PROCEEDINGS OF SCIENCE

Operation and performance of the NA62 GigaTracKer

Alina Kleimenova[a,1]

[a] *EPFL-SB-IPHYS-LPHE,*
BSP – Cubotron, Lausanne, Switzerland

E-mail: alina.kleimenova@cern.ch

The GigaTracKer is a hybrid silicon pixel detector designed for the fixed-target experiment NA62 at the CERN SPS aiming to measure the branching ratio of the very rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ with 10% precision. The detector has to provide measurements of momentum, direction and time of beam particles arriving at a rate of 750 MHz. The tracking system consists of four stations installed in vacuum ($\sim 10^{-6}$ mbar), 60.8×27 mm^2 each, with a total material budget of less than 2%X_0. Each station is cooled with a microchannel cooling plate used for the first time in a high energy physics experiment. The beam particles are tracked in 4 dimensions by means of time-stamping pixels (300×300 μm^2) with the single hit time resolution reaching 115 ps. This performance has to be maintained despite the beam irradiation amounting to a yearly fluence of 4.5×10^{14} 1MeV n$_{\text{eq}}$/cm^2/200 days. The detector has been fully operational since 2016. We describe the GigaTracKer design and performance in the 2016-2022 years of NA62 data taking.

The 32nd International Workshop on Vertex Detectors (VERTEX2023)
16-20 October 2023
Sestri Levante, Genova, Italy

[1]On behalf of the GigaTracKer working group.

PoS(VERTEX2023)008

1. Introduction

NA62 is a fixed target kaon experiment located in the North Area of the CERN SPS, designed to measure the branching ratio of the ultra-rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ with 10% precision, using a decay-in-flight technique [1]. The current prediction for $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ is $(8.60 \pm 0.42) \times 10^{-11}$ [2].

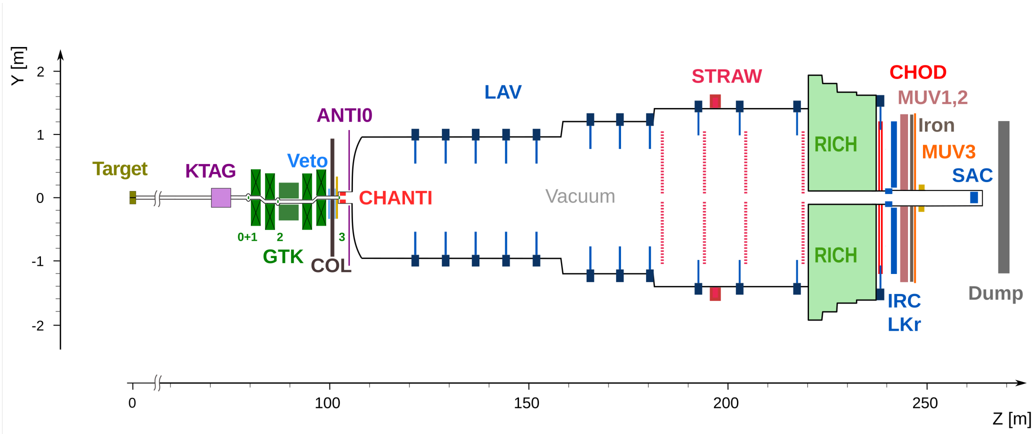

Figure 1: Schematic layout in the Y-Z plane of the NA62 experiment.

The schematic of the NA62 beamline and detector setup is shown in Figure 1 and described in detail in [3]. NA62 uses an unseparated hadron beam of positively charged particles (6% are kaons) produced by interactions of 400 GeV/c protons on a beryllium target. The 750 MHz beam of (75 ± 1) GeV/c is collimated and transported through the NA62 detector. Incoming beam kaons are identified in the differential Cherenkov counter (KTAG) located 70 m downstream from the target. KTAG is followed by the beam spectrometer GigaTracKer (GTK), where the momentum, direction and time of beam particles are precisely measured. The STRAW spectrometer placed at the end of a 110 m long vacuum tank measures the momentum and direction of particles produced inside the fiducial volume. Particle identification is performed using downstream Cherenkov counter, RICH.

The $K^+ \to \pi^+ \nu \bar{\nu}$ event signature consists of one incoming kaon track and one outgoing pion track, with no other activity in the detector. The high background rejection required is provided by combining kinematic suppression, highly efficient photon and muon vetoes and time resolution. The momenta of the kaon and pion are used to reconstruct the signal candidate squared missing mass defined as $m^2_{\mathrm{miss}} = (P_{K^+} - P_{\pi^+})^2$, where P_{K^+} and P_{π^+} are the 4-momenta of the kaon and pion respectively. To achieve 10% precision, kinematic suppression of the order of $O(10^4)$ is required. This rejection can be achieved if the resolution of the $K^+ \to \pi^+ \pi^0$ squared missing mass is smaller than 0.001 GeV^2/c^4, corresponding to an angular and momentum resolution on the beam particle at the exit of the GTK of $p_{x,y}/p_z = 16$ μrad and $\delta p/p = 0.2\%$. The squared missing mass for this channel splits the signal region in two.

2. The GigaTracKer detector

The GTK [4] is the NA62 beam spectrometer, which provides momentum and direction measurement for the incoming beam particles. The detector comprises three stations of silicon pixel detectors installed inside the beam pipe in vacuum and two pairs of dipole magnets, each arranged in an achromat configuration. The schematic view of the GTK is shown in Figure 2. In 2021, an additional station, GTK0, was added 50 mm before GTK1 to improve tracking efficiency further.

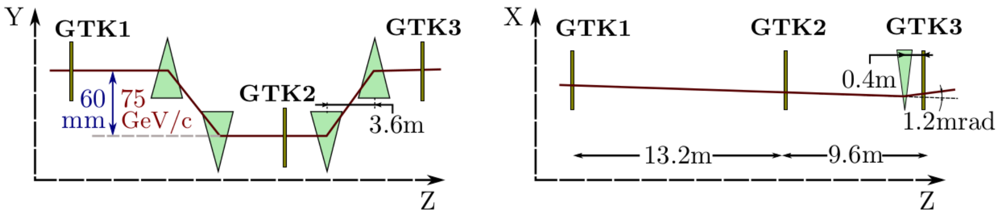

Figure 2: Schematic view of the beam spectrometer GTK. The green triangles represent bending magnets. The layout was updated in 2021 by adding GTK0 in front of GTK1.

The required angular and momentum resolution discussed in the previous section constrains the maximum amount of material crossed by the beam in the GTK to $0.5\%X_0$ per station in order to reduce the number of inelastically scattered beam particles. Moreover, for unambiguous reconstruction and association of a beam track with signals in other subdetectors, the GTK has to provide a time resolution for single hits better than 200 ps. On top of that, all these constraints must be satisfied despite the beam irradiation amounting to a yearly fluence of 4.5×10^{14} 1MeV $\mathrm{n_{eq}/cm^2/200}$ days. The GTK was designed and built to fulfil the specifications listed above.

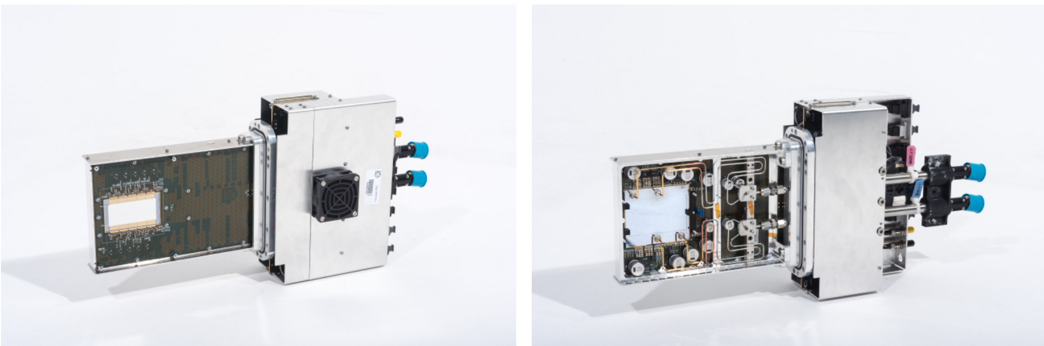

Figure 3: Photograhs of a GTK module viewed from the sensor side (left) and from the cooling plate side (right).

A GTK module is shown in Figure 3. Each module consists of an assembly of a hybrid silicon pixel detector and a cooling plate inserted into the countersink of the carrier board. The carrier board is glued into a steel vessel ending with a flange, used to mount the station in the beam pipe of the experiment. This configuration allows prompt access and replacement of the station if needed.

The 60.8×27 mm^2 sensitive part of each module is made of 200 μm thick planar silicon sensor. The sensor is segmented into 18000 pixel cells, 300×300 μm^2 each, and is bump-bonded to two rows of five custom-made ASICs, the TDCPix [5], thinned to 100 μm. The chip is divided into two separate areas: the 40×45 pixel matrix, where the hit signals are digitised and the End-of-Column region (EoC), where digitised hits are time-stamped and serialised. The power consumption is about 4 W per chip and varies across the chip as 4.8 W/cm^2 in the EoC and 0.32 W/cm^2 in the pixel matrix. The sensor bonded to 10 chips is glued on a silicon plate serving as a heat exchanger and mechanical support. The cooling device is a 210 μm thick, 70×80 mm^2 silicon plate fabricated by bump-bonding silicon wafers together, where one of the wafers is etched to have 150 micro-channels with a cross-section of 200×70 μm^2 organised into two circuits. The liquid coolant C_6F_{14} flows at 3 g/s, keeping the sensor and the front-end electronics at less than 5°C.

3. Performances

The GigaTracKer has been fully operational since mid-September 2016. In total, 15 separate GTK modules were used during the data taking periods between 2016 and 2023, and a few modules were reused several times, keeping the fraction of dead pixels below 0.5% in all stations. The beam intensity was around 35% of the nominal intensity in 2016, reaching 100% in 2018. All modules were equipped with n-in-p sensors, except for one p-in-n, and mounted on cooling plates with thicknesses varying from 210 μm to 380 μm. The nominal operational bias voltage was 100 V. However, starting in 2021, the bias voltage was gradually adjusted during the data taking.

The time resolution was measured for each sample of $K^+ \to \pi^+\pi^+\pi^-$ decays collected during 8-10 consecutive hours of data taking. The time of the kaon candidates reconstructed with three pion tracks was measured using two detectors: RICH as an average time of three pions and KTAG as the time of the kaon candidate. These candidates were then matched with a track reconstructed by the GigaTracKer, with hits in all three or four stations, using only geometrical and kinematic information.

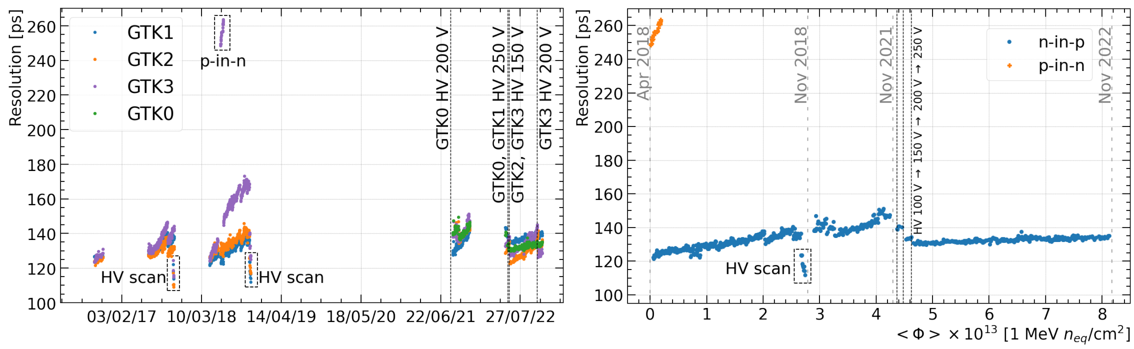

Figure 4: GTK single hit time resolution as a function of time (left) and fluence (right). The plot on the left displays the time resolution for each GTK station, while the plot on the right shows the most irradiated n-in-p module used in various data taking periods compared to a p-in-n module.

The GTK station-to-station time differences were compared to measure standalone resolution. The time resolution of each station as a function of time is shown in Figure 4 left. While the time resolution is increasing over time, reaching 170 ps (+30%) for one of the most irradiated modules at the end of 2018 data taking, all n-in-p modules demonstrated a single hit time resolution well below 200 ps. Studies of the time resolution as a function of bias voltage (labelled as HV scan on Figure 4 left) showed a slight but systematic improvement of the single hit time resolution, at best reaching 115 ps at a bias voltage of 250 V [4]. Therefore, to keep resolution stable, gradual bias voltage increase was employed in the following years, shown with vertical dashed lines in Figure 4 left.

Modules used for several data taking periods provide an excellent opportunity to study single hit time resolution as a function of fluence. One such study made for the most irradiated module so far is shown in Figure 4 right. It can be noted that the time resolution grows linearly with fluence, with only a few discontinuities corresponding to the bias voltage change. By November 2022, the module reached peak (average) fluence of $2.5(0.81) \times 10^{14}$ 1MeV $\mathrm{n_{eq}/cm^2}$, corresponding to ∼120 days at nominal intensity; nonetheless, time resolution below 160 ps was maintained.

As discussed in the first section, GTK kinematic performance is crucial for efficient background rejection. The resolution of the squared missing mass was studied with a sample of $K^+ \to \pi^+\pi^0$ decays as a function of the charged pion momentum for 2016 data. The data was observed to agree with expectations based on nominal performance [4], indicating that angular and momentum resolution obtained with GTK matches the design specifications.

4. Conclusions

Designed as the NA62 beam tracker, the GigaTracKer was engineered to deliver precise measurements of the momentum, direction, and timing of incoming beam particles in a beam with a flux as high as 750 MHz. Meeting its demanding design specifications required adopting a revolutionary approach to tracking centred around particle time-stamping at a sub-nanosecond precision level. A custom-made chip, the TDCPix, which aimed to provide time resolution better than 200 ps, a carefully designed sensor and a micro-channel cooling plate, the first high energy physics experiment application, allowed the GTK to achieve the requested performance. A time resolution for single hits of 115 ps was reached, surpassing the design specifications. Moreover, experience gained during years of data taking demonstrated that excellent timing performance can be maintained even after reaching the peak (average) fluence of $2.5(0.81) \times 10^{14}$ 1MeV $\mathrm{n_{eq}/cm^2}$.

A new kaon program, high-intensity kaon experiments HIKE, was proposed at the CERN SPS [7], requiring the new beam tracker to operate at intensities four times higher than NA62. Several promising R&D projects are ongoing, and their outcome could be adopted for HIKE.

References

[1] E. Cortina Gil *et al* (the NA62 Collaboration), *JHEP* **06** (2021) 093.

[2] A. Buras, E. Venturini, arXiv:2109.11032 [hep-ph]

[3] E. Cortina Gil *et al* (NA62 Collaboration), *JINST* **12** (2017) P05025

[4] G. Aglieri Rinella *et al*, *JINST* **14** (2019) P07010

[5] G. Aglieri Rinella *et al*, *Nucl. Instrum. Methods* A **1053** (2023) 168331

[6] G. Romagnoli *et al*, *Microelectron. Eng.* **145** (2015) 133-137

[7] E. Cortina Gil *et al* (HIKE Collaboration), arXiv:2211.16586 [hep-ph]