“Vacuum-Compatible, Ultra-Low Material Budget MVD for the CBM Experiment : Group Report”

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CBM-MVD related contributions

This talk

M. Koziel: “Vacuum-Compatible, Ultra-Low Material Budget MVD for the CBM Experiment.”
Monday 14:00  HK 7.1

• M. Deveaux: “On drift fields in CMOS Monolithic Active Pixel Sensors.”
  Monday 14:45  HK 7.3

• Erik Krebs: “Background rejection in dilepton analysis with CBM-MVD”
  Monday 17:45  HK 10.5

• D. Doering / M. Deveaux: “Ein Röntgenspektrometer auf der Basis von hochspannungstauglichen CMOS-Sensoren mit hochdotiertem Dopiniggradienten im aktiven Medium.”
  Tuesday 14:30  HK 21.2

• B. Linnik: “Status of the radiation hardness of CMOS Monolithic Active Pixels Sensors for the CBM experiment.”
  Tuesday 14:45  HK 21.3

• T. Bus: “Strahlenschäden in dotiertem Silizium aufgrund Neutroneneinfangs Bor als Erweiterung des NIEL-Modells.”
  Wednesday 18:30  HK 45.49

• P. Klaus: “Thin and Reliable Connectivity for the CBM-MVD”
  Thursday 18:00  HK 60.7
• The CBM-MVD: reminder

• Simulations
  – Tracking performance
  – Background rejection in dielectron analysis

• Sensor development

• PRESTO Project

• Summary
CBM-MVD:
- Improve secondary vertex resolution (open charm)
- Tracking of low-momentum particles
- Background rejection in di-electron measurements
- Hosts highly granular silicon pixel sensors featuring low material budget, fast read-out, excellent spatial resolution and robustness to radiation environment.

### Required performances (SIS-100)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation tolerance</td>
<td>$&gt; 10^{13} n_{eq}/cm^2$ &amp; $&gt;1$ Mrad</td>
</tr>
<tr>
<td>Read-out speed</td>
<td>$&gt; 30$ kframes/s</td>
</tr>
<tr>
<td>Intrinsic resolution</td>
<td>$5-10 \mu m$ - physics case driven</td>
</tr>
<tr>
<td>Operation in vacuum &amp; magnetic field</td>
<td></td>
</tr>
<tr>
<td>Support &amp; cooling</td>
<td>Material budget $\sim 0.3 % x/X_0$ Double-sided sensor integration</td>
</tr>
</tbody>
</table>

STS MVD SIS100 setup
The CBM Micro Vertex Detector: Reminder p.2

<table>
<thead>
<tr>
<th>Station</th>
<th>Radius [mm]</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Distance from target [mm]</td>
<td>Inner</td>
</tr>
<tr>
<td>0</td>
<td>50</td>
<td>5.5</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>8.3</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>11</td>
</tr>
</tbody>
</table>

Minimum geometrical acceptance shown
CBM-MVD: integration challenge

4 stations populated with sensors
- Sensor development
- Sensor commissioning

Sensor support (CVD-Diamond & TPG)

Readout & services
- R/O electronics
- Flex Print Cables (FPC)

INTEGRATION
- Jigs
- Dispensing tools
- Procedure

MVD mechanics
- Quality assessment
- Metrology
- Alignment

Geometrical acceptance:
- station 0
- station 1
- 10:1
- 1:1
- 16
- 3
- 6
- sensor
- flex cable
- glue

QUADRANTS

VACUUM APPROVED
Erik Krebs:  “Background rejection in dilepton analysis with CBM-MVD”
Monday  17:45   HK 10.5
MC simulations => MVD+STS tracking capability

Monte Carlo simulations

Setup = 4 MVD + 8 STS stations

Primary tracks considered

Studied:
- Impact parameter resolution
- Momentum resolution
- Tracking efficiency
- For particles with momentum smaller than 0.5 GeV/c

Conclusion: MVD improves the CBM tracking capability due to added value, that is spatial resolution and geometrical acceptance.
The light vector mesons $\rho$, $\omega$ and $\phi$ are considered as excellent probes of the strongly interacting matter under extreme conditions... but rare -> efficient background rejection.

Single electron or positron tracks from incompletely detected $\gamma$-conversions and Dalitz decays of $\pi^0$-mesons are the most abundant source contributing to the combinatorial background.
Background rejection with MVD

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Single electron or positron tracks from incompletely detected $\gamma$-conversions and Dalitz decays of $\pi^0$-mesons are the most abundant source contributing to the combinatorial background.

Tracking of low momentum tracks, helps to suppress background (mainly from conversion) as being e.g. well established by HADES collaboration.
• M. Deveaux: “On drift fields in CMOS Monolithic Active Pixel Sensors.”
  Monday  14:45   HK 7.3

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  Erweiterung des NIEL-Modells.”
  Wednesday  18:30   HK 45.49
Advantages of CMOS sensors:

- **granularity**: pixels of 10×10 µm, high spatial resolution
- **10-20 µm thick sensing volume**: low material budget (typically 50 µm Si)
- **in-chip signal processing**: compact sensors with on-board intelligence, e.g. data sparsification
- **in addition**: cost, multi-project run frequency, room temperature operation, potentially HR EPI
# CBM-MVD sensor specification

## Parameter Table

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>~ 5 µm</td>
</tr>
<tr>
<td>Maximum power dissipation (full occupancy) [mW/cm²]</td>
<td>&lt; 200</td>
</tr>
<tr>
<td>- Reduced rate, Station 2-3</td>
<td>&lt; 350</td>
</tr>
<tr>
<td>- Full rate, Station 0-1</td>
<td></td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>~30 x 30 µm²</td>
</tr>
<tr>
<td>Operation temperature [°C]</td>
<td>-40 to +30</td>
</tr>
<tr>
<td>Operation temperature gradient on sensor [K/cm]</td>
<td>5</td>
</tr>
<tr>
<td>Radiation doses [n_{eq}/cm²]</td>
<td></td>
</tr>
<tr>
<td>@ -20°C</td>
<td>3 x 10^{13}</td>
</tr>
<tr>
<td>@ +30°C</td>
<td>1 x 10^{13}</td>
</tr>
<tr>
<td>Radiation doses [Mrad]</td>
<td></td>
</tr>
<tr>
<td>@ -20°C</td>
<td>3 Mrad</td>
</tr>
<tr>
<td>@ +30°C</td>
<td>1 Mrad</td>
</tr>
<tr>
<td>Radiation doses [HI/cm²]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10^{10} ?</td>
</tr>
<tr>
<td></td>
<td>High uncertainty</td>
</tr>
<tr>
<td>Radiation dose (gradient)</td>
<td>100%</td>
</tr>
<tr>
<td>Readout time (µs)</td>
<td>~10</td>
</tr>
<tr>
<td>Average hit rate (1/mm²/s)</td>
<td>1.5 x 10^5</td>
</tr>
<tr>
<td>Peak hit rate (1/mm²/s)</td>
<td>7 x 10^6</td>
</tr>
<tr>
<td>Maximum Data rate (Gbps/cm²)</td>
<td>~1.6</td>
</tr>
<tr>
<td>Minimum Data rate (Gbps/cm²)</td>
<td>0.16</td>
</tr>
<tr>
<td>Encoding</td>
<td>24bit/hit</td>
</tr>
</tbody>
</table>

## Additional Parameters

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>&gt; 99%</td>
</tr>
<tr>
<td>- New</td>
<td>~99%</td>
</tr>
<tr>
<td>- End of lifetime</td>
<td></td>
</tr>
<tr>
<td>Fake hit rate</td>
<td></td>
</tr>
<tr>
<td>- New</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>- End of lifetime</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Data interface</td>
<td>320 Mbps</td>
</tr>
<tr>
<td>Minimum number of data lines/sensor</td>
<td></td>
</tr>
<tr>
<td>I/O Standard</td>
<td>GBT-comp.</td>
</tr>
<tr>
<td>Bonding technology</td>
<td>Wedge</td>
</tr>
<tr>
<td>Bias voltage mismatch tolerance</td>
<td>0.3V</td>
</tr>
<tr>
<td>Variation in currents</td>
<td>5%</td>
</tr>
<tr>
<td>Slow control</td>
<td></td>
</tr>
<tr>
<td>Clock down</td>
<td>Factor 2 (Uncertain)</td>
</tr>
<tr>
<td>Sensor surface (sensitive)</td>
<td>3 x 1 cm²</td>
</tr>
<tr>
<td>Sensor surface (insensitive)</td>
<td>3 x 0.3 cm²</td>
</tr>
<tr>
<td>Thickness</td>
<td>50 µm</td>
</tr>
<tr>
<td>ESD - Protection</td>
<td></td>
</tr>
<tr>
<td>Pads for probe testing</td>
<td></td>
</tr>
<tr>
<td>Unique ID for sensors</td>
<td></td>
</tr>
<tr>
<td>Alignment markers</td>
<td></td>
</tr>
<tr>
<td>Temperature markers</td>
<td></td>
</tr>
</tbody>
</table>
How to improve radiation tolerance of CPS

How to improve the non-ionizing hardness:

Aim for a larger depletion zone !!!
• Diffusion -> drift in electric field
  • Doping profile
  • Higher depletion voltage

Calls for CMOS processes providing a High Resistivity epitaxial layer.

The way to improve ionizing hardness:

Investigate processes with small feature size, 0.18 µm and below.
Aim: investigate the radiation hardness of the JAZZ-TOWER 0.18 µm CMOS process

Key point: a high-resistivity (> 1kΩ*cm) EPI (HR-EPI) layers with different doping profiles

Outcome: top radiation tolerance for HR-EPI featuring gradient doping profile (publication during write-up)
Towards fully-depleted CMOS pixel sensors: PEGASUS sensor

**Aim:** Design, manufacture and study the sensor with pixels powered from higher (~12.5 V) than standard (0.6-2.8 V) bias voltage.

**Outcome:** High bias voltage increases the size of the depleted volume to almost (?) full epitaxial layer thickness.

D. Doering et al., “CMOS-sensors for energy-resolved X-ray imaging”

http://dx.doi.org/10.1088/1748-0221/11/01/C01013
Why we do not deplete CMOS Pixel Sensors?

Theory

\[ d = \sqrt{\frac{2\varepsilon \varepsilon_0}{e} + \left(\frac{1}{N_A} + \frac{1}{N_D}\right)(U_{bi} - U)} \sim \sqrt{U_{depl}} \]

\[ \begin{align*}
N_A &= 10^{18} / \text{cm}^3 \\
N_D &= 10^{12} / \text{cm}^3 \\
U_{depl} &= -0.6 \text{ V}
\end{align*} \]

\[ d = 30 \mu\text{m} \]

...but full CMOS HR-EPI depletion at 0.6 V never observed...
Why we do not deplete CMOS Pixel Sensors?

**Theory**

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...but full CMOS HR-EPI depletion at 0.6 V never observed...

**Reality**

Geometry of a real pixel does not fit

\[ d_{CMOS} \approx \sqrt[6]{U_{depl}} \]

M. Deveau: “On drift fields in CMOS Monolithic Active Pixel Sensors.”

Monday 14:45 HK 7.3
According to NIEL (non-ionizing energy loss) scaling, any particle fluence can be reduced to an equivalent 1 MeV neutron fluence producing the same bulk damage in a specific semiconductor. The scaling is based on the hypothesis that generation of bulk damage is due to non-ionizing energy transfers to the lattice.

\[ ^{10}\text{B} + \text{n} \rightarrow \text{Li} + \alpha + 3\text{MeV} \]

Radiation from this process to be considered

No problem if P-doping $<< 10^{15}\text{cm}^3$
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On the NIEL scaling for low-energy neutrons

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Factor of \(~500\) !!!

Compatible with P-doping of \(10^{18}/\text{cm}^3\)

T. Bus: “Strahlenschäden in dotiertem Silizium aufgrund Neutroneneinfangs Bor als Erweiterung des NIEL-Modells.”

Wednesday 18:30  HK 45.49
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T. Bus: “Strahlenschäden in dotiertem Silizium aufgrund Neutroneneinfangs Bor als Erweiterung des NIEL-Modells.”

Wednesday 18:30  HK 45.49
P. Klaus, M. Wiebusch et al., “Prototyping the read-out chain of the CBM Micro Vertex Detector”
Accepted for publication

M. Koziel et al., “Vacuum-Compatible, Ultra-Low Material Budget Micro Vertex Detector of the Compressed Baryonic Matter Experiment at FAIR”
In preparation

P. Klaus: “Thin and Reliable Connectivity for the CBM-MVD”
Thursday 18:00  HK 60.7
**PRESTO: PREcursor of the Second sTatiOn**

**WHAT'S THAT?**

15 MIMOSA-26 sensors integrated on both sides of a $8 \times 8 \text{ cm}^2$ 350 µm thin TPG carrier

- 9 on the front in a $3 \times 3$ arrangement
- 6 sensors on the back in a $2 \times 3$ arrangement
- Support size of MVD station #1
- Complexity ~ of MVD station #2
- Sensors are connected with the DAQ system employing new flex cables (10 FPCs / PRESTO)

**MOTIVATION:**

2\textsuperscript{nd} phase of prototyping (1\textsuperscript{st} step, station “0” oriented) aiming for 2-sided, vacuum compatible, quadrant integration.

**Geometrical acceptance:**

- station 0
- station 1
- 10:1
- 1:1
- 16
- 3
- 13
- 6
PRESTO: construction

Measured edge-to-edge distance [µm]

- # entries
- 0-4
- 5-9
- 10-14
- 15-19
- 20-24
- 25-29
- >29
PRESTO: vacuum compatibility

No change in sensor performance after several pressure cycles
(atmospheric – 10^{-4} mbar)
Accomplished MVD-related PhDs: 2015

Dennis Doering

“Untersuchungen zur Verbesserung der Strahlenhärte von CMOS-Sensoren zum Einsatz in Vertexdetektoren von Schwerionenexperimenten.”

Tobias Tischler

“Mechanical Integration of the Micro Vertex Detector for the CBM experiment.”

Borislav Milanovic

“Development of the Readout Controller for the CBM Micro Vertex Detector.”
SUMMARY:

• Wide range of activities towards the CBM-MVD

• PRESTO project
  • proves that one can built a vacuum compatible device based on a bare TPG carrier and employing ultra-thin, but industrial flex cable.
  • Construction of the second side is ongoing (last R&D step before MVD production)

• MVD: flexibility to adopt to physics case

• Sensors implemented in Jazz-Tower CMOS process seems to meet radiation tolerance requirements

• Technical specification of the MVD sensor in advance stage, synergy with other experiments, mainly STAR (running!) and ALICE upgrade