8. Summary and conclusion

The work presented in this thesis addresses a key issue of the CBM experiment at FAIR, which aims to study charm production in heavy ion collisions at energies ranging from 10 to 40 AGeV. For the first time in this kinematical range, open charm mesons will be used as a probe of the nuclear fireball. Despite of their short decay length, which is typically in the order of few 100 µm in the laboratory frame, those mesons will be identified by reconstructing their decay vertex.

The most essential sub-detector for efficient open charm reconstruction is a high resolution micro vertex detector (MVD) installed in the vicinity of the experimental target. Achieving the required spatial resolution conflicts with the necessity to cope with the high particle flux and radiation level inherent to the proximity of the target. Since usual pixel technologies do not provide a satisfactory trade-off between these antagonistic requirements, the adequacy of CMOS Monolithic Active Pixel Sensors (MAPS) was investigated. The objective of the thesis was to demonstrate that these devices could allow to collect, identify and analyze at least 10,000 $D^0$-mesons produced in heavy ion collisions. Such a large sample is expected to allow shedding light on fundamental phenomena such as the appearance of Quark-Gluon Plasma (QGP) and as chiral symmetry restoration.

Demonstrating the necessary sensitivity of a MAPS based MVD required performing R&D to clear up and approach the ultimate performances of the novel MAPS technology. Extensive simulation and design studies were done to refine and improve the design of the MVD. Finally, a high statistics simulation was used to show that the combination of improved MVD and pixel design allows for reconstructing a sufficient amount of $D^0$-mesons.

The R&D discussed in the thesis focused on the radiation tolerance of MAPS, which was still poorly known a few years ago. A $^{55}$Fe-source and minimum ionizing particle beams were used to study the performances of MAPS being irradiated either with neutrons or X-rays. This allowed clarifying, how ionizing and non-ionizing radiation damage manifest themselves in this specific technology. As expected, ionizing radiation dominantly causes an increase of the leakage current of the pixels, which translates into increased shot noise. Non-ionizing radiation generates modest increases in terms of leakage currents but can reduce substantially the lifetime of the signal electrons in the pixel. The latter was found to cause a dramatic drop of the signal if the lifetime of the electrons shrinks below the time required for charge collection.

The performances of irradiated detectors were studied as a function of the operation conditions, i.e. in terms of temperature and integration time of the pixel. It was demonstrated that running the detectors at low temperature ($\lesssim -20^\circ$C) and with short integration time efficiently reduces their leakage currents and noise. This may restore the initial performances of detectors being irradiated with ionizing radiation. For chips being exposed to non-ionizing doses, both measures are helpful to dim the effects of leakage current. However, they have no significant impact on the lifetime of the signal electrons.

The understanding achieved allowed proposing several generations of MAPS pixels with improved radiation hardness. The latter was reached by removing the radiation soft, thick $SiO_2$ in the vicinity of the sensing diode and by putting guard rings around the diode. The modified structure exhibited much better performances after irradiation than previous designs. Moreover, the radiation tolerance against non-ionizing doses was found to improve by almost one order of
magnitude when reducing the pixel pitch by a factor of two, thereby shortening the charge collection time. The modifications allowed to maintain satisfactory detection performances after an exposure to ionizing radiation of \( \sim 1 \text{ MRad} \) or to a fluence of \( \sim 2 \times 10^{12} \text{ n}_{\text{eq}}/\text{cm}^2 \).

Further progress in terms of radiation tolerance might be reached by further reducing the charge collection time of the pixels. This can be done by using a smaller (< 20 \( \mu \text{m} \)) pixel pitch, a graded epitaxial layer or a collection diode based on deep N-well implantations. Moreover, the drop in the lifetime of signal electrons might be alleviated by operating the detector at cryogenic temperatures. Finally, it remains to be clarified if thermal annealing of the chips might have a beneficial effect. A radiation tolerance of MAPS in the order of \( \sim 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2 \) is considered as a realistic estimate for the ultimate performances of this technology.

The feasibility of a massive parallel readout of MAPS, which will presumably allow for a time resolution of \( \sim 10 \ \mu\text{s} \), has been demonstrated in parallel to this work. Though not belonging to the research program presented here, the main outcomes of the development of fast sensors were presented and embedded into the general detector concept.

Despite of the progress achieved, the technological studies showed that MAPS will presumably not reach the time resolution and radiation tolerance required for operating them at the high nominal collision rate of CBM, which may reach \( 10^7 \) collisions per second. This is because the radiation doses caused by this collision rate would shrink the lifetime of the detector to a few days. Moreover, given the time resolution of the chips, pile-up would become a major concern (up to 100 collisions per frame are expected).

It was however demonstrated that a balanced configuration exists where, for lower beam interaction rate, enough \( D^0 \)-mesons can be collected and analyzed to investigate their production properties with a satisfactory sensitivity. To do so, a preliminary concept for integrating individual MAPS chips into a vertex detector station was developed. The concept accounted for the major technological constraints derived from the detector R&D and for the need to operate the vertex detector in vacuum. The latter seems necessary to eliminate the material, which would otherwise be introduced by the beam pipe.

The integration of MAPS into a detector is mainly constrained by the need for good radiation tolerance, which calls for operating the sensors at temperatures of \( \lesssim -20 ^\circ\text{C} \). An efficient and vacuum compatible cooling system is thus needed. Moreover it was shown, that \( \lesssim 50\% \) of the surface of MAPS featuring \( \sim 10 \ \mu\text{s} \) time resolution will host data processing circuits. This surface is not sensitive and has thus to be covered with the active surface of a neighboring chip.

In order to account for all requirements, it was proposed to stagger two layers of silicon, which are installed on the opposite sides of a layer formed by micro tubes. The latter provides the necessary mechanical stability and evacuates the heat produced by the sensors by means of liquid cooling. Though the design is considered as preliminary, it provides guidelines for further studies and allows for a first estimate of the material budget of a MVD-station. This estimate suggests that this budget might be as low as a few per-mille of radiation length.

Systematic studies were undertaken to design a well performing MVD made of a few individual detector stations. The geometry of the MVD was tuned in a systematic way in order to find the best compromise between good tagging efficiency (calling for a small distance between target and detector) and low radiation doses (calling for an increase of this distance). The geometries were benchmarked with their ability to reconstruct a maximum number of \( D^0 \)-mesons before the radiation doses exceed the radiation tolerance of the sensors. To do so, the radiation dose per collision and the reconstruction efficiency for \( D^0 \to K + \pi \) were estimated for each geometry considered. It was shown that increasing the distance between target and first detector station

\(^1\)This value is presently rather around \( \sim 30\% \).
from 5 cm to 10 cm provides a valuable compromise, as the substantial improvement reached in terms of detector lifetime dominates the modest losses in charm reconstruction efficiency.

For the best performing MVD-geometry, a high statistics simulation based on $2.4 \times 10^7$ central Au+Au collisions at a beam energy of 25 AGeV, was carried out. A collision rate of about $10^5/s$, which prevents from pile-up effects, was observed to be viable. Assuming the predicted production multiplicity of $1.2 \times 10^{-4}$ $D^0$-mesons per central collision, it was shown that the MVD allows to reconstruct $\sim 2.5 \times 10^4$ $D^0$-mesons, with a $S/B = 2.0$ ($>0.53$ with 95 % probability) and an excellent significance of $Sign. = 130_{-40}^{+30}$. Those results, which can be obtained within a few months of beam time, fit the physics requirements defined by the CBM-collaboration.

The main systematic uncertainties of the results arise from the early stage of the system integration studies, from the modest precision of the predicted production multiplicities of open charm at FAIR energies and the need to extrapolate the technological progress of the MAPS technology over several years. The consequences of major biases in the estimates used were therefore studied. It was shown that nowadays radiation tolerance of MAPS allows for a significant ($Sign. \geq 5$) reconstruction of $D^0$-mesons for production multiplicities of $\gtrsim 10^{-5}$ mesons per central collision. Assuming the presumed ultimate radiation hardness of MAPS, production multiplicities down to $\gtrsim 5 \times 10^{-6}$ mesons per central collision are sufficient. As however the absolute number of reconstructed particles shrinks, the physics studies achievable would be limited by statistics if the actual production multiplicity misses the predictions by more than a small order of magnitude.

Because of technical constraints, the hadron identification abilities of the time-of-flight system of CBM were not fully accounted for in the simulation presented. Any hadron identification going beyond proton rejection might therefore substantially ameliorate the numbers presented. Moreover, a regular replacement of the most irradiated parts of the vertex detector station can improve the global detection performance substantially. The replacement is considered as feasible taking into account both, system integration and financial aspects.

The beam time required for a measurement would shrink, if some pile-up of nuclear collisions in the MVD could be tolerated. This was so far not studied systematically because of technical and time constraints. However, given the high granularity of MAPS, it seems likely that modest pile-up will have no substantial impact on the detector performances. The limitation may rather come from the central tracker and its track extrapolation abilities.

Concluding, one may state that a MAPS based MVD will allow for doing $D$-physics at CBM. This holds in particular for beam energies of 35 AGeV since the production multiplicities of those mesons increases strongly with energy. For 25 AGeV, the simulations of the present work indicate that the necessary performances will be reached but the safety margins are not sufficient to guarantee a satisfactory amount of reconstructed particles if reality departs from the assumptions made in this study by more than a factor of about three.

The feasibility of doing open charm physics at a beam energy of 15 AGeV and of reconstructing the $\Lambda_c$ were not addressed in the thesis. Given the poor production multiplicities of $D$-mesons at this beam energy and the short lifetime of the $\Lambda_c$, reaching the ambitioned sensitivity seems questionable. One may therefore start the physics program of CBM at high beam energies with a MAPS based vertex detector. Doing so will provide the necessary time for developing a second generation MVD relying on newly arising detector technologies, like SOI-detectors or detectors based on vertical VLSI integration. Despite the fact that both technologies are presently still in a very early phase of their development, their conceptual potential justifies considering them for covering the low energy part of the CBM physics program.