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KABES: a novel beam spectrometer for NA48

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Abstract *– In order to investigate predictions concerning CP violation in the charged kaon sector, a new beam line providing concurrently K^+ and K^- has been constructed at CERN for the NA48/2 experiment. Several modifications and upgrades have been made in the apparatus; one of them being the implementation of a beam spectrometer named KABES. This detector is based on the Time Projection Chamber (TPC) principle; the amplification of the ionization signal is achieved by using Micromegas devices. The performance of KABES is found to be excellent in high-intensity hadron beams. The achieved space resolution of 100 μm provides a measurement of track momentum with a precision better than 1% and the time resolution, better than 1 ns, allows the charged kaons in NA48 to be identified with almost no ambiguity. The measurement of the direction and momentum of the K^+ and K^- tracks makes possible the precise study of their decay modes, particularly those for which one or more particles escape detection in the NA48 detector.*

I. INTRODUCTION.

The main objective of NA48/2 is to measure small asymmetries from charged kaon decays into three pions [1] to reveal a possible signature of direct CP violation. The original set-up of NA48 for the detection of neutral kaon decays [2] has been modified to achieve this goal. The new K12 beam line is designed specifically to transport simultaneously positive and negative particles with a central momentum of 60 GeV/c. In order to compare the two channels $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ with minimal biases, the NA48 decay region is expanded upstream by 20 m to optimize the acceptance for charged kaon beams which are focused at the DCH spectrometer position. The positive and negative beams are produced with 400 GeV/c primary protons from the SPS accelerator with a nominal intensity on target of 7×10^{11} protons per 4.8 s duration spill, every 16.8 s. A narrow band spectrum of ~ 4% width around the nominal value of 60 GeV/c is selected with a set of dipole magnets, collimators and quadrupoles forming a front-end achromat located 14 m downstream of the target. The KAon BEam Spectrometer is located further downstream, starting at 55 m, where a second achromat is instrumented with high rate detectors to measure precisely the direction and momentum of each particle. This spectrometer makes use of two stations separated by 8 m along the beam line (Figure 1) in which small TPCs provide measurements of the transverse coordinates of the charged tracks.

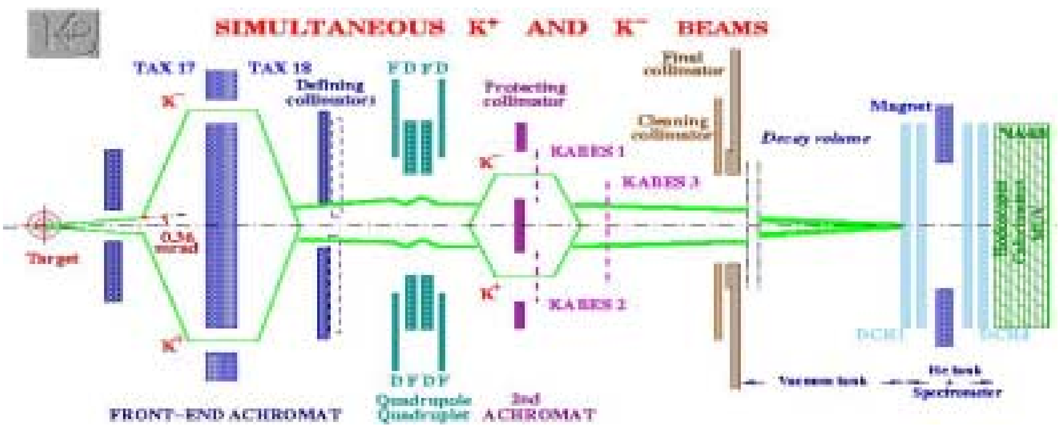

Figure 1: The K12 charged kaon beam line with KABES and K^+/K^- focusing at the DCH spectrometer.

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The upstream station, which contains two doublets of detectors, KABES-1 (up) and KABES-2 (down), is located at the position where the K^+ and K^- beams are separated in the achromat and allows the sign of the charged tracks to be identified. The downstream station, KABES-3, using only one doublet of detectors and positioned where the positive and negative particles are collinear, has to sustain the rate from both beams. This minimal spectrometer configuration with only two longitudinal positions has to rely on the focusing properties of the beams to obtain the momentum of individual K^+ and K^- particles from the difference between the vertical coordinates recorded in KABES-1/2 and in KABES-3. Typical beam intensities per spill in KABES are respectively 3.8×10^7 for the positive particles and 2.6×10^7 for the negative ones. In this configuration, K^+ and K^- represent about 6% of the total charged flux dominated by pions, providing about 2×10^4 reconstructed $K^\pm \rightarrow (3\pi)^\pm$ decays per spill.

II. DETECTOR DEVELOPMENT.

The efficient detection and accurate measurement of the charged particle tracks in the high intensity beams rely on both the Micromegas [2] and TPC techniques, the latter permitting the mesh to be positioned outside the high intensity region covered by the beam spot. To minimize the amount of material in the beam, two TPC-type detectors are used along the beam axis with opposite electric fields perpendicular to the track direction. In the first TPC of each doublet, the horizontal drift direction points to the left and in the second one, it points to the right so that the measured times on both sides provide accurate track time and horizontal position.

A feasibility test was performed in November 2001 to verify the basic principle of this detector. The TPC geometry is achieved with a prototype in which the opposite drift fields are obtained between two sets of parallel electrodes of 10x10 cm^2 area arranged as capacitors with a 6 cm gap. Micromegas devices built with 100 µm amplification gap are positioned in the central regions of the anode sides. The pulses from the front end preamplifier, available with or without RC filter before the discriminator stage, are transported for digitization to TDC modules housed in a CAMAC crate and read out with a PC. High-intensity hadron beams from the SPS/M2 line were made available to us by the NA58/COMPASS Collaboration. For each signal detected on the strips by the front-end circuit, the discriminator senses the leading time T_1 and the trailing time T_2. The Time over Threshold ToT $= T_2 - T_1$ represents the width of the ionization pulse. These ToT quantities provide crude but valuable information about the amplitudes needed to measure the vertical cluster position with the weighted strip coordinates while the horizontal position is derived from the drift time measurement. The test of this prototype, performed at up to 2×10^7 particles per spill, demonstrated good space and time resolution of 100 µm and 0.8 ns, respectively, with a spark probability per track below 10^{-9}. However, the drift velocity was deficient in uniformity and the 100 µm gap, producing signals with ToT larger than 50 ns, turned out to be marginal at the highest rates.

The detector development leading to the final design aimed at a more uniform electric field while keeping the longitudinal depth of the detector as small as possible in order to minimize multiple scattering in the various materials (Table 1).

Detector element	X/X_0 (10^{-3})
Beam-pipe windows	0.36
KABES windows	0.12
Gas mixture	0.74
Air gaps	0.07
Total	1.29

Table 1: Components of multiple scattering.

The field uniformity was improved by replacing the capacitor plates of the first prototype by two compact cages in which equipotential lines are engraved on thin Mylar windows (Figure 2). The field cages provide a constant gradient of 0.83 kV/cm resulting in a uniform drift velocity of 8 cm/µs. Two of them are mounted in each station and they operate with opposite polarity at a distance of 2 cm within the detection volume.

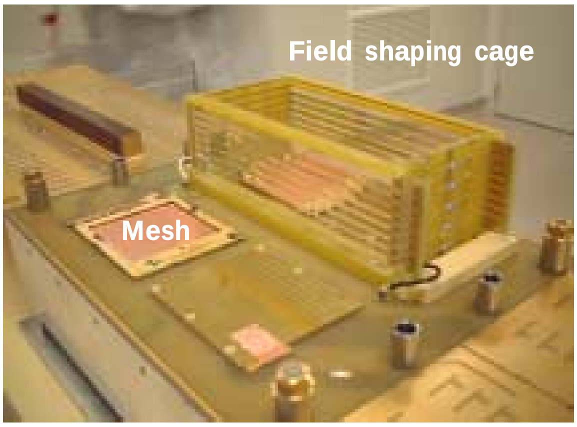

Figure 2: The field cage with aluminum lines and the mesh of the amplification gap.

Finally, the detectors installed in the beam have to withstand ~ 20 MHz of charged hadrons concentrated in a few cm^2 and to meet these requirements, a Micromegas mesh with a 50 µm amplification gap has been chosen. The meshes are produced at CERN [4] from a 50 µm thick copper-plated Kapton foil. After etching, the 5 µm thick copper layer contains 25 µm diameter holes with 60 µm pitch while Kapton is kept in form of spacers with a 0.835 mm x 0.835 mm two-dimensional pitch providing thus a self-supporting gap with uniform thickness. The 4x4 cm^2 tensioned mesh is glued on a metallic frame, which is screwed on a printed circuit board containing 4 cm long strips positioned parallel to the beam with a 0.835 mm pitch.

The gas in the detector is a typical mixture with three components and flows at about 5 liters per hour. It is pre-mixed in compressed bottles with Ne (79%) + C_2H_6 (11%) + CF_4 (10%) and gives satisfactory performance for this application. The sensitive gas in the TPC represents the largest contribution to multiple scattering (Table 1).

The detector in its modified mechanical configuration and with its final front-end electronics was ready in July 2002 for a second test. The latter was performed with 100 GeV/c hadrons on the H6 beam line at CERN. Protons extracted from the SPS with an LHC type structure containing buckets of 48 bunches, 25 ns apart, and repeated every 23 µs during a spill time of about 1.5 s, were used. The performance of the detector was studied under these conditions and up to an instantaneous intensity of $2x10^7$ particles per second. Careful analysis of the data confirmed that Micromegas detectors would make a valuable contribution to the NA48/2 physics program, and three identical stations were constructed. Two of them were installed on the K12 beam line (Figure 3) and their commissioning was completed a week before the beginning of data taking in May 2003. During 2002, the design, test and construction of the dedicated read-out system for KABES were also completed.

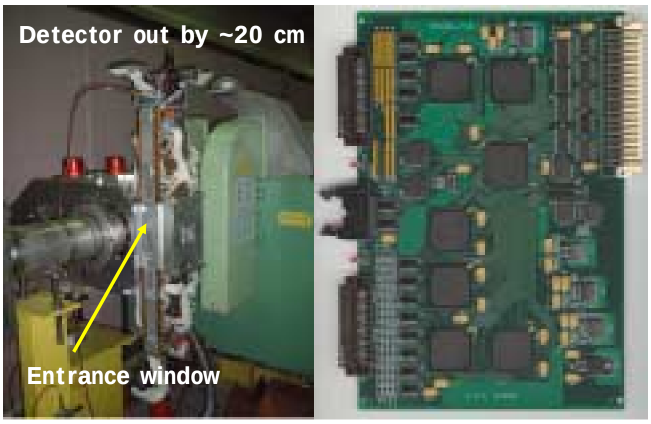

Figure 3: One detector in the K12 beam line (left) and the HPTDC read-out card (right).

III. OPERATION WITH NA48/2 AND RESULTS

The KABES sub-detector in the NA48 experiment must be integrated into the existing on-line system based on level_l/level_2 signals time-stamped with 25 ns granularity. The KABES information comes entirely from the front-end circuit card and contains the measurement of leading and trailing times for each channel. It relies on the use of a High Performance TDC [5] developed at CERN. This TDC chip is the central part of the digitization system whose dedicated read-out was simulated in great detail [6] to account for the high-rate conditions of the experiment (Table 2).

Characteristics	Unit
VME-bus transfer rate	160 MB/s
Number of TDC channels	6x48
Time resolution (LSB)	86ps
Maximum rate per channel	8 Mhit/s
Maximum trigger latency	5.5µs
L1 trigger FIFO depth	16 events
Maximum event size	1KB/ROC
L2 trigger ring memory size	64 KBytes
Maximum L2 trigger rate	25 KHz

Table 2: The main features of the read-out system.

The KABES read-out is designed to work at an input rate of up to 40 Mhits/s with a maximum of 8 Mhits/s on each strip, for a total rate of 960 MBytes/s per chamber. The detector pulses are digitized (Figure 4) by 6 HPTDC, housed in a single Read Out Card (ROC) VME module (Figure 3). For the entire beam spectrometer, the data from one SPS burst stored in 6 ROCs are first extracted and buffered on L1 request, then read out and stored at L2 decision via 200 m S-link optical transmission on the RAM of a standard desktop PC. This process must be completed before event-building with other sub-detector data during the SPS interburst.

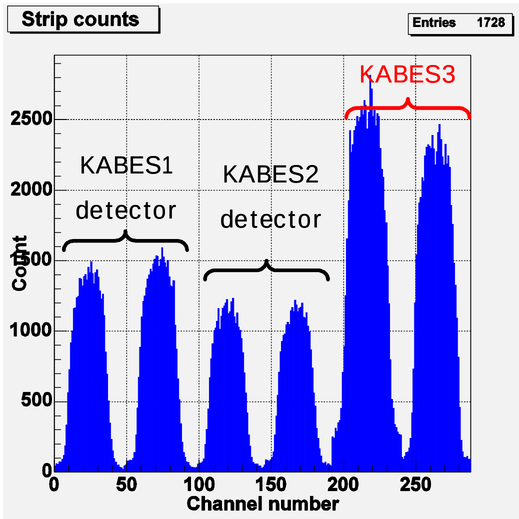

Figure 4: The online display of beam profiles recorded by the three double stations.

The run lasted for four months in 2003 and several 10^9 K^+ and K^- decays were recorded. During the run KABES operated with an efficiency close to 100% in hadron fluxes reaching a few MHz/cm^2 with a ~ 2MHz peak rate on the strips located at the centre of the beam spot. The operating point (gas amplification and threshold) is adjusted to reduce signal overlaps on a single strip while high detection efficiency is maintained. A mean cluster size of 1.5 strips per track corresponding to ToT ≈ 35 ns is obtained with 325 V on the meshes and a 30 mV discrimination threshold. Due to the smaller average strip multiplicity, the measurement of the vertical positions of the tracks is slightly worse than in the 2002 beam tests. Nevertheless the determination of the beam momentum is achieved with a precision better than 1% (Figure 5). The quality of the pattern recognition and track fitting in KABES, obtained after careful alignment and calibration, was studied using large samples of $K^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}$ decays reconstructed with the DCH spectrometer.

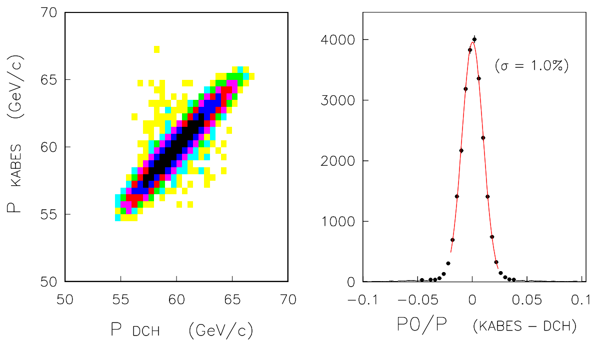

Figure 5: KABES momentum versus DCH spectrometer momentum and their difference.

An important factor for ensuring a good track association in KABES is the time resolution. The precise time of each track hit is obtained from T1 and corrections derived from T2 to account for slewing effects that can be as large as 15 ns. The time resolution of KABES is obtained by comparing the track time measured in the beam spectrometer with the event time of the $(3\pi)^{\pm}$ decay products recorded by the trigger hodoscope (Figure 6). The KABES track time resolution is found to be less than 0.6 ns, corresponding to a space resolution in the horizontal drift direction of 70 µm. The mistagging probability can be inferred from the fraction of wrong-charge tags and the rates measured in the KABES detectors. Mistagging occurs mostly when two pulses on the same strip overlap within typically ±35 ns, causing thus the T1 and T2 information for each pulse not to be recorded properly.

Based only on track time information, the mistagging probability at the nominal rate of 20 MHz is measured to be 4%. This fraction of misidentified kaons can be reduced by more than a factor of two if the charge and the vertex position of the decay products are used as constraints.

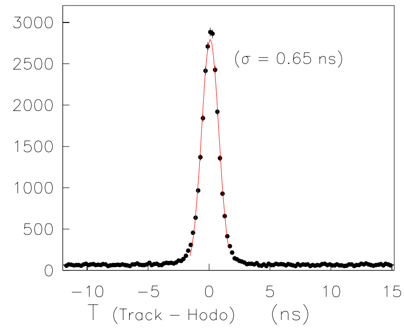

Figure 6: Time resolution of KABES with respect to the trigger hodoscope.

The total of 288 channels performed reliably during the whole run and at up to twice the nominal flux of 7x10^7 particles per spill.

IV. CONCLUSIONS

A novel detector using Micromegas amplification in a TPC has been operated successfully in a high-intensity hadron beam. It provides accurate momentum, time and spatial coordinate measurements of charged particles in the K12 beam at CERN. Its excellent performance, tested up to 40 MHz, provides invaluable kinematical constraints for kaon decays having only one charged track and possibly neutrinos in the final state. Their study should reveal new details on the nature of CP violation and allow better analysis of relatively rare $K^{\pm}$ decays. The technique represents a breakthrough in hadron beam spectroscopy at high intensity.

Future improvements of the tagging capability of this beam spectrometer can be obtained by using an FADC read-out system that will provide better time and amplitude measurements of the detector pulses. Recent laboratory tests performed with thinner Micromegas meshes of 25 µm have given promising results. They produce shorter pulses with a width of about 20 ns, thus allowing the detector occupancy to be significantly reduced.

V. REFERENCES.

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