Performance of a Quintuple-GEM Based RICH Detector Prototype

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Abstract—Čerenkov technology is one of the first choices when it comes to particle identification in high energy particle collision applications. Particularly challenging is the deployment in the high pseudorapidity (forward) direction where particle identification must allow for high lab momenta, up to about 50 GeV/c. In this region Čerenkov Ring-Imaging is among the most viable solutions and will provide the desired performance if the radiator has a low index of refraction, high yield of photoelectrons, and allows precise measurement of the position of each photoelectron. A RICH detector prototype based on a novel concept that allows the use of a significantly shorter radiator length compared to conventional RICH detectors has been constructed and tested. The setup and the results obtained are described.

Index Terms—Čerenkov detectors, RICH Detectors, Micropattern gas chambers, GEM detectors, Particle measurements, Particle detectors, Nuclear physics instrumentation.

I. INTRODUCTION

The Electron Ion Collider (EIC) [1], envisioned to be constructed in the early 2020s will, for the first time, precisely image the gluons and sea quarks in the proton and nuclei. It will accelerate polarized electrons and a variety of light and heavy ions, from $H$ ($p$ and $d$) to $U$, of which the lightest ions can also be polarized. The EIC aims to completely resolve the proton’s internal structure and explore a new QCD frontier of ultra-dense gluon fields in nuclei at high energy. It has been given highest priority of the U.S. QCD community for new construction.

A detector capable of measuring the fragments of Electron-Ion collisions has to overcome a number of challenges. The particle flow is highly boosted into the forward direction due to the beam kinematics, which creates a very high density of particle tracks in the lab frame. A solution for Hadron particle identification (PID) is a Ring Imaging Čerenkov (RICH) detector with at least two radiators, with larger refraction index for covering small(er) momenta and small refraction index for covering the highest momentum range. The latter is usually achieved by using gas as radiator medium. However, the amount of photoelectrons is limited due to the relatively small number of single photons “produced” in the dilute medium. A novel RICH concept has been developed and a detector prototype tested as

1) proof-of-principle test in an electron-test-beam environment at SLAC ESTB
2) under real-test conditions within a test-beam environment with various hadrons at various momenta at FTBF
In the following sections we describe the novel RICH technology, the detector prototype setup, and the operation in the test-beam facilities. Results from the tests will be described and discussed.

II. NOVEL RICH TECHNOLOGY

For semi-inclusive and exclusive measurements in an EIC detector particle identification will be a critical element. One aims for hadron identification with better than 90% efficiency and better than 95% purity. For higher momentum particles (forward direction) one needs to achieve these measurements to momenta of up to 50 GeV/c. Only low refractive index gas-Čerenkov detectors can operate in this regime.

A gas like Tetrafluoromethane CF$_4$ has a very low index of refraction, $n_\text{r}(\lambda) \approx 1 - 6.0 \times 10^{-4}$ for 140 nm [2] and extraordinary high photon yield of more than 300 photons per MeV [3]. Čerenkov light yield follows the relation [4][5]

$$\frac{dN_\gamma}{dx} = 2\pi \alpha \sin^2 \theta_C \int_{\lambda_{\min}}^{\lambda_{\max}} \varepsilon(\lambda) \frac{d\lambda}{\lambda^2},$$

with $\varepsilon(\lambda)$ as quantum efficiency, and one can see that the largest photon yield per radiator length is dominated by the smallest wavelengths. Consequently, Vacuum Ultraviolet (VUV with $10\text{ nm}>\lambda>200\text{ nm}$) photons in large number are produced, which, however, provide a challenge for focusing and conversion into photoelectrons.

For measuring the ring diameter of a charged particle traversing the radiator medium, with sufficient precision requires the measurement of a sufficiently large number of photoelectrons. This in turn requires a sufficient number of Čerenkov photons produced in the radiator medium but also reflected from the mirror.

To overcome this challenge two novel technologies have been implemented in the presented RICH detector prototype setup:

1. Spatial coordinate describing the angle of a particle relative to the beam axis: $\eta \equiv -\ln \tan \left( \frac{\theta}{2} \right)$
2. 2014 Long-range plan, Joint Town Meetings on QCD, Temple University
3. End Station (A) Test Beam
4. Fermilab Test Beam Facility
A. Quintuple GEM photoconversion
B. VUV high reflective mirror coating

A. Quintuple GEM

The Gas Electron Multiplier, invented by F. Sauli in the mid-1990s [6] serves as the general amplification structure for the RICH detector prototype. A thin polymer foil with copper-cladding, perforated with a high density of microscopic holes (see Fig. 1), acts as the element for electron multiplication due to applied high-voltage across the capacitor-like structure. The foils can be stacked such that the amplification load is reduced at each element, allowing for safe operating conditions. For using GEMs as photomultipliers one deposits a thin layer of photosensitive material (e.g., CsI) on top of the copper layer of the GEM that is facing the radiator medium (see Fig. 2).

Fig. 1. Scanning Electron Microscope picture of a GEM. The thickness of the polymer foil is 50 µm, 5 µm copper layer on each side, pitch 150 µm, and hole diameter 80 µm.

A stack of five GEMs to our knowledge has not been used before and provides sufficient gain to measure single photoelectrons with very high efficiency, which will eventually determine the ring from Čerenkov photons. To a good approximation, only single photoelectrons experience an avalanche in the first GEM layer and thereby produce a charge similar to that of a MIP. It has been found that one can achieve gains of $10^5$ or higher in this configuration. However, due to a larger number of amplification elements the probability exists that electrons from primary ionization in the gas volume between the upper GEMs can be amplified, yielding additional false hits. One can avoid this by minimizing the gaps between the upper GEMs and optimizing the transmission efficiency of electrons from previous amplification elements. The quintuple-GEM setup has been tested regarding its gain properties, in particular the efficiency of amplification; see Fig. 3. A radioactive source ($^{55}$Fe) with well known intensity was used to create a signal creation for the quintuple-GEM. The procedure will be further discussed later in Sec.III-B.

A known amount of charge is deposited in the drift volume of the GEM-detector, in forward bias, and compared with the charge reaching the readout and processed electronically based on the APV25 chip [7] and a Scalable Readout System (SRS [8]) as back-end. Varying the potential across the GEM-stack results in various gain settings. The readout plane of the detector is a square array composed of 512 tessellated ~5 mm in diameter hexagons (Fig. 4) to detect and determine the position of the individual photoelectrons. Individual pads were chosen over a two-dimensional strip readout board because of an increased charge collection along readout strips that line up tangentially to the Čerenkov ring.

The APV25 chip has been designed in a 0.25 micron CMOS process and has 128 readout channels, each consisting of a 50 nanosecond CR-RC type shaping amplifier, a 192 element deep pipeline and a pulse shape processing stage. Analog output samples are then multiplexed onto a single differential output for subsequent optical transmission to the DAQ system. The output data frame consists of these analogue samples preceded by a digital header which includes a digital address of the pipeline column from which the data originates.

The SRS is designed around a bivalent scalability concept and introduces a modular concept that offers the possibility to connect different front-end ASICs to the standard SRS electronics, allowing the user to choose the most suitable front-end for the detector technology employed. The front-end DAQ unit is broken into two parts, one composed of a chip-carrier hybrid which is mounted on the detector. An ASIC-dependent adapter-module which hosts the specific electrical interface of the front-end chip makes the connection between the front-end hybrid and the rest of the system. The second part of the DAQ unit consists of an SRS standard
FPGA-based card (FEC) which accepts different adapter modules as plug-in cards. Four APV25 chip cards have been connected to the readout pads with two cards each daisy-chained and connected to the FECs.

![Fig. 4. Readout board with hexagon pads.](image)

Electronic noise is the inevitable distortion of a desired signal readout and needs to be addressed. The noise introduced in the described setup was identified to be \( \sim 1000 \ e^{-} \). To read out the desired signal one aims to have a good signal to noise ratio S/N. For single photon detection with a S/N of 10/1 this requires a gain of \( 10^{4} \).

During tests it was realized that the pad size for the described detector prototype setup was not optimal, i.e., the pad size was too large. With smaller pad size there is an increased chance of charge sharing requiring the gain to be increased to \( 10^{5} \) for the desired S/N.

For obtaining a reliable signal one has to trigger the readout of the signal outside the noise-band. Dependent upon the reliability requirement of the signal readout one chooses typically several sigmas of the noise-level. With increasing sigma-levels the efficiency of collecting events decreases (Fig. 3) while increasing the purity of events, i.e., the chance of collecting real events and not noise.

For avoiding damages due to electric breakdowns one has to minimize the energy that is stored on the GEM. The stored energy in a capacitor is \( E = \frac{1}{2}CV^2 \), with \( C \) the capacitance and \( V \) the applied voltage. Consequently, one can either reduce the capacitance or voltage applied across the capacitor, or both. The reduction in capacitance can be achieved by reducing the area of the capacitor. For a GEM foil one can subdivide the surface into smaller areas, i.e., introducing electrically insulated sectors on the surface. This was implemented for the described setup, as can be seen in Fig. 5.

High voltage (HV) across the multi-GEM stack was provided through a HV resistor chain (Fig. 6). The resistor chain allows one to supply a potential difference across the GEMs for proper amplifying, but also proper transmission of the electrons through the GEM and the transfer/induction gaps. In addition, the scheme allows one to provide a potential difference through an independent power supply between a mesh (top of Fig. 6) and the top of the first GEM. Within this volume electrons can be released by charged traversing particles. These electrons will distort the signal creation based on Čerenkov photons and need to be suppressed. To remove this source of noise we apply a reversed voltage across the volume between a mesh and the top of GEM 1, this is called reverse bias. A mesh is used for allowing photons to pass through with high probability. In reverse bias mode high-voltage is applied between the top GEM and the mesh, in our case made of stainless steel with 88% optical transparency. Electrons released by a charged particle traversing the volume between the top GEM and mesh will drift towards the mesh, thus stopping the ionization electrons from being amplified.
by the GEM stack. Photons, on the other hand, will not be affected and might release electrons from the CsI layer due to the photoelectric effect. These electrons are not ejected far enough so that they will predominantly experience the electric field from the capacitor-like structure. This configuration allows one to distinguish photoelectrons from Čerenkov photons with electrons due to primary ionization. When run in reverse bias, the stability criteria are effectively driven by typical performance of a 4-GEM stack.

For the case of a failure of either power supply a dangerous high potential difference between the mesh and the top of GEM 1 can build up. This may cause sparks and damage to the GEMs. For avoiding this effect a pair of facing Zener diodes are connected between the mesh and the top of GEM 1 so that in case of a device failure the potential difference between the two surfaces will never exceed 200 Volts which is known to be a safe and stable condition.

B. VUV mirror

The reflectivity of mirrors is limited by the hostile environment for regular mirror materials. Aluminum serves as mirror raw material, however, it immediately becomes Aluminum-Oxide once exposed to air and degrades in its reflectivity properties (see Fig. 7). Thus, a coating has to be applied to protect the material from oxidizing. The consequence is the limited reflectivity of the coating for photons at smaller wavelengths. A mirror technology has been developed by commercial partners that provides sufficient reflectivity deep in the VUV. This technology was developed in the 1960s and uses a carefully tuned thickness of MgF₂. The focusing mirror is polished, fused silica coated with Al and MgF₂ approximately 250 Å thick, so that thin film effects are playing a role: MgF₂, under regular circumstances is not transmissive below ~140 nm, as seen in Fig. 7. However, at this thickness the overcoating not only protects the Al from oxidation, but also serves as a thin-film reflector with a peak reflectivity at λ=120 nm (see Fig. 7).

The relatively small mirror (Ø 18 cm with curvature radius of 2 m) for the detector prototype was purchased from Acton with a reflectance as shown in Fig. 8. Due to prohibitively high cost, we will attempt to develop a large mirror ourselves.

III. RICH DETECTOR PROTOTYPE

A. Detector Prototype Setup

The detector prototype consists of a 1 meter long, 20 cm radius cylindrical tank made out of stainless steel. The cylinder was machined such that one could apply vacuum-like conditions to the setup and allowed various insertions without breaking the sealing of the gas volume.

The tank was equipped with a quintuple-GEM module (see Sec. II-A) on one side of the tank and a mirror as described in Sec. II-B on the other side. A diagram of the setup can be seen in Fig. 9 and a photograph of the setup in Fig. 10. In a test-beam environment the charged particle traverses the radiator, from left to right (Fig. 9). The photons of the Čerenkov-cone are reflected from the mirror of the right side and focused onto the readout plane on the left side. The curvature radius of the mirror is 2 m such that the focal plane of the mirror is on the surface CsI-coated GEM of the GEM stack. Here, photoconversion takes place and the photoelectrons released are accelerated into the GEM structures and undergo multiplication to produce a sizable electronic signal on the readout plane.

CsI-coating is a well established procedure and was successfully used for the Hadron-Blind-Detector (HBD) for the PHENIX experiment. As long as the photocathode exceeds a certain minimum thickness (enough to absorb the photon) of photosensitive substance the efficiency of photoabsorption is high. This minimum thickness was measured to be ~200 nm for CsI, and the described detector prototype used a layer of 300 nm or more. A reproducible high quantum efficiency of up to 70 % at smallest wavelengths has been achieved which allows a very efficient use of CsI-GEMs as photocathode material.

A recirculating gas system providing the CF₄ radiator with high purity (grade 5.7) has been constructed and used for the test-beam setup. Reecirulating, for saving the rather costly gas.

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**Fig. 7.** Reflectivity for bare Al-blanks after exposure to air and two MgF₂ coatings at different thicknesses which result in cutoff wavelengths of 120 nm respectively 160 nm.

**Fig. 8.** Reflectance curve measured for the mirror used in this prototype.
radiator requires a purification system that removes contaminants with negative effects for the operation of the RICH. In particular, H$_2$O can cause the CsI-layer on the GEM foil to crystallize and renders the photocathode useless. O$_2$ is electronegative and will reduce the electron avalanche needed for a proper signal readout, and more importantly, reduces the transparency in the gas for VUV photons. H$_2$O and O$_2$ was reduced with commercial purifiers well below the 1-ppm-level. The gas system was equipped with a pump, mass flow controllers and a manometric system so that it could provide the detector system with a constant, slightly pressurized radiator medium.

B. Preparation

The setup was tested in its final configuration so that it was ready to be operated in a test-beam environment. The preparational tests consisted of

- Gain calibration
- Pedestal correction and
- Common-mode noise calibration.

These tests were performed before the setup moved to one of the test-beam sites and were also partially performed while at the test-beam site for verifying the detector prototype’s functionality.

Gain Calibration: Calibration of the gain was accomplished by using an $^{55}$Fe source which could be inserted through a flange with a retractable arm. This allowed the source to be moved across the surface of the GEM. The source produced, on average 110 electrons within a distance of about 1.6 mm between the mesh and the top-GEM. The resulting signal throughout the GEM-stack could be read-out via a capacitive pick-off circuitry which was attached to the bottom surface of the last GEM along the stack. Fig. 11 shows the result of the calibration. The variation can be explained with non-uniformity in flatness of GEMs throughout the stack. In particular, the top-right corner in this figure indicates a variation in height between the mounting of the GEMs in that corner.

Pedestal Correction: Pedestals occur due to baseline shifts based on inherent background noise. This noise might be different for each individual channel and constitutes a distortion for the real signal to be collected. This is particularly true for triggering on real events, i.e., one could trigger on falsely identified events based on noise. Appropriate corrections have to be performed to account for pedestal levels which are obtained by randomly triggering the signal, for instance with a defined pulser signal. The fake signal is recorded with the APV/SRS, histogrammed, and a Gaussian fit is applied. The obtained mean value and variance of the pedestal response were used for analyzing events under consideration in test-beam conditions. For recovering the true signal, the pedestals have to be subtracted from the signal output.

Common-Mode Noise Calibration: A collective change of all pedestals because of pickup noise is called common-mode noise. Similar to pedestal correction this noise has to be adjusted for so that each electronics channel can be brought to the same threshold.

IV. Test-Beam SLAC-ESTB

A. Setup

The detector prototype setup was sent to SLAC and set up in the beam line of SLAC’s ESTB. The main task for this procedure was to test the functionality of the detector prototype’s devices with single electrons. Since electrons saturate the Čerenkov ring’s diameter at already very low energies no attempt has been undertaken to determine the ring diameter’s dependence on velocity.

ESTB makes use of a small fraction of the available 13.6 GeV electron beam from the Linac Coherent Light Source (LCLS) for test beam capabilities in End Station A (ESA). Kicker
magnets installed in a Beam Switch Yard (BSY) divert 5 Hz of LCLS beam to the A-line. This beam can be transported all the way to ESA for beam instrumentation and accelerator physics studies at full electron beam intensity. Alternatively, it can be directed against a thin screen in the A-line, to produce secondary electrons or positrons with energies up to the incident energy, and a wide range of intensities including single particles/pulse suitable for detector studies. Electron beams of exceptional purity, momentum definition, and small size can and have been delivered.

For the test-beam operation of the RICH detector prototype a 5 Hz, 9 GeV electron beam was collimated into the test-beam area. With 70% probability the electron bursts were empty (no electrons). That means that to a large extend bursts with two or more electrons were excluded. For triggering and selecting in the analysis stage a plastic scintillator and Lead-Glass (PbGl) calorimeter were placed downstream and included into the data acquisition via a DRS4 chip system [12].

B. Results

Data were collected for about 80 hours of beam-time. Each run consisted of circa 30 minutes. Events were triggered by the beam clock, i.e., all events during the spill were collected. This allowed for about 9000 events to be recorded for each run.

Events that contained single electrons were filtered by using scintillator and calorimeter information. This was obtained by selecting events according to a correlation between scintillator pulse height and calorimeter pulse height; see Fig.12.

Fig. 12. Correlation of pulse heights of scintillator and PbGl calorimeter. The encircled region corresponds to pulse heights that originate from single electrons.

The main analysis focus of data taken is the identification and measurement of rings that were projected onto the readout plane. Pattern recognition identifies pad candidates that make up the ring and a fitting procedure determines the ring based on its position information and diameter \( \{x,y,d\} \).

1) Combinatorial Hough Transform: A combinatorial Hough transform (CHT [13]) algorithm has been applied for comparing all possible hit combinations that make up the ring and identifying the ring parameters by choosing the most probable combination of the \( \{x,y,d\} \)-triplet. A typical example of a ring that is taken as input for CHT can be seen in Fig. 13.

A source of background was identified by analyzing data with outliers of hits outside the expected ring region. It was later confirmed with the test-beam campaign at Fermilab in conjunction with tracker data, where shadow track hits appeared. Cross-talk between neighboring channels in the APV readout was responsible for this background. It was concluded that various traces that connect individual pads along a column of pads on the readout board were overlapping with traces of neighboring pads in the same column and resulted in capacitances between theses traces in adjacent layers. No ground layer was present in the readout board.

The determination of the background was established by a procedure that subdivided the readout board into four quadrants so that each APV25 card could be considered individually. In each column of a single quadrant a signal was accepted, i.e., not to be background if it registered with a charge above the pedestal value plus a predetermined width \( \sigma \) and if it was the hit with the largest value in its half-column of pads. This procedure guaranteed that only a maximum of one hit was present within a single column of each quadrant. This algorithm apparently lowers the count of pads for a ring compared to the photon count. A Monte Carlo study was performed to estimate a possible degradation because of this rejection cut.

2) Charge distribution: Data from the detector has been analyzed regarding its expected behavior of charge deposited on the readout pads, Čerenkov-photons produced, and photo-electrons released. Charge has been found to be distributed according to an exponential spectrum as can be seen in Fig. 14 and follows the expected trend of increasing slope for increasing gain.

A feature of the APV25-chip distorted the charge distribution so far that the baseline (pedestal) signal moved when many channels were triggered with large pulse heights. A common mode rejection algorithm was applied which fits the shifted baseline and restores it. However, it worsens the width of
Fig. 14. Charge spectrum for various gain settings. Upper: two rather low gain settings show the exponential spectrum for deposited charge on pads and its increasing (decreasing in magnitude) slope. Lower: for higher gain settings a low pulse height component appears.

the pedestal and is believed that the broadening of the noise pedestal introduces the prominent peak in the charge distribution (Fig. 14 lower part). This feature can be removed by applying an absolute pulse-height cut.

The number of responding pads is saturating as a function of gain and the number of pads was determined to be nine (9). Not necessarily did the number of responding pads correspond to the number of photons that were contributing to the signals on the pads. For instance, one photon could lead to a response on two pads, or two photons could lead to a response on one pad only.

For obtaining the number of Čerenkov-photons that were recorded per measured ring a Monte Carlo simulation was performed that took into account the transverse diffusion of the charge cloud during the amplification process and the wavelength dependence of the refractive index of CF₄, thus $n_r(\lambda) \rightarrow R(\lambda)$, as well as a weighting for the Čerenkov intensity according to Eq. [1]. The result can be seen in Fig. 15. The result of this simulation is a probability of a radius per photon of $\sigma_r/\sigma \sim 2.5\%$. The calculated number of used pads for both a discrete number of simulated photons, and for a Poisson distribution around a specified number of simulated photons showed a linear relationship between the number of responding pads to the number of photons. The result was that on average nine (9) photons were making up the Čerenkov ring. This is in discrepancy to the expected number of photons, which was 16 based on the parameters of the RICH detector prototype. It is under investigation as to where this discrepancy is resulting from; it is possible that the very thin MgF₂ coating on the spherical mirror may have degraded over time, and/or that the quantum efficiency of the photocathode might have also degraded during transport and handling.

The size of the charge cloud along the amplification path can be calculated with a diffusion constant $\sigma_{\text{transv}} = 60 \mu m$. However, an “additional” diffusion was accomplished because of the misalignment of the hole pattern over the five GEM foils. This was calculated to be $\sigma_{\text{hole}} = 118 \mu m$ with a Monte Carlo method. Adding in quadrature one obtains a total transverse size of the charge cloud of $\sigma_{\text{total}} = 132 \mu m$.

With the above described methods a Monte Carlo simulation was used to determine the response of the readout to the number of photons. Fig. 16 shows the result of the simulation and shows the radius of the rings to be 33.20 mm with $\sigma_R/\bar{R} = 3.0\%$. The measured ring radius is in excellent agreement with the obtained simulation result.

7 An extensive compilation for various gas compounds can be found at Saga University: ILC-TPC Gas Properties
V. Test-Beam FTBF

A. Setup

The principal goal at FTBF was to extend the knowledge from the RICH detector prototype's performance in electron beam at SLAC, wherein all beam particles have saturated their ring radius, to true identification of hadrons. The FTBF facility delivers secondary beams with analyzed momenta from collisions of the 120 GeV/c proton beam impinging on a target. The FTBF facility has two targets. The upstream target delivers 8-66 GeV/c particles. Unfortunately, beams from that target are virtually devoid of Kaons due to decay in flight. The downstream target provides 1-32 GeV/c secondaries and was used for the studies.

The same setup as used at ESTB was used at FTBF. However, in contrast to the setup at ESTB, where single electrons on rather precise trajectories, as test beam probes were used, at FTBF higher rates for various particles and angular spread have been used. Because the current implementation of the detector pad plane has coarse segmentation (5mm hexagons), the ring radius resolution would be limited by the determination of the ring center. To overcome this limitation, two $10^3 \times 10^3 \text{cm}^2$ triple-GEM tracking detectors have been used.

For discriminating the various particles a differential Čerenkov counter provided by FTBF was used; see Fig. 17. Two photomultiplier (PMT), labeled as “inner” and “outer” PMT can selectively be used, dependent on the ring radius of the particle under consideration. The mirror M2 has a small hole in its center which allows small ring radii to pass onto inner PMT, else will be reflected to outer PMT and counted. The pressure of the radiator gas could be tuned so that with varying $n_r$ the threshold and ring diameter of the Čerenkov signals velocities of the different massive particles could be distinguished by selecting signals only from the inner, respectively outer PMT. The consequence of this setup is that kaons would give a signal in the inner PMT, pions in the outer PMT, protons in neither. The downstream target only provided $\sim 1\%$ content of kaons. For this reason, a trigger on the inner Čerenkov counter to take “kaon-only” data was developed. The running period was divided such that 50% of the clock time was dedicated to kaon trigger data.

The Čerenkov threshold for kaons in CF$_4$ is $\sim 16$ GeV/c. FTBF was optimized for tunes in 5 GeV/c increments which allowed for three beam momenta useful for collecting data: 20 GeV/c, 25 GeV/c, and 32 GeV/c.

B. Results

For intense rings, well above the Čerenkov threshold, it was possible to determine the ring center using the ring itself. An empirical alignment was determined by plotting the correspondence between the self-determined ring center with the direction vector of the tracks from the trackers. Once aligned, rings are determined by histogramming hit pads in their apparent radius, determining a trial radius with the maximum of that histogram, collecting pads in a region around the peak channel, and eventually fitting collected pads to a ring radius.

Histograms with responding pads for pions, kaons, and protons can be seen in Fig. 18 in the upper two graphs and left lower. The lower right graph there shows the expected linear scaling (see Eq. 1) of the photon yield with the radius squared. A yield of twelve (12) photons per ring for the pion sample can be concluded from these data. This is in better agreement with 16 expected photons per ring at saturated ring diameter. The particle identification was performed by comparing the radii measured for known particles at known momenta. As one can see in Fig. 19 the separation for most abundant particles in a collision experiment is very well achieved. The peaks in Fig. 19 can be well understood in terms of radius and width. The radius is determined by the particle velocity. The upper panel of Fig. 20 shows the correlation between

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Fig. 17. Schematics of the FTBF differential Čerenkov counter.

Fig. 18. Distributions for the number of responding pads for various particles. Lower right: dependence of the radius on number of responding pads.

Fig. 19. Particle identification with the RICH detector prototype.

Fig. 20.
the measurement and the calculation with the best fit index of refraction $n=1.00055$ (in agreement with published results). The lower panel of the same figure shows the expectation for the width accounting for dispersion in the gas, segmentation of the RICH, momentum spread $\delta p/p = 5\%$ of the FNAL beam line, and a constant term of 240 $\mu m$ to account for all other factors. It is assumed that the imperfection of the fit in that panel is influenced by the momentum spread. For discriminating pions and kaons in real experimental conditions one needs to be able to separate quite clearly the ring diameter of the particle under consideration from other particle species, provided the momentum of that particle is known. Fig. 21 shows the separation power based on various readout structures that provide a certain position resolution for the photons of the Čerenkov ring. The worst assumptions that went into the lower panel of Fig. 20 were applied to the calculation of the points in Fig. 21. If one considers $2.5\sigma$ separation as sufficient for discriminating pions from kaons one can see in that figure that the hexagon readout pads used for this detector prototype will not be sufficient, but for 500 $\mu m$ resolution this goal can be achieved up to $p \approx 60$ GeV/c, more than required for the EIC physics program.

VI. CONCLUSION

A RICH detector prototype with novel technologies, quintuple-GEM readout structure and dielectric mirror was successfully tested and operated at two test-beam facilities. The first test beam campaign confirmed the proof-of-principle test and validated a set of basic observations as expected. Expected was the measurement of a Čerenkov ring with sufficient number of photons and with an expected diameter. The second test beam campaign provided the separation of various common particle species in collider experiments (pions, kaons, protons) up to momenta of 32 GeV/c. Very promising results have been obtained, to name one, the rather short radiator size of a RICH but still capable to separate various particle species in the forward direction of collider experiments up to high momenta. One important result is the observation of required position resolution for photon detection to maintain a good separation power in real experimental conditions. The verification of that statement is subject of an improved readout structure for the RICH-detector and subsequent test in beam.

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