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# STUDIES FOR THE K12 HIGH-INTENSITY KAON BEAM AT CERN

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*Abstract*

The NA62 experiment is a fixed target experiment located in the North Area of CERN and has as main goal the measurement of the branching ratio of the rare decay $K^+ \rightarrow \pi^+ \nu \overline{\nu}$. The primary proton beam from the SPS accelerator interacts with the T10 beryllium target and the generated 75 GeV/c secondary particles, containing about 6% of positive kaons, are transported by the K12 beamline to the NA62 experiment. Studies in this paper present detailed simulations of the K12 beamline developed in both FLUKA and BDSIM codes, which reproduce the current configuration of K12 for the NA62 experiment. The beam optics parameters of K12 are studied in BDSIM and compared to MADX optics and tracking calculations. The models in FLUKA and BDSIM are used for beam studies at various locations along the beamline, and the parameters obtained from simulations are benchmarked against data recorded by the experiment. The impact of the Cherenkov kaon tagging detector (CEDAR) on the beam quality is calculated for two different gas compositions in view of a possible upgrade of the detector.

## INTRODUCTION

The North Area at CERN hosts a number of fixed target experiments that use secondary beams produced by slow-extracted 400 GeV/c primary protons from the SPS. One of these experiments is NA62, which uses 75 GeV/c $K^+$ beam generated in the T10 beryllium target and transported via the K12 beamline to the detectors [1], see Fig. 1 for a scheme of the experiment. The goal of NA62 is to conduct precision

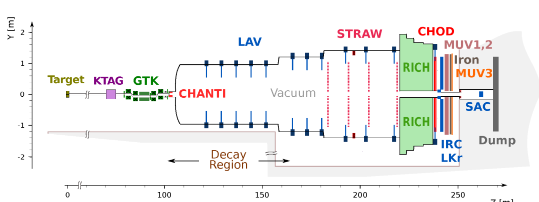


Figure 1: Scheme of the K12 beamline and the NA62 detector [1].

tests of the Standard Model via rare decay studies, in particular, via the measurement of the rate of the ultra-rare decay mode $K^+ \rightarrow \pi^+ \nu \overline{\nu}$. This would lead to the determination of the CKM matrix element $V_{td}$ with a precision better than 10%. NA62 collected data in 2016, 2017 and 2018 before the CERN Long Shut Down 2. Data analysis is ongoing and several publications are in preparation, as well as an upgrade of the system for the next run starting in 2021.

The studies conducted in this paper aim at a precise characterization of the K12 beamline that could describe eventual background sources and be used for their background mitigation. For this purpose two beamline models have been built, one in FLUKA [2,3] and one in BDSIM [4] (GEANT4 based software). To test the precision of the models a first comparison to data is performed of the spatial and angular distribution of the beam at the end of the beamline, where a silicon trackers are located (GTK, see next section). After this first benchmarking the model is used to study the increase of divergence at the Cherenkov Detector, the CEDAR (also called KTAG): Cherenkov Differetial Counter with Achromatic Ring Focus [5].

The models presented in this paper reproduce the configuration of NA62 in the 2018 run. The optics of the beamline is also studied using MADX [6] tracking and the results compared to BDSIM.

## THE K12 BEAMLINE

As already mentioned, the K12 beamline transports the positive kaon beam to the NA62 detector. The centre of the T10 target is defined as the start of the K12 beamline, the target itself is contained inside a massive iron shielding and is followed by two fixed collimators. The beam passing through these two collimators is focused by the first series of quadrupoles through the first achromat that is composed of four bending magnets. The achromat lets the beam pass through a narrow and adjustable aperture in the main dump-collimator, the TAX, that permits a narrow band momentum selection of $\pm 1\%$ $\Delta p/p$. In the TAX the remaining primary proton beam is dumped. In the next part of the beamline the beam is collimated and refocused up to the CEDAR. This detector is filled with nitrogen gas over a length of approximately 6 meters and is used for positive kaon tagging. After the CEDAR the 75 GeV/c kaons go through a second achromat and are tracked via three tracking stations, the GTK 1-3, composed of Si-pixel arrays [1]. Before GTK3 a horizontal steering magnet, called TRIM5, is used to deflect the beam by an angle of 1.2 mrad and match the downstream

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detector design. The description of the NA62 detector itself is outside the scope of present article and can be found in [7].

## BEAM OPTICS COMPARISON

The optics studies have been performed in MADX and BDSIM. A MADX Twiss file can easily be converted into a BDSIM model for optics comparison. The simulated beam is a 75 GeV/c kaon beam with $10^6$ primary particles. The comparison between MADX and BDSIM is particularly interesting since the two codes use a different approach in optics calculation. MADX uses the matrix multiplication method whilst BDSIM a back-tracking approach. On the top of the picture in Fig. 2 is shown a scheme of the beamline. In this survey the blue blocks represent dipoles, the red one quadrupoles and the black ones the collimators. Most ones of the dipoles do not bend the nominal beam trajectory and are used as muon sweepers for cleaning the beam from the background particles. The beta twiss function along the beamline is calculated in MADX and BDSIM and shown in the same figure. MADX results are plotted with solid lines, whereas BDSIM's are represented with points at the end of each sampling plane (end of every beamline element). It can be noticed that there is an excellent agreement between MADX and BDSIM within the relative error-bars is observed.

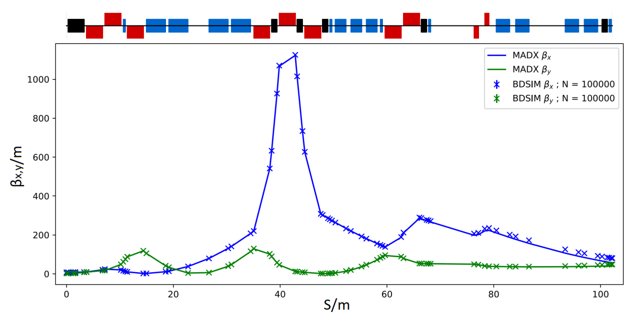


Figure 2: Beta function in X and Y plane as function of distance along the beam calculated for $10^6$ primary particles. Continuous line for MADX, points for BDSIM.

## FLUKA AND BDSIM MODEL

NA62 is a high precision experiment. Therefore, simulation models need to adequately describe the data. In the K12 beam, nine different magnet models are used, all with different apertures, yokes and coils. All the collimators in the beamline are different, with some of them having tapered apertures and inserts. The design of the single components has been realised in FLAIR [8] for FLUKA and with PYG4OMETRY [9] (a tool to create GDMLs) for BDSIM.

Almost all the field maps (except for two HALO [10] field maps) have been produced using the Opera 2D [11] software. A linear interpolation of the maps has been done in FLUKA and BDSIM. The interpolation process required a routine written in FORTRAN for the FLUKA model, this routine accounts for rotation and translation of the magnets. In BDSIM, the interpolation is made using the predefined interpolating routines. The complete models can be seen in Fig. 3.

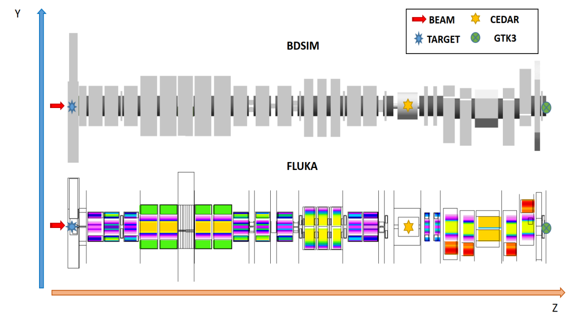


Figure 3: K12 model in BDSIM and FLUKA. In FLUKA the magnets fields are shown as well.

## SIMULATION RESULTS

For this paper, the version 2011-3.0 of FLUKA and 3.0-8a of FLAIR have been used. Also, BDSIM version 1.4 with GEANT4.10.4.p03 and GEANT4 physics list FTFP-BERT. In order to limit computation time, proton interactions on target have not been simulated, instead, a $K^+$ beam distribution after the target has been assumed with parameters obtained from sensitivity studies on the model. The simulations have been performed with $10^7$ particles for both BDSIM and FLUKA.

As already mentioned, one of the observables in the experiment is the angular distribution of the beam at GTK3. Data for beam distribution (angular and spatial) have been provided by the NA62 collaboration. A scatter plot of the angular distribution as measured by NA62 is depicted in Fig. 4. The one-dimensional projections on the x and y axes of the data are shown together with the results from FLUKA

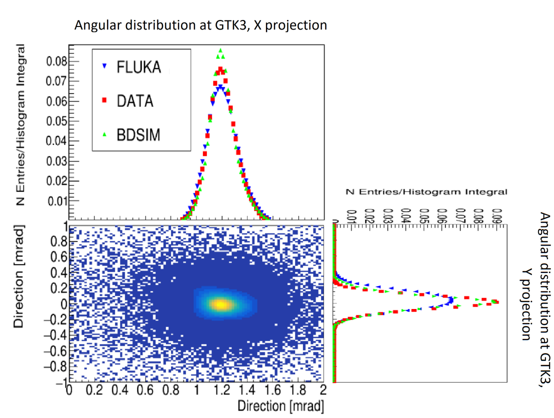


Figure 4: Angular distribution of the beam at the GTK3. 2D histogram for data, projections in X and Y for data, BDSIM and FLUKA.

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and BDSIM, both normalised to their integral. The particles following the kick of TRIM5, correctly distribute around the expected 1.2 mrad direction in the horizontal (X) plane at GTK3. For the Y axes, the beam is distributed around zero. In the plot can be seen a good overall agreement between simulations and data, especially considering that these quantities are scored at approximately 100 m distance from the target and therefore undergo several interactions. The differences between FLUKA and BDSIM are given by the fact that the two codes use different physics lists.

Table 1 lists the directional and spatial beam parameters at the GTK3. Average X and Y ($\overline{X}$,$\overline{Y}$) and their RMS are reported for: data, FLUKA and BDSIM.

Table 1: Beam Parameters at the GTK3

| POINTS | $\overline{X}$ | $\overline{Y}$ | RMS X | RMS Y |
|---|---|---|---|---|
| FLUKA ANGLE [mrad] | 1.21 | -0.04 | 0.12 | 0.11 |
| BDSIM ANGLE [mrad] | 1.21 | -0.02 | 0.11 | 0.11 |
| DATA ANGLE [mrad] | 1.21 | -0.01 | 0.11 | 0.09 |
| FLUKA POSITION [cm] | 0.04 | -0.02 | 1.01 | 0.66 |
| BDSIM POSITION [cm] | 0.03 | -0.02 | 1.01 | 0.60 |
| DATA POSITION [cm] | -0.01 | -0.01 | 1.05 | 0.58 |

## STUDIES ON BEAM INTERACTION IN THE CEDAR

In NA62 kaons cannot be separated from pions and protons at the beam level. For this reason a particle identification detector is needed, NA62 uses a differential Cherenkov detector with achromatic ring focus, the CEDAR. In the current configuration, the CEDAR uses nitrogen at 1.73 bar but this detector could work almost as well with hydrogen at 3.85 bar. The aim of these studies is to calculate the divergence that the two possible configurations would generate. Divergence needs to be minimized for various reasons, in particular: to avoid showers produced by particles at large angles and to reduce the emitted radiation affecting NA62 electronics.

The divergence is calculated as the RMS of the angular distribution for the curves shown in Figs. 5 and 6. The RMS parameters are reported in Table 2. It can be seen from the simulations curves that the angular distribution is slightly narrower according to BDSIM. This type of difference is

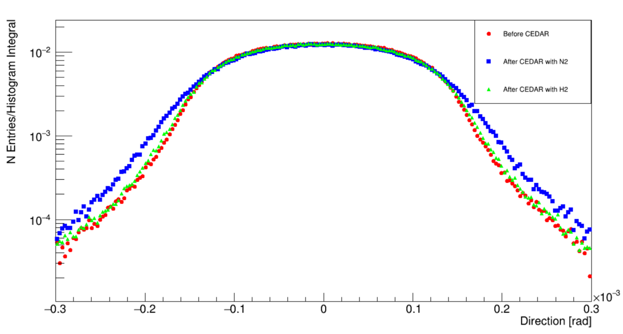


Figure 5: Angular spread of the beam before CEDAR and after CEDAR with $N_2$ and $H_2$. Simulations in FLUKA.

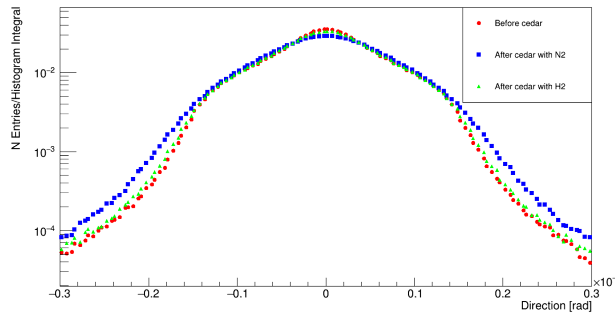


Figure 6: Angular spread of the beam before CEDAR and after CEDAR with $N_2$ and $H_2$. Simulations in BDSIM.

expected since the two codes intrinsically use a different set of physics processes. In both cases filling with hydrogen gas will cause less spread, in particular visible for the tails of the distributions. Tails are important for interaction of beam in tight apertures. This so-called upstream background is the main source of background for NA62 and needs to be optimized. It can help in particular to reduce probability for interaction in the NA62 Straws, which can be mistaken for a pion, and is the signature of the NA62 $K^+ \rightarrow \pi^+ \nu \nu$ measurement. Therefore, the use of hydrogen is preferred.

Table 2: Divergence (RMS of Angular Distribution) Before and After CEDAR

| DIVERGENCE | Before CEDAR | H2 CEDAR | N2 CEDAR |
|---|---|---|---|
| FLUKA [μ rad ] | 82.17 | 83.38 | 88.27 |
| BDSIM [μ rad ] | 68.46 | 69.98 | 75.46 |

## CONCLUSION

Beam simulations have been compared to data measured from NA62 experiment. This comparison shows a good overall agreement of both FLUKA and BDSIM codes with data. These models represent the first full models of K12 developed in FLUKA and BDSIM. A calculation of divergence downstream the CEDAR has been done in FLUKA and BDSIM showing differences depending on the Cherenkov gas used. Based on the present study, the use of hydrogen gas is recommended for the use in Cherenkov detector. Future studies using these models are being developed in order to quantify the muon background in the NA62 detector and the environmental radiation impact of the experiment.

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