ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM070

KAON BEAM SIMULATIONS EMPLOYING CONVENTIONAL HADRON BEAM CONCEPTS AND THE RF SEPARATION TECHNIQUE AT THE CERN M2 BEAMLINE FOR THE FUTURE AMBER EXPERIMENT

F. Metzger*[1,2], D. Banerjee[1], A. Baratto Roldan[1], J. Bernhard[1], M. Brugger[1]
N. Charitonidis[1], L. A. Dyks[1], L. Gatignon[3], A. Gerbershagen[4], B. Ketzer[2], R. Murphy[1,5,6]
C. A. Mussolini[1,5,7], L. J. Nevay[1], E. Parozzi[1], B. Rae[1], S. Schuh-Erhard[1]
P. Simon[1], V. Stergiou[1,8], F. Stummer[1,5,6], M. Van Dijk[1]
[1]CERN, 1211 Meyrin, Switzerland
[2]Helmholtz-Institut für Strahlen- und Kernphysik,
Rheinische Friedrich-Wilhelms-Universität Bonn, 53115 Bonn, Germany
[3]Lancaster University, Lancaster, LA1 4YW, United Kingdom
[4]PARTREC, UMCG, University of Groningen, 9747 AA, Groningen, Netherlands
[5]John Adams Institute, United Kingdom
[6]Royal Holloway University of London, Egham, TW20 0EX, United Kingdom
[7]University of Oxford, Oxford, OX1 3RH, United Kingdom
[8]Physics Department, National Technical University of Athens, 15772 Zografou, Greece

Abstract

The AMBER-experiment [1, 2], located in the North Experimental Area at CERN, is the successor of the NA58/COMPASS [3] experiment which ran from 2002-2022. AMBER will start its data taking in 2023. The experiment is served by the M2 beamline, employing secondary and tertiary beams produced by 400 GeV c^{-1} protons from the CERN Super Proton Synchrotron (SPS) impacting the T6 target. For the second phase of their measurements, AMBER will require high-intensity kaon beams [4, 5]. This requirement for high-intensity beams implies a need for accurate particle identification allowing tagging particles of interest that would otherwise be lost for analysis. The beam particle identification is carried out using Cherenkov (CEDAR) detectors [6], whose tagging efficiency depends critically on the beam divergence. In this paper we investigate the beam parameters required, the performance achievable with the current layout of the beamline, as well as possible improvements.

PRESENT PERFORMANCE

The M2 beamline in the North Experimental Area at CERN has provided muon and hadron beams for the COMPASS experiment for many years. For COMPASS, the main interest was in the pion content rather than the kaon content of the beam. This will change during the proposed second phase of the AMBER experiment, when there will be several periods of data taking dedicated to particles and physics with strangeness.

In the current layout of the M2 beamline, there are in total 80 m of sections without vacuum, where the beam is traversing air[1]. In these air sections, the beam undergoes multiple scattering. The contribution of the scattering can be calculated with Moliere's formula [7, 8]. For air, the radiation length is 303.9 m [9, p. 144], resulting in a multiple scattering angle of $\theta_0 = 34.9$ µrad at 190 GeV c^{-1} beam momentum.

The beam divergence $x' = \frac{dx}{ds}$, $y' = \frac{dy}{ds}$ at the CEDAR location in the M2 line for the current layout is depicted in Fig. 1a. The distribution shows long tails in both directions. Although, the distributions are wide, what is actually important is the inclination angle (wrt. the beam axis) of a single particle. In order to be detected by and distinguishable in the CEDAR, the combined divergence, $\sqrt{x'^2 + y'^2}$, needs to be limited to 60 µrad [6]. This limit is motivated by the difference in Cherenkov angles between kaons and pions, as these are the two species that emit Cherenkov light at angles closest to each other. It is represented by the black ellipses in Fig. 1 and 2.

POSSIBLE IMPROVEMENTS

One has several possibilities to improve the beam quality at the CEDAR location. On the one hand, one can limit the amount of multiple scattering by installing vacuum pipes. On the other hand, there are improvements that can be made to the beam optics and collimation settings. The influence of such changes will be discussed in the following sections. The results are based on simulations using the BDSIM package [10], version 1.6.develop, with Geant4 [11] version 10.7.2 and the physics list *FTFP_BERT*.

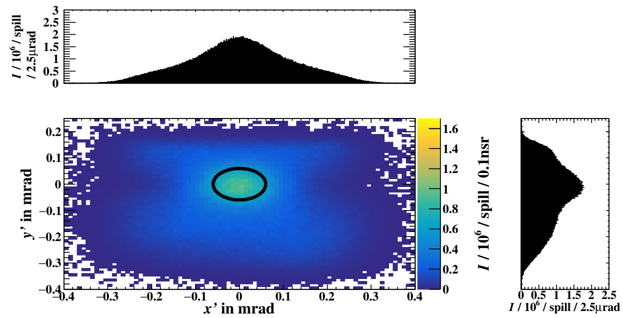
* Corresponding author: fabian.metzger@cern.ch

[1] These air sections were never important in the original design as a beamline for muons.

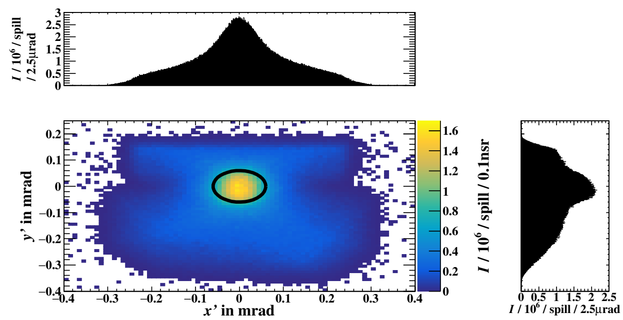
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM070

Suppression of Multiple Scattering

The first study looked at the influence of replacing the in-air sections of the beamline with in-vacuum sections by installing beam pipes in these regions. The beam divergence at the CEDAR location in M2 in this case is shown in Fig. 1b.



(a) Divergence for the current M2 layout.



(b) Divergence for a full vacuum implementation.

Figure 1: Beam divergence at the CEDAR location. The black ellipses represent the maximal angle a particle can have to be distinguishable in the CEDAR which is 60 µrad.

Comparing the distributions for both cases, one can observe that the width does not noticeably decrease when placing additional vacuum sections along the whole beamline. This is to be expected as the beam needed to be small and loosely collimated to keep the background to the experiment at a reasonable level. However, what is clearly visible is that the beam core in the full vacuum case is 50 % more intense than in the in-air case, meaning that there are many more particles having angles small enough to be tagged by the CEDAR detector. This originates from two effects: a cleaner collimation as the correlations between x and x', and y and y' expected from the beam optics are not washed out by multiple scattering due to the better vacuum conditions; and the overall increase in the total flux by 20 % when installing beam pipes along the whole beamline as the number of particles lost along the line is smaller. The gain in total flux can also be partly explained by the cleaner collimation scheme.

With this implementation, the overall gain in terms of kaon intensity could be in the order of 50 % going from $2{\times}10^6$ to $3{\times}10^6$ kaons within the CEDAR acceptance for a total of about $1.2{\times}10^{13}$ protons on the T6 target. Approximately one quarter of the beam would be then tagged by the particle identification system.

Beam Optics

In addition to putting the entire beamline under vacuum, it is also possible to modify the beam optics to enhance the total number of hadrons and thus kaons transmitted. In the original hadron beam implementation of the beamline, the beam had to be small and loosely collimated shortly upstream of the CEDAR to ensure the background was acceptable for the COMPASS-experiment. In such secondary beamlines, a small beam naturally comes with a large divergence resulting in less efficient particle identification. This effect can be explained by Liouville's theorem and is valid as long as no particles are lost. However, as soon as the beam does not undergo too much multiple scattering (we assume completed vacuum along the line) it can be collimated far upstream of the experiment, still in the underground part, and transported to the CEDAR detector without impacting experimental backgrounds. It is then possible to profit from a large, low divergence beam allowing an efficient particle identification with the CEDAR detector. The comparison of the beam optics for both configurations of the line is depicted in Fig. 3. As the most important parameters for the beam size are R_{12} (horizontal) and R_{34} (vertical) the comparison has been limited to only those even though the other beam optics parameters have also been changed.

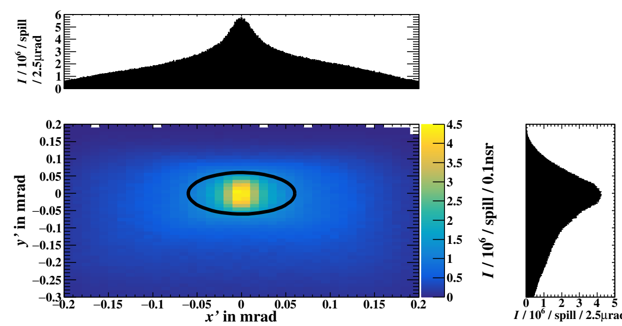


Figure 2: Beam divergence for the modified beam optics. In the simulation a full vacuum implementation has been assumed. The black circle represents the maximal angle a particle can have to be distinguishable in the CEDAR which is 60 µrad.

As Fig. 2 shows, the modified optics results in an intense beam spot within the CEDAR tagging acceptance. In such a beamline setup, it would be possible to identify in the order of $5{\times}10^6$ to $6{\times}10^6$ kaons per spill for about $1.2{\times}10^{13}$ protons on target. Compared to the current implementation this would result in a factor 3 improvement in the total number of kaons identified.

Collimation

As shown in the previous sections, it is possible to significantly improve the overall secondary beam intensity sent via the M2 beamline to the AMBER-experiment. As it is not

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM070

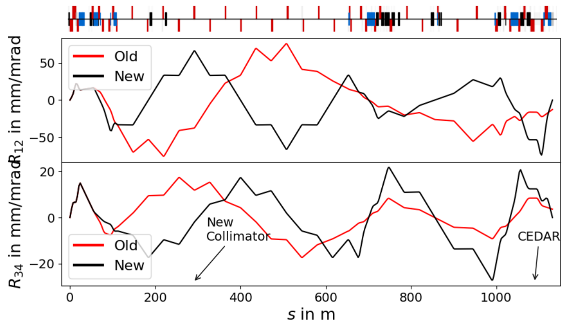


Figure 3: Comparison of the main changes in the beam optics between the old and new configuration. The position of the new collimator required is shown. R_{12} and R_{34} describe the evolution of the particle position as a function of its initial angle in the horizontal and vertical plane respectively. Modifying those parameters has the most influence on the beam size and therefore on the divergence (R_{22} and R_{44} are 0 at the CEDAR to guarantee a parallel beam).

the total beam intensity but the kaon intensity that matters, from a radiation protection point of view, it would be desirable to limit the total intensity without impacting the kaon intensity. As the latter is defined by the number of particles identified by the CEDAR detector, the total intensity can be reduced by collimating the parts of the beam that cannot be tagged by the CEDAR without impacting the useful kaon intensity. The effect of an additional collimator for this purpose has therefore been studied. The proposed position of this collimator is shown in Fig. 3.

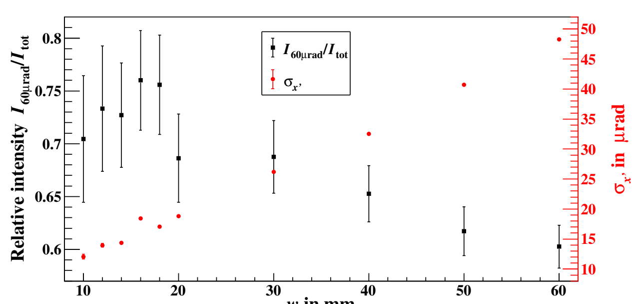


Figure 4: The intensity in 60 µrad relative to the full intensity transmitted through the horizontal collimator for different openings w is shown in black. The error bars represent the statistical error. In red, the of the horizontal divergence of the beam is depicted. The error bars are based on variations of the distributions widths for different simulations.

Fig. 4 shows the influence of this newly added collimator on the beam intensity and divergence at the CEDAR location. From Fig. 4, one can deduce that the intensity in 60 µrad relative to the full intensity through the collimator grows when closing its opening w, meaning that one cuts beam particles with large angles that would have not been identified by the CEDAR. This is also underlined by the horizontal beam divergence which gets reduced when closing the collimator.

Of course, further collimation would only be needed in case the intensity needs to be reduced due to radiation-protection limits. The proposed new collimator only works horizontally and can clearly improve the beam divergence at the CEDAR location. The effect of a vertical collimator has also been investigated, but as the M2 line is a vertical beamline, there are vertical bending magnets that introduce dispersion. Due to this the gain in kaon acceptance by is small compared to the intensity loss that comes from collimating the beam.

CONCLUSION

The current performance of the M2 beamline has been investigated in terms of optimising beam parameters at the location of the particle identification system, to have a large, low-divergence beam for efficient CEDAR tagging. By putting the whole beamline under vacuum and modifying the beam optics, one can gain a factor of 3 in the kaon rate that can be tagged by the CEDAR compared to the current beamline layout.

Due to the non-optimal particle identification limited by the beam divergence, the COMPASS-collaboration developed an algorithm to use the tracking with the COMPASS-spectrometer and gain information about the inclination angle at the CEDAR-position by tracking it back to the according location [12]. This is especially helpful in case of runs with highest intensities. As in those cases the beam needs to be collimated as little as possible, one has the possibility to also identify particles outside of the CEDAR acceptance. Future possibilities to improve the kaon rate compared to the total rate include filtering out unwanted species from the beam using a so-called RF separation technique [4, 5]. The limiting factor for this implementation is the cavity size which impacts the overall kaon rate. To overcome this problem, the number of protons on target would need to be increased. However, as the quantity that matters the most is the absolute number of kaons tagged by the CEDAR, optimisation of the beamline as demonstrated in this paper is still preferable to a dedicated filtering system as long as the filtering system itself is still limiting the total transmission.

REFERENCES

[1] B. Adams *et al.*, “Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS (COMPASS++/AMBER),” 2018.

[2] B. Adams *et al.*, “COMPASS++/AMBER: Proposal for Measurements at the M2 beam line of the CERN SPS Phase-1: 2022-2024,” 2019. `http://cds.cern.ch/record/2676885`

[3] “The COMPASS experiment at CERN,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 577, no. 3, pp. 455–518, 2007. `doi:10.1016/j.nima.2007.03.026`

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM070

[4] A. Gerbershagen *et al.*, "Design of beam optics for RF-separated kaon and antiproton beams in the M2 beam line of the CERN North Area," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1048, p. 168 004, 2023. doi:https://doi.org/10.1016/j.nima.2022.168004

[5] A. Gerbershagen *et al.*, "RF-Separated Beam Project for the M2 Beam Line at CERN," 2022. https://cds.cern.ch/record/2806692

[6] C. Bovet, R. Maleyran, L. Piemontese, A. Placci, and M. Placidi, *The CEDAR counters for particle identification in the SPS secondary beams: a description and an operation manual*. CERN, 1982. doi:10.5170/CERN-1982-013

[7] G. Molière, "Theorie der Streuung schneller geladener Teilchen.I. Einzelstreuung am abgeschirmten Coulomb-Feld. II. Mehrfach- und Vielfachstreuung," *Z. Naturforsch. A*, vol. 2, pp. 133–145, 1947. http://cds.cern.ch/record/425612

[8] H. A. Bethe, "Molière's Theory of Multiple Scattering," *Phys. Rev.*, vol. 89, pp. 1256–1266, 6 1953. doi:10.1103/PhysRev.89.1256

[9] Particle Data Group, P. A. Zyla, *et al.*, "Review of Particle Physics," *Progress of Theoretical and Experimental Physics*, vol. 2020, no. 8, 2020, 083C01. doi:10.1093/ptep/ptaa104

[10] L. Nevay *et al.*, "BDSIM: An accelerator tracking code with particle–matter interactions," *Computer Physics Communications*, vol. 252, p. 107 200, 2020. doi:10.1016/j.cpc.2020.107200

[11] S. Agostinelli and other, "Geant4—a simulation toolkit," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, 2003. doi:10.1016/S0168-9002(03)01368-8

[12] S. Wallner *et al.*, "CEDAR PID using the Likelihood Approach for the Hadron-Beam," 2017. https://wwwcompass.cern.ch/compass/notes/2017-1/2017-1.pdf