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

Brian Page

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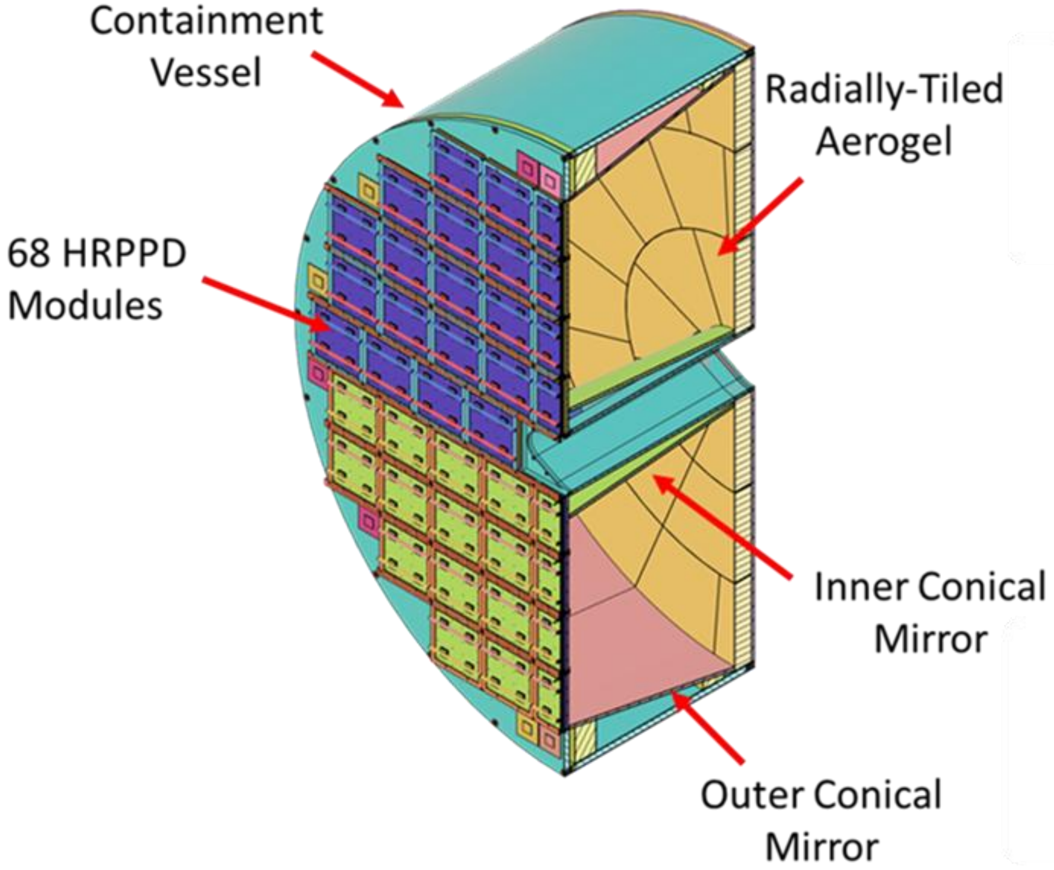
Brookhaven National Laboratory

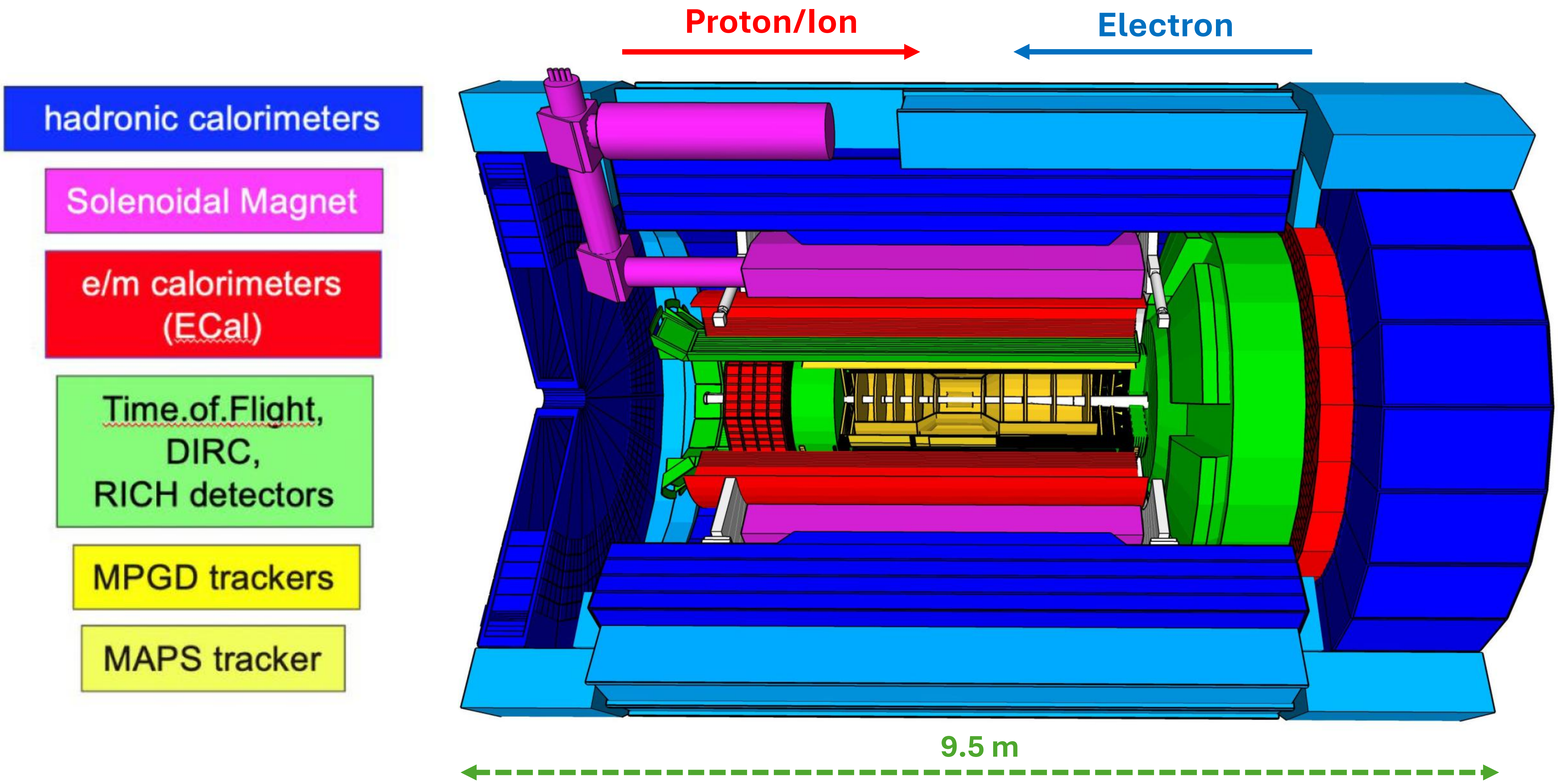
ePIC

Outline

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



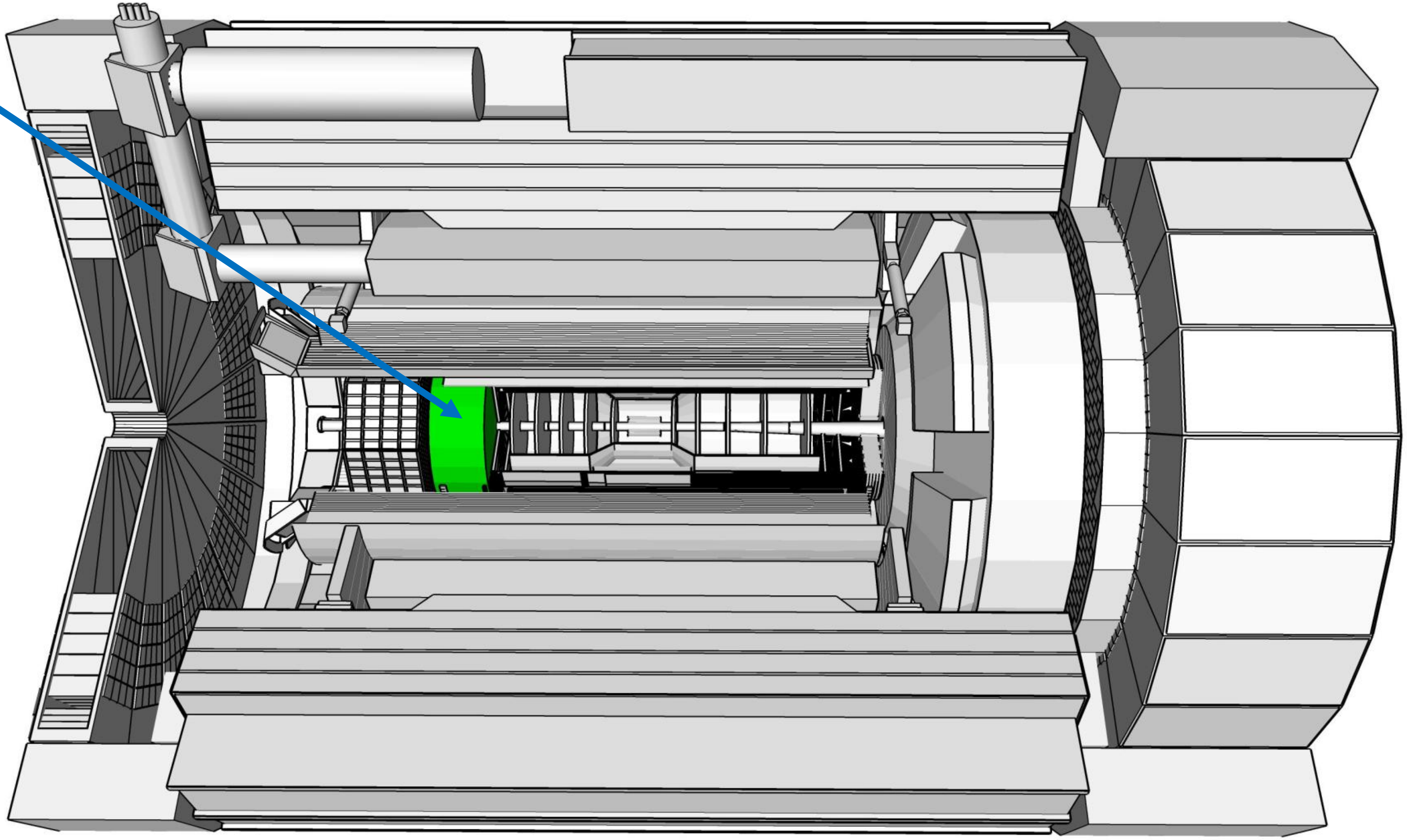
The ePIC Detector



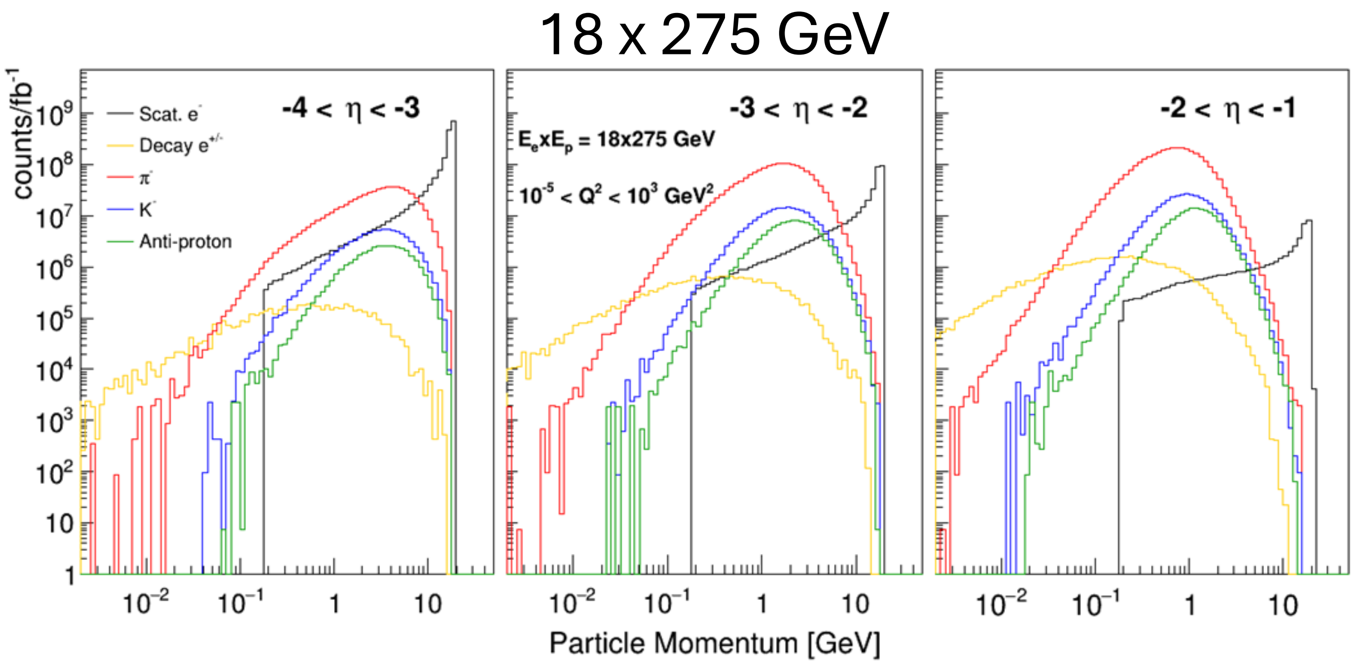
The ePIC Detector

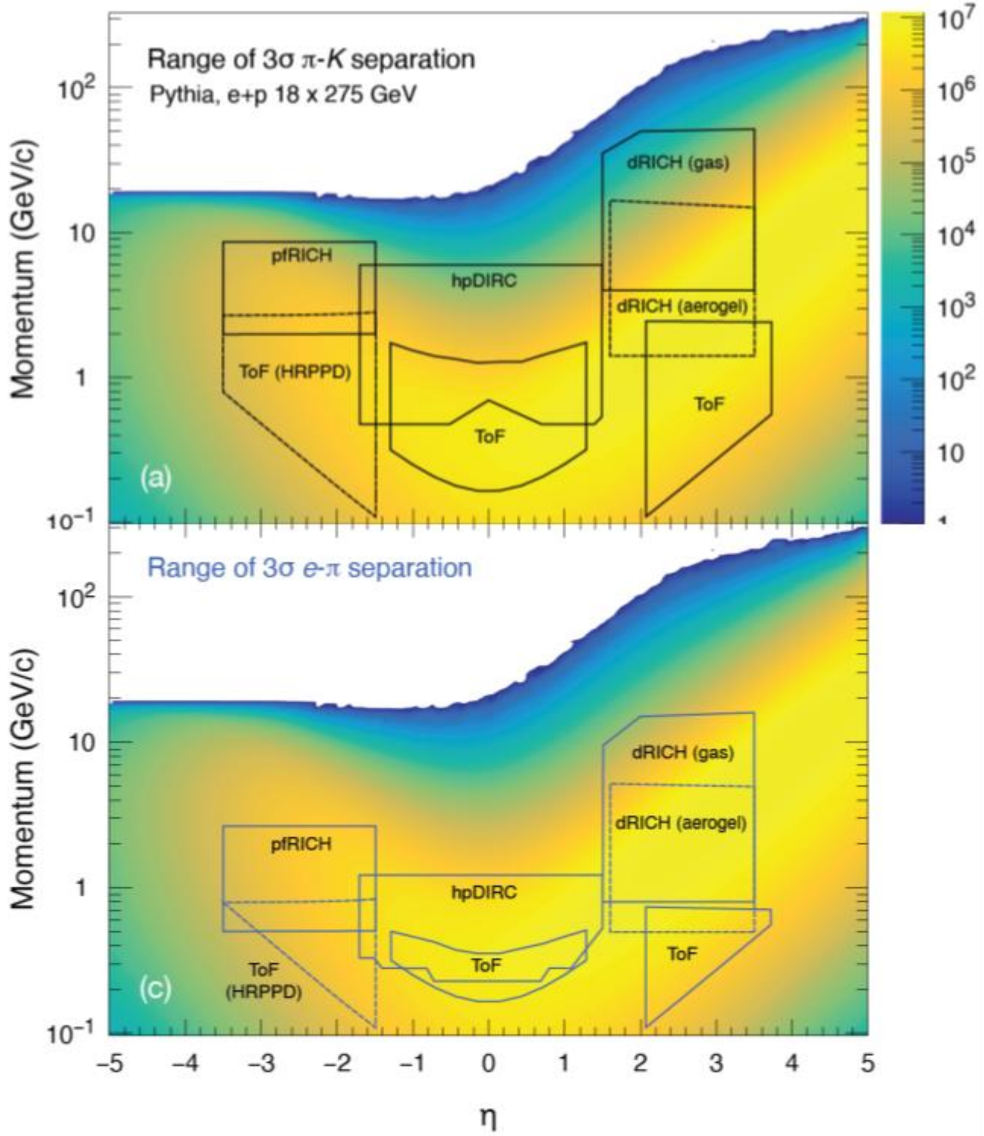
pfRICH

- Provide hadron identification (π/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



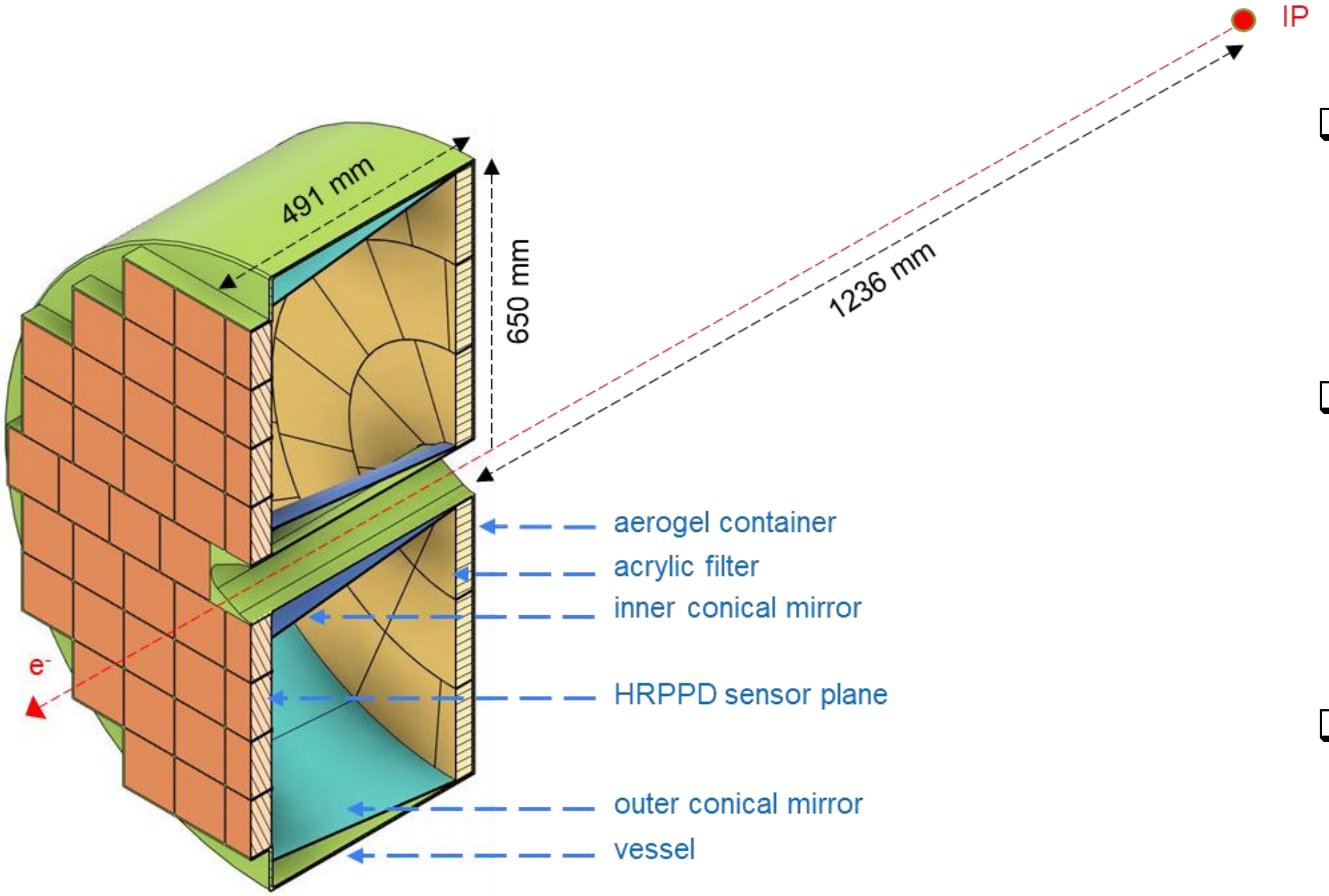
pfRICH Kinematic Coverage





- Provide >3σ π/k separation for momenta up to 7 GeV/c for -3.5 < η < -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

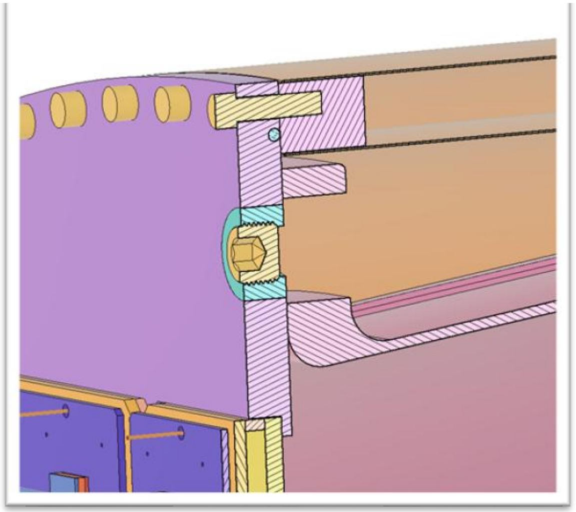
Vessel Components and Fabrication

- Vessel consists of
  - Cylindrical body (SBU)
  - Reinforcing end-rings (Purdue)
  - Sensor plane (Purdue)
  - Aerogel wall (Purdue)

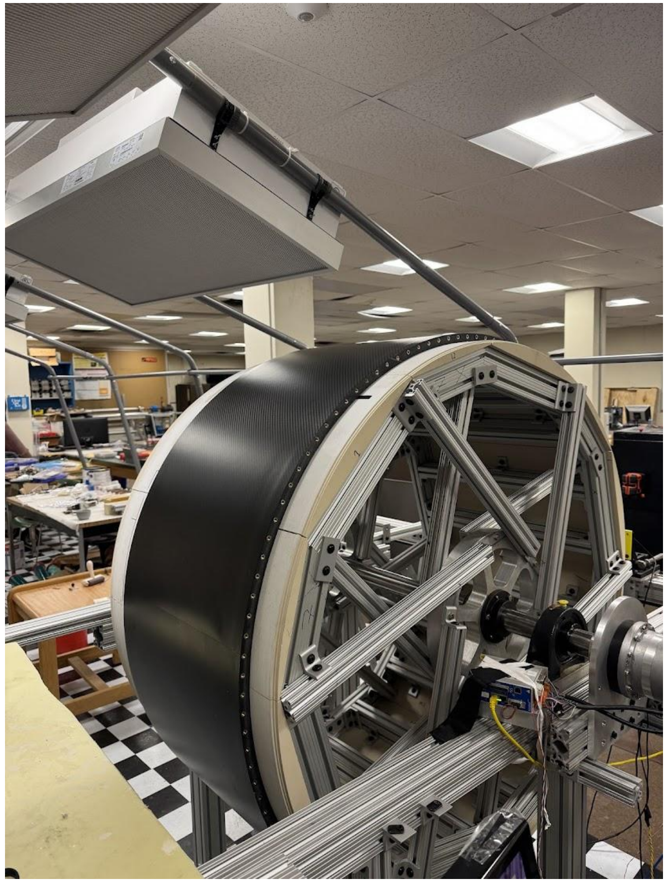
- The vessel wall will be a carbon fiber sandwich -> light-weight, gas and light tight

- Machined carbon-fiber end-rings provide stability and connection points for sensor and aerogel walls

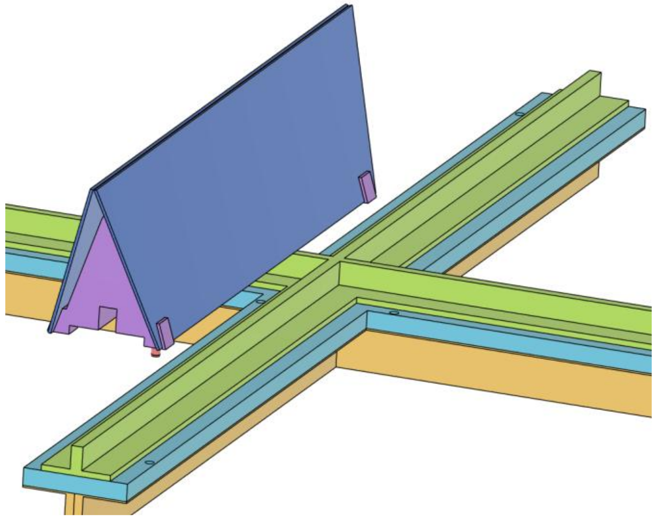
- Engineering test article vessel wall with end-rings incorporated completed mid-May 2025 – metrology studies ongoing



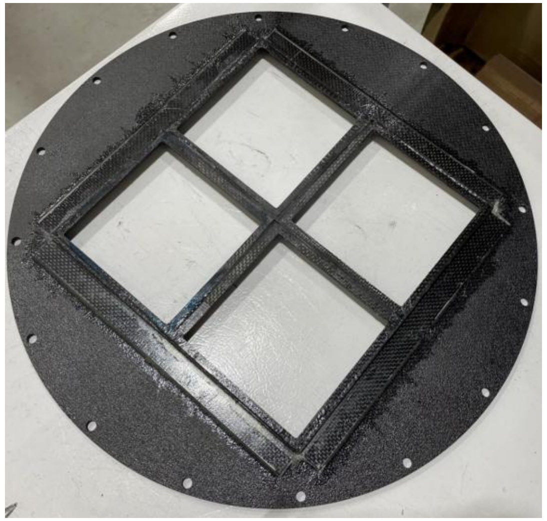
- Shape: 1/2” thick cylinder (12.7 mm)
- Outer Diameter: 1300 mm
- Length: 491 mm
- Precision: < 1 mm radius and length (Dedicated metrology and visual checks)
- Technology: Carbon-fiber composite material with Nomex honeycomb core



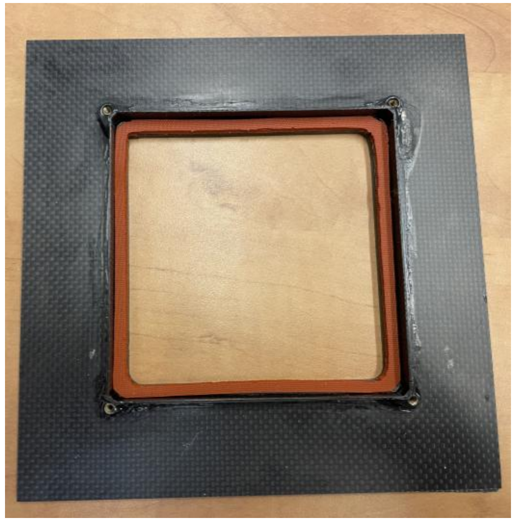
Vessel Components and Fabrication



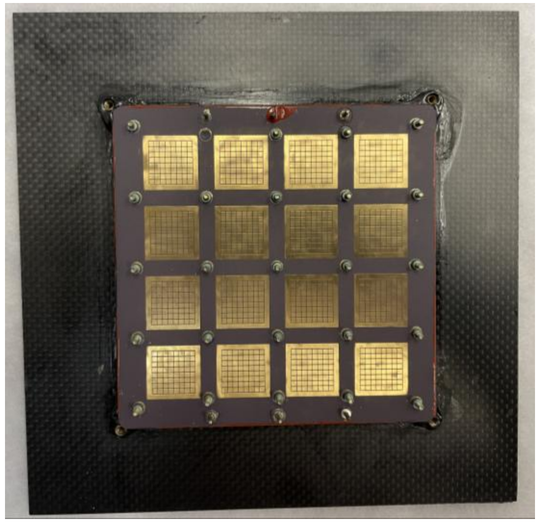
Sensor Plane Model



Test Windowpane Unit

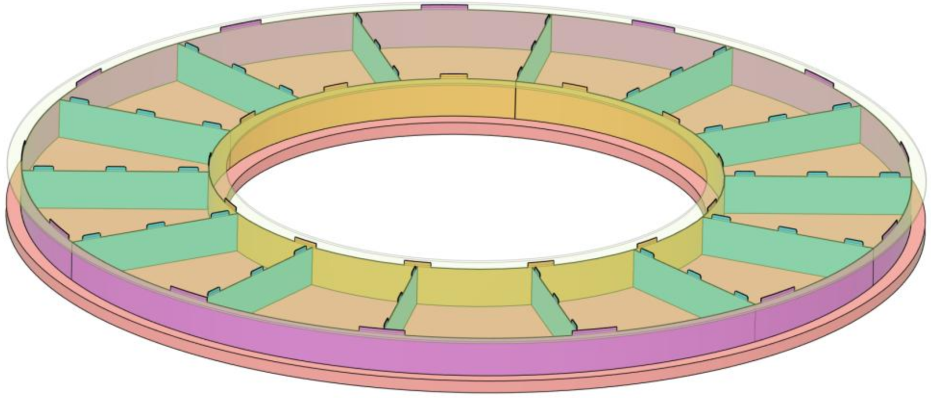


Holder and Sealing Gasket



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

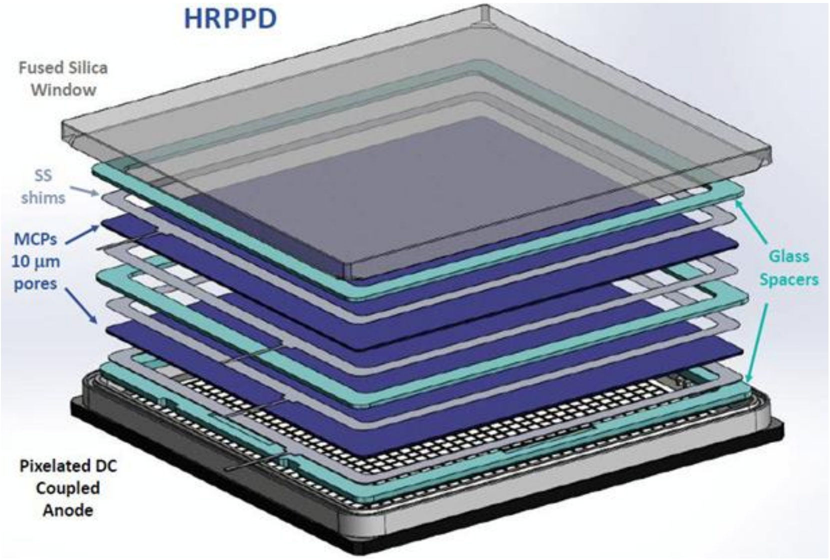


Model of Prototype Aerogel Wall (1 ring)

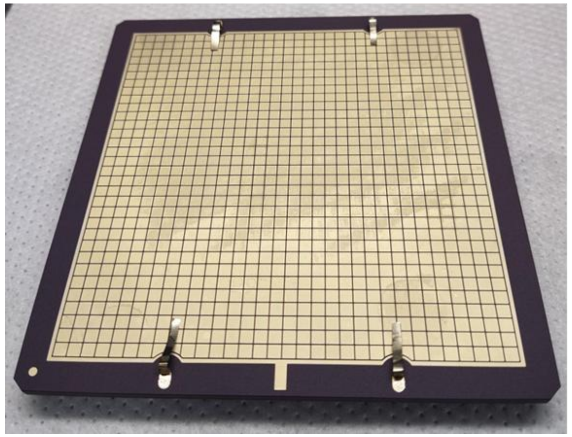
Photo-Sensors

- Basic requirements:
  - Provide a timing reference at the level of ~20 ps for the barrel and forward ToF subsystems
  - Provide spatial resolution ~1mm
  - 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

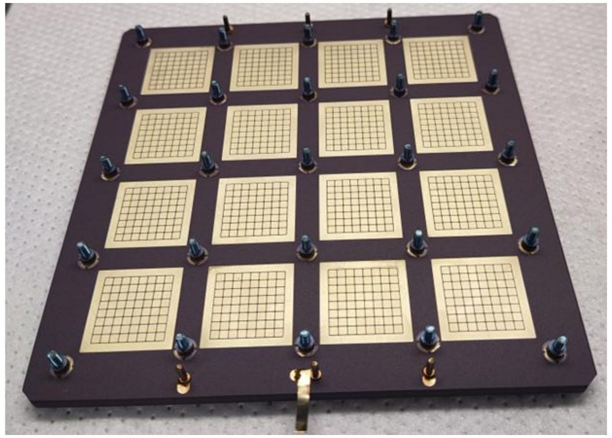
- **Photosensor: HRPPD by Incom Inc.**
  - High intrinsic SPE timing resolution
  - High Quantum Efficiency
  - Low Dark Count Rate (compared to SiPMs)
  - Low cost (compared to other MCP-PMTs)



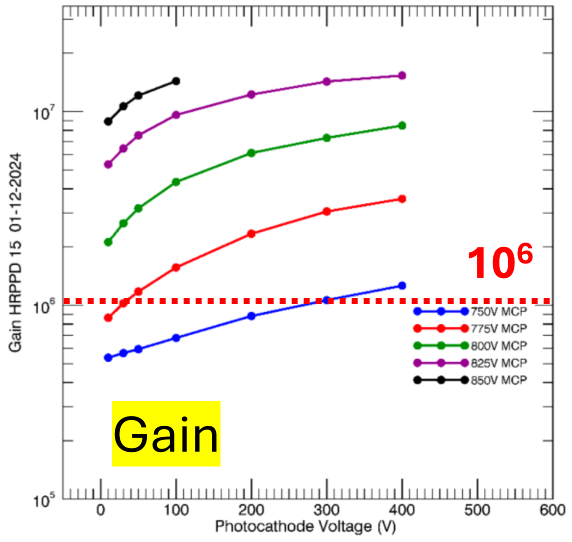
Anode plate vacuum side

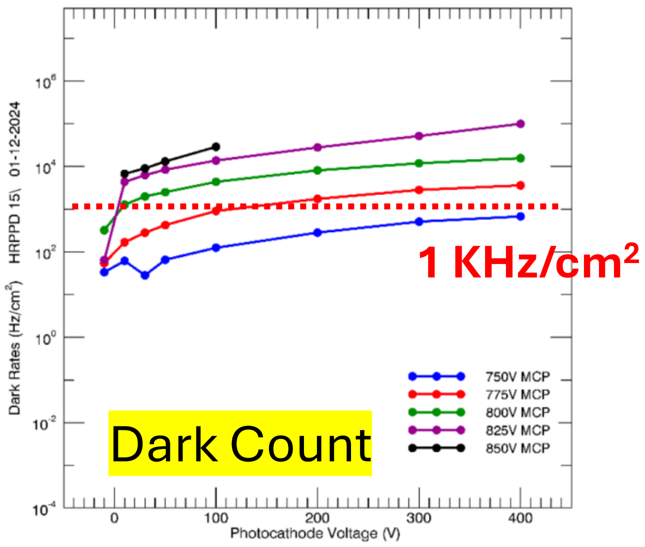


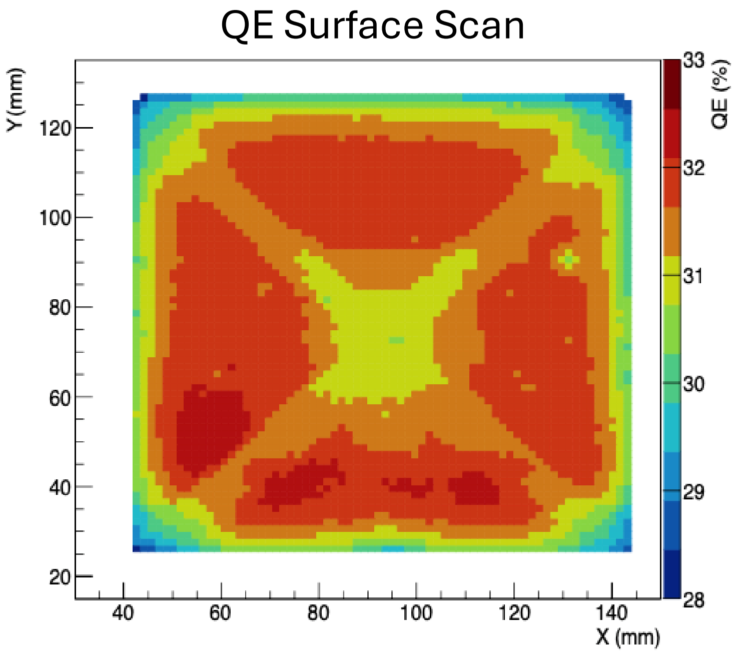
Anode plate air side

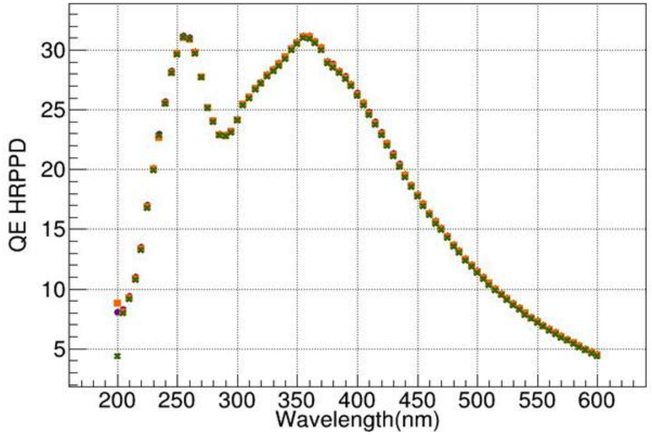


HRPPD Performance

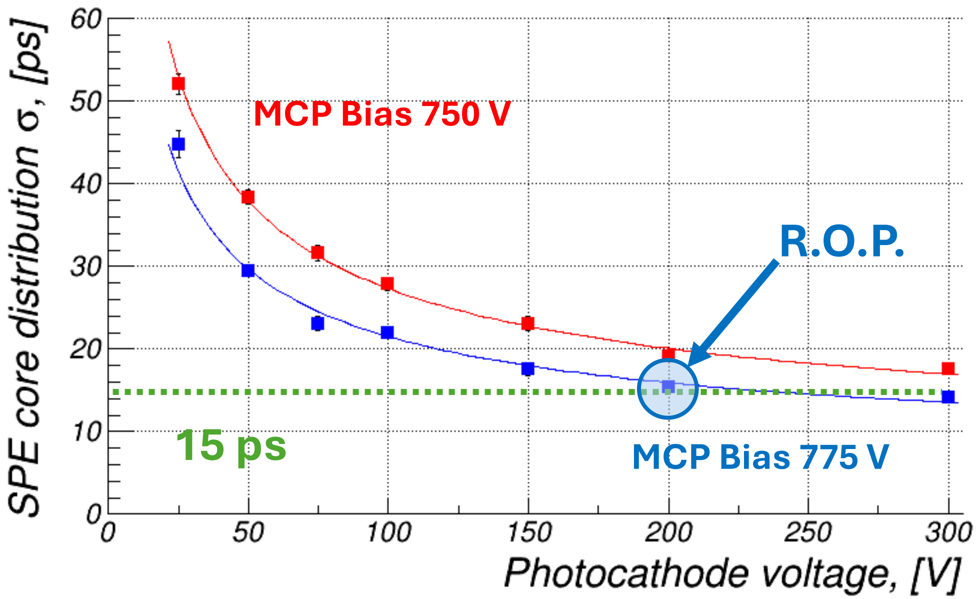




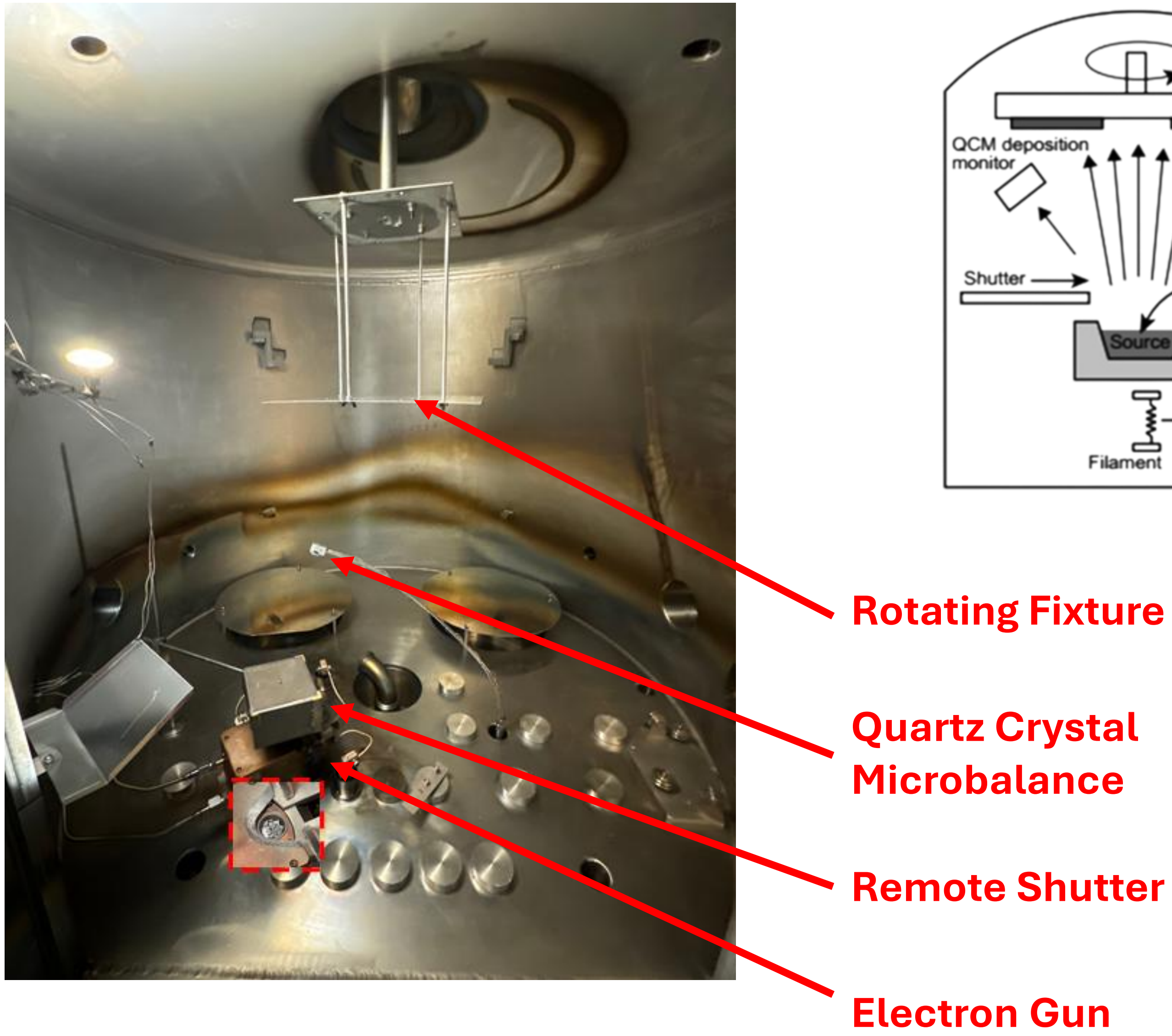


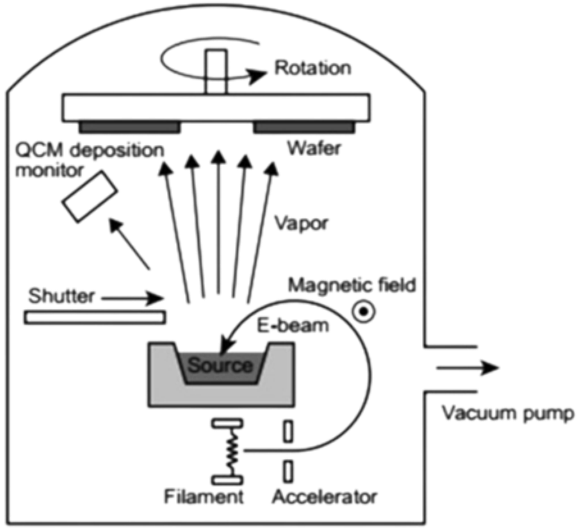


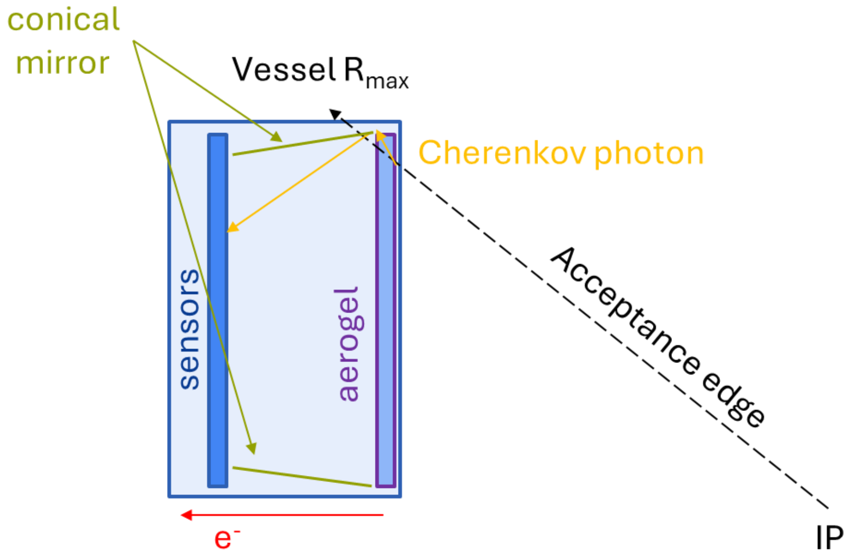
- HRPPDs demonstrate large gain at low MPC bias voltage with reasonable dark count rates (<1KHz for gains in the 10^6 region)
- Peak Quantum Efficiency above 30% with good uniformity over sensor surface
- Single photon timing resolutions ~15 ps for recommended bias and photocathode voltage working points



Mirrors



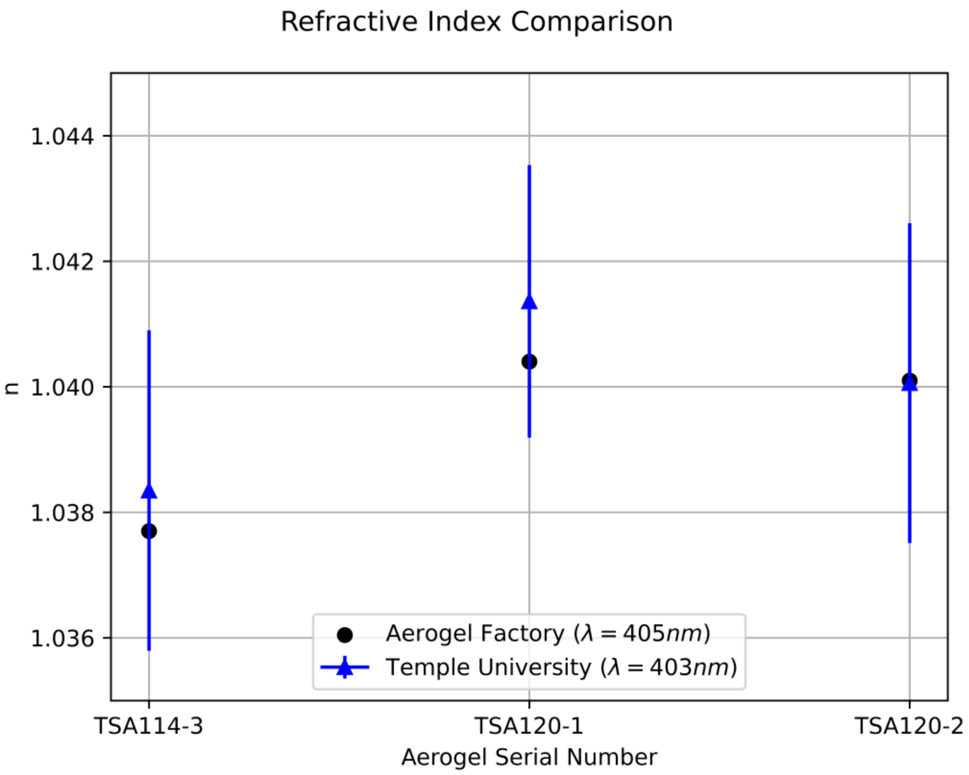




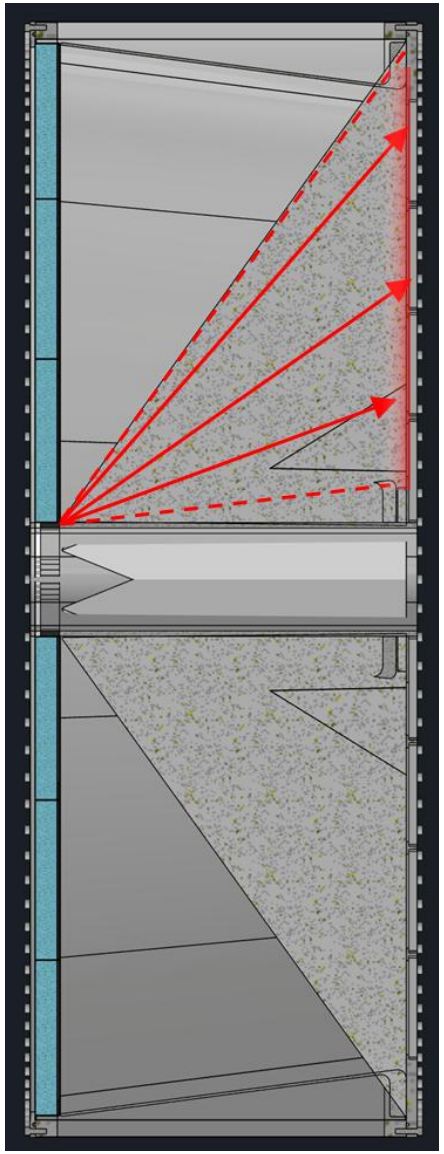
- Inner and outer conical mirrors and pyramidal mirrors increase detector photon acceptance
- Mirrors fabricated "in-house"
  - Straight and curved substrates produced by Purdue
  - Lexan co-bonded to carbon fiber – optimization of bonding procedure ongoing
  - Mirror coating applied using evaporator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

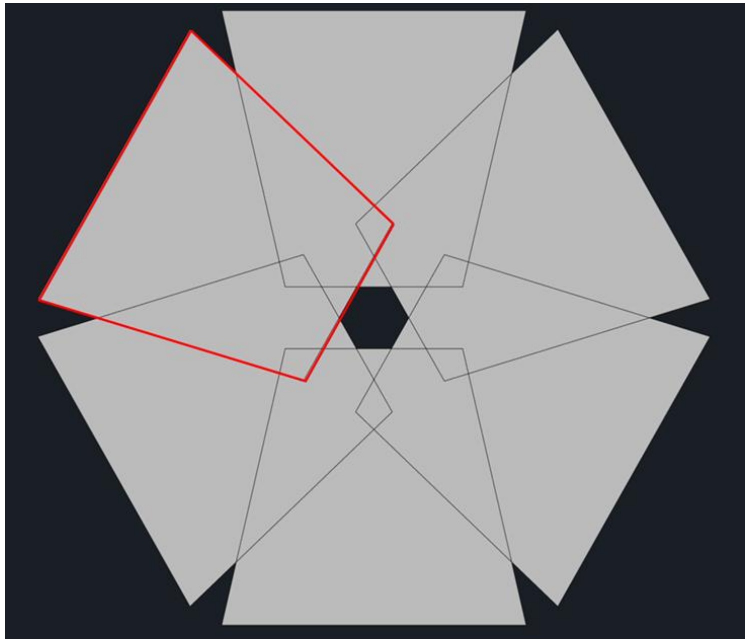
Aerogel

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

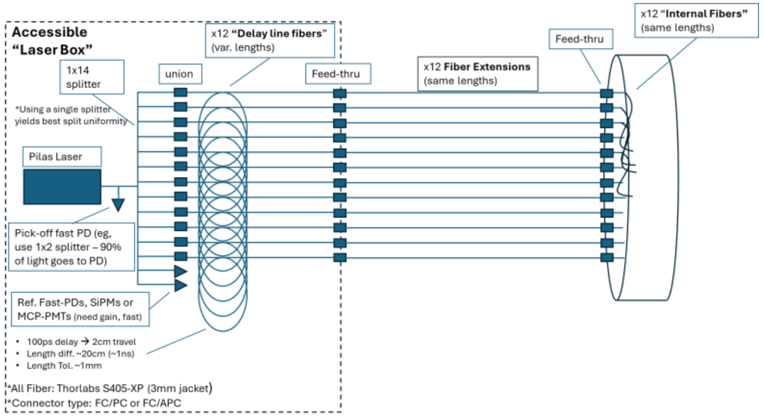


Light Monitoring System

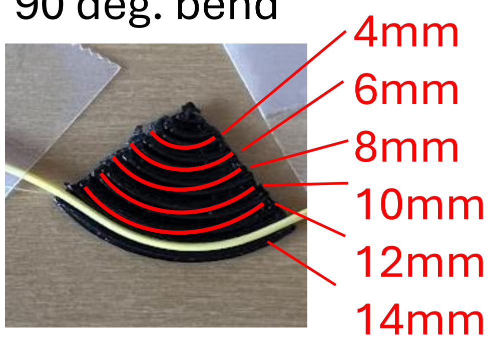


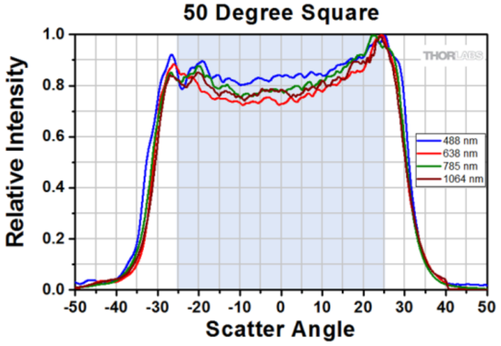


- Want a way to monitor HRPPD timing performance, signal amplitude, QE, and mirror reflectivity over the lifetime of the experiment
- Introduce an array of 12 optical fibers from the aerogel side of the vessel: 6 illuminate the photosensors directly and 6 bounce light off mirrors first
- Distance from 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



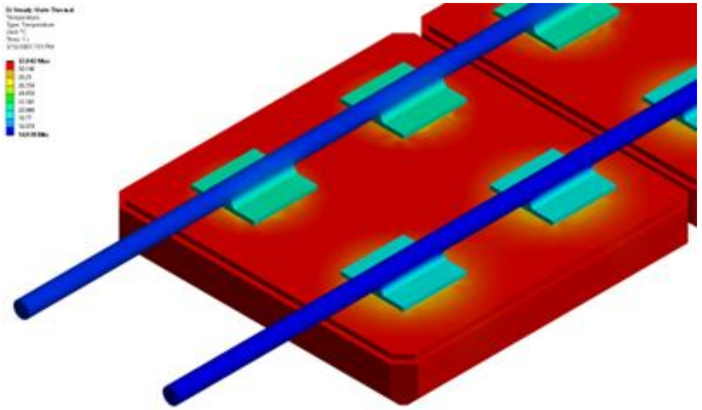
90 deg. bend

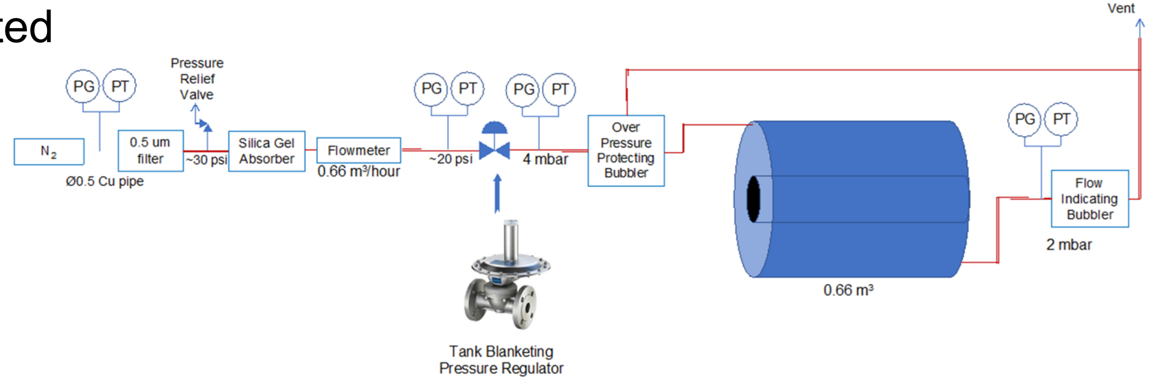




Services

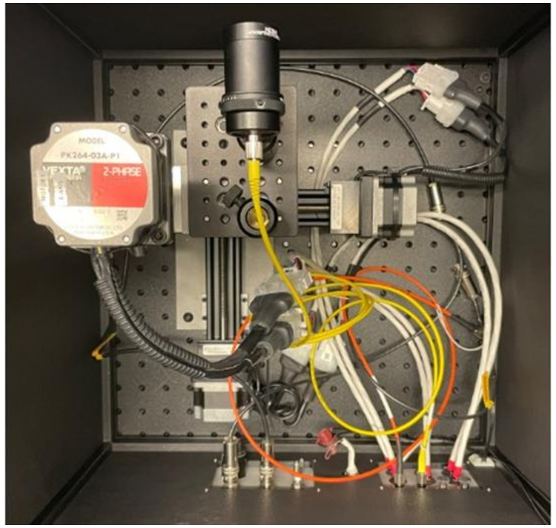
- HV system components have been identified and initial layout explored
- LV power system designed assuming 4 EICROC (256 chs/chip) per HRPPD – will be reevaluated once FCFD parameters available
  - 1024chs/sensor x 3mW/ch = ~3W/sensor -> @ 1.2V = 2.5A per sensor
  - 68 sensors x 2.5A = 170A total current
  - Add 20% for on-board components and safety margin: 170A x 1.2 x 1.2 = 245A current for full detector
  - Total power: 245A @ 1.2V = 294W
- 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



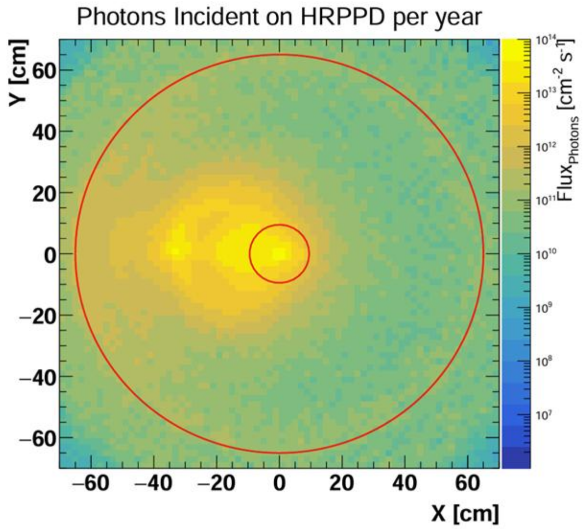


HRPPD Evaluation

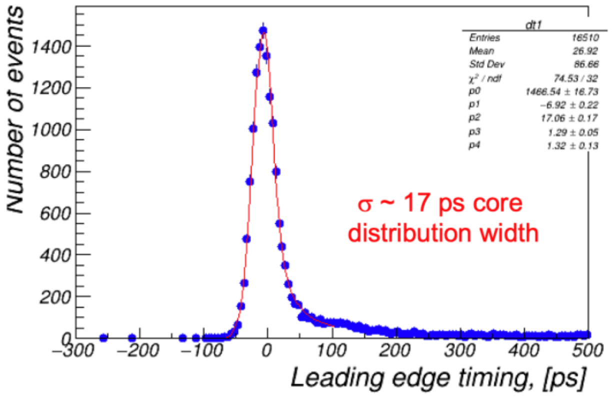
- ❑ Number of studies carried out across several institutions to evaluate suitability of HRPPDs for EIC needs
- ❑ Primary QA at JLab
  - ➢ Mechanical, basic functionality
- ❑ More systematic active area scans at BNL
  - ➢ Timing, QE, DCR, PDE
  - ➢ Utilize femtosecond laser to minimize impact of laser 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



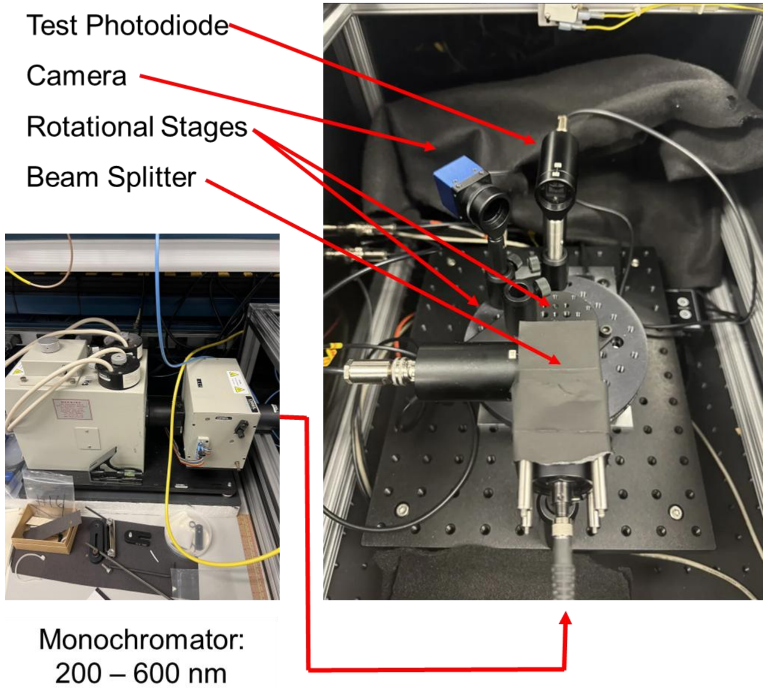
Fluence simulation for aging studies

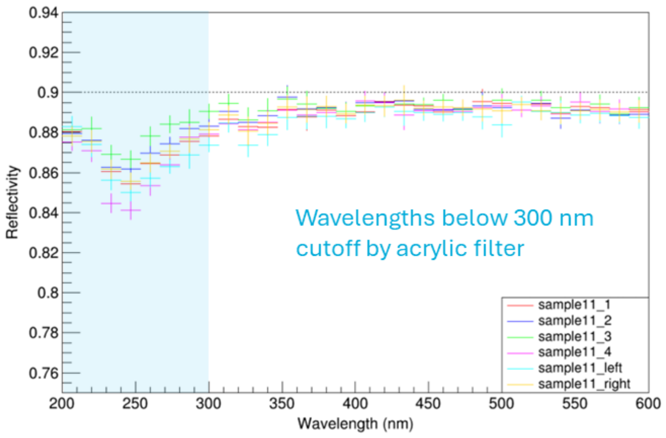


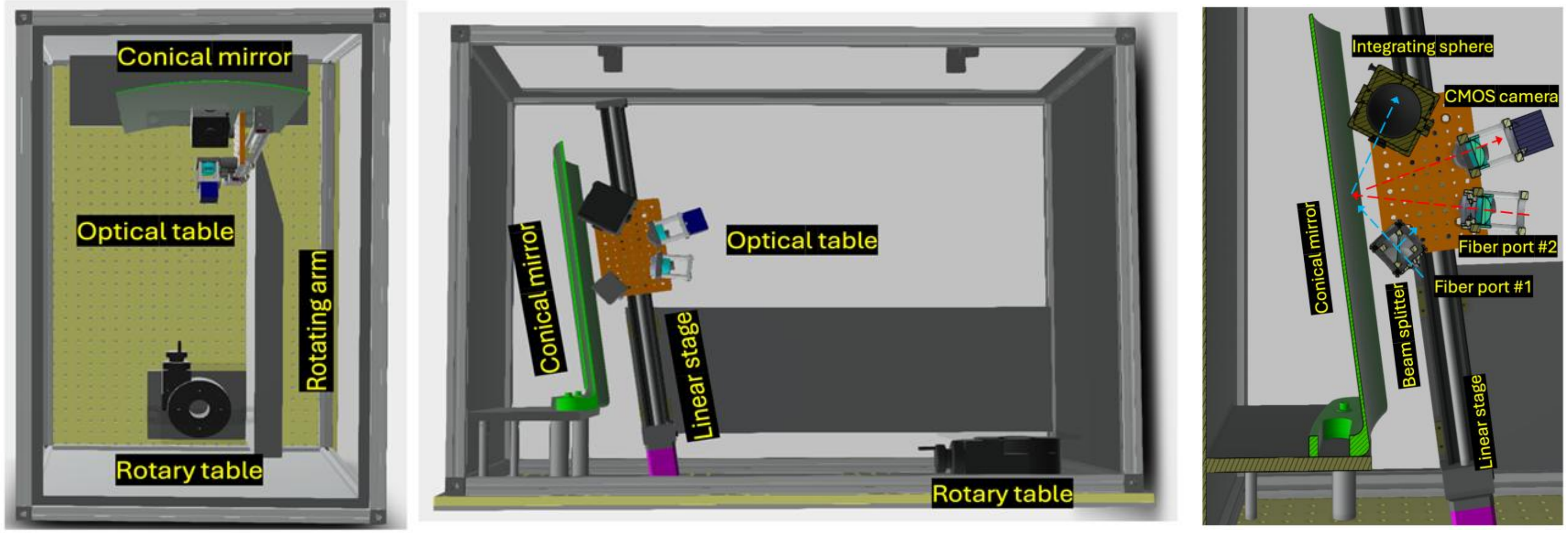
Sample Timing Curve

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

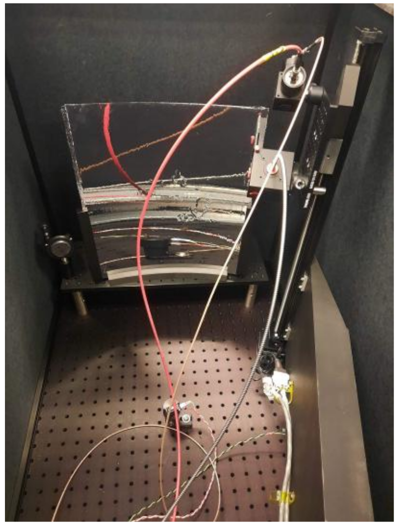
Mirror Evaluation





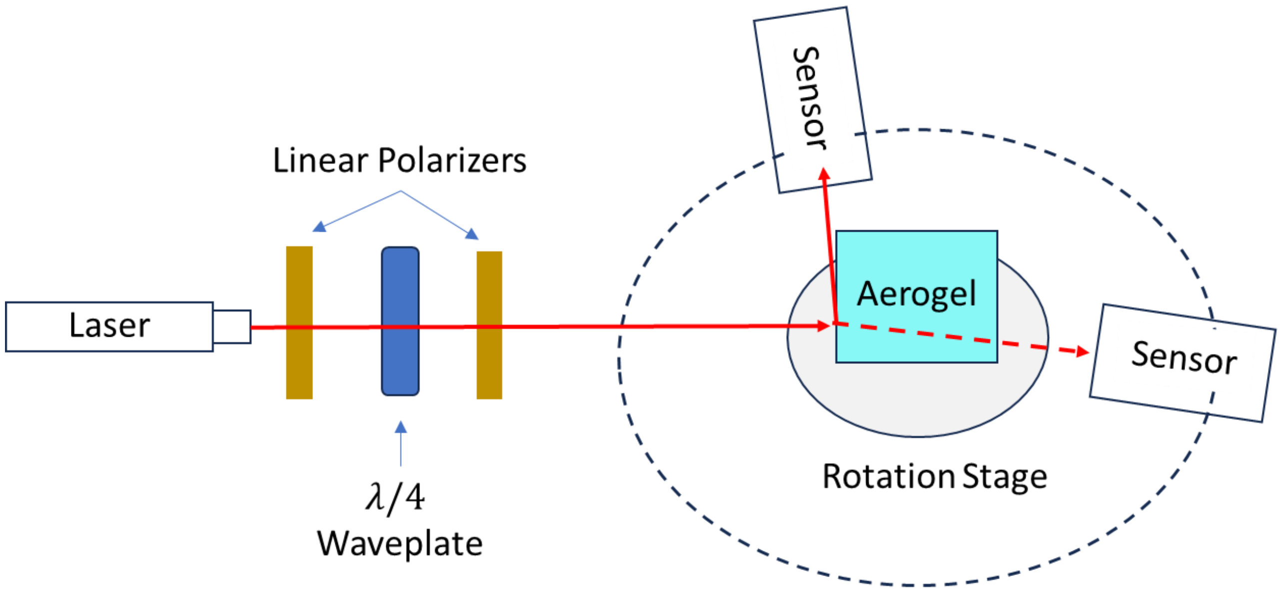


- ❑ Two optical test stands at BNL for mirror evaluation and QA
- ❑ Small test stand used to measure reflectivity of mirror samples allowing for optimization of coating and fabrication procedures
- ❑ Large test stand designed to measure reflectivity and surface quality of the full-size curved mirrors

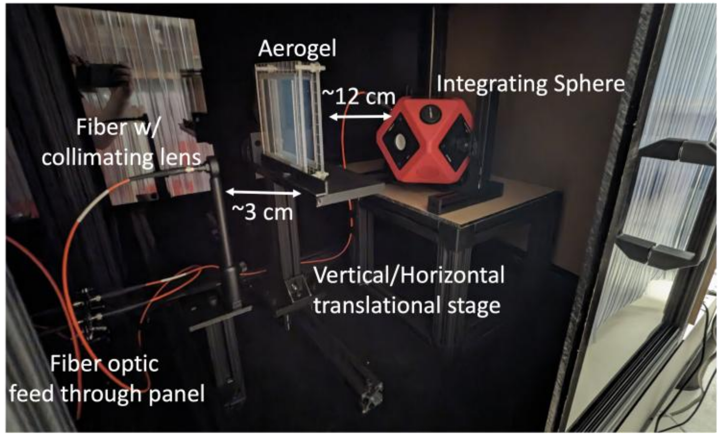


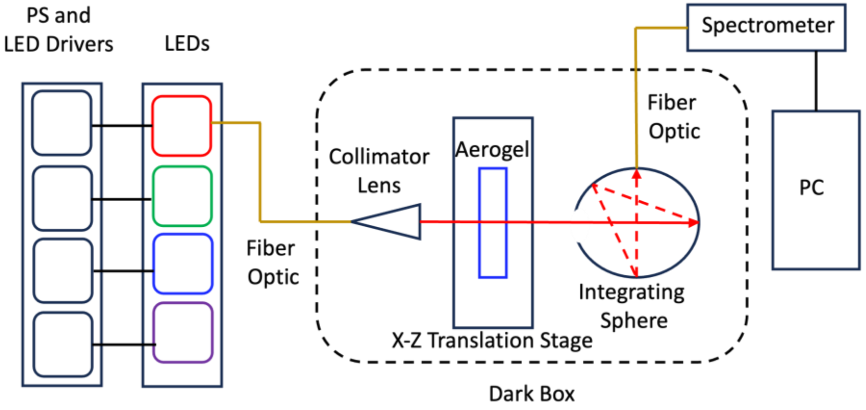
Aerogel Evaluation

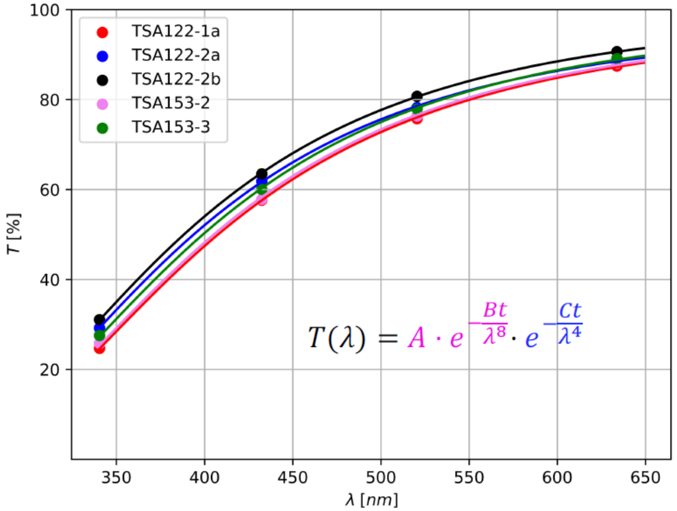
Schematic setup for Brewster's angle measurement



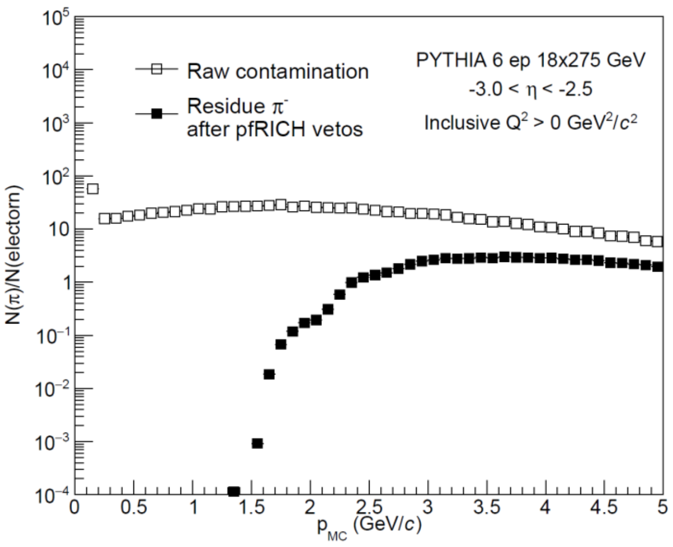
- Aerogel tile QA being carried out at Temple University
- Exploit polarized light to measure index of refraction over the aerogel surface: Brewster's angle and ellipsometry
- Investigation of extraction of refraction index using Brewster's method is ongoing
- Transmittance also measured and in good agreement with factory values

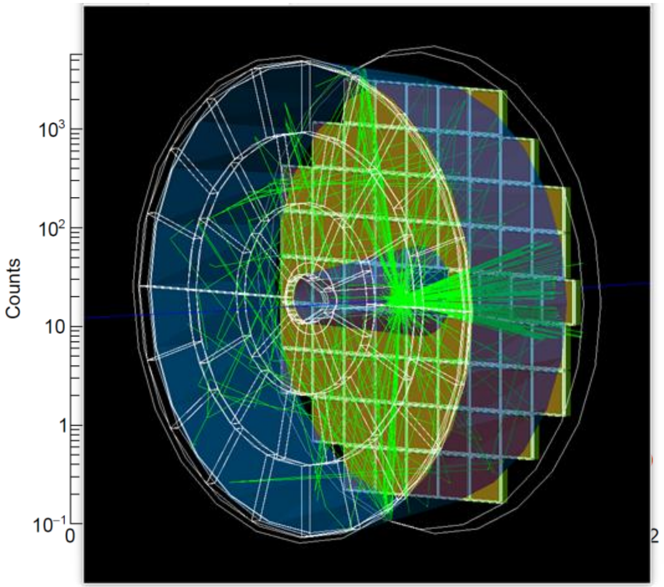


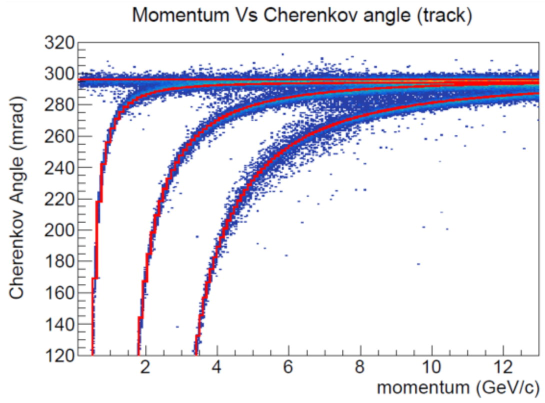


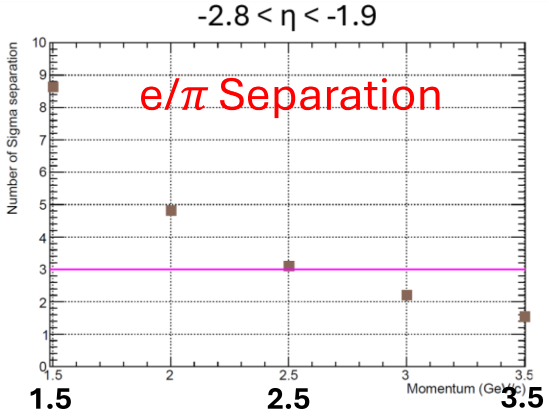


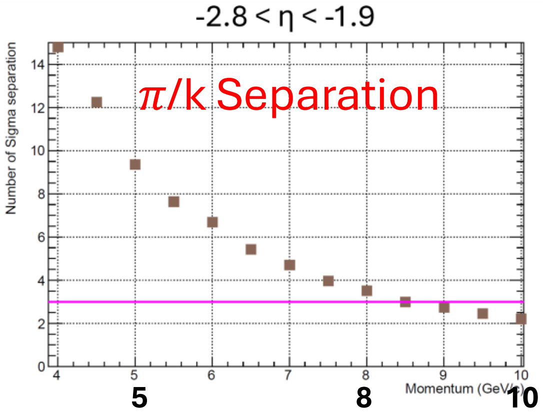
Performance Simulation











- ❑ 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

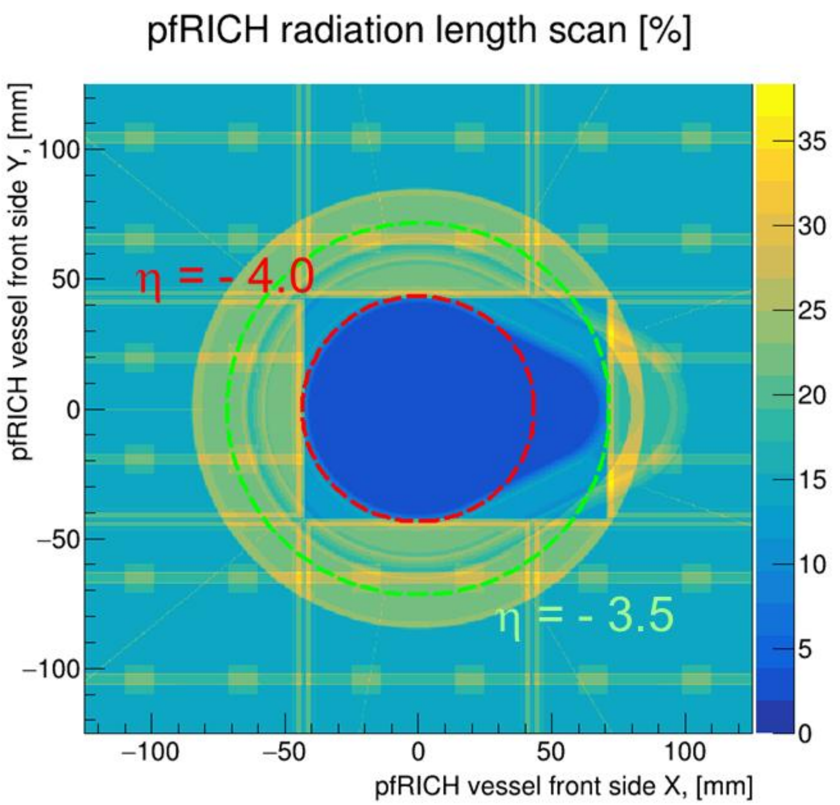
- Hadron identification crucial to many of the physics goal at the EIC – PID in the electron going direction provided by a proximity focusing RICH detector
- Carbon fiber vessel construction minimizes material budget – first engineering article demonstrating construction techniques recently completed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

BACKUP

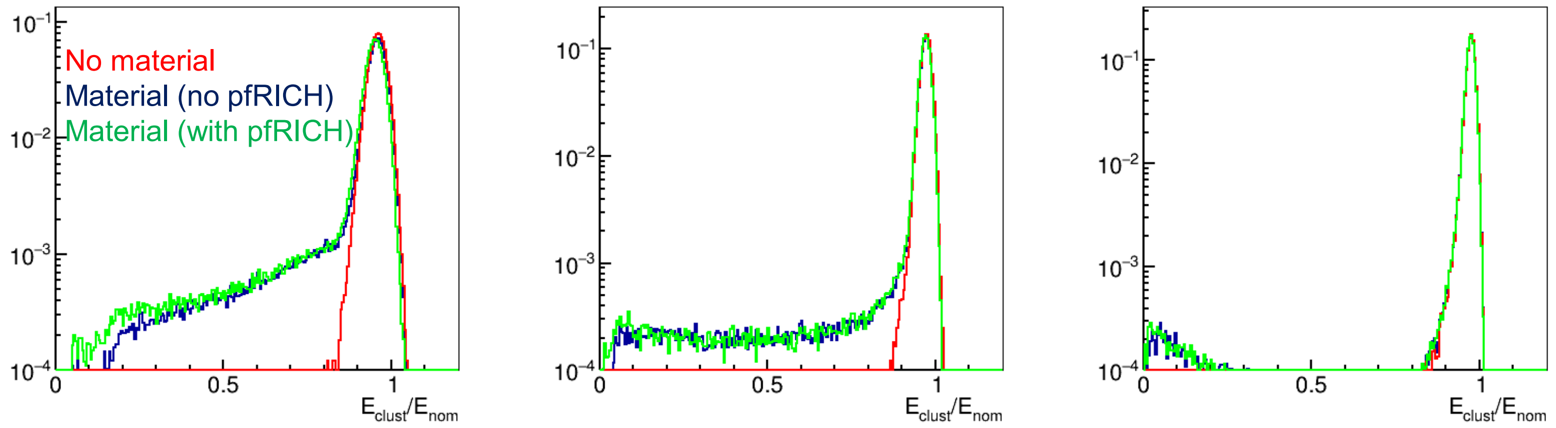
pfRICH Material Effect on Backward EmCal

- pfRICH GEANT implementation imported in ePIC framework as a GDML file
  - Material implemented to the best of our knowledge (vessel, HRPPDs, cooling system, etc)

$-3.3 < \eta < -1.9$

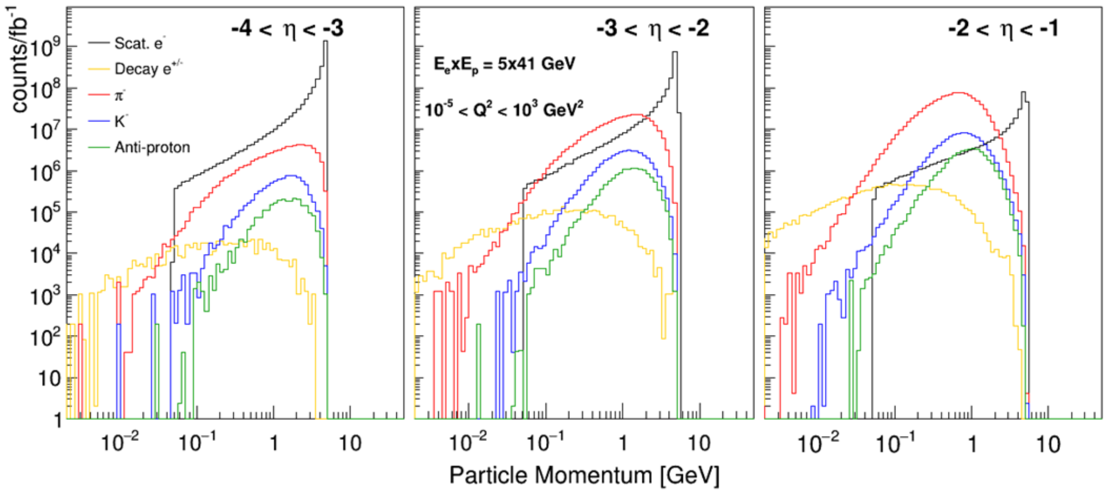


1 GeV | 4 GeV | 10 GeV

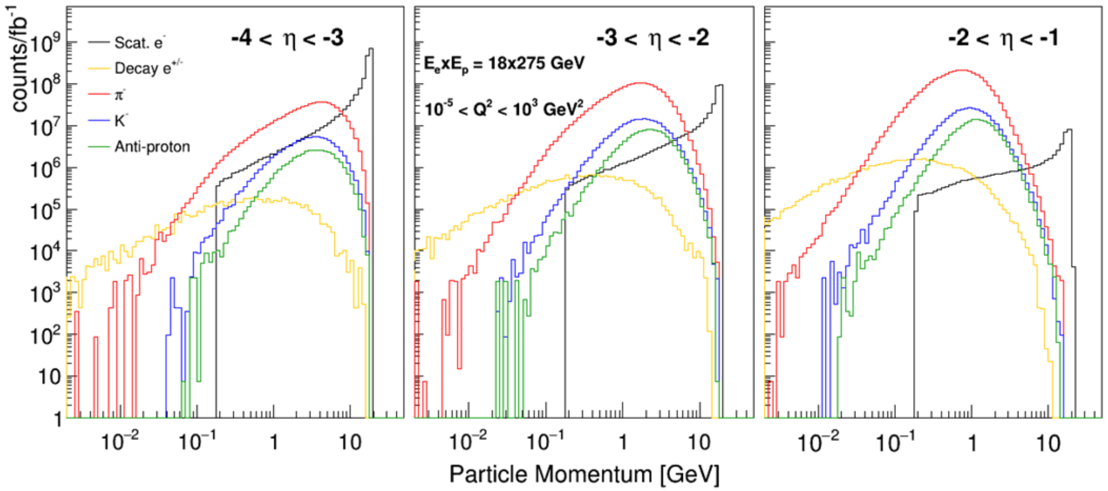


- No effect on (~gaussian) peak width
- Lower energy tails (the largest at 1 GeV)
- No effect for high energy electrons (10 GeV)
- Minimal effect from pfRICH overall

Particle Kinematics



5 x 41 GeV

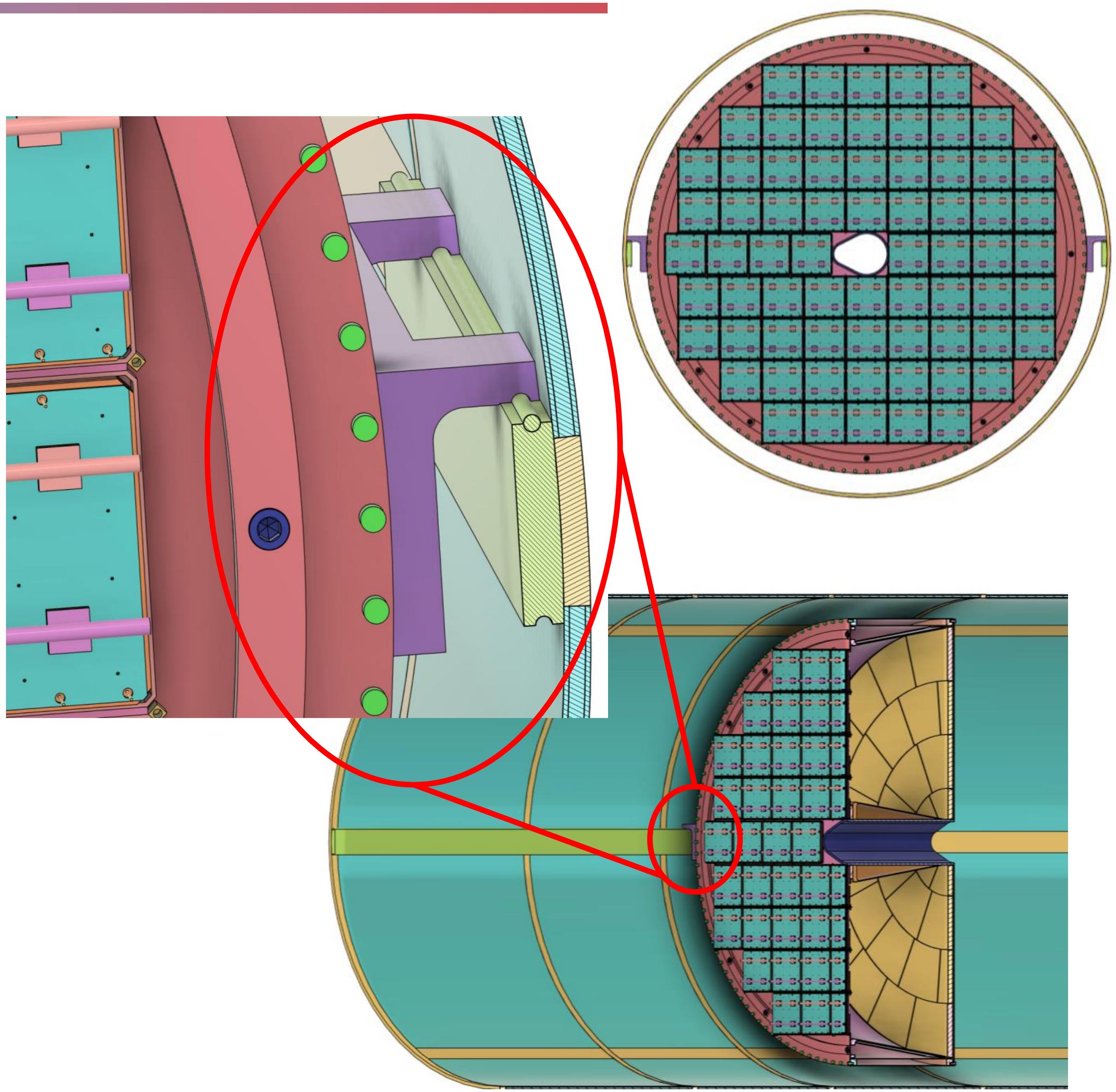


18 x 275 GeV

pfRICH Installation

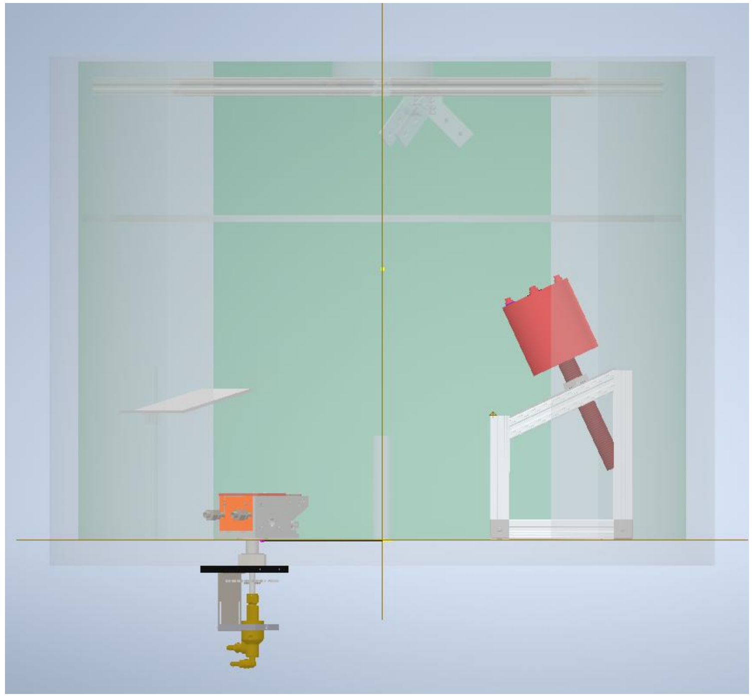
- Installation steps:
  - Installation cart (design forthcoming) is placed on an installation platform
  - Rails between installation cart and global support tube (GST) aligned on the platform
  - pfRICH slides into the GST into its operating position

- 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

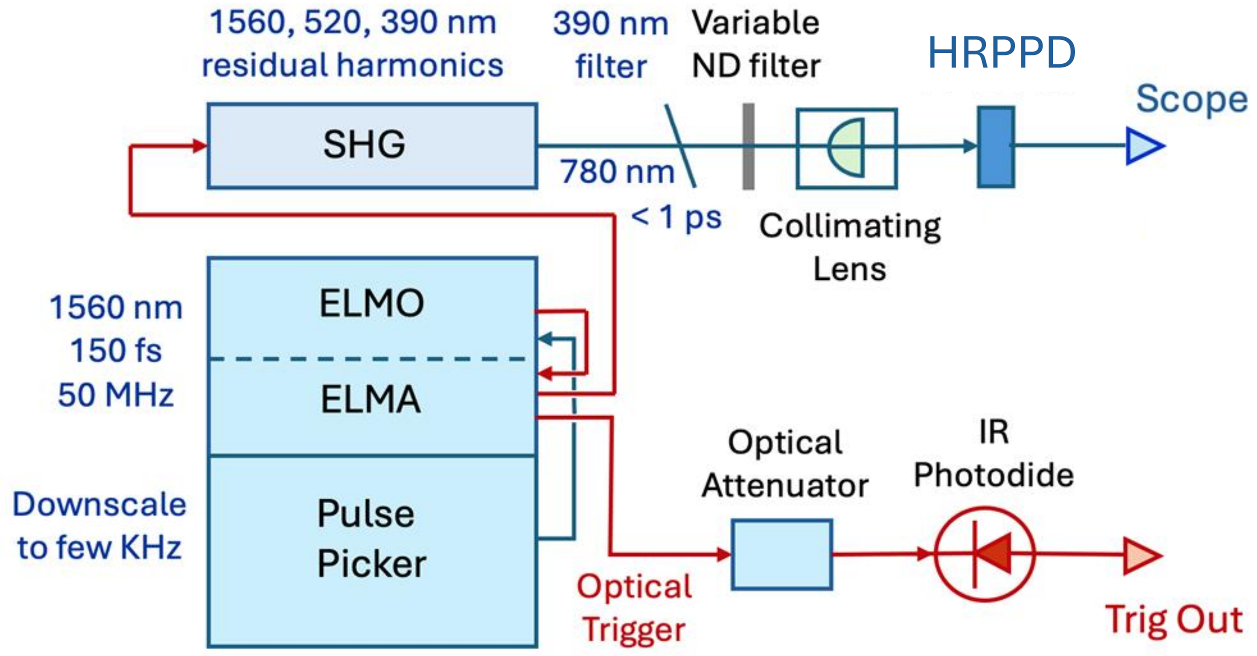
Elmo 780 Femtosecond Laser System @ BNL

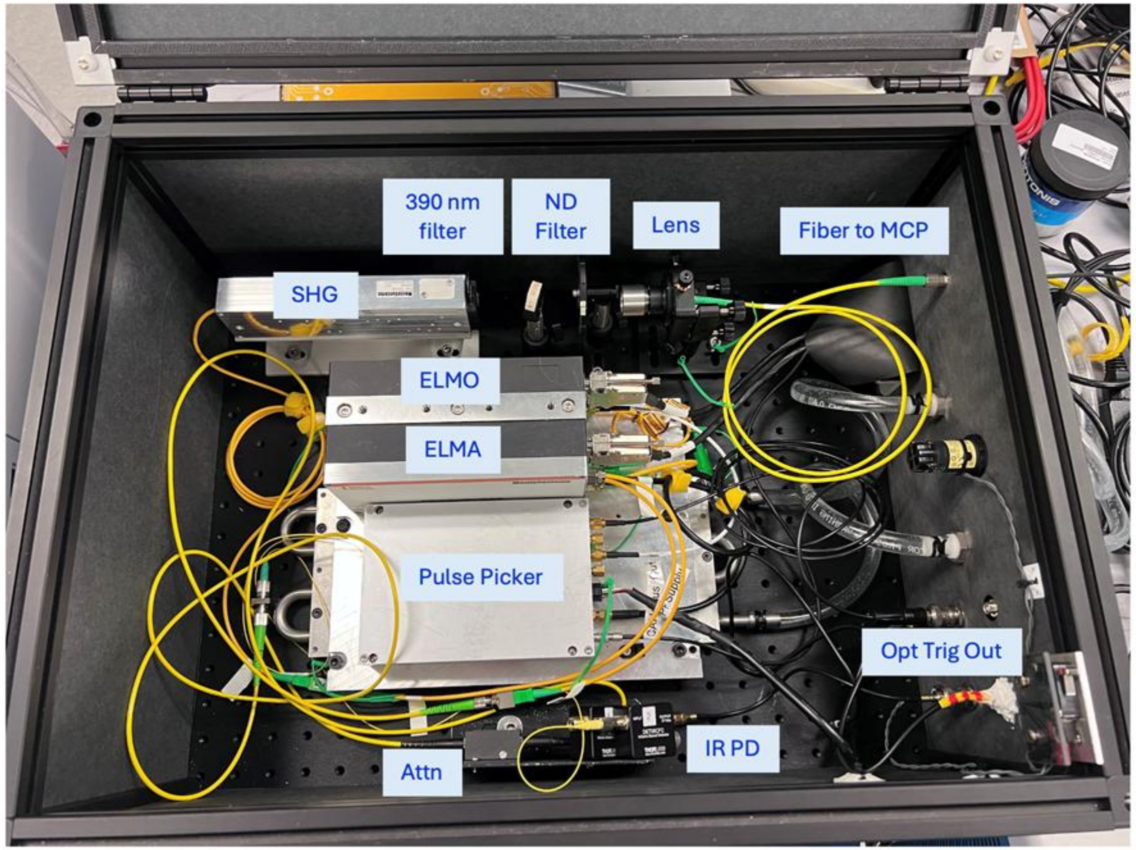
Menlo Systems Elmo 780 Erbium Fiber Femtosecond Laser

ELMO = Primary Laser Oscillator

ELMA = Optical Amplifier

SHG = 2nd Harmonic Generator



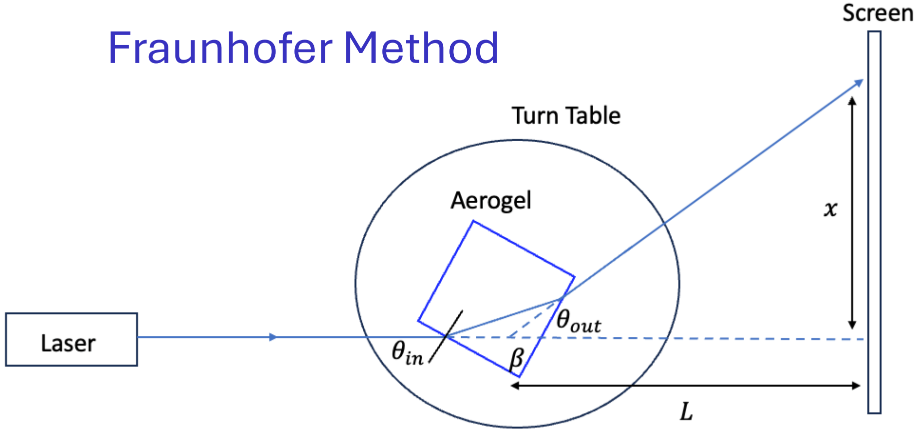


We make use of a very low intensity 4th harmonic @ 390 nm

Alternate Refractive Index Determination

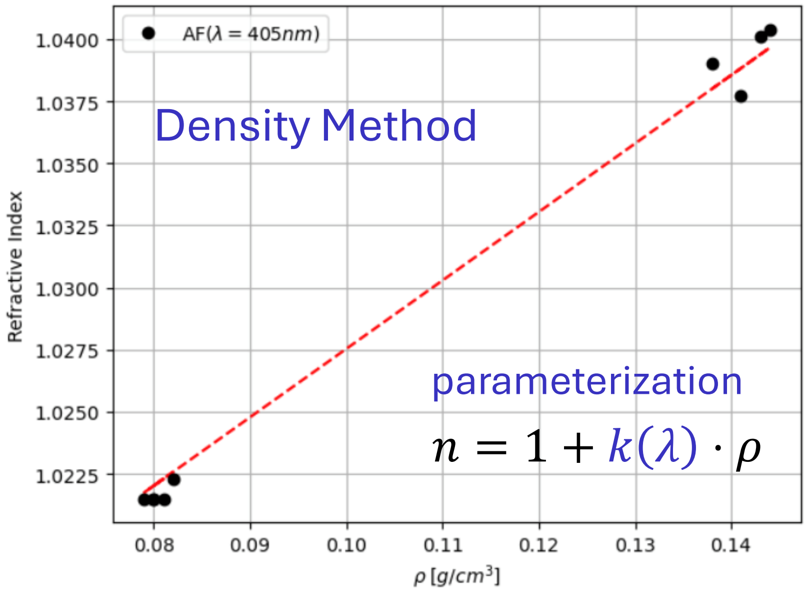
- Current index of refraction methods utilize Fraunhofer Method, where light passes through corner of aerogel and minimum deflection angle is used to obtain refractive index
  - Limitations: QA only at corners of aerogel tiles. Production tile edges will not be of optical quality and not representative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

Fraunhofer Method



- 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)

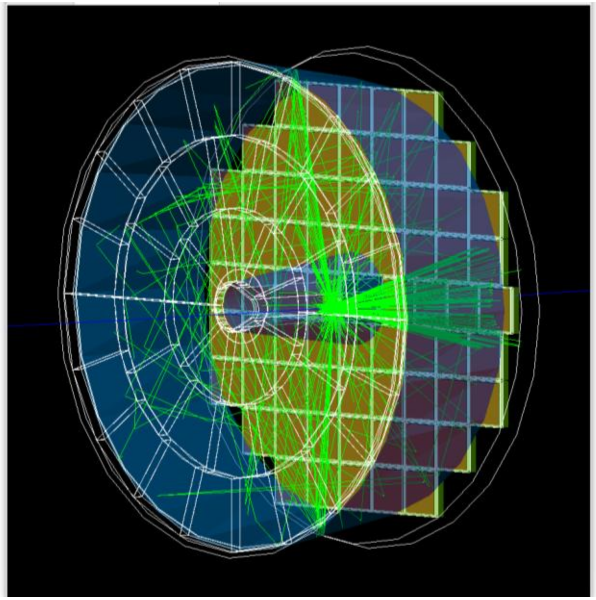
Density Method

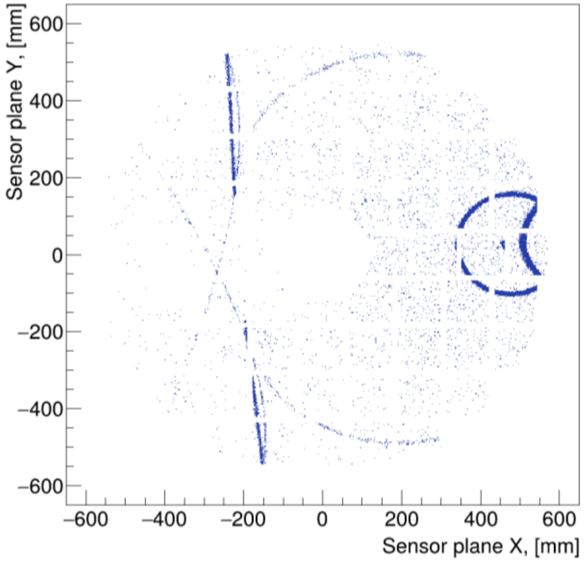


parameterization

$$n = 1 + k(\lambda) \cdot \rho$$

Interface With ePIC Simulation Environment

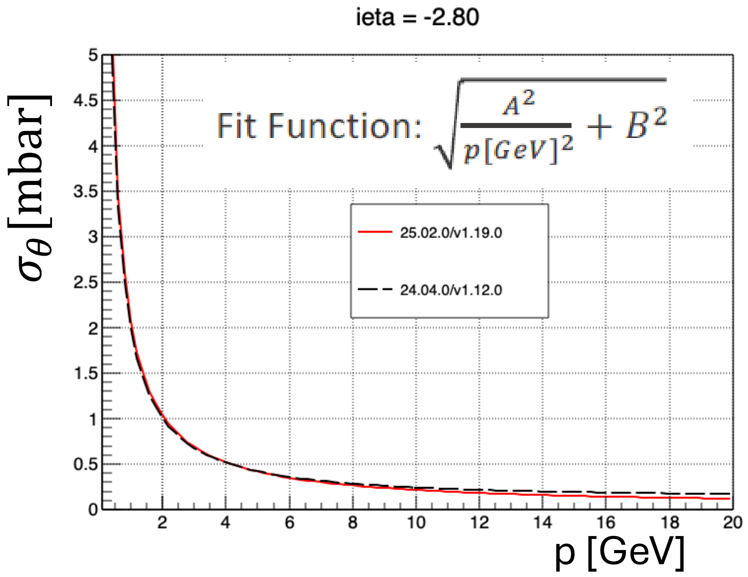


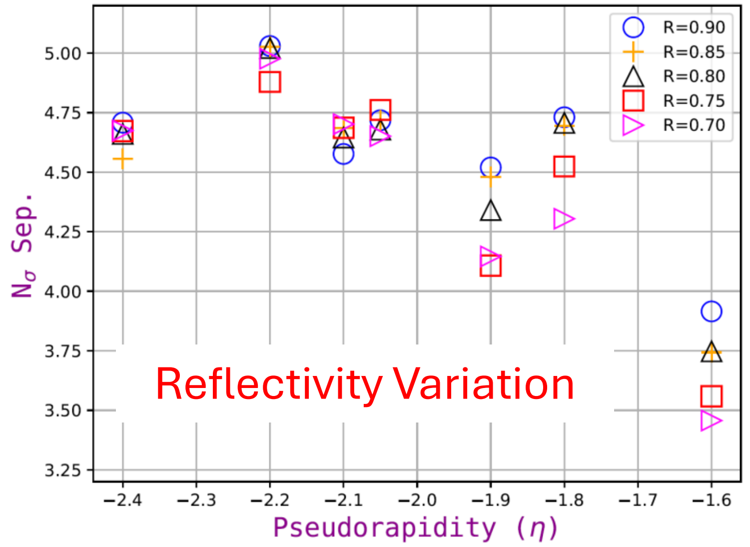


- ❑ All simulated evaluations of pfRICH design and performance have come from standalone model
- ❑ Priority now is to incorporate pfRICH geometry and reconstruction into global ePIC environment
- ❑ Will allow ultimate evaluation of dependency on ePIC tracking
- ❑ Collaborate with dRICH group, whose integration 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 > 3σ 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 hight: 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