Lightweight Thermal Management Strategies for the Silicon Detectors of CBM at FAIR

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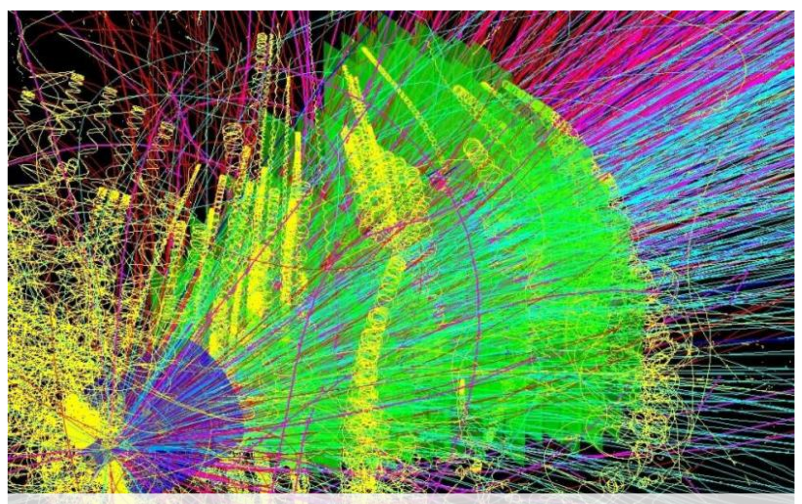
Compressed Baryonic Matter Experiment at FAIR

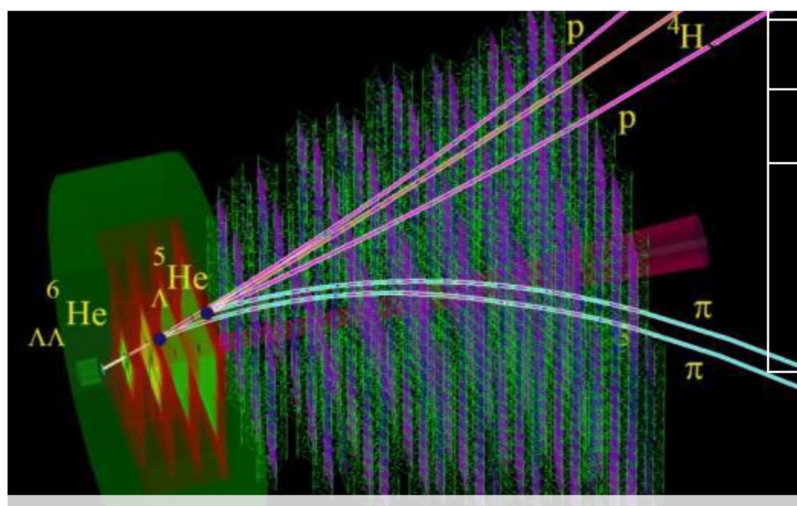
CBM-FAIR & Its Silicon-Based Inner Tracker

Fixed-target heavy-ion collision experiment to study strongly interacting matter at neutron star core densities

- ≤ 10^7 reactions/s at $\sqrt{s_{NN}}$ = 2.9 – 4.9 GeV
- Determination of vertices (σ ≈ 50 μm)
- Identification of leptons and hadrons
- Di-electron and muon setup
- Fast and radiation hard detectors
- Trigger-less free-streaming readout
- Online event selection
- 4-D event reconstruction



Reconstructed High-Multiplicity Collision Event



Hypernuclei Selection ($^{6}_{\Lambda\Lambda}He$) Reconstruction

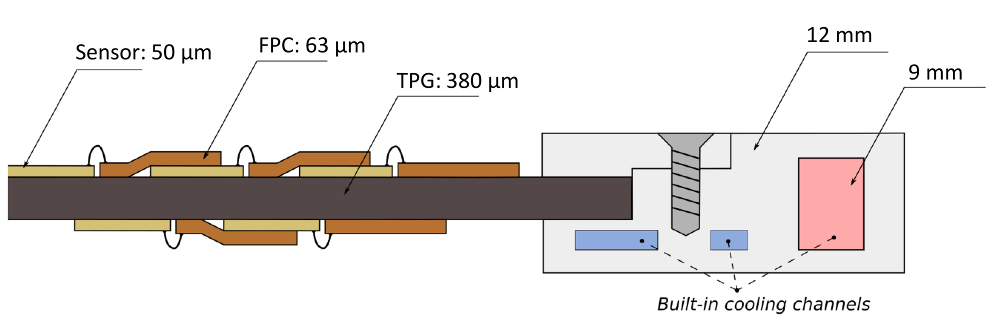
Micro-Vertex Detector (MVD)	Silicon Tracking System (STS)
4 planar layers, z = 8 – 20 cm (in vacuum)	8 planar layers, z = 30 – 100 cm (in air)
≈ 0.15 m² area, 288 sensors, 150M pixels	≈ 4m² area, 876 sensors, 1.8M channels
CMOS MAPS (MIMOSIS; TowerJazz 180 nm)	Double-Side Strips (Hamamatsu w/ SMX)
≈ 0.3% – 0.5% X_0 per layer	≈ 0.3% – 2% X_0 per layer
σ_{xy} = 5 μm, σ_z = 70 μm, t_{frame} = 5 μs	σ_{xy} = 25 μm, σ_t = 5 ns
< 0.7 × 10^{14} n_{eq}/cm², 5 MRad	< 1 × 10^{14} n_{eq}/cm²
< 80 MHz/cm² ; 0.1 MHz reactions	< 10 MHz/cm² ; 10 MHz reactions

In field of a superconducting dipole magnet (1 T·m), azimuthal acceptance of 2.5 – 25°

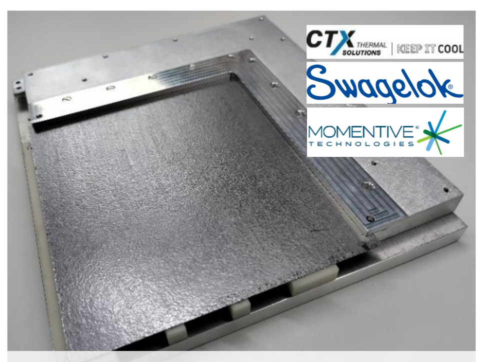
Lightweight, large-area, fast, radiation hard silicon detectors deployed for vertex (MAPS-based) and track (strip-based) reconstruction

Thermal Management Strategies

MVD: Liquid-assisted conductive cooling



Cross-Sectional View (Illustration) of the MVD Quadrant



Full-scale MVD Quadrant (191.0×170.4 cm²)

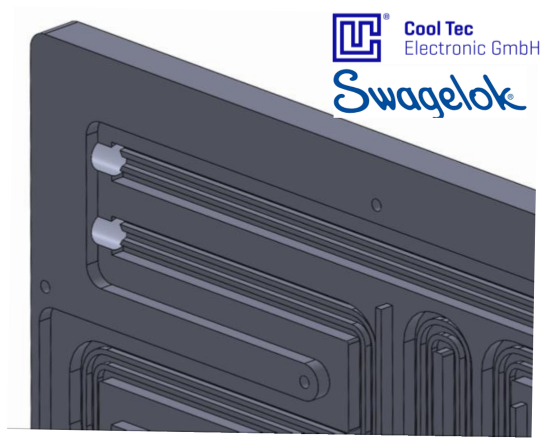
- Temperature: ~ 0 °C, down to –20 °C
- Power: 50 - 100 mW/cm², ~ 200 W total
- Liquid-cooled Heat Sink
  - Outside physics acceptance
  - Monophase 3M™ NOVEC™ 649 ≥ –20 °C
  - Vacuum-brazed aluminium heat sink
- Sensors passively cooled via Thermal Pyrolytic Graphite (TPG) carriers
  - Thermally Conductive (λ > 1500 W/m·K)
  - Low material budget (X_0 = 19.3 cm)
  - Polishing, laser ablation cutting, hatching
  - Parylene coating, plasma activation

STS: Liquid-assisted impinging air-jet cooling

STS-Module: Silicon Sensors (6.2×6.2 cm²) + Microcables (Shielded) + FEE-Boards (10×3 cm², 25 W)

- Temperature: ~ +10 °C
- Silicon Sensors
  - Power: 50 mW/cm² at +10 °C, EOL
  - Impinging air-jets via perforated CF tubes
- Front-End Electronics
  - Outside physics acceptance (40 kW in 3 m³)
  - Monophase 3M™ NOVEC™ 649 @ –20 °C
  - Friction-stir welded aluminium plates
  - Thermally conductive heat path

"Lighter" air cooling for silicon sensors

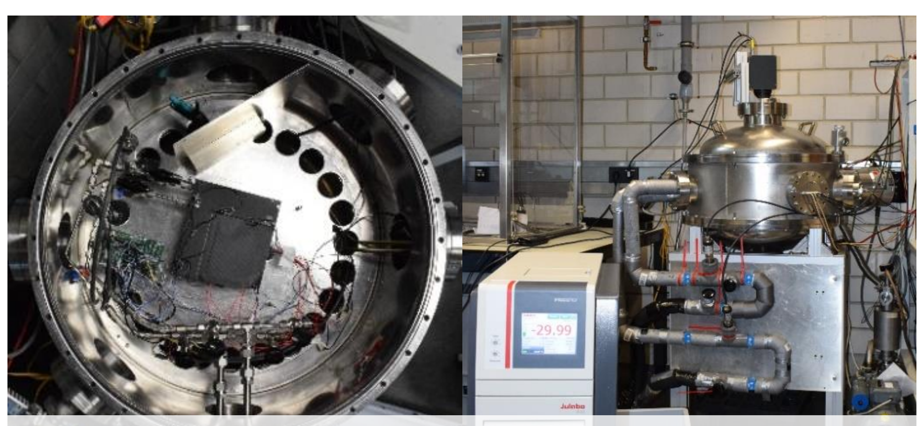


"Heavier" liquid cooling for FEE (milled channels)

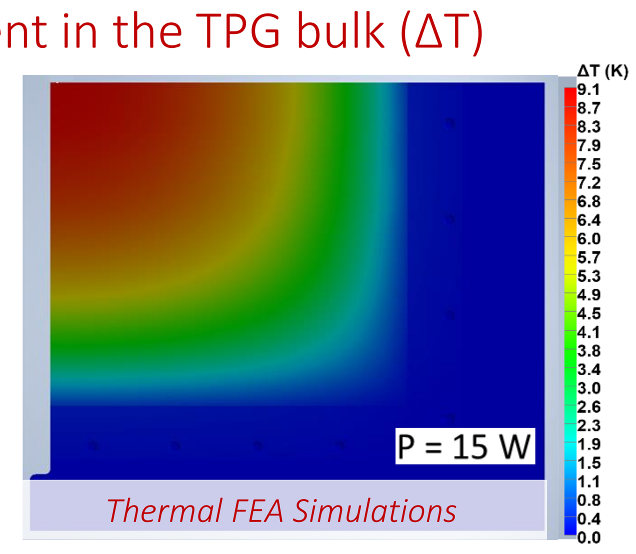
Experimental Validation with Realistic Demonstrators

Operational parameters and margins studied with thermal demonstrators under realistic conditions

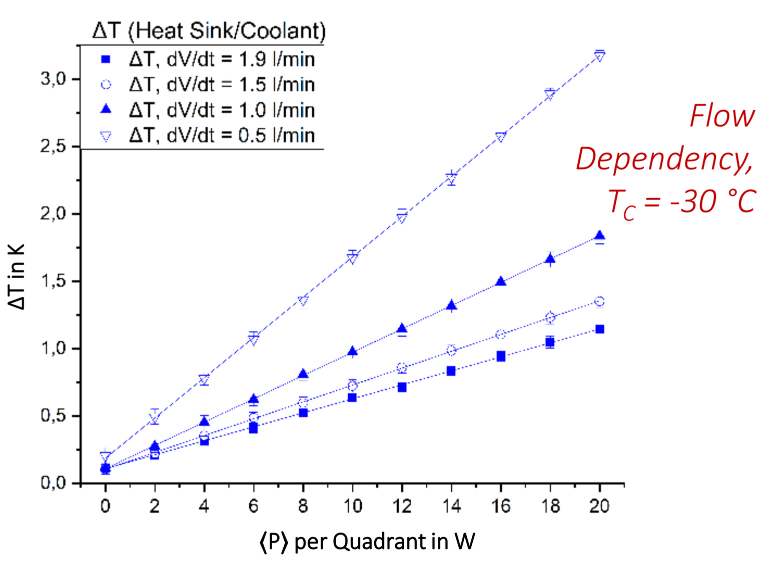
MVD Observable: Temperature gradient in the TPG bulk (ΔT)

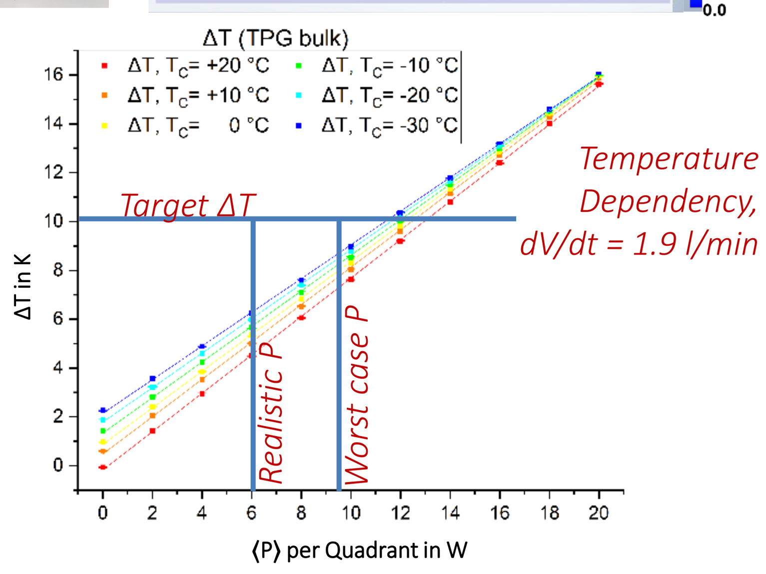


Experimental Setup (MVD Test Stand @ Uni. Frankfurt)



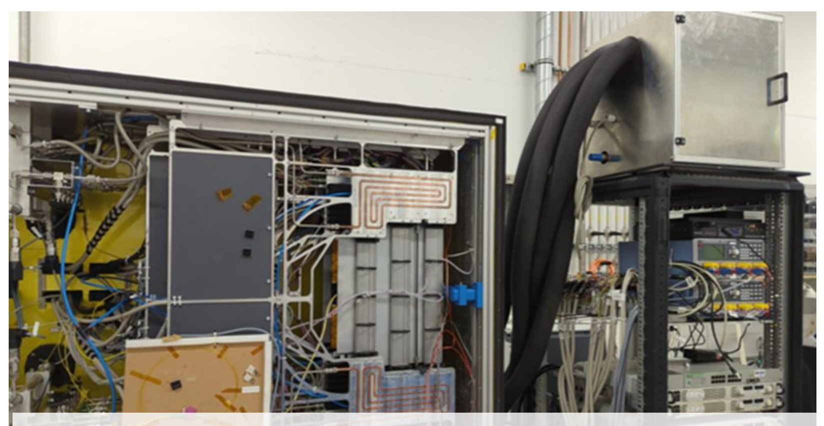
Thermal FEA Simulations



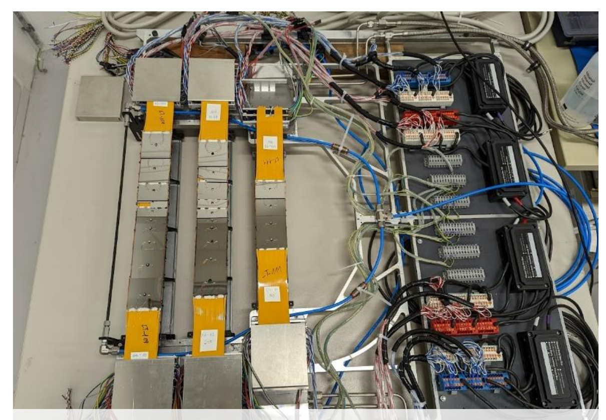


- Vacuum and cooling test stand for MVD quadrants
- Pre-series cooling element prototypes
- Exploration of operational parameters
- Substantial safety margins
- Agreement with quadrant-level thermal FEA simulations (ΔT in TPG bulk)
  - Simulations: ΔT = 5.0 K
  - Experiment at -30°C: ΔT = 6.7 K
  - Experiment at +20°C: ΔT = 4.9 K

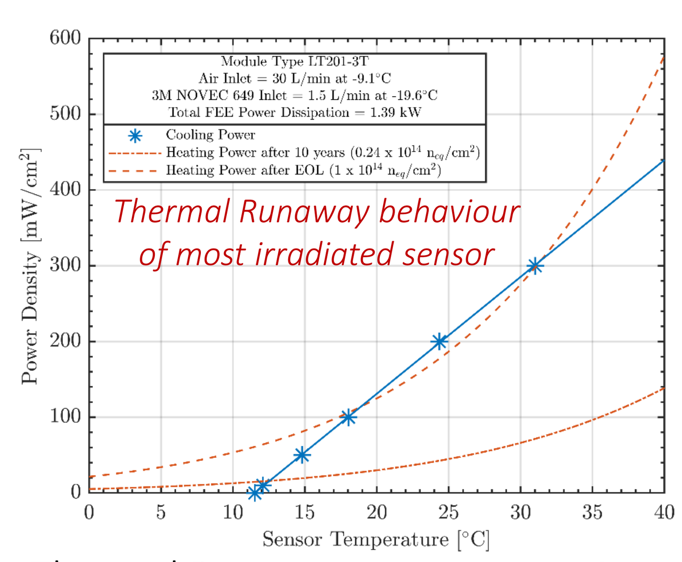
STS Observable: Thermal runaway behavior at EOL fluence

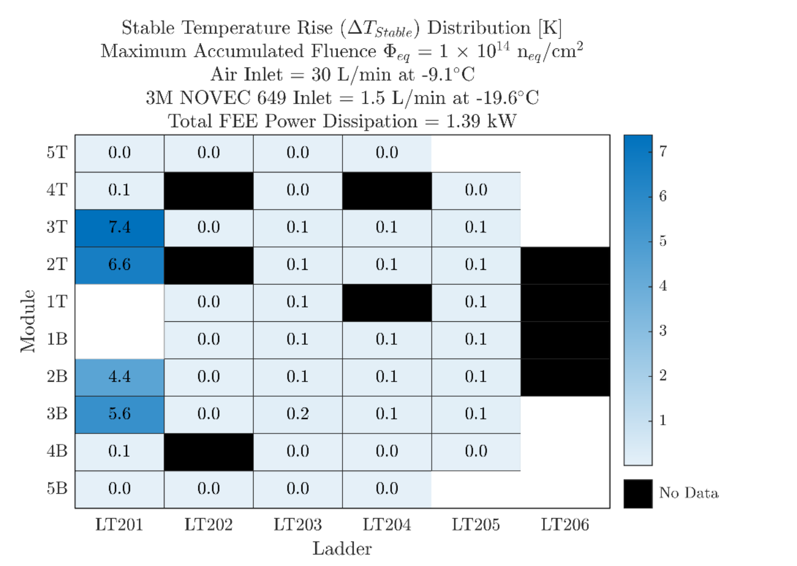


Experimental Setup (Thermal Demonstrator @ GSI)



Assembled C-frame





- Thermal Demonstrator to experimentally verify the sensor and FEE cooling concept
- Pre-series cooling element prototypes
- Exploration of operational parameters
- Substantial margins at EOL fluence
- Temperature hotspots ∝ fluence
  - Impinging Jets: ΔT < 7.5 K (only central ladders)
  - Natural Convection: ΔT ≈ 0 K (outer ladders)

Detector mechanics: Design finalized. First-of-series production: Starting soon. CBM global commissioning in 2028.

References

- CBM Collaboration, Eur. Phys. J. A 53 (2017) 3, 60
- Technical Design Report for the CBM Micro Vertex Detector (MVD) (2021)
- Technical Design Report for the CBM Silicon Tracking System (STS) (2013)
- F. Matejcek, 'Using Novec 649 as the coolant for the MVD' (Technical Note, 2022)
- F. Matejcek, 'Integration of the CBM MVD Pre-Series Module', (MSc Thesis, 2024)
- K. Agarwal, H. R. Schmidt et al., Engineering Design Review CBM-STS Cooling (2023)

This work was supported by HFHF, BMBF and GSI.