The Proximity Focusing RICH at ePIC

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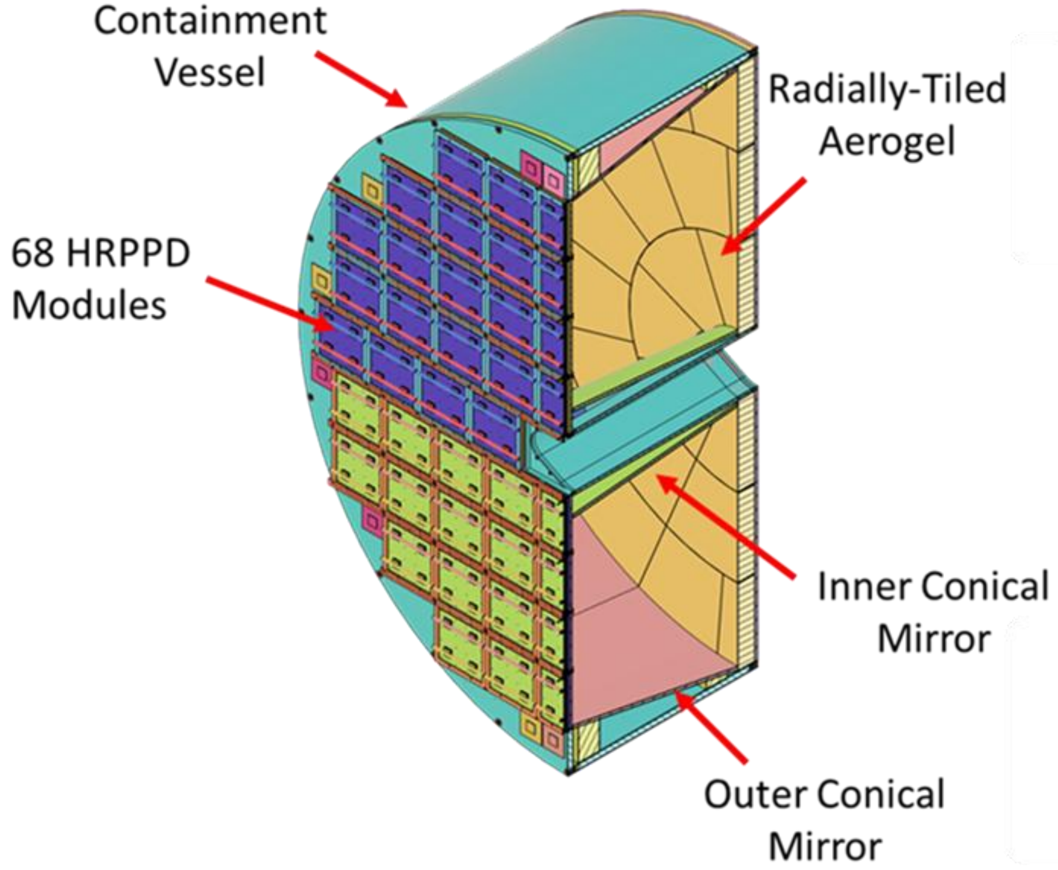
New Horizons with Fixed-Target Proton-Nucleus Experiments at Intermediate Energies

July 10th – 11th, 2025

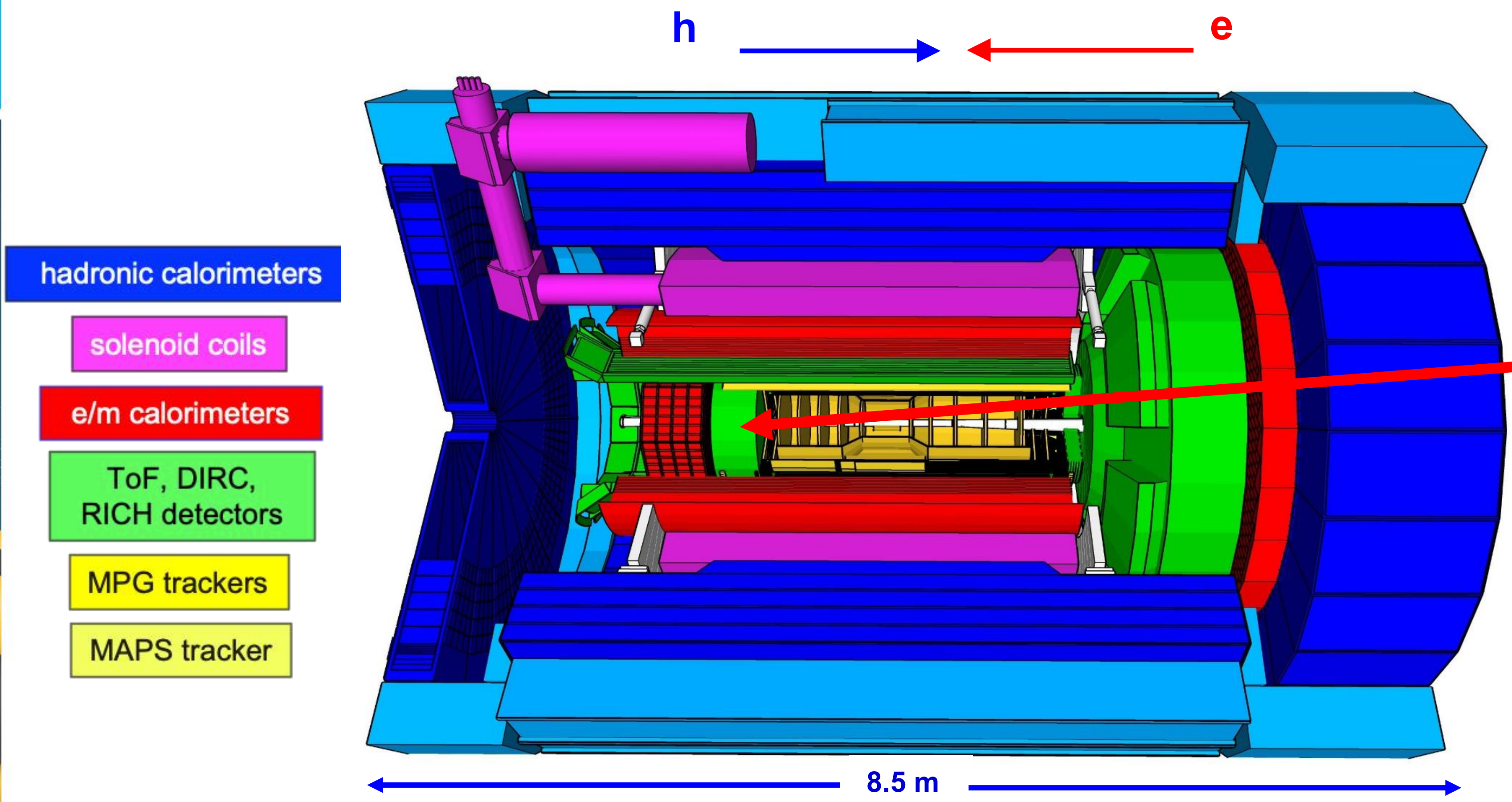
Electron-Ion Collider

Outline

- ❑ pfRICH Overview
- ❑ Subsystem Descriptions
  - ➢ Vessel
  - ➢ Sensors
  - ➢ Mirrors
  - ➢ Aerogel
  - ➢ Light Monitoring System
  - ➢ Services (HV/LV, cooling, gas)
- ❑ Simulation
- ❑ Timeline
- ❑ Test Beam



pfRICH at ePIC

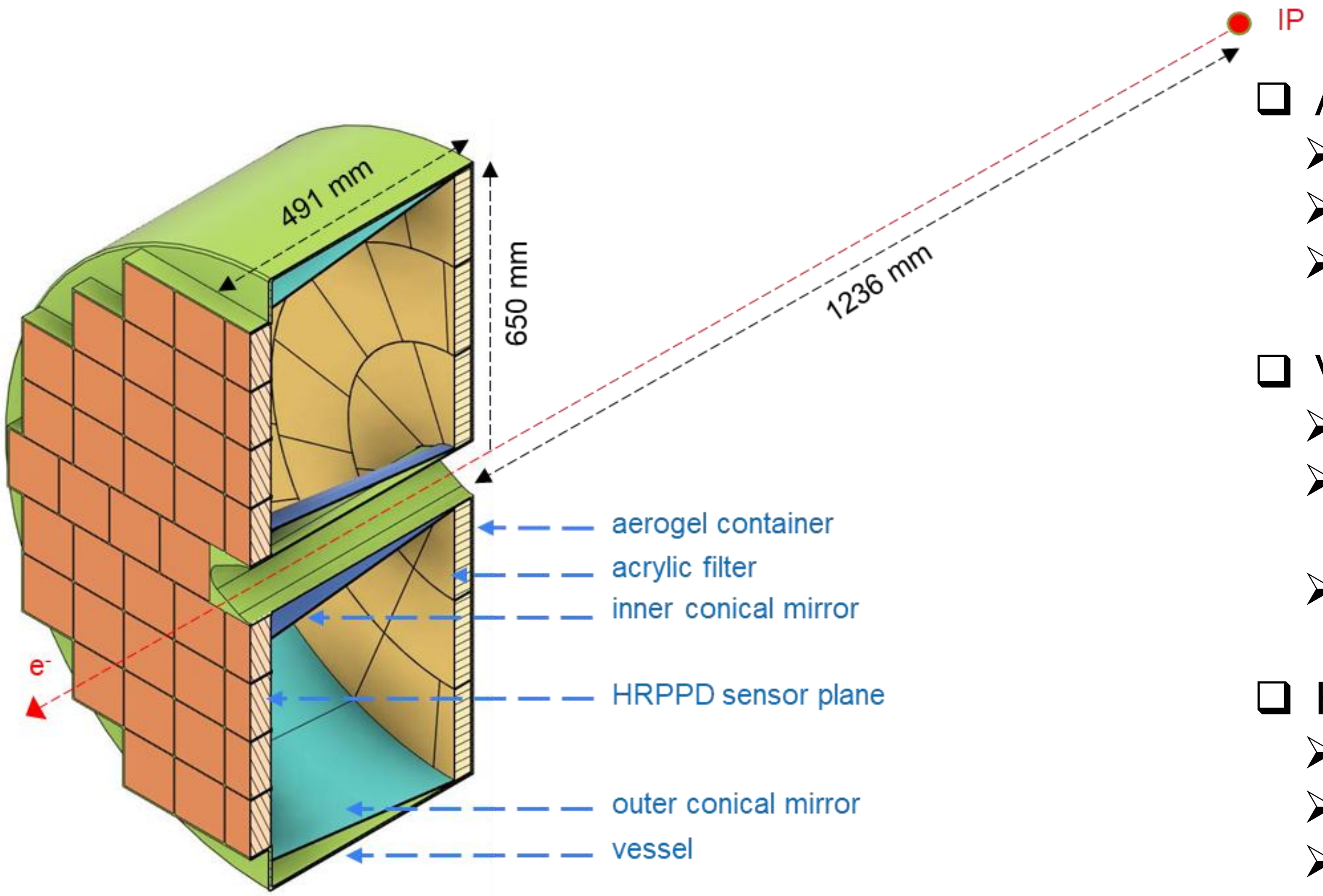


Tracking:
- New 1.7 T solenoid magnet
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:
- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal + HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Detector Design Summary

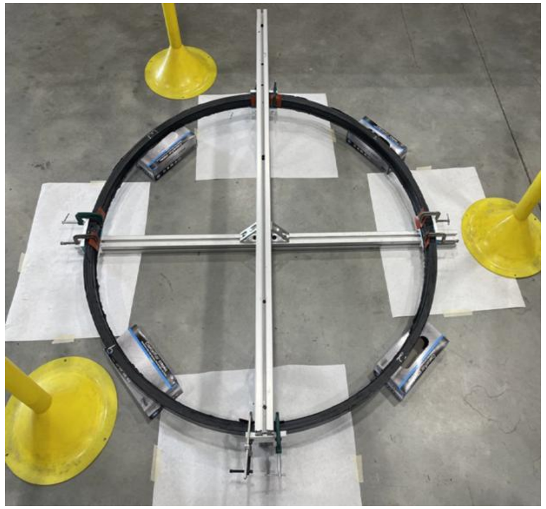


- Aerogel
  - Three radial bands
  - Opaque dividers
  - 2.5 cm thick, 42 tiles total
- Vessel
  - Lightweight structure
  - Reinforced carbon fiber and 3D printed materials
  - Filled with nitrogen
- HRPPD photosensors
  - 120 mm size
  - Tiled with a 3.0 mm gap
  - 68 sensors total

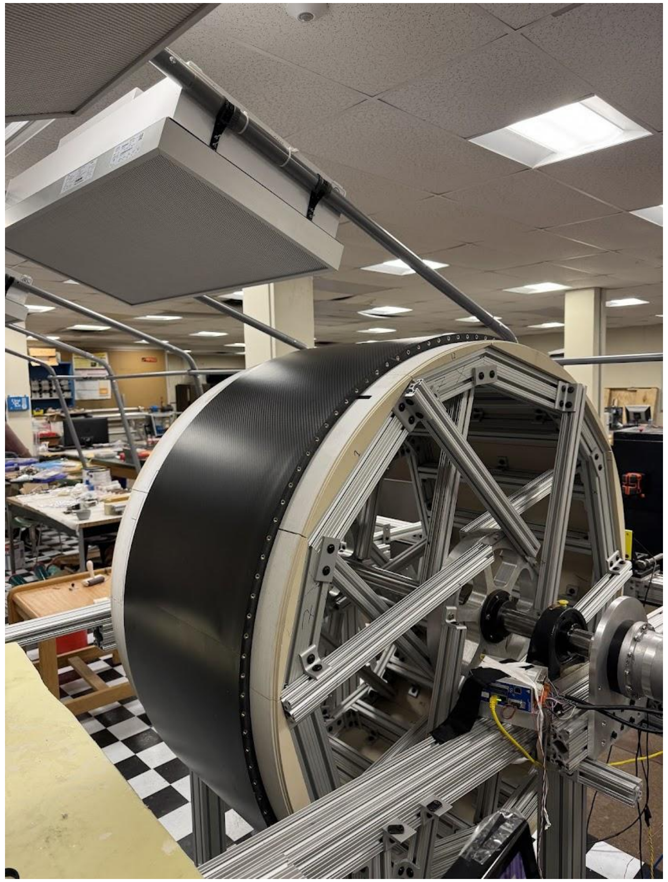
Chosen as a technology baseline for ePIC in April 2023

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

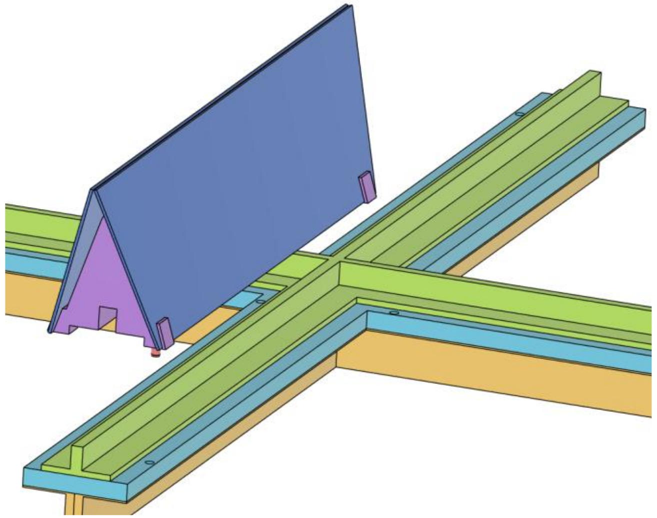


- Shape: 1/2” thick cylinder (12.7 mm)
- Outer Diameter: 1300 mm
- Length: 491 mm
- Precision: < 1 mm radius and length (Dedicated metrology and visual checks)
- Technology: Carbon-fiber composite material with nomex honeycomb core

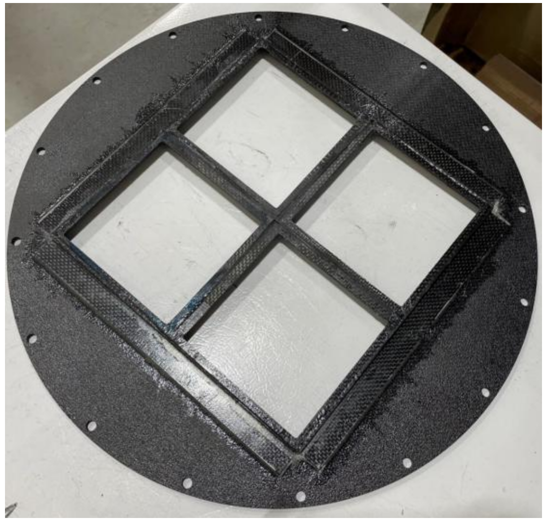


Vessel Components And Fabrication

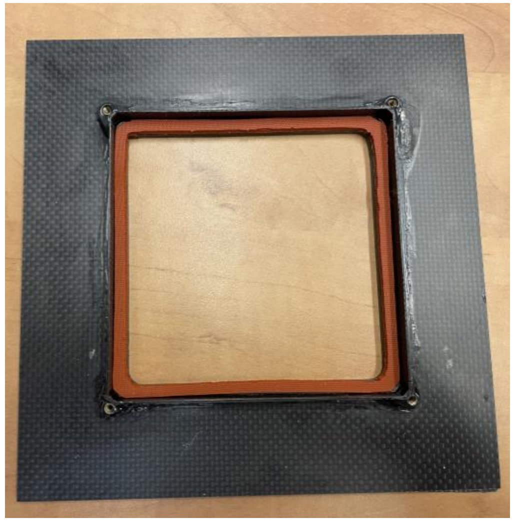
Sensor Plane Model



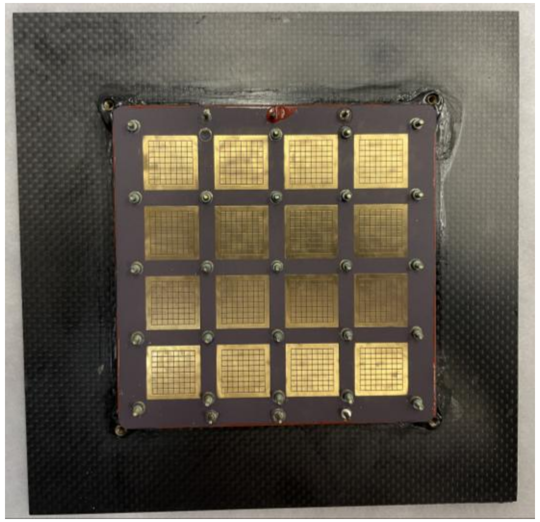
Test Windowpane Unit



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)

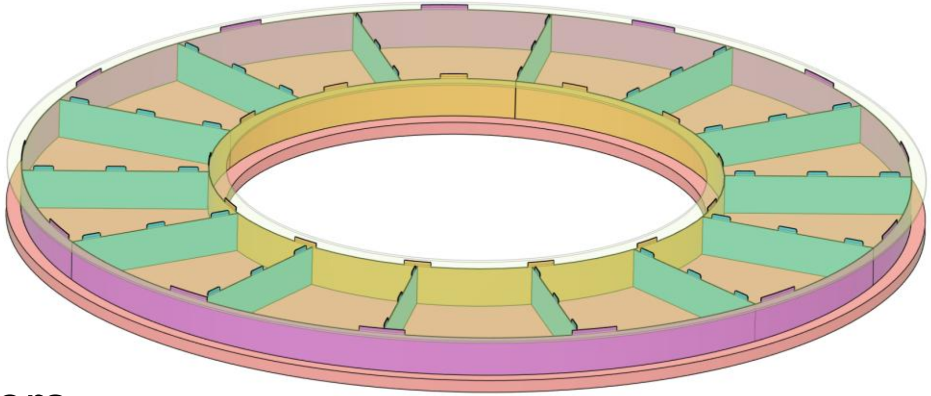
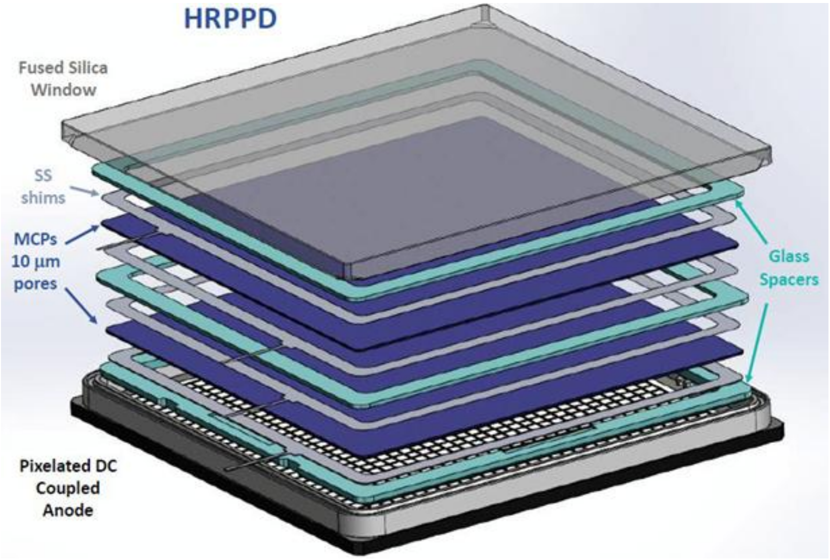
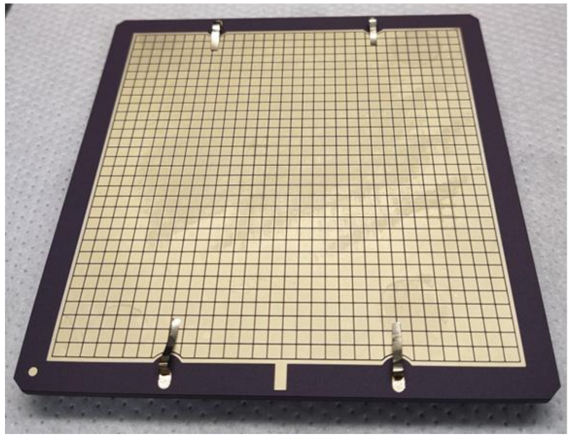


Photo-Sensors

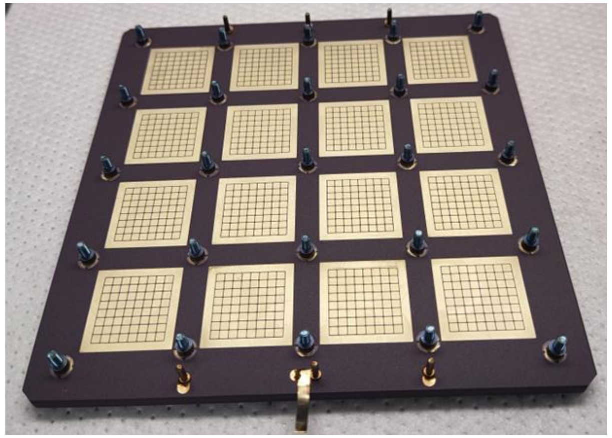
- Basic requirements:
  - Provide a timing reference at the level of ~20 ps for the barrel and forward ToF subsystems
  - Provide spatial resolution ~1mm
  - Have small Dark Count Rate
  - Have reasonable power dissipation in mW per channel
    - a low material budget cooling system in front of the PWO 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



Anode plate vacuum side

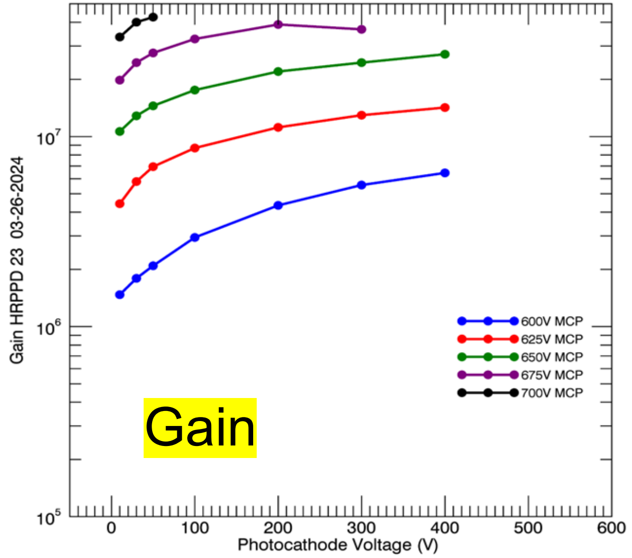


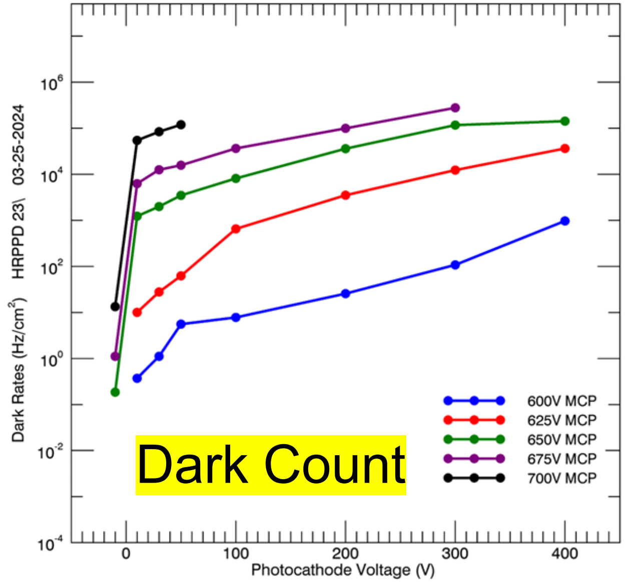
Anode plate air side

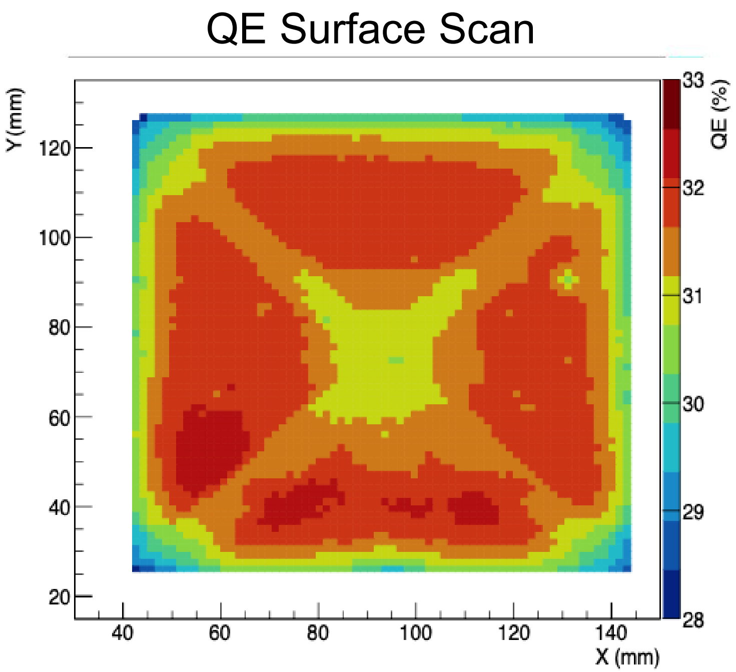


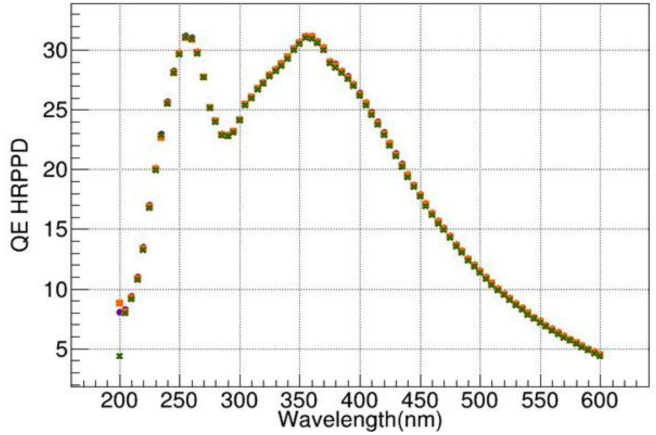
- **Photosensor: HRPPD by Incom Inc.**
  - High intrinsic SPE timing resolution
  - High Quantum Efficiency
  - Low Dark Count Rate (compared to SiPMs)
  - Low cost (compared to other MCP-PMTs)

HRPPDs: Performance

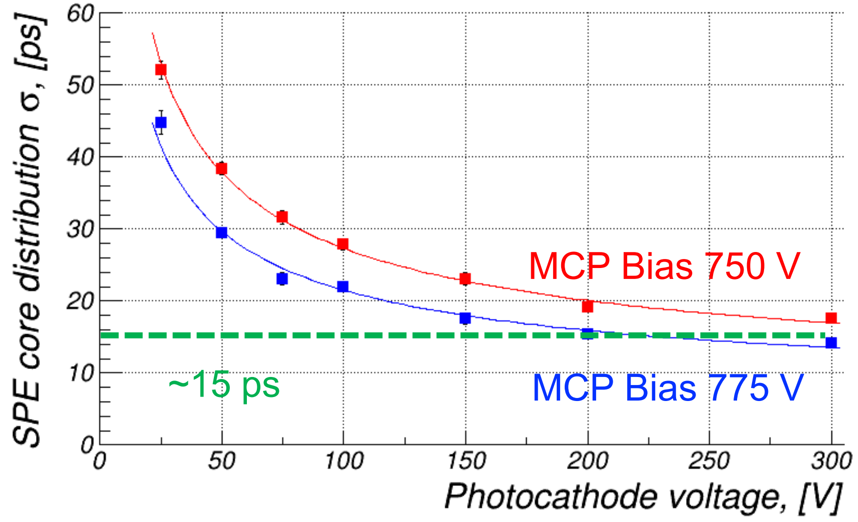






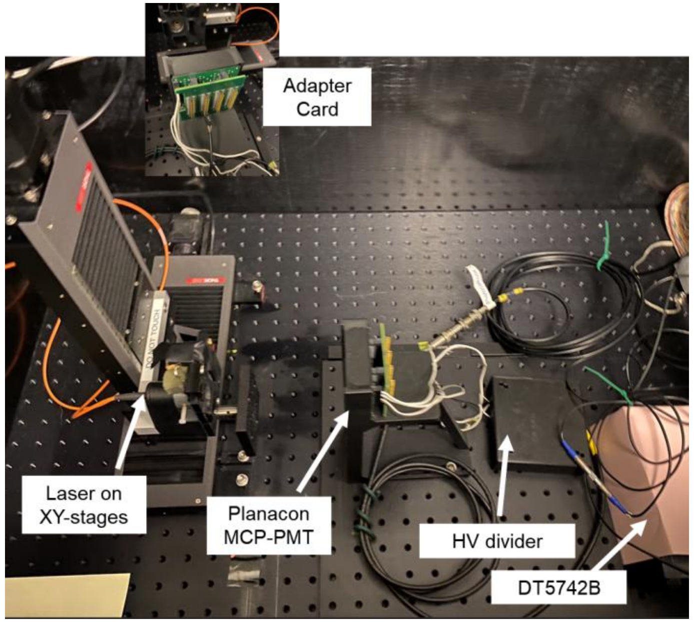


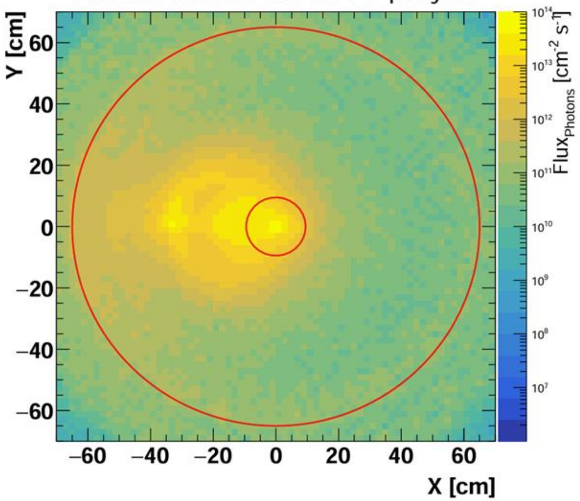
- HRPPDs demonstrate large gain at low MPC bias voltage with reasonable dark count rates (<1KHz for gains in the 10^6 region)
- Peak Quantum Efficiency above 30% with good uniformity over sensor surface
- Single photon timing resolutions ~15 ps for recommended bias and photocathode voltage working points

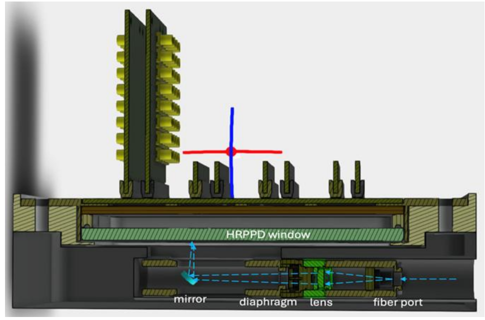


HRPPD Evaluation

- ❑ 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
- ❑ 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



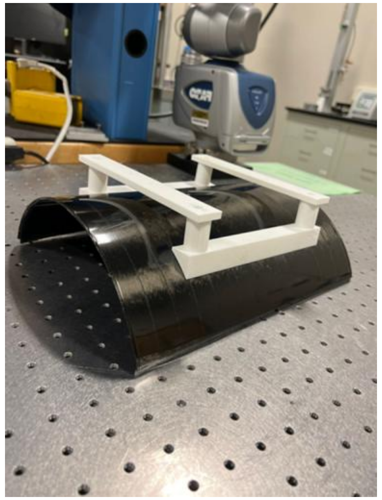


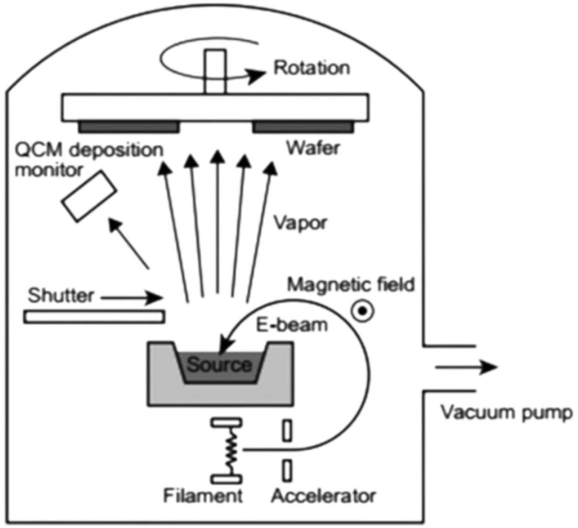


A type 18D72 2.2 Tesla dipole with a 6” gap

Mirror Fabrication

- ❑ 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





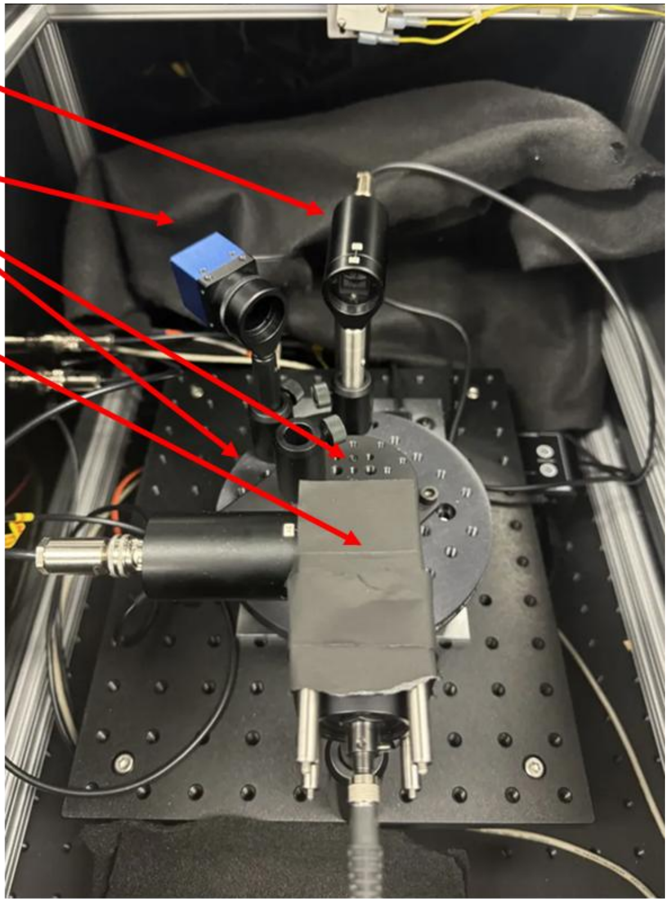
Rotating Fixture

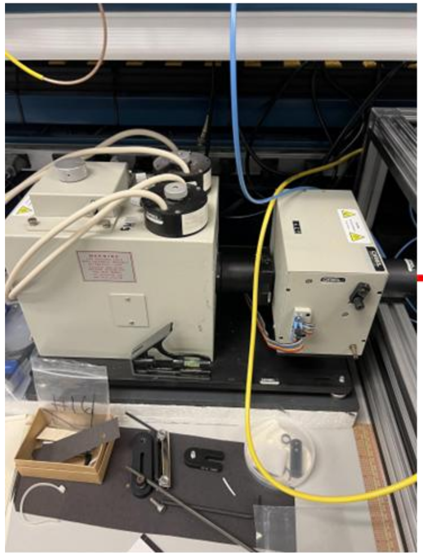
Quartz Crystal Microbalance

Remote Shutter

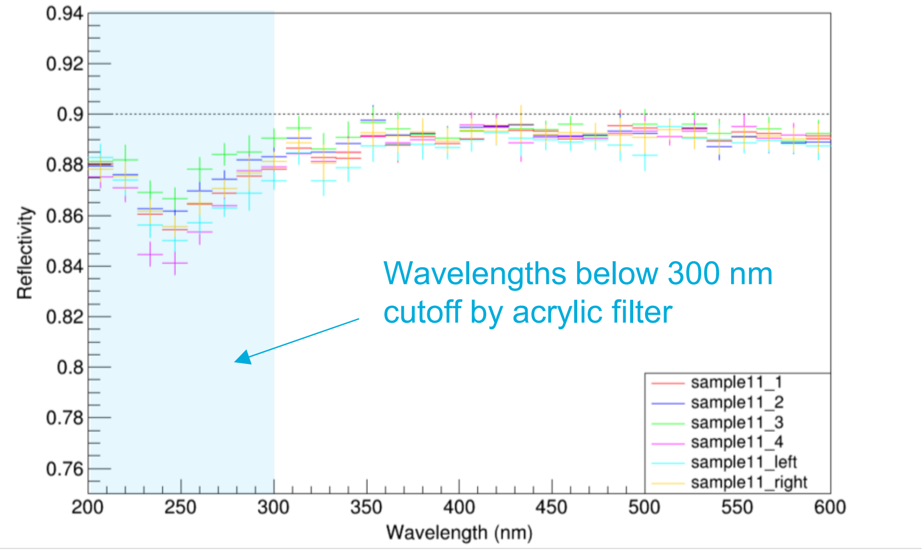
Electron Gun

Mirror Fabrication: Reflectivity Tests





Monochromator:
200 – 600 nm



- After coating at SBU, mirror sample reflectivity measured at BNL
  - Ballpark 90% reflectivity to ensure maximum reco efficiency for tracks at edge of acceptance – value used in simulation model
- Monochromator light source + dark box with camera/photodiode and sample holder on separate rotational stages
- Allowed for rapid evaluation of coating mixtures

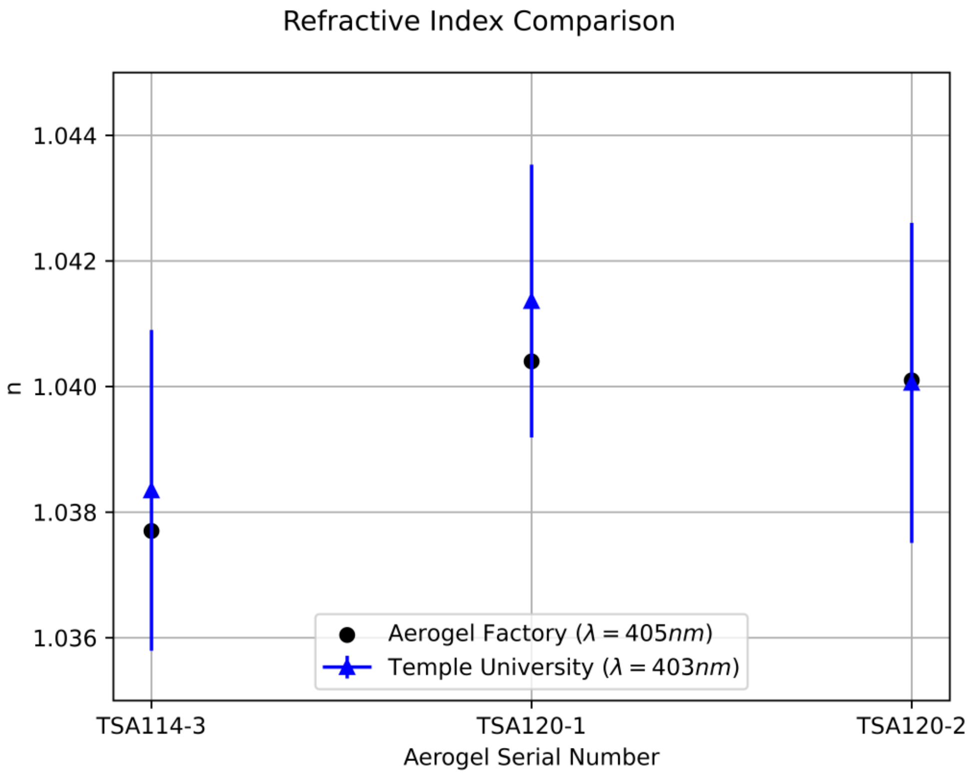
Choice Of Aerogel

- ❑ 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

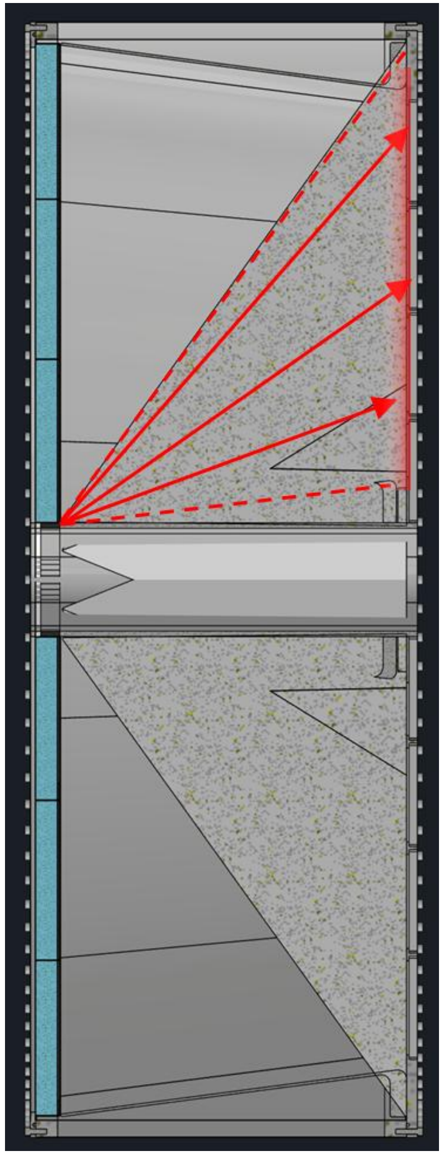
- ❑ Consider using a high n ~ 1.040
  - ➢ 300 nm acrylic filter cutoff for imaging
  - ➢ $\langle N_{pe} \rangle$ ~ 11-12

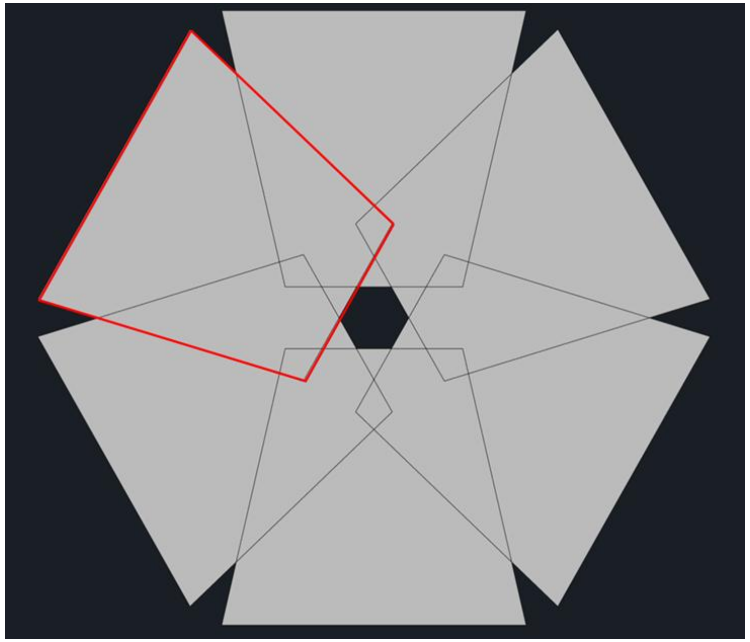
  - ➢ *For ToF still make use of the UV range for abundant Cherenkov light produced in the window*

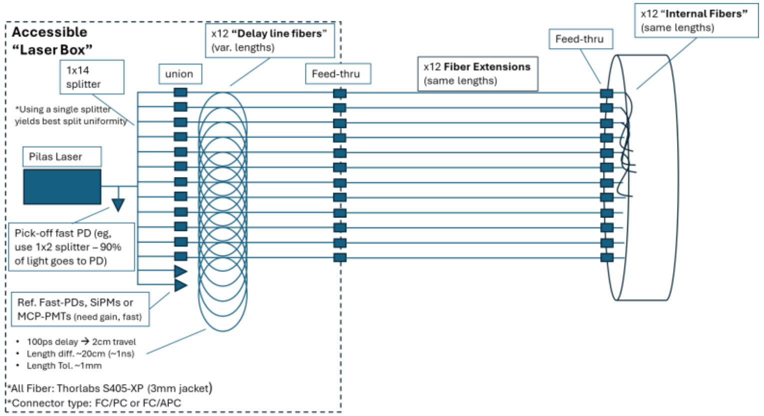
  - ➢ Natural hardware reference: Chiba University aerogel (n = 1.040)
  - ➢ 3 sample tiles have been purchased
  - ➢ Extensive characterization / QA by Temple University group
  - ➢ Confirm manufacturer specs and develop QA procedures



Light Monitoring System

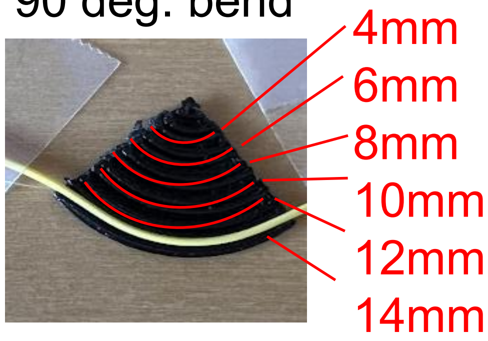


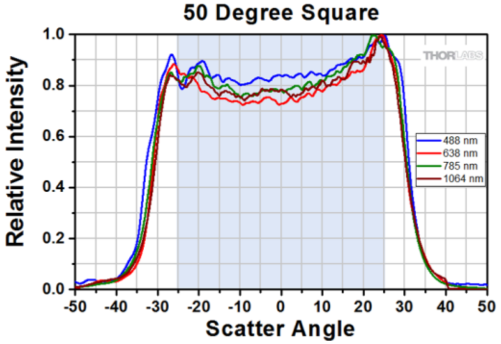




- ❑ Want a way to monitor HRPPD timing performance, signal amplitude, QE, and mirror reflectivity over the lifetime of the experiment
- ❑ Introduce an array of 12 optical fibers from the aerogel side of the vessel: 6 illuminate the photosensors directly and 6 bounce light off mirrors first
- ❑ Distance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

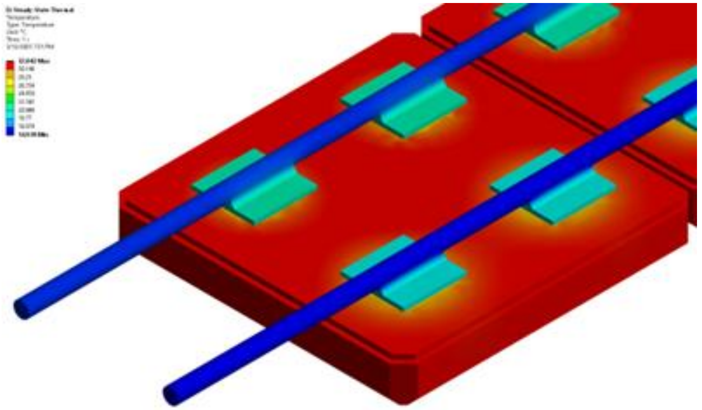
90 deg. bend



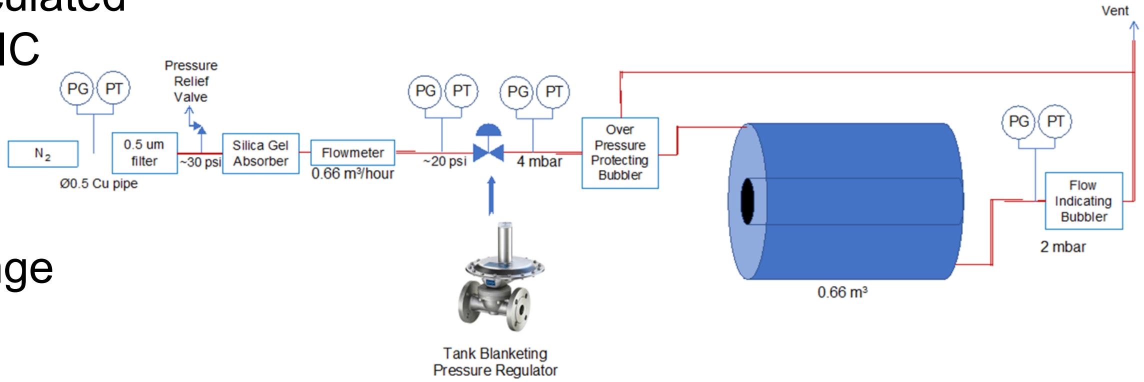


Services

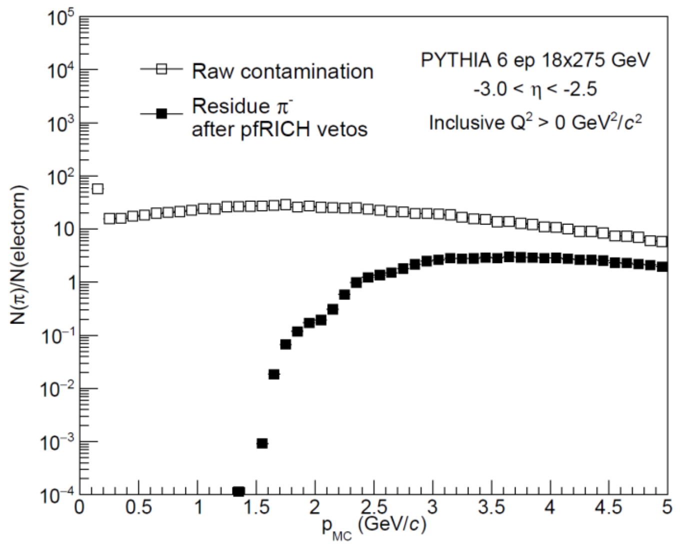
- ❑ HV system components have been identified and initial layout explored
- ❑ LV power system designed assuming 4 EICROC (256 chs/chip) per HRPPD – will be reevaluated once FCFD parameters available
  - ➢ 1024chs/sensor x 3mW/ch = ~3W/sensor -> @ 1.2V = 2.5A per sensor
  - ➢ 68 sensors x 2.5A = 170A 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

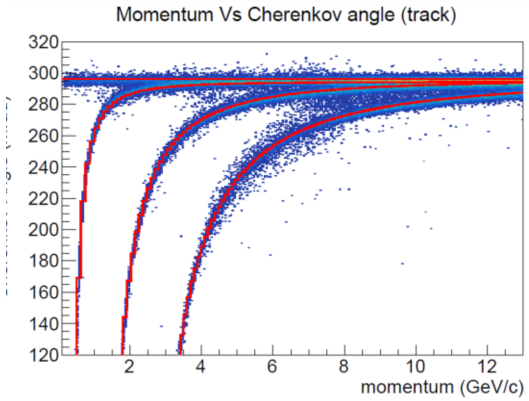


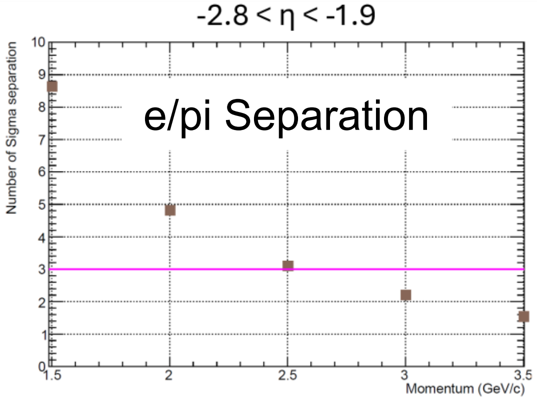
- ❑ Cooling system designed to handle power dissipation calculated above – may require mechanical redesign for different ASIC formfactor
- ❑ Gas system designed to supply nitrogen (grade to be determined) at slight overpressure with ~1 volume exchange per hour

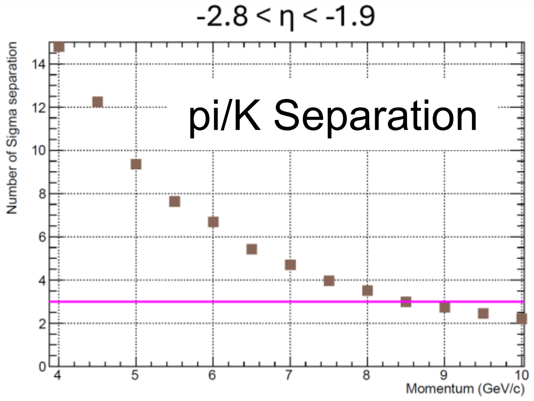


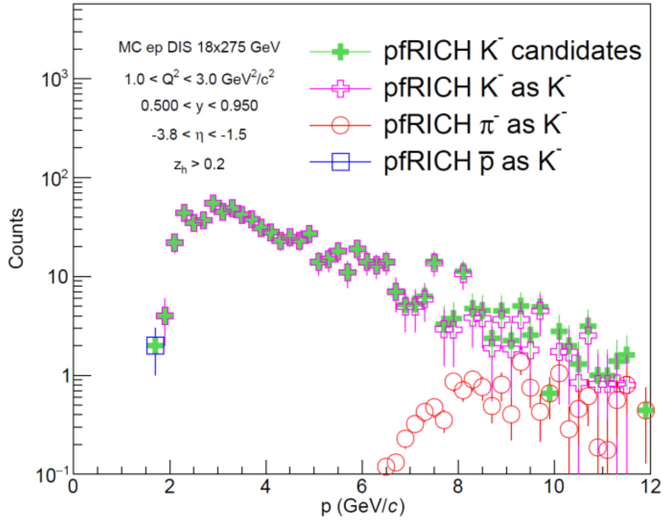
Performance Simulation











- ❑ Validate detector design choices and evaluate performance with standalone GEANT4 model including relevant optical effects
- ❑ 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

Near-Term Goals And Timelines

- Near-term goal for first article vessel fabrication includes components needed for upcoming test beam evaluations
  - Vessel shell and end-rings complete by beginning of May 2025 (Done!)
  - Sensor plane (5 HRPPDs) and Aerogel wall (3 aerogel tiles) complete by summer 2025
- Curved mirror substrates (2 outer and 1 inner mirrors) expected from Purdue by early summer 2025
  - Several weeks likely needed to coat
- Completion of full-sized mirror QA station expected by summer 2025
- Alternative test opportunities
  - Cosmic ray test stand at SBU (in collaboration with hpDIRC) to test aerogel + HRPPD + ASIC
  - CRT evaluations on order of 1 year from now

Test Beam Thoughts

Test Beam Goals:

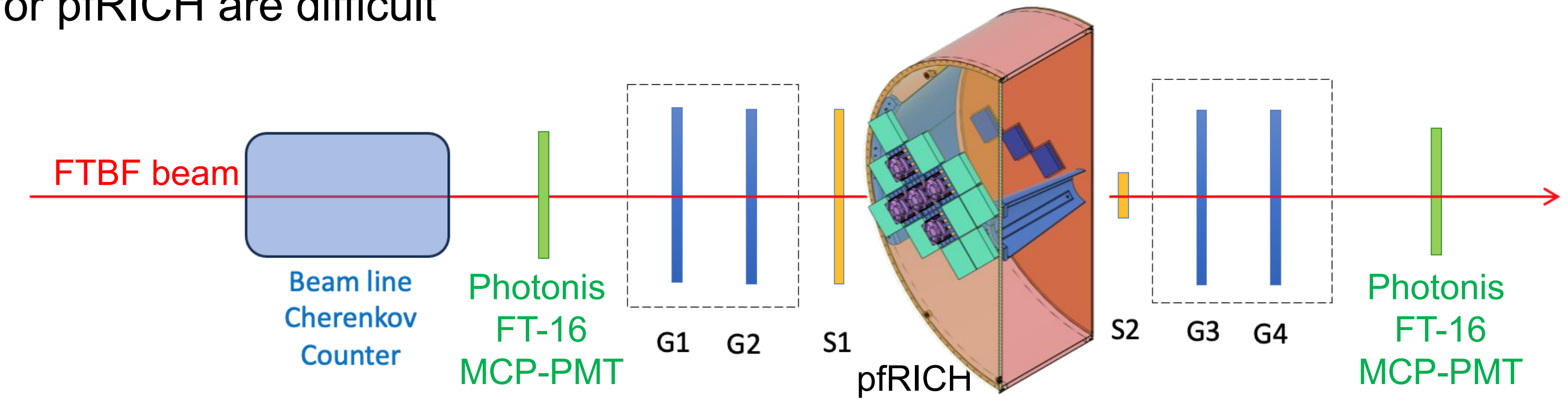
- ❑ Evaluate the aerogel + HRPPD + proximity gap performance
- ❑ Confirm pi/k separation reach (imaging) and high-resolution timing performance

Test Beam Status relevant for pfRICH:

- ❑ Fermilab test beam facility is unavailable for an unknown amount of time
- ❑ CERN can provide hadronic test beam, but logistics for pfRICH are difficult

Timelines:

- ❑ pfRICH test article will be ready this summer/fall
- ❑ Possibility for cosmic ray test at SBU in conjunction with hpDIRC in ~1 year
- ❑ CD3 decision (start of construction) envisioned for 4th quarter CY 2027 - less need for test beam as construction progresses



Summary

- Passed 60% Project Design Review at the end of April
- pfRICH technical performance requirements well defined and achievable with current detector design
- Design of pfRICH subcomponents well understood
- Fabrication of vessel engineering test article underway with completion by summer/fall 2025
- Standalone simulation model confirms design meets requirements and work on integration into ePIC simulation ongoing
- Test beam validation will be difficult due to facility availability, but extensive bench tests and possible CR test stand provide potential alternatives


QUESTIONS


BACK UP

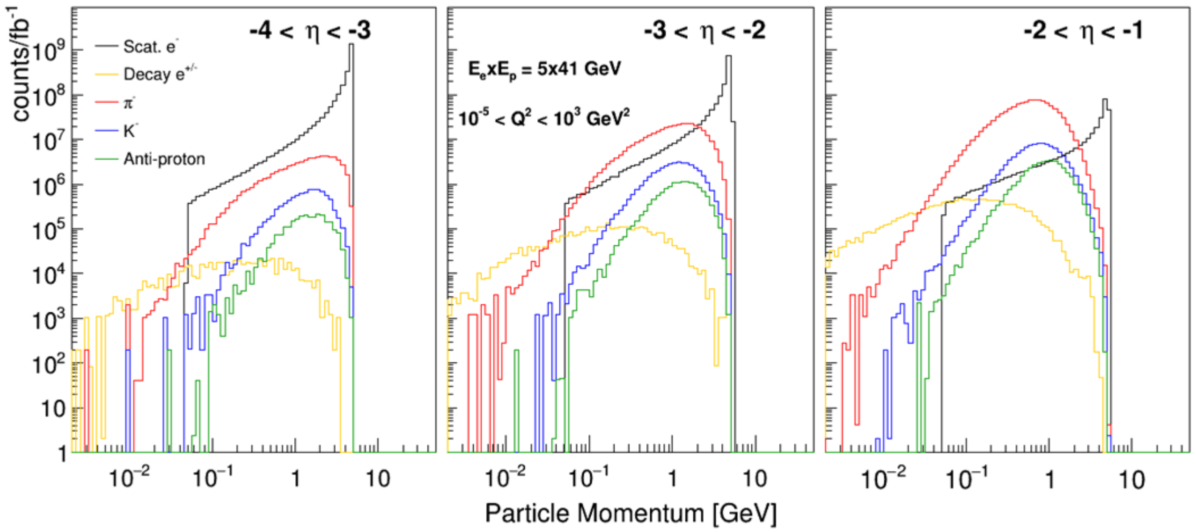
Requirements

SCIENCE REQUIREMENTS
AND DETECTOR
CONCEPTS FOR THE
ELECTRON-ION COLLIDER

EIC Yellow Report

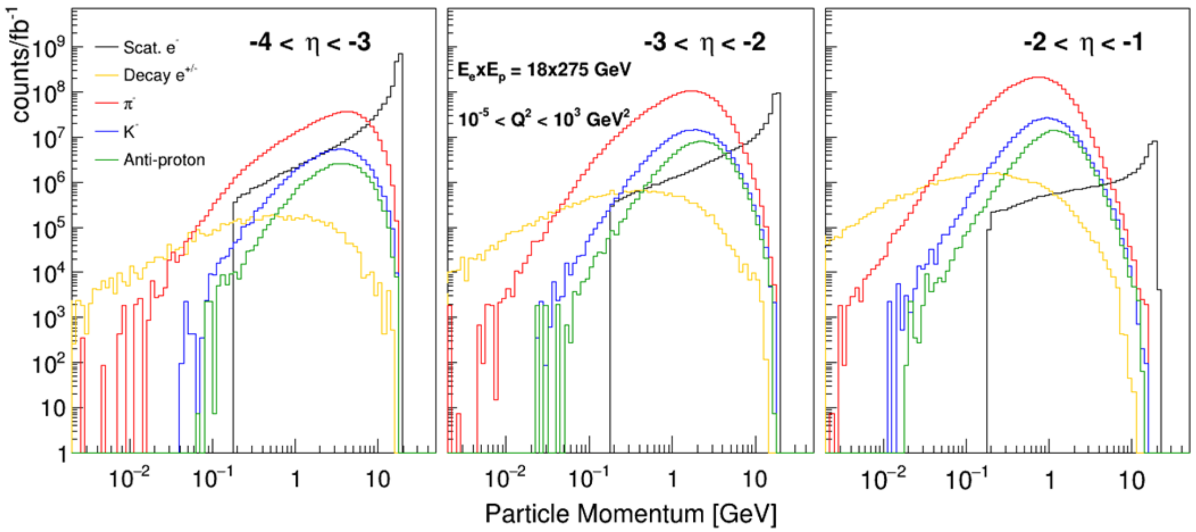
- ePIC backward RICH must provide PID coverage in the eta range determined by the reach of the barrel DIRC and the acceptance of the crystal calorimeter in the e-endcap, therefore ~ -3.5 < eta < ~ -1.65, at a minimum
- Yellow report requirement: 3σ π/K separation up to 7 GeV/c

Particle Momenta Spectra in pfRICH Acceptance



5 x 41 GeV

- Momentum dependency of p/K/p distributions is similar
  - With a p:K ratio ~3
- There is not much above ~7 GeV/c, especially at lower beam energies

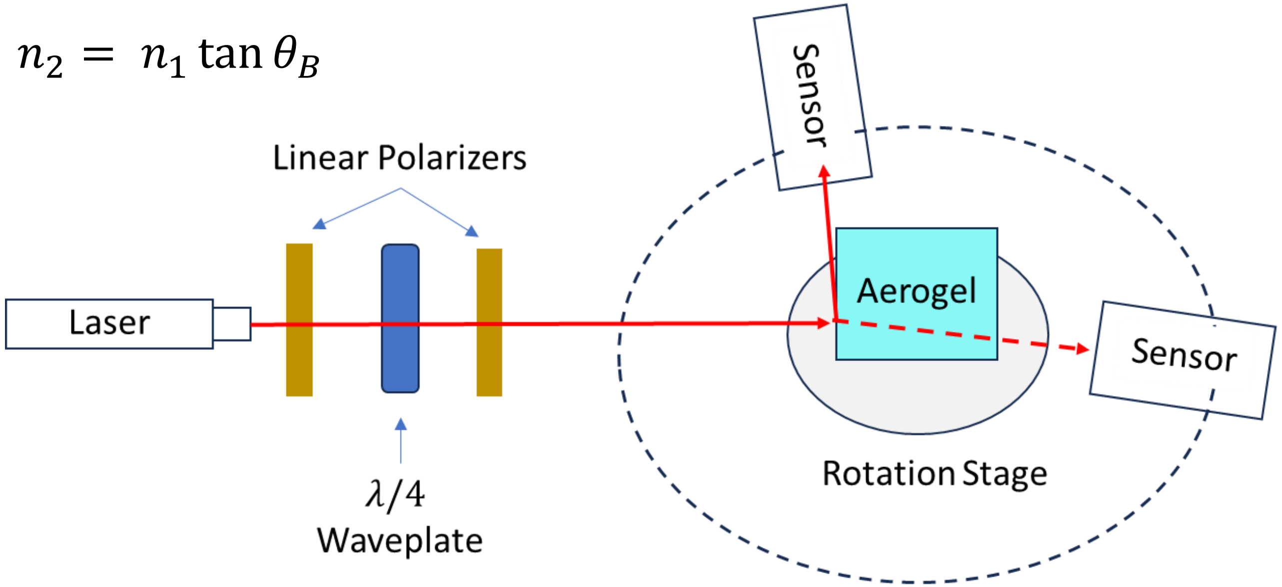


18 x 275 GeV

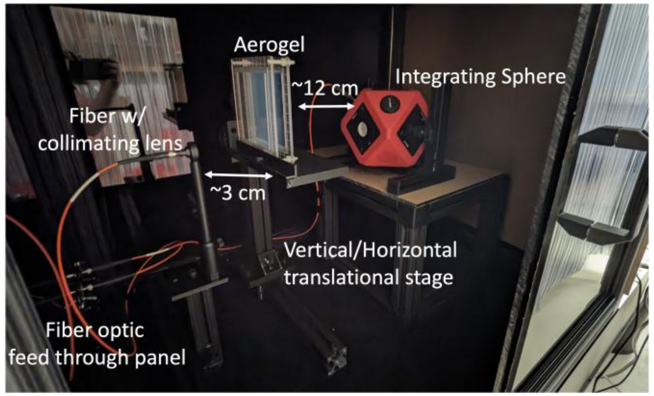
Aerogel Evaluation

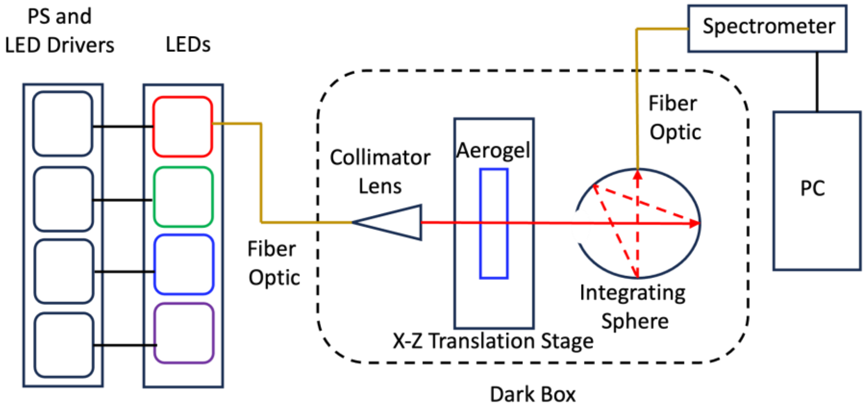
Schematic setup for Brewster's angle measurement

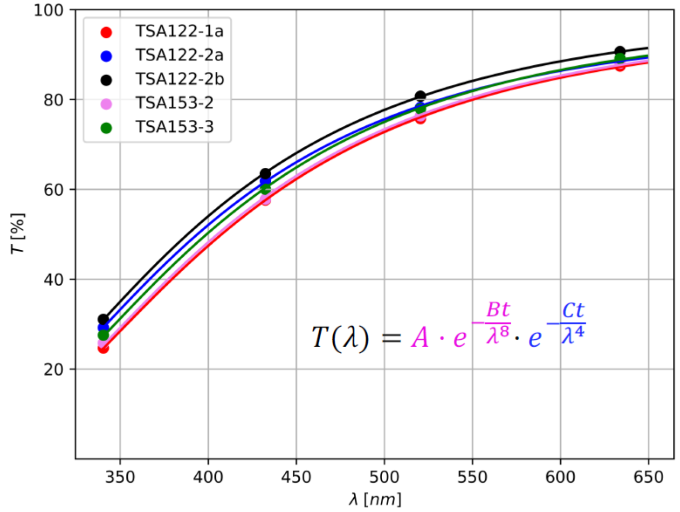
$$n_2 = n_1 \tan\theta_B$$



- Aerogel tile QA being carried out at Temple University (M. Posik)
- 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

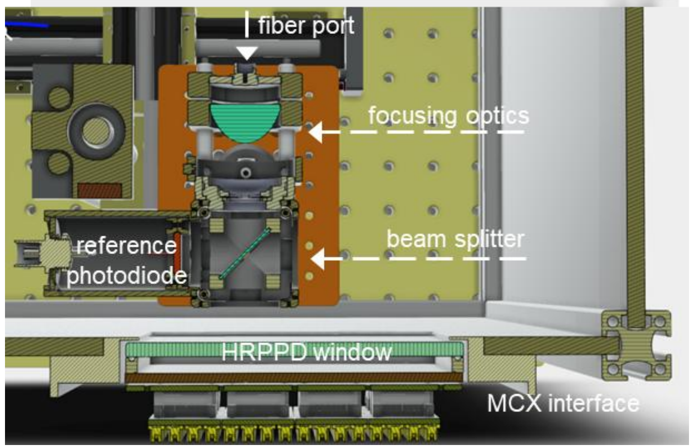


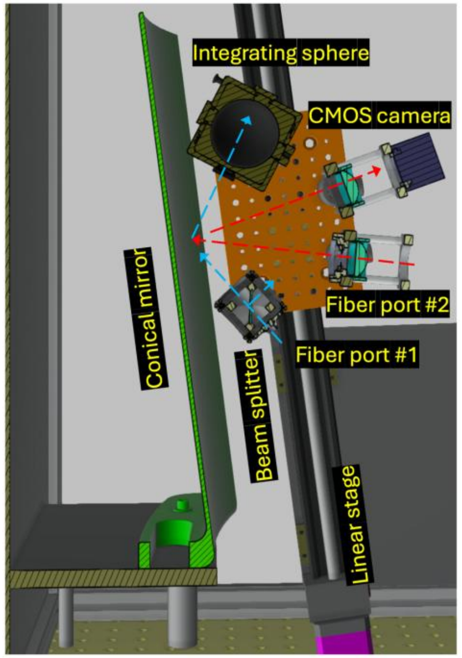




Component Quality Assurance

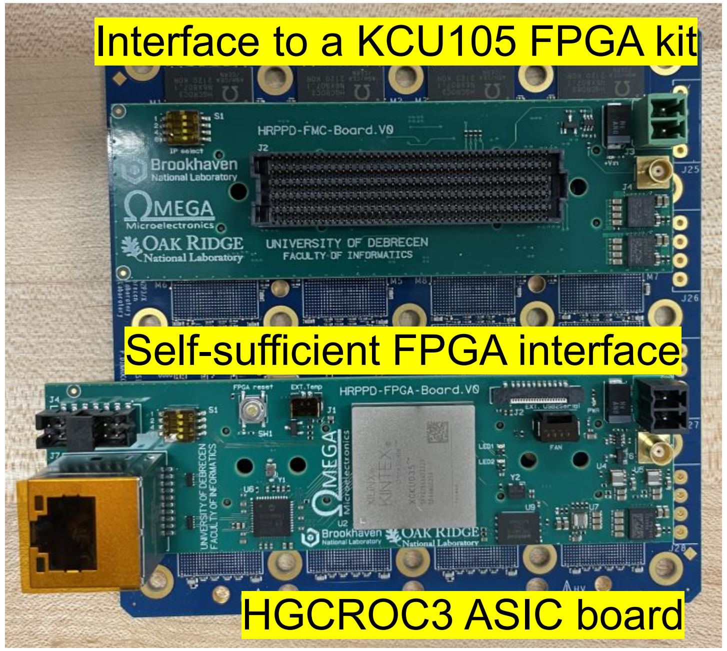
- Plan is to QA all sensor, aerogel, and mirror units which will go into pfRICH
  - In-situ monitoring of mirror and HRPPD performance accomplished by laser monitoring system
- HRPPD QA
  - 2 test stands suitable for EIC HRPPD evaluation exist
  - Check each sensor for quantum efficiency, photon detection efficiency, gain, dark count, and mechanical / assembly integrity
- Aerogel QA
  - Will be carried out at Temple University
  - Check each tile for refractive index, transmittance, physical dimensions
- Mirrors
  - Mirror QA will be carried out using scanning station at BNL
  - Produce map of reflectivity over mirror surface and measure actual curvature





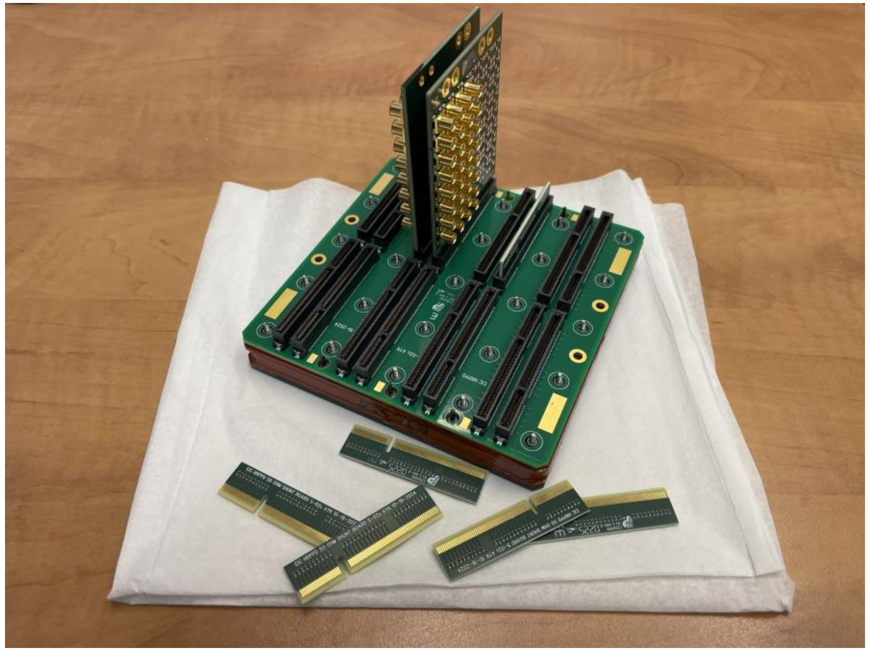
Readout Electronics

Present concept: ASIC backplane



- ❑ Work in progress before FCFD ASIC available
- ❑ Synergy with ePIC calorimetry (LFHCal) - same HGCROC3 ASIC & a very similar FPGA interface
- ❑ A possible synergy with hpDIRC (CRT), to have early performance data with real particles

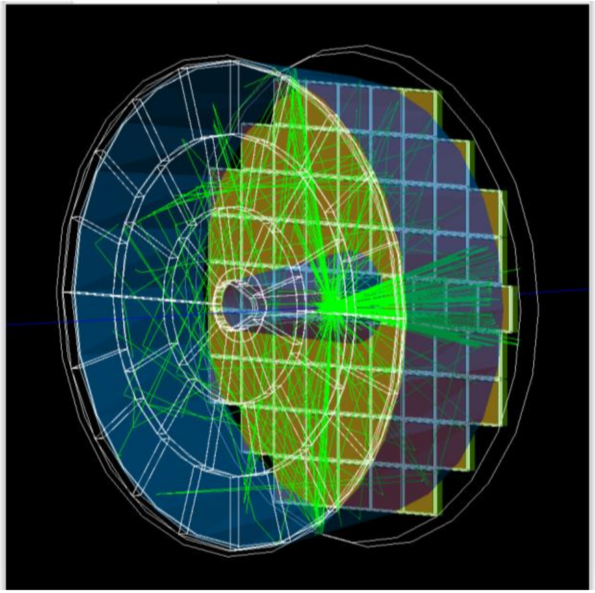
Alternative layout: passive backplane + plugin cards

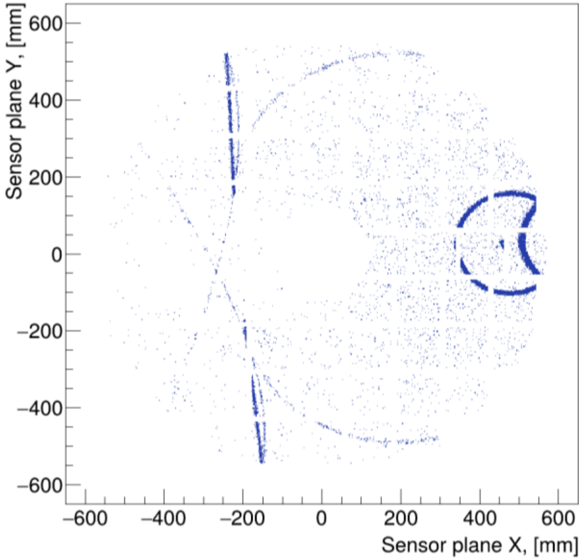


- ❑ Interface to Xilinx KCU105 FPGA kit is functional
- ❑ Interface with FPGA backplane needs more work
- ❑ Once this is functional, we'll check it with real HRPPD signals and see how to proceed further
- ❑ Picture on the right (passive interface) shows an alternative backplane for lab studies with a potential ASIC plugin card formfactor

Interface With ePIC Simulation Environment and dRICH

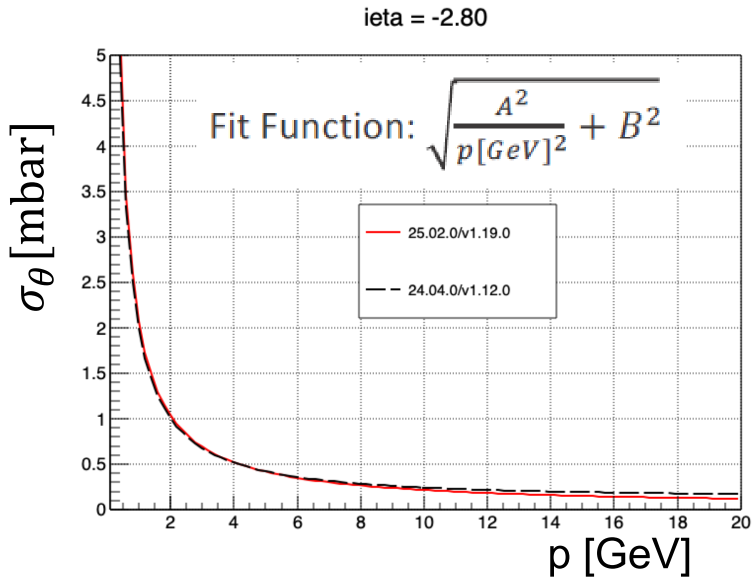
- Move pfRICH simulation and reconstruction from stand-alone implementation to global ePIC framework
- Will allow ultimate evaluation of dependency on ePIC tracking and impact of background on reconstruction
- Leverage synergies with dRICH group, whose integration needs are very similar to the pfRICH
  - Combine workforce
  - Unified geometry / optical properties descriptions
  - Common reconstruction algorithm
  - Common output data format
- Substantial progress on geometry and readout has been made
  - pfRICH and dRICH geometries with mirrors and individual sensors integrated
  - Digitized hits from sensors can be accessed from ePIC framework
  - Common reconstruction algorithm and diagnostic scripts implemented
  - Further development: establish format and content of a common PID data model

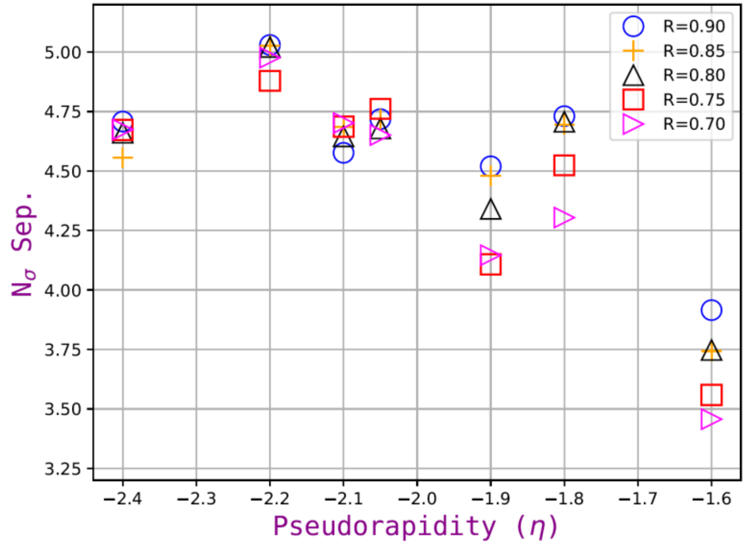




Simulation Parameters

- 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
- See backup for list of other relevant parameters

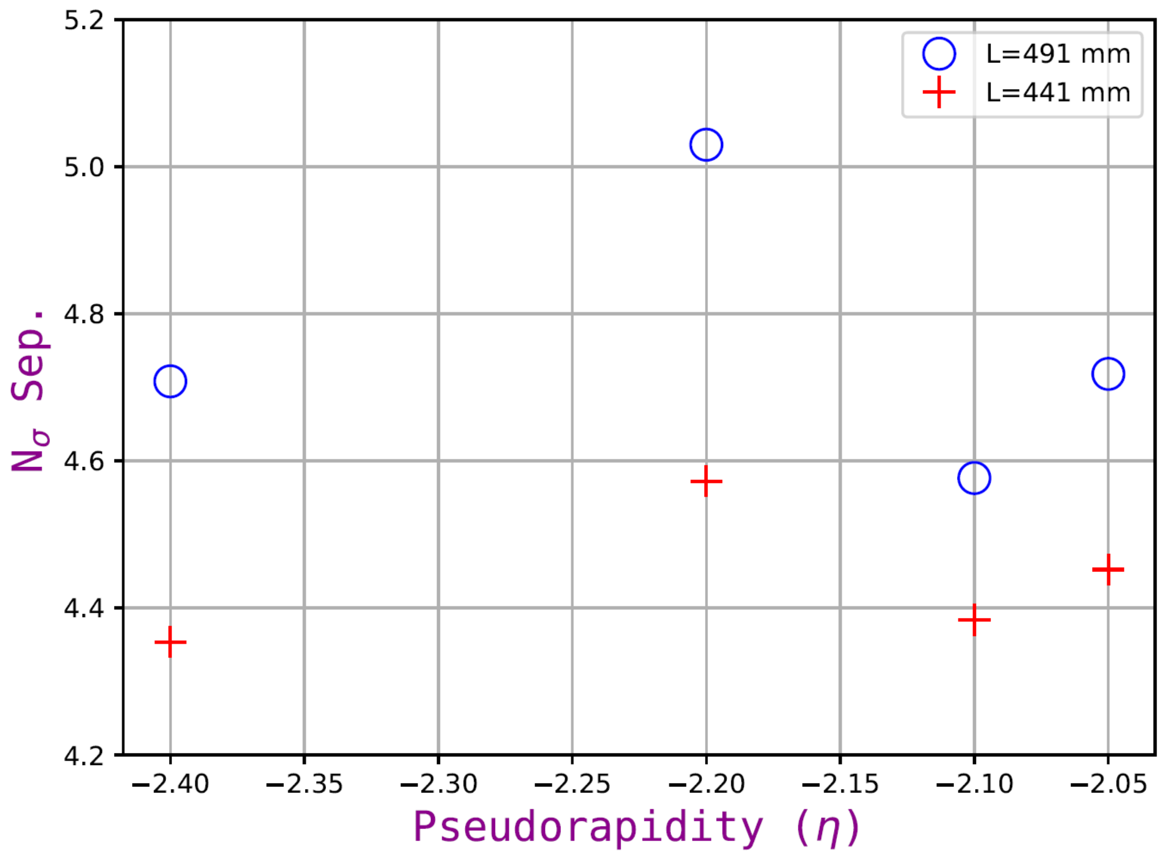




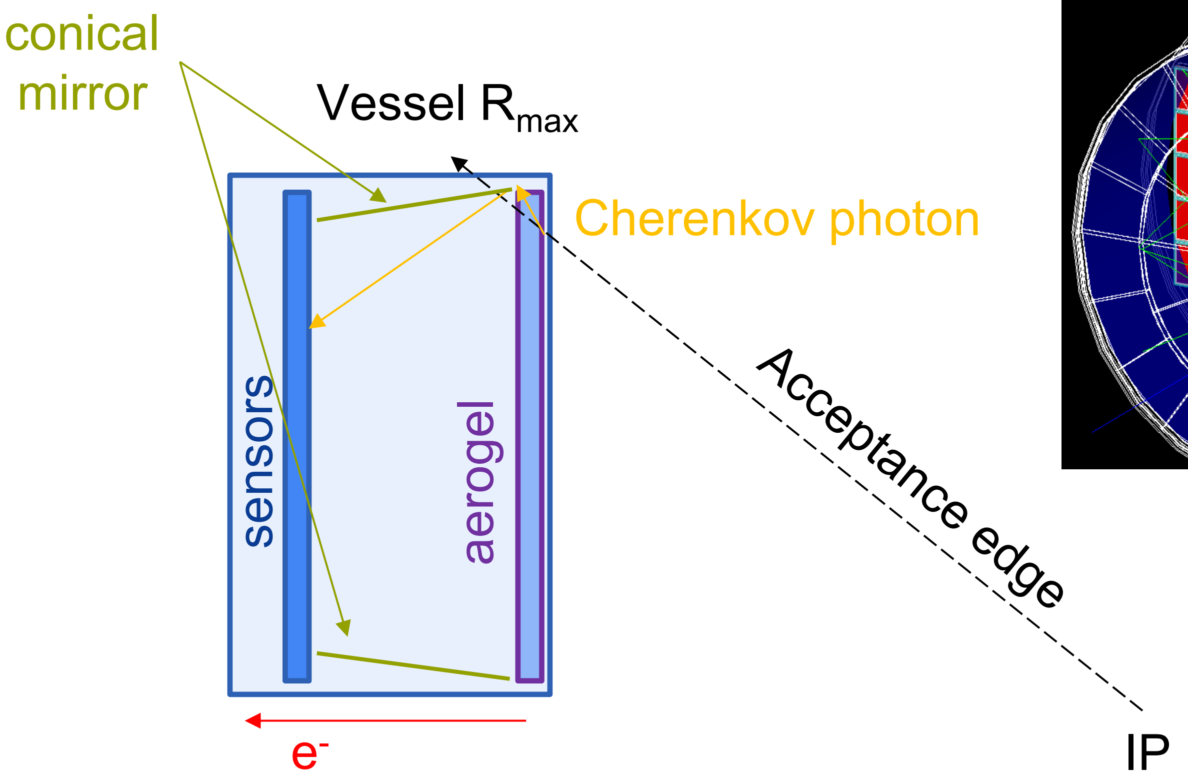
Simulation Parameters

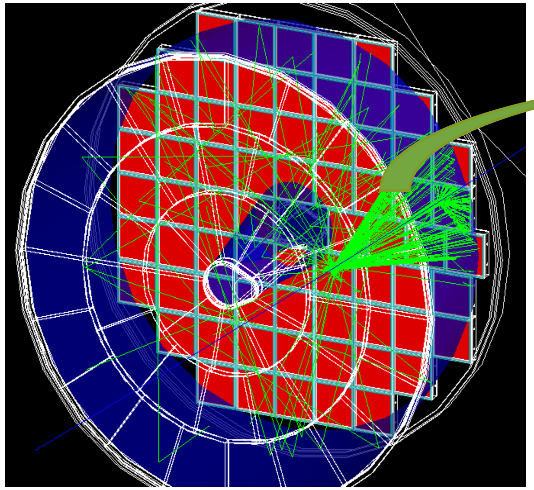
- The standalone simulation model contains several parameters directly relevant to the pfRICH performance
  - Mirror reflectivity: 90%
  - Pyramid mirror hight: 30 mm
  - Primary vertex z smearing: 35 mm
  - ePIC B-field map
  - Proximity gap length: 491 mm
  - Aerogel refractive index: 1.040
  - Aerogel thickness: 2.5 cm
  - HRPPD window thickness: 5 mm
  - HRPPD window material: fused silica

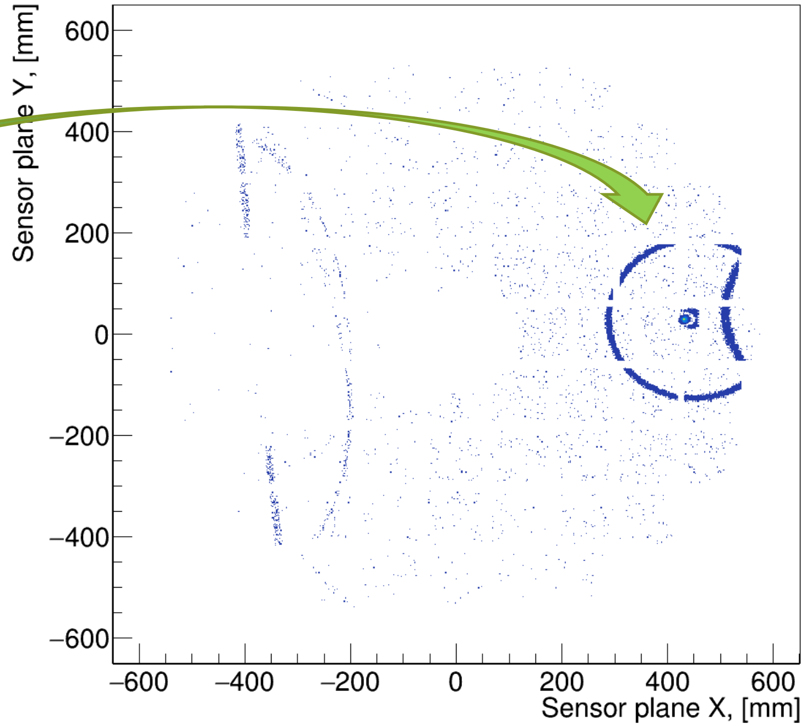
- Reducing proximity gap by 50 mm reduces π/k separation power by 5 to 8%



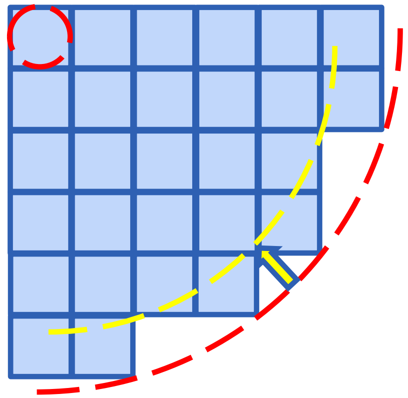
Angular Acceptance Optimization





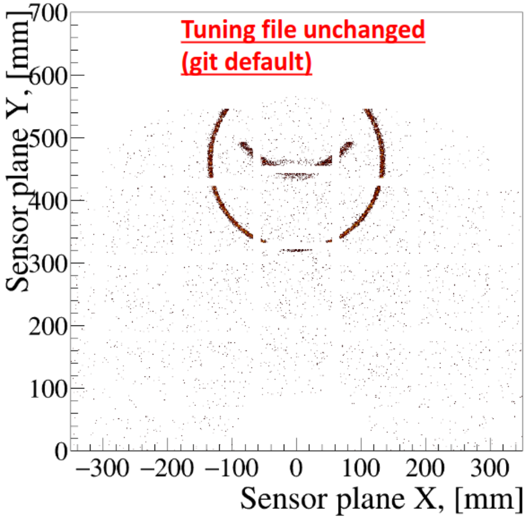


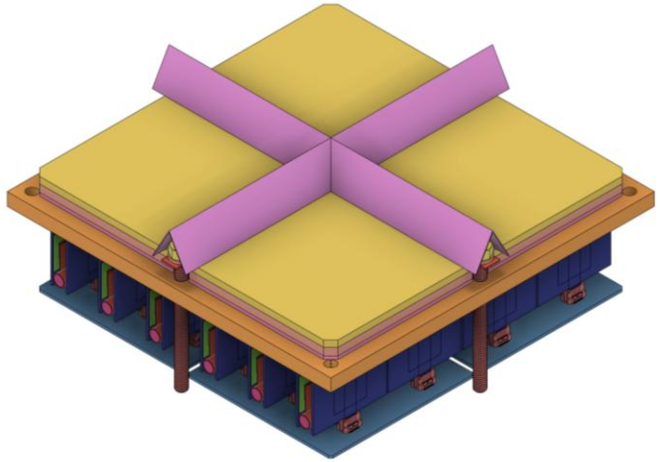
- Use side wall mirrors to increase η acceptance
  - Achieve $-3.5 < \eta < -1.5$ coverage (hence overlap with the DIRC)
  - Make mirrors *conical* to avoid inefficiency on the sensor plane

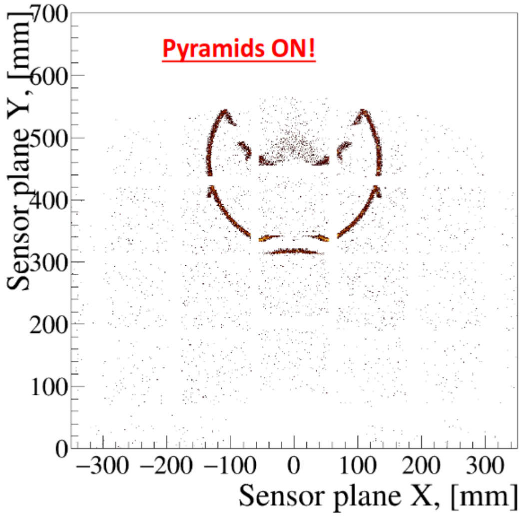


Performance enhancements

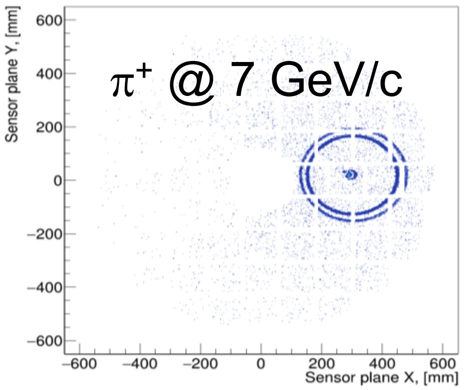
- Installation of small funneling mirrors around each sensor dead area boundaries







- Use of a dual aerogel configuration

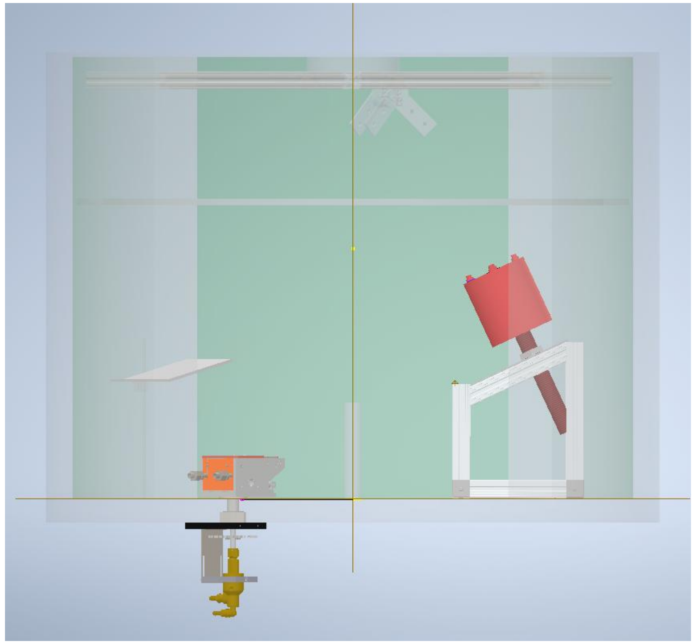


- Both options implemented in software
- Both give a substantial increase in photon yield

- Recently added to the baseline configuration as a consequence of a complex ePIC detector tracker optimization (pfRICH expansion volume was shortened by ~5cm)

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%

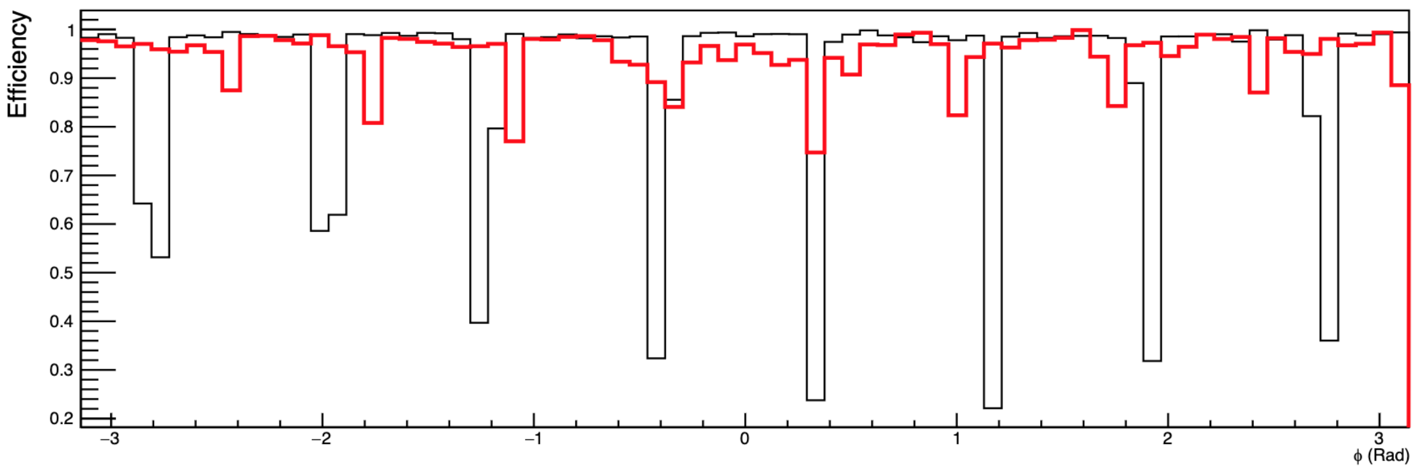
Future Improvements:

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

Geometric efficiency for timing purposes

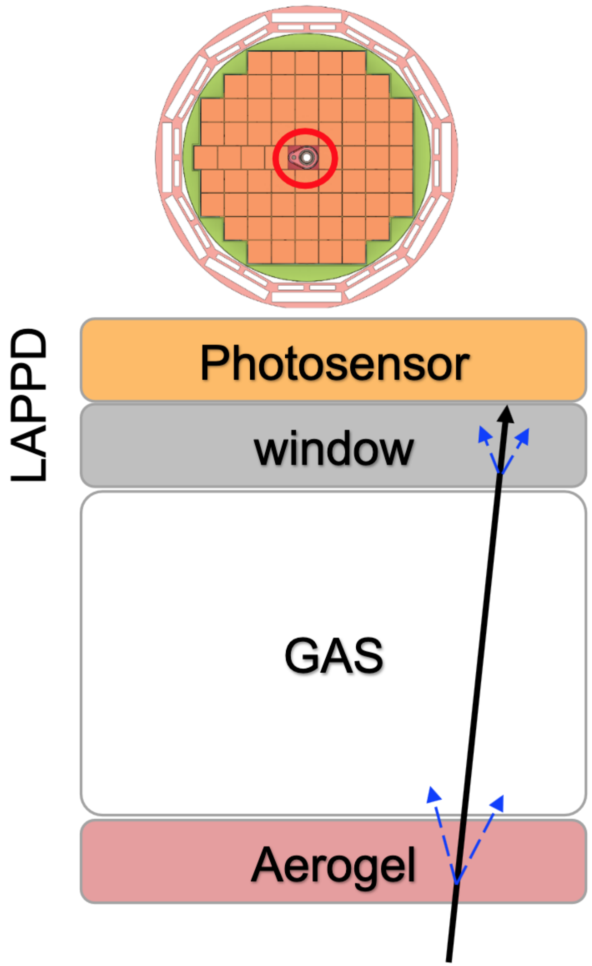
- Timing provided by both aerogel (<N_{pe}> ~12) and HRPPD window photons (<N_{pe}> above 80)
  - Their combined geometric acceptance will be ~100%

- **ToF** meas. ← # photon hits created by particles
  - pfRICH receives photon hits from aerogel, acrylic filter, gas in expansion volume, and **LAPPD window**
- **Efficiency** (η, ϕ): prob. of particle creating N_{pe} > 5.
  - **20 ps t_0 resolution** by having 6 photons, assuming 50 ps single photon time resolution (timing resolution **20ps = 50ps / $\sqrt{6}$**).



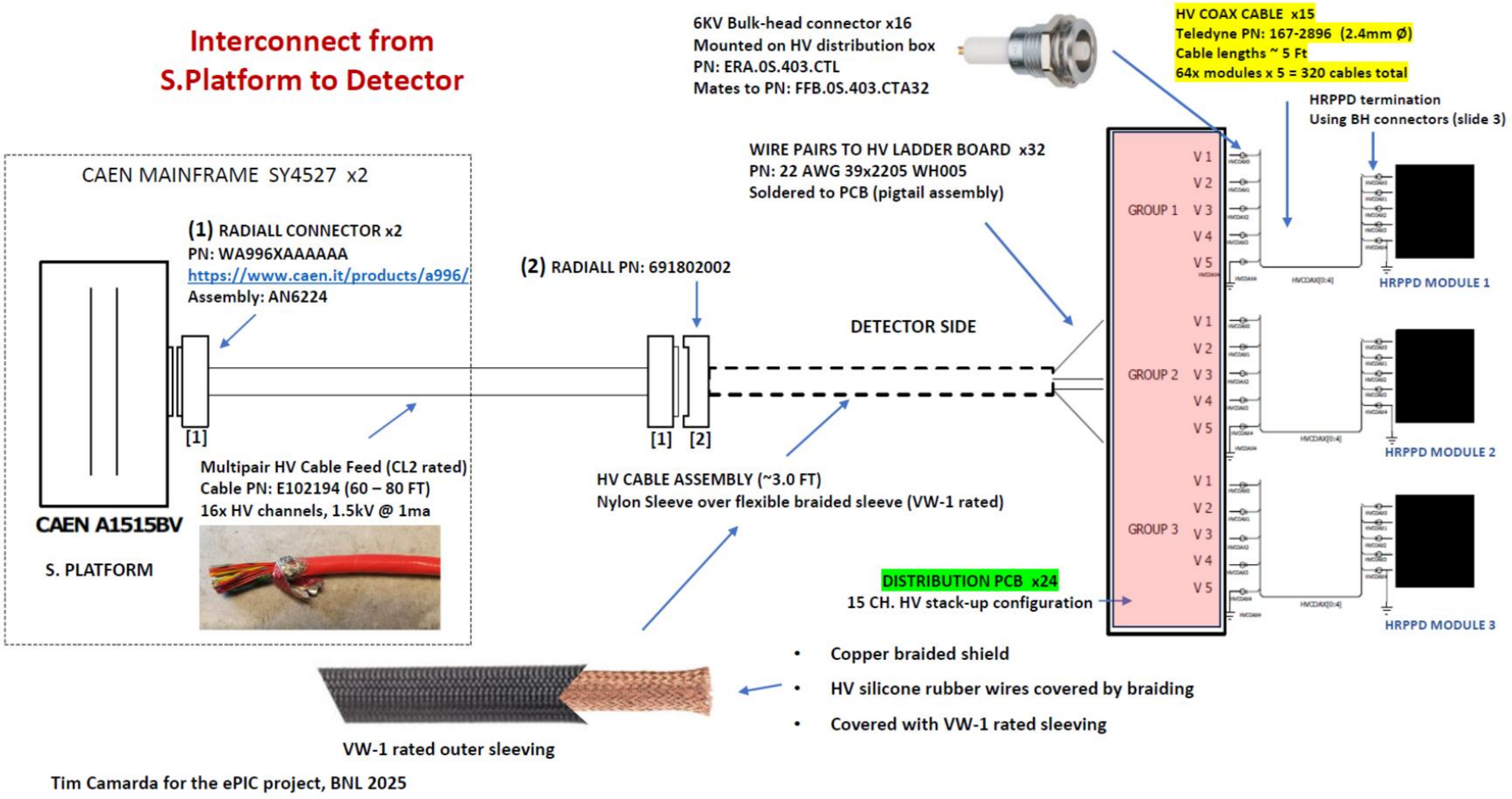
Red dips → ribs from Aerogel wall

Black dips → ribs from window ceramic boundary

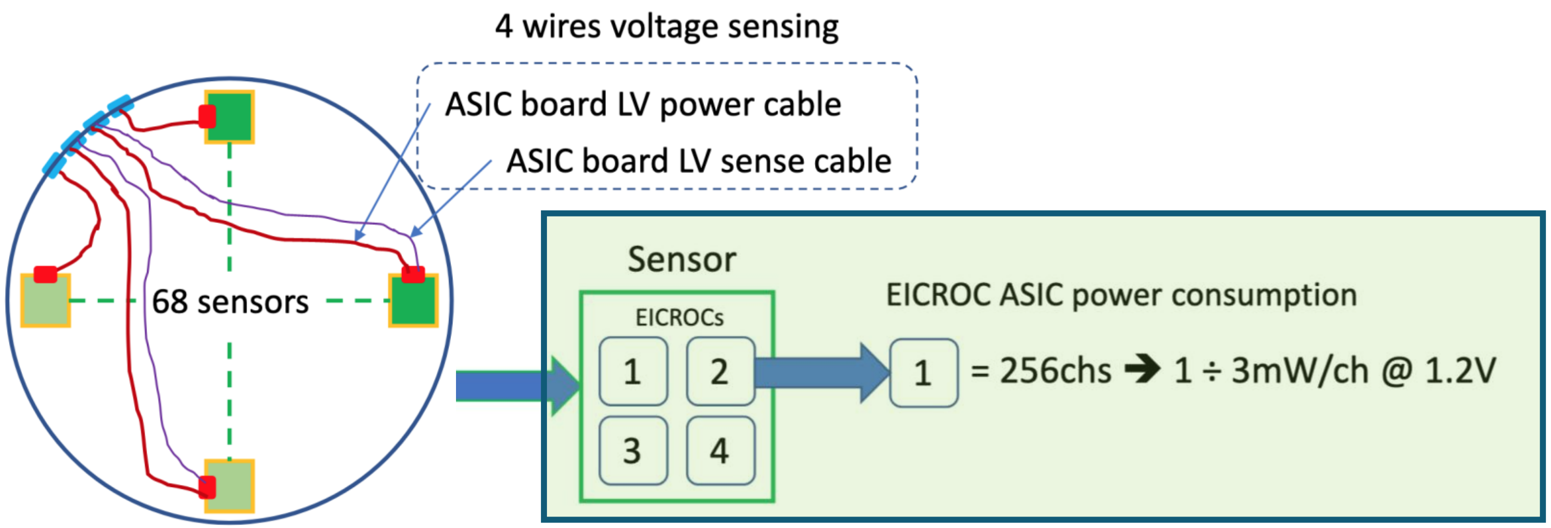


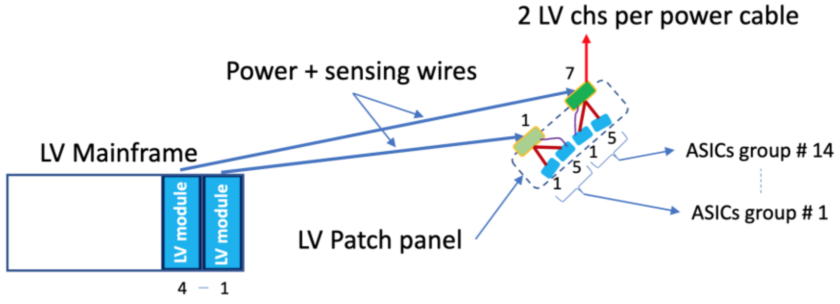
Single Particles fired at $\eta = -3$

High-Voltage System



Low-Voltage System





Wiener LV mainframe and modules

- ❑ Calculate LV power needs assuming 4 EICROC (256 chs/chip) per HRPPD
  - ➢ 1024chs/sensor x 3mW/ch = ~3W/sensor -> @ 1.2V = 2.5A per sensor
- ❑ Full detector consists of 68 HRPPDs
  - ➢ 68sensors x 2.5A = 170A total current
- ❑ Add 20% current for ancillary components of ASIC and 20% to that as a safety margin
  - ➢ 170A x 1.2 x 1.2 = 245A current for full detector
  - ➢ 245A @ 1.2V = 294W

- ❑ Note: Baseline ASIC is FCFD
- ❑ LV layout and power needs were calculated based on EICROC specifications
- ❑ We do not expect power needs for FCFD to be substantially different and therefore do not expect major changes to LV system

Cooling System

Off Detector

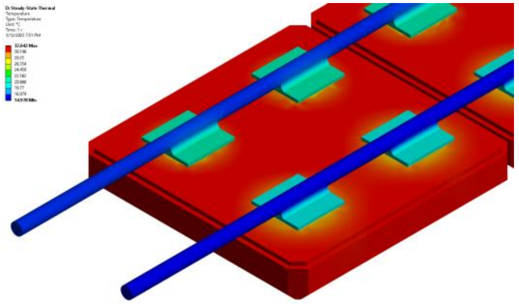
- ❑ Chilldyne Circulator
  - ➢ 8 lpm
  - ➢ -10 psi
  - ➢ 5℃ to 40℃

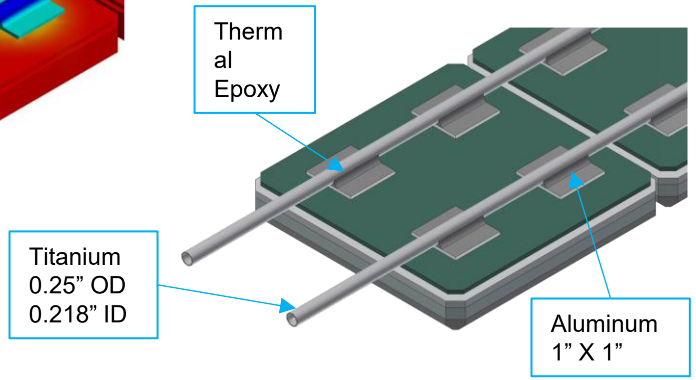
- ❑ Polyscience Chiller
  - ➢ 9.8 l/min @ 43.4 psi
  - ➢ -20℃ to 40℃ +/-0.1℃
  - ➢ 800 W @ 10℃

- ❑ Distribution Panel
  - ➢ Flowmeters
  - ➢ Flow Transmitters

On Detector

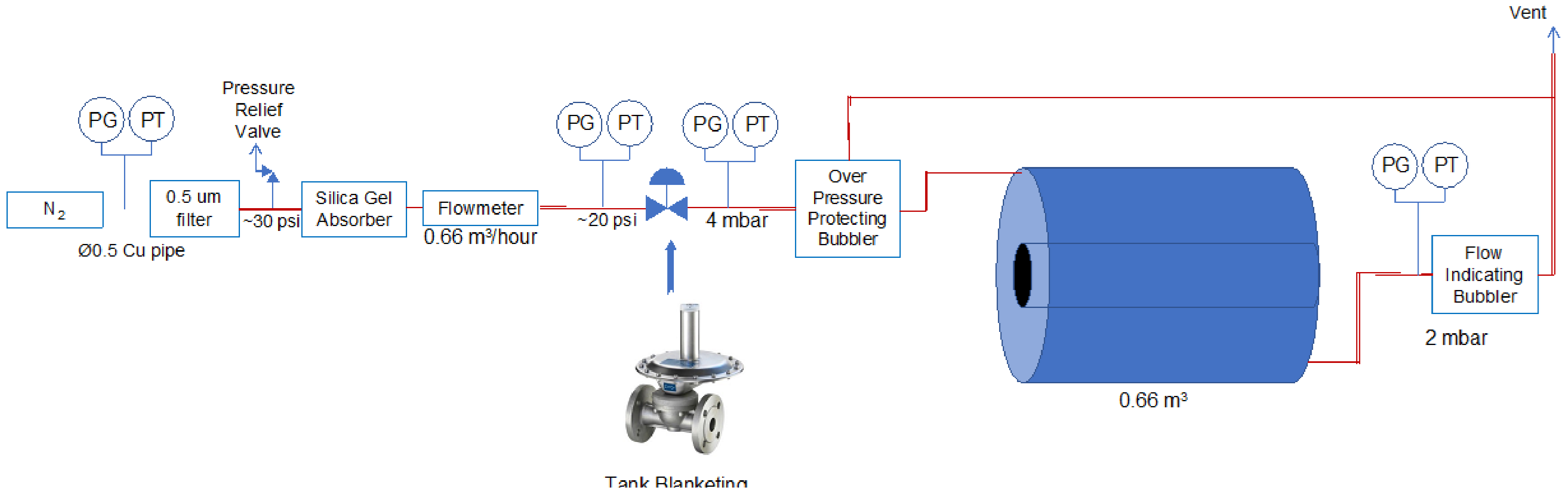
- ❑ Heat dissipation: 400 W
- ❑ Tube @ Δ2℃: ~3 lpm
- ❑ ΔP ~0.25 psi
- ❑ 9 Modules:
  - ➢ ~50 W
  - ➢ ~Δ17℃
  - ➢ Water ~Δ1.2℃

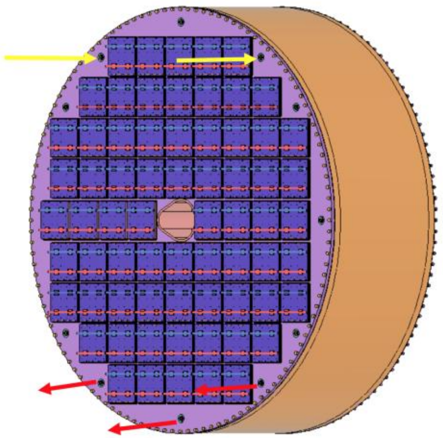




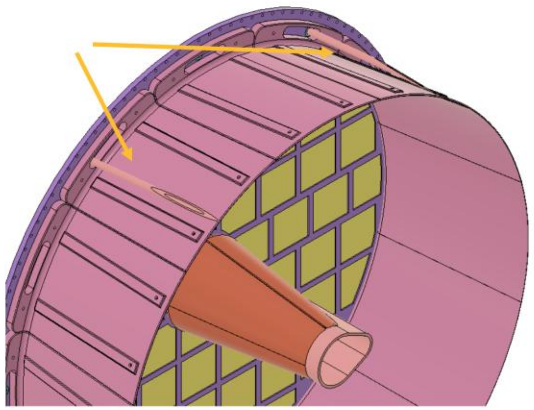
❖ Design and requirements on cooling system based on expectations from EICROC ASIC – FCFD ASIC solution may necessitate slight mechanical redesign but should not affect power consumption significantly

Gas System





Two 3/8" ID Inlets, Three 3/8" ID outlets

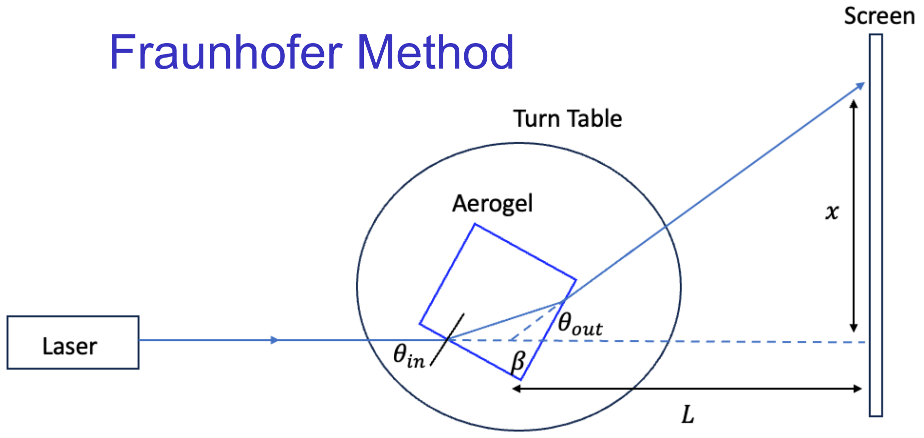


Inlets have two long 3/8" ID tubes at the top with taper pointing to cylindrical vessel walls

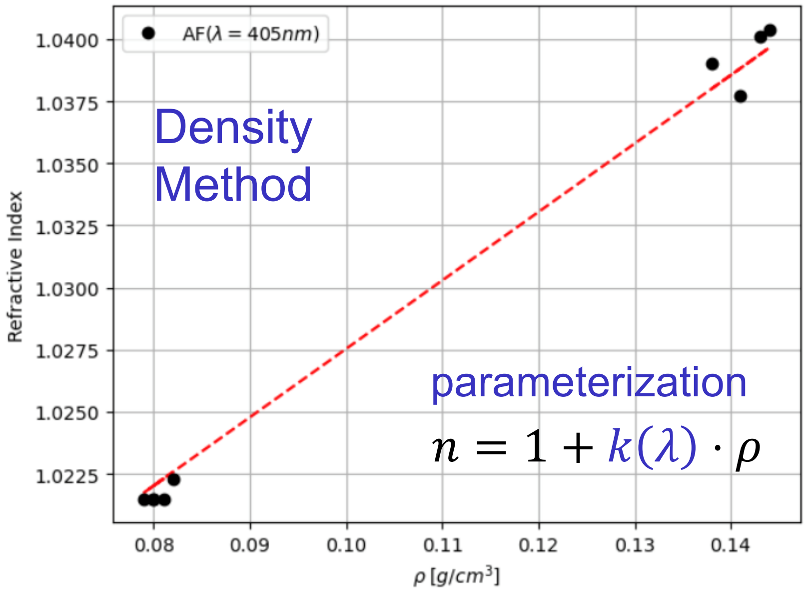
- Assume nitrogen only configuration
- One volume exchange per hour at a pressure 2-4 mbar
- Gas quality (industrial, ultra-pure,…) needs to be finalized

Refractive Index QA: Current Status

- 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



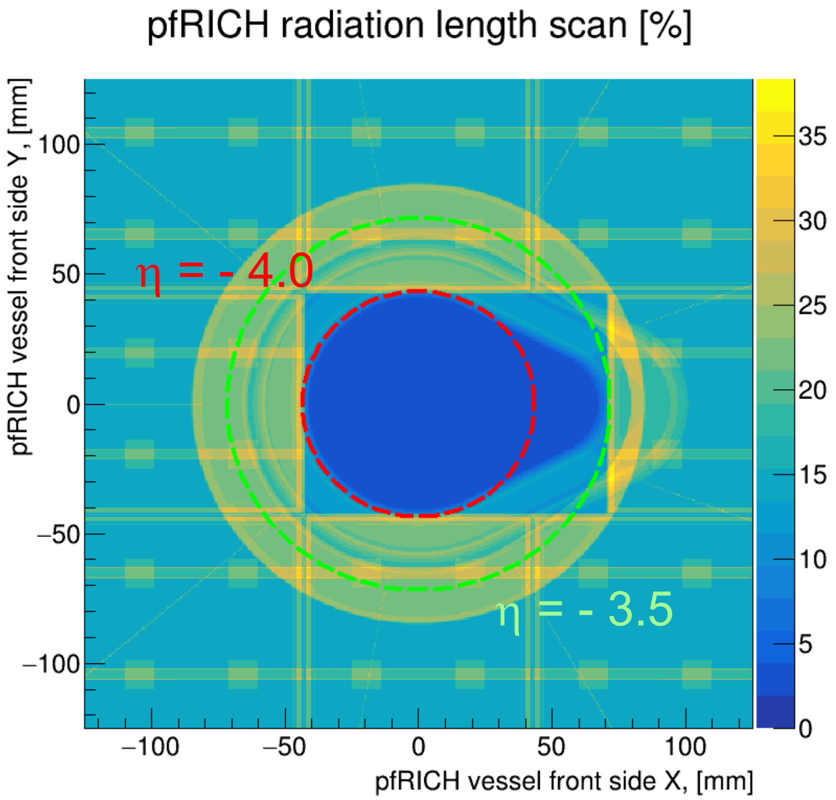
- Alternative: Density method - parameterize refractive index vs. density from aerogels with known refractive index (e.g. refractive index measured via Fraunhofer method) , then use parameterization and aerogel density to extract a refractive index
  - Limitations: Provides one refractive index determined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

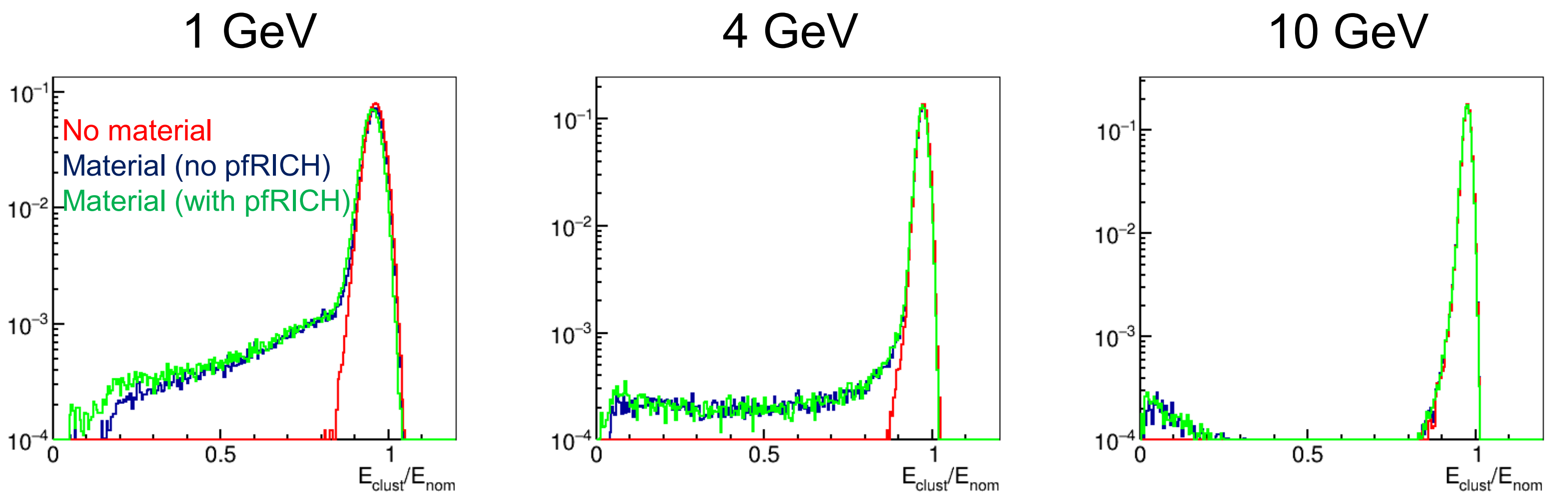


pfRICH material effect on the backward EmCal

- 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 < η < -1.9





- 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

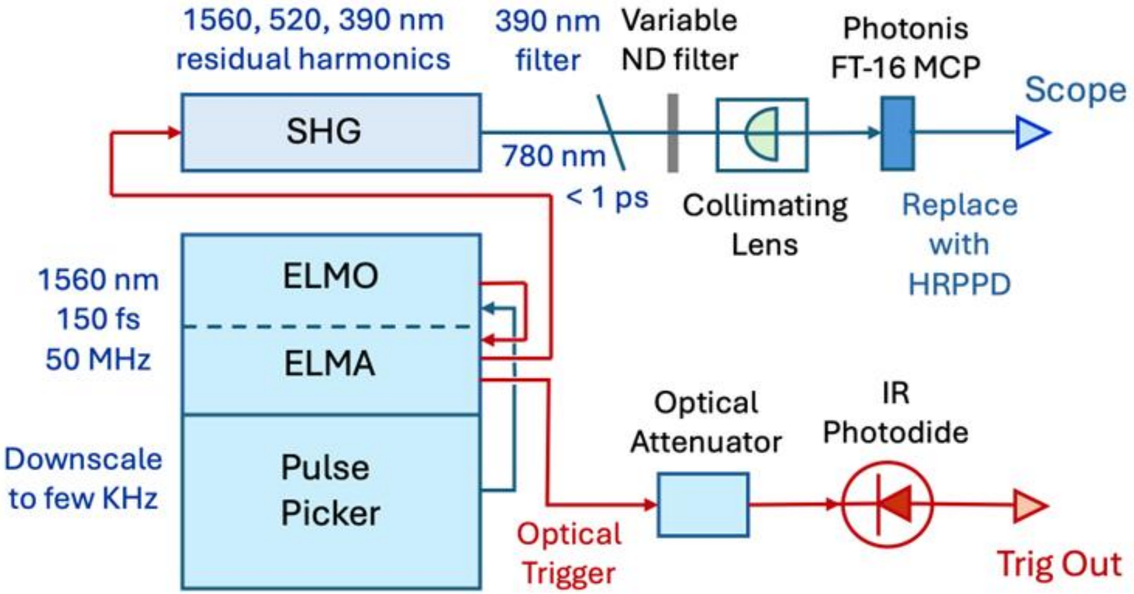
Femtosecond Laser System at BNL

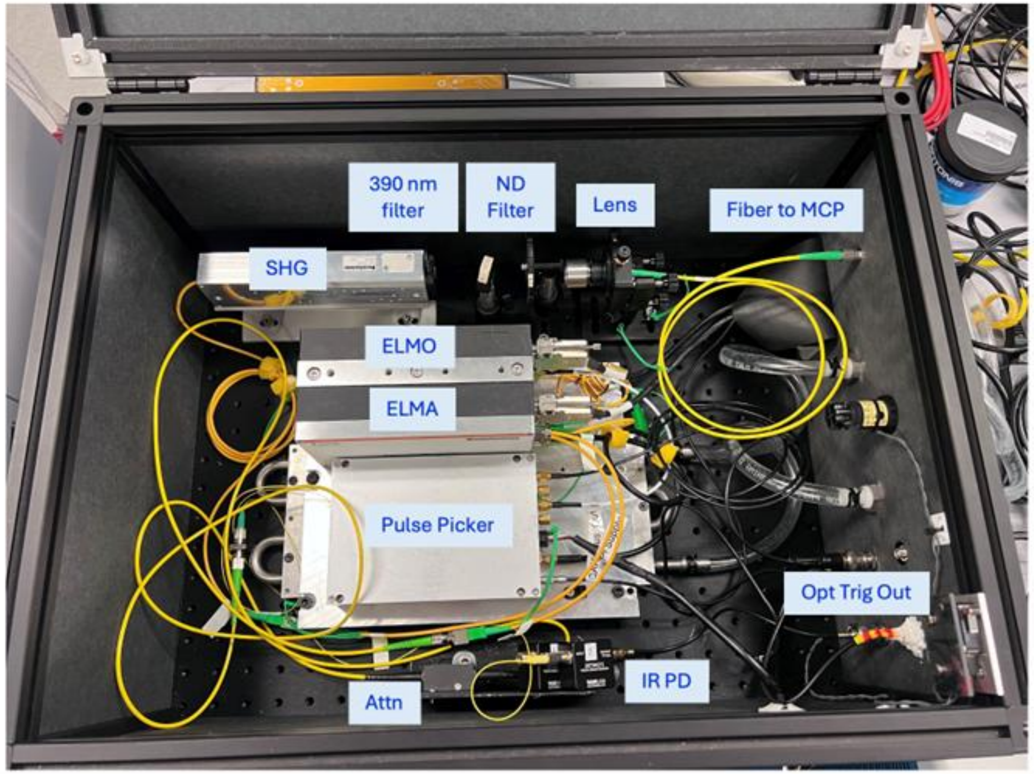
Menlo Systems Elmo 780 Erbium Fiber Femtosecond Laser

ELMO = Primary Laser Oscillator

ELMA = Optical Amplifier

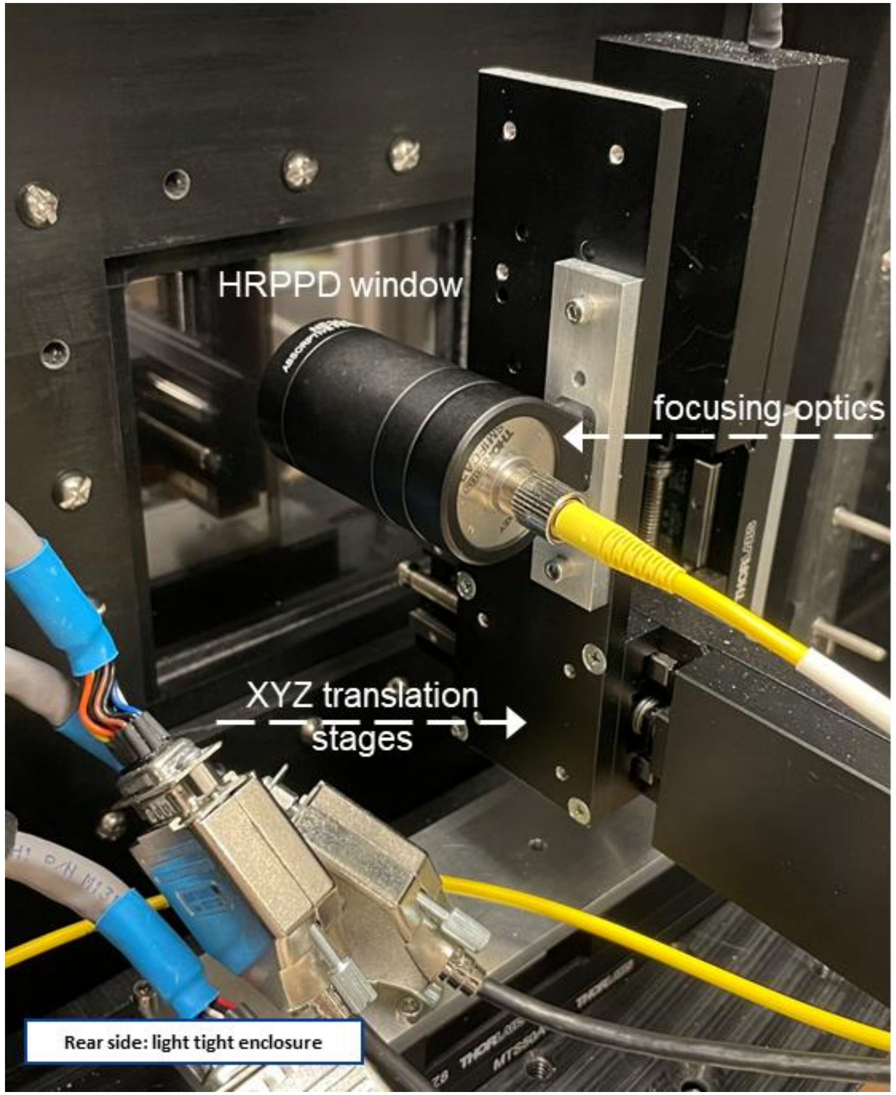
SHG = 2nd Harmonic Generator





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

HRPPD Test Stand at BNL



- Picosecond PiLas laser
- Compact light-tight enclosure
- 480 DRS4 channels (V1742 digitizers)
- Interface board with a compression interposer interface
  - MMCX and high-density Samtec connector interface to DRS4