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A new hydrogen-filled Cherenkov detector for kaon tagging at the NA62 experiment at CERN

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The NA62 experiment at CERN uses a Cherenkov differential counter with achromatic ring focus (CEDAR) with a bespoke readout system to identify charged kaons in an unseparated hadron beam. A new hydrogen-filled CEDAR (CEDAR-H) was constructed to reduce the amount of material in the path of the beam, including an optical system accounting for the dispersive properties of hydrogen. The new detector was designed using detailed simulation, with its performance validated during a test beam at CERN. The CEDAR-H was installed and commissioned at the NA62 experiment in early 2023. The detector improves on the previously used nitrogen-filled CEDAR and exceeds the requirements of both the efficiency of kaon identification and the resolution on determining the kaon crossing time.

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1. Introduction

The NA62 experiment at CERN [1] was designed to perform a measurement of the ultra-rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$ using a decay-in-flight technique. The kaons are supplied to the experiment as a minority component of an unseparated hadron beam produced by 400 GeV/c protons from the CERN SPS impinging on a beryllium target. The hadron beam travels though an array of magnets and collimators, designed to select particles of 75 GeV/c momentum with a 1% RMS width. The beam comprises pions (70%), protons (23%), kaons (6%) and other particle species (1%), and is characterised by a nominal intensity of 600 MHz. The measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ process requires efficient detection of and precise matching between the upstream kaon and downstream pion, both in space and time. The K^+ is characterised by a momentum measurement from a beam spectrometer together with a positive identification verdict and a crossing time determined by a Cherenkov differential counter with achromatic ring focus (CEDAR [2]) with a bespoke readout system, jointly termed the KTAG [3]. The performance requirements for the KTAG include a kaon identification efficiency of 95% and a pion misidentification probability of $<10^{-4}$, necessary to minimise the background arsing from beam particle interactions with upstream material. To match the timing performance of downstream detectors characterising the pion, a time resolution of <100 ps is required.

2. CEDAR detectors

Components of a monochromatic unseparated hadron beam can be identified by employing the Cherenkov effect. This principle was utilised in CEDAR detectors developed in the 1980s for use at the CERN SPS. The schematics of a CEDAR detector are shown in Figure 1. Beam particles enter the cylindrical CEDAR vessel through an upstream aluminium window and generate Cherenkov photons by interactions with the gaseous medium along the detector, before exiting through a downstream aluminium window. The emission angle of photons relative to the beam axis is determined by particle velocity, β and the refractive index of the radiator medium, n. The light is incident on a Mangin mirror [4] positioned at the downstream end, with a central hole allowing for passage of the beam. The mirror focuses Cherenkov light generated through the whole length of the

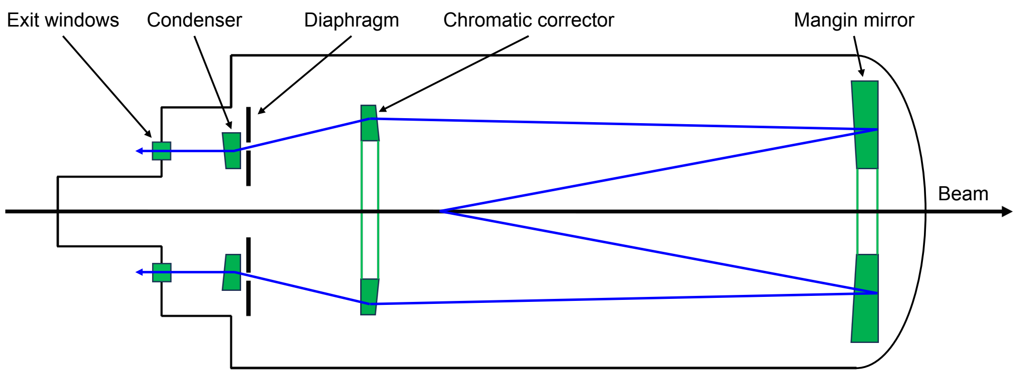

Figure 1: The longitudinal schematics of a CEDAR vessel. The blue lines indicate the propagation of Cherenkov light generated by a beam particle travelling along the axis of the cylinder. [5]

radiator vessel on an annular plano-convex lens, employed to to correct for the chromatic dispersion in the medium and the Mangin mirror. After the corrector lens, the light is incident on an annular slit of variable width, known as the diaphragm and centred around the beam axis at a radius of $R_D = 100$ mm. The selected photons then impinge on eight condenser lenses, symmetrically spaced in the transverse plane, which focus them on eight exit windows. In the original CEDAR design, the light is read out by eight photomultiplier tubes (PMTs) placed behind each of the windows. At the NA62 experiment, it is reflected radially outwards towards an array of photomultipliers (PMs). A single readout module, i.e. a PMT or an array of PMs, is referred to as an octant.

The particle species to be identified by a CEDAR in an unseparated hadron beam is chosen by selecting a radiator medium such that

$$n = \cos(R_D/f)/\beta, \tag{1}$$

where f is the effective focal length of the optical system. Historically, two types of CEDAR detectors have been used: He-filled CEDAR-N and N_2-filled CEDAR-W, with the gases chosen for optimal high and low beam momentum sensitivity, respectively. The positions and properties of the optical components for the two types were independently optimized. The fine-tuning of the refractive index to select a particle species in a beam of fixed momentum is performed by adjusting the gas pressure, under the assumption of constant temperature, as enabled by thorough insulation of the radiator vessel. The width of the diaphragm slit is varied to ensure small contamination from other particle species.

Prior to the 2023 data-taking campaign, the NA62 detector included a CEDAR-W operated at a pressure of 1.71 bar, set to select 75 GeV/c kaons. In such conditions, the beam pions generate a light ring centred at $r = 102$ mm in the diaphragm plane, leading to an operational value of the diaphragm aperture being ~2 mm. The crossing time of a beam kaon is defined as the mean time of detection of coincident photons observed in at least 5 octants of the CEDAR. Both the kaon identification efficiency and the resolution on the crossing time depend on the mean number of photons detected per particle. This quantity is maximised by aligning the axis of the radiator vessel to the direction of the beam by using a set of motors, which allow for transverse movement of the upstream end of the CEDAR.

3. CEDAR-H motivation and design

The identification of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events in the NA62 apparatus requires finding a downstream pion kinematically consistent with a kaon decay. Such a signature can easily be mimicked by a beam pion scattered by beamline material upstream of the target decay region. While the resolution of the NA62 downstream tracker allows upstream-scattering events to be rejected at analysis level, pion trajectories consistent with this hypothesis were found to constitute ~40% of events collected by the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ trigger in 2022 [5]. Consequently, reduction of the material in the path of the beam would allow to reduce the potential background due to upstream scattering of pions and optimise the use of the available trigger bandwidth.

Figure 2: Picture of the CEDAR-H during construction at CERN. The black metal support frame for optical components is present to the right, including the diaphragm slit at the end. To the left, the silver cylindrical gas vessel if shown. [5]

In the NA62 configuration including the N_2-filled CEDAR-W, the dominant contributors to the amount of material in the path of the beam were: the CEDAR radiator gas ($35 \times 10^{-3}\,X_0$), the beam tracker ($20 \times 10^{-3}\,X_0$) and the CEDAR aluminium windows ($3.9 \times 10^{-3}\,X_0$). A H_2-filled CEDAR-W operated at a gas pressure of 3.67 bar, chosen for optimum kaon-pion separation, would reduce the radiator medium contribution to $3.4 \times 10^{-3}\,X_0$, more than halving the total amount of beamline material. Such a setup would lead to 40% light loss at the diaphragm plane due to different dispersive properties of H_2 and N_2, with the solution not satisfying the NA62 kaon tagging requirements. Hence, a new CEDAR vessel was designed (CEDAR-H), with the position of optical components fixed to those of CEDAR-N but their optical properties optimised. Exercising the cylindrical symmetry of the CEDAR geometry, a full 2-dimensional optical simulation was performed using GEANT4 [6], while iteratively changing the parameters of the Mangin mirror and chromatic corrector to minimise the width of the kaon light ring centred on R_D. The procedure was repeated in the H_2 pressure range 3.8 to 4.1 bar, giving negligible differences due to opposing effects of increased light-yield and the light spot fitting the shape of the readout PM array of the KTAG. The chosen operational point was 3.8 bar due to H_2 safety considerations. The CEDAR-H was constructed at CERN, see Figure 2, with detailed parameters available in [5].

4. CEDAR-H test beam at CERN

The CEDAR-H was installed on the H6 beamline at CERN in October 2022 for testing of the performance and alignment of optical components and a validation of its kaon tagging capability. The beam composition was similar to that of NA62, with 71% pions, 25% protons and 4% kaons. The CEDAR-H was read out by eight PMTs, with a trigger signal taken as a coincident hit from a pair of scintillator counters placed on either end of the vessel. The average efficiency of the PMT was measured as 98% during operation with the diaphragm wide open to accept light from all three particle species. The detector was aligned to the beam direction by considering the asymmetries in fraction on PMT hits per trigger while operating at a pion pressure of 3.7 bar and a small diaphragm aperture. A diaphragm scan was then performed by varying the aperture in the 0.6 to 19.0 mm range at the kaon pressure of 3.85 bar and measuring the fraction of 6-fold PMT coincidences per

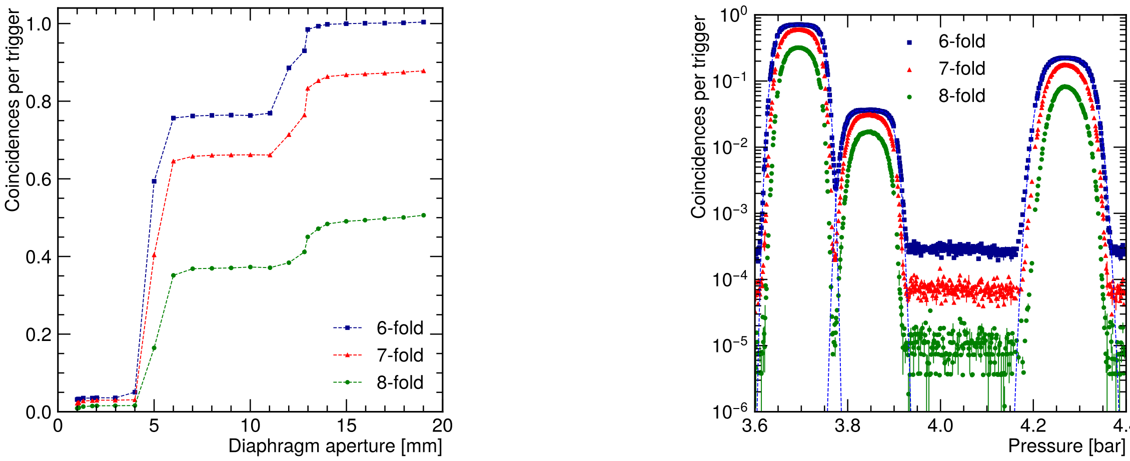

Figure 3: CEDAR-H validation performed during the 2022 test beam at the H6 beamline at CERN. Left: diaphragm scan at the pressure of 3.7 bar. Right: pressure scan with a diaphragm aperture of 1.7 mm. [5]

number of triggers, with the result shown in the left panel of Figure 3. For apertures up to 4 mm, only the kaon light ring contributes, with the following gradual inclusion of fthe pion and proton features, fully within the aperture at 6 mm and 13 mm, respectively. The total recorded fraction of 6-fold PMT coincidences with the diaphragm aperture at the maximum was 99% and the measured beam composition agreed with the known values. An array of pressure scans was also conducted by reducing the pressure from 4.4 to 3.6 bar at diaphragm openings in the 1.7 to 2.3 mm range to find the kaon peak pressure and the optimal kaon-pion separation. The optimum was found at 1.7 mm, with the result of the scan shown in the right panel of Figure 3. The pion contamination at the kaon pressure was estimated by extrapolating the fit to the pion feature (leftmost in right panel of Figure 3) to the kaon pressure, yielding a fraction of $<10^{-4}$. The ratios of 6-,7-, and 8-fold PMT coincidences were used to compute the average number of detected photoelectrons as 19.6.

5. CEDAR-H commissioning and performance at the NA62 experiment

The CEDAR-H was installed at the NA62 experimental cavern in early 2023 and connected to the bespoke photon readout system. A multi-level and purpose-designed safety system was implemented to mitigate the risks associated with H_2. The calibration of the CEDAR-H was performed at 10% of the nominal NA62 intensity. The detector was aligned with the direction of the beam by maximising the light yield, initially using a large diaphragm opening at the proton peak of 4.3 bar, then at the kaon pressure of 3.88 bar with an aperture of 1 mm, fine-tuning it. A pressure scan was performed in the 3.6 to 4.4 bar range at the diaphragm value of 1.8 mm, with the result shown in the left panel of Figure 4. The peaks from left to right correspond to observing the light rings due to pions, kaons and protons respectively, with the first feature affected by readout saturation. The extrapolation of the fit to the pion peak to the kaon pressure yielded a pion contamination of $<10^{-4}$. The CEDAR-H was used in the 2023 and 2024 NA62 data collection campaigns. The number of detected photoelectrons per kaon candidate (one composed of coincident hits from at least 5 octants) for the CEDAR-H in 2023 and the CEDAR-W in 2022 is presented

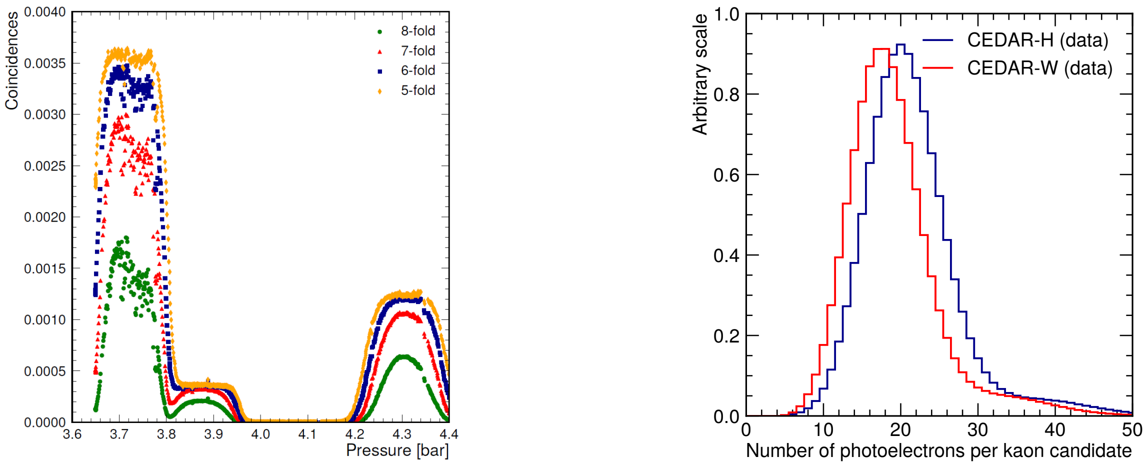

Figure 4: Left: A CEDAR-H pressure scan performed during commissioning at the NA62 experiment with a diaphragm aperture of 1.8 mm. Right: The number of PM hits recorder per kaon candidate (one composed of signal from at least 5 KTAG octants) for the CEDAR-W in 2022 and the CEDAR-H in 2023 data. [5]

in the right panel of Figure 4. The mean number of recorded hits increased from 18.1 for the CEDAR-W to 20.6 for the CEDAR-H. Assuming a single readout PM time resolution of 300 ps, the kaon crossing time is determined by the CEDAR-H with a ~65 ps resolution. The long-term kaon identification efficiency of the CEDAR-H measured as the presence of a kaon candidate in $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+\pi^0$ events selected in 2023 data is 99.7%. Overall, the CEDAR-H exceeds the kaon tagging requirements of the NA62 experiment and improves on the performance of the previously used CEDAR-W.

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