PROCEEDINGS OF SCIENCE

GigaTracker, the NA62 Beam Tracker

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The GigaTracker measures the momentum, the direction and the crossing time of all the NA62 secondary beam particles. It is composed of three hybrid silicon pixel stations and four achromatic magnets. All the stations have a rate capability above 750 MHz, a single hit time resolution better than 200 ps and a thickness less than 0.5 % of X/X_0. The stations' sensor is read out by ten custom *TDCpix* ASICs. An innovative microchannel cooling solution is used to keep the sensor temperature below 0 °C. The stations are operated in vacuum and are easily swappable.

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1. Introduction

NA62 is a fix target experiment hosted at the CERN SPS. Its main objective is to measure the branching ratio (BR) of the rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay with a relative statistical uncertainty around 10 % [1]. A better experimental knowledge of this channel can lead to new constraints on beyond the Standard Model physics scenarios. Indeed, many of them predict effects on the $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio [2, 3, 4]. The first beam will be delivered to the experiment October 6, 2014. A first two months data taking period will allow us to commission the subdetectors and the data acquisition systems. Subsequently, NA62 is scheduled to take data for at least three years.

The Standard Model prediction is $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$ [5]. The first uncertainty is related to the input variables (CKM mixing matrix parameters, top quark mass, etc.) while the second is linked to the theoretical development. The best measurement of the branching ratio was made by the E949 collaboration at the Brookhaven AGS. They collected seven candidates using a stopped Kaon technique. They reported $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [6]. The uncertainty is mainly due to the low statistics.

1.1 NA62 Experimental Technique

The NA62 beam is formed by the impact of the SPS primary proton beam on a beryllium target. Subsequently, a 100 m beam line takes care of the momentum selection and the shaping of the secondary beam. The final product is an unseparated 75 GeV/c beam (p:π^+:K^+,10:3:1) covering an area of about 27.5 mm × 11.4 mm.[1]

NA62 uses a decay in flight technique. The experimental setup can be divided into two parts. The upstream section detectors measure the secondary beam properties while the downstream ones analyses all the decay products of the secondary beam. The undecayed particles goes through the downstream detectors without interacting with them. The upstream and downstream regions are separated by a 60 m evacuated decay volume (the pressure is about 10^{-6} mbar) surrounded by photons vetoes.

Up to 92 % of the background for the $K^+ \to \pi^+ \nu \bar{\nu}$ signal is rejected using the $m^2_{\mathrm{miss}} = (p_K - p_\pi)^2$ variable. For the remaining 8 % and to increase the rejection factor we rely on veto detectors and particle identification.

Two spectrometers, GigaTracker (GTK), upstream of the decay volume, and STRAW, downstream of the decay volume, provide the kinematic information entering the m^2_{miss} computation. The required resolution on the m^2_{miss} variable led to the GTK specifications in term of momentum and angular resolution.

A complete description of the NA62 detector can be found in [1].

1.2 GigaTracker, a Thin and Fast Silicon Pixel Tracker

GigaTracker is a magnetic spectrometer, its role is to track the secondary beam particles [7]. The active part of the detector consist of three identical hybrid silicon pixel stations. To allow the momentum measurement one station is displaced by 60 mm with respect to the beam axis and

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[1] Beam size at the third GigaTracker station. The sizes are defined as two times the beam RMS.

placed between four achromatic magnets. The two first stations are 13.2 m apart while the second and third are 9.6 m apart.

To meet the requirements in terms of missing mass the relative momentum resolution and the absolute direction resolution must be about 0.2 % and below 16 µrad, respectively. Furthermore, to match the decay products with the parent particle hit time resolution has to be below 200 ps. The read-out electronic has to cope with a spatially non-uniform beam rate of 750 MHz. Finally, to minimize the beam induced background and to preserve the beam divergence the material budget has to be kept below 0.5 % X/X_0 which corresponds to 470 µm of silicon.

2. Sensor and Front End

The GigaTracker stations track all the beam particles. The beam rate is about 750 MHz which corresponds to 120 kHz/pixel at the center of the sensor. The sensitive 60.1 mm × 27.3 mm surface covers all the beam area. Ten TDCpix [8] read-out ASICs are bump bonded to each sensor. The chips are arranged in two rows of five chips. The upper row is mirrored. The whole forms a GigaTracker assembly.

2.1 Sensor

The GTK assembly is build around a 200 µm thick planar silicon sensor. The most probable charge released by the crossing of a 75 GeV/c Kaon is about 2.4 fC. The thickness was chosen to meet the strong timing requirement while keeping the total material budget under 0.5 % of X/X_0 in the beam area. The silicon sensor is segmented into 200 × 90, 300 µm × 300 µm, pixels. In the inter-chip region the pixel size is increased to 400 µm × 300 µm to avoid any geometrical inefficiencies.

The baseline sensor type is p-in-n. However, TDCpix ASIC can also handle n-in-p type sensors. The n-type sensor bulk is phosphorous doped. Its typical resistivity is 4 - 8 kΩ. A multi guard ring structure is implemented in to allows high bias voltage (300 - 600 V) and to reduce the leakage current.

The particle fluence at the center of the sensor will be around 2×10^{14} 1 MeV n eq./cm^2 after 100 days of operation.

2.2 Read-out Chip

The read-out ASIC, the TDCpix, was developed specifically for GigaTracker. It uses a 130 nm CMOS process. Each chip covers an area of 12 mm × 20.37 mm and reads out 1800 pixels. The ASICs are thinned to 100 µm. One end of the chip overhangs from the sensor by 5 mm and is therefore out of the beam acceptance. All the connection pads are placed at the end of the overhang.

The chip is divided in four logically identical QuarterChip (QChip). An "end-of-column" (EoC) architecture is used. The digital electronic is concentrated in the EoC region of the chip. There are no clock signals distributed in the analogue pixel array (Fig 1). In each pixel, the charges are collected by a fast charge preamplifier. The signal is then passed to a shaper with a peaking time of about 5 ns and finally to a time over threshold discriminator. The signal is then asynchronously sent over a transmission line to the digital section of the chip, in the EoC region. There, five not neighboring pixels are connected to a single TDC which timestamps the leading and trailing edge

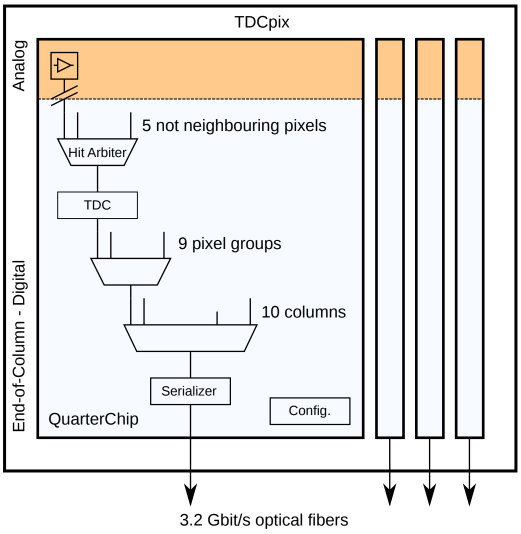

Figure 1: Sketch of the architecture of the read-out chips. Each chip is subdivided in four identical QuarterChip sections.

of the signal. In case of simultaneous hits in a group, a *pile-up bit* is set to indicate that the trailing edge timing information may be inaccurate. The probability to have more than one hit in a group was simulated to be 0.67 % for the central chip and with a one gigahertz beam rate. The TDC bin size is about 97 ps. Finally, the data stream is shipped off the chip via four 3.2 Gbit/s serializers. The TDCpix can handle 210 MHits/s.

To reach the required time resolution one has to compensate the time walk dependency over the energy deposition. The correction algorithm exploits the relation between the time over threshold and the time walk. A linear correction per pixel is foreseen, it will be applied offline.

The TDCpix chips are connected to the sensor by flip chip bonding. The quality of the bonding process was assessed using dummy assemblies. Resistance measurements were carried out on bump bounds chains. The first results are good, with a yield above 99 %.

To assess the performance of the electronic a test beam was done at the CERN PS. Four 45 pixels GTK demonstrator were put in the beam. After time walk compensation and for a bias voltage of 300 V the hit time resolution was found to be about 175 ps. The margin on V_{bias} will allow us to compensate for the radiation damage (Fig 2).

The performances of the GTK assembly are summarized in Table 1.

3. Electrical Integration

The GTK assembly is connected to the off-detector data read-out and to the low and high voltages power supplies via the GTK carrier printed circuit board (GTK carrier PCB). It carries the high speed serial links, the control links, and the power supply lines trough the atmosphere-vacuum interface. The GTK assembly is attached to the GTK carrier with a three point fixation system. This arrangement reduces the mechanical stress while keeping a good alignment precision. The electrical connections are assured by wire bonds.

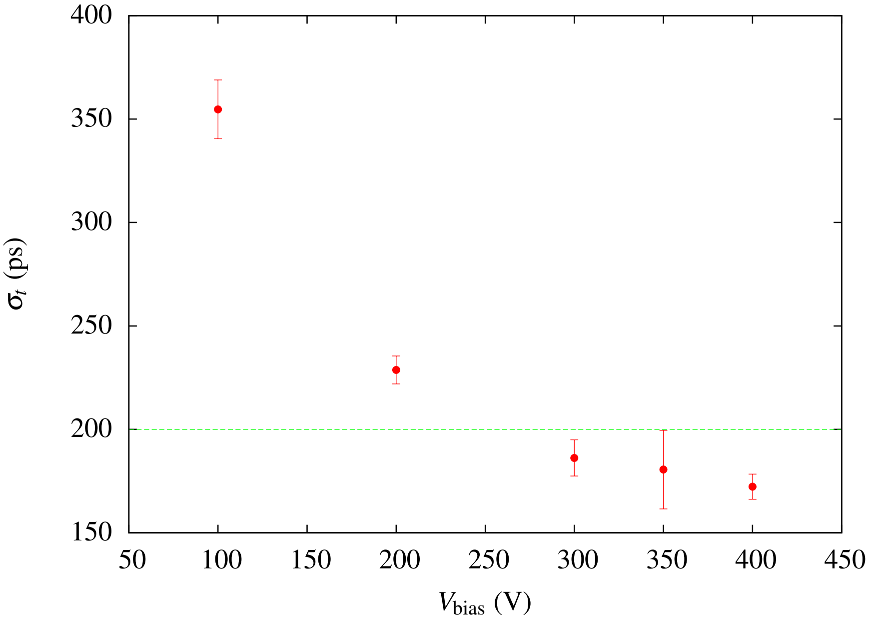

Figure 2: GigaTracker demonstrator hit time resolution. The results were obtained during a test beam at CERN PS.

TDCPix full chain jitter	< 72 ps RMS
Hit time resolution (test beam)	< 200 ps RMS
Hit spatial resolution	86 µm
Max. hit rate capabilities	Up to 210 MHits/s/chip
Material budget	< 0.5 % X/X_0
Maximum fluence	Up to 2×10^{14} 1 MeV $\text{n}_{\text{eq}}/\text{cm}^2$
Power dissipation	3.2 W/chip

Table 1: Figures of merit of the GTK assembly.

The low voltage power supplies are installed next to the detector in the cavern. High voltage power supplies and the GTK off-detector read-out boards (GTK-RO) are sitting in the upstairs counting room. Each station ships the data to ten GTK-RO boards over forty optical links. Clock distribution, configuration and status links are also running between the stations and the GTK-RO boards.

The GTK-RO boards buffer the data while waiting L0 trigger decisions which arrives with a latency of about 1 ms. The boards also take care of the distribution of the timing, trigger and control signals to the TDCpix ASICs using a TTC interface. Upon reception of a trigger decision, the GTK-RO boards send the data that fall in a 75 ns time window around the selected event to the NA62 off-the-shelf PC farm via Gigabit Ethernet links.

4. Thermo-mechanical Integration

Each TDCpix chip dissipates about 3.2 W of power. The power dissipation is not uniformly distributed over the chip surface. Indeed, the contribution from the analog section and the digital section are 0.4 W/cm^2 and 2.5 W/cm^2, respectively. Since the stations are in vacuum and because the sensor has to be cooled to below 0 °C to mitigate the radiation damage effects the heat has to be actively removed. The allowed material budget for the cooling solution is around 0.15 % X/X_0. The previous considerations put strong constraints on the cooling technique. After a careful review a microchannel cooling solution was selected.

4.1 Microchannel Cooling

A microchannel plate consists of a set of capillaries etched in a piece of silicon that is afterwards covered by another piece of silicon. Both parts are are joined together by anodic bonding. Liquid perfluorohexane (C_6F_{14}) is forced through the capillaries to remove the heat. This arrangement opens new integration possibilities.

For the GigaTracker application, the capillaries cross section is 200 µm × 70 µm. The pitch between them is 400 µm. The top and bottom walls are thinned to 30 µm in the beam acceptance region leading to a total of 130 µm of silicon in the beam. One the side, four connectors are brazed to distribution manifolds. A set of tubes are carrying the cooling fluid to the plate. To meet the cooling requirements the foreseen mass flow is 8 g/s. The Cooling Plant can provide fluid in a range between -10 °C and -25 °C. The operating temperature will be optimized to limit the radiation damage. A 300 W cooling plant is installed in the vicinity of the GTK stations. It should be noted that this is the first application of microchannel cooling in high energy physics.

Tests were carried out with dummy GTK assembly that reproduce the nominal power dissipation spatial distribution. Maximum temperature difference was found to be 1 °C across the sensor, 3 °C across the chip and < 5 °C across the GTK assembly. The fluid temperature at the inlet was -20 °C.

4.2 Mechanical Integration

Each GTK carrier assembly is fixed to an aluminum frame witch is bolted on a vacuum flange. Part of the GTK carrier PCB goes thought the flange and carries the signal, control and power lines outside of the vacuum. Great care was taken to reduce the material surrounding the beam area. The two first stations sit in independent vacuum vessel while the third station share the CHANTI detector vessel. All the stations are easily swappable since regular exchange is foreseen due to radiation damages.

5. Conclusion

GigaTracker provides key kinematic information needed to reach a background rejection factor of 10^{-12} for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay.

The stations tracks the whole NA62 secondary beam. They can handle a crossing rate above 750 MHz. The hit time resolution was shown to be higher than 200 ps under real conditions. An innovative microchannel cooling solution allows to keep the sensor at a temperature below 0 °C, in vacuum, with 130 µm of silicon in the beam acceptance. It is the first application of such a technique in high energy physics. The station total thickness in the beam area is 450 µm, lower than 0.5 % of X/X_0.

GigaTracker is now ready to deliver its first data. A three months data taking period starting October 6, 2014 will allow us to commission the detector for the 2015 NA62 physics run.

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