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# Status of the Micro Vertex Detector of the Compressed Baryonic Matter Experiment

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The CBM experiment will investigate heavy-ion collisions at beam energies from 8 to 45 AGeV at the future accelerator facility FAIR. The goal of the experiment is to study the QCD phase diagram in the vincinity of the QCD critical point. To do so, CBM aims at measuring rare probes among them open charm. In order to identify those rare and short lived particles despite the rich combinatorial background generated in heavy ion collisions, a micro vertex detector (MVD) providing an unprecedented combination of high rate capability and radiation hardness, very light material budget and excellent granularity is required. In this work, we will discuss the concept of this detector and summarize the status of the R&D.

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# 1. Introduction

## 1.1 CBM, a FAIR experiment

The Compressed Baryonic Matter (CBM)-experiment [1] will be a next generation fixed target detector to be operated at the FAIR heavy-ion synchrotrons SIS-100 and SIS-300 [2]. It will receive fully stripped ion beams with intensities of up to $2 \cdot 10^9/\mathrm{s}$ at beam energies from 8 to 35 AGeV (45 AGev for ions with Z/A = 0.5). Complementary to the low energy programs of RHIC and SPS, CBM aims to probe various collision systems (p+p, p+A, A+A) with very rare probes like strange, multi-strange (K, $\phi$,$\Lambda$, $\Xi$, $\Omega$) and open charm hadrons (D, $D_S$,$\Lambda_C$). Moreover, short lived vector mesons and charmonium states will be investigated via their di-leptonic decay into $e^+/e^-$ and $\mu^+/\mu^-$-pairs. The measurements on charmonium states together with open charm measurements will allow a comprehensive study of charm production near the production threshold.

The envisaged measurements of rare probes calls for an unique instrument providing simultaneously an outstanding rate capability and precision. The need to combine both was the guide line of our global design, which is discussed in [3]. This work will focus on the measurement of open charm particles and the related detector system, the Micro Vertex Detector (MVD) [4] of CBM. To do so, in section 1.2 and 2, we will introduce the global geometry and the requirements of the the MVD. Hereafter, in section 3 and we will report a status of the R&D on sensor development and sensor integration in section 2 and 4, which were carried out in the context of the MVD-demonstrator project. Finally, in section 5 we will give an outlook on our plans to build an MVD-prototype.

## 1.2 The CBM Micro Vertex Detector (MVD)

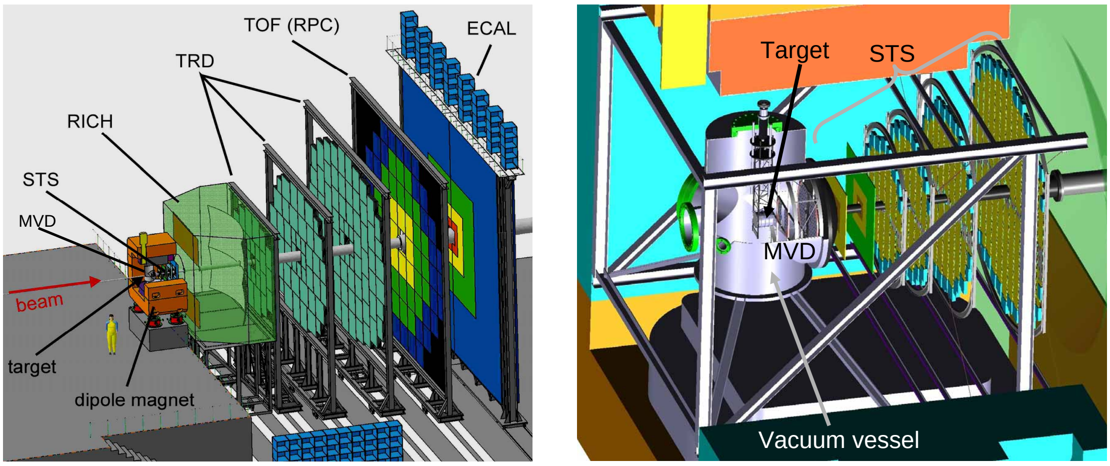

**Figure 1:**
*Artistic view of the di-electron setup of CBM (left, see text) and a zoom into the MVD and STS (right).*

The CBM experiment is currently planned with two configurations among which one is optimized for di-electron spectroscopy and one for di-muon spectroscopy. Open charm measurements will presumably rely on the CBM di-electron setup shown in Figure 1 (left). This setup is formed by a Micro Vertex Detector (MVD) and a Silicon Tracking System (STS), which operate in a 1 Tm

| | Phase 1/2 | Phase 3 | MAPS 2009$^{(1)}$ | Mimosa-26 | MAPS 2015 | MAPS 2018 |
|---|---|---|---|---|---|---|
| Spat. resol. [ $\mu$m] | $\lesssim 5\ \mu$m | $\lesssim 5\ \mu$m | $1^{(2)} - 5^{(3)}\ \mu$m | $5\ \mu$m $^{(3)}$ | $5\ \mu$m $^{(3)}$ | $5\ \mu$m $^{(3)}$ |
| Mat. budget [$X_0$] | $\sim 0.3\%^{(4)}$ | $\sim 0.3\%^{(4)}$ | $0.05\%$ $^{(5)}$ | $0.05\%$ $^{(5)}$ | $0.035\%$ $^{(5)}$ | $\sim 0.05\%$ $^{(5)}$ |
| Rad. tol. [$n_{eq}/cm^2$] | few $10^{13}$ | $\sim 10^{14}$ | $> 3 \cdot 10^{13}$ | few $10^{12}$ | $3 \cdot 10^{13}$ | $10^{14}$ |
| Time resolution | few 10 $\mu$s | few $\mu$s | 25 $\mu$s | 110 $\mu$s | $\sim 30\ \mu$s $^{(6)}$ | few $\mu$s |

**Table 1:** Requirements on the sensors for open charm physics at SIS-100 (+ SIS-300 top energy) and SIS-300 (close to kinematical threshold). Present (2009) and predicted performances of MAPS.
**Remarks:** $^{(1)}$: Obtained with different specialized sensors. $^{(2)}$: Analog readout. $^{(3)}$: Digital readout. $^{(4)}$: Full station. $^{(5)}$: Sensors only.

magnetic field. Electron identification is provided by a RICH at lower particle energies and by a set of Transitions Radiation Detectors (TDR) at higher energies. A Time-Of-Flight (TOF) system is to identify low and medium momentum hadrons. The setup is completed by an electro-magnetic calorimeter, which allows the measurement of direct photons, and by a forward hadronic calorimeter (not shown), which measures the energy of spectators of the nuclear collision.

Figure 1 (right) shows a zoom into the region of MVD and STS. Both systems are segmented planar detectors with an acceptance angle ranging from $\vartheta = 2.5^\circ$ to $\vartheta = 25^\circ$ with respect to the beam axis. The MVD will operate in the moderate vacuum of the target chamber. A vacuum window located between detector and target would cause an intolerable amount of multiple scattering and thus degenerate the secondary vertex resolution of the experiment.

## 2. Requirements on the CBM-MVD

Currently we consider three major phases of open charm measurements at CBM. The first phase will be carried out with SIS-100, which will deliver protons of 30 AGeV and heavy ions of 12 AGeV. At this ion energy, open charm is produced in sub-threshold processes. Due to the very poor production rates, detecting the particles is most likely out of reach of a first generation MVD. Open charm studies will therefore focus on the higher energies obtained in $p+p$ and $p+A$ collisions. The detector performances needed for those measurements will presumably be relaxed with respect to the one of the second phase, which will consist in measuring 35 AGeV $Au+Au$ collisions systems at SIS-300. A further detector upgrade will allow for performing the particularly challenging measurements close to the open charm production threshold.

The requirements on the CBM-MVD for the different phases have been motivated in [4] and some key parameters are listed in table 1. The detector will have to provide a secondary vertex resolution of $\sigma_z \lesssim 70\ \mu$m, which requires a spatial resolution of $\lesssim 5\ \mu$m and a material budget of $\sim 0.3\%\ X_0$ for the first station. Given the ambitioned collision rate of $10^5 - 10^6\ s^{-1}$, the expected average hit rate of up to $\sim 3.5$ hits$/mm^2/$collision will induce harsh constraints on the radiation hardness and the time resolution of the sensors. Moreover, the need for vacuum operation calls for an ultra light, active cooling system to evacuate the $\gtrsim 1\ W/cm^2$ dissipated by the sensors.

## 3. Sensor design

Currently the highly granular CMOS Monolithic Active Pixel Sensors (MAPS) [5, 6] form our guide line sensor technology for the MVD. They are believed to provide the best technological

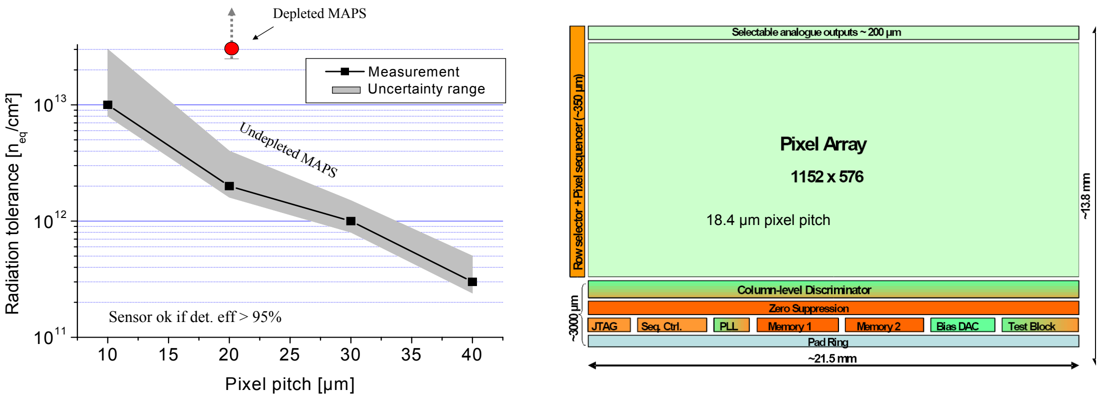

**Figure 2:** *Radiation tolerance against non-ionizing doses (left). Block diagram of MIMOSA-26 (right).*

compromise between the necessary accuracy and light material budget on one hand and the required rate capability and radiation hardness on the other hand. The technology allows for building pixels with a typical size of $\sim 20 \times 20\ \mu\text{m}^2$ and a excellent spatial resolution of $\lesssim 2\ \mu$m ($\sim 5\ \ \mu$m with digital readout). Moreover, MAPS were thinned down to a material budget of 0.05% $X_0$ without performance loss. However, their radiation tolerance and time resolution are still to be improved substantially before matching the requirements of CBM, e.g. regarding the beam intensity.

In the field of radiation tolerance, our major task was to compensate for the radiation induced shortening of the lifetime of free signal electrons in silicon. As MAPS collect those electrons slowly by means of thermal diffusion, this fundamental effect causes a crucial loss of signal charge already in sensors irradiated with few $10^{12}\ n_{eq}/\text{cm}^2$. To recover this drop, we aimed to accelerate the charge collection process by reducing the pixel pitch and by applying an electric drift field to the sensor. While reducing the pixel pitch was up to some point easy to exploit, the latter strategy seemed initially excluded due to the high doping of commercial CMOS-wafers. This doping limits the break through voltage of the collection diodes to some volts, which is insufficient for depleting a sizable fraction of the sensor volume. The approach became only feasible with the arising of novel industrial CMOS-processes with high resistivity epitaxial layers. This option is for example available in the the XFAB 0.6 $\mu$m PIN process, which was used for manufacturing a first, partially depleted test sensor (MIMOSA-25). This sensor was irradiated with up to $3 \times 10^{13}\ n_{eq}/\text{cm}^2$ fission neutrons at the MEDAPP facility of the FRM-II reactor and tested at the the CERN-SPS. It survived this radiation dose, which is beyond the minimum requirements on the CBM-MVD, with encouraging reserves in terms of S/N [7]. Over all, a progress of more than one order of magnitude in terms of radiation hardness with respect to elder designs (see figure 2, left) was reached.

Improvements in terms of readout speed and time resolution of MAPS were reached by implementing a column parallel readout of the sensor. This concept was for a first time realized in the prototype MIMOSA-26 [8], which implemented 1152 columns of each 576 pixels. As shown in a block diagram in figure 2 (right), each of the columns is read out via its own discriminator block located on the same chip aside the sensor matrix. The discriminated data stream is zero suppressed with a dedicated digital logic, which may accept up to 9 hits per line and streams out the compressed data via two serial digital links with 80 Mbps each. Despite the readout time of the sensor (110 $\mu$s) is not yet suited for CBM, it is likely that the concept can be scaled to $\sim 30\ \mu$s by reading

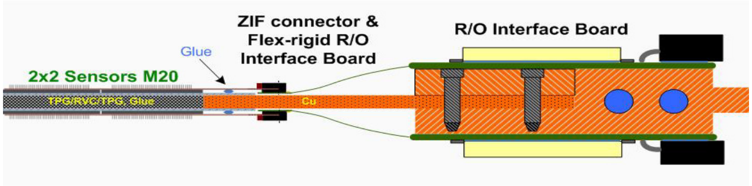

**Figure 3:** *Schematic cross-section of the MVD-demonstrator*

out the columns from both sides and by optimizing the analogue electronics for speed. The latter performance would be sufficient to match the requirements on the CBM phase 1/2.

## 4. System integration

The global design concept of the MVD has been discussed in detail in [4]. It is driven by the fixed target geometry of CBM, which allows for moving structures with sizable material budget outside the detector acceptance. Each sensor station will host two pixel layers; the signal processing circuits of MAPS located in the first layer are covered by the sensors of MAPS located in the second layer. As shown in figure 3, the chips will be glued on a highly heat conductive mechanical support, which is to drive their dissipated power ($\sim 1\ \mathrm{W/cm^2}$) toward a heat sink outside the MVD acceptance. This heat sink will also host some FEE-boards, which provide a stabilized low voltage and buffer the signals of the sensors.

A feasibility study for the above mentioned concept has been performed within the MVD-demonstrator project [9]. The project did not yet aim to reach the ultimate performances needed for CBM in terms of material budget and readout speed but focused on evaluating the necessary specialized materials and identifying potential weak points in our concept. To do so, a first vacuum compatible detector ladder was build and tested. This ladder integrated four real size MIMOSA-20 sensors[1]. Those sensors were provided by IPHC Strasbourg and glued on a sandwich formed from the highly heat conductive TPG[2] and the ultra light RVC[3]. The serial analog readout was done via two three layers flex print cables.

Tests of the cooling concept of this ladder, which were carried out by simulation (with Siemens: NX-IDEAS) and laboratory tests, confirmed excellent thermal management. Remarkably, the weakest point was formed by the limited heat contact between the ladder and our heat sink on one hand and the heat sink and the cooling fluid on the other hand. This points to the need of an advanced concept for this component, which will in future have to handle substantially more power while space constraints in the MVD call for a more compact design. Moreover, we noticed that TPG and RVC are, despite their good thermal and vacuum properties, not fully suited for an application in the CBM-MVD. This is because the mechanical softness of the graphite materials, which eases the generation of unwanted carbon grains and complicates the thinning of TPG below 150 $\mu$m. On the other hand, flex print cables equipped with 50 $\mu$m thick sensors were encouragingly easy to handle. Using them allows for reducing the material budget of our setup to about 1% $X_0$. In a beam test carried out at the CERN-SPS, we measured a spatial resolution of 5.6 $\mu m$. This matches the specification of CBM despite the ultimate resolution expected for a MAPS with

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[1] 204k pixels with $30 \times 30\ \mu\mathrm{m}^2$ ($\sim 2\ \mathrm{cm}^2$ surface). Serial analog readout within $\sim 2$ ms, slow control with JTAG.

[2] Thermal Pyrolitic Graphite, $\lambda = 1500\ \mathrm{W/mK}$

[3] Reticulated Vitreous Carbon

30 $\mu$m pixel pitch was not reached. The latter is assumed to be due to a known noise issue of MIMOSA-20, which was caused by a (meanwhile fixed) processing problem within the industrial sensor production.

## 5. Next steps: The prototype project

After completing the demonstrator project, we are designing a "MVD-prototype", which should reach a close to detector performance. The project aims at improving our concept in particular in terms of scalability, low material budget and fast sensor readout. To do so, we foresee to design a DAQ-system, which will be compatible with the novel fast MIMOSA-26 sensor and can be scaled to the amount of chips needed for a full MVD. Moreover, the setup will be adapted to the geometry of the MVD detector stations and further reduced in material budget. As the latter is currently dominated by the flex print cables, we explore together with our partners from IPHC and IMEC (Leuven, Belgium) the option to embed thinned MIMOSA-sensors into an ultra thin polyamide film, which host at the same time ultra thin printed metal lines. We hope to reach a material budget of $0.06\% - 0.15\%$ $X_0$ for the full system including sensors depending on the length of the ladder. Given the small detector surface, the ladders could be hosted by a cooling support made of CVD-diamond, which would conceptually allow for reaching a material budget of $0.3\%$ $X_0$ for the first and $0.5\%$ $X_0$ for the last detector station.

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