The Silicon Tracking System of the Compressed Baryonic Matter (CBM) Experiment at FAIR

Hans Rudolf Schmidt, for the CBM Collaboration

University of Tübingen
CBM (Compressed Baryonic Matter Experiment)

- Modularized Start Version (MSV) of FAIR currently under construction
- first beams (p, ..., U) expected 2024
- $E_{\text{beam}} = 11 - 29 \text{ AGeV}$
FAIR Construction Site

- areal view
FAIR Construction Site

- excavation of the SIS100 tunnel
excavation of the SIS100 tunnel (May 2018)
CBM Physics Mission

- Exploration of the QCD phase diagram at high $\mu_B$ and moderates temperatures
  - de-confinement and chiral transitions
  - equation-of-state relevant for neutron stars and neutron star mergers
    - utilizing rare probes: di-lepton, multi-strangeness
- Note: this is generally low-$p_t$ physics
- CBM sub-detectors must be capable to measure at rel. low momentum but at high interaction rates ($\sim 10 \, MHz$)
CBM Fixed Target Detector Setup

- Silicon Tracking System (STS)
- main tasks: momentum and secondary vertex determination
1 Tm superconducting dipole magnet
inside magnet: thermally insulating box

side walls removable for maintenance
8 stations of the silicon tracking system

≈ 1 m

heat exchanger plates (blue) for fast, triggerless front-end readout electronics
cut view inside of the STS

vacuum beam pipe

~ 900 silicon sensors on CF ladders box for mounting front-end ASICs
CF Ladder with Sensors

Sensor type: double-sided silicon-strip

- 285/320 ± 15 µm thick
  - Impact of thicker sensors (400 or 500 µm) under evaluation
- n-type silicon
- 1024 strips of 58 µm pitch on both sides
- Angle front/back: 7.5°/0°

Sensor sizes:
- 6.2 x 2.2 cm²
- 6.2 x 4.2 cm²
- 6.2 x 6.2 cm²
- 6.2 x 12.4 cm²

Steeply falling multiplicity density

Hit density (cm⁻²)
Challenges I: Material Budget

- best possible momentum resolution at low momenta
  ⇒ minimize multiple scattering \( \Theta_m = \frac{13.6 \text{MeV}}{\beta \cdot c \cdot p} \cdot \frac{X}{X_0} \) ⇔ minimize material budget

- basic functional unit is a module, consisting of:
  - FEB with r/o ASICs
  - **ultra-thin micro cables**
  - sensor

- geometry/multiplicity density dictates 18 different module types!
  - different sensor, different cable, different bandwidth of r/o
Challenges II: Signal/Noise

- Design goal: $\text{ENC}_{\text{total}} < 1000\text{e RMS}$
- $\text{ENC}_{\text{FEE}} < 500\text{e RMS}$ (complex, many contributions)

- Noise scales with total capacitance:
  - $C_T = C_{\text{det}} + C_{\text{cable}} + C_{\text{ESD}_{n/p}} + C_{\text{gs1}} + C_{\text{gd1}} + C_{\text{PCB}}$
  - Careful design of $\mu$-cables to minimize capacitance
Read-out Cables

- main design constraints: capacitance, bonding scheme, production yield
- signal layer: 64 lines - 116 µm pitch, 14 µm thick, on 10 µm polyimide
  - 32 cables/sensor
  - mesh layer between signal and ground layer to decrease capacitance
- alternative mounting schemes:
  - Aluminum-Polyimide technology, tab bonding (LTU Ltd, Kharkov, Ukraine)
  - Copper-Polyimide technology, stud bonding (KIT, Karlsruhe)
- Cable total capacitance
  \[C_{\text{cable}} = 0.382 \pm 0.020 \text{ pF/cm}\]

- Sensor interstrip capacitance
  \[C_{\text{interstrip}} = 0.38 \pm 0.2 \text{ pF/cm}\]

- Design goal: cable capacitance/cm² should not exceed interstrip value of sensor
- Cable length up to 55 cm!
material budget ranges from $X/X_0 = 0.3$ (sensor only) to $X/X_0 = 1 - 1.5\%$ (sensors + cables) resulting in:

- reconstruction efficiency (simulation): $\epsilon \approx 98\%$
- momentum resolution (simulation): $\frac{\delta p}{p} \approx 1.5 - 2\%$
Challenges III: Radiation Tolerance

- life time fluence: $\Phi_{eq} = 10^{14} n_{1\text{MeV}} cm^{-2}$
  - 5-10 month of running at 10 MHz
- corresponding full depletion voltage: $V_{FD} \approx 120 \text{ V}$
- to recover charge collection eff.: $V_{FD} > 350 \text{ V}$
- high current or breakdown essentially sets limit to the lifetime

Break-down voltage

Charge collection efficiency irradiated sensors

Type inversion with fluence

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Challenges IV: Cooling

- Effects in high radiation environment:

\[ I_{\text{leak}}(V, \Phi) = \alpha V \Phi \]

\[ I_{\text{leak}}(T) = I_{\text{leak,293}} \left( \frac{T}{293} K \right)^2 \exp \left( -\frac{E_{\text{gap}}(T)}{2k_B} \right) \left( \frac{1}{T} - \frac{1}{293K} \right) \]

- Leakage current increase with fluence \( V, \Phi \) and temperature \( T \)

\[ \Rightarrow \] sensor cooling mandatory to avoid thermal runaway

\[ \Rightarrow \] keep sensors permanently at \( T = -10^\circ C \)

Up tp 6 mW/cm\(^2\) at end of life time (\( \Phi_{eq} = 10^{14 \text{MeV} cm^{-2}} \))

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Cooling Requirements

- fast readout electronics produces 40 kW thermal power within insulation volume

- Efficient high power CO₂ cooling system under development to neutralize 40 kW thermal power from r/o electronics!
- but: innermost sensors produce up to 6 mW/cm² – cooling by forced N₂ convection??

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Cooling R&D

- optimization of:
  - heat exchanger (P=120 bar)
  - thermal interfaces
  - large scale cooling demonstrator

see poster by Kshitij Agarwal

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STS Functional Demonstrators

- module test at COSY, Feb. 2018
  - proton beam, 1.7 GeV/c
  - 128 channels /side read out
  - microcable 25 cm long
- design parameters verified
  - ENC = 1090 ±150 e (n)
  - ENC = 1350 ±200 e (p) (?)
  - signal-to-noise: 15±3

- miniSTS in demonstrator experiment miniCBM at GSI/SIS18 in 2018/19
  - up to 4 layers of silicon
  - full system test including streaming readout
Summary

- CBM STS design optimized wrt material budget and radiation tolerance
  - sensor R&D finished
  - sophisticated QA methods developed (see poster by E. Lavrik)
  - cooling R&D ongoing

- sensor production readiness review (April 2018)
  - ready for tendering
  - sensor purchasing & module production 2019-2020

- participating laboratories
  - GSI Darmstadt (QA, assembly, integration)
  - JINR Dubna (QA, assembly)
  - University of Tübingen (QA, cooling)
  - KIT Karlsruhe (cables, assembly)
  - AGH, Cracow (readout ASICs)
  - JU, Cracow (readout)
  - WUT, Warsaw (readout)
backup
Interaction Rates

- utilizing rare probes requires high luminosity (high interaction rates)
- $R_{int} = 10 \text{ MHz}$, several OoM higher than at colliders at comparable collision energies
- CBM sub-detectors must be capable to measure at rel. low momentum but at high rates
Mutual interest by CBM groups from Germany and Russia to install, commission and use 4 CBM-like Silicon Tracking Stations in BM@N in 2019 – 2021

Au beams up to 4.5 GeV/u