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The CHarged ANTIcounter for the NA62 experiment at CERN

F. Ambrosino[a,b], G. Corradi[c], D. Di Filippo[a,b], P. Massarotti[a,b], C. Paglia[c], V. Palladino[a,b], M. Napolitano[a,b], G. Saracino[a,b,*], L. Roscilli[b], D. Tagnani[c]

[a] *Università degli studi di Napoli Federico II*
[b] *INFN sezione di Napoli*
[c] *INFN Laboratori Nazionali di Frascati*

Abstract

The NA62 experiment at CERN aims at the very challenging task of measuring with 10% relative error the Branching Ratio of the ultra-rare decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, which is expected to occur only in about 8 out of 10^{11} kaon decays. This will be achieved by means of an intense hadron beam, an accurate kinematical reconstruction and a redundant veto system for identifying and suppressing all spurious events. In particular, beam induced background, caused by inelastic interactions of the hadron beam with the Si based detector which measures kaon momentum (the so called Gigatracker, GTK) can mimic the signal in case only one pion is detected downstream. To suppress this background we have designed the so called CHarged ANTIcounter (CHANTI) i.e. a series of six guard counters, to be operated in vacuum and covering a wide angular region downstream the last GTK station. CHANTI must have time resolution ~1 ns, must be highly efficient in detecting charged particles and must cope with rates which in the inner part can be some kHz/cm^2. We have adopted a solution based on triangularly shaped scintillator bars coupled with fast wavelength shifting fibers and individually read by means of Silicon Photomultipliers (SiPM). The full scale prototype of one counter has been built and tested using a prototype front end electronic board which allows fast amplification and individual channel fine bias setting with O(mV) resolution and 0.1% stability. We show first results on the response of the detector to minimum ionizing particles as well as on its time resolution, which are well in line with the specifications.

Keywords: NA62, kaon decay, veto, scintillator, fiber, Silicon Photomultiplier, MPPC

1. Introduction

The NA62 experiment [1] has been proposed to measure the very rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at the CERN SPS. Assuming a branching ratio of $\sim 10^{-10}$ and a global signal efficiency of ~10%, the experiment is designed to collect ~100 events in two years of data taking with a signal to background (S/B) ratio of 10:1. Presently, the only existing measurement is based on nine signal events collected by BNL-AGS-E787(E949) [2], that estimated a BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) $= 17.3^{+11.5}_{-10.5} \times 10^{-11}$. The Standard Model predicts for this decay a B.R. of 8×10^{-11} with 5% error, so an accurate

*Corresponding author
Email address: saracino@na.infn.it (G. Saracino)

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measurement of this B.R. allows a precise test of the Standard Model and a measurement, with 10% error, of the CKM parameter $|V_{td}|$ ([3],[4]),[5]). Furthermore, as this decay is very sensitive to physics beyond the Standard Model, clean signal of new physics could be obtained ([6],[7]).

2. Experimental remarks

The experimental requests needed to achieve the measurement are particularly demanding. The kaon beam must be very intense in order to collect a significant statistics sample in reasonable time. The kaon beam, with a mean momentum of 75 GeV/c and a $\sigma(p)/p \simeq 1\%$ spread, will be produced by impinging 400 GeV/c protons from CERN SPS on the NA62 target. The main advantage of using high kaon momentum is in the resulting high photon energy from π^0 decay which improves the photon detection efficiency. The main disadvantage is that pions and protons cannot be separated by kaons and constitute ~70% and ~20% of the beam respectively. Precise measurement of the beam particles momentum and arrival time are needed in order to reconstruct the kaon decay vertex. This task is accomplished by a silicon based detector called Gigatracker (GTK) consisting of three different stations.

The number of SPS proton per pulse will be 3×10^{12} with a duty cycle of 4.8 s spill every 16.8 s. This should allow to produce 4.8×10^{12} K^+ decay per year. With a signal acceptance of ~ 10% and a BR of 10^{-10} we can collect ~50 signal events per year.

A critical point is the rejection power of all the much more probable kaon decays that can mimic the signal. In order to obtain the expected S/B a suppression of order 10^{12} must be obtained. Particular care is needed for the two-body decays $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$, that have BR up to 10^{10} times greater than the signal one. To achieve this result kinematical constraints and particle identification have to be used in conjunction. This is done by using straw-tubes detector to track charged secondaries and a set of different detectors to identify photons and muons [8] . A schematic layout of the NA62 apparatus is given in fig. 1.

3. CHANTI Detector: purposes and requirements

The Charged ANTI (CHANTI) detector is required in order to reduce critical background induced by inelastic interactions of the beam with the collimator and the GTK stations as well as to tag beam halo muons in the region immediately close to the beam. The most critical events are the ones in which the inelastic interaction takes place in the last GTK station (GTK-3). In such cases, pions or other particles produced in the interaction, if emitted at low angle, can reach the straw tracker and mimic a K decay in the fiducial region. If no other track is detected, these events can appear like a signal event, i.e. one single π^+ in the final state. A GEANT4 simulation has shown that kaon inelastic interactions with GTK-3 happen in about 0.1% cases, so that the combined rejection factors of the analysis cuts and the CHANTI veto must lead to a remaining inefficiency of 10^{-8}. The purpose of the CHANTI is to identify inelastic interactions in the GTK by tagging particles at higher angles with respect to the beam. This can be achieved by placing a number of guard counters right immediately after GTK3. At the same time the CHANTI can also veto beam halo (muons) in the region closest to the beam.

The CHANTI detector must be able to tag inelastic events with high efficiency. Given that it will be sensitive to the muon halo and to the inelastic interactions the expected rate of particles that release enough energy to be detected will be around 2 MHz. Even if it is not intended as a trigger veto at L0, the CHANTI must have a good time resolution (≤ 2 ns) to keep the random veto rate at an acceptable level: for instance, assuming a 5 sigma (10 ns) time coincidence window with the event fine time at reconstruction level, a 2% inefficiency on the signal would be induced by CHANTI random vetoes. Although tracking capability may be not mandatory for the system, it can help in distinguishing beam halo events from inelastic interactions and in monitoring the beam halo itself very close to the beam. Last but not least, position sensitivity is useful in improving time resolution without increasing too much the granularity of the detector. Charge measurement is needed only to the extent of obtaining time slewing corrections, and, in the layout proposed, to improve the spatial resolution.

4. CHANTI design

The CHANTI is composed of six stations, of square shape, placed inside the vacuum tube respectively at 27-77-177-377-777-1577 mm distance from the GTK-3. Outer square side length is 300 mm and presents a rectangular hole

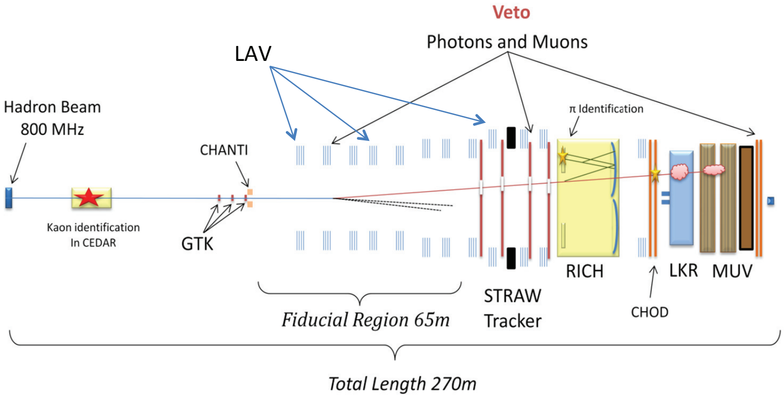

Figure 1: The NA62 detector layout.

of 65 mm in y and 95 mm in X due to the rectangular shape of the beam. For particles hitting the GTK-3 center the CHANTI covers hermetically the angular region between 38 mrad and 1.38 rad w.r.t the beam axis, for particles hitting one of the GTK-3 corners the coverage is hermetic between 57 mrad and 1.16 rad. This must be compared to the highest angle under which a Large Angle Veto (LAV) station is possibly able to detect particles produced in the GTK-3 that is 49 mrad for particle produced at GTK-3 corner, so that LAV complements at low angles the information given by CHANTI. The CHANTI, by itself, is able to veto about 95% of all inelastic interactions of K in GTK-3 regardless of the final state. This vetoing efficiency reaches almost 99% if one restricts to potentially signal-like events, namely the ones where the kaon either did not survive the inelastic interaction or did not decay in the fiducial volume, and one track is reconstructed by the straw spectrometer. Each station is made up of two layers, called layer x and y respectively. A y(x) layer is composed of 22 (24) scintillator bars arranged parallel to the x(y) direction and individually shaped at the appropriate length. Each layer is composed by two sublayers, made of 10+12 (10+14) bars, and staggered by half bar. Each bar is triangularly shaped, and two staggered bars face oppositely as shown in fig. 2. Light is collected by means of one WLS fiber placed inside each bar and read at one side by a silicon photomultiplier (SiPM).

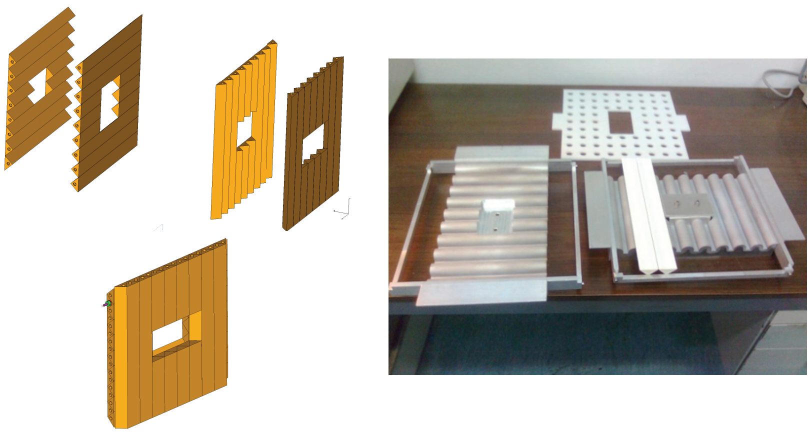

Figure 2: Left: Layout of a complete CHANTI station. Right: Jig used to align bars during gluing; on top Teflon mask to distribute glue spots

The basic building block of the CHANTI is a scintillator bar in form of a triangular prism similar to the ones used in the D0 pre-shower detectors [9] and in the MINERVA experiment [10]. It is produced at the NICADD-FNAL extruded scintillator facility [11] and consists of an extruded polystyrene core (Dow Styron 663 W) doped with blue-emitting fluorescent compounds (PPO 1% by weight and POPOP 0.03% by weight) and a co-extruded TiO_2 coating

(0.25 mm thick) for reflectivity. The cross-section of the bar is a isosceles triangle with a base 33 mm and height of 17 mm, with a hole placed at 8.5 mm from the base . The hole has 1.7 mm diameter to host a WLS fiber. Optical glue ensures the coupling between the fiber and the scintillator. The main characteristics of the scintillator are: good light yield (comparable with Kuraray SCSN-81one), radiation hardness (5% degradation observed after 1Mrad irradiation), low cost and fast response (few ns). The WLS fiber used is Bicron BCF92 [12] and have been chosen for the short fluorescence time (2.7 ns). The fiber is read only at one side and, in order to recover light emitted in the direction opposite to the photodetector, it has been mirrored at one end, by means of Al sputtering in vacuum, using the same technique developed for the fibers of the ALICE e.m. calorimeter [13]. The WLS fiber is coupled to a SiPM device for photon detection. The triangular shape allows a gap-free assembly when two bars are put one facing the other, in an almost self-sustaining shape. Moreover, the amount of light shared between two adjacent bars depends on the position of the impact point of the particle w.r.t the triangle centers (i.e. the position of the WLS fibers). This allows to determine the impact position in the direction orthogonal to the fiber with about 3mm resolution, much better than the one expected for rectangular shaped bars (roughly 10 mm) given the 33 mm spacing of the fibers.

The six CHANTI stations are placed inside a single vacuum tight vessel of rectangular cross-section, together with the GTK-3 station. A light Al frame is supporting mechanically each station to avoid any risk of ungluing and to fix the station to the outer vessel. One station is composed of 46 bars with different length. The bars outside the beam gap, called long bars (L), have all of the same length of 300 mm. Since the gap is of rectangular shape, the bars in the central parts are of two different lengths, depending whether they are in the horizontal layer or in the vertical one. They are the so-called middle (M) bars of 117,5 mm length and the short (S) bars of 102,5 mm length. Every scintillator bar is provided with a custom designed connector (see fig. 3) which is inserted in a precision hole (1.02 mm diameter) and coupled to the photodetector. A precisely machined screw cap holds the photodetector in the right position. Alignment between the fiber center and the photodetector sensitive area is guaranteed at the level of 50 μm and is dominated by the tolerance in the position of the photodetector area w.r.t. its frame as provided by Hamamatsu. It is worth to note that it is possible to substitute a photodetector by just unscrewing the connector. Moreover, quality tests can be easily arranged by using the same photodetector for all bars. The precise definition of the position of the bars is given by a custom machined reference jig, (see fig. 2.) on which each bar is placed cusp down to form a planar surface with the nominal dimensions. Bars in the orthogonal direction are then glued to these ones to form a waffle like structure . The complementary bars are finally added in both directions to form the final planar station.

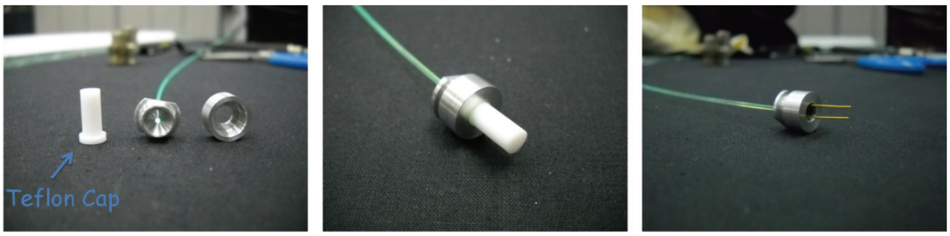

Figure 3: Fiber connector: Left:components. Center: assembled connector. Right:Connector with SiPM

5. Photodetectors

The use of Silicon Photomultiplier (SiPM) [14],[15],[16] devices as alternative to traditional photomultipliers tube (PMT) is becoming a widespread solution in particle detectors when high number of channels or high level of integration is needed.

SiPMs are intrinsically radiation hard devices. There is however, as for all semiconductor detectors, a known issue with their behavior after intense neutron flux irradiations. The ASTM E722-93 standard practice allows to compare damage on silicon devices from different neutron sources by normalizing it to the damage induced by mono energetic 1 MeV neutrons. In this context the figure of merit of an environment for SiPM devices is the number of equivalent 1 MeV neutron /cm^2 crossing the detector. It is known from literature [17] that a neutron irradiation corresponding to $4 \times 10^8/\text{cm}^2$ 1 MeV equivalent neutron or less gives no visible effect on SiPMs, while increasing further the irradiation the dark noise starts increasing, reaching about 10 times its initial value at about $2-3\times10^9/\text{cm}^2$

neutron fluence. Even if a 10 times larger noise w.r.t. to the standard one could still be manageable by increasing the threshold by 1-2 p.e., we have checked that the radiation should be below this level at the CHANTI for at least two years of operation. Two different simulation have been carried out: the first, using FLUKA, has shown that the neutron dose at the CHANTI, generated by the primary proton beam on target should be of the order of 0.04 Gy/y which corresponds roughly to 10^8neq/cm^2/y. The second simulation has been done using GEANT4, to understand the contribution to the neutron flux from the inelastic scattering of the beam in GTK, which were not considered in the first simulation. It has shown that the expected neutron fluence from GTK corresponds to less than 10^8neq/cm^2/y. Combining the two result we have that in two years running of NA62 the CHANTI SiPMs should integrate no more than 4×10^8neq/cm^2 i.e. should operate in safe conditions. In order to choose the best solution for our photodetectors we tested some Hamamatsu SiPM series 13-50, 11-50 and 11-100 (first number 13 or 11 is the SiPM dimensions in tenths of millimeter, second number 50 or 100 is the pixel size expressed in microns). Hamamatsu provides, for each SiPM, specifications and working parameters as bias voltage, gain and dark rates, all of them measured at 25°C. In order to reproduce climatic conditions we used a thermostatic chamber that could fix temperature better than 0.1°C. A collimated Sr^{90} source has been used to compare different devices coupled to the same scintillator bar. Signals are amplified using a fast 10X amplifier. Data are collected using a Tektronix TDS5054 5GS/s oscilloscope via GPIB connection and a custom LabView program. Oscilloscope bandwidth is 500MHz, enough to follow few nanoseconds signal rise time. Relative comparison in terms of number of photoelectrons collected is our figure of merit. First of all we measured for each SiPM single photoelectron response (SPR), this operation has been done using thermal-generated signals (dark noise). Once obtained the single photoelectron normalization factor the ratio signal/SPR for the irradiated bar could be used to compare different devices. Measured light yield for each SiPM is reported in [8]. We concluded that SiPM serie 11-50 has a significantly lower photoelectron yield, while both 13-50 and 11-100 series seem viable solutions for our purposes. The CHANTI detector is located in the TTC8 cavern site at Prevessin. The gallery temperature is known to be quite constant during the whole year: T=20/pm1 C. This small variation is monitored by a set of temperature sensors located on each of the six CHANTI station. It is worth to note that the extremely small value of the power dissipated by the sensors (less than 10 μW) can be dissipated through black body radiation in vacuum without noticeable temperature increase. The change of the SiPM temperature has, as principal effect, the change of the breakdown voltage Vbd (about 50 mV/C). In order to keep constant the main SiPM parameters, gain and photo-detection efficiency, the over-voltage Vbd- Vbias must remain invariant. This can be achieved by changing the Vbias voltage that can be modified independently for each channel with a step of 10 mV by the slow control. For each sensor this will be done taking into account the value of its Vbd and the slope of its variation with temperature which will be measured in the range 15-25 C, using a thermostatic chamber, prior to installation.

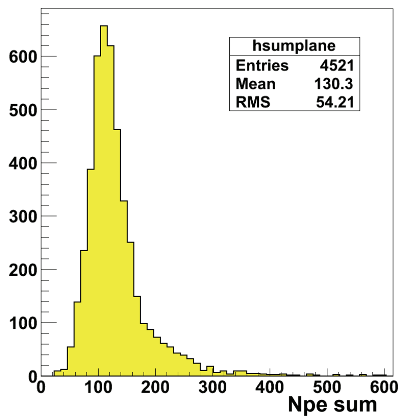

Figure 4: Photoelectron yield measurement using cosmic rays. The sum of the number of photoelectrons produced by two neighbor triangular bars is shown, corresponding to ~ 1.7 cm of scintillator crossed

In order to have an absolute scale of the expected number of photoelectrons for a MIP we selected cosmic rays almost perpendicular to the scintillator surface : results show that scintillator bars, cut at about 300 mm length, and equipped with a (mirrored at one side) BCF92 fiber coupled to a Hamamatsu S10362-13-050-c. generates an average $\geq$ 100 p.e./plane if crossed by perpendicular MIPs i.e. more than 50 p.e. per channel/ MIP (equivalent to $\sim$ 25 p.e./MeV (see fig. 4). This allows to operate the device with a threshold in the range of 3-4 p.e. per channel or more with negligible efficiency losses.

6. Prototype construction

CHANTI prototype has been assembled in Napoli at the end of July 2010. It is a full dimension prototype of a X-Y station. Scintillator bars for the prototype were obtained courtesy of FNAL and Al sputtering of the fibers was performed at LNF. The construction procedure adopted is hereby briefly described. First to simplify the mechanical assembly some custom tools were developed. The assembly took about 20 days and can be divided in three main parts: 1) Gluing fibers into bars, 2) Test of the bars, 3) Assembly all test-passed bars into final X-Y station. All operations have been done in a class 100 clean room environment and all components have been accurately washed using an ultrasound cleaning before manipulation. The gluing of the fibers into bars is done in two steps. First mirrored fibers and connectors are glued together and finally this ensemble is glued into a bar. Each connector is provided together with a Teflon cap used as tool to define a reference plane for the fibers as well as to protect the polished side of the fiber during transport and handling.

During the prototyping phase different glues were tested and the epoxy ARALDITE^{TM} 2011 was found to be the best choice for the gluing of fibers into the connector. Its high viscosity helps to prevent glue leaking into the wrong connector side. This glue is also solvent-free avoiding cladding damages. Optical properties are not important at this level, because no coupling is required. Fibers are plugged in their final position into connector, being careful they reach the Teflon cap. A special support has been developed in order to parallelize this operation. It is able to carry 24 fiber-connector couples. When the fiber is in its correct position glue is put using a syringe (with a 1.3 mm diameter needle).

Once obtained the fiber-connector ensemble they were glued into the bars. A custom tool allowing to fix the bars in vertical position was developed. It can host up to 10 bars, and is used to hold the bars during the hardening of the glue. Five days are necessary to glue all the bars of one station. Glue used is SCIONIX Silicon Rubber Compound RTV615, that guarantees a good fiber-scintillator optical coupling and is known from NASA database [18] to be low outgassing. The glue is injected from the bottom using again a syringe, this method reduces the risk of trapping air bubbles in the glue. The required glue quantities are adapted for each bar length (L $\rightarrow$ 2.1 ml , M $\rightarrow$ 1.0 ml, S $\rightarrow$ 0.9 ml). This is important in order to avoid leaking at the top of the bar. The whole prototype contains about 65 ml of glue.

Since after complete assembly any bar substitution is impossible a quality test before assembly is needed. For each bar the response to a Sr^{90} collimated beta-source is measured. Measurements have been carried out with the same setup described in section 5 for the SiPM comparison, in a controlled temperature environment using the same photodetector (an Hamamatsu 13-50 type) coupled each time to a different bar.

Relative comparison among different bars in terms of number of photoelectrons collected is again our figure of merit. We concluded that the bars quality is very uniform. Only one bar showed a significant difference. The cause of low light response was understood after inspection of the bar: the fiber edge was found slightly backward with respect to its reference plane facing the SiPM sensitive surface, leading to lower light collection efficiency.

Once all the material was ready, a prototype could be assembled in 2 steps. Each step takes one day. During the first day a half-layer X and Y are glued together. First of all bars are arranged on a jig, afterwards glue points (3M Scotch-Weld EPX^{TM} Adhesive DP490) are defined using a Teflon mask. Then the bars of the other half-layer were aligned on top. A second jig is put on top of the assembly to align the last half-layer. Pressure is added to increase the glue uniformity. Each glue spot contains 0.1ml of glue.

7. Readout

As previously sketched each scintillator bar is coupled individually to a SiPM which converts light collected by the fiber into electrical signals. Each SIPM has two pins which are used both to polarize it and to read these signals.

Bias voltage and signal are carried in and out, respectively, the vacuum vessel trough an appropriate vacuum tight flange using the same coaxial cable. Signal and SiPM bias voltage are carried by the same coaxial cable. A first piece of cable,1.5m long, is located in the vacuum tank, and from SiPM reaches the flange. A second piece of cable is 2 m long and reaches the FEE crate where the signal is amplified

Typical signals are expected of order of few mV (on 50 Ω impedance) with a fast rise time (1 ns) and a somewhat long decay time (in the range 10-100 ns). The maximum expected rate in input to the FEE will be, for the inner bars, of the order of about 1 MHz per bar, as shown by Geant4 simulations, plus the dark rate (for Hamamatsu SiPMs, some 100 kHz). In order to keep a safety factor, the electronics is being designed to cope with a 5 MHz rate. The FEE boards provide for each channel: a way to control the Vbias with O(10 mV) accuracy, a fast, DC coupled, conversion to a Time Over Threshold-LVDS signal output and a temperature and/or a dark current (with nA resolution) monitor for slow control adjustment of the Vbias. The LVDS output will be directly sent to a TEL62 board [19] equipped with TDC for both leading and trailing edge measurement. The total number of channels needed is 46 X 6 = 276. One TEL62 board equipped with three 128 ch TDC boards will be able to readout the whole system and provide also a large number of spare channels. The Time Over Threshold technique will allow also approximate charge measurement to improve the spatial resolution of the system. The CHANTI is not supposed to contribute to L0 trigger. The highest multiplicity in the CHANTI is expected from the beam halo events, who cross all six stations. If fully efficient on these events the system will give at most 4 X 6 = 24 hits or 192 bytes per event. These events occur at 1 MHz rate. Inelastic interactions in the GTK will be detected at approximately the same rate, with comparable hit multiplicity. So a maximum of 200 bytes at 2 MHz data flow can be safely estimated. Assuming a 1 MHz trigger rate and a readout time window of O(100 ns) one expects O(200 kHZ) of such events in coincidence with a trigger. This would generate a data rate of about 40 MB/s well below the TEL62 specifications.

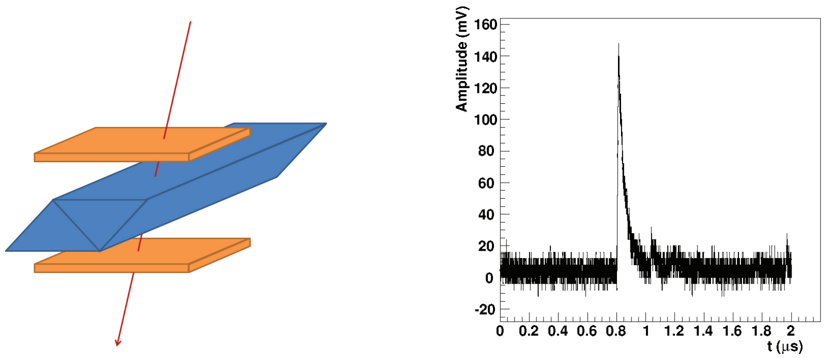

Figure 5: Left: Sketch of the setup to select cosmic rays. Rigth:Typical cosmic signal.

8. Time resolution measurements

In fig. 5 a sketch of the system used to measure the time resolution is shown. Two small ($3 \times 3cm^2$) scintillators coupled with standard phototubes select cosmic rays almost orthogonal to the couple of bars under test. Signal from SiPMs are pre-amplified after 1.5 long coaxial cable, to test the use of the pre-amplifiers outside the vacuum vessel where the detector is located. Preamplifier (20 ×) are mounted on a prototype board, where 6 channels are available. This board provide also the individual bias voltage for the SiPM , with an accuracy of O(mV) and 0.1% stability. Amplified signal are acquired after 3m long coaxial cable using an oscilloscope with 500 MHz bandwidth and 5 GS/s sampling. The logical AND between the two trigger scintillators is acquired in the same way. The full waveform of signals is acquired for off-line analysis. The detector prototype is located inside a climatic chamber where temperature is kept constant at 25±0.1°C during the data acquisition. The signal transit time at a fixed voltage threshold is evaluated from the registered waveform of each bar. In our analysis we chose a voltage threshold equivalent to ∼ 15 p.e. In fig. 6 (left) the time distribution is shown. In this plot no corrections are applied and a $\sigma = 1.0$ ns is obtained, including a contribution of $\sigma = 450$ ps due to the trigger. The main correction to the time resolution is the time walk due to the different amplitudes of the signal, originated mainly from the triangular shape of the bars. In our test set-up both the charge and the Time Over Threshold of the signals are available. We have found that the two methods are almost equivalent for cosmic rays. In the real experiment only Time Over Threshold will be available. Using this correction we found the distribution shown in the right plot of fig. 6 improving the time resolution (σ = 850 ps). The best time resolution is found combining data coming from both the bars. Using the mean value between the two times, if both signal are over threshold, otherwise only the one over threshold, the time resolution is reduced further, and a value of σ = 760 ps has been found (including the trigger contribution).

9. Conclusions

We designed a detector, based on plastic scintillator bars coupled with WLS fiber and SiPM sensors, to veto potential background due to inelastic beam interactions with the GTK detector. The main detector requirements are: capability to operate in vacuum, particles rate up to kHz/cm^2, high detection efficiency and time resolution ~1 ns. We built a complete station prototype. Preliminary measurements of the photoelectron yield and time resolution fulfill requested performances.

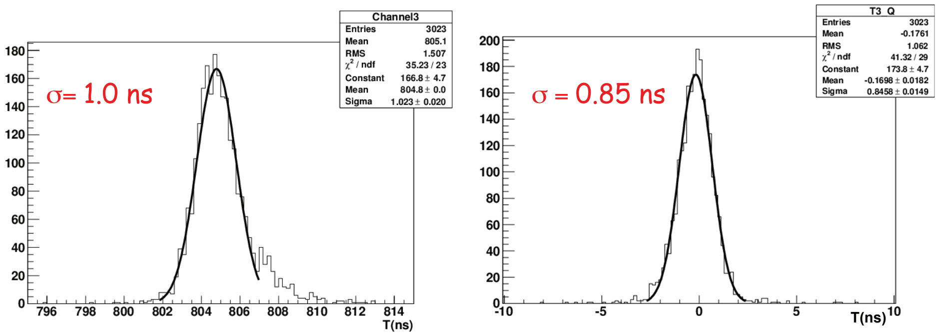

Figure 6: Time distributions: Left: No corrections applied. Right: Time Walk with Time Over Threshold correction applied

10. Acknowledgements

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