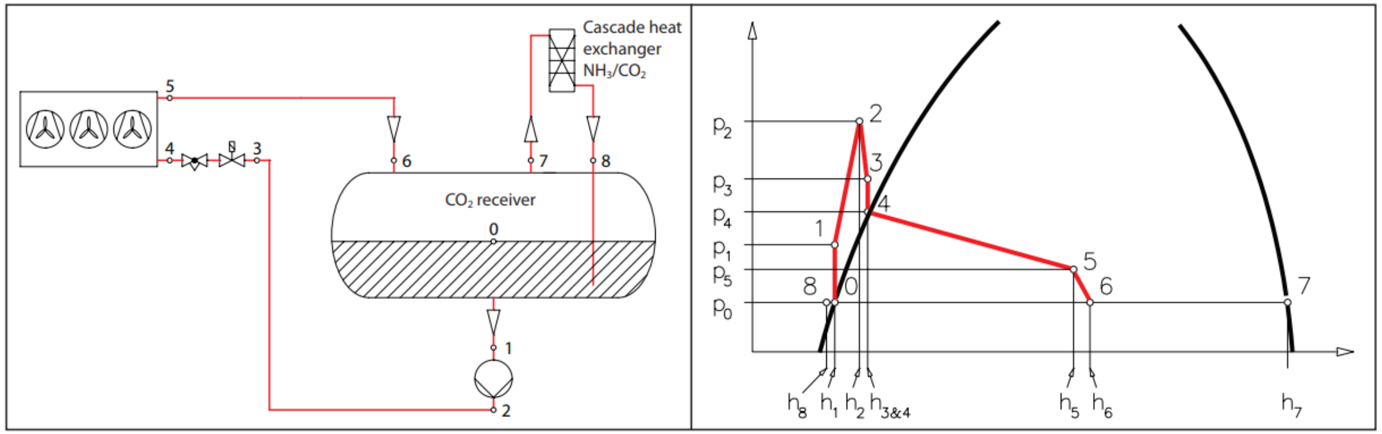


Figure 1 - General diagram of CO_2 pumped system.

Conceptually available from Danfoss and Emerson Climate Tech (only by-parts), but no ready-made cooling plants available

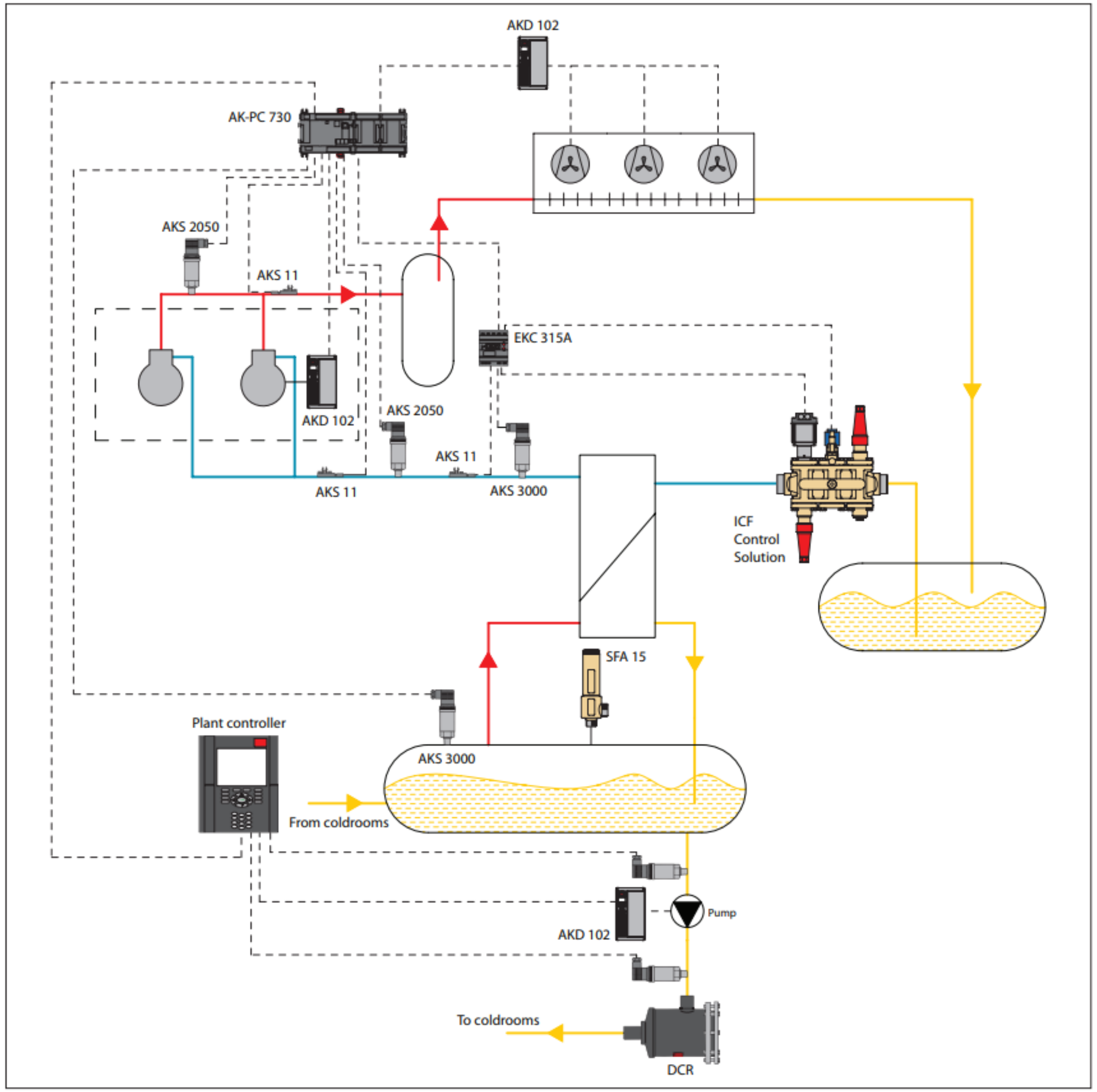


Figure 3 - Integrated control of pump-circulated CO_2 systems

More Info:-

- *http://files.danfoss.com/TechnicalInfo/Dila/01/DKRCIPA000E102_Pumped_co2_in_industrial_refrigeration_systems_Final.pdf*
- *http://www.emersonclimate.com/Documents/FlowControls/pdf/2015CO2-07-R2-Commerical-CO2-Handbook-(Sept2015).pdf*

CONCLUSIONS AND OUTLOOK

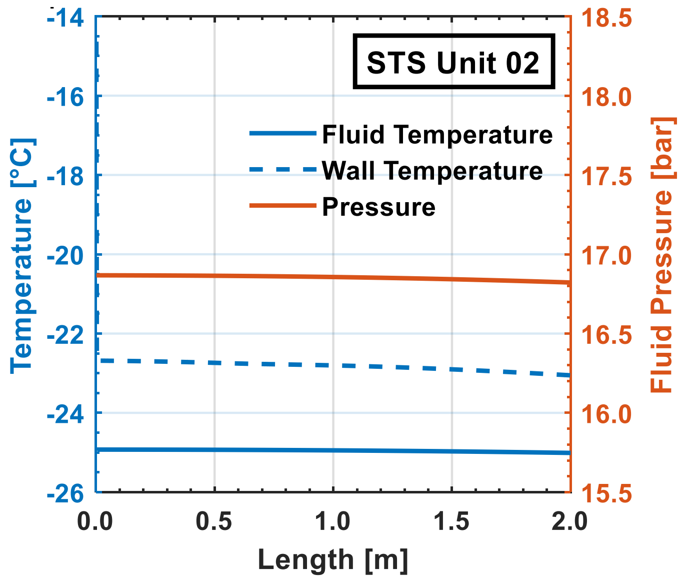
- CBM-STS Cooling Requirements:
  - Electronics: ~ 40kW → at most -10°C → Bi-Phase CO_2 cooling
  - Sensors: ~ 6mW/cm² at end-of-life → -10°C around beam pipe → Forced N_2 cooling
  - Detector operation in a thermal insulating box (CF sandwiches) → RH << 1%@25°C
- Bi-Phase CO_2 calculations done to obtain operational parameters
  - Inspired from CoBra; calculations are comparable ☺
  - Possibility to extrpolate to other coolants, if needed
- Aforementioned calculations combined with Thermal FEA
  - Reasonable 1st order approximation
  - FEE temp. < -10°C ☺
  - Open possibility for more accuracy in calculations for better understanding
- Thermal interface optimisation done for removable interfaces
  - Flattening the surfaces improves the results substantially
  - Grease gives better thermal performance than Graphite Foil (given the FEE integration concepts)
- Cooling demonstrator under design to realistically show cooling concepts viability → Cooling plant with ~ 5.5kW cooling capacity needed!!

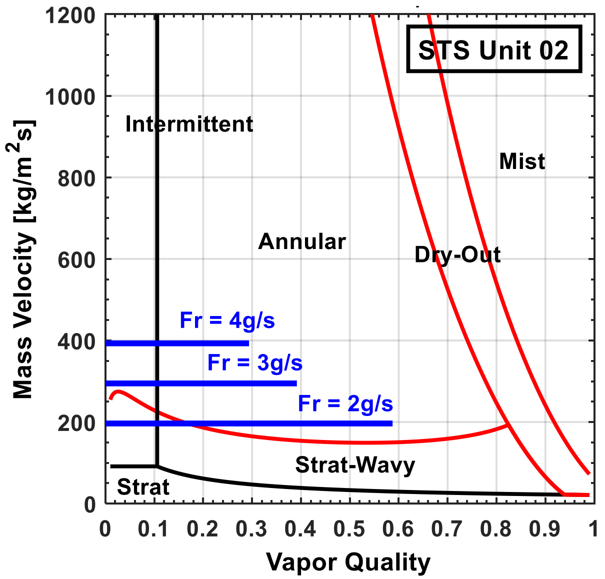
Thanks A Lot

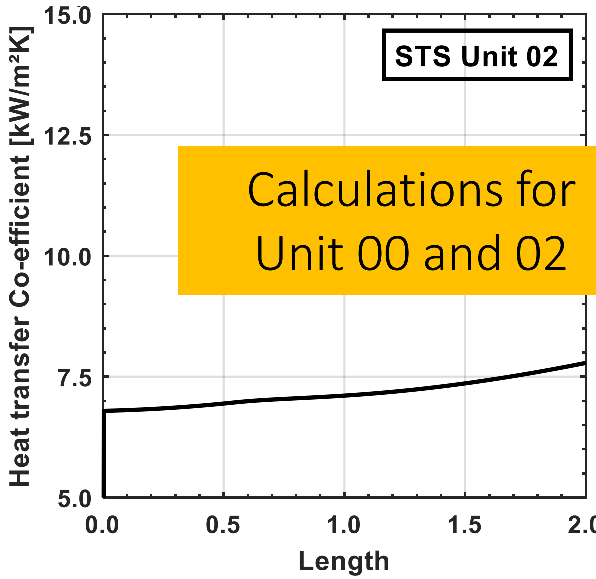
Excavation of SIS100 tunnel
(as of May 2018)

BUT WAIT! THERE'S MORE… BACKUP

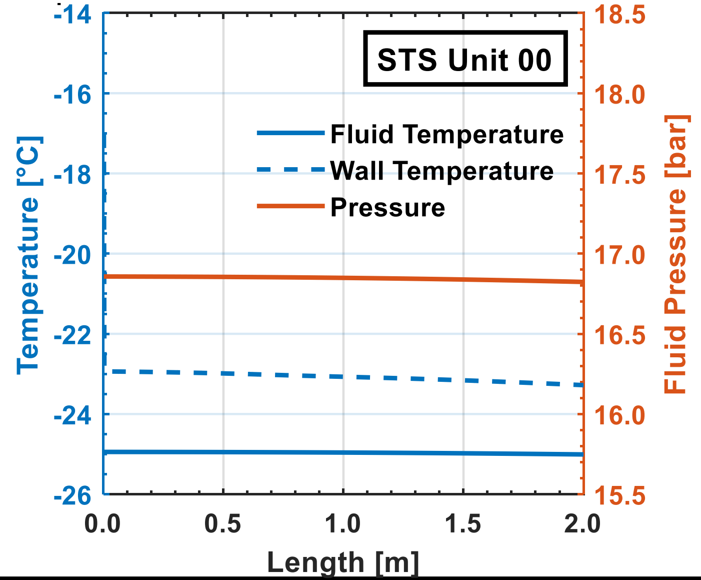
OPTIMISATION OF OPERATIONAL PARAMETERS – DEMONSTRATOR

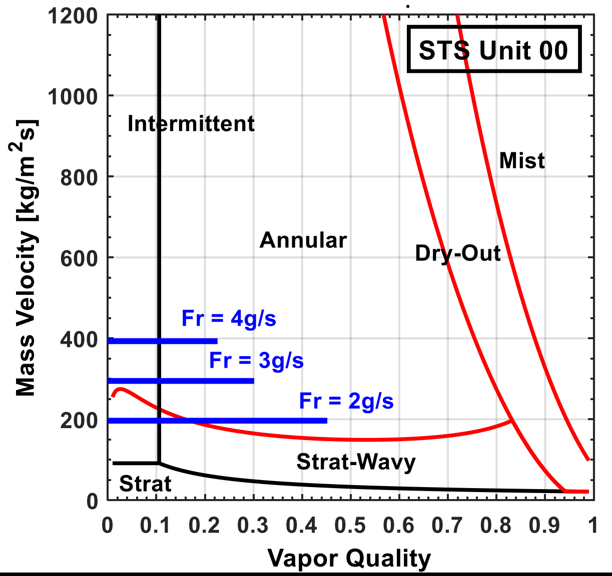


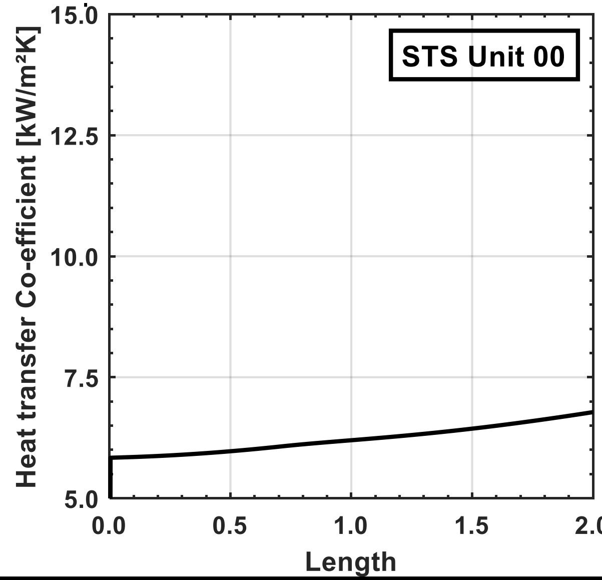




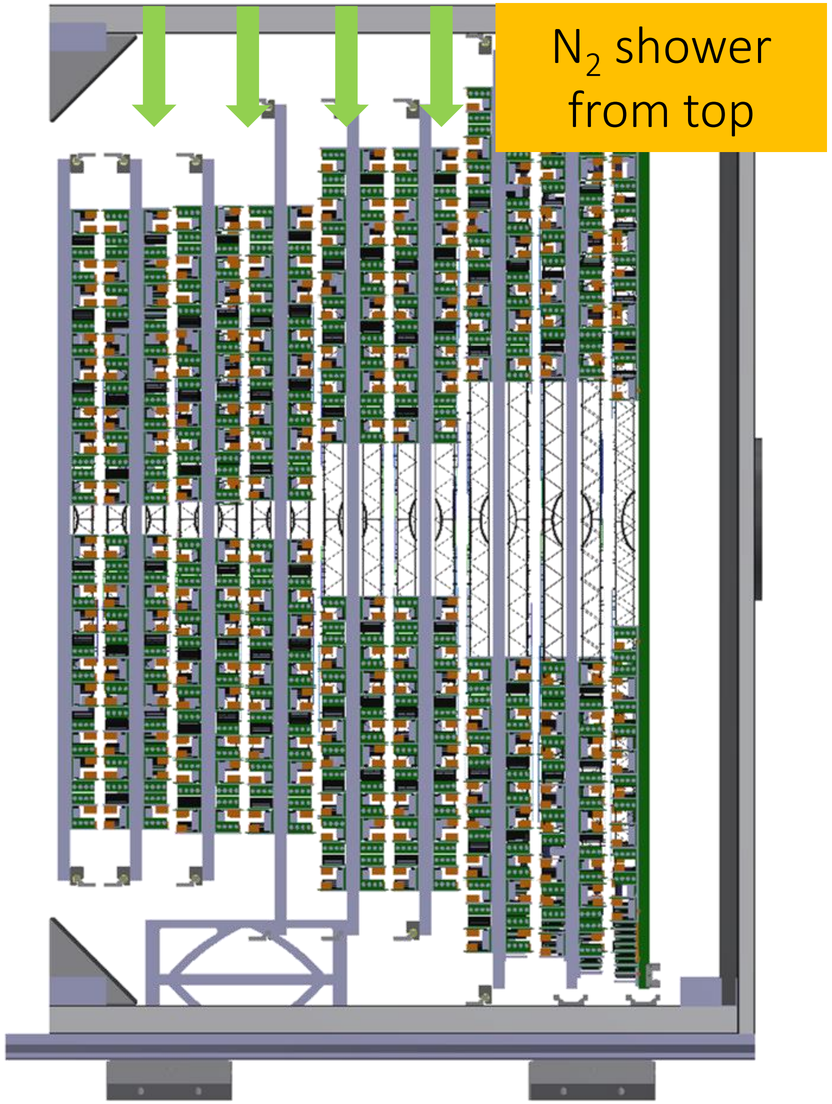
Calculations for Unit 00 and 02

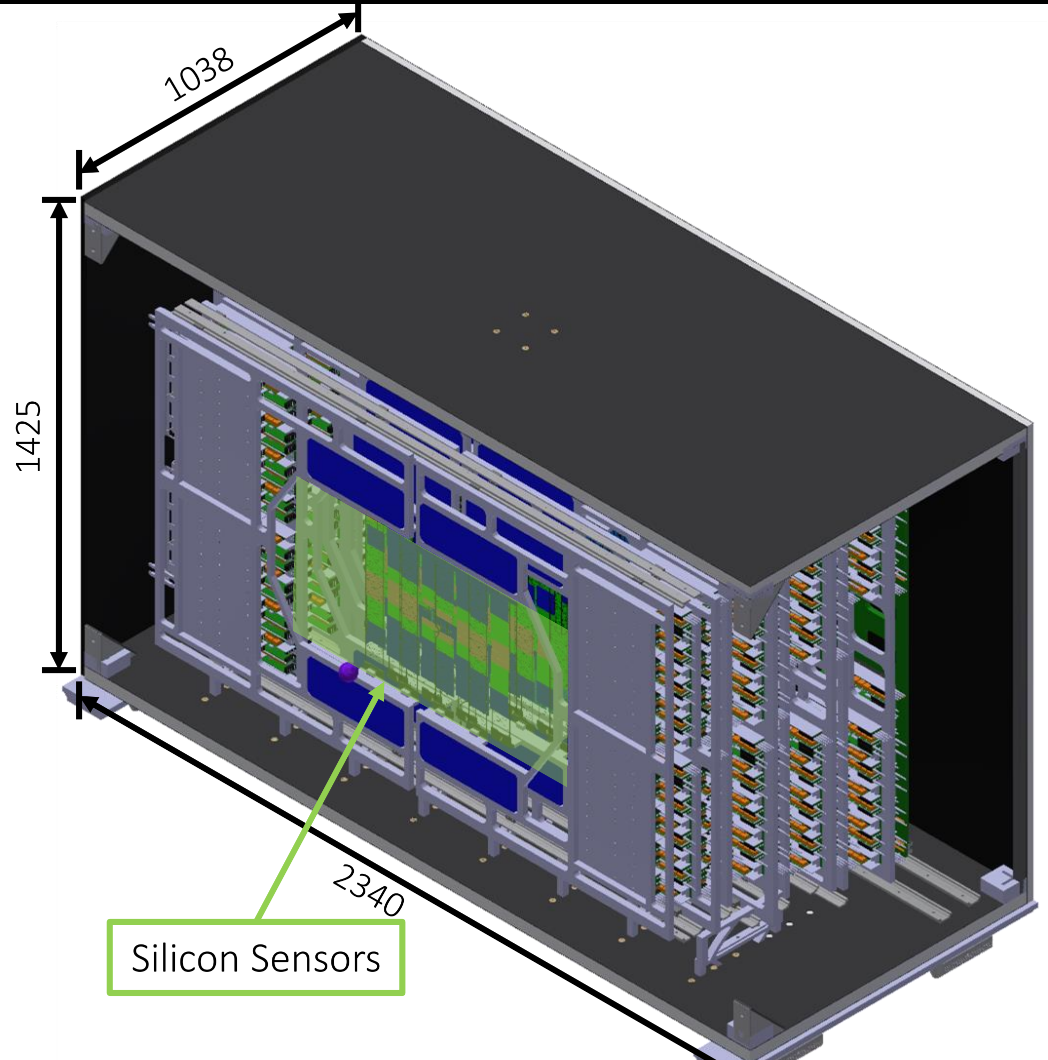






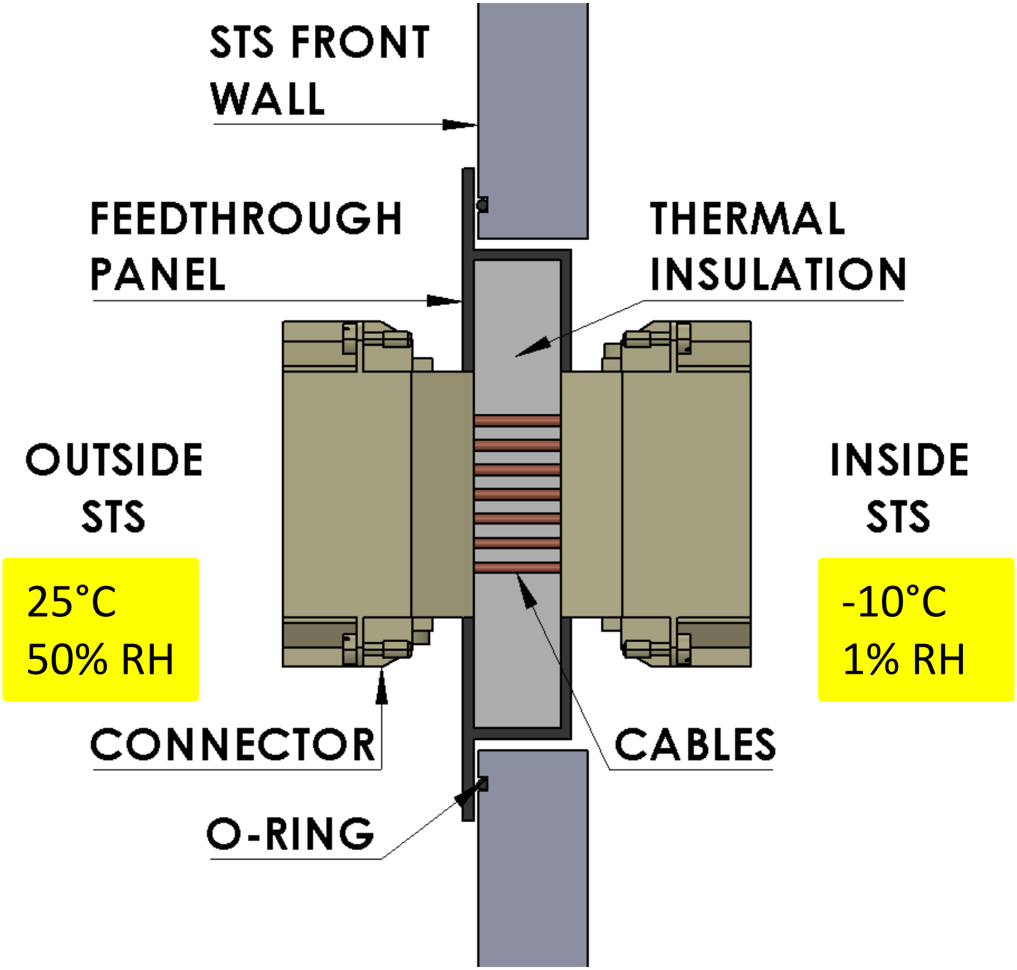
Cooling Requirements - Sensors

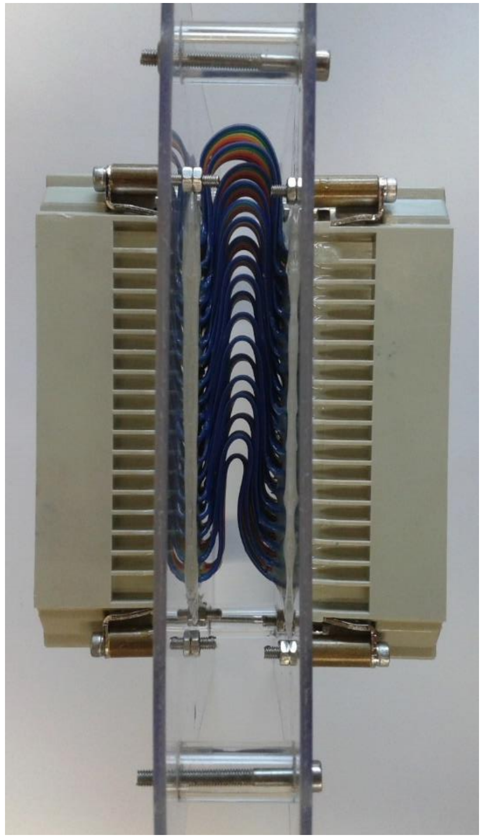




Silicon Tracking System in a thermal enclosure

FEEDTHROUGHS

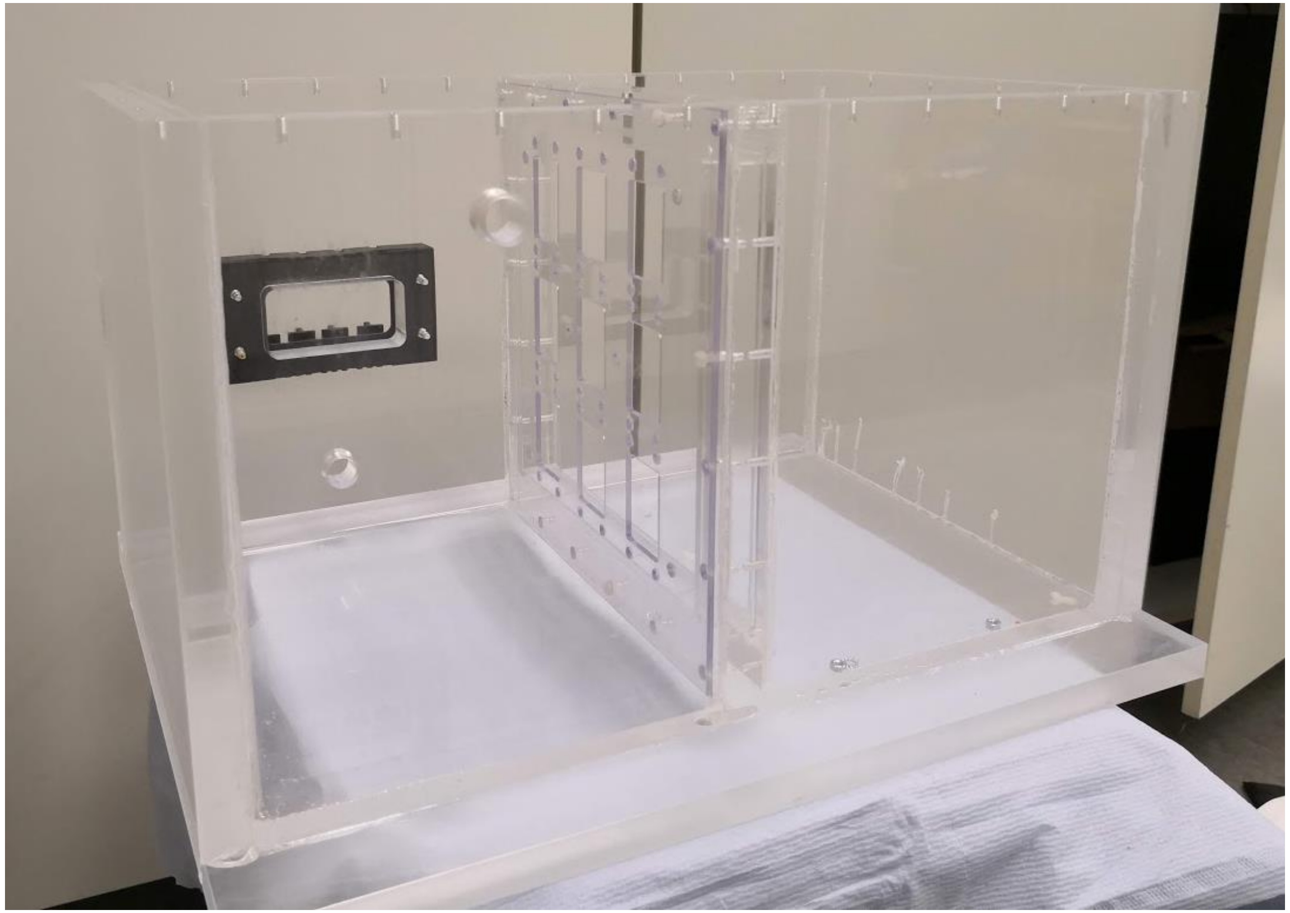


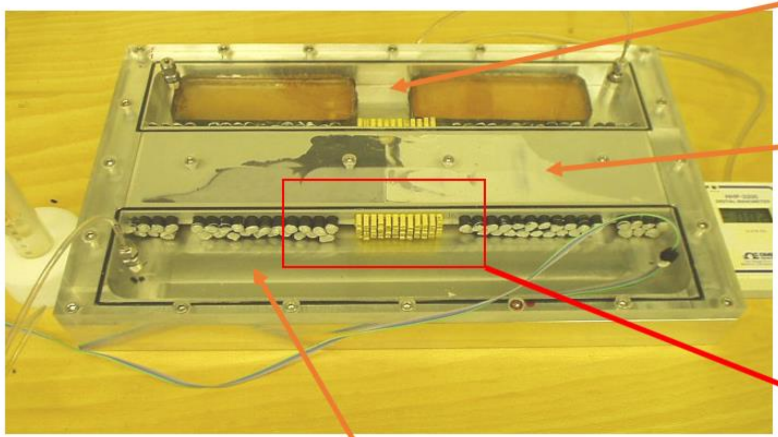


1st Dummy

- 108 cables squeezed in 2cm gap!
- Sealed with silicone & filled with PUR foam

FEEDTHROUGHS





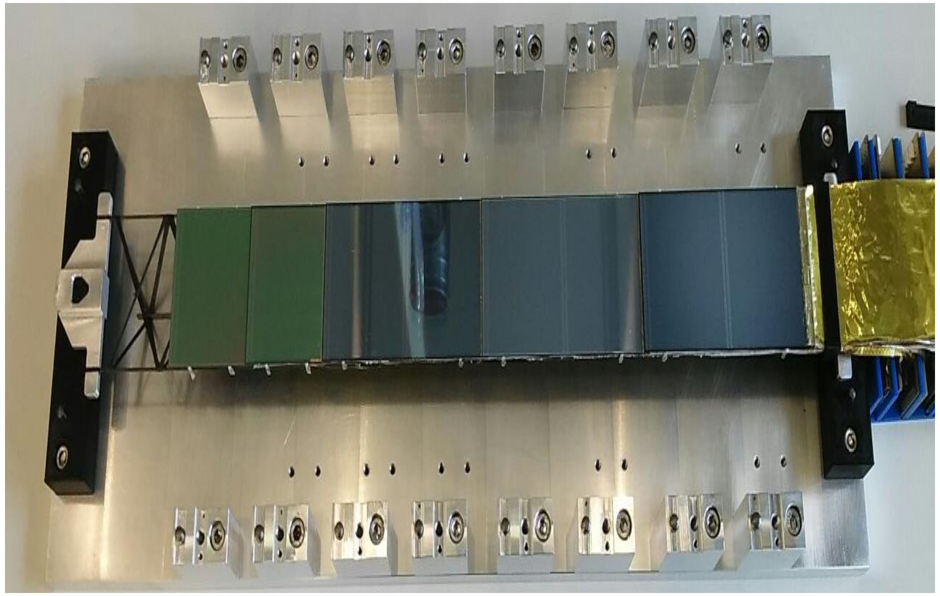
Testing for CMS Tracker Feedthrough System (by P. Petagna)

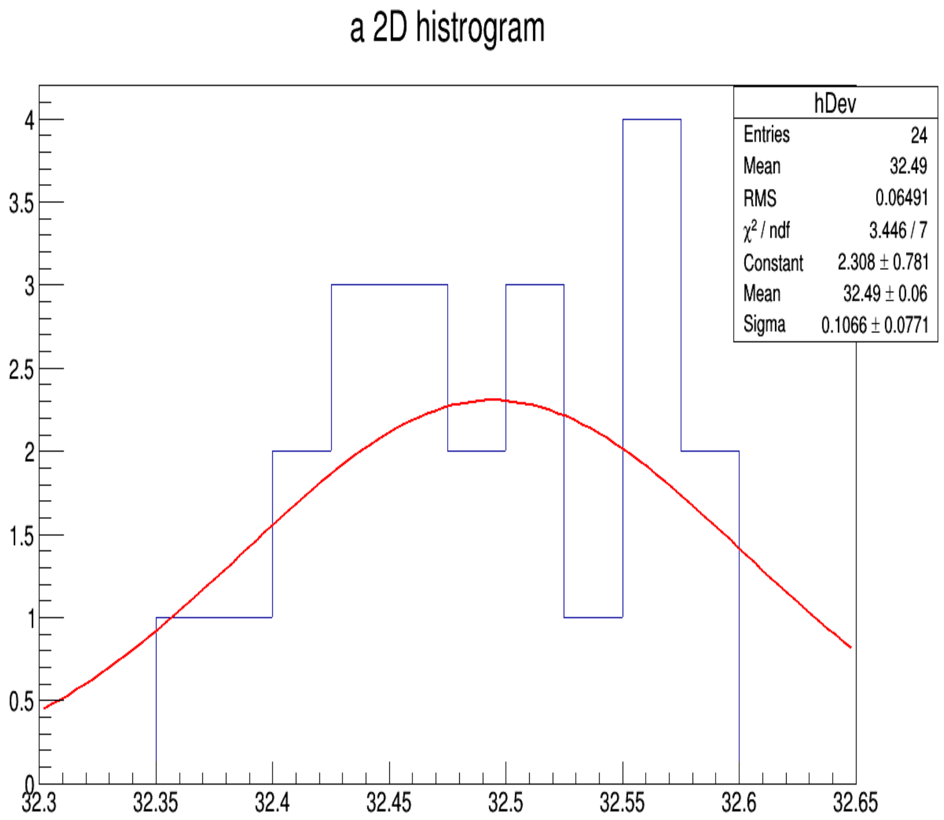
Similar tests would be done for all kinds on connectors (HV, LV, cooling, optical etc)

Test setup already under fabrication in Uni. Tubingen workshop (to be delivered by end of this month)

STS Integration Meeting

22.06.2018





Plot showing deviation in Z

STS Integration Meeting

22.06.2018