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

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Outline

- The NA62 Experiment at CERN
- Kaon identification at NA62
- The new CEDAR-H detector
- Test beam at CERN
- Commissioning and Performance in NA62

NA62 at CERN

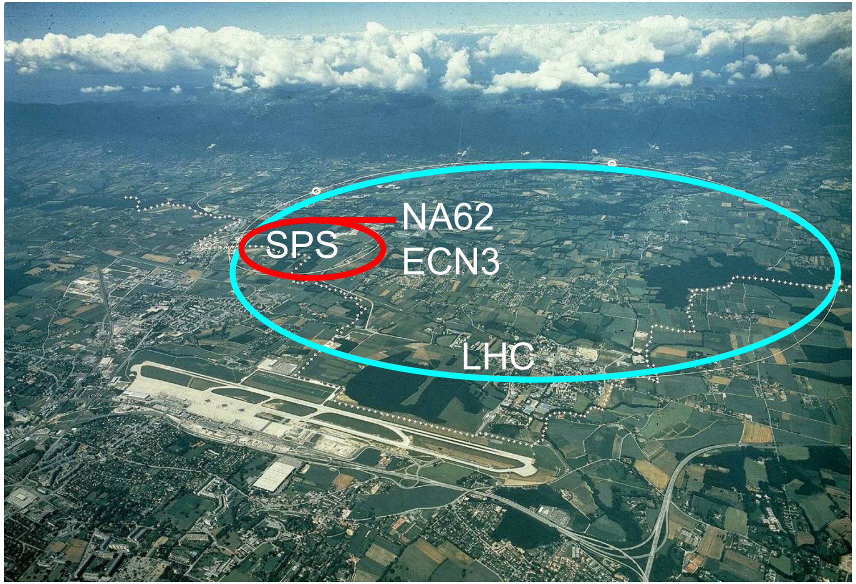
Fixed target experiment located in the ECN3 experimental hall at the North Area of SPS at CERN

[JIST 12 05 (2017) P05025]

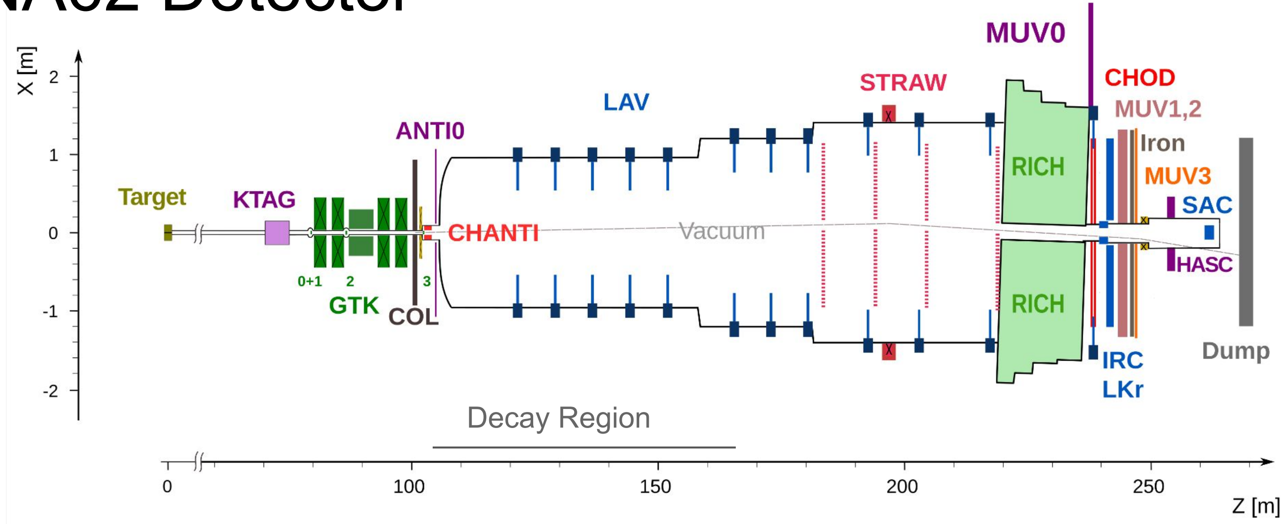
Main goal to measure the branching ratio of the ultra-rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay

Run 1 resulted in 20 observed events, measured $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$

[JHEP 06 (2021) 093]



The NA62 Detector



400 GeV/c primary proton beam from SPS on a Be target, producing a 75 GeV/c secondary hadron beam: proton = 23%, π^+ = 70% and K^+ = 6%.

Upstream of decay region: KTAG (kaon tagger), GTK (silicon beam tracker)

Downstream of decay region: STRAW (charged track spectrometer), PID (RICH, LKr, MUVs), Photon Veto System (LAV, IRC, SAC), CHOD (charged hodoscope)

Kaon Identification at NA62

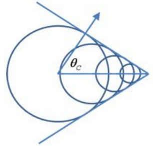
A detector is required to “TAG” the kaons in the 750 MHz unseparated hadron beam

The requirements for kaon tagger detector are strict:

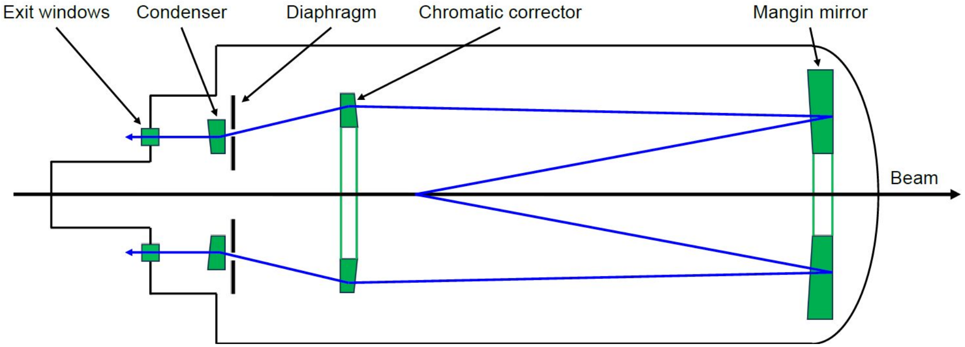
- ❑ Sustain a kaon rate of ~ 45 MHz
- ❑ Time resolution better than 100 ps
- ❑ At least 95% kaon tagging efficiency
- ❑ The probability of misidentifying a pion as a kaon less than 10^{-4}

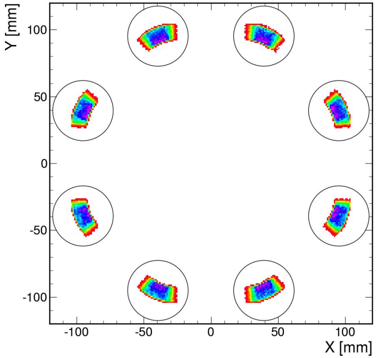
For this, we use a differential cherenkov counter with a purpose-built photodetection system (KTAG)

The CEDAR Detector



$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$





Light distribution at Quartz windows

The Cherenkov Differential counter with Achromatic Ring (CEDAR) is a 1.1m^3 volume filled with nitrogen with an adjustable aperture of 0-20mm.

The CEDAR is sensitive to different beam particles at different pressures. Kaons are selected in the CEDAR by setting a small aperture (~2mm) and a nitrogen pressure of 1.7 bar.

Original design with 8 PMTs on the exit windows of CEDAR does NOT satisfy the requirements for NA62. Requiring a purpose-built photodetection system

The KTAG

The upgraded design for NA62: The light from exit windows are focused onto 8 spherical mirrors and reflected radially onto 8 PMT planes.

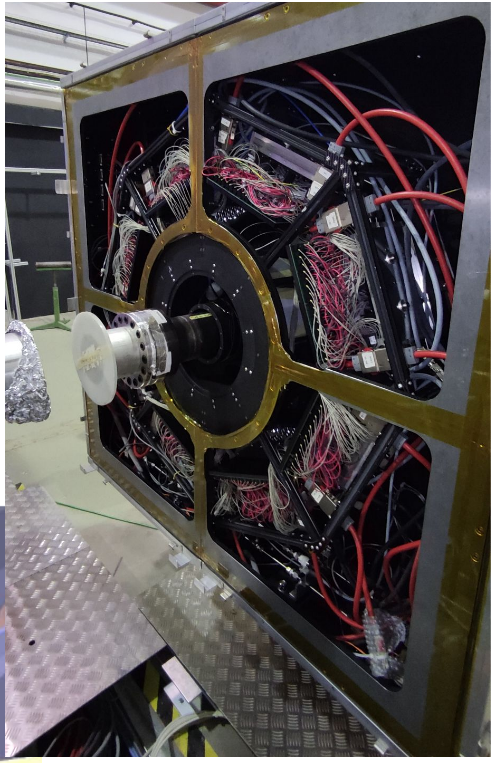
Arrays of 48 PMTs (Hamamatsu, 32 R9880-110 + 16 R7400)

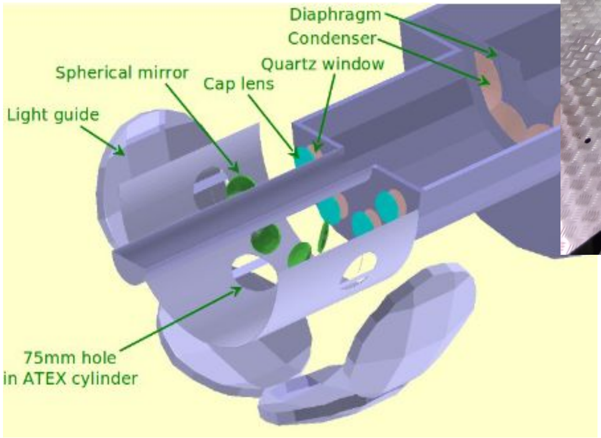
KTAG working point:

Time resolution ≈ 70ps

Number of photons per kaon = 19

[NIM A (2015) 86-94]





Motivation for a new CEDAR-H detector

Measurements of ultra-rare kaon decays rely on identification of the backgrounds from dominant kaon decays and from the interaction of the beam in upstream sub-detectors.

A CEDAR filled with nitrogen at 1.7 bar contributes to the largest amount of material in the NA62 beamline. 3.9% X_0 , with 3.5% X_0 coming from the gas.

Switching to hydrogen at a pressure of 3.8 bar would reduce the material contribution from the CEDAR to 0.73% X_0.

New CEDAR optics needed to be designed and built to accommodate the different dispersive properties of hydrogen

The CEDAR-H Detector

CEDAR type		CEDAR	CEDAR-H
Nominal gas type		N_2	H_2
Nominal pressure at NA62 [bar]		1.71	3.80
Gas vessel cylinder	Length	4500	4500
	Inner radius	267	267
Gas vessel cap	Length	339	280
	Inner radius	139	139
Chromatic corrector	Position along the beam axis	1855	1902
	Radius of curvature	1385	1307
	Central thickness	20	20
	Inner radius	75	75
	Outer radius	160	160
Mangin mirror	Position along the beam axis	5353	5362
	Radius of curvature:		
	- refracting surface	6615	8994
	- reflecting surface	8610	9770
	Central thickness	40	40
	Inner radius	50	40
	Outer radius	150	150
Diaphragm	Position along the beam axis	872	911
	Aperture central radius	100	100
Condensers	Position along the beam axis	832	871
	Maximum thickness	10	10
	Radius of curvature	300	300
Quartz windows	Position along the beam axis	472	531
	Thickness	10	10
	Radius	22.5	22.5
	Radial distance to window centre	103	103
Optical caps	Position along the beam axis	450	450
	Maximum thickness	4.24	4.24
	Radius of curvature	114.62	114.62
Spherical mirrors	Position along the beam axis	322	322
	Radius of curvature	51.68	77.52
	Diameter	50	50
	Radial distance to mirror centre	106	106

A detailed 3D simulation in GEANT4 of CEDAR optics was designed at the University of Birmingham

The simulation was used to maximise the number of photons reaching the PMTs with hydrogen radiator gas

The CEDAR-H detector was built at CERN with the new optics optimized for hydrogen

Test beam at H6 beam-line at CERN

Aims:

1) Validate the optical components
2) Measure kaon photon yield and pion misidentification probability

CEDAR-H was installed in the H6 beamline at CERN in October 2022

400 GeV/c primary proton beam from CERN SPS on a beryllium target, produced a 75 GeV/c secondary beam. Similar to the NA62 beam

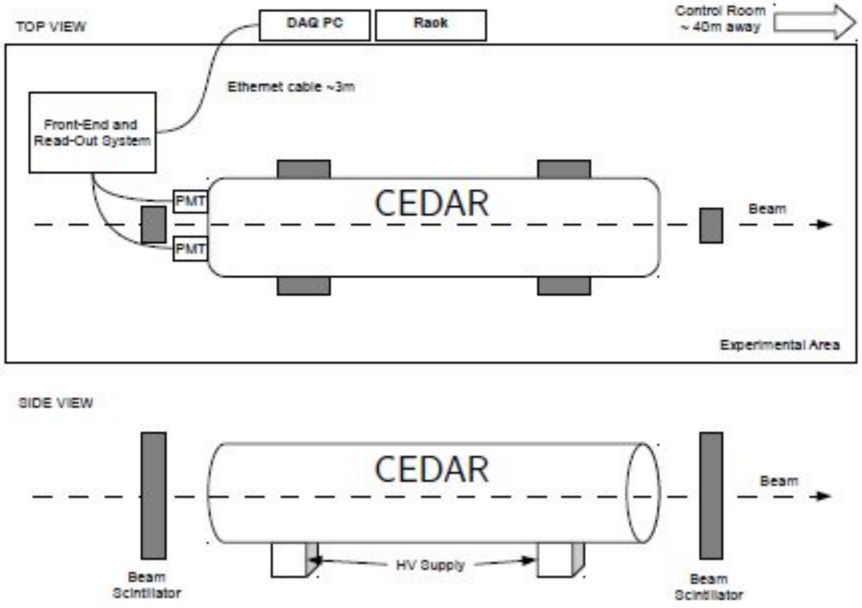
proton = 25%, π^+ = 71% and K^+ = 4%.

The test beam was conducted over 2 weeks in October 2022

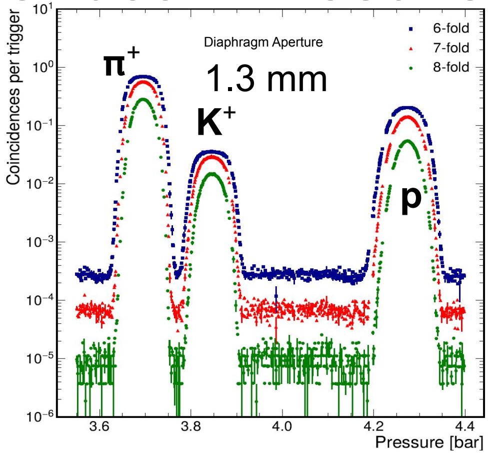
Test Beam setup

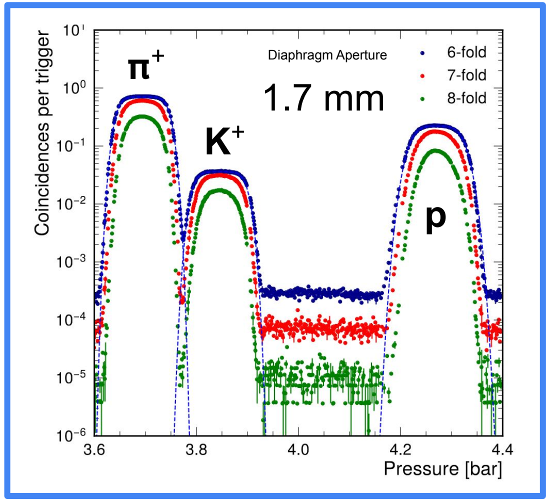
The CEDAR-H was equipped with 8 ET 9280QB PMTs, placed one outside each of the quartz windows

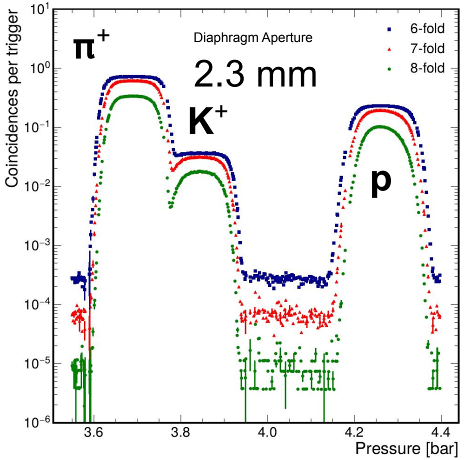
A pair of scintillator chambers placed at either end provided a trigger signal



Test beam Results





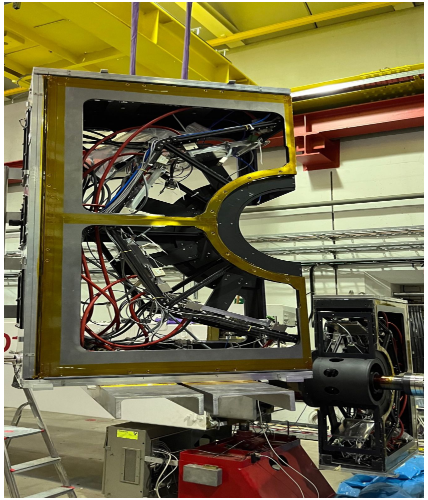
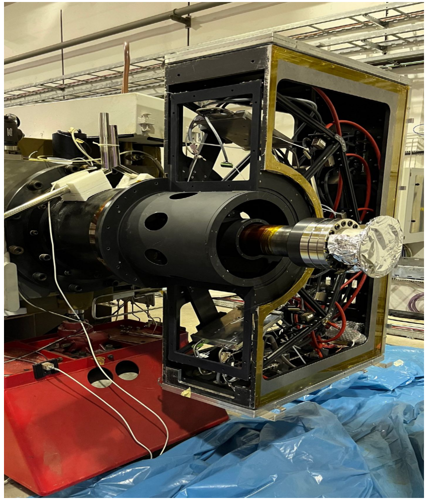


A number of pressure scans were completed. This was done with diaphragm apertures between 1.3 - 2.3 mm.

An optimal aperture of 1.7mm was chosen to balance the number of photons detected per kaon, with the pion misidentification probability

At **3.85 bar,** a light yield of 19.1 photons per kaon was measured and a pion misidentification probability **$< 10^{-4}$** was estimated by fitting the falling edge of the pion peak.

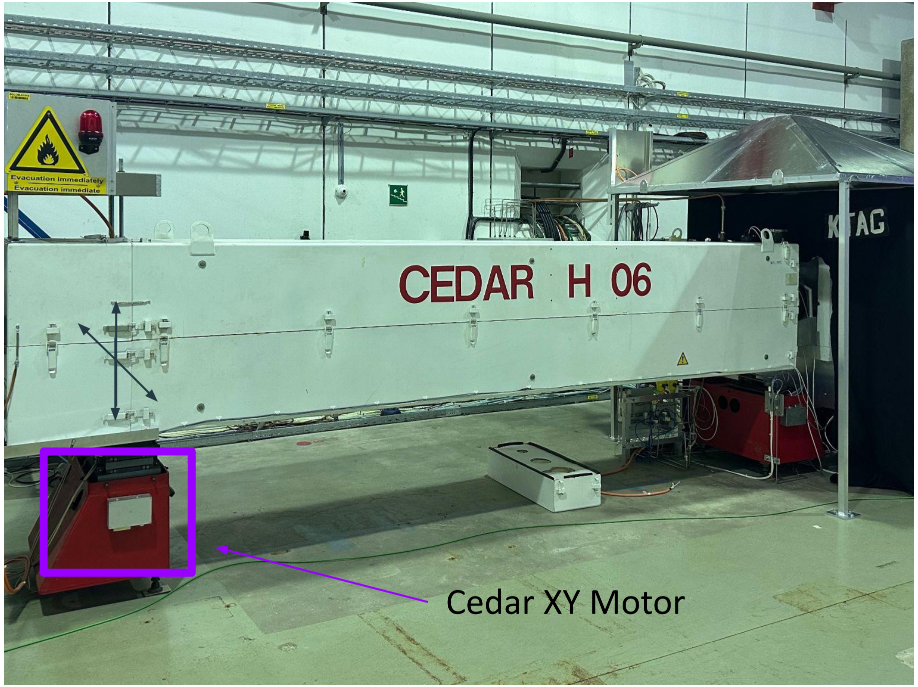
Installation into NA62 beamline

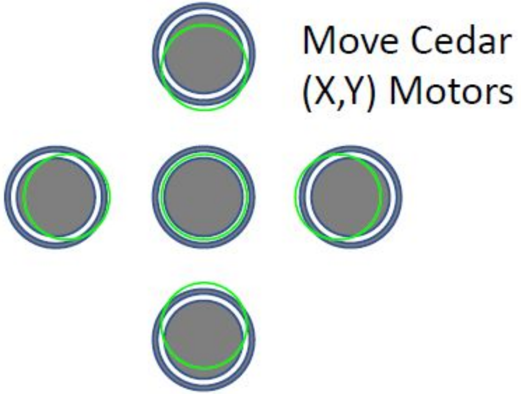



The installation was conducted between the end of 2022 run and start of 2023 run

CEDAR-H was transported to ECN3 and installed, replacing the original CEDAR in NA62 beam line.

CEDAR-H Commissioning: Alignment



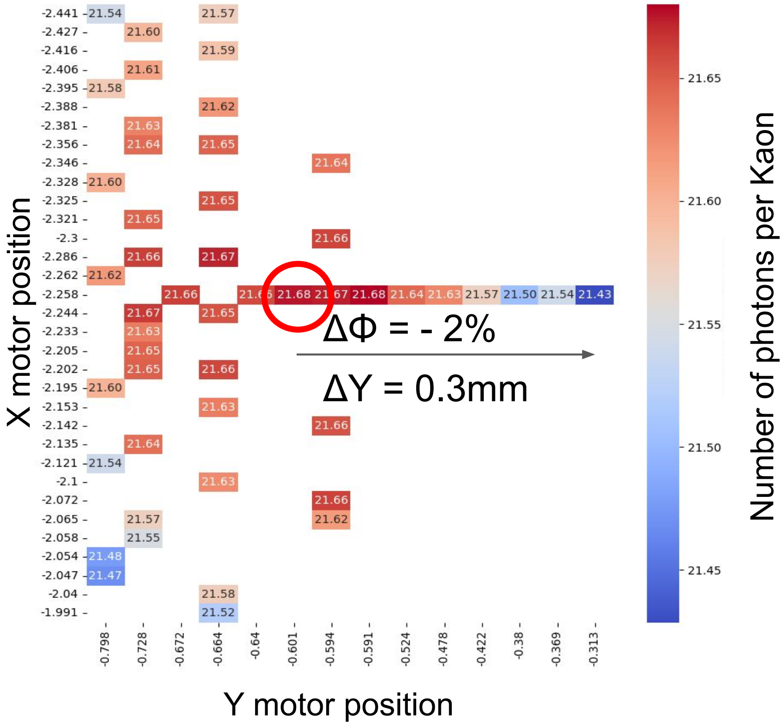


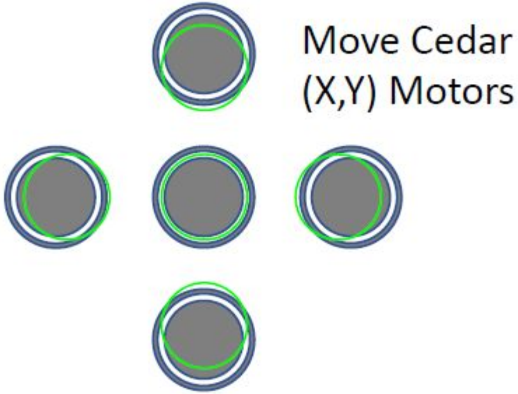
It is important that the CEDAR is perfectly aligned with the beam to maximize the number of photons passing through the diaphragm

Aligned when the maximum number of photons per Kaon is achieved.

Phase space was searched in X and Y

CEDAR-H Commissioning: Alignment





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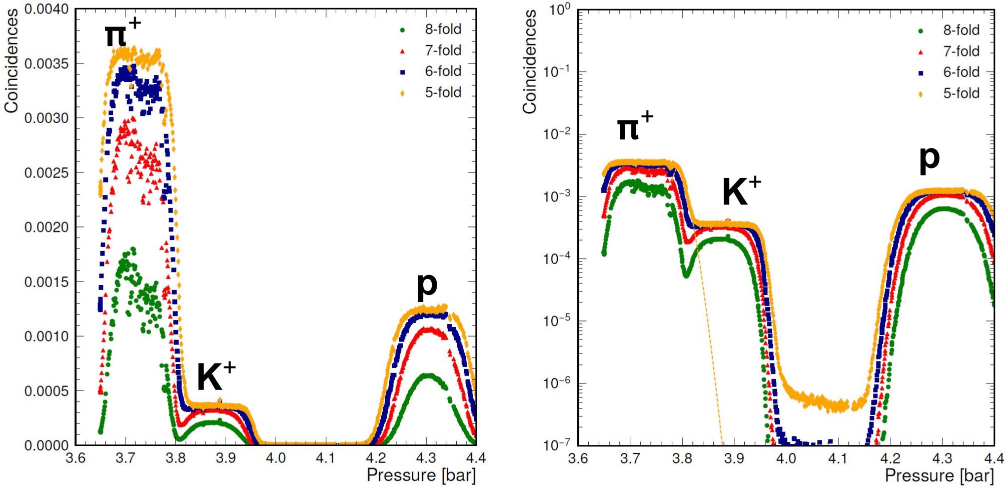
CEDAR-H Commissioning: Pressure Scans



Similar to the test beam, a number of pressure scans were completed to find the optimal diaphragm aperture

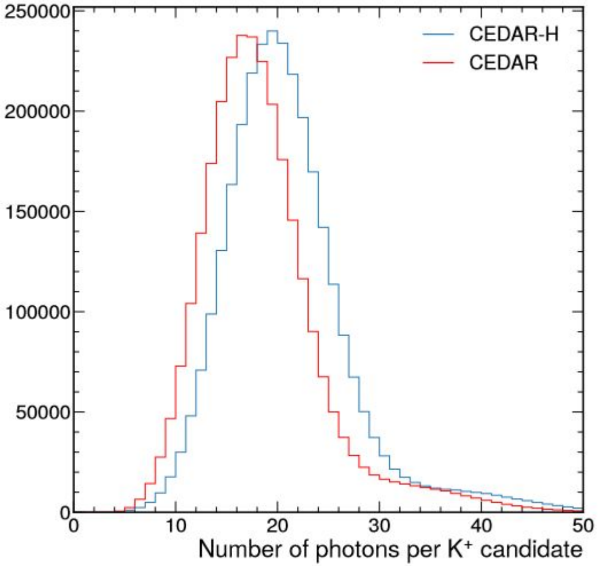
1.8mm was chosen for its excellent light yield and pion misidentification probability

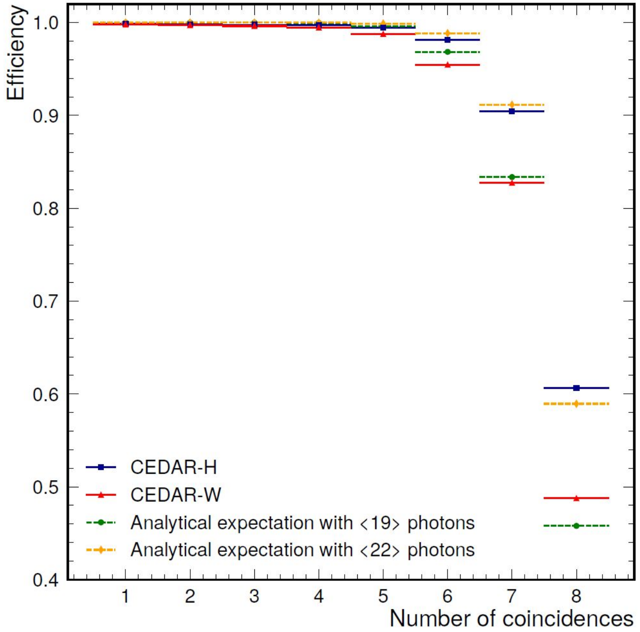
Kaon Pressure: 3.88 bar

The heights of the peaks are proportional to the beam composition (K:6%, p: 23% and π: 70%)

A light yield of 21 photons per kaon was measured, and pion misidentification probability is estimated to be $\leq 10^{-4}$.

CEDAR-H Performance





$$\sigma_t^K = \frac{\sigma_t^{PMT}}{\sqrt{N_{PMT}}} \approx 65ps$$

The photon yield with CEDAR-H is 10-15% larger wrt to the yield achieved using previous CEDAR with nitrogen

The K^+ ID efficiency based on 5 coincidences is greater than 99.5%

Conclusions

CEDAR-H proposed to reduce the material in the path of the beam by switching from N_2 to H_2. This required a redesign of the optical system.

The CEDAR-H detector was successfully tested in the 2022 test beam at CERN.

CEDAR-H was then installed into the NA62 beam line before the 2023 run.

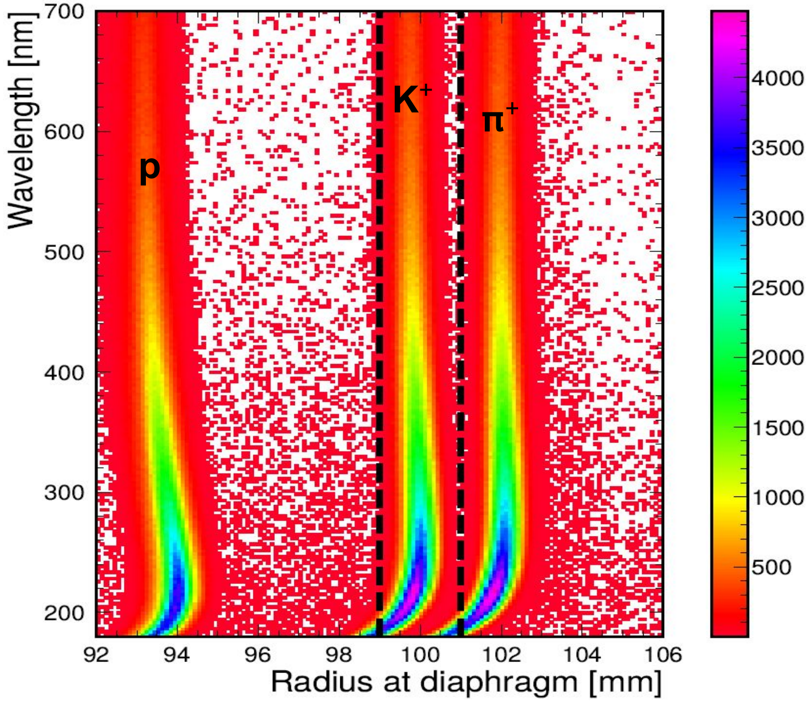
The KTAG with CEDAR-H was commissioned at the start of the 2023 run and has been running with stable operation since May 2023:

- Kaon time resolution ≈ 65 ps
- Kaon identification efficiency of 99.5%
- Pion misidentification probability $\leq 10^{-4}$

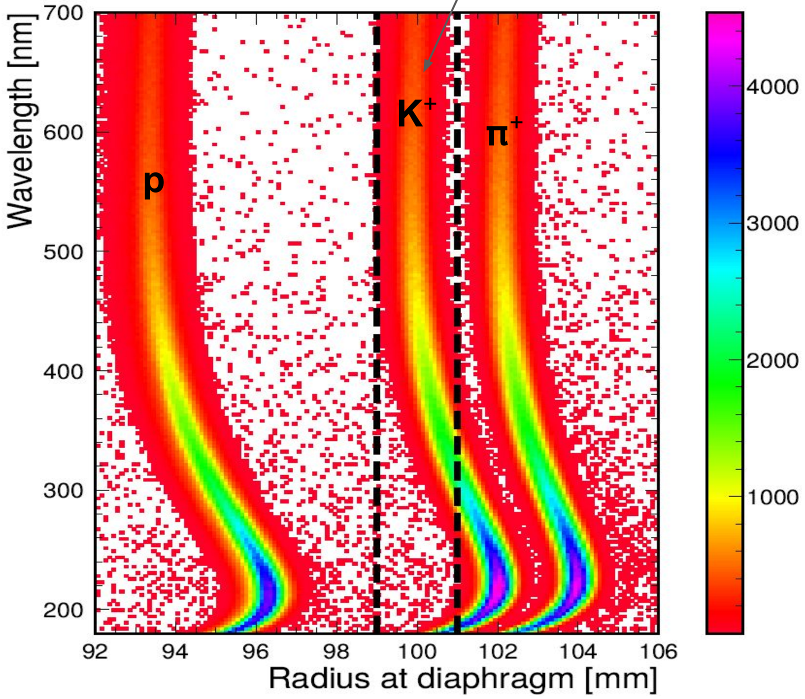
CEDAR-H fulfils all NA62 requirements and improves on the previous CEDAR

Extras: CEDAR Design with Hydrogen

Not possible to select all photons produced by kaons



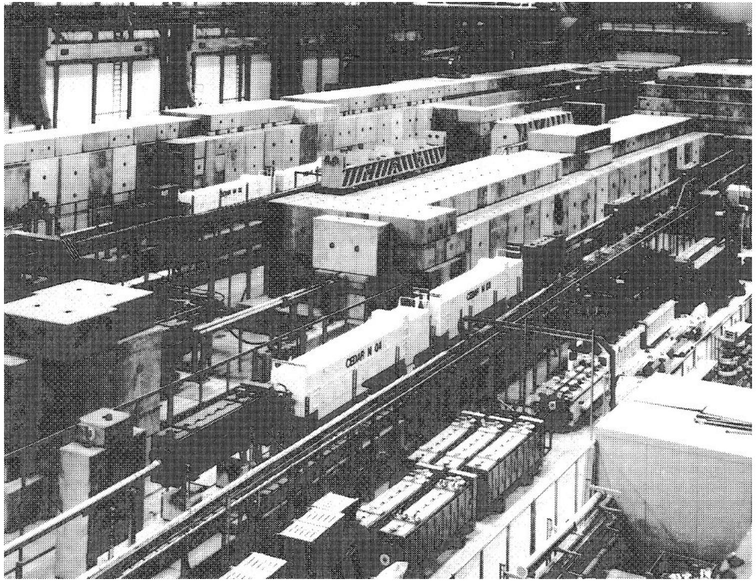
CEDAR nitrogen 1.7 bar
(Simulation)

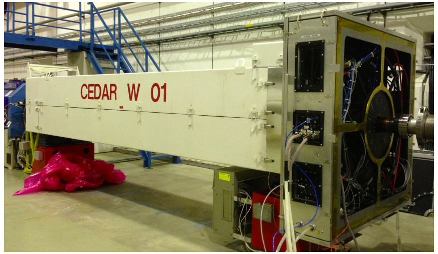


CEDAR hydrogen 3.67 bar
(Simulation)

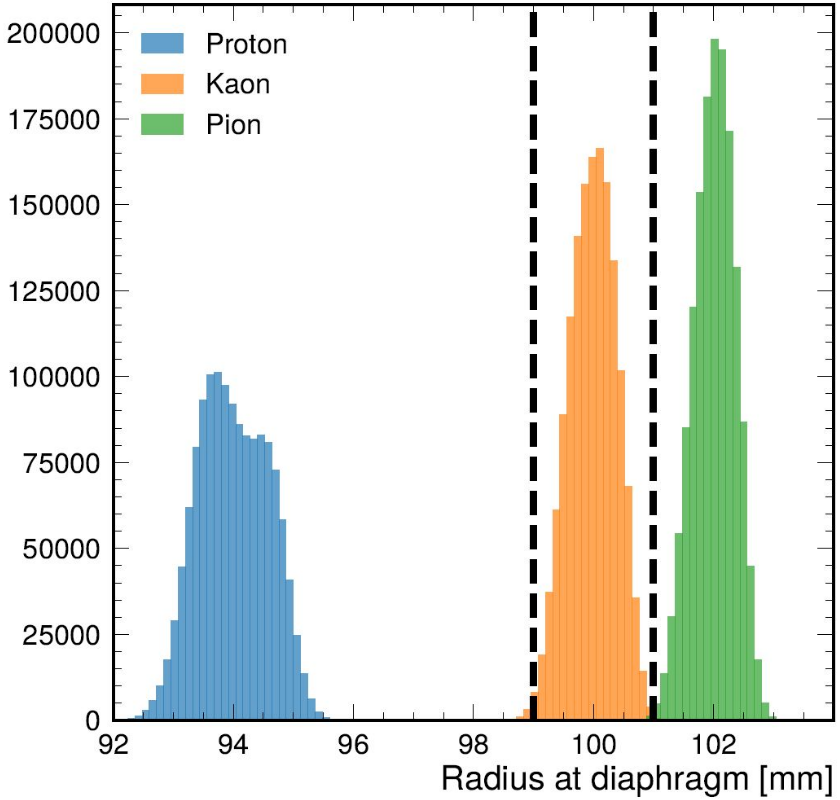
Extras: CEDAR

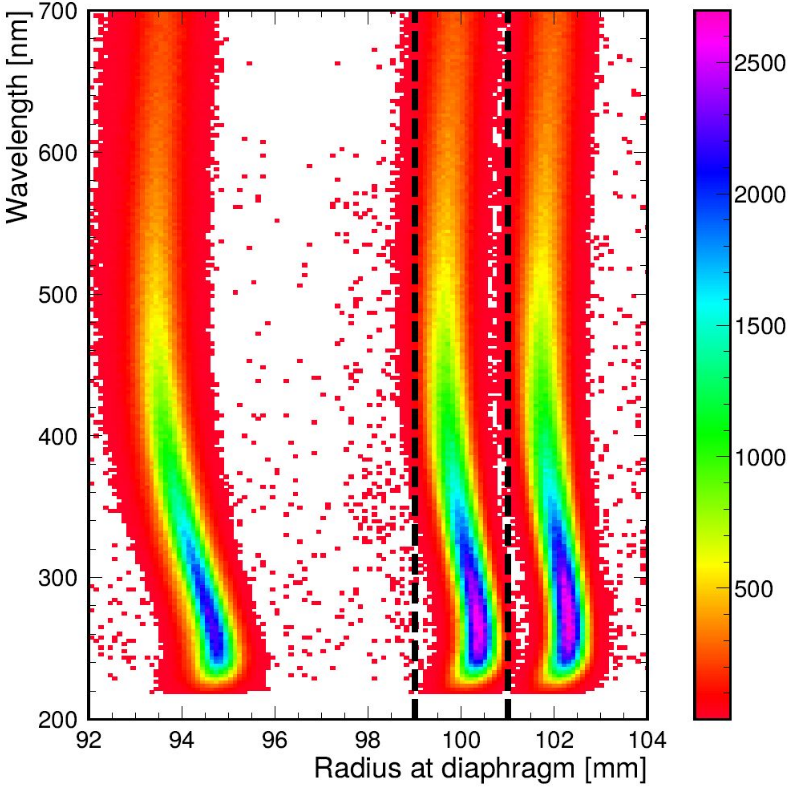
[CERN Report CERN-82-13]





Extras: CEDAR-H Detector





Extras: CEDAR-H Performance