PROCEEDINGS OF SCIENCE

The Gigatracker of the NA62 experiment at CERN

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NA62 is a fixed-target experiment at the CERN SPS designed to measure the branching ratio of the very rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% precision. Measurements of time, momentum and direction of incoming beam particles are provided by a beam spectrometer called GigaTracker. The GigaTracker is made of three stations of hybrid silicon pixel detector installed in vacuum ($\sim 10^{-6}$ mbar). Each station consists of 18000 pixels of $300 \times 300\mu m^2$ area each, arranged in a matrix of 200×90 elements corresponding to a total area of $62.8 \times 27mm^2$. The beam particles, flowing at 750 MHz, are tracked in 4-dimensions by means of time-stamping pixels 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} $1MeV$ $n_{eq}/cm^2/200$ $days$. In order to limit multiple scattering and beam hadronic interactions, the station material budget is reduced to $0.5\%X_0$ by using micro channel cooling (first application in HEP). We will present the detector design and performances during the NA62 data taking periods.

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1. Introduction

NA62 is a fixed target experiment located in the North Area of CERN which aims to measure the branching fraction of the ultra rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% precision, using a decay-in-flight technique. This process is well-understood theoretically and thus comparison between experimental measurement and theoretical predictions can bring significant insights into new physics processes [1, 2]. The Standard Model (SM) prediction [3] for this decay is $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$.

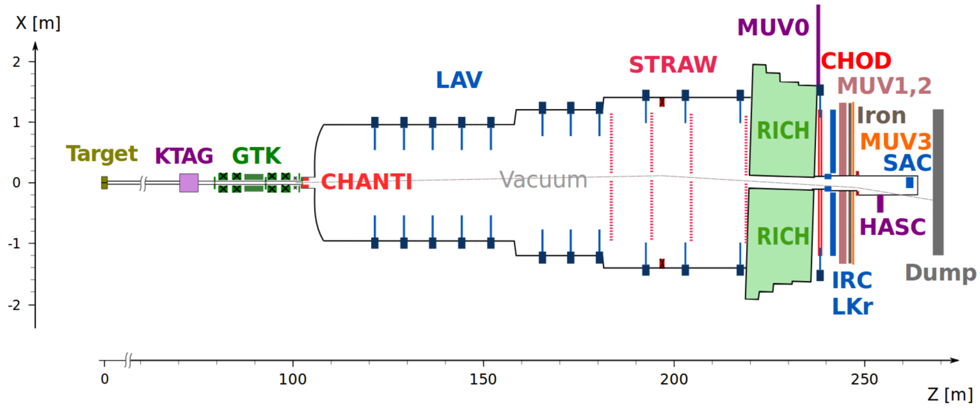

Figure 1: Schematic top view of the NA62 experiment.

NA62 uses unseparated hadron beam of positively charged particles, produced by interactions of 400 GeV/c protons on a beryllium target. The beam of (75 ± 1) GeV/c composed of 70% pions, 23% protons and 6% kaons with a total nominal rate of 750 MHz, is collimated and transported through the detector.

The NA62 beam line and detector layout are described in detail in [4] and are shown in Figure 1. Incoming beam kaons are identified by the differential Cherenkov counter (KTAG) located 70 m downstream from the target. Momentum, direction and time of beam particles are precisely measured by the beam spectrometer GTK. Momentum and direction of downstream particles are measured by the STRAW spectrometer placed in the end of 110 m long vacuum tank.

The signature of $K^+ \to \pi^+ \nu\bar{\nu}$ event 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 various techniques: kinematic suppression, highly efficient vetos and time resolution.

Kinematic rejection of the most abundant kaon decay modes is obtained by selecting two restricted regions of the squared missing mass defined as $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$, where P_{K^+} and P_{π^+} are the 4-momenta of the K^+ and π^+ respectively. Measuring the signal branching fraction with a 10% precision requires a kinematic suppression of the order of $\mathscr{O}(10^4)$. Based on simulation, to obtain this rejection the resolution on the $K^+ \to \pi^+ \pi^0$ squared missing mass is required to be smaller than $0.001 GeV^2/c^4$. This corresponds to an angular and momentum resolution on the beam particle at the exit of the beam spectrometer of $p_{x,y}/p_z = 16 \mu rad$ and $\delta p/p = 0.2\%$.

2. The GigaTracker detector

The GigaTracker (GTK) [5] is the NA62 beam spectrometer, which provides momentum and direction measurement of the incoming beam particles. The GTK made of three stations of silicon pixel detectors installed inside the beam pipe in vacuum and two pairs of dipole magnets, arranged in an achromat configuration. The schematic view of the detector is shown on Figure 2.

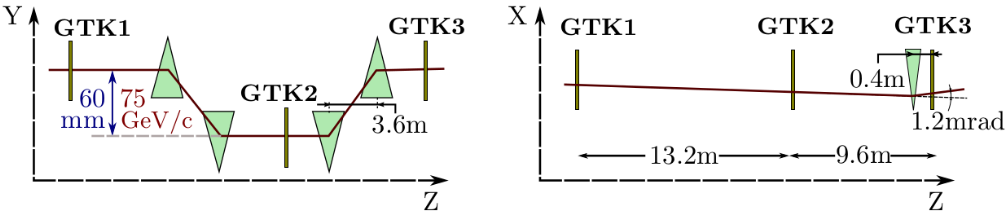

Figure 2: Schematic view of the GTK. The green triangles represent bending magnets.

The GigaTracker was designed and build to fulfill a number of challenging specifications. The required angular and momentum resolution discussed in the previous section constrains the maximum amount of material crossed by the beam in the GigaTracker. Besides that, in order to reduce the number of inelastically scattered beam particles the material budget for the whole detector is limited to $1.5\% X_0$. To unambiguously reconstruct and associate a track with signals in other subdetectors, the GTK has to provide a hit time resolution better than $200 ps$. Finally, all these constraints must be satisfied despite the beam irradiation amounting to a yearly fluence of 4.5×10^{14} $1 MeV\ n_{eq}/cm^2/200\ days$.

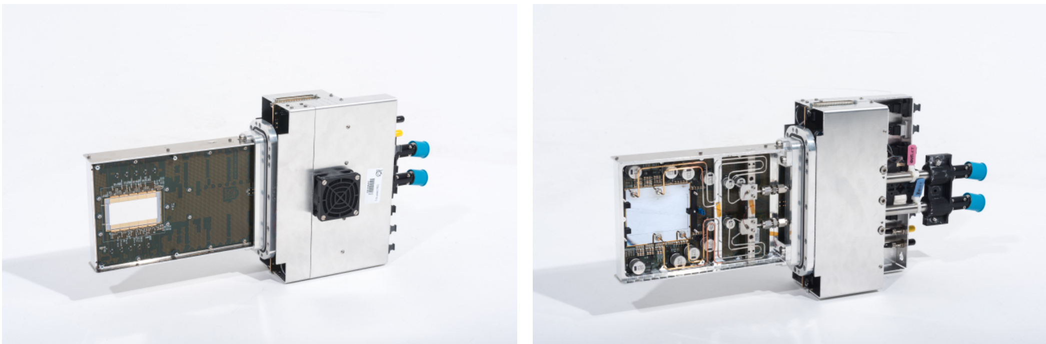

Figure 3: Photograhs of a GTK station viewed from the sensor side (left) and from the cooling plate side (right).

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

The $60.8 \times 27 mm^2$ sensitive part of the detector is made of $200 \mu m$ thick silicon sensor. Such thickness was found to be optimal to produce sufficiently large signal and keep material budget at the level of $0.2\% X_0$. The sensor is segmented into 18000 $300 \times 300 \mu m^2$ pixel cells and is designed to be bump-bonded to two rows of five custom made ASICs, the TDCPix [6], thinned to $100\mu m$ ($0.1\% X_0$).

The TDCPix was built with the $130nm$ IBM technology. The chip is made of two separated areas: the 40×45 pixel matrix, where the hit signals are digitized and the End-of-Column (EoC) where digitized hits are time-stamped and serialised. The digital hit signals are shipped via a dedicated transmission line to the EoC area where groups of 5 pixels are multiplexed into nine time stamping units. Each unit consists of two Time to Digital Converters (TDC) with time bin of $97ps$, which register leading and trailing edges of the signal. The hit pixel address and its time stamp are sent out of the chip via one of the four $3.2GHz$ serializers, each one serving a set of 10 pixel columns. The power consumption is about $4W$ per chip and varies across the chip as $4.8W/cm^2$ in the EoC and $0.32W/cm^2$ in the pixel matrix. Taking into account that detector is placed in vacuum, active cooling is required.

The GTK cooling plate is the first application of micro-channel cooling system in HEP [7]. The cooling device is a $70 \times 80mm^2$ silicon plate fabricated by bonding silicon wafers together. The plate is etched to have 150 micro-channels with a cross-section of $200 \times 70\mu m^2$ through which a liquid coolant C_6F_{14} flows at $3g/s$ keeping the sensor and the front-end electronics at less than $5°C$. The cooling plate thickness was minimised to $210\mu m$ ($0.2\% X_0$) to meet the design requirements.

3. Performances

The GigaTracker is fully operational since mid-September 2016. The same detectors were used during 2017 data taking period with the fraction of dead pixels below 0.5% in all stations. All three stations were equipped with n-in-p sensors and mounted on cooling plates with thickness of $380\mu m$ for GTK1 and GTK2 and $280\mu m$ for GTK3. Thus the material budget in the beam acceptance for GTK1,2 and GTK3 is $0.73\% X_0$ and $0.62\% X_0$ respectively.

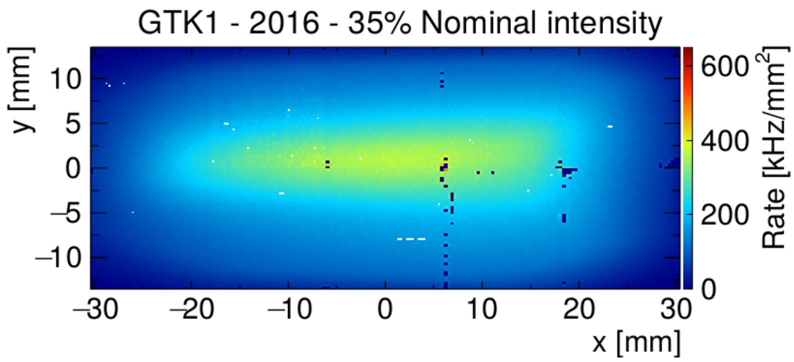

Figure 4: Hit rate per pixel in kHz/mm^2 in the first GTK module recorded in 2016 at around 35% of nominal beam intensity.

During data taking, the stations were operated at a bias voltage of 100 V. The beam intensity was around 35% of the nominal intensity in 2016 and 60-65% in 2017. A typical hit map from 2016 data taking period is shown on the Figure 4. At the end of the 2017 data taking period, a peak (average) fluence of $1.3(0.26) \times 10^{14}$ $1MeVeq.n/cm^2$ was integrated in the stations installed first (GTK1 and GTK3). This corresponds to around 60 days of operation at full beam intensity.

3.1 Time resolution

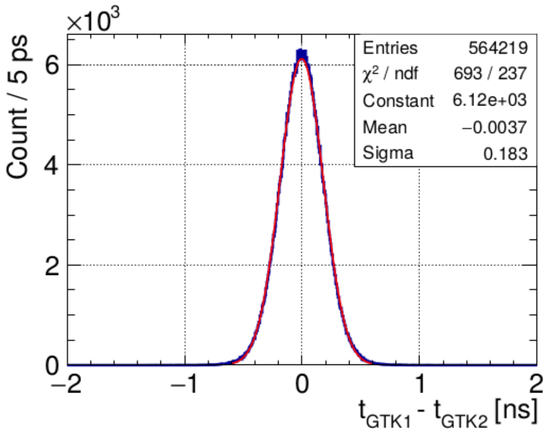

Figure 5: Time difference distribution between hits in the first and second GTK statio corresponding to the same K^+ track. A Gaussian function is fitted to the distribution (red).

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

To measure standalone resolution the three GTK station to station time differences were compared (Figure 5). Assuming that the time measurements are not correlated, the hit time resolutions are $\sigma(GTK1) = 132ps$, $\sigma(GTK2) = 127.1ps$ and $\sigma(GTK3) = 129ps$ resulting in a track time resolution of 74.7 ps.

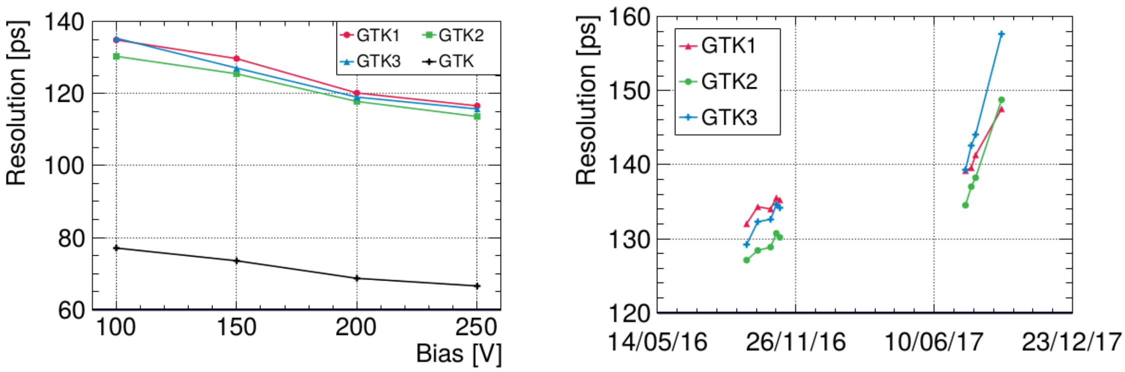

Figure 6: GTK station time resolution and average time resolution as function of the bias voltage (left) and evolution of the time resolution over time (right)

The time resolution was also studied at different sensor bias voltages during a ten day period at the end of the 2016 data taking period. The results show a systematic improvement of the station time resolution of 20 ps increasing the sensor bias from 100 V to 250 V with 50 V step (see Figure 6 left). A single station time resolution of 115 ps and a track resolution of 65 ps was achieved at a bias voltage of 250 V.

Since the same detectors were used during the data taking periods of 2016 and 2017, GTK time resolution can be studied as a function of time. The results of this study are shown at the Figure 6 right. Time resolution increases over time and reaches 146–158 ps at the end of the 2017 data taking period which can be explained as an effect of the detector irradiation.

3.2 Kinematics performances

As it was discussed in the first section, the Gigatracker kinematic performances are crucial for efficient background rejection. The figure of merit in this study is the squared missing mass resolution for $K^+ \to \pi^+\pi^0$ decay.

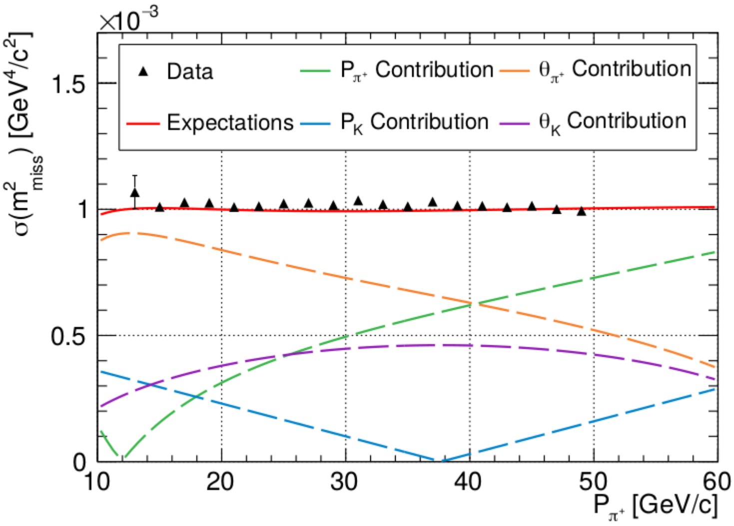

Figure 7: Squared missing mass resolution for $K^+ \to \pi^+\pi^0$ as function of the π^+ momentum for the 2016 data (black triangle) overlaid with the resolution expected based on nominal performance (plain red line) and the expected contributions (dashed line).

The resolution of the squared missing mass for $K^+ \to \pi^+\pi^0$ decay as a function of the charged pion momentum for 2016 data is shown on Figure 7. The agreement between data and the expectations based on nominal performance indicates that the angular and momentum resolutions obtained with the GTK match the design specifications.

4. Conclusions

The NA62 beam spectrometer GigaTracker was designed to provide precise measurements of momentum, direction and time of incoming beam particles in a 75GeV hadron beam with a rate of 750MHz. Its challenging design specifications required a radically novel approach to tracking, based on particle time-stamping at the sub nanosecond level. A custom made chip, the TDCPix, which aimed to provide time resolution better that 200ps, carefully designed sensor and a micro-channel cooling plate, which was the first application in HEP, allowed the GTK to achieve requested performances. Moreover, the time resolution for the single hit reached 115 ps, which corresponds to a track time resolution of 65 ps, surpassing the specifications.

References

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