

A Proximity Focusing RICH Detector for the ePIC Experiment at the EIC

Brian Page

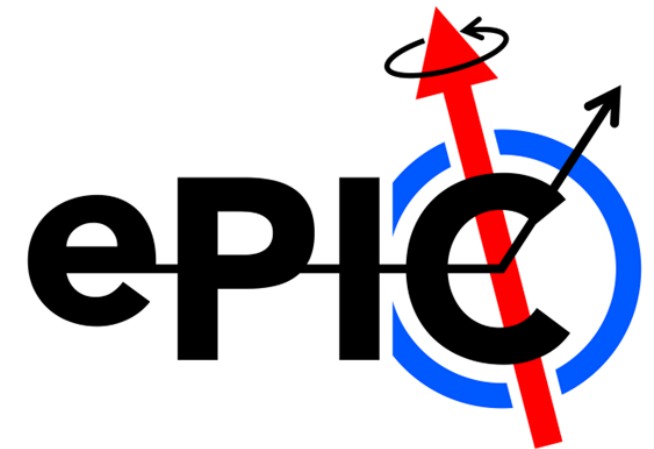
XII International Workshop on Ring Imaging Cherenkov Detectors

September 15 – 19, 2025

The logo for RICH 2025 features the text "RICH 2025" in a large, bold, orange font. Below it, in a smaller, yellow font, is the text "XII International Workshop on Ring Imaging Cherenkov Detectors". At the bottom left of the logo, there is a stylized orange graphic of a ring detector structure. The background of the logo is a painting of a church with a large tower and spires, set against a dramatic, cloudy sky with a sunset or sunrise glow.

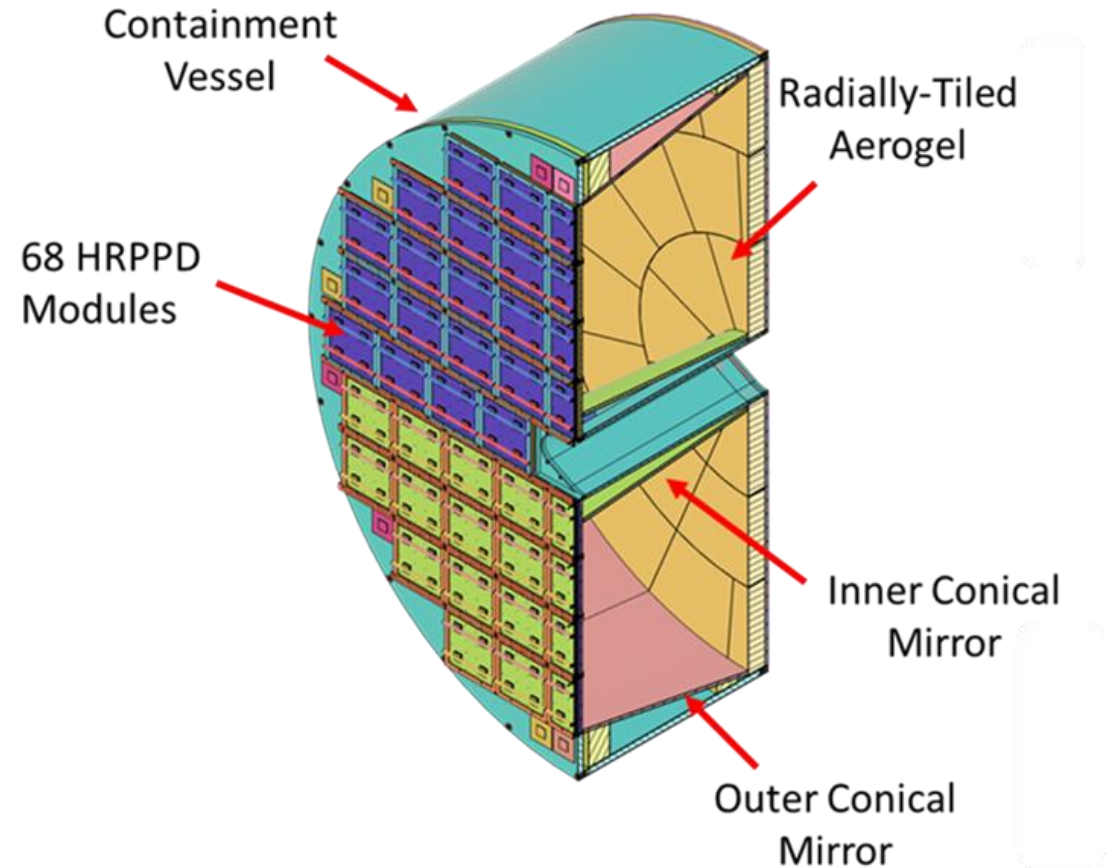
RICH 2025

XII International Workshop on Ring Imaging Cherenkov Detectors
Mainz, Germany 15-19 September 2025

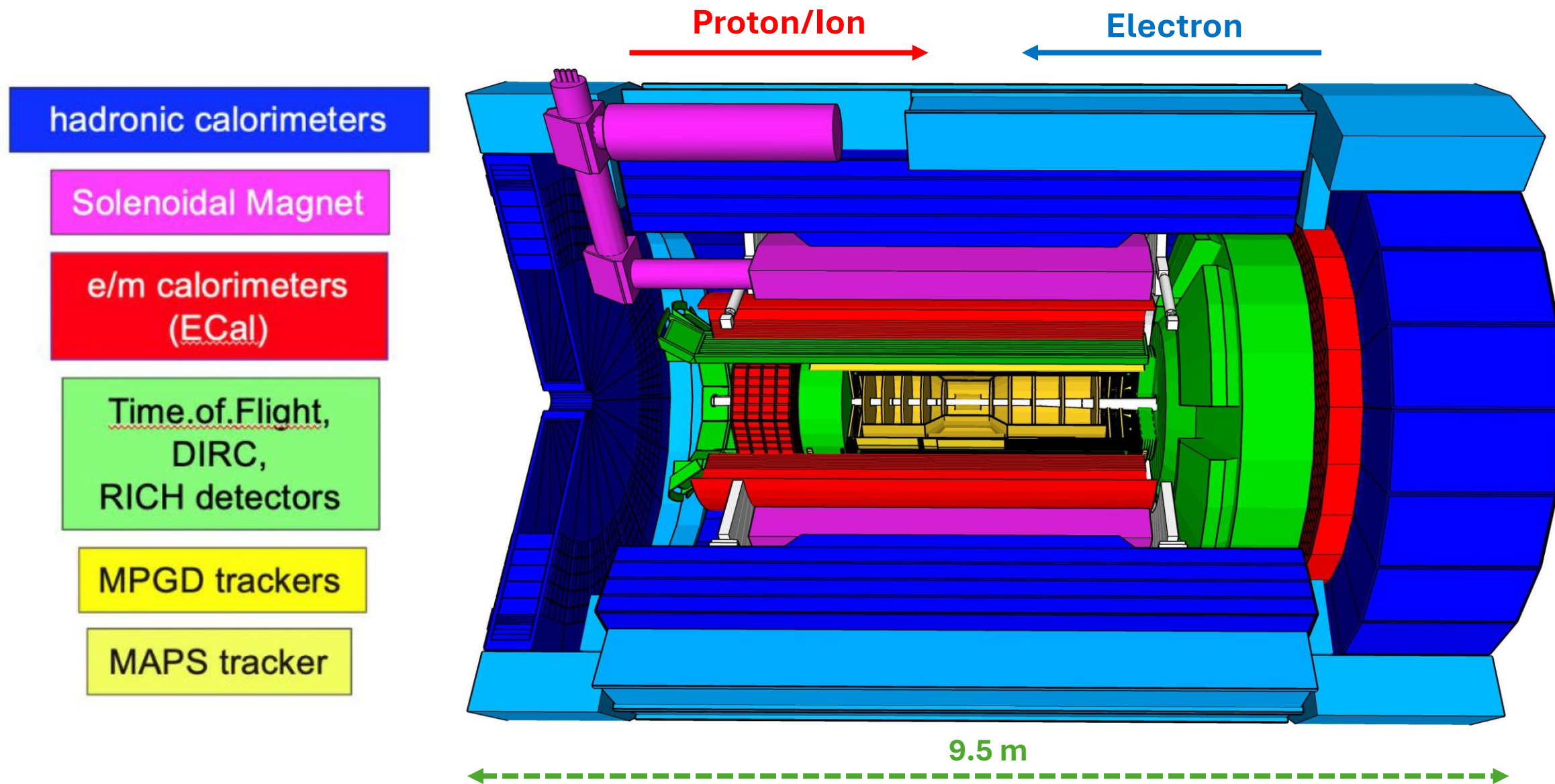


Outline

- ❑ ePIC and pfRICH Overview
- ❑ pfRICH Subcomponent Descriptions
 - Vessel
 - Sensors
 - Mirrors
 - Aerogel
 - Light Monitoring System
 - Services
- ❑ Component Testing and QA
- ❑ Simulation



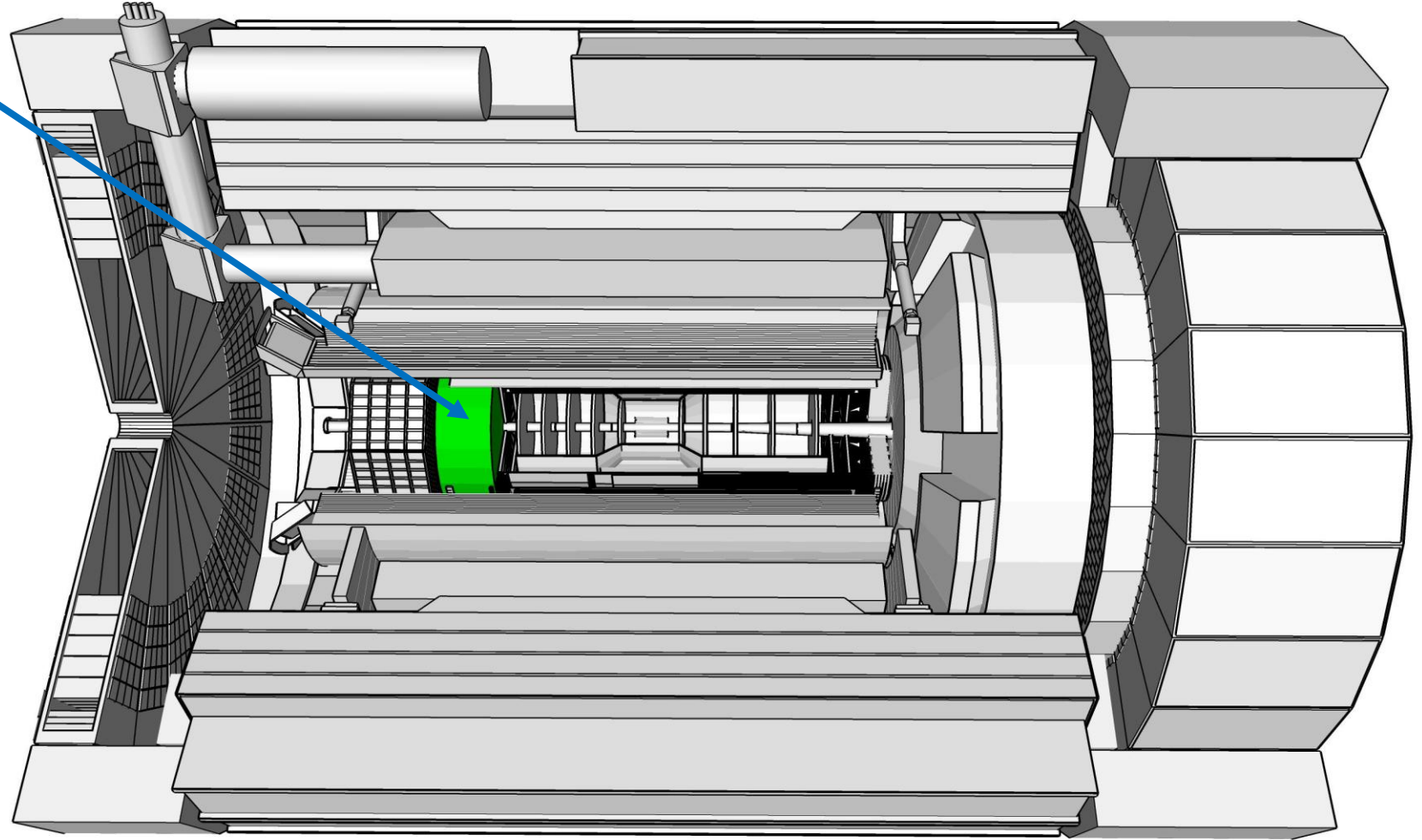
The ePIC Detector



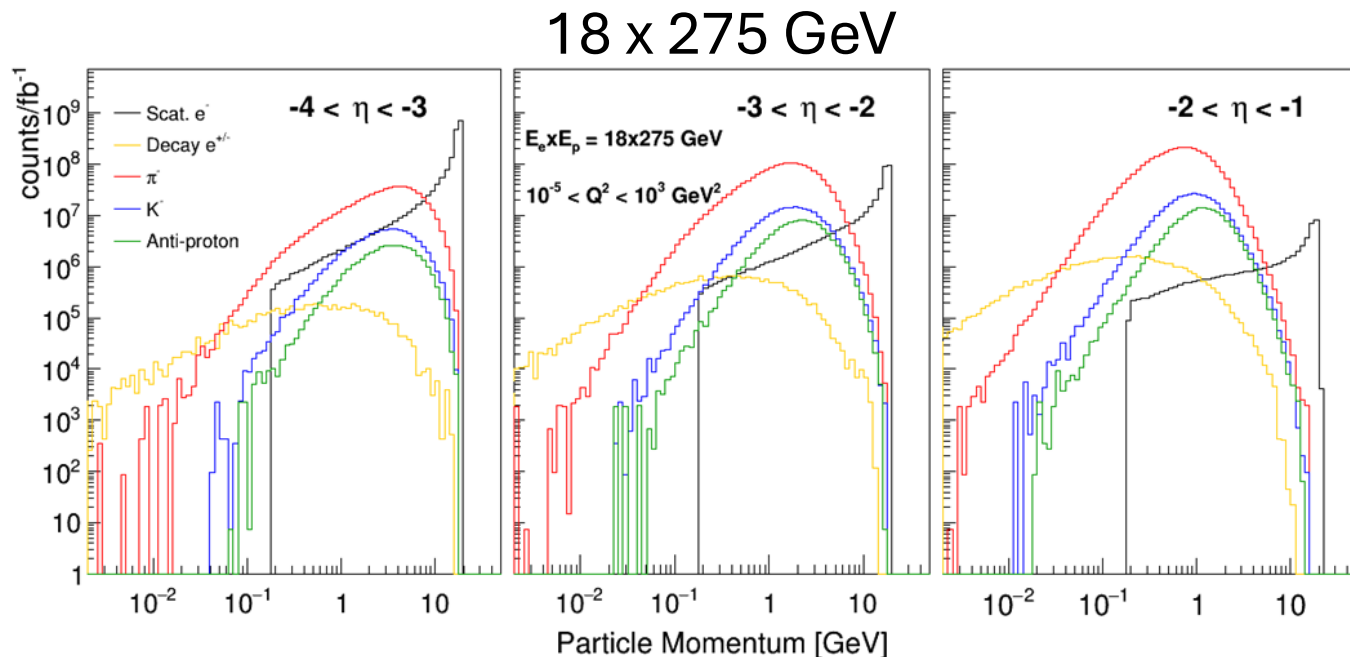
The ePIC Detector

pfRICH

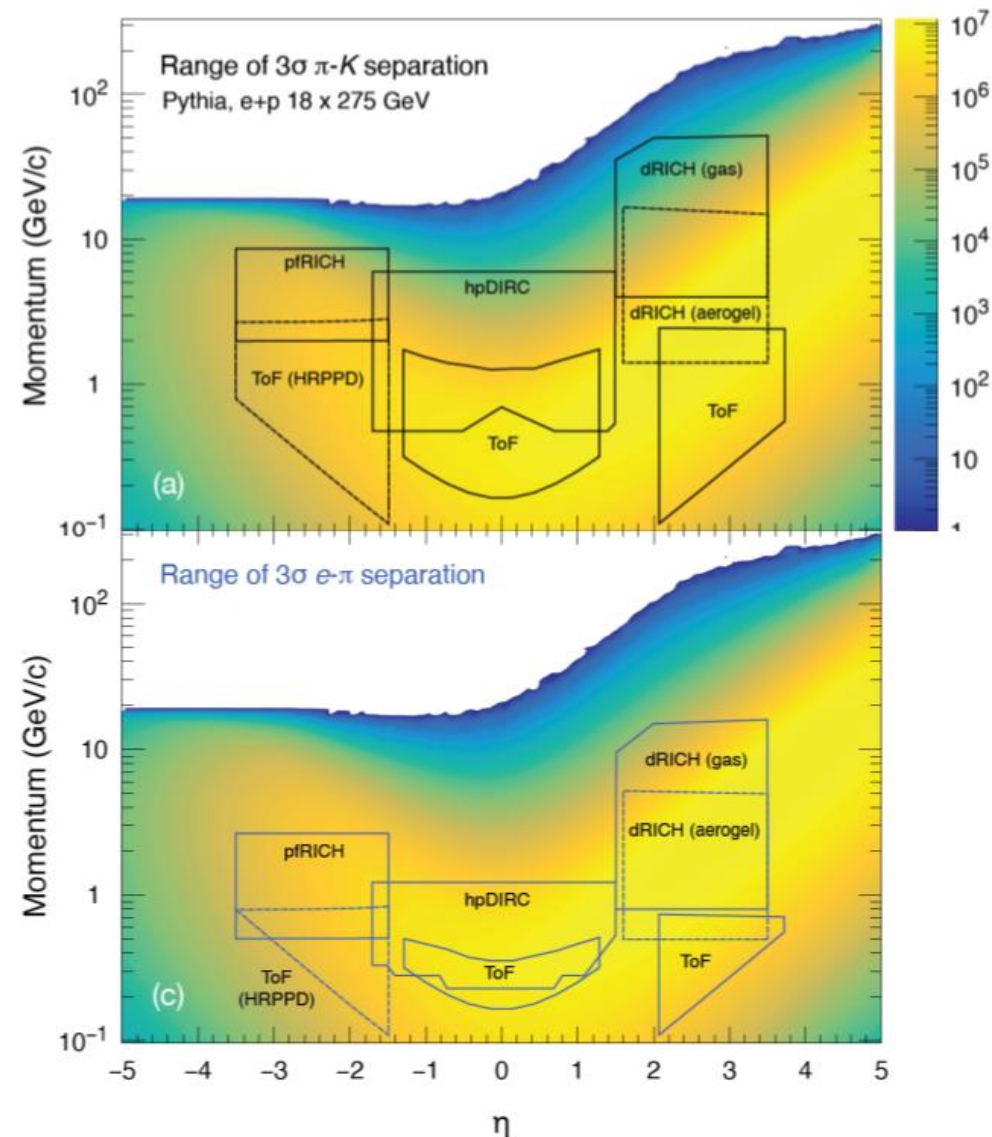
- ❑ Provide hadron identification ($\pi/k/p$) in the backward (electron-going endcap)
- ❑ Aid in e/h discrimination at low momentum where tracking and calorimetric methods are less efficient
- ❑ Minimize material budget and thermal load on electromagnetic calorimeter directly down-stream



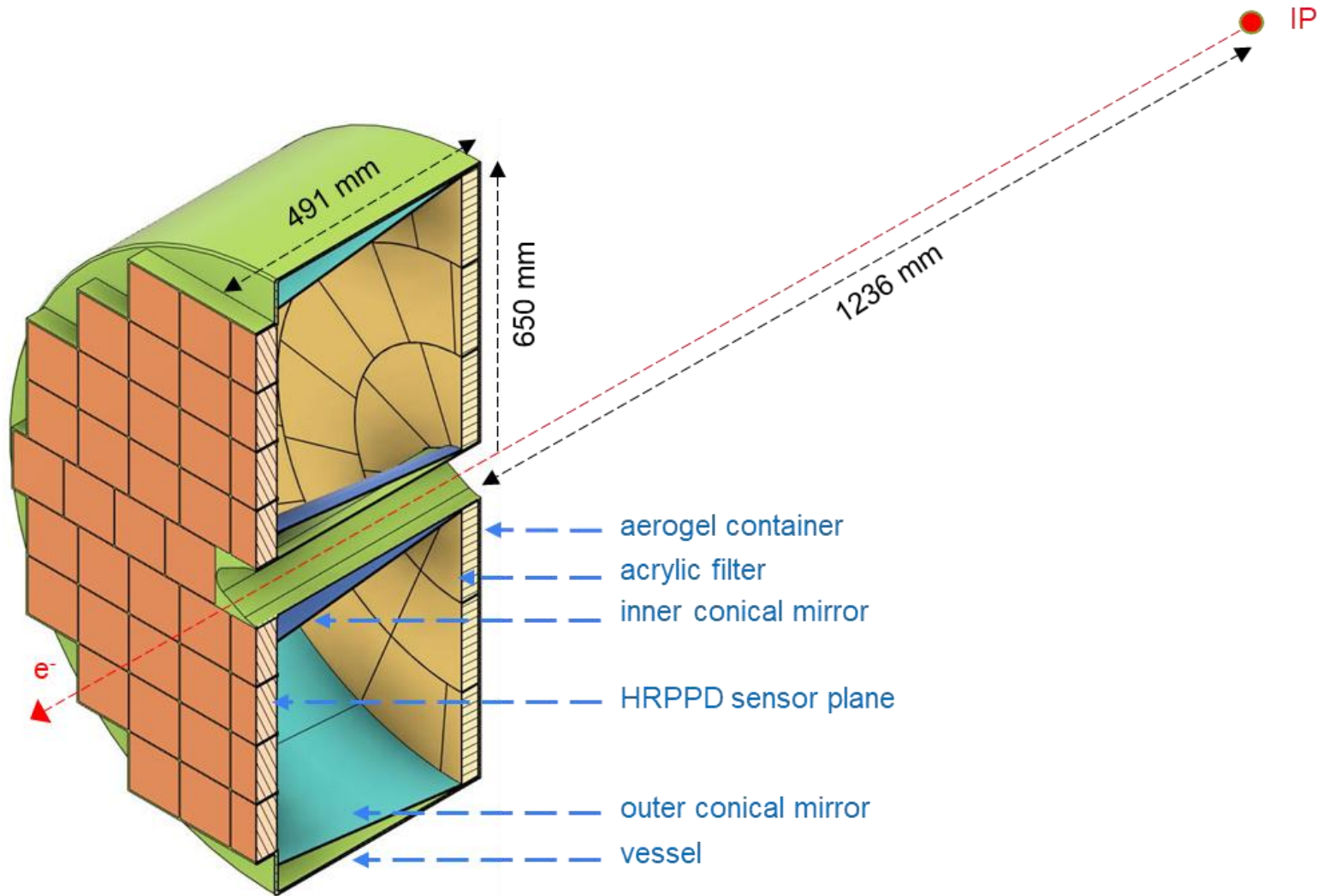
pfRICH Kinematic Coverage



- ❑ Provide $>3\sigma$ π/K separation for momenta up to 7 GeV/c for $-3.5 < \eta < -1.5$
- ❑ Determination of low- x kinematics requires identifying low momentum electrons – huge hadron background – need PID in addition to e/p
- ❑ Timing capability of sensors allows for ToF functionality at low momentum



pfRICH Design Summary



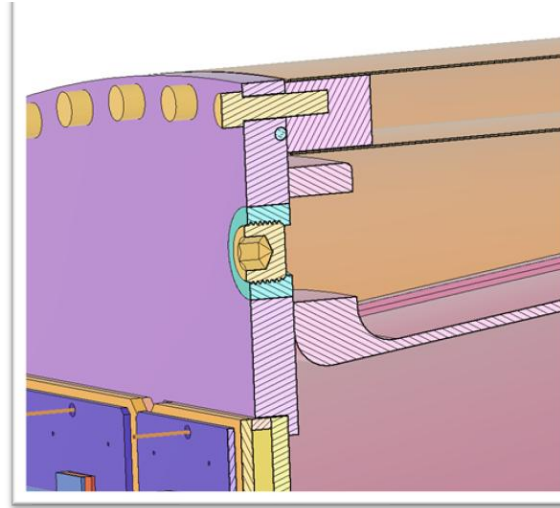
- ❑ Aerogel
 - Three radial bands
 - Opaque dividers
 - 2.5 cm thick, 42 tiles total

- ❑ Vessel
 - Lightweight structure
 - Reinforced carbon fiber and 3D printed materials
 - Filled with nitrogen

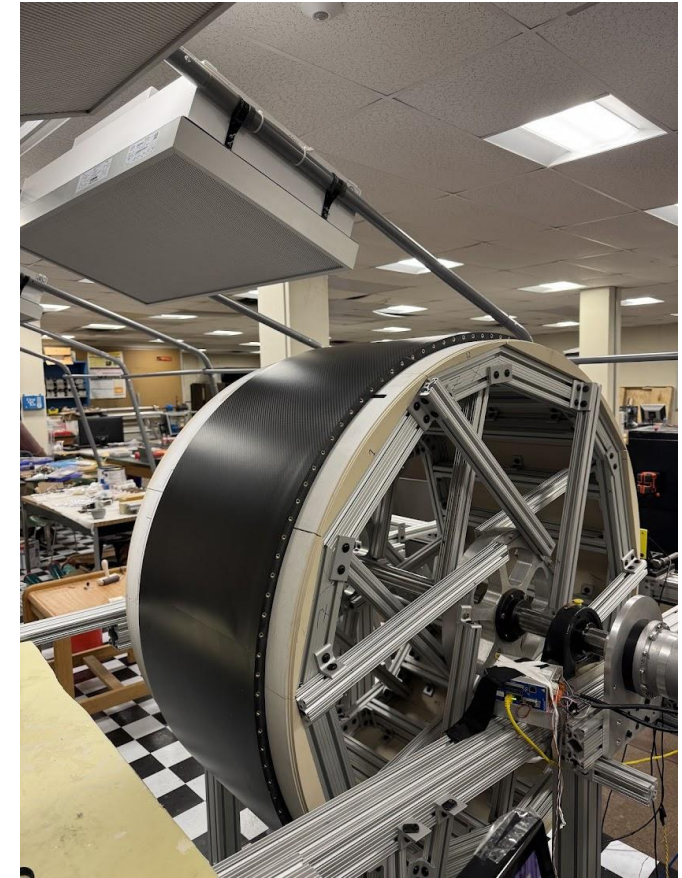
- ❑ HRPPD photosensors
 - 120 mm size
 - Tiled with a 3.0 mm gap
 - 68 sensors total

Vessel Components and Fabrication

- ❑ Vessel consists of
 - ❑ Cylindrical body (SBU)
 - ❑ Reinforcing end-rings (Purdue)
 - ❑ Sensor plane (Purdue)
 - ❑ Aerogel wall (Purdue)
- ❑ The vessel wall will be a carbon fiber sandwich -> light-weight, gas and light tight
- ❑ Machined carbon-fiber end-rings provide stability and connection points for sensor and aerogel walls
- ❑ Engineering test article vessel wall with end-rings incorporated completed mid-May 2025 – metrology studies ongoing

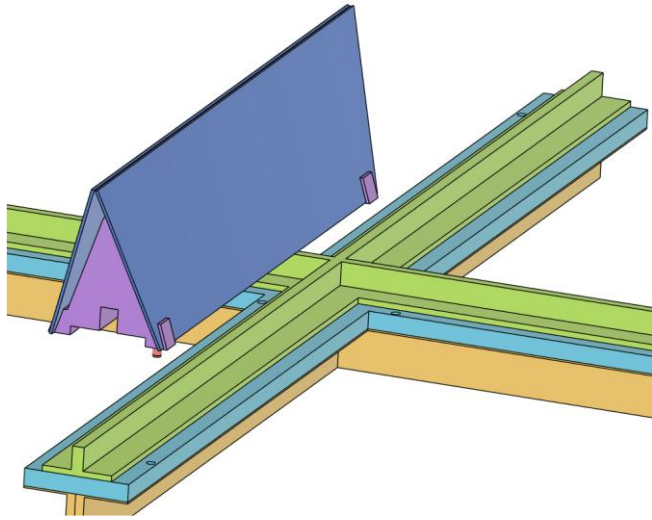


- Shape: 1/2" thick cylinder (12.7 mm)
- Outer Diameter: 1300 mm
- Length: 491 mm
- Precision: < 1 mm radius and length (Dedicated metrology and visual checks)
- Technology: Carbon-fiber composite material with Nomex honeycomb core

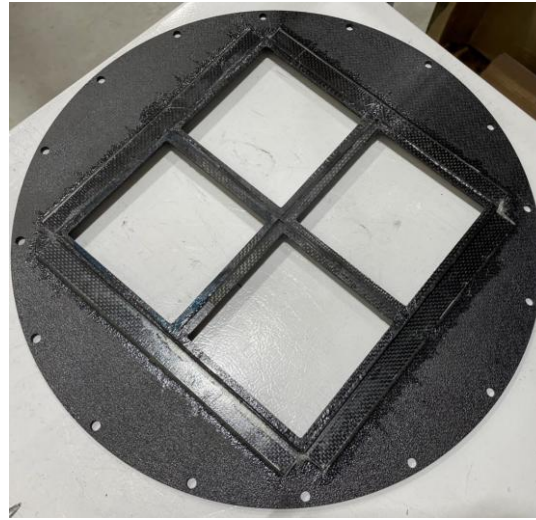


Vessel Components and Fabrication

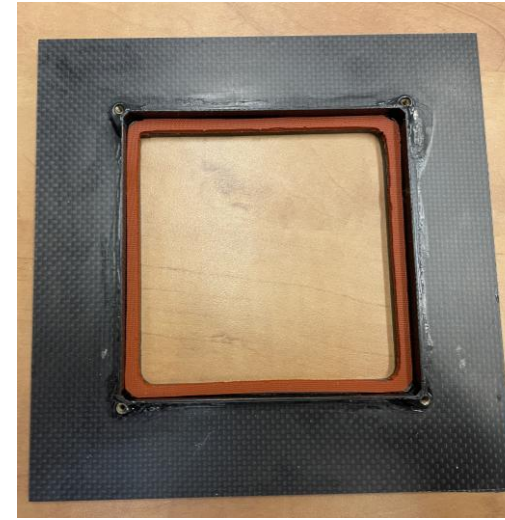
Sensor Plane Model



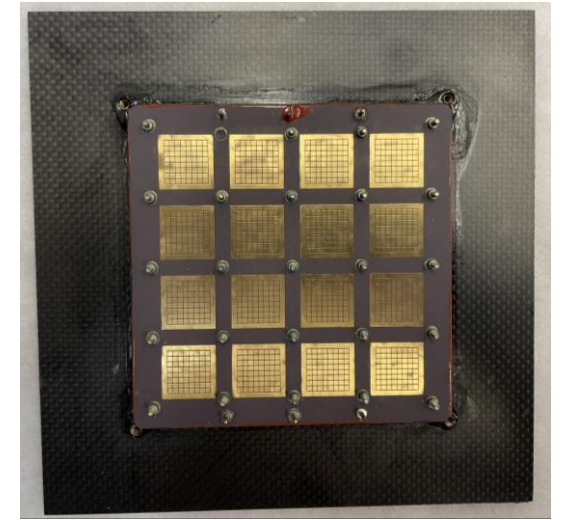
Test Windowpane Unit



Holder and Sealing Gasket



HRPPD Sealing Test



- Sensor plane will consist of carbon fiber “windowpanes” attached to base-plate
 - Base-plate will also hold pyramid mirrors
- Test 2x2 windowpane and base-plate assembly produced
- Individual HRPPD holders produced for sealing tests
- Final aerogel wall design in preliminary stages
 - Individual compartments, acrylic filter attachment, holders

Model of Prototype Aerogel Wall (1 ring)

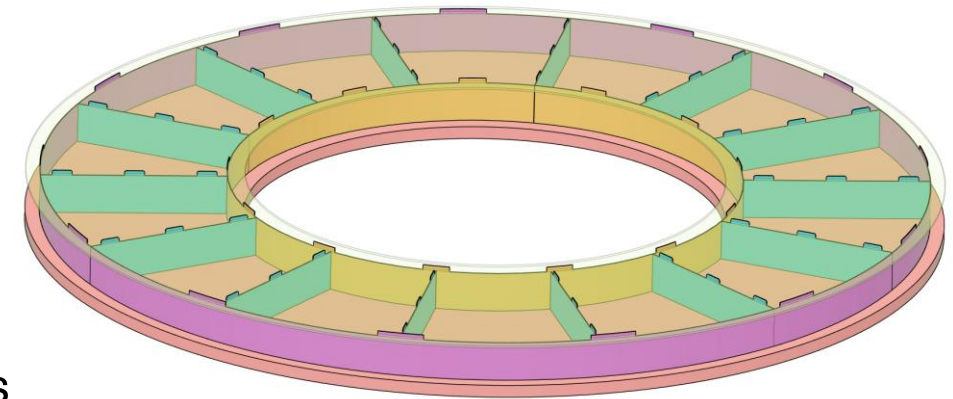


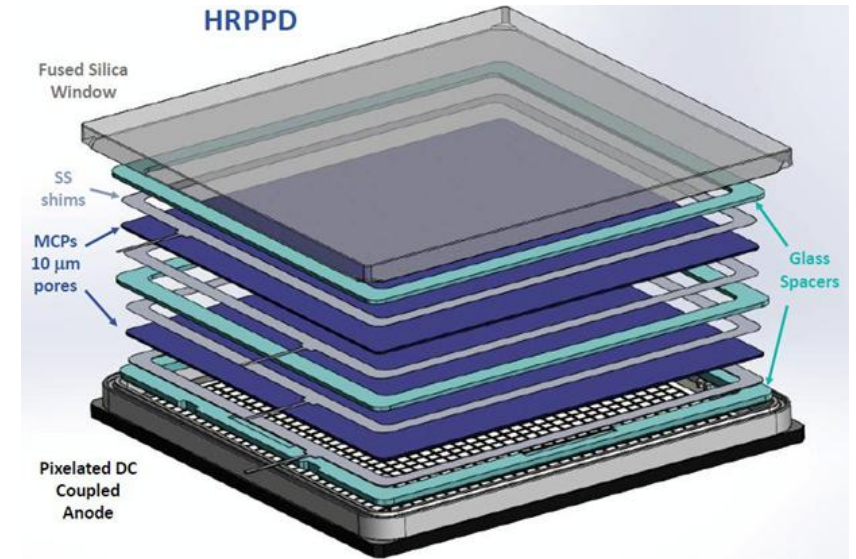
Photo-Sensors

❑ Basic requirements:

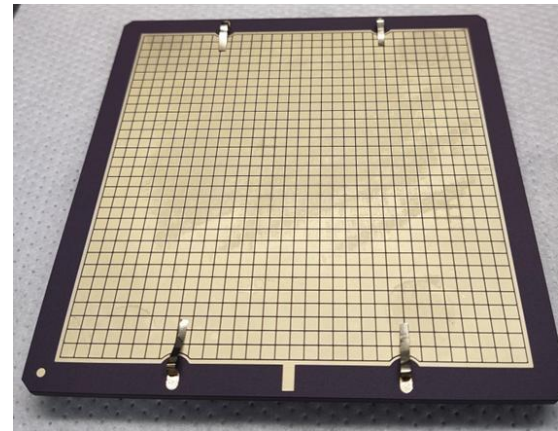
- Provide a timing reference at the level of ~ 20 ps for the barrel and forward ToF subsystems
- Provide spatial resolution ~ 1 mm
- Have small Dark Count Rate
- Have reasonable power dissipation in mW per channel
 - a low material budget cooling system in front of the PWO EmCal
 - as little influence on the thermal environment around the EmCal as possible
- Allow for a compact solution to leave more space for the proximity gap

❑ Photosensor: HRPPD by Incom Inc.

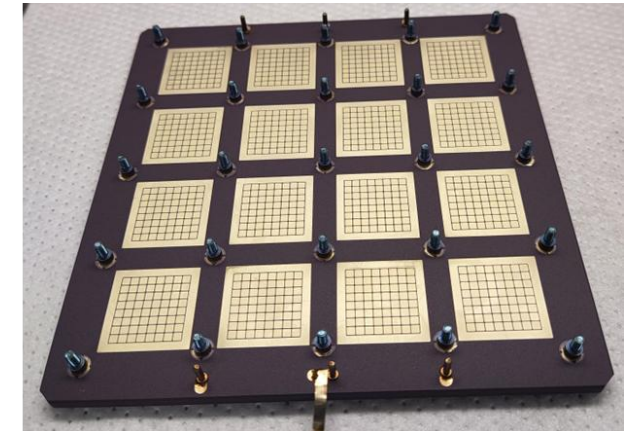
- High intrinsic SPE timing resolution
- High Quantum Efficiency
- Low Dark Count Rate (compared to SiPMs)
- Low cost (compared to other MCP-PMTs)



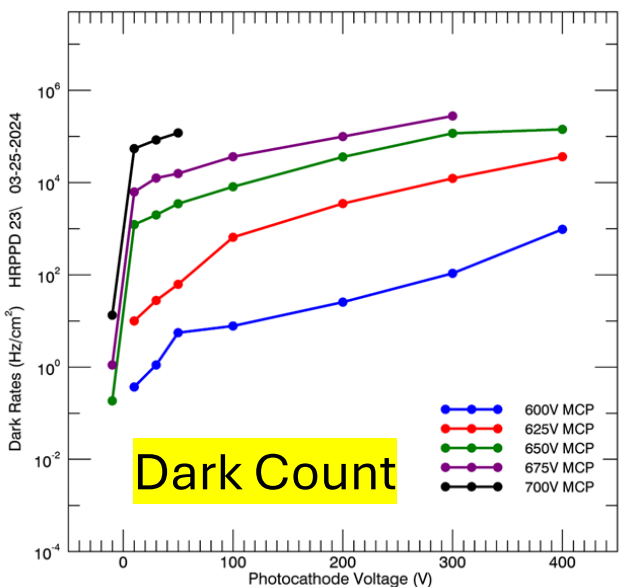
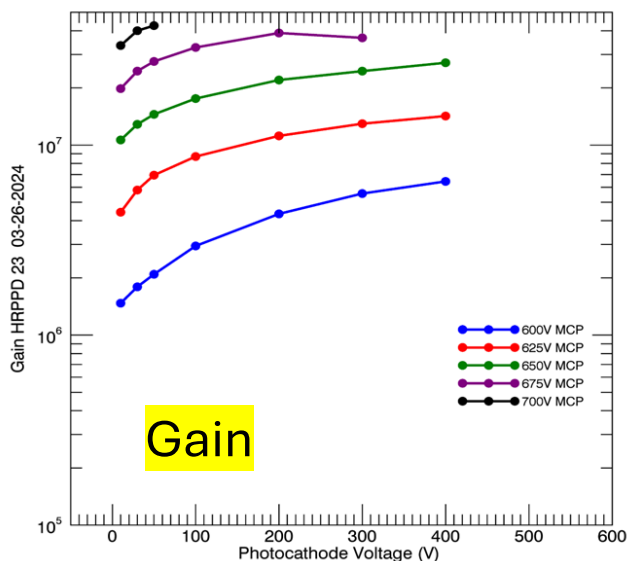
Anode plate vacuum side



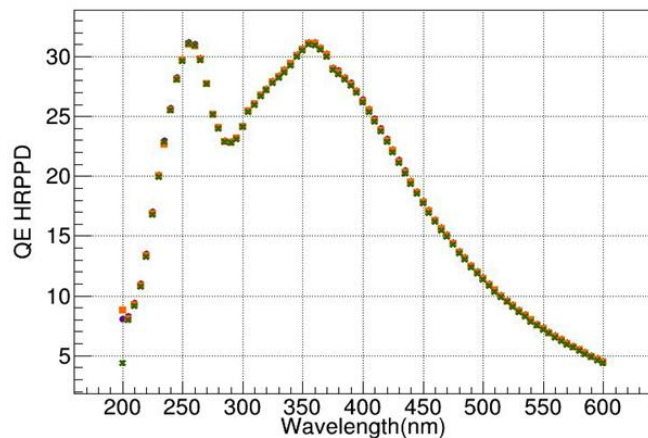
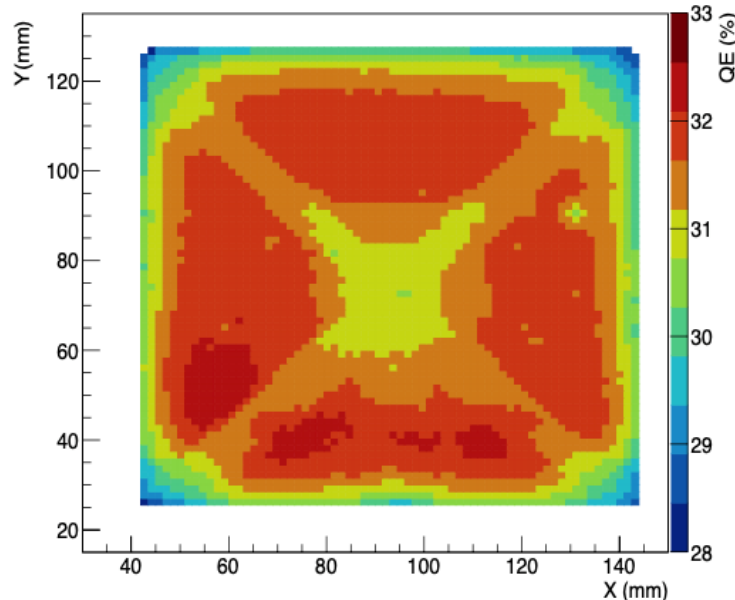
Anode plate air side



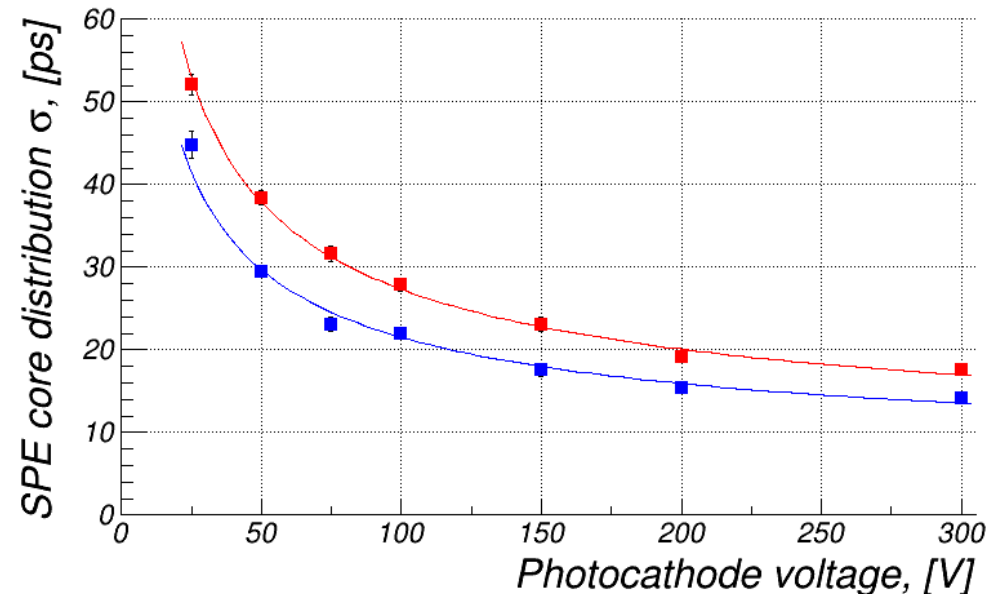
HRPPD Performance



QE Surface Scan



- HRPPDs demonstrate large gain at low MPC bias voltage with reasonable dark count rates ($<1\text{KHz}$ for gains in the 10^6 region)
- Peak Quantum Efficiency above 30% with good uniformity over sensor surface
- Single photon timing resolutions $\sim 15\text{ ps}$ for recommended bias and photocathode voltage working points



Mirrors

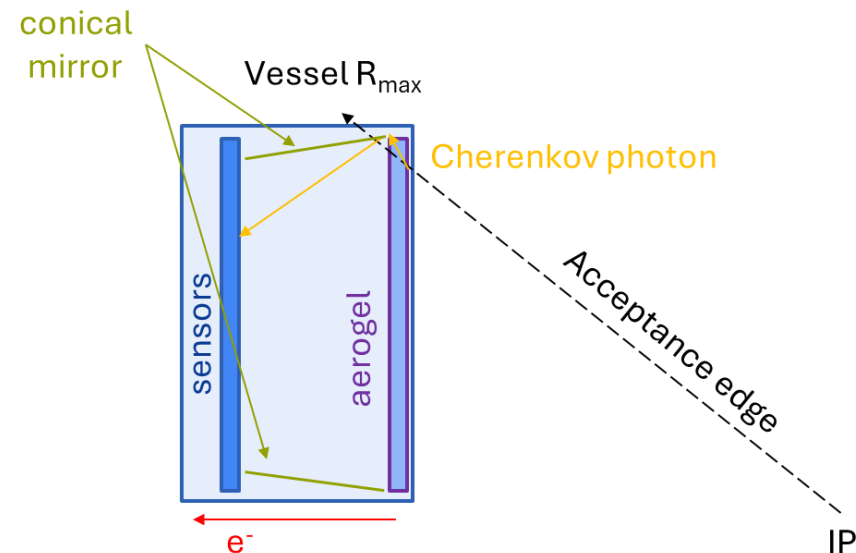
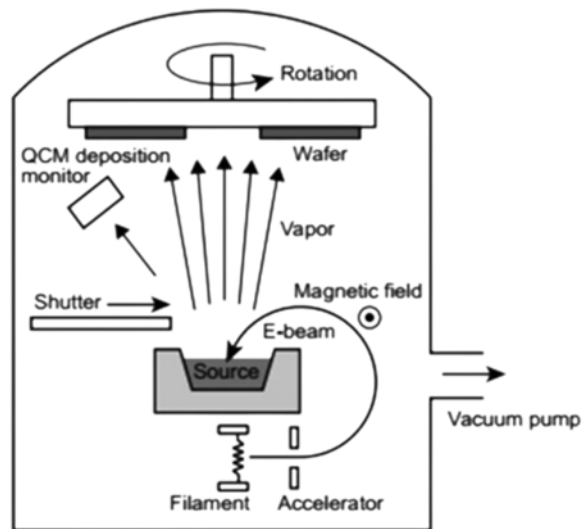


Rotating Fixture

Quartz Crystal Microbalance

Remote Shutter

Electron Gun



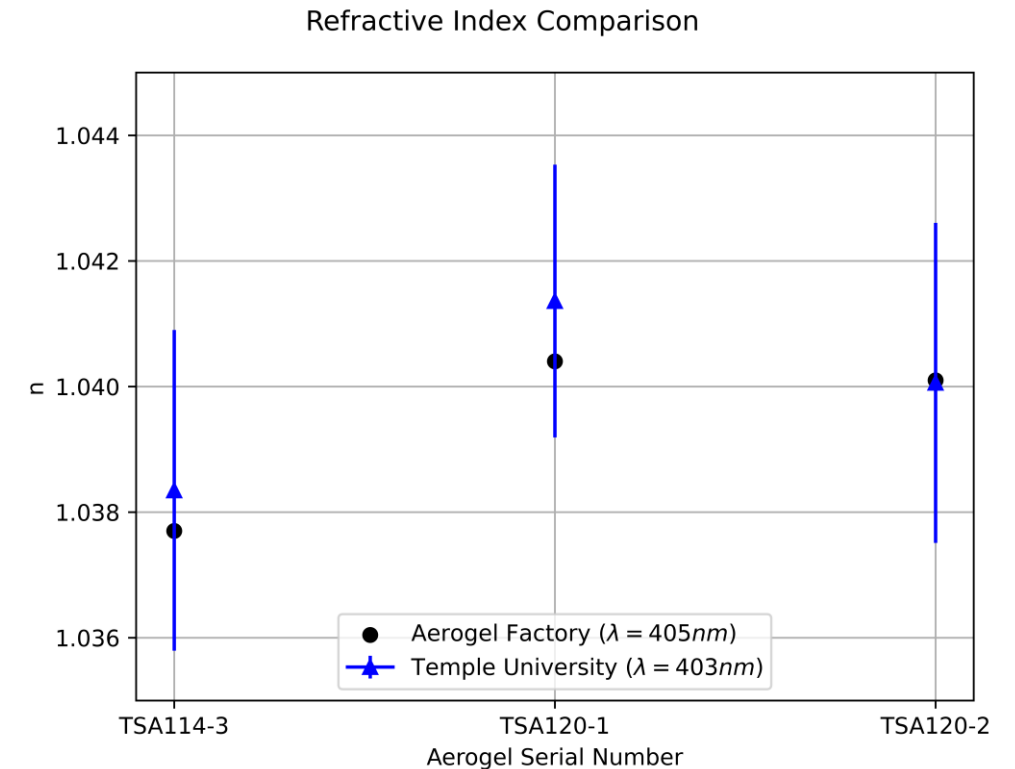
- ❑ Inner and outer conical mirrors and pyramidal mirrors increase detector photon acceptance
- ❑ Mirrors fabricated “in-house”
 - Straight and curved substrates produced by Purdue
 - Lexan co-bonded to carbon fiber – optimization of bonding procedure ongoing
 - Mirror coating applied using evaporator setup at SBU

Aerogel

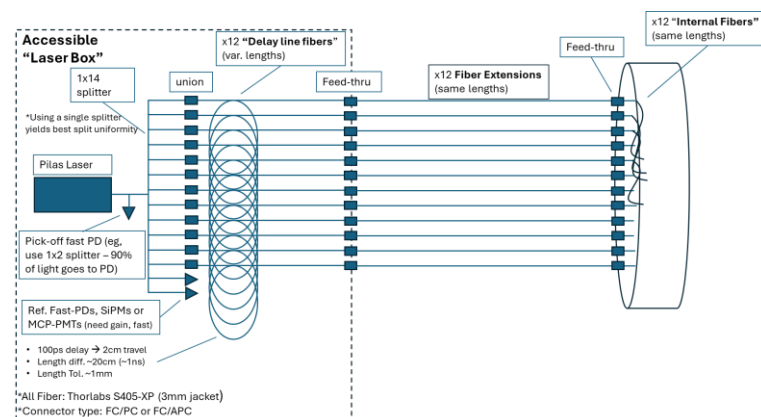
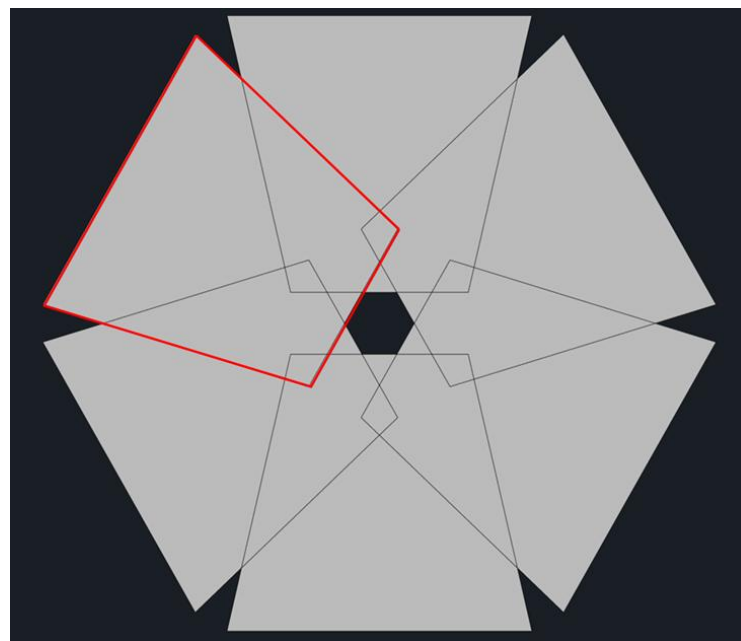
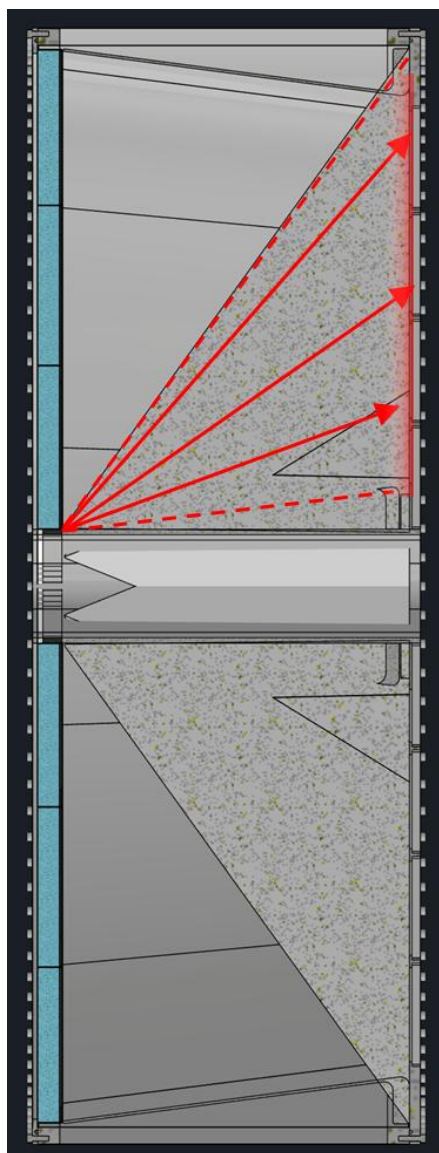
- ❑ A relatively moderate momentum reach is required for this RICH detector
- ❑ HRPPD PDE is expected to be substantially smaller than of the SiPMs
 - And peak value shifted to the UV range, where it cannot be used for ring imaging
- ❑ Consider using a high $n \sim 1.040$
 - 300 nm acrylic filter cutoff for imaging
 - $\langle N_{pe} \rangle \sim 11-12$

 - *For ToF still make use of the UV range for abundant Cherenkov light produced in the window*

 - Natural hardware reference: Chiba University aerogel ($n = 1.040$)
 - 3 sample tiles have been purchased
 - Extensive characterization / QA by Temple University group
 - Confirm manufacturer specs and develop QA procedures

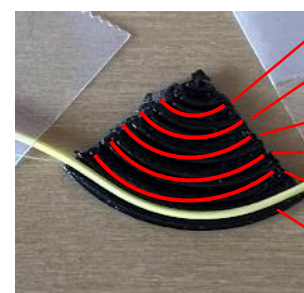


Light Monitoring System

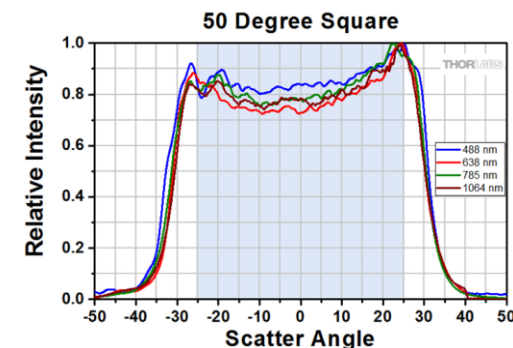


- ❑ Want a way to monitor HRPPD timing performance, signal amplitude, QE, and mirror reflectivity over the lifetime of the experiment
- ❑ Introduce an array of 12 optical fibers from the aerogel side of the vessel: 6 illuminate the photosensors directly and 6 bounce light off mirrors first
- ❑ Distance from fiber to photosensor determines timing and overlapping illumination areas are distinguished by time via fiber delays
- ❑ Appropriate square diffuser identified and fiber bending radius tests need to be performed

90 deg. bend

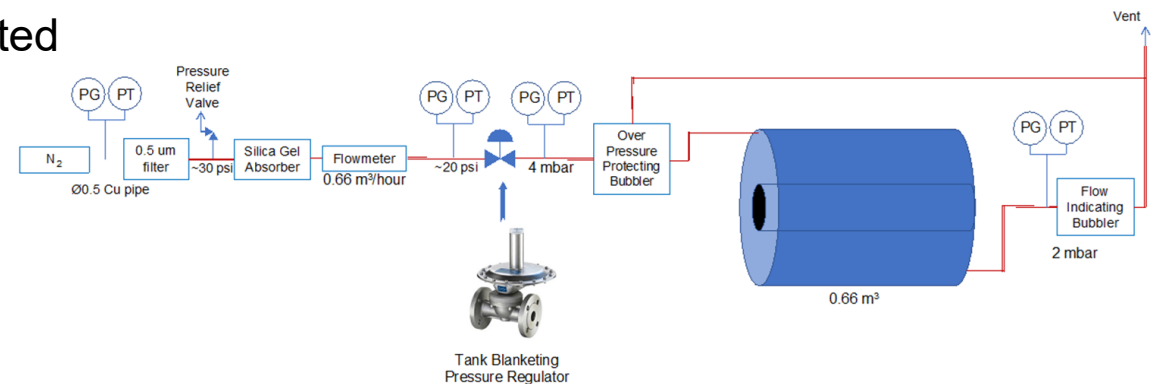
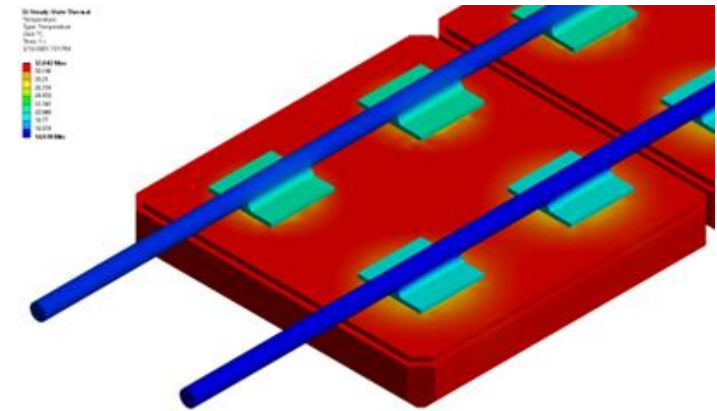


- 4mm
- 6mm
- 8mm
- 10mm
- 12mm
- 14mm



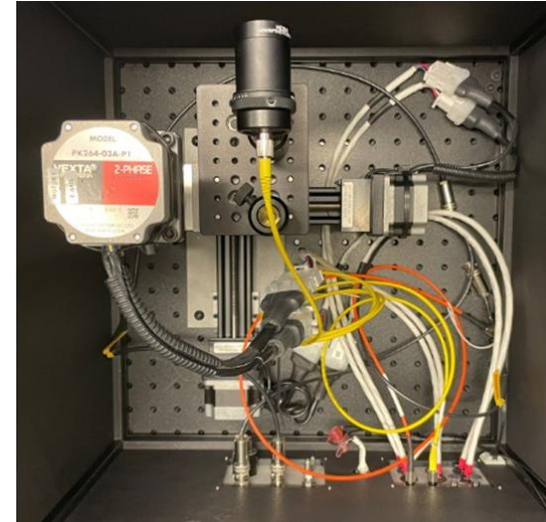
Services

- ❑ HV system components have been identified and initial layout explored
- ❑ LV power system designed assuming 4 EICROC (256 chs/chip) per HRPPD – will be reevaluated once FCFD parameters available
 - $1024\text{chs/sensor} \times 3\text{mW/ch} = \sim 3\text{W/sensor} \rightarrow @ 1.2\text{V} = 2.5\text{A}$ per sensor
 - $68\text{ sensors} \times 2.5\text{A} = 170\text{A}$ total current
 - Add 20% for on-board components and safety margin:
 $170\text{A} \times 1.2 \times 1.2 = 245\text{A}$ current for full detector
 - Total power: $245\text{A} @ 1.2\text{V} = 294\text{W}$
- ❑ Cooling system designed to handle power dissipation calculated above – may require mechanical redesign for different ASIC formfactor
- ❑ Gas system designed to supply nitrogen (grade to be determined) at slight overpressure with ~ 1 volume exchange per hour

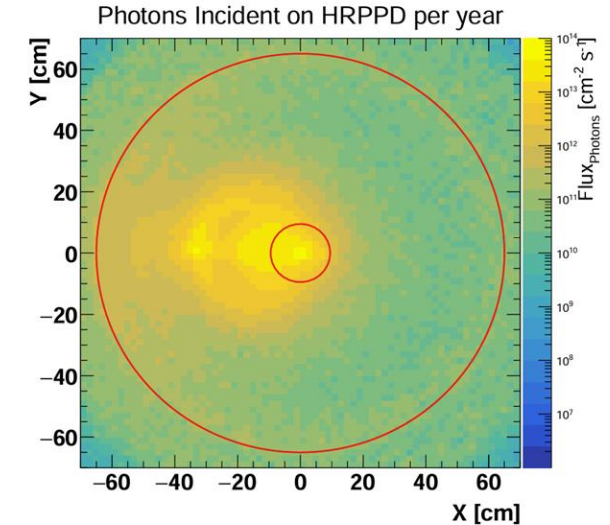


HRPPD Evaluation

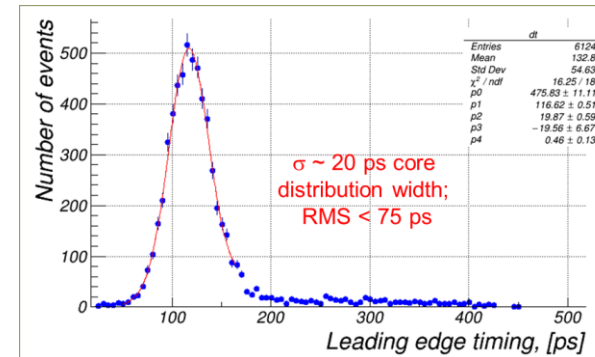
- ❑ Number of studies carried out across several institutions to evaluate suitability of HRPPDs for EIC needs
- ❑ Primary QA at JLab
 - Mechanical, basic functionality
- ❑ More systematic active area scans at BNL
 - Timing, QE, DCR, PDE
 - Utilize femtosecond laser to minimize impact of laser jitter on results
- ❑ Magnetic field resilience studies at BNL
 - Recovery of gain and timing performance in B-field
- ❑ Aging studies at JLab / BNL / INFN Trieste
 - Quantify performance loss due to expected photon flux
- ❑ Side by side Photek Auratek & Incom HRPPD comparison in Glasgow



Dark Box @ BNL



Fluence simulation for aging studies

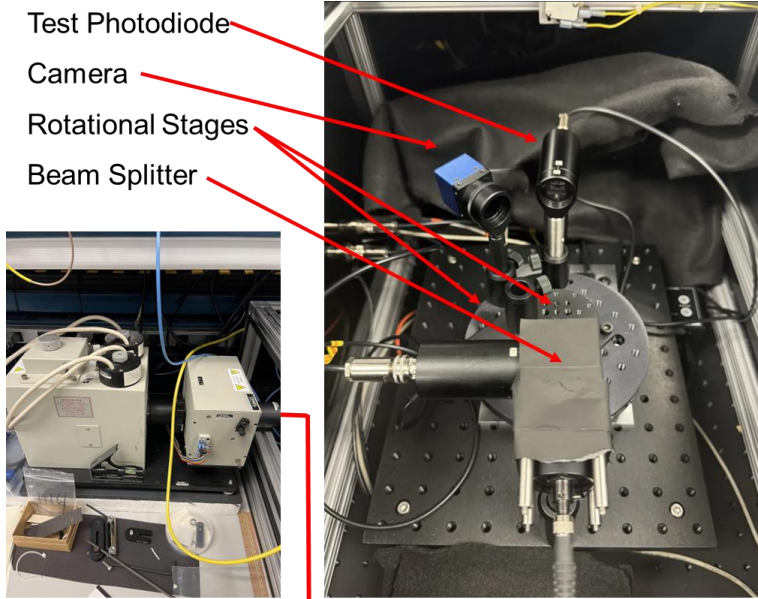


Sample Timing Curve

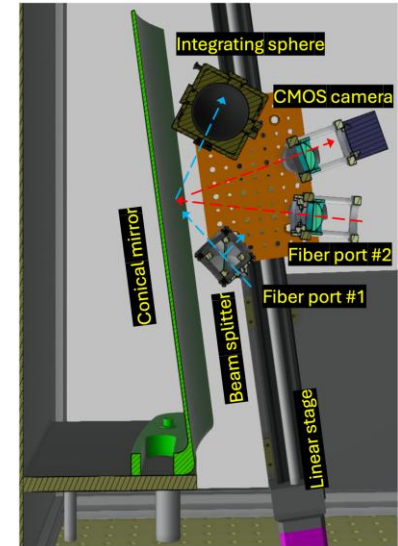
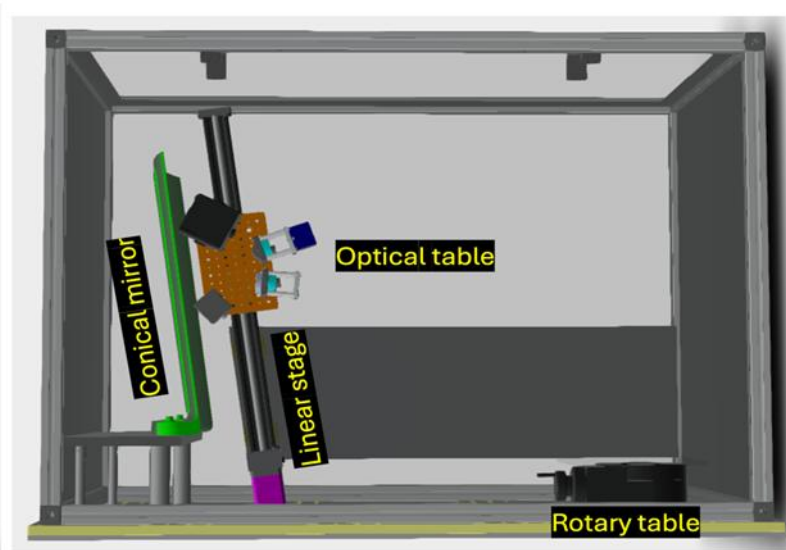
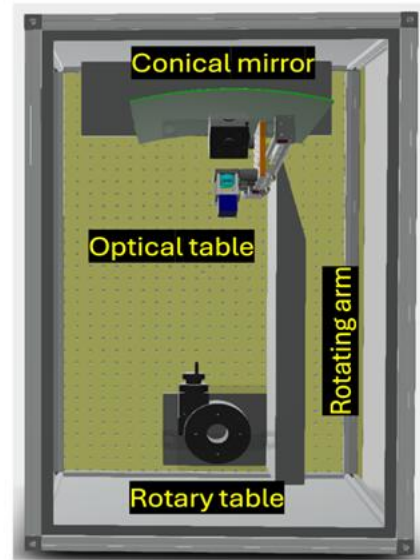
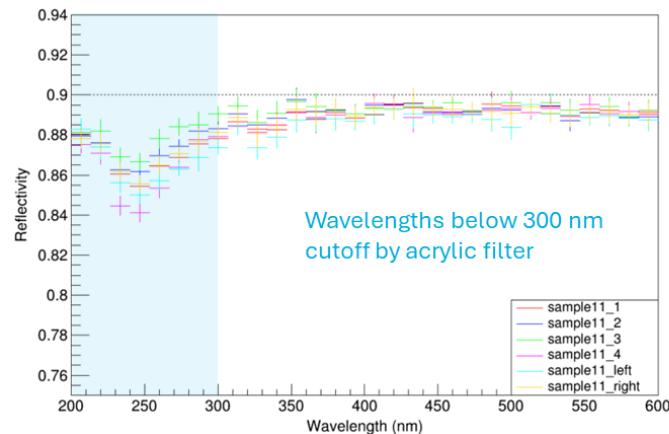


A type 18D72 2.2 Tesla dipole with a 6" gap

Mirror Evaluation



Monochromator:
200 – 600 nm

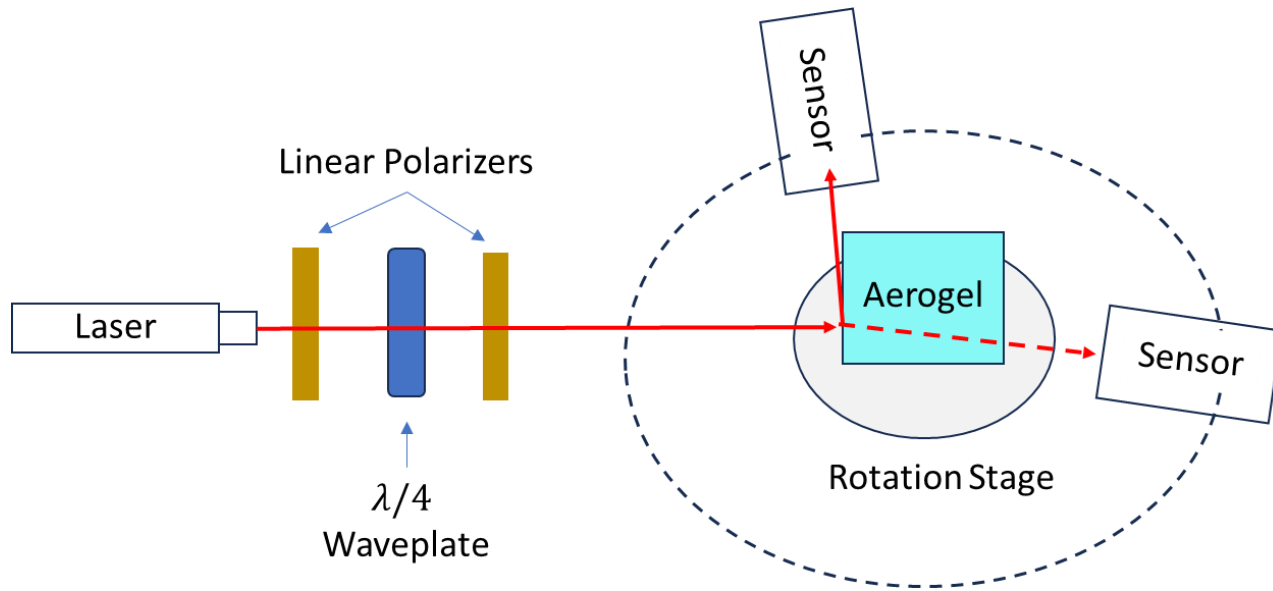


- ❑ Two optical test stands at BNL for mirror evaluation and QA
- ❑ Small test stand used to measure reflectivity of mirror samples allowing for optimization of coating and fabrication procedures
- ❑ Large test stand designed to measure reflectivity and surface quality of the full-size curved mirrors

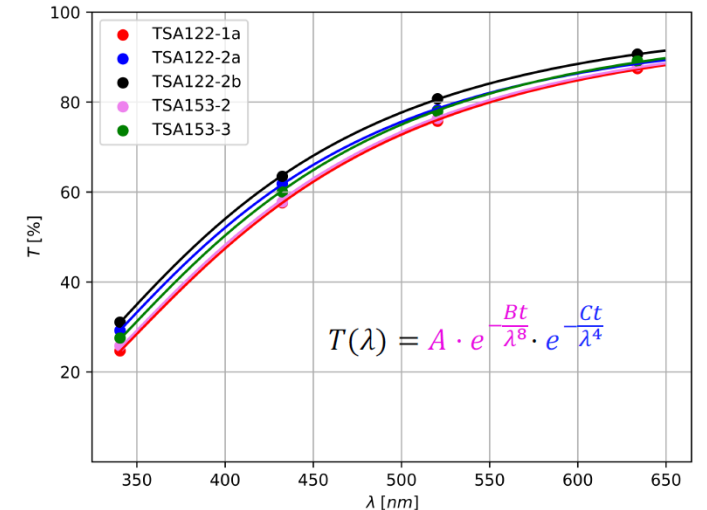
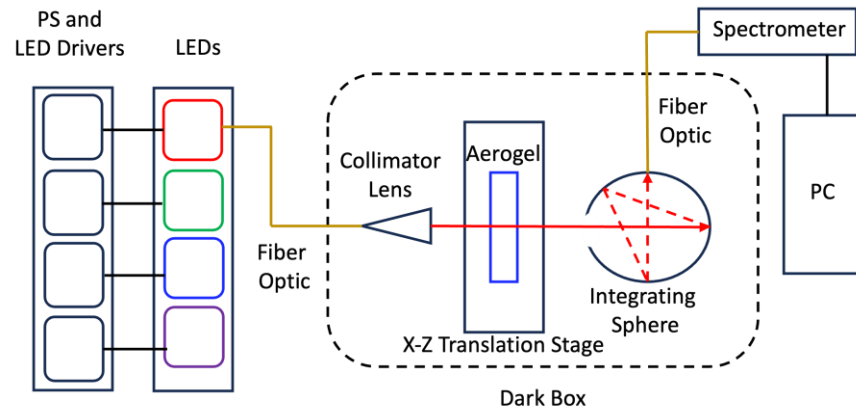
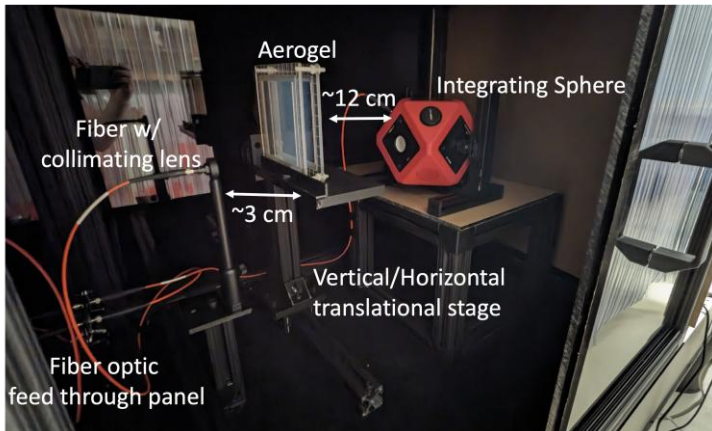


Aerogel Evaluation

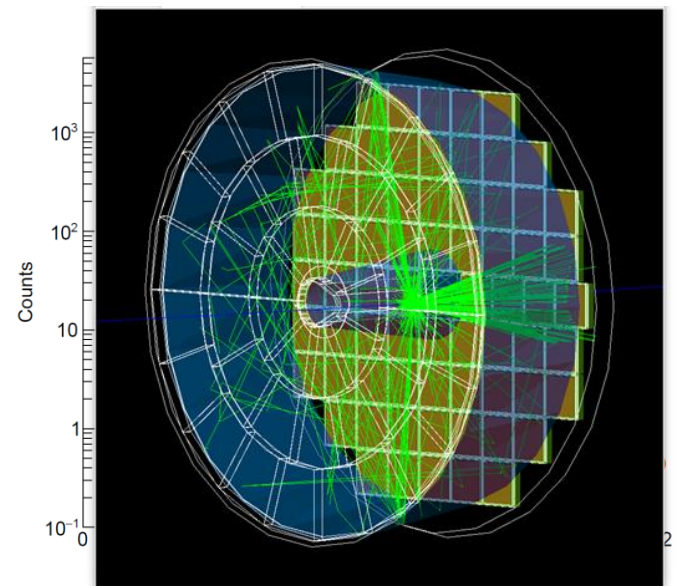
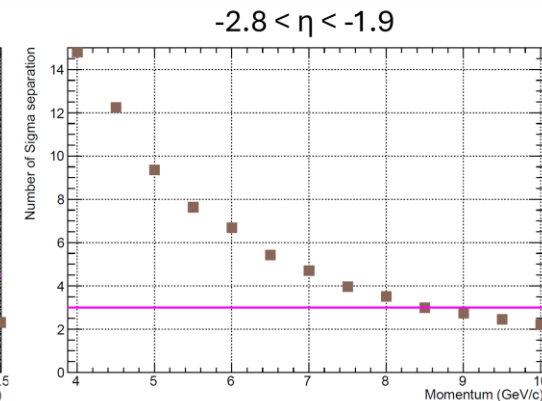
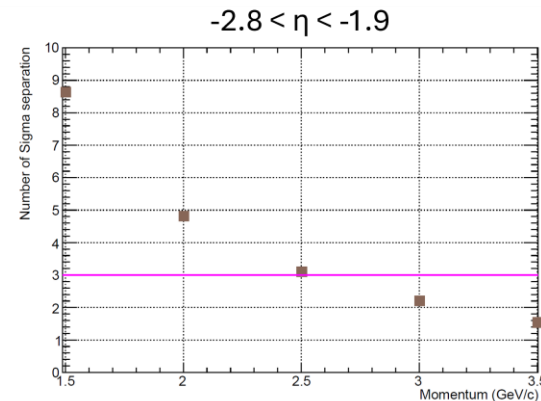
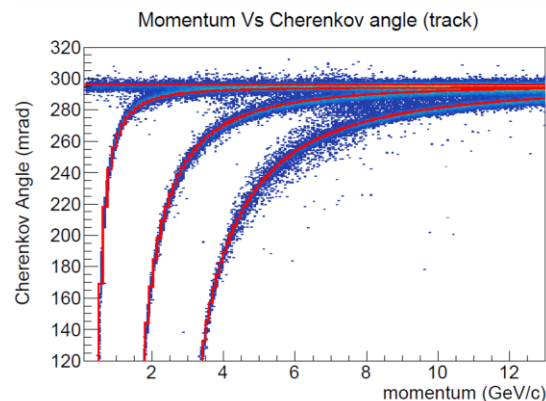
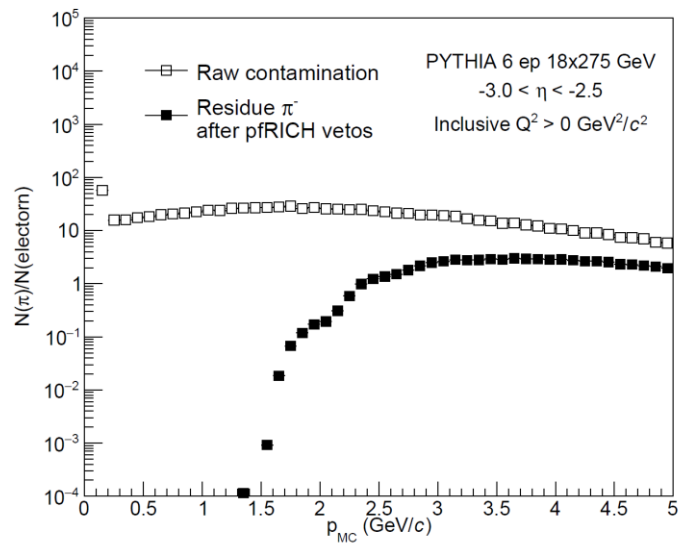
Schematic setup for Brewster's angle measurement



- ❑ Aerogel tile QA being carried out at Temple University
- ❑ Exploit polarized light to measure index of refraction over the aerogel surface: Brewster's angle and ellipsometry
- ❑ Extraction of refraction index using Brewster's method will be investigated this summer
- ❑ Transmittance also measured and in good agreement with factory values



Performance Simulation



- ❑ Validate detector design choices and evaluate performance with standalone GEANT4 model including relevant optical effects – integration of reconstruction into ePIC simulation framework ongoing
- ❑ Model parameters reproduce realistic ePIC tracking performance, mirror reflectivity, vessel dimensions, sensor, and aerogel properties
- ❑ Implement and event-level digitization/reconstruction chain utilizing a χ^2 based algorithm with full combinatorial hit-to-track ambiguity resolution
- ❑ Achieve 3σ π/k and e/π separation up to 8.5 GeV/c and 2.5 GeV/c, respectively, for bulk of detector acceptance

Summary

- ❑ Hadron identification crucial to many of the physics goal at the EIC – PID in the electron going direction provided by a proximity focusing RICH detector
- ❑ Carbon fiber vessel construction minimizes material budget – first engineering article demonstrating construction techniques recently completed
- ❑ Photosensor, radiator, and mirror solutions identified
- ❑ Developed extensive infrastructure for evaluation and QA of subcomponents
- ❑ Performance studied using detailed simulation models

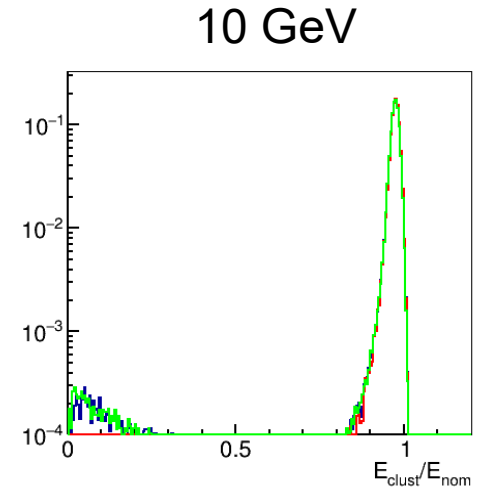
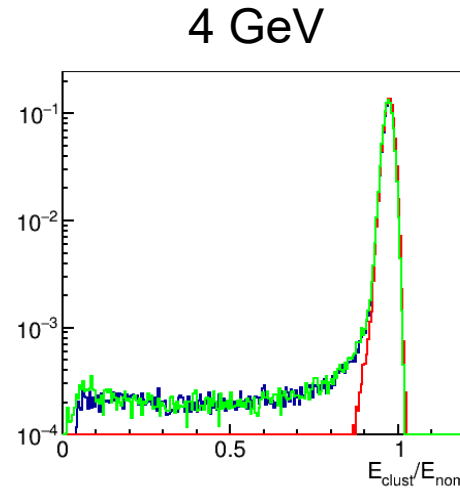
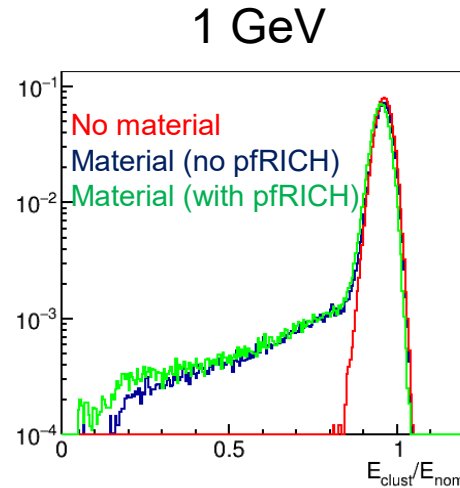
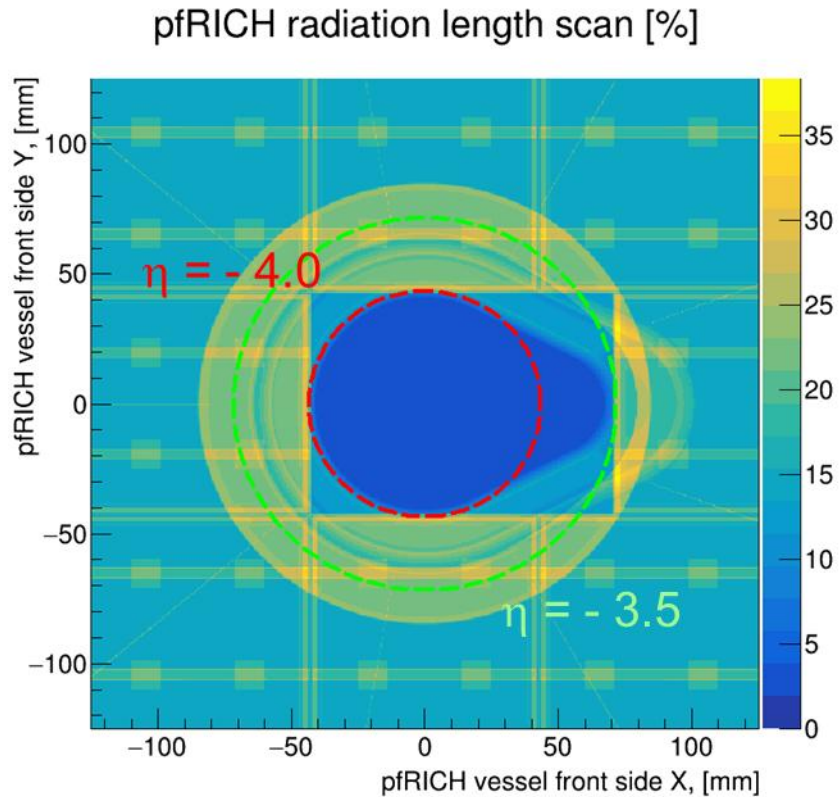
BACKUP

pfRICH Material Effect on Backward EmCal

□ pfRICH GEANT implementation imported in ePIC framework as a GDML file

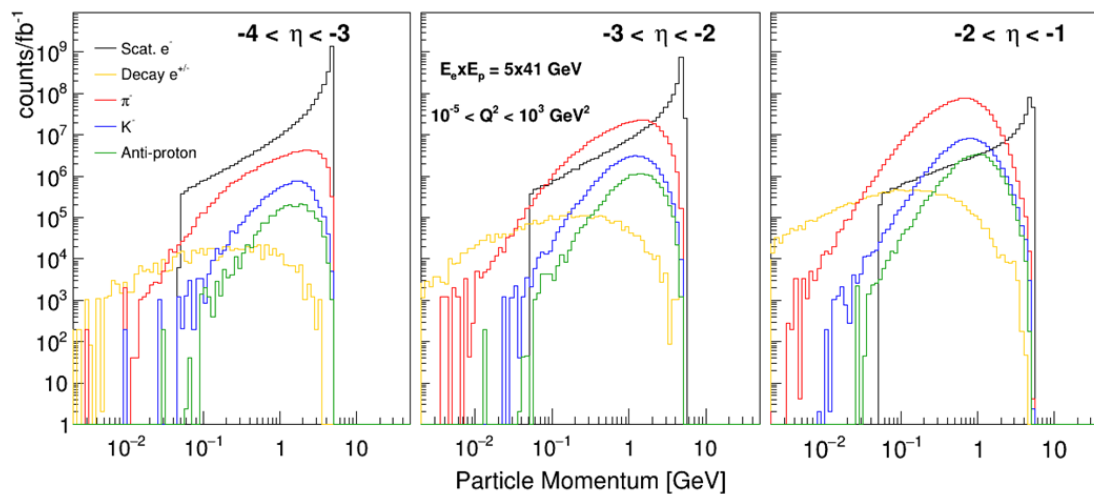
- Material implemented to the best of our knowledge (vessel, HRPPDs, cooling system, etc)

$-3.3 < \eta < -1.9$

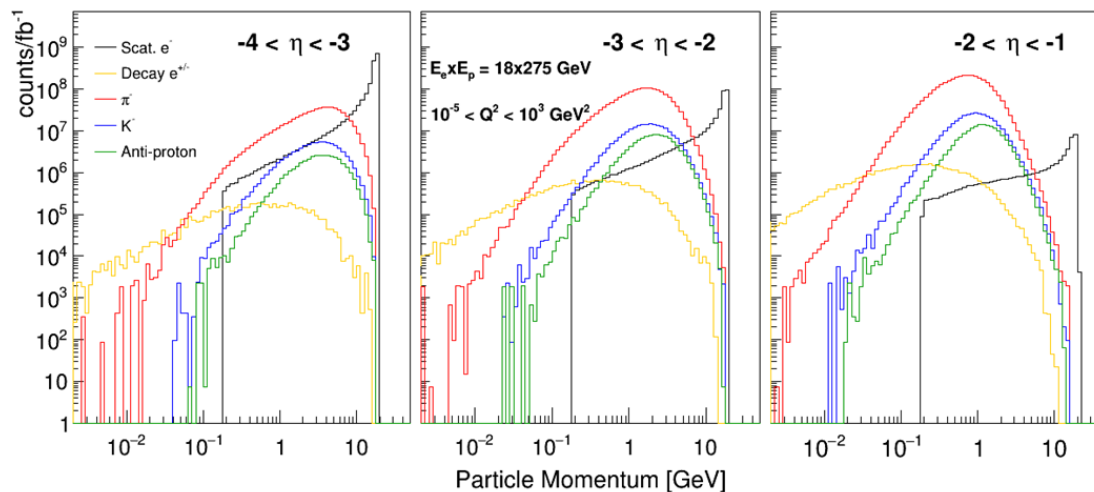


- No effect on (\sim gaussian) peak width
- Lower energy tails (the largest at 1 GeV)
- No effect for high energy electrons (10 GeV)
- Minimal effect from pfRICH overall

Particle Kinematics



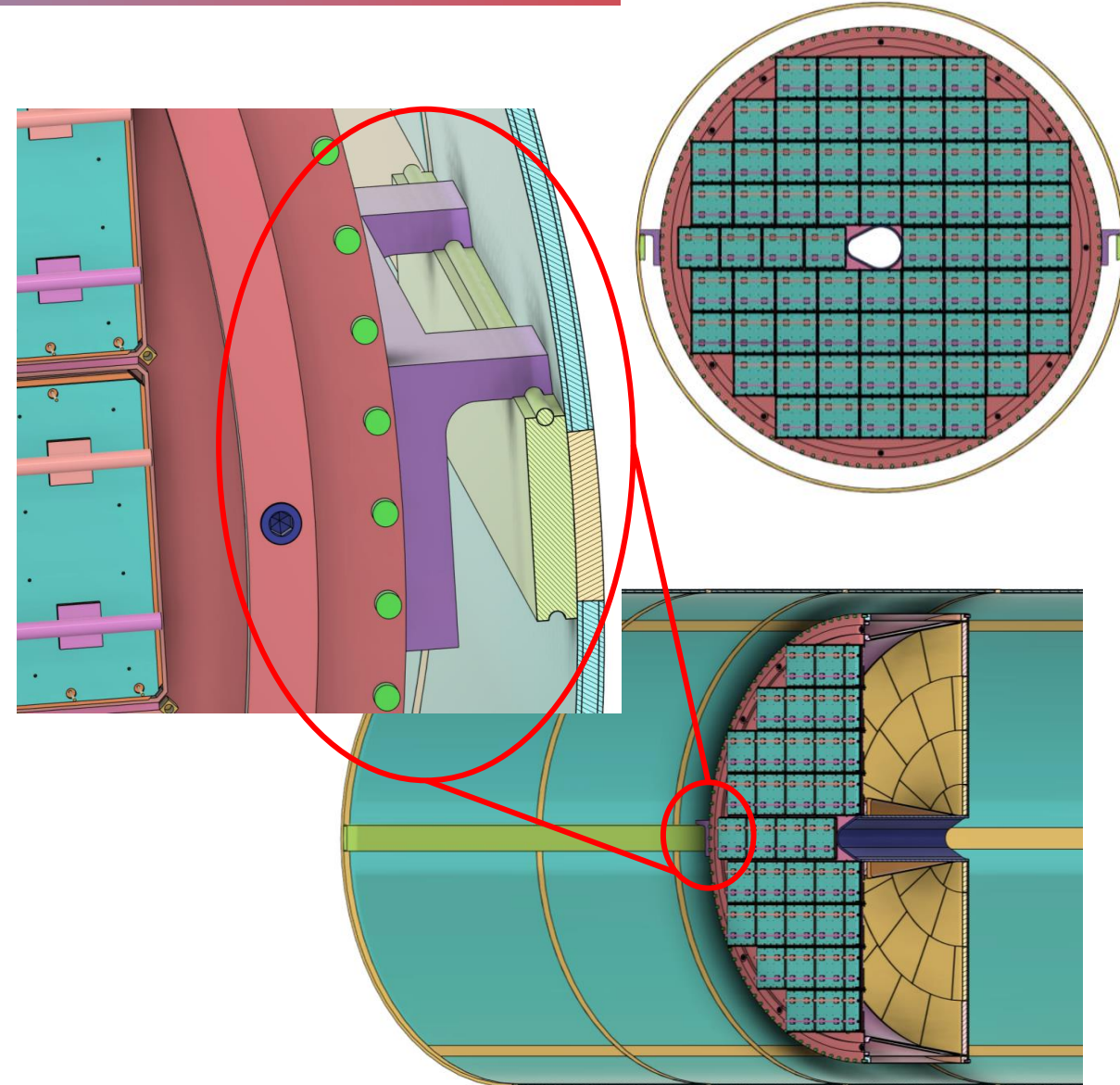
5 x 41 GeV



18 x 275 GeV

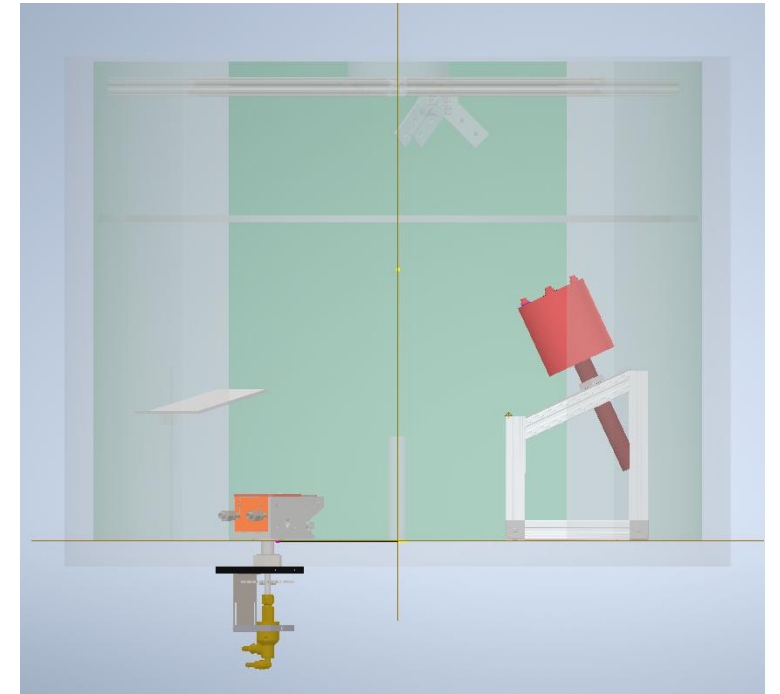
pfRICH Installation

- ❑ Installation steps:
 - Installation cart (design forthcoming) is placed on an installation platform
 - Rails between installation cart and global support tube (GST) aligned on the platform
 - pfRICH slides into the GST into its operating position
- ❑ Support System:
 - pfRICH rail system is being co-developed with GST engineers
 - GST rails utilize a similar design to CMS (CERN) project
 - Adjustment will be integrated into the pfRICH rails as the design progresses



Mirror Fabrication: Coating

Evaporation Number	Coating Recipe (Values at QCM)	Procedural Changes	Reflectivity
7	Cr: 5.19 KAng Al: 12.03 KAng	Decrease in total deposition amount from previous coatings 70 KAng → 17 KAng	88%
10	Cr: 4.66 KAng Al: 22.24 KAng	Increased Aluminum Coating	86%
11	Cr: 5.08 KAng Al: 12.36 KAng	Consistency Check Repeat of #7	89%
12	Cr: 5.17 KAng Al: 12.27 KAng	Substrate Waviness Test + Rotation Decrease 60 RPM → 30 RPM	88%
13A	Cr: 0.11 KAng Al: 0.93 KAng	NA62 / COMPASS recipe	20%
13B	Cr: 1.13 KAng Al: 2.578 KAng	Account for QCM to Substrate deposition ratio [rough estimate of distance discrepancy]	74%



- ❑ Many test coatings done to refine Cr/Al recipe and thicknesses
- ❑ Other parameters such as substrate placement, rotation rate, etc also explored
- ❑ Settle on ~90 nm Al and 10 nm Cr -> 90% peak reflectivity between 300-700 nm with uniformity of 1-2%

Future Improvements:

- Mounts for larger substrates
- Introduce dielectric coating (SiO_2) to improve resilience of coating
- Ion gun to smooth coating
- Better vacuum

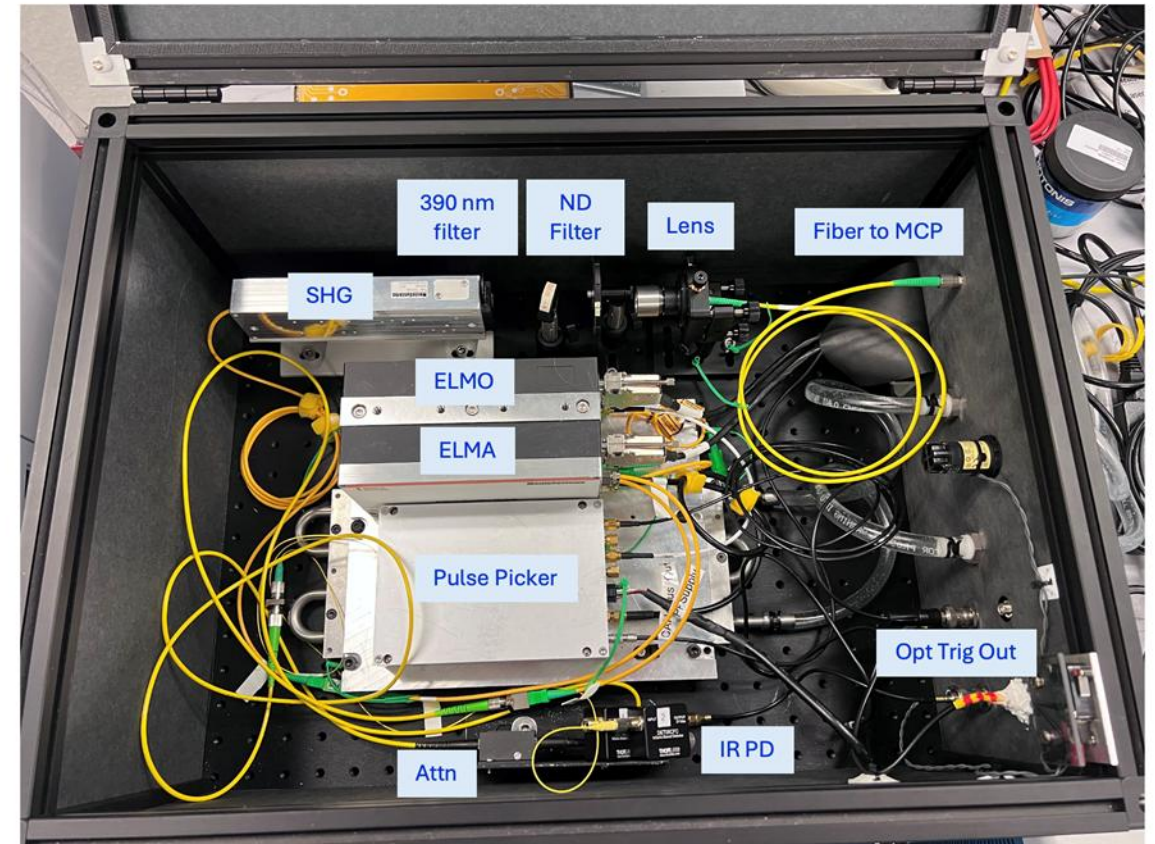
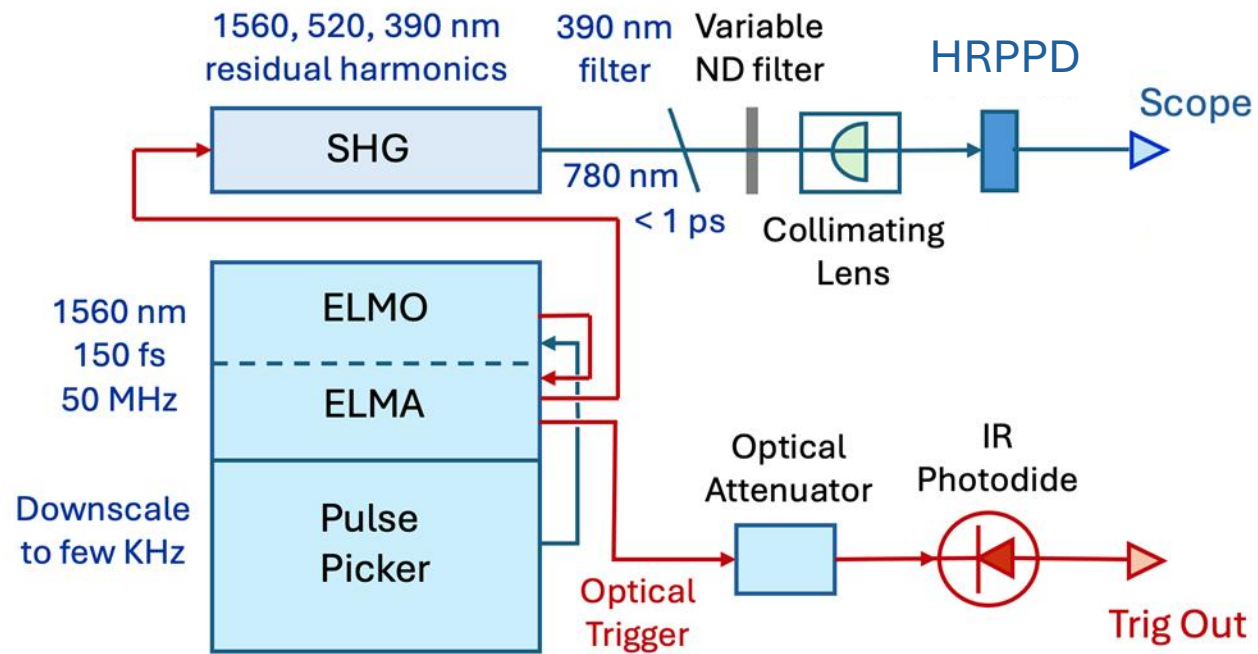
Elmo 780 Femtosecond Laser System @ BNL

Menlo Systems Elmo 780 Erbium Fiber Femtosecond Laser

ELMO = Primary Laser Oscillator

ELMA = Optical Amplifier

SHG = 2nd Harmonic Generator



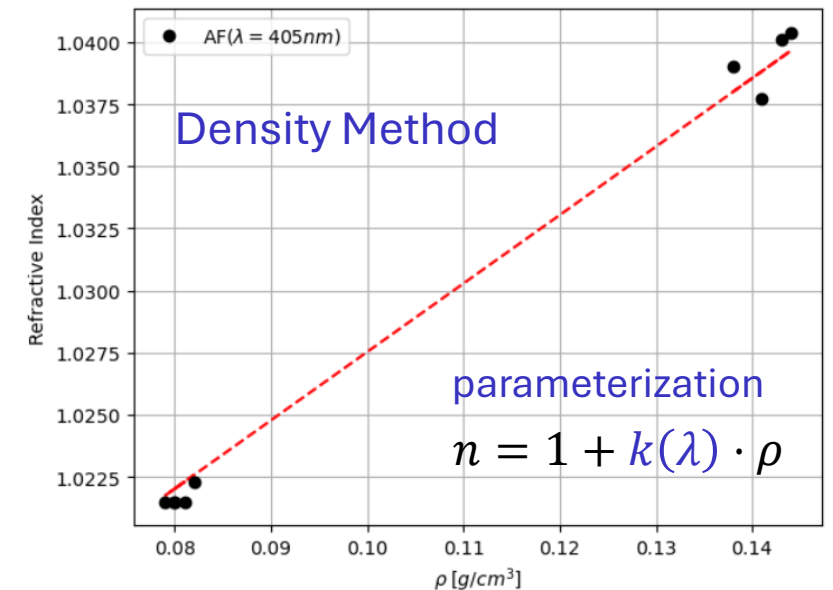
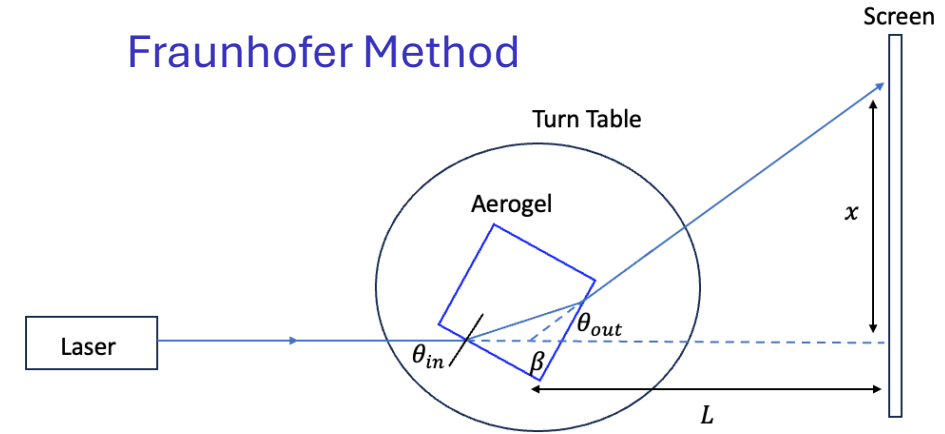
We make use of a very low intensity 3rd harmonic @ 390 nm

Alternate Refractive Index Determination

- ❑ Current index of refraction methods utilize Fraunhofer Method, where light passes through corner of aerogel and minimum deflection angle is used to obtain refractive index
 - Limitations: QA only at corners of aerogel tiles. Production tile edges will not be of optical quality and not representative of aerogel quality

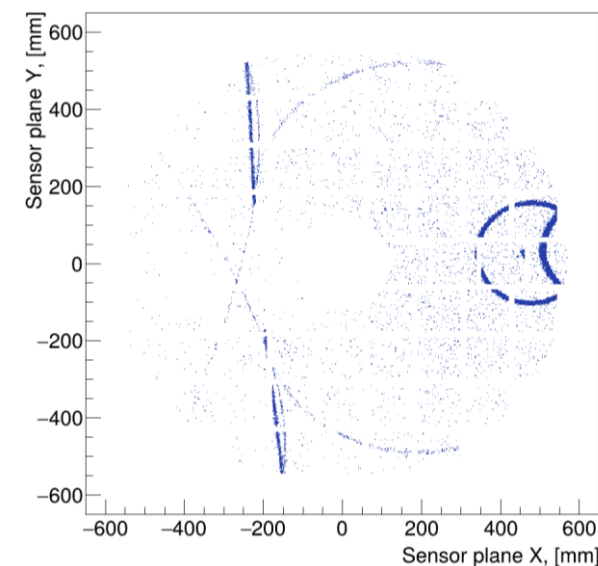
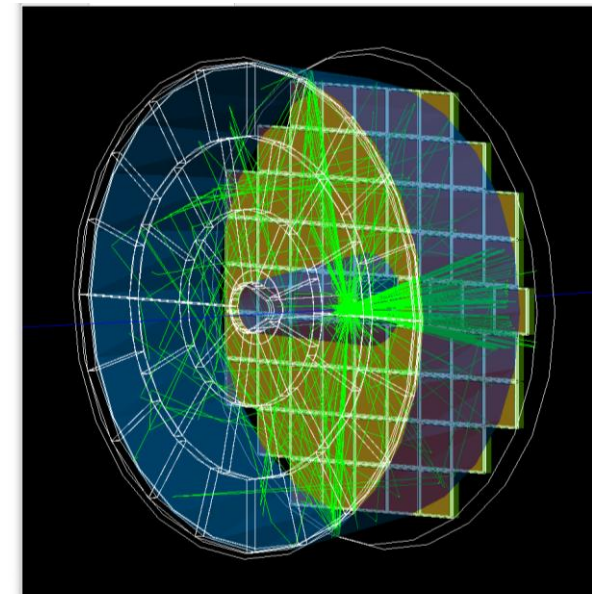
- ❑ Alternative: Density method - parameterize refractive index vs. density from aerogels with known refractive index (e.g. refractive index measured via Fraunhofer method) , then use parameterization and aerogel density to extract a refractive index
 - Limitations: Provides one refractive index determined from only four local measurements (e.g. corners)

Fraunhofer Method



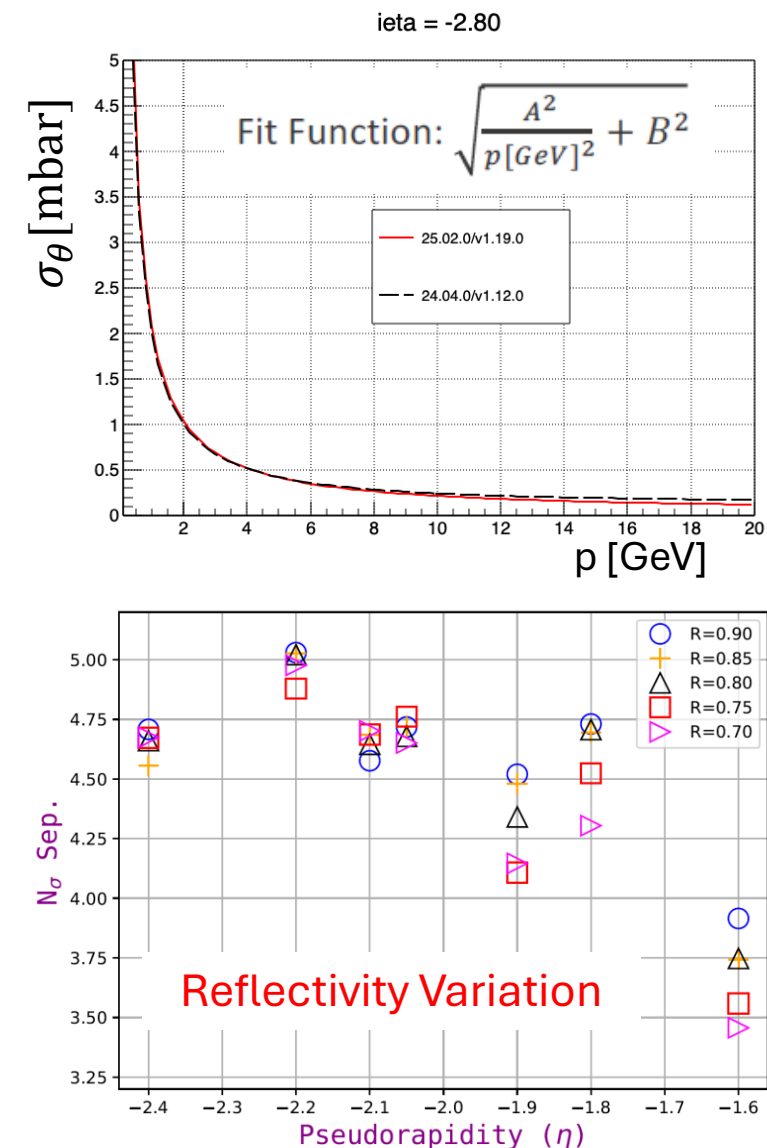
Interface With ePIC Simulation Environment

- ❑ All simulated evaluations of pfRICH design and performance have come from standalone model
- ❑ Priority now is to incorporate pfRICH geometry and reconstruction into global ePIC environment
- ❑ Will allow ultimate evaluation of dependency on ePIC tracking
- ❑ Collaborate with dRICH group, whose integration needs are very similar to the pfRICH
 - Combine workforce
 - Unified geometry / optical properties descriptions
 - Common reconstruction algorithm
 - Common output data format
- ❑ Substantial progress on geometry, reconstruction, and readout has been made
 - pfRICH geometry with mirrors and individual sensors integrated
 - Digitized hits from sensors can be accessed from ePIC framework
 - Updated reconstruction based on Inverse Ray Tracing algorithm is being tested



Simulation Parameters

- ❑ Ultimate performance of the pfRICH depends on several parameters including tracking performance, physical dimensions, and properties of aerogel, sensors, and mirrors
- ❑ ePIC tracking performance (resolution) is critical to pfRICH PID reach – include realistic parameterization of track resolution in model
 - Current tracking performance is sufficient to reach pfRICH performance goals
- ❑ Mirror reflectivity
 - Assume mirror reflectivity of 90%
 - Modest decrease in π/k separation power with lower mirror reflectivity – still reach $> 3\sigma$ in our acceptance for $R = 70\%$
- ❑ Vessel dimensions
 - Assume nominal proximity gap of 491 mm
 - Reduction of gap by 50 mm due to possible larger readout footprint leads to 5 to 8% reduction in π/k separation power



Simulation Parameters

□ The standalone simulation model contains several parameters directly relevant to the pfRICH performance

- Mirror reflectivity: 90%
- Pyramid mirror height: 30 mm
- Primary vertex z smearing: 35 mm
- ePIC B-field map
- Proximity gap length: 491 mm
- Aerogel refractive index: 1.040
- Aerogel thickness: 2.5 cm
- HRPPD window thickness: 5 mm
- HRPPD window material: fused silica

