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
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

More Info on CBM Physics:-
The CBM physics book: Compressed baryonic matter in laboratory experiments
(DOI: 10.1007/978-3-642-13293-3)

Challenges in QCD matter physics -The scientific programme of the Compressed Baryonic Matter experiment at FAIR
(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

FEE with r/o ASICs
Ultra-thin Microcables
Silicon Sensor
Outside Acceptance
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: $\leq 10^{14} \text{n}_{\text{eq}} \text{ cm}^{-2}$ (5-10 months operation @10MHz Au-Au)
    - Sensor leakage current increases with fluence
      \[ \Delta I = \alpha \cdot \Phi_{\text{eq}} \cdot (A \cdot d) \]
    - Sensor leakage current increases with temperature
      \[ I_L(T) \propto T^2 \exp(-1/T) \]
  - Signal-to-noise $\geq 10$
    - 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

More Info on STS Radiation Environment:
COOLING REQUIREMENTS

- Total Electronics Power $\sim 40$kW
- FEE temp. $<-10^\circ$C to avoid any heat transfer to sensors
- Less space available for respective cooling plates $\rightarrow$ Small tubes needed

Fluid Requirements:
- High Vol. Heat Transfer Co-efficient
- Long operational lifetime ($\sim 10$ years)
- Radiation hardness
  - (NI dose outside detector acceptance $< 10^{12} \text{n}_{\text{eq}} \text{cm}^{-2}$ @10MHz for 1month)

- Sensor power dissipation up to $\sim 6$mW/cm²
- Sensor temp. $\sim -10^\circ$C
- Cooling with minimal additional $X_0/\text{station}$

- Forced $\text{N}_2$ convection directly on sensors

Bi-Phase $\text{CO}_2$ Cooling

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 Requirements:
- High Vol. Heat Transfer Coefficient
- Long operational lifetime (∼ 10 years)
- Radiation hardness (NI dose outside detector acceptance < 10^{12} n_{eq} cm^{-2} @10MHz for 1 month)

- Sensor power dissipation upto ∼ 6mW/cm² (at end-of-life ϕ_{eq} = 10^{14} n_{eq} cm^{-2})
- Sensor temp. ∼ -10°C
- Cooling with minimal additional X_{0}/station

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

Forced N₂ convection directly on sensors

Silicon Tracking System in a thermal enclosure
**STS COOLING DEMONSTRATOR**

**CO₂ Cooling Plant**  
(1kW TRAČI-XL @GSI-Darmstadt)

**Distribution System**

**Thermal Enclosure**  
(CF Sandwich)

**FEE Boards**

**Read-out + Power-out boards**

**Silicon Sensors**

**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 *

<table>
<thead>
<tr>
<th>Quarter-Station #</th>
<th>P_{FEE} (W)</th>
<th>P_{POB-ROB} (W)</th>
<th>P_{SENSORS} (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 0</td>
<td>265.0</td>
<td>346.25</td>
<td>0.22</td>
</tr>
<tr>
<td>Unit 1</td>
<td>609.5</td>
<td>780.125</td>
<td></td>
</tr>
<tr>
<td>Unit 2</td>
<td>344.5</td>
<td>400.50</td>
<td></td>
</tr>
<tr>
<td>TOTAL_{1/4 STATION}</td>
<td>1219.0</td>
<td>1526.875</td>
<td></td>
</tr>
<tr>
<td>TOTAL_{1/2 STATION}</td>
<td>2438.0</td>
<td>3053.75</td>
<td></td>
</tr>
<tr>
<td>TOTAL_{DEMONSTRATOR}</td>
<td>5401.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Including 25% margin

5.4kW Electronics Power Dissipation
FEE COOLING – CONCEPT

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
FEE Cooling – Concept

- Optimisation of cooling pipe geometry w.r.t CO\textsubscript{2} operational conditions
- Optimisation of thermal interfaces
- Experimental tests to check the concept

Optimisation of FEE Cooling Block:
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 CO₂ 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
OPTIMISATION OF OPERATIONAL PARAMETERS – COMPARISON

![Graphs showing various parameters vs length](image-url)
COOLING PLATE (HEAT EXCHANGER)

- 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 H₂O were done at EKU – Tübingen
OPTIMISATION OF OPERATIONAL PARAMETERS – DEMONSTRATOR

Cooling Demonstrator – FEE Operational Parameters

\( T_{\text{CO}_2} = -25^\circ C, \text{ Tube } D_{eq} = 3.6\text{mm (O.D. 6mm), } L = 2\text{m} \)

<table>
<thead>
<tr>
<th>Quarter-Station #</th>
<th>P_{\text{FEE}} (W)</th>
<th>Fr (g/s)</th>
<th>D.O. Margin (%)</th>
<th>( \Delta P ) (bar)</th>
<th>( \Delta T_{2\text{PHASE}} ) (°C)</th>
<th>( L_{1\text{PHASE}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unit 0</td>
<td>265</td>
<td>4</td>
<td>70.14</td>
<td>0.0376</td>
<td>0.43</td>
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<tr>
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<td>Unit 1</td>
<td>609.5</td>
<td>7</td>
<td>51.53</td>
<td>0.1120</td>
<td>0.84</td>
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<tr>
<td>2</td>
<td>Unit 2</td>
<td>344.5</td>
<td>4</td>
<td>60.45</td>
<td>0.0496</td>
<td>0.47</td>
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*Figures for Unit 00 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 computational 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 ($k_{\text{air}} = 0.026 \text{ W/(m-K)}$)
- Relative measurements done with $\text{H}_2\text{O}$ at 15°C

Experimental Setup

- Assembled FEE Cooling Block
- FEB-8 with ceramic resistors and PT100 sensors
- CoolTec Cooling Plate
- IR Camera
- FEE Box
- Cooling Plate
Flattening interfaces improves the results substantially (~5°C)

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

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

<table>
<thead>
<tr>
<th>Material</th>
<th>$k$ (W/m·K)</th>
<th>$d$ (µm)</th>
<th>$R_\Theta$ (=d/k; m²·K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grease (KP97)</td>
<td>5.0</td>
<td>30</td>
<td>6.0 x 10⁻⁶</td>
</tr>
<tr>
<td>C-Foil (QGF-G03)</td>
<td>16.0</td>
<td>125</td>
<td>7.8 x 10⁻⁶</td>
</tr>
</tbody>
</table>

More Info:
**Optimisation of Thermal Interfaces – Takeaways**

**TIM Optimisation**

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

<table>
<thead>
<tr>
<th>Interface #1</th>
<th>Interface #2</th>
<th>Maximum Fin Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grease</td>
<td>Grease</td>
<td>29.7</td>
</tr>
<tr>
<td></td>
<td>C-Foil</td>
<td>29.6</td>
</tr>
<tr>
<td>C-Foil</td>
<td>Grease</td>
<td>33.7</td>
</tr>
<tr>
<td></td>
<td>C-Foil</td>
<td>33.9</td>
</tr>
</tbody>
</table>

Viscous TIM (grease) is better. FEE shielding works. ☑️

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Forum on Tracking Detector Mechanics - 25/06/2018
K. Agarwal - Thermal Management of CBM-STS
FEE Cooling – Concept

**TO-DO LIST**

- Optimisation of cooling pipe geometry w.r.t CO₂ operational conditions
- Optimisation of thermal interfaces
- Experimental tests to check the concept

Optimisation of FEE Cooling Block:

**Open Questions – Cooling Plant**

*CO₂ Cooling Plant*

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

But we need 5.4kW cooling power! Industrial solution with CO₂ or some other fluid???
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!
Conceptually available from Danfoss and Emerson Climate Tech (only by-parts), but no ready-made cooling plants available

More Info:-
CONCLUSIONS AND OUTLOOK

- CBM-STS Cooling Requirements:
  - Electronics: \( \sim 40\text{kW} \rightarrow \text{at most} -10^\circ\text{C} \rightarrow \text{Bi-Phase CO}_2 \text{ cooling} \)
  - Sensors: \( \sim 6\text{mW/cm}^2 \text{ at end-of-life} \rightarrow -10^\circ\text{C around beam pipe} \rightarrow \text{Forced N}_2 \text{ cooling} \)
  - Detector operation in a thermal insulating box (CF sandwiches) \( \rightarrow \text{RH} << 1\% @ 25^\circ\text{C} \)

- Bi-Phase CO\(_2\) calculations done to obtain operational parameters
  - Inspired from CoBra; calculations are comparable 😊
  - Possibility to extrapolate to other coolants, if needed

- Aforementioned calculations combined with Thermal FEA
  - Reasonable 1\(^{st}\) order approximation
  - FEE temp. < -10\(^{\circ}\text{C} \)
  - 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 \( \rightarrow \text{Cooling plant with} \sim 5.5\text{kW cooling capacity needed!!} \)
THANKS A LOT

Excavation of SIS100 tunnel (as of May 2018)
BUT WAIT! THERE’S MORE...
BACKUP
OPTIMISATION OF OPERATIONAL PARAMETERS – DEMONSTRATOR

Forum on Tracking Detector Mechanics - 25/06/2018
K. Agarwal - Thermal Management of CBM-STS
COOLING REQUIREMENTS - SENSORS

Silicon Tracking System in a thermal enclosure

N\textsubscript{2} shower from top

Silicon Sensors
FEEDTHROUGHS

1st Dummy
- 108 cables squeezed in 2cm gap!
- Sealed with silicone & filled with PUR foam

STS FRONT WALL
FEEDTHROUGH PANEL
THERMAL INSULATION
OUTSIDE STS
CONNECTOR
O-RING
INSIDE STS

25°C 50% RH
-10°C 1% RH
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