A RICH Detector: HBD and Meta-material Technology

EIC PID Workshop @ SBU

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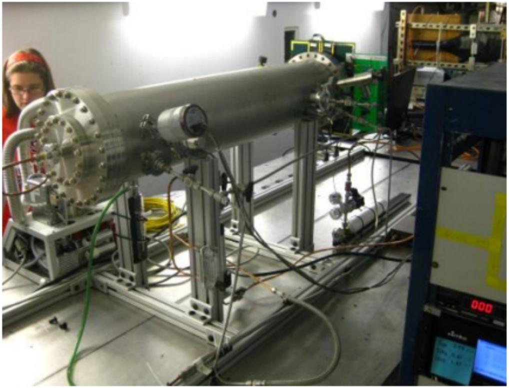
SUNY Stony Brook

July 10, 2019

SBU RICH Prototype in eRD6

Ring Imaging Cerenkov - RICH Detector with high momentum reach aims at

- Low index of refraction of the radiator medium → CF_4
- Short radiator length, windowless
- High count of measured photoelectrons
- Precise position determination of each photo-electron



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RICH Technology

- Ring imaging requires focusing of Cerenkov photons into ring $\rightarrow$ radius directly related to Cerenkov angle
- One option: perform focusing with mirror $\rightarrow$ place photo-detector at focal plane
- Cerenkov light yield

$$\frac{dN_{p.e.}}{dx} = 2\pi\alpha Z^2 \sin^2 \theta_{\mathbf{C}} \int_{\lambda_{min}}^{\infty} \varepsilon(\lambda) \frac{d\lambda}{\boldsymbol{\lambda^2}}$$

$\varepsilon(\lambda)$: overall efficiency factor leading to detection of $N_{p.e.}$; includes effects due to absorption, reflection, transmission, and detection probability

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Vacuum Ultraviolet (VUV with 200 nm $> \lambda >$ 100 nm) photons should be principle goal in making most compact detector design

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Issue 1: Photo-sensitive detector physically separated from medium

Issue 2: Mirror $\rightarrow$ cutoff wavelength

$\varepsilon(\lambda)$: overall efficiency factor leading to detection of N$_{p.e.}$; includes effects due to absorption, reflection, transmission, and detection probability

A Possible "Solution"

A. Windowless photocathode

- Use medium for photo-detection $\rightarrow$ gas detector with photo-cathode

B. Quintuple GEM photo-detector

- Flexible Micro-pattern Gas Detector (MPGD)

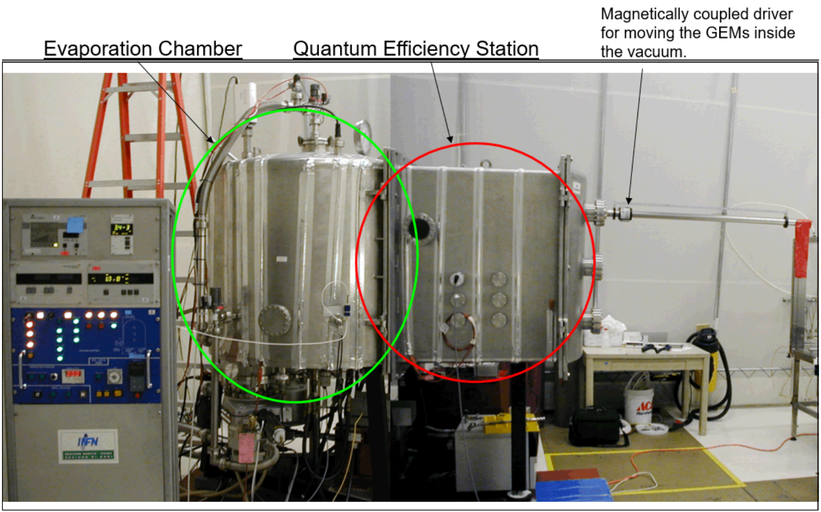
C. VUV high reflective mirror coating

- Di-electric mirror with MgF_2 coating

Windowless Photocathode & Quintuple GEM

- Gas Electron Multiplier (GEM) invented 1997 by F. Sauli
- Thin polymer foil with copper-cladding, perforated with a high density of microscopic holes
- Foils can be stacked $\rightarrow$ amplification load reduced at each element, allowing for safe operating conditions
- Can be combined with photo-cathode
  - ⋆ GEMs have Ni and Au over-coatings to hide the copper
  - ⋆ Deposition of thin layer ($\sim$ 300 nm) of CsI on top of GEM that is facing the radiator medium
  - ⋆ Work-function of CsI $\sim$ 6.2 eV $\rightarrow \lambda <$ 200 nm
- Photo-detector directly exposed to Cerenkov medium

GEM Coating In-house



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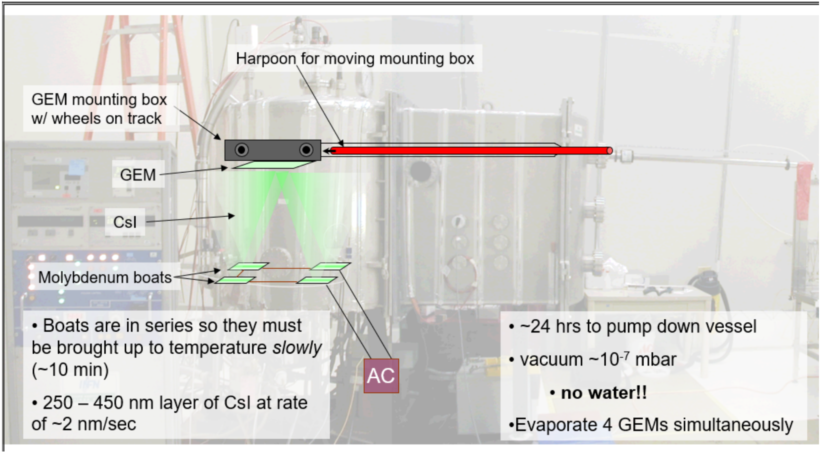

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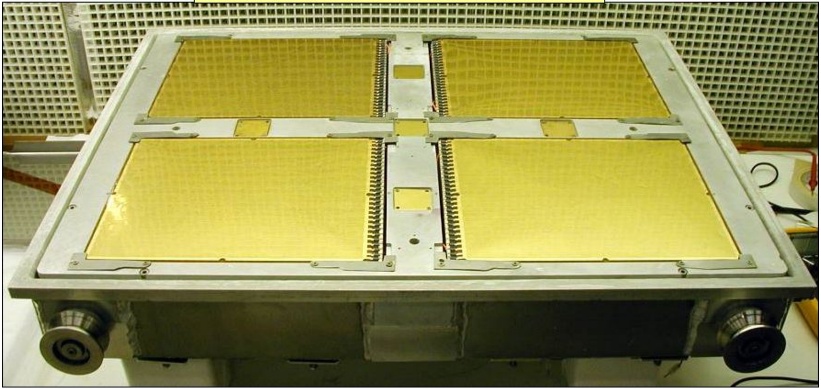
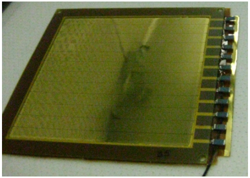
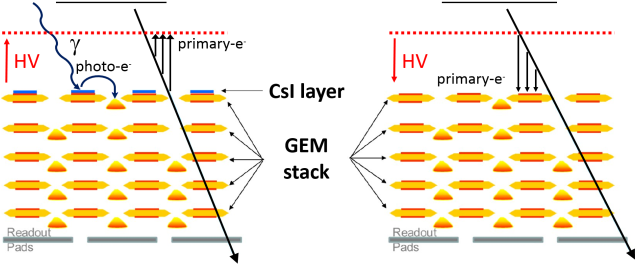
GEM Coating In-house

READY FOR EVAPORATION



GEM-stack photocathode combination à la Hadron Blind Detector (HBD) @ PHENIX





Quintuple GEM

- Why Quintuple-GEMs?

  A. High detection efficiency for single photo-electrons;
  CsI coated GEM could limit gain capability $\rightarrow$ HBD application yielded efficiency for single photoelectron avalanche detection was $\frac{1}{e} \sim 37\%$ with triple-GEM setup

  B. Success in achieving high gain from photosensitive GEM stack is partly due to fact that photocathode itself is optically shielded from avalanche $\rightarrow$ mirror poses risk of background light from avalanches in the first hole layer (CF_4 produces light at $\sim$ 160 nm during avalanche) being reflected back onto the photocathode surface;
  fifth GEM to be operated at gain $\sim$ 1 for minimizing risk

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Scintillation no issue due to high granularity of readout

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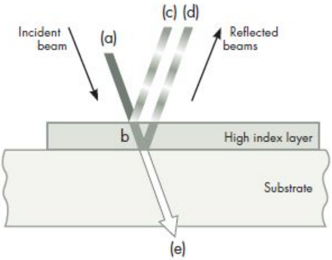
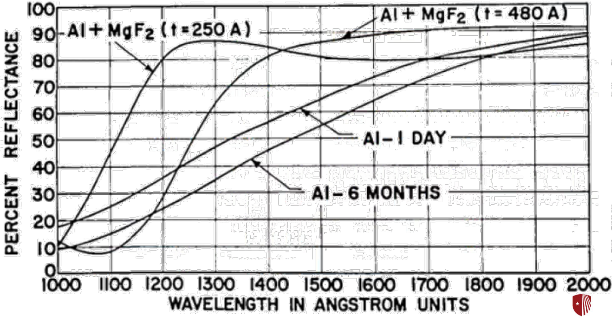
VUV mirror



Thin optical coating principle

Carefully tuned thickness of MgF_2 enables high reflectivity in VUV



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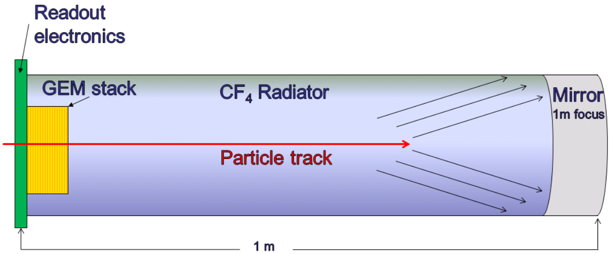
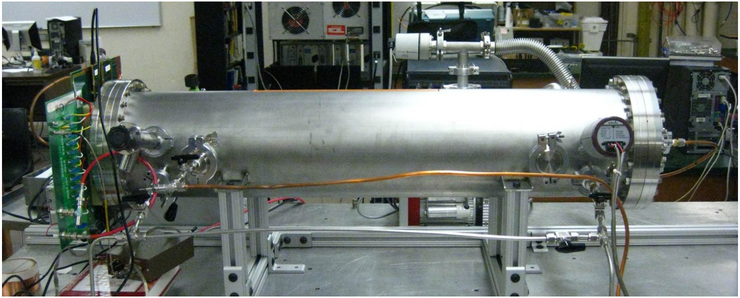
RICH Detector Prototype Setup





Detector Prototype Setup

- Quintuple-GEM module
  - ⋆ detection plane/entrance window
  - ⋆ standard 10×10 cm^2 GEMs with a hole diameter of 70 μm and 140 μm pitch
  - ⋆ CsI coating → to exceed a certain thickness of photosensitive material ($>$ 200 nm)
  - ⋆ high quantum efficiency of up to 70% at smallest wavelengths ($\sim$ 120 nm)
  - readout via square array composed of 512 tessellated hexagons with apothem of $\sim$2.5 mm
  - electronically readout with APV25 chip
    - 128 readout channels per chip, 192 element deep pipeline
    - 50 ns CR-RC type shaping amplifier, pulse shape processing stage
    - noise $\sim 600e^-$, gain $\sim 10^4$
- Mirror
  - ⋆ focusing device/exit window
  - ⋆ curvature radius r = 2 m → focal plane of mirror coincides with surface of CsI-coated GEM

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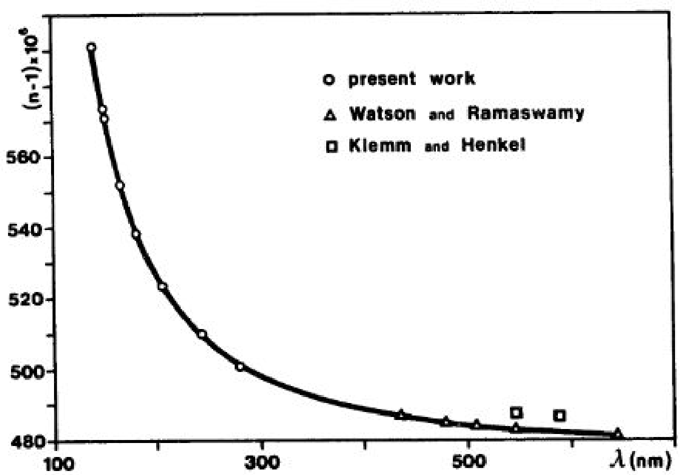
Detector Prototype Setup

- Radiator
  - ⋆ Tetrafluoromethane CF_4, $n_{CF_4}(\lambda \leq\ 200\ nm) \geq 1.00052$
  - ⋆ recirculating, clean gas system → control impurities (H_2O, O_2)



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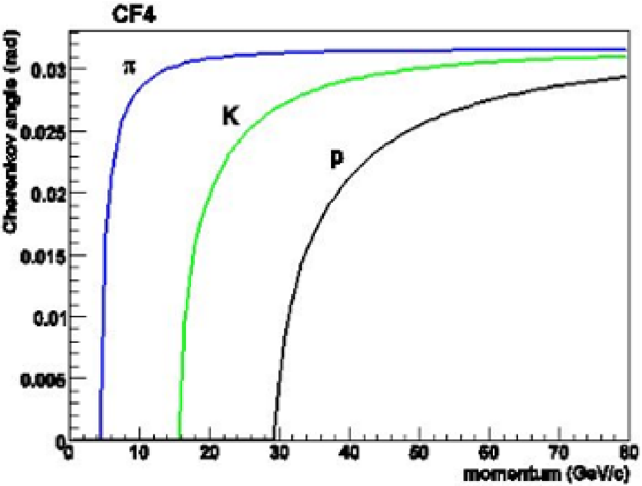

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Test-Beam SLAC-ESTB

SLAC provides electrons: proof-of-principle test

- Electrons saturate Cerenkov angle at already low energies $\rightarrow$ no velocity measurements necessary
- 9 GeV electron beam @ 5 Hz was collimated into test-beam area
- With 70% probability electron bursts were empty (no electrons) $\rightarrow$ most bursts containing two or more electrons were excluded
- Triggering with plastic scintillator and Lead-Glass (PbGl) calorimeter downstream, included into data acquisition via a DRS4 chip-based readout system

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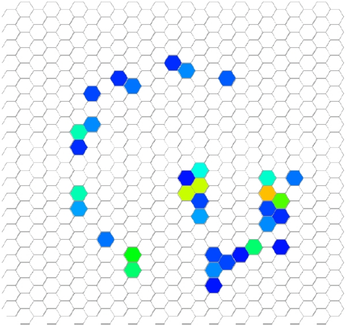
Test-Beam ESTB

Data analysis

- Analysis according to identification and measurement of the ring diameters
- Pattern recognition algorithm for identifying pads that were producing rings
- Fitting procedure for determining position and diameter of ring $\{x,y,d\} \rightarrow$ combinatorial Hough transform chose most probable triplet-combination



Typical event from ESTB campaign

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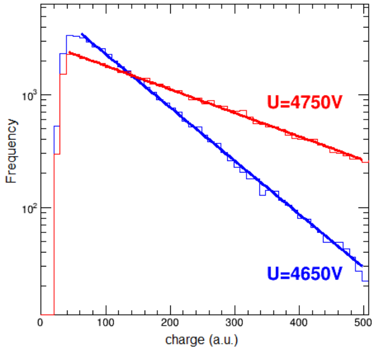
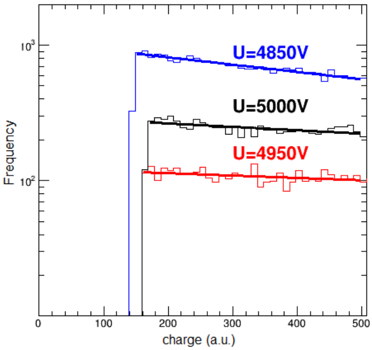
Test-Beam ESTB

Charge spectrum for "low" gain setting



Classic pulse height distribution behavior according to exponential form

Charge spectrum for "high" gain setting



Polya distribution; saturation and firing of neighboring pads

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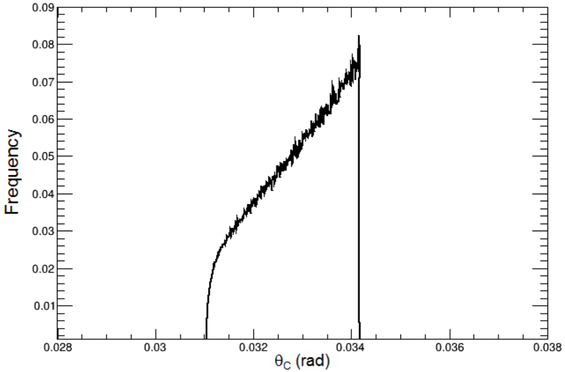
Expected number of photons per ring

MC simulation taking into account

- ⋆ transverse diffusion of the charge cloud during amplification process,
- ⋆ Cerenkov-angle function of wavelength
- ⋆ weighting effect for the Cerenkov intensity



Chromatic dispersion $\sigma_{\theta_C}/\theta_C \sim 2.5\%$, $\overline{n}_{\gamma,MC} = 16$ vs $\overline{n}_{\gamma,meas.} = 9$

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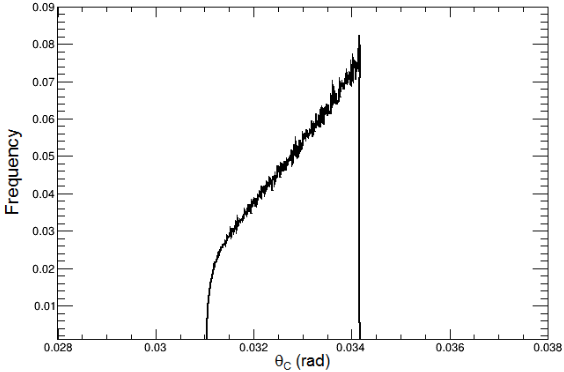

Degradation of photocathode/mirror most likely caused

$$\overline{n}_{\gamma,meas.} << \overline{n}_{\gamma,MC}$$

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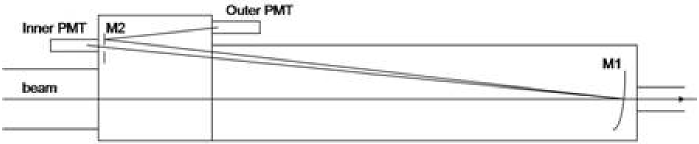
Test-Beam Fermilab-FTBF

Main goal: assess detector performance for identification of hadrons

The hadrons

- secondary particles produced by 120 GeV/c proton beam indecent upon a target
- momentum range of secondaries is 1-32 GeV/c (limited by the beamline optics)
- trigger on particles under consideration with FTBF differential Cerenkov counter (adjustable index of refraction $\rightarrow$ gas pressure)
- π/K/p @ 20 GeV/c, 25 GeV/c, and 32 GeV/c



Higher momentum secondaries available from the "upstream target" $\rightarrow$ most kaons produced upstream would have decayed before reaching our apparatus

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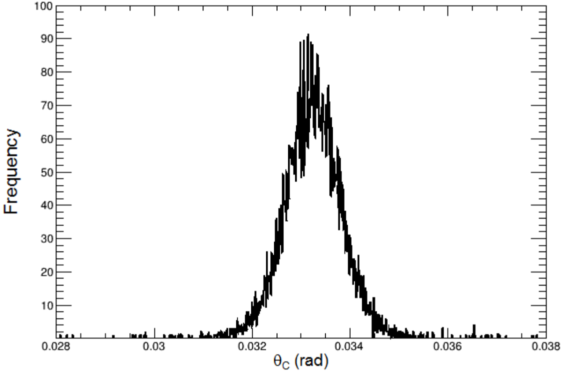
Test-Beam FTBF

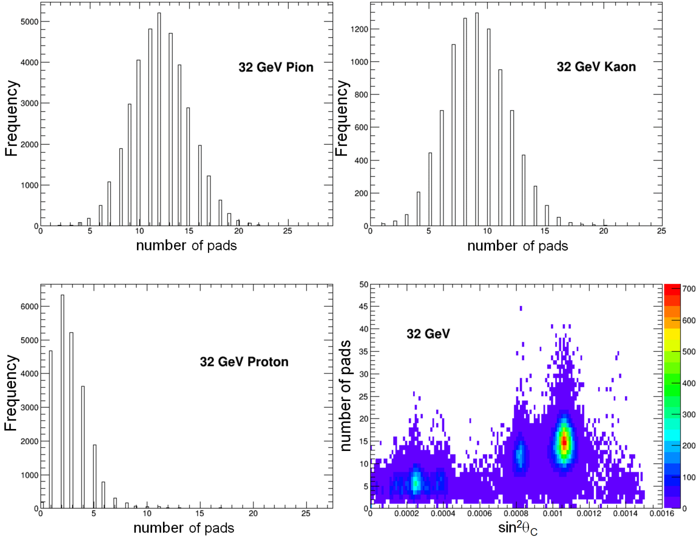
- Same setup as at ESTB with refurbished CsI-GEM
- GEM-tracker hodoscope for determining ring center
- Preparation for FTBF with simulations

Simulated Cerenkov angle for pions with momentum of 32 GeV/c in $CF_4 \rightarrow \theta_C = (33.2 \pm 1.0)\ mrad$



Test-Beam FTBF

Distributions for number of responding pads for various particles



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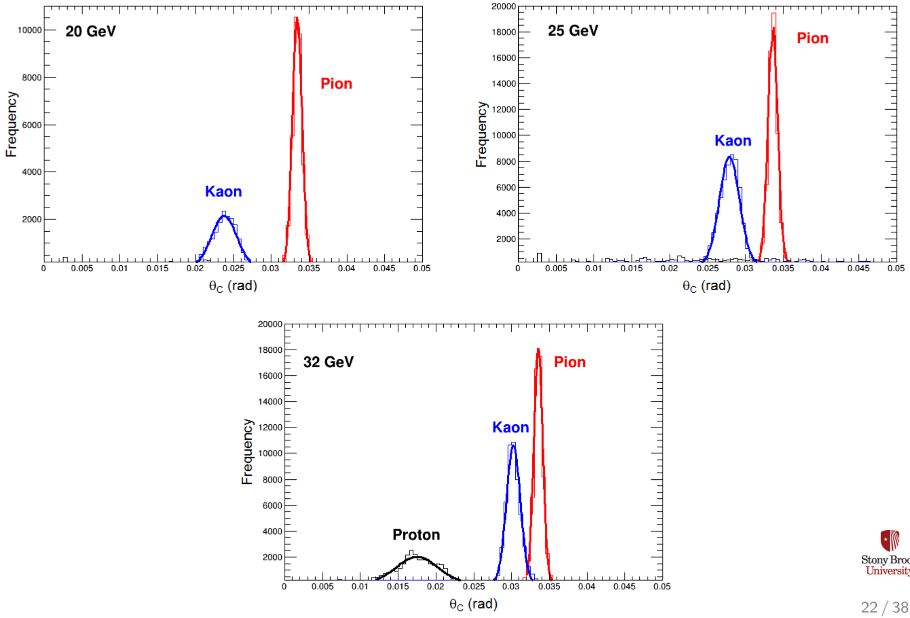
Test-Beam FTBF - Particle Separation



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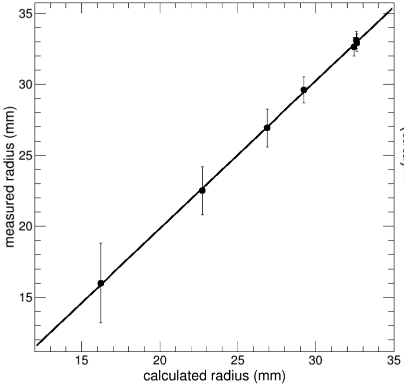
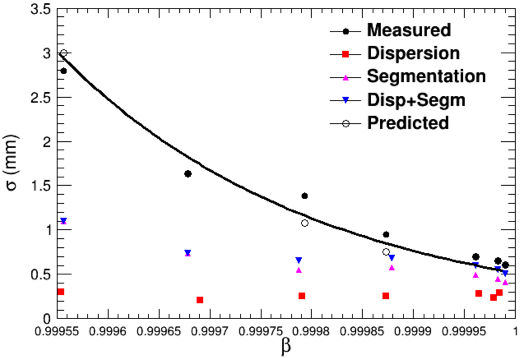
Test-Beam FTBF

Good matching of radii



Contributors of resolution smearing



(Not a fit, rather guidance for the eye)

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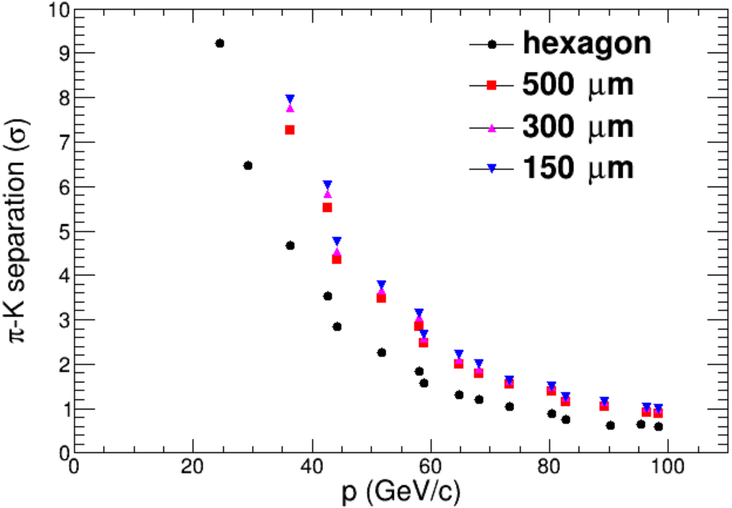
Test-Beam FTBF: Separation Power



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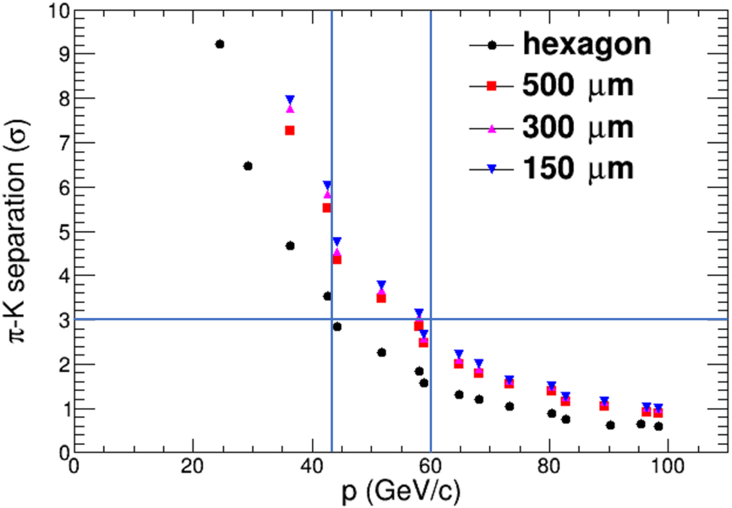
Hexagonal pads not sufficient for separation @ 50 GeV/c



RICH Prototype Studies in eRD6 - 2015

Conclusion then:

- ... segmentation of the readout, we have used for our prototype is not sufficient ...
  ... radiator gas, CF_4 provides only little diffusion so that charge sharing over more than one pad on the readout plane is essentially excluded ...

Possible solution then:

- ... to overcome this limitation one has to either reduce the pad size which will result in a significantly higher channel count ...
- ... to introduce charge broadening via resistive layers, however, this introduces other complications which makes this approach less desirable ...
- ... unconventional pad shapes ...

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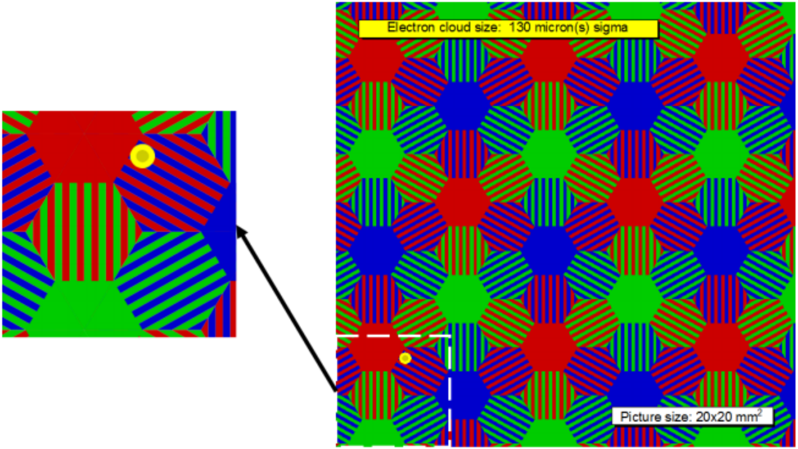
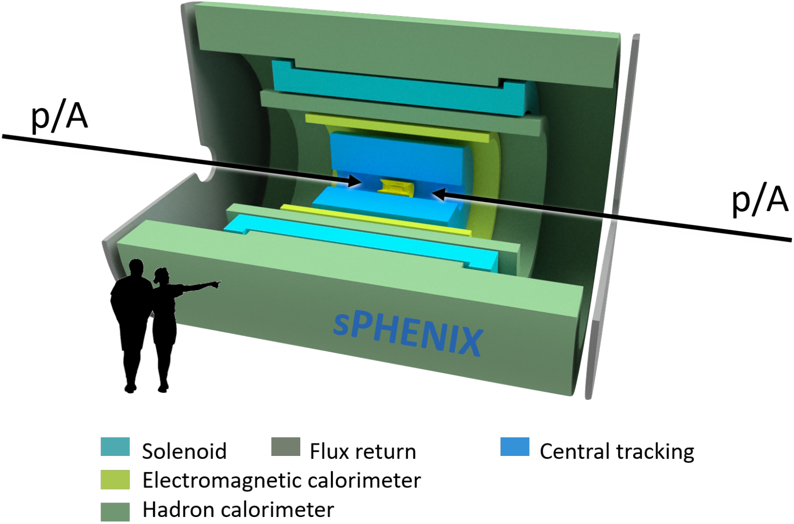
Alexander Kiselev



Motivation - Reuse sPHENIX for Day-1 EIC-Detector



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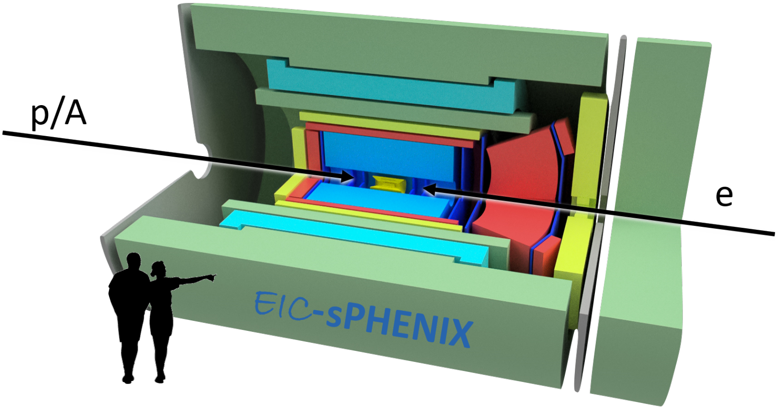

Solenoid
Flux return
Central tracking
Electromagnetic calorimeter
Forward/backward tracking
Hadron calorimeter
Particle ID

Detector gets very crowded → Particle ID with least space

Least space and many more issues might be resolved!

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RICH Prototype Studies in eRD6 - 2018 → Proposed

Possible solution now:

- ... to change the conditions for the radiator material in the way that it acquires properties of high index-of-refraction material in one direction and small index-of-refraction in the other direction ...
- It is conceivable that a material can be constructed whose permittivity and permeability values may be designed to vary independently and arbitrarily throughout a material
- *transformation optics* → correspondence between coordinate transformation and material implementations

Transformation Optics Meta-materials (TOM)

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Transformation Optics

- Spatially changing refractive index leads to changes in light-propagation characteristics → MIRAGE
- Artificial media that have spatially changing optical properties can bend light in almost any manner
- Manipulate optical properties → Transformation Optics
  - Framework exploiting form-invariance of Maxwell's equations in design of material parameters of optical devices
  - Form-invariance of Maxwell's equations under coordinate transformations → equivalence between geometries and media

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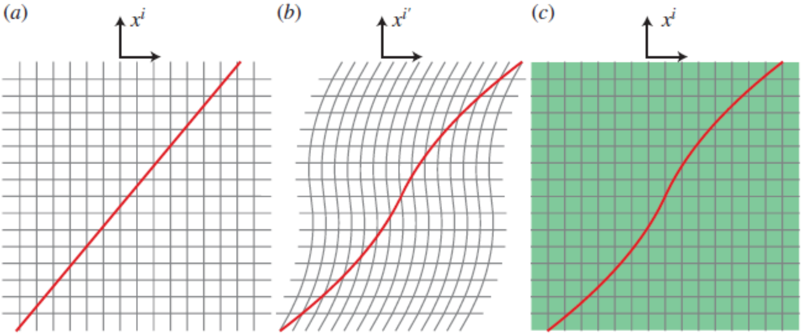
- Equivalence between geometries (Electromagnetic Space **ES**) and media (Physical Space **PS**)

TOM Principle



(a) **ES** in Cartesian coordinate system
(b) Same **ES** in deformed coordinate system $x' = f(x, y)$; $y' = y$
(c) **PS**, in which meta-material is implemented as of curved **ES** (b)

Cherenkov Photon Manipulation

- Sought after properties: material parameters of medium for Cherenkov radiation along x-axis in medium with background refractive index $\varepsilon_b = n_b^2$, with *linear coordinate stretching* along principle axes: $x' = f(x), y' = g(y)$ and $z' = h(z)$
- Equivalence relation of transformation optics yields material properties

$$\frac{\varepsilon_{x,x}}{\varepsilon_0 \varepsilon_b} = \frac{\mu_{x,x}}{\mu_0} = \frac{g'(y)h'(z)}{f'(x)}$$

$$\frac{\varepsilon_{y,y}}{\varepsilon_0 \varepsilon_b} = \frac{\mu_{y,y}}{\mu_0} = \frac{f'(x)h'(z)}{g'(y)}$$

$$\frac{\varepsilon_{z,z}}{\varepsilon_0 \varepsilon_b} = \frac{\mu_{z,z}}{\mu_0} = \frac{f'(x)g'(y)}{h'(z)}$$

with f', g', h' transformations into **PS**

Ginis V. et al. "Controlling Cherenkov Radiation with Transformation-Optical Metamaterials". In: *Physical Review Letters* 113.167402 (2014). DOI: 10.1103/PhysRevLett.113.167402.

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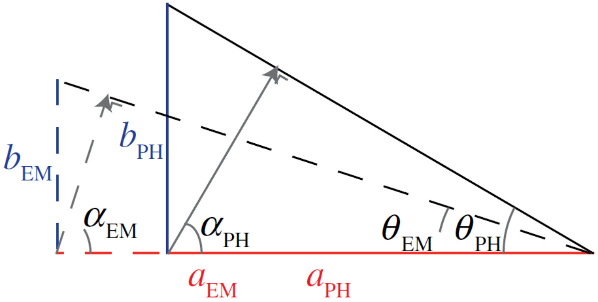
Cherenkov Photon Manipulation

- Cherenkov radiation obeys geometry of electromagnetic reality
- Cherenkov cone can be manipulated with material parameters $\rightarrow$ coordinate transformations
- Inhomogeneous Maxwell equations with plane monochromatic wave as solution yields dispersion relation $\rightarrow$ calculate Cherenkov angle in TOM



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Cherenkov Photon Manipulation

- Resultant [5]:

$$\tan(\alpha_{PH}) = \frac{k_y}{k_x} = \frac{G}{F}\frac{\sqrt{F^2\epsilon_b\omega^2/c^2 - k_x^2}}{k_x} = \frac{G}{F}\tan\left(\theta_{Ch,n_b}\right)$$

θ_{Ch,n_b}: angle of Cherenkov radiation emitted in a medium with refractive index n_b

$$\Rightarrow \alpha_{PH} = \arctan\left(\frac{G}{F}\tan\left(\arccos\left(\frac{c}{n_b F v}\right)\right)\right)$$
$$= \arctan\left(\frac{G}{F}\tan\left(\arccos\left(\frac{1}{F n_b \beta}\right)\right)\right)$$

Compare to classical Cherenkov angle:
$\cos\theta_{Ch} = \frac{1}{n\beta} \Rightarrow \theta_{Ch} = \arccos\frac{1}{n\beta}$

[5] $F = f',\ G = g',\ H = h'$

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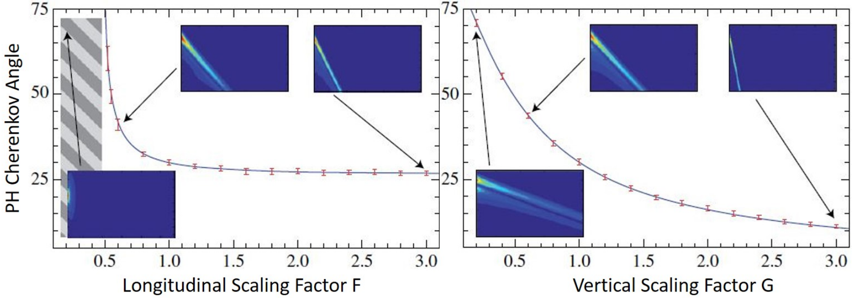
Cherenkov Photon Manipulation

Full-wave numerical simulations of Cherenkov radiation

$c/n_b v = 0.5$



$G = 1$ $F = 1$

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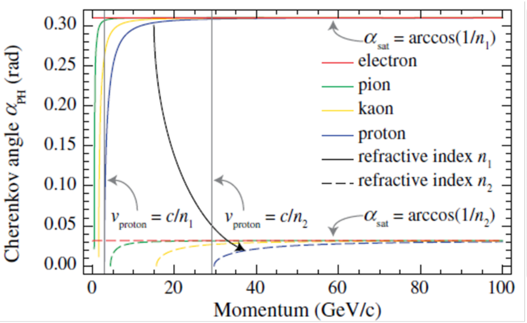
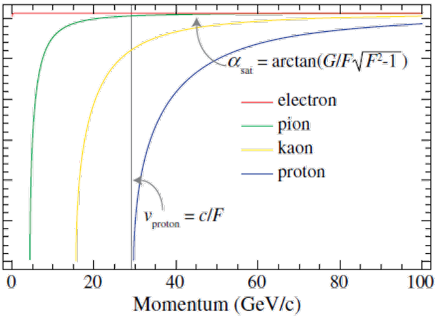
Cherenkov Photon Manipulation





Aerogel vs CF_4

Meta-CF_4

$F = 1.0005 \quad G = 10$

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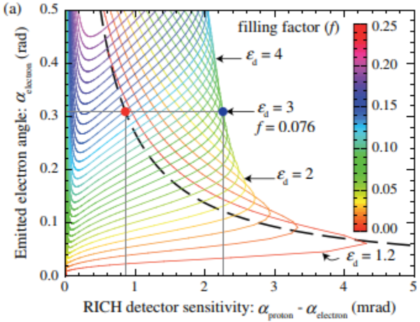
Meta-Materials

What are Meta-materials?

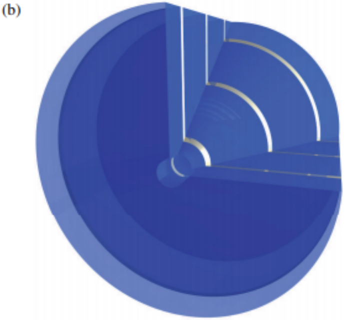
Meta-materials are fabricated structures and composite materials that either mimic known material responses or qualitatively have new, physically realizable response functions that do not occur or may not be readily available in nature.

Meta-Materials for Cherenkov-Radiation Detection

- Fabricate devices that provide materials with inhomogeneous indices of refraction $\rightarrow$ photonic crystals and meta-materials
- Formed by building units of size s intermediate between the molecular scale $m = (1-3)\ nm$ and the optical wavelength λ



Comparison between traditional radiators and meta-material radiators for fixed momentum (40 GeV/c) and wavelength ($\lambda = 700\ nm$)



Implementation of meta-material: Several thin silver cylinders embedded in a dielectric with $f = 0.076$

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R&D Program

- Perform calculations and simulations for determining the material parameters that constitute particle detectors with enhanced detection sensitivity
- Work out with commercial providers a realistic meta-material implementation of such a detector with transparent dielectrics
- Upgrade our existing RICH prototype with photo-multipliers (SiPMs?) and adapt mirror to new detection conditions
- BIG Challenge: find appropriate material composition that resemble desired radiator properties $\rightarrow$ trial-and-error approach at first

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