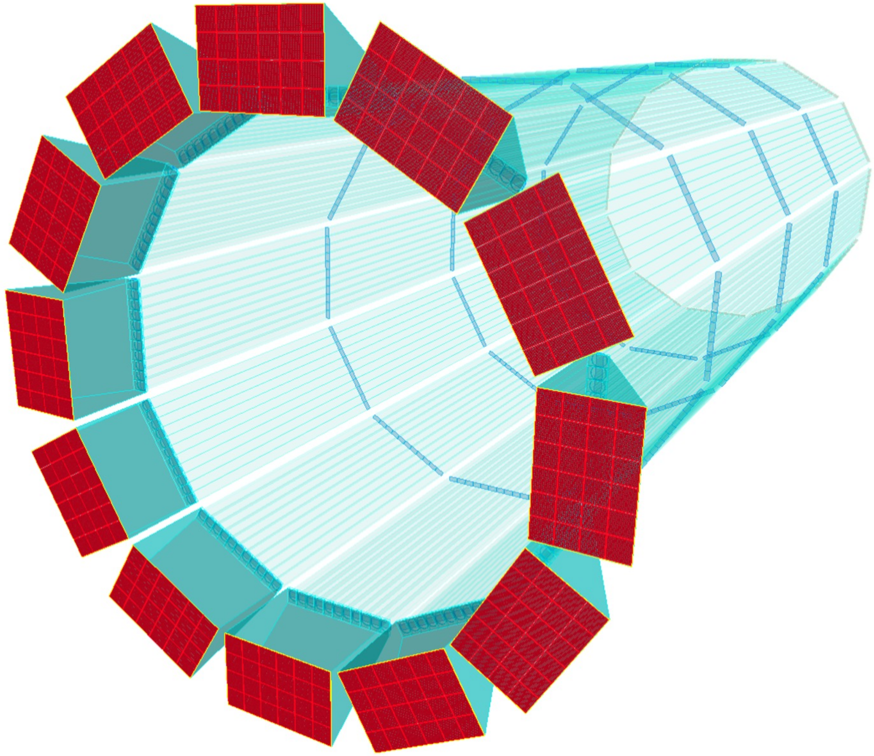
The hpDIRC Detector for the ePIC Experiment



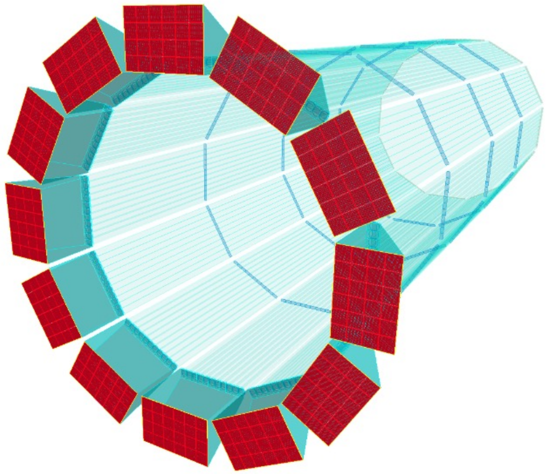
Greg Kalicy CUA

EIC DAC Meeting

June 12th, 2025

CUA GSI Jazan University Jefferson Lab Old Dominion University Stony Brook University University of South Carolina Wayne State University William & Mary

EXECUTIVE SUMMARY



- The hpDIRC has been selected for the barrel PID of the EIC ePIC Detector
- Expected PID performance meets ePIC requirements (Yellow Report), separation: ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.1 GeV/c
- Key elements, simulation and focusing lenses, validated in particle beams in 2018
- Main remaining steps towards production readiness and TDR in 2026:
  - Validation of reusing BaBar DIRC radiator bars
  - Evaluation of sensors and readout ASIC (synergy with pfRICH and electronics/DAQ)
  - Completion of mechanical design and integration
- No challenges expected for ES&H and QA
- hpDIRC DSC includes nine institutions with well-established expertise and interest in work packages
- Plans for remaining studies, QA preparations, and construction match project schedule
- Passed 60% Design review in April 2025

Incremental Preliminary Design and Safety Review

- April 1-2, 2025: 60% Design Review of ePIC PID systems: pfRICH, dRICH, and hpDIRC
- Review Committee:
  - Peter Krizan (U Ljubljana), Chair
  - Floris Keizer (CERN)
  - Ana Amelia Machado (UniCamp)
  - Koji Nakamura (KEK)
  - Justin Stevens (W&M)
- Slides from Review are available as pre-brief material
- Feedback:
  - "The PID detectors are fully on track for the CD2/3 review on the current project timeline."
  - Significant progress acknowledged and final experimental validation tests encouraged
  - Clear directions to prepare comprehensive documentation of remaining studies

EIC DAC Review Charge

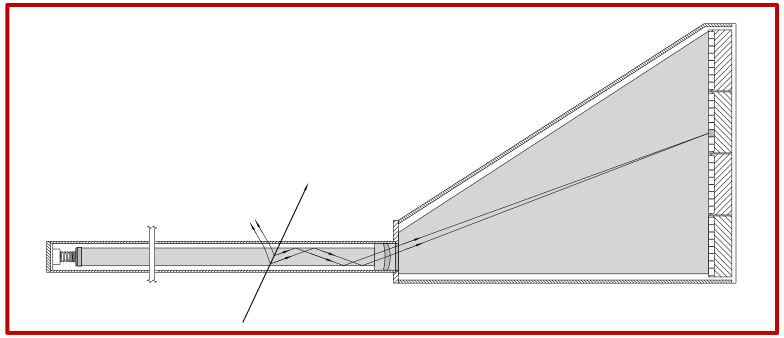
1. Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
2. Are the remaining work and technical, cost and schedule risks adequately understood?

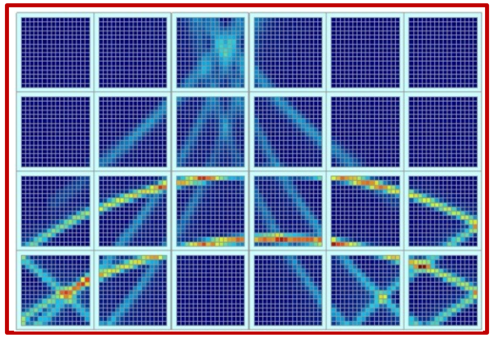
   Are there opportunities?
3. Will the detector be technically ready for baselining by late 2025?
4. Are the detector integration and planning for installation and maintenance progressing well?

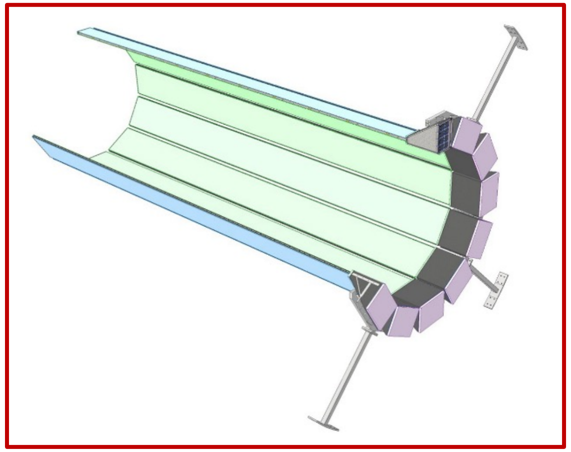
   Are there areas where further ideas should be pursued?
5. Will the detector be ready for start of construction by late 2026?

Outline

- Introduction
  - ePIC requirements for hadronic barrel PID
  - DIRC principle
- High-performance DIRC for ePIC
  - R&D
  - Preliminary design
  - Simulation and expected performance
  - Validation with prototype in particle beams and CRT
- Main components
  - Specifications, validation plans
- Mechanical design and detector integration
- Quality control and assurance
- hpDIRC collaboration and responsibilities
- Schedule





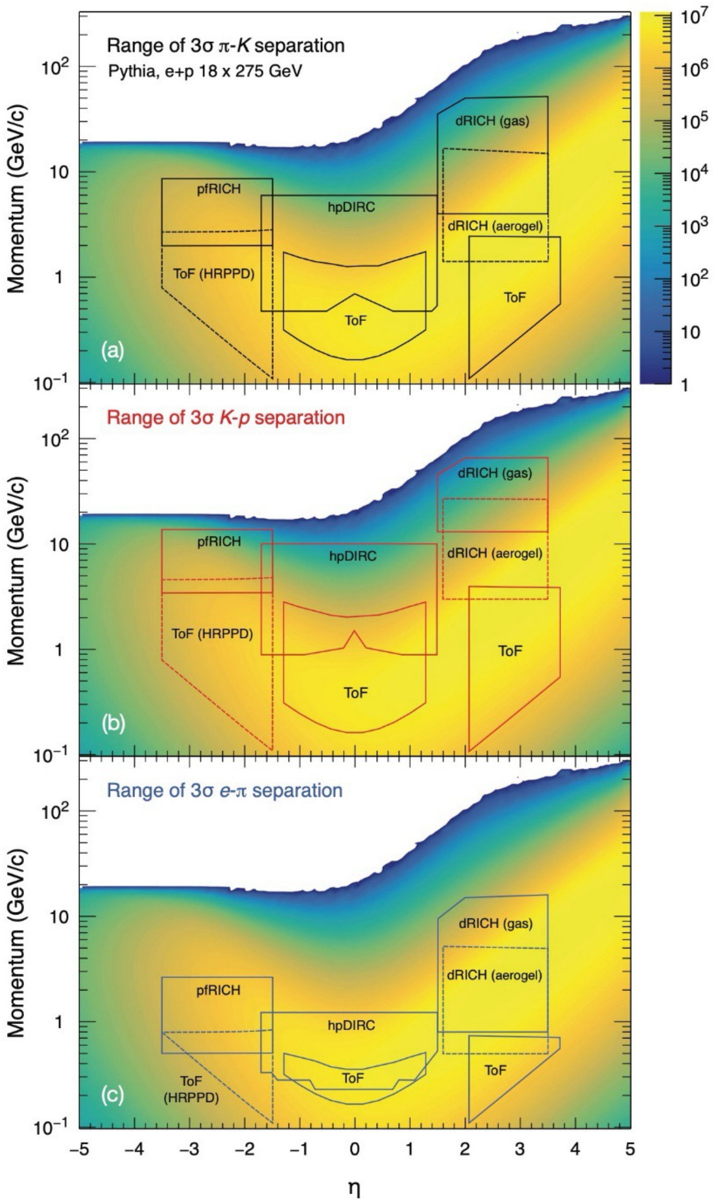


Charged PID Requirements in ePIC

Performance requirement definition

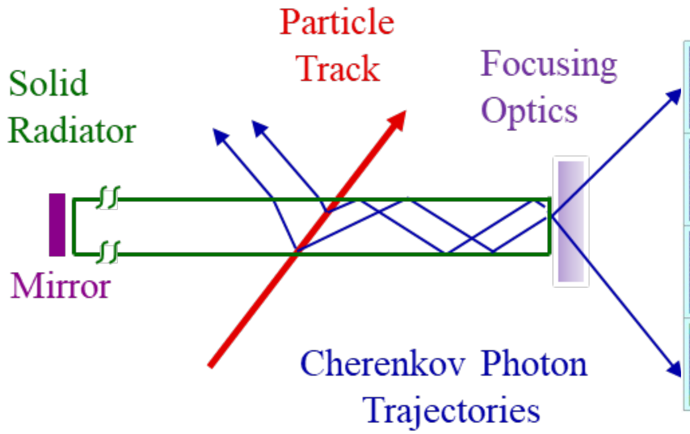
- EIC physics requires clean and efficient PID over a wide angular range
- Hadronic PID required to separate:
  - Electrons from charged hadrons -> electron ID mostly provided by calorimeters, supplemented for lower momenta by DIRC/RICH detectors
  - Charged pions, kaons, and protons from each other
- Requirements for barrel PID (-1 ≤ η ≤ +1):
  - Main separation power requirement: ≥ 3 s.d. π/K up to 6 GeV/c
  - System needs to be radially compact (impact on cost of outer systems)
  - Minor changes to detector position and dimensions do not impact hpDIRC performance (sensor in B-field and detector integration)
  - Low demand on detector services (simplified integration and operation)
- hpDIRC capable of reaching required performance at 6 GeV/c for 0.5 mrad tracking angular precision

Summary of PID requirements in ePIC

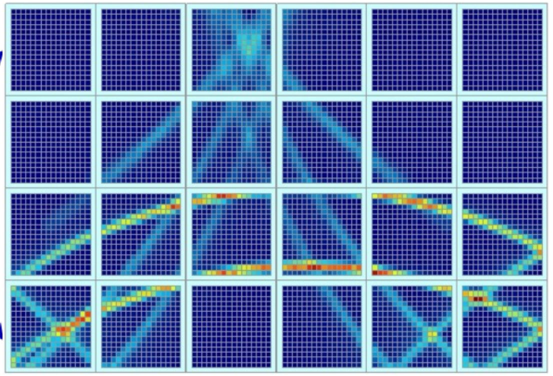


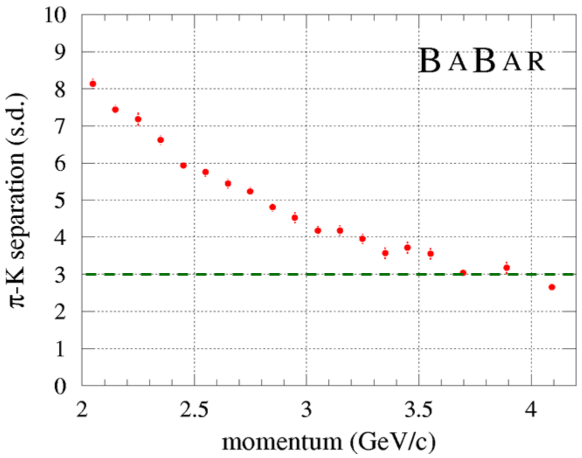
Detection of Internally Reflected Cherenkov Light

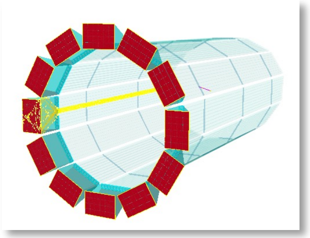
- Pioneered by the BaBar experiment at the SLAC National Accelerator Laboratory
- Fused silica bars or plates used as radiator and light guide
- Detector surface is outside active volume
- Cherenkov angle is conserved during internal reflections and reconstructed from detected photons
- Ultimate deliverable: PID likelihoods
- BaBar DIRC achievement: 3 s.d. π/K separation up to 3.5 GeV/c



Accumulated ePIC hpDIRC hit pattern (Geant4)



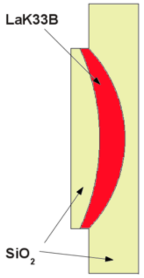




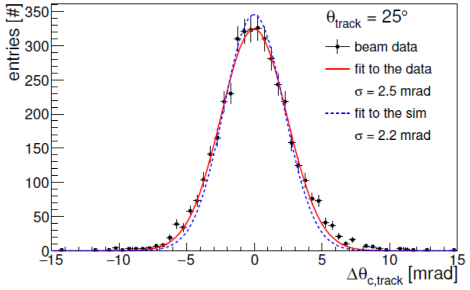
HIGH-PERFORMANCE DIRC R&D

- 10+ years ago: DIRC good candidate for hadronic particle in EIC detector barrel – if π/K momentum coverage achieved by BaBar DIRC is increased by 50%
- R&D for a high-performance EIC DIRC started in 2011 (synergetic with PANDA DIRC) *(Funded by DOE/BNL/JLab as RD2011-3, eRD4, eRD14, eRD103)*
- EIC DIRC R&D Milestones:
  - 2012: First multi-layer high-refractive index lens concept to avoid photon loss at air gaps
  - 2012: First 2-layer and 3-layer prototype lenses produced by industry
  - 2014: Simulation showed that lens-based design is expected to reach 1 mrad Cherenkov angle resolution, equivalent to 3 s.d. π/K separation at 6 GeV/c
  - 2015: First successful CERN beam test with muti-layer spherical lens
  - 2017: Identified sapphire and PbF_2 as radiation-hard material candidates for lenses
  - 2018: Validated 3-layer spherical lens performance and Geant4 simulation with PANDA DIRC prototype with particle beam at CERN
  - 2019: First radiation-hard lens prototypes fabricated by industry
  - 2022: hpDIRC selected as barrel PID solution for EIC detector
  - 2024: Transportation and start of BaBar bar box assembly, separation of first bar

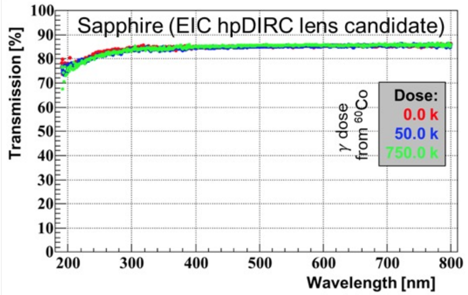
Initial 3-layer lens concept



Cherenkov angle per particle, CERN 2015

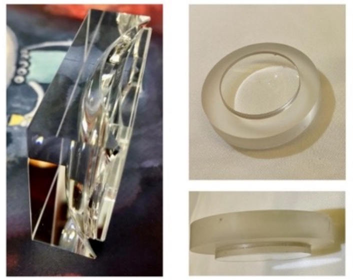


radiation hardness of sapphire



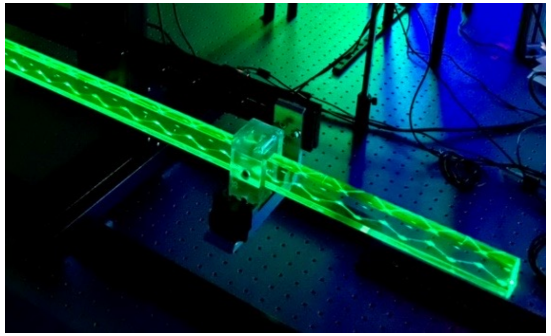
radiation hard lens prototypes

Sapphire (RMI, USA) PbF_2 (HIT, China)



HIGH-PERFORMANCE DIRC R&D

- Milestone reached: hpDIRC R&D concluded
- Preparation for production readiness of hpDIRC: key components tested on dedicated optical benches, integrated vertical-slice prototype ready for tests within the Cosmic Ray Telescope (CRT) facility.
  - All major design questions have been resolved, confirming the maturity of the hpDIRC baseline.
  - Lens design and performance validated through systematic test bench measurements.
  - First legacy DIRC radiator bars successfully separated and undergoing detailed characterization.
  - Sensor and readout electronics development is actively progressing, led by collaborative efforts within eRD109 and eRD110.
  - Full chain system validation of the complete hpDIRC setup will be performed in the CRT before entering the construction phase.



High-Performance DIRC Overview

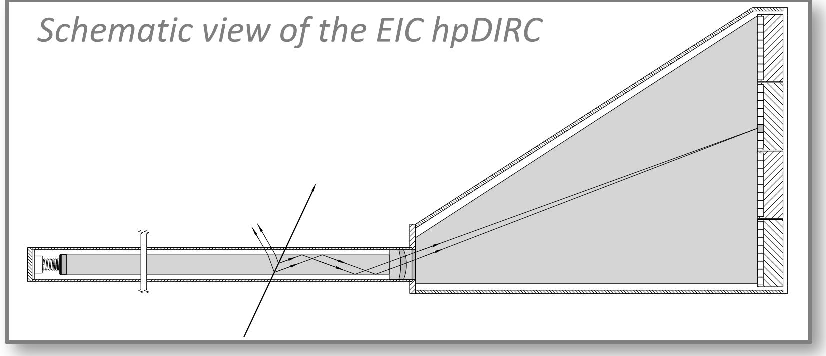
Extending DIRC π/K separation coverage to 6 GeV/c

- Concept: fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction.
- Radiation-hard 3-layer spherical lens to reduce bar image size and shape imaging plane;
- Lifetime-enhanced MCP-PMTs with fine anode segmentation to reduce pixel size;
- Fast photon timing for chromatic dispersion mitigation and background rejection;
- Narrow bars for robust performance in high-multiplicity jet events;
- Compact expansion volume to simplify integration into central detector.
- Benefit from additional ePIC detector improvements:
  - High-precision tracking, expect 0.5 mrad polar angle resolution;
  - Post-DIRC tracking layer (EMCal AstroPix) for multiple scattering mitigation.
- Predicted performance for central rapidity range $-1.5 \leq \eta \leq +1.5$:

  3σ π/K separation up to at least 6 GeV/c (Cherenkov angle resolution per particle ≤ 1 mrad),

  supplemental e/π separation up to 1.1 GeV/c.

Schematic view of the EIC hpDIRC



HPDIRC DESIGN

Radiator bars:

- Barrel radius: 780 mm, 12 sectors
- 10 long bars per sector, 4500 mm x 35 mm x 17 mm (L x W x T)
- Long bar: 4 bars, glued end-to-end
- Short bars made from highly polished synthetic fused silica
- Flat mirror on far end

Focusing optics:

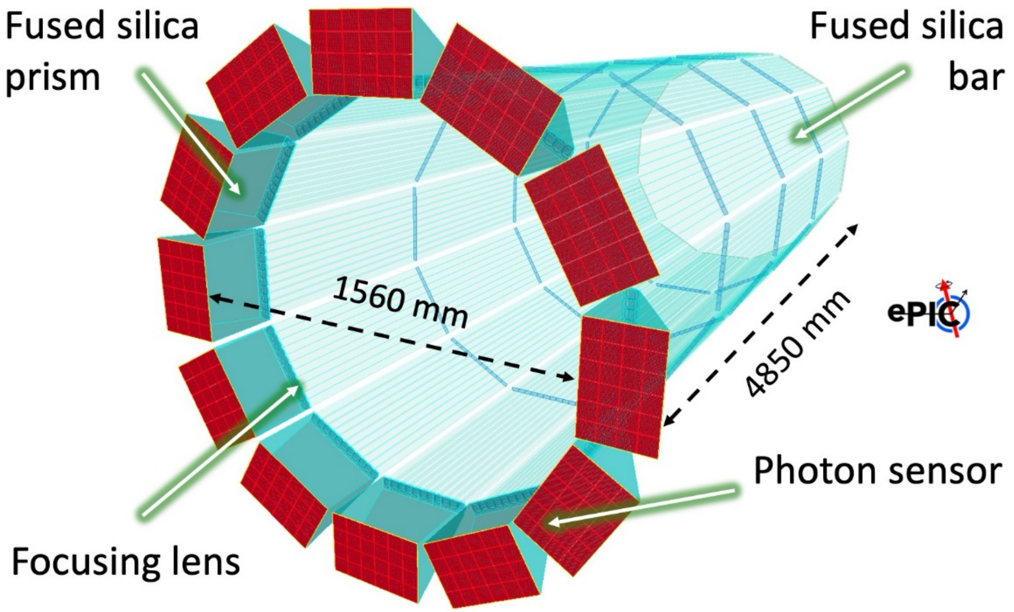
- Radiation-hard 3-layer spherical lens (sapphire)

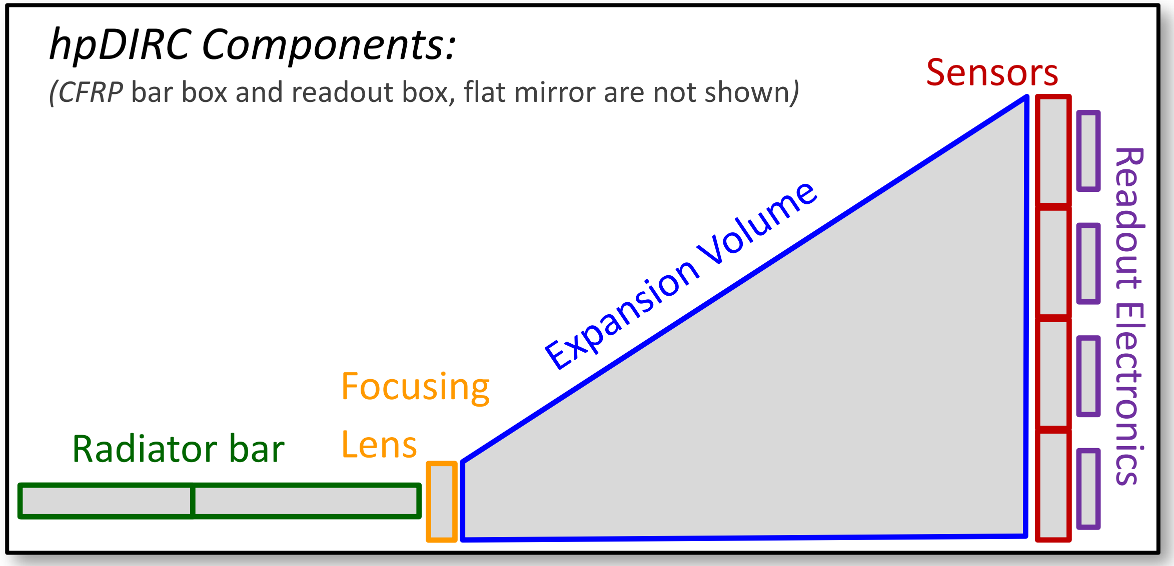
Expansion volume:

- Solid fused silica prism: 25 x 35 x 30 cm^3 (H x W x L)

Readout system:

- MCP-PMT Sensors (Photek/Incom)
- ASIC-based Electronics (FCFD)





Stand-alone Geant4 Simulation

- Realistic optics, geometry, and material properties – based on prototypes and experimental data, wavelength-dependent material properties and processes
- Validated with test beam data
- Used for design optimization studies and to test novel design options

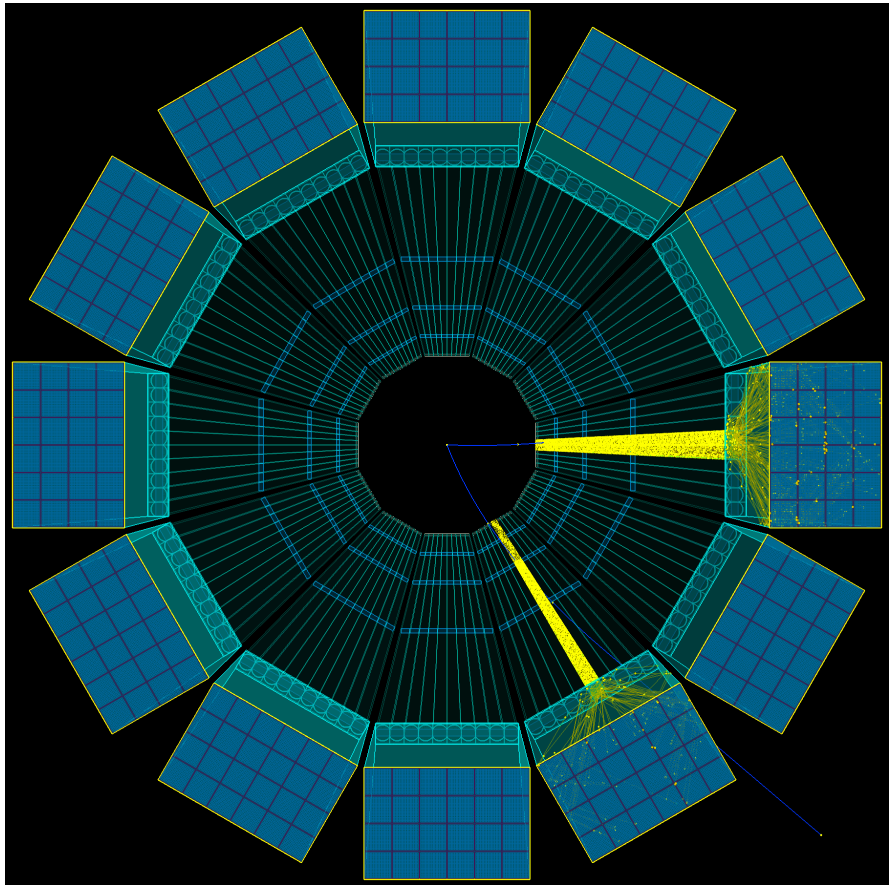
Full ePIC Simulation:

- Functionality of Stand-alone simulation imported and integrated
- Repeat physics background and detector impact study in the full software stack

Reconstruction and PID methods:

- Geometrical (BABAR-like), robust and fast method based on Look-Up Tables, delivers Cherenkov angle per particle and Single Photon Resolution (useful for calibration and in prototype tests), does not depend on precise time measurement
- Time Imaging (Belle II TOP-like), uses Probability Density Functions (analytical or simulation-based), makes optimum use of precision of position and time information

Pythia events in hpDIRC simulation

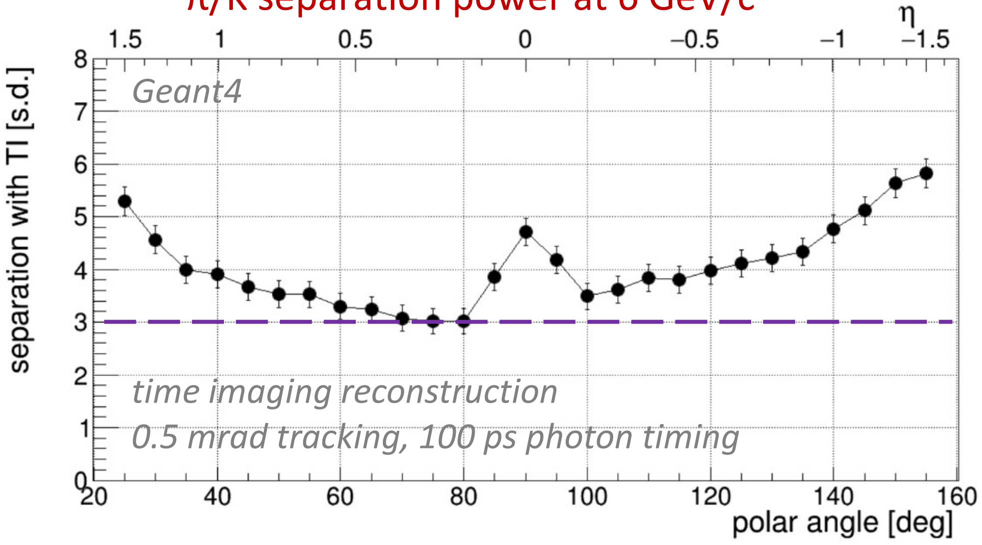


hpDIRC Simulation

Recent hpDIRC related studies:

- Confirmed robust performance in magnetic field, using physics events (Pythia) to include backgrounds, multiple tracks per bar (WSU)
- Performance with latest ePIC angular track resolution maps (GSI)
  → High-precision angular resolution crucial for reaching required hpDIRC performance.
- Verifying optimal sensor coverage (CUA, GSI)
- Study of the impact of bar imperfections on the hpDIRC performance relevant for the BaBar bar refurbishment (GSI)
- Impact of bar/lens misalignments on performance (Jazan)
- Machine Learning approach to reconstruction (W&M)
- Preparation for hpDIRC full chain test setup operation at CRT (SBU, GSI, ODU)

π/K separation power at 6 GeV/c



Simulation studies performed with

- Stand-alone Geant4 simulation
- Single particles from particle gun
- No magnetic field, no other ePIC subsystems
- 0.5 mrad tracking resolution

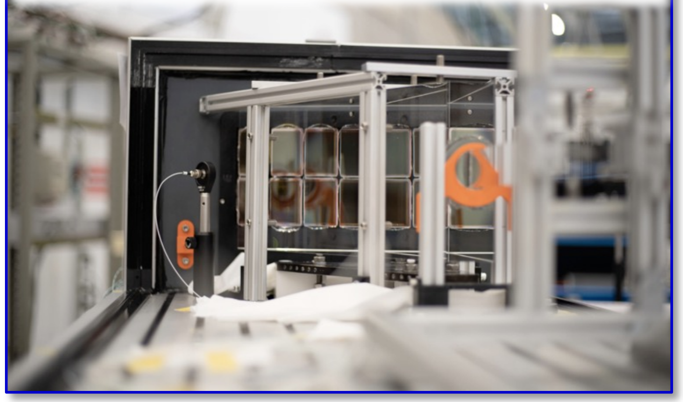
→ Performance requirements reached: ≥ 3 s.d. π/K separation at 6 GeV/c for all angles

VALIDATION OF SIMULATION AND COMPONENTS

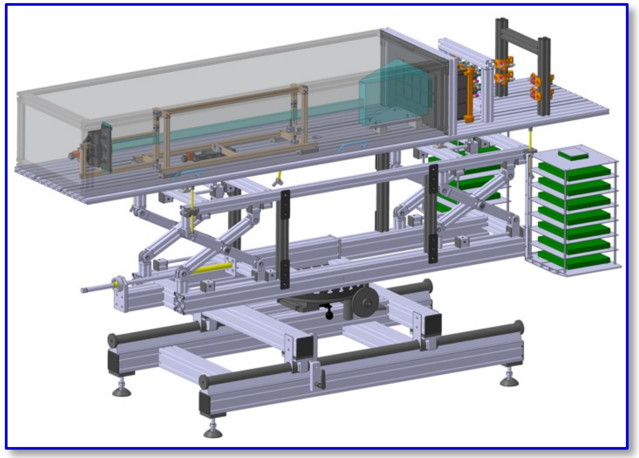
Performance validation: synergetic beam test with PANDA prototype at CERN PS in 2018

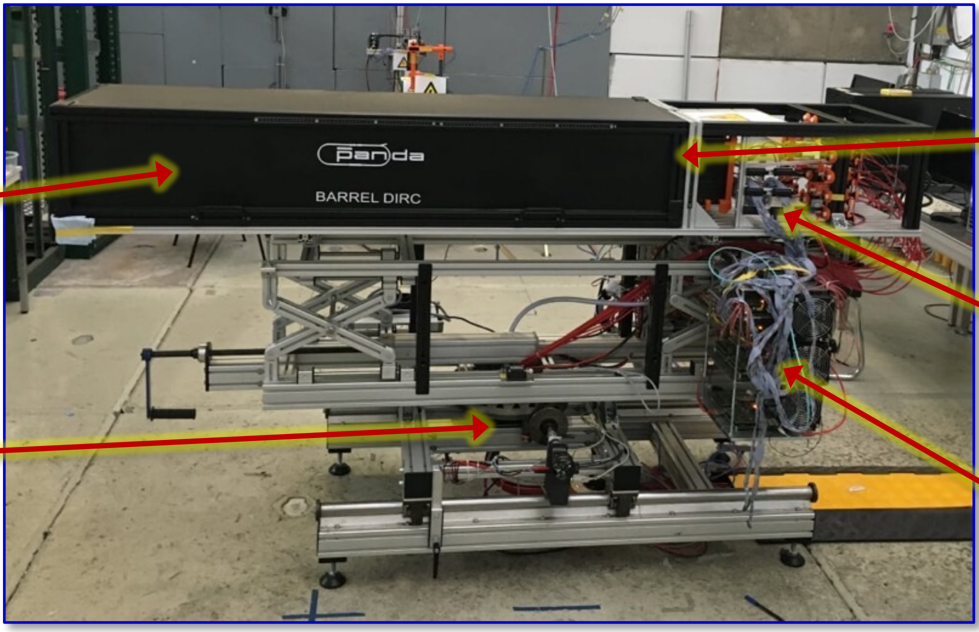
- Narrow fused silica bar, hpDIRC 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array (larger pixels, slower readout electronics than EIC)
- PiLas picosecond laser calibration system
- 7 GeV/c π/p beam equivalent to 3.5 GeV/c π/K
- MCP-TOF system to cleanly tag π and p events

View from inside the Barrel DIRC dark box



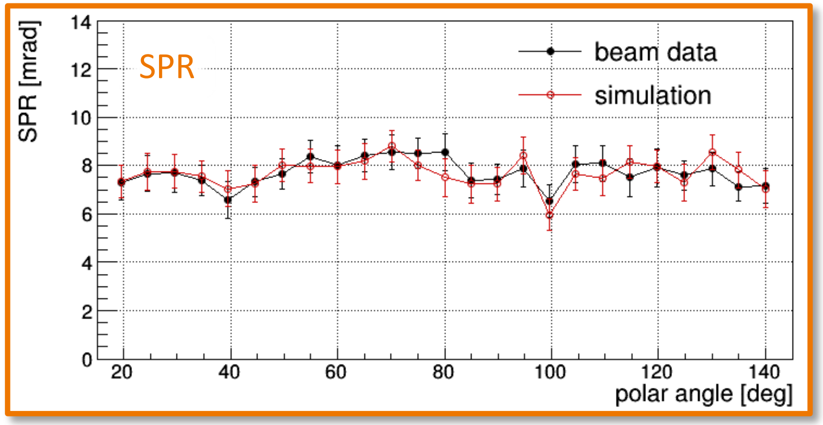
Schematic view of 2018 prototype

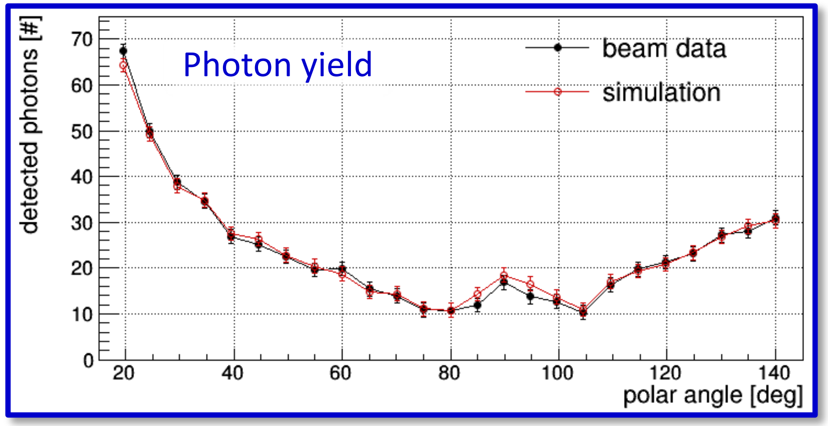




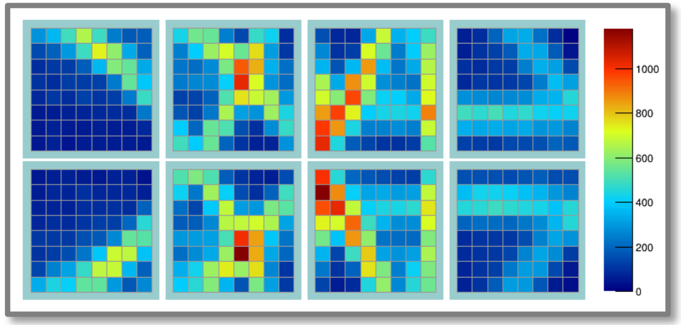
Validation of Simulation and Components

Performance validation: 2018 prototype at CERN PS

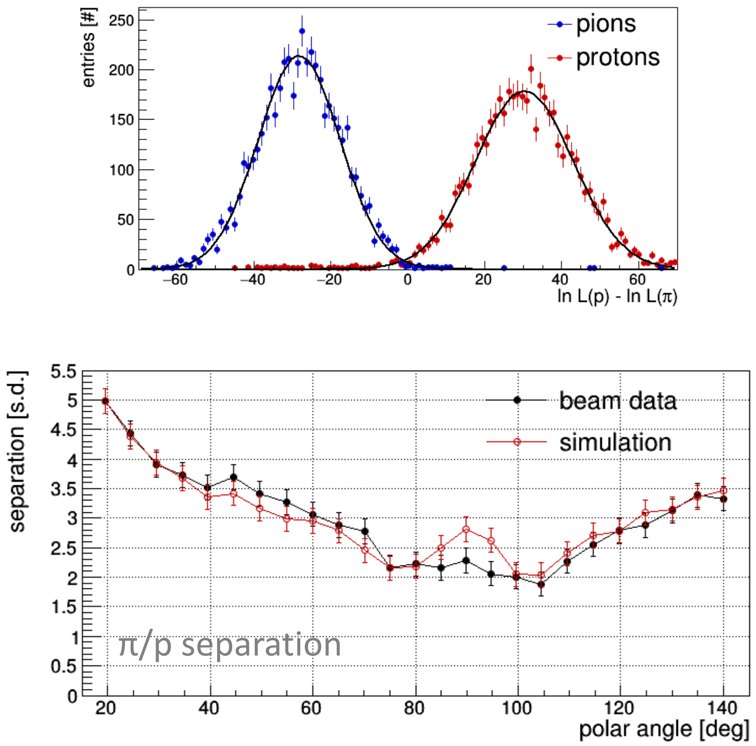




observed hit pattern at polar angle 20°



π/p separation power @ 7 GeV/c



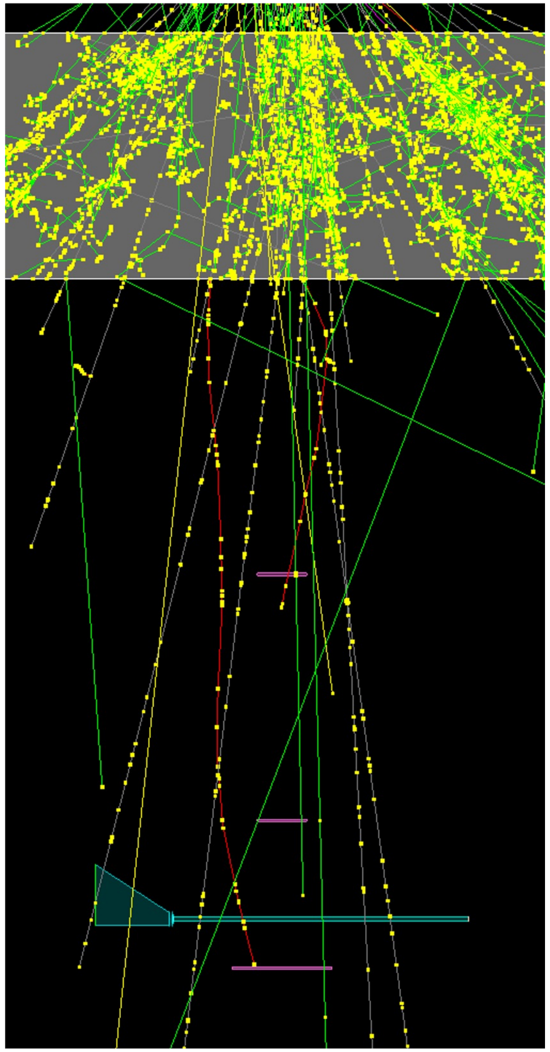
- Measured Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation in excellent agreement with expectation and Geant4 simulation
- Achieved π/K separation power of N_{sep}=5.2 s.d. with time imaging reconstruction for PANDA configuration, will improve with smaller pixels, better PDE and timing
- Same simulation/reconstruction code used for EIC high-performance DIRC
  -> Confidence in Geant prediction for hpDIRC performance

Cosmic Ray Telescope (CRT) at SBU

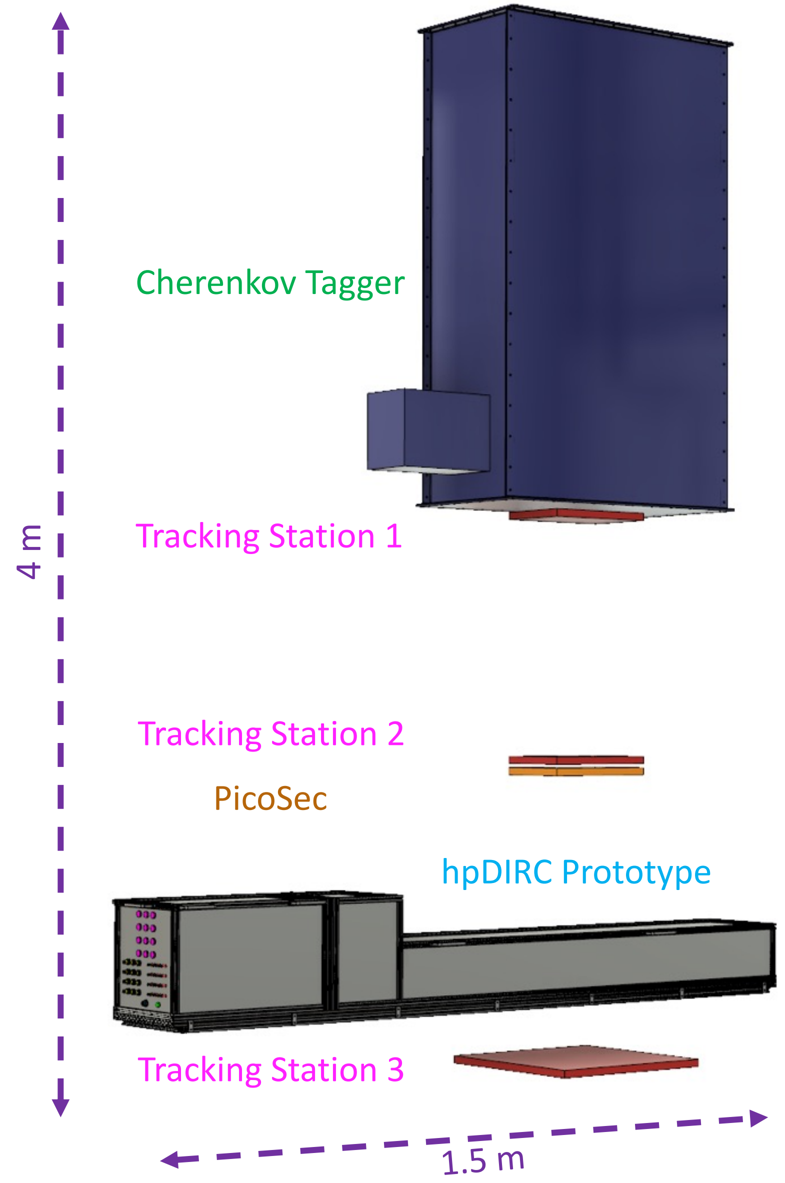
Facility to test incremental upgrades of setup with hpDIRC components, performance evaluation

- Initial PANDA Barrel DIRC-based setup for commissioning
- Modular design will allow to add new ePIC hpDIRC components once they become available
- Cherenkov Tagger to select muons above 3.5 GeV/c
- Three tracking stations for high-precision 3D-track reconstruction (location optimized with simulations)
- PicoSec detector for event timing (JLab group committed prototype and personnel to project)
- Geant4 simulation used to optimize setup arrangement

Geant4 simulation of CRT setup

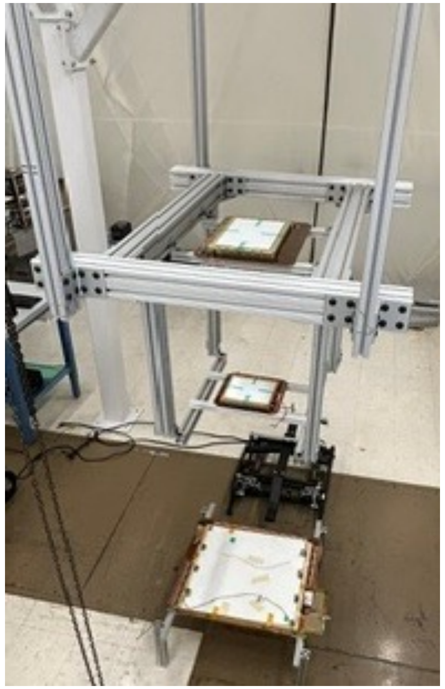


CRT setup CAD schematic

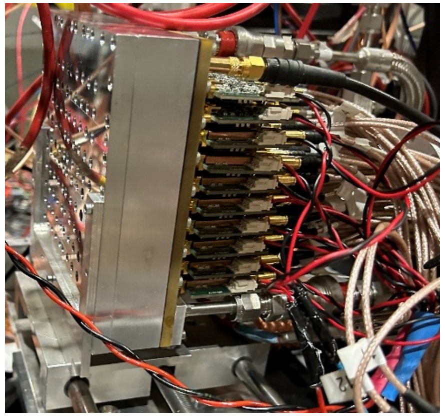


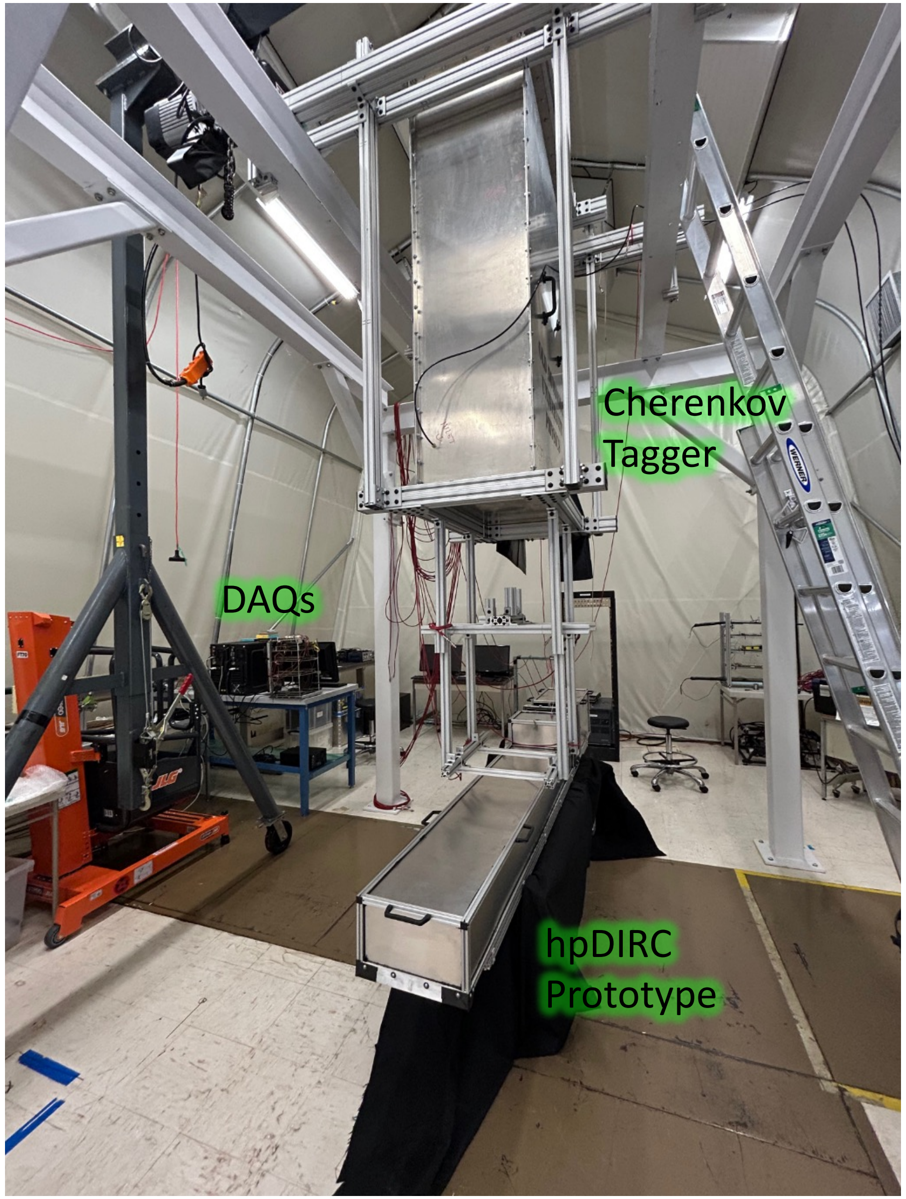
VALIDATION OF SIMULATION AND COMPONENTS

Trackers in the CRT



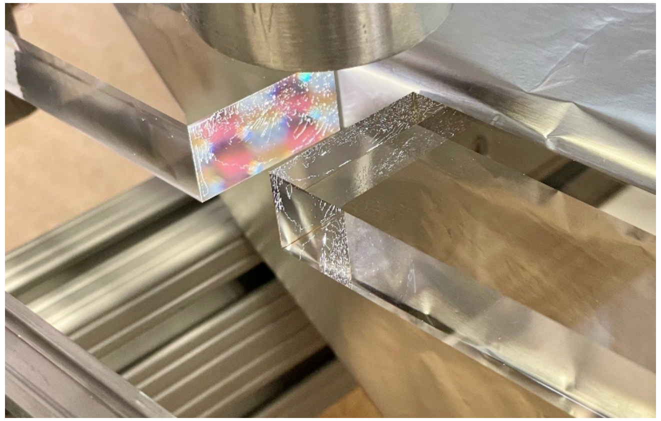
Large area PICOSEC



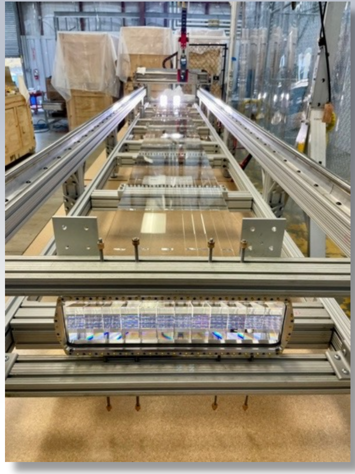


Reuse of BaBar DIRC Bars

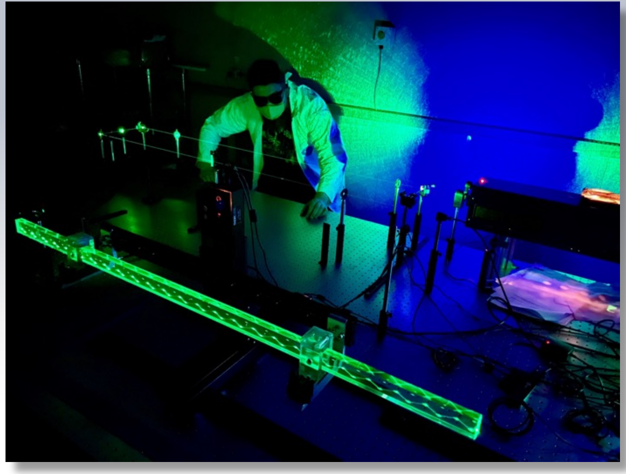
- BaBar DIRC decommissioned in 2010, SLAC/DOE made DIRC bars available for reuse, 4 bar boxes awarded to JLab and installed as GlueX DIRC in 2018, remaining 8 boxes awarded to JLab for potential use in EIC DIRC
  - Bar boxes transported to JLab in April 2024
- BABAR bar boxes are too long for the ePIC barrel, existing wedges at readout end are incompatible with lens focusing: need to disassemble bar boxes for reuse
  - Facility, setups, and tools developed, disassembly of first bar box in progress
- hpDIRC barrel requires total of 360 short bars (1.225 m length)
- Eight bar boxes currently located at JLab could yield up to 384 short bars, sufficient to cover rapidity range $-1.65 \le \eta \le +1.65$
- Additional 120 bars required for the light guide section, $\eta \le -1.65$, to couple to lenses
- Quality of bar surfaces, 25 years after initial production and disassembly, to be verified
  - QA of first disassembled bars in progress



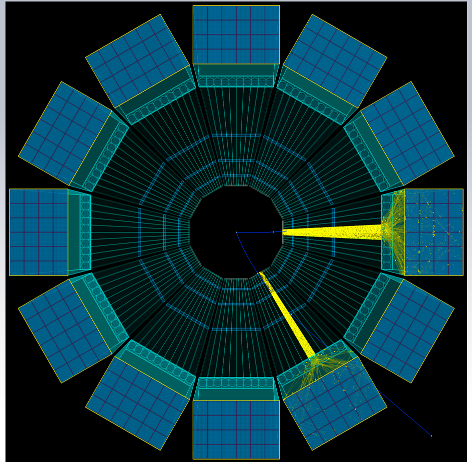
BABAR DIRC bar boxes at SLAC



Opened BABAR DIRC bar box at JLab



BABAR DIRC bar in JLab QA setup



PYTHIA events in ePIC hpDIRC

PID Review – April 2nd
JLab EIC Meeting – April 4th

ePIC hpDIRC

DIRC Bar Specifications and BABAR DIRC Bar Refurbishment for ePIC

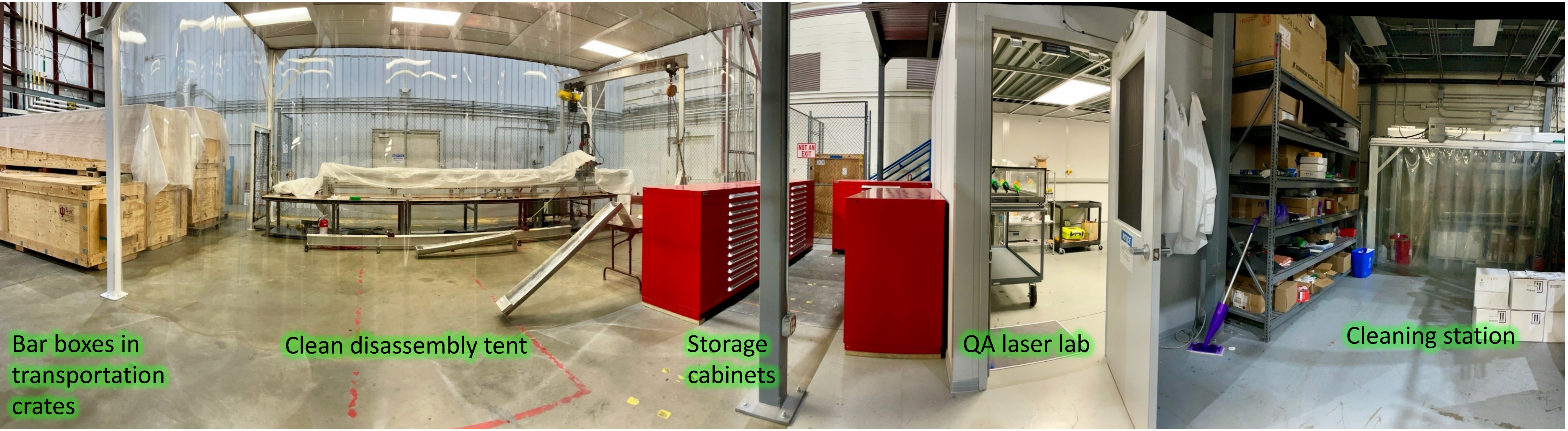
Final Design Review of the BABAR DIRC Bar Refurbishment for the High-Performance DIRC Particle Identification Detector

Jochen SCHWIENING

GSI Helmholtzzentrum für Schwerionenforschung GmbH

CUA GSI Jefferson Lab Old Dominion University Stony Brook University University of South Carolina Wayne State University William & Mary

Reuse of BaBar DIRC Bars



Disassembly process in JLab:

- Bar boxes are disassembled and bars are separated in clean tent
- Cleaning station to remove residue glue, visually inspect bars
- QA laser lab to inspect quality of the bars after disassembly
- Measured bars are wrapped, tagged and stored in cabinets

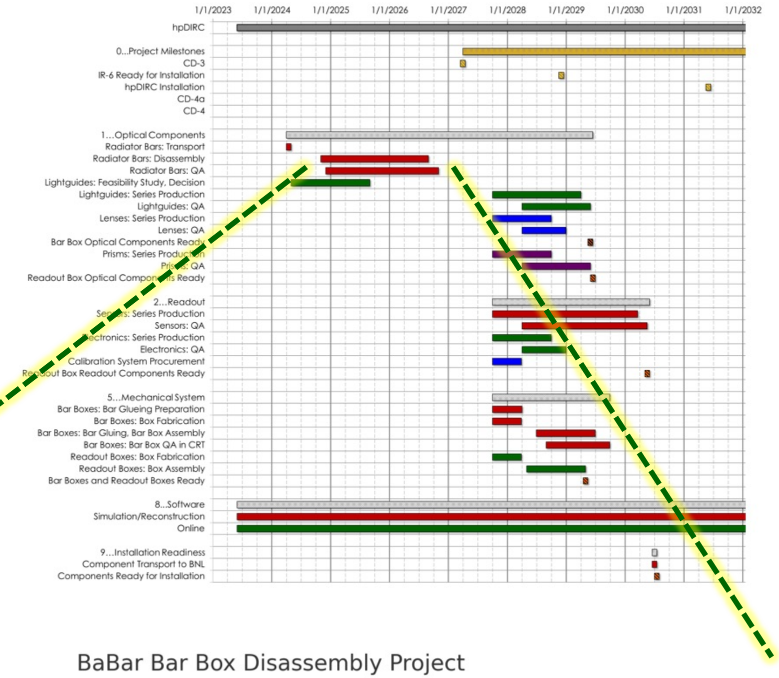
Team working on disassembly:

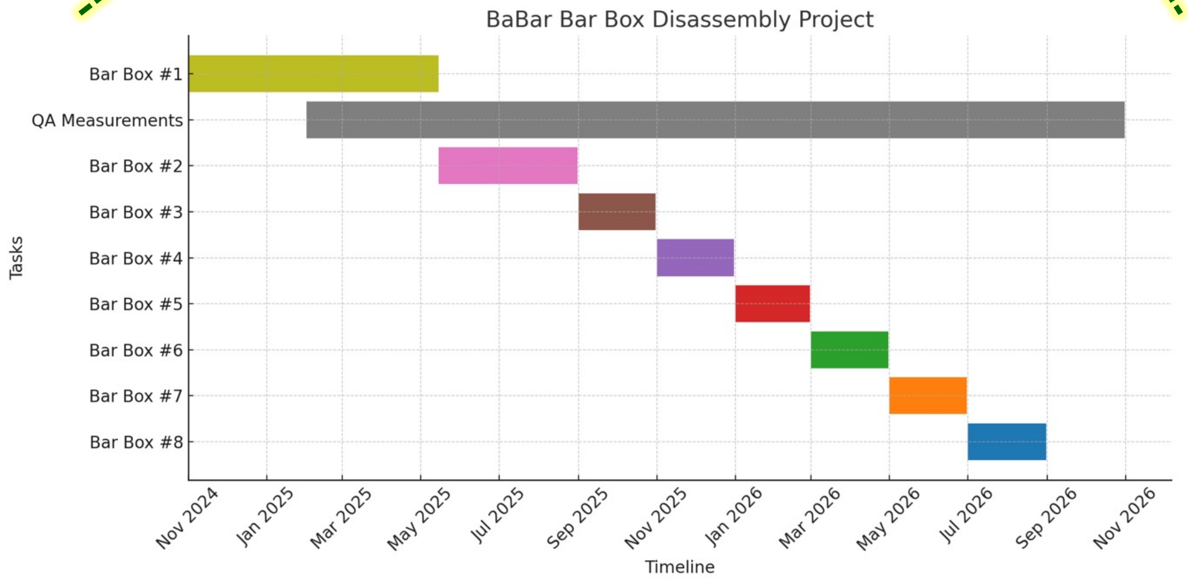
- 3 JLab Technicians: Andrew Lumanog, Caleb Graham, David Edwards
- 2 Scientists: Greg Kalicy (CUA), Sourav Tarafdar (JLab)
- JLab DSG Group: Tyler Lemon, George Jacobs, Mindy Leffel
- Graduate Students: Shelby Arrigo (W&M)

REUSE OF BABAR DIRC BARS

Resource-loaded schedule for refurbishment

- Expect work on each bar box to take about 2 months
  - Disassemble and remove one bar box shell: 2 weeks
  - Decouple 3 bar-bar joints, clean bar ends: 2 days
  - Clean and visually inspect one bar, tag ID, place bar in holder: ½ day
  - Laser QA measurement, wrap, move to storage: 1 day
- Spreadsheet keeps track of bar tag ID, properties, location
- Some of the task executed in parallel
- Task completion expected by Nov 2026





Refurbishment schedule fits overall ePIC hpDIRC schedule

READOUT

hpDIRC readout: Microchannel-Plate PMTs + ASIC-based electronics

- MCP-PMTs capable of meeting all hpDIRC requirements *(A. Lehmann review talk at RICH2022)*
- Baseline sensor for hpDIRC: 2'' Photek MAPMT 253 MCP-PMT
- Potential solution: DC-coupled Incom HRPPD

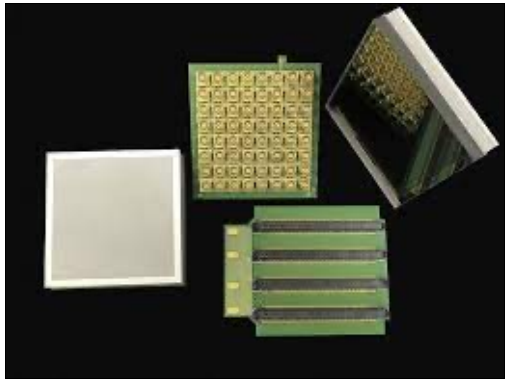
  Making use of synergy with pfRICH, optimizing cost and workforce

  - See pfRICH presentation from Brian for more HRPPD details and Alexander's slides on sensors from recent PID Review
- Setups are ready for side-by-side comparison and evaluation of key performance parameters with clear plan to have initial results and decision on sensor before TDR

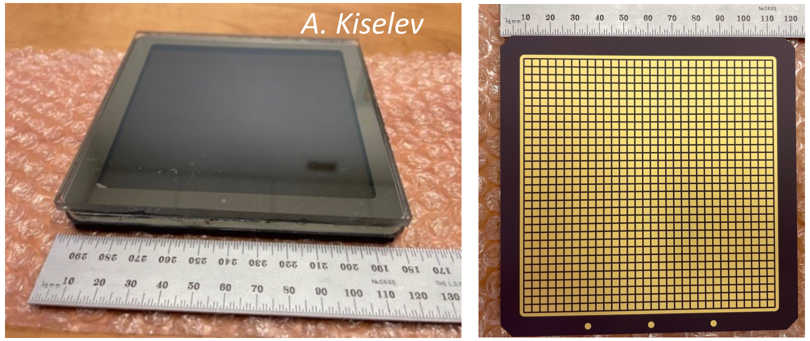
Baseline front-end board: FCFD

- Synergetic development with ePIC AC-LGAD and pfRICH systems
- Low-power ASIC, 128 channels per board
- Will deliver hit time, time over threshold
  - See readout presentation from Fernando and DAQ presentation from David

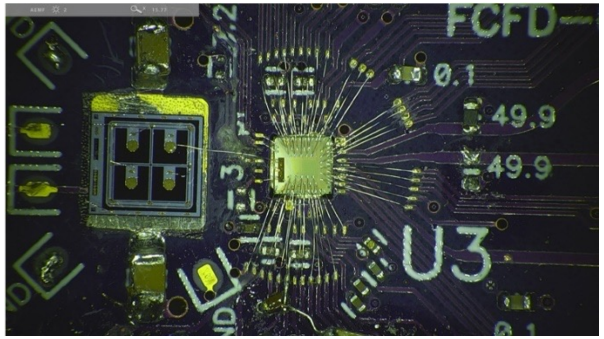
Photek MAPMT 253



INCOM Gen III HRPPD prototype (front/back view)



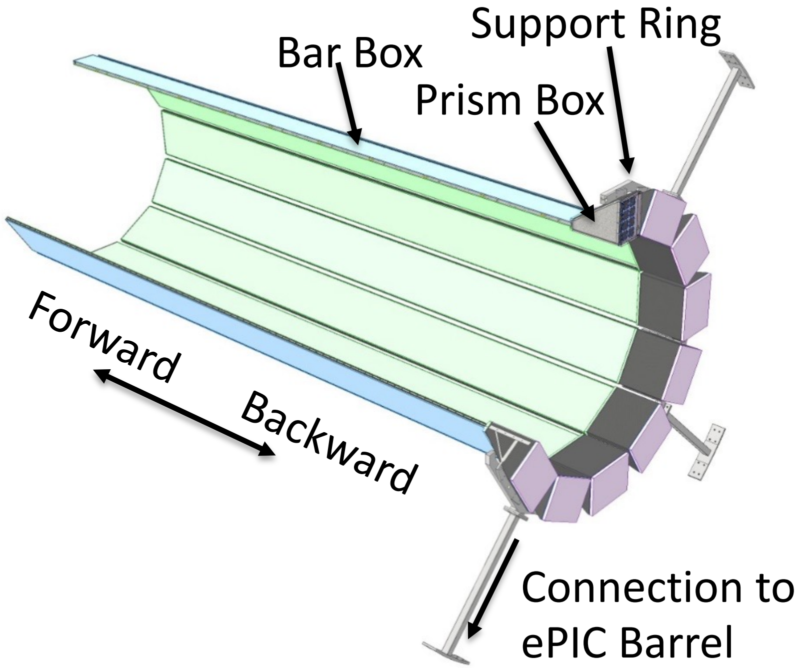
FCFDv0

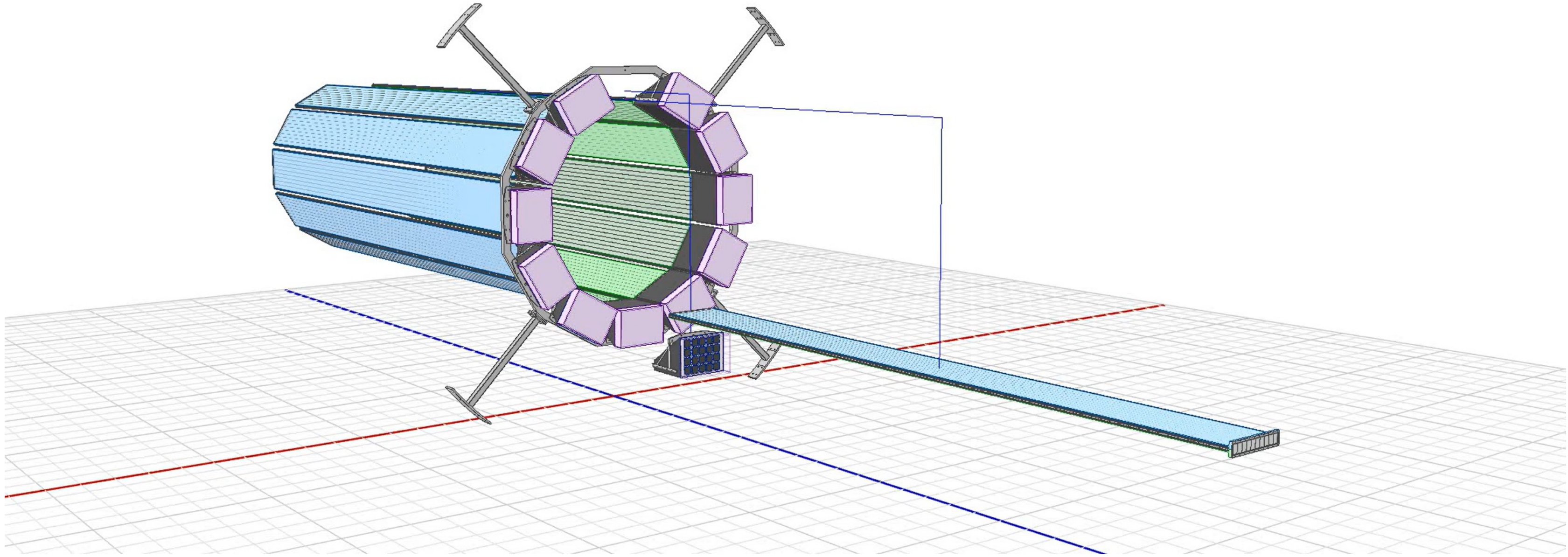


Engineering/integration support for hpDIRC from EIC project:

Avishay Mizrahi (MIT)

Kris Cleveland (JLab)

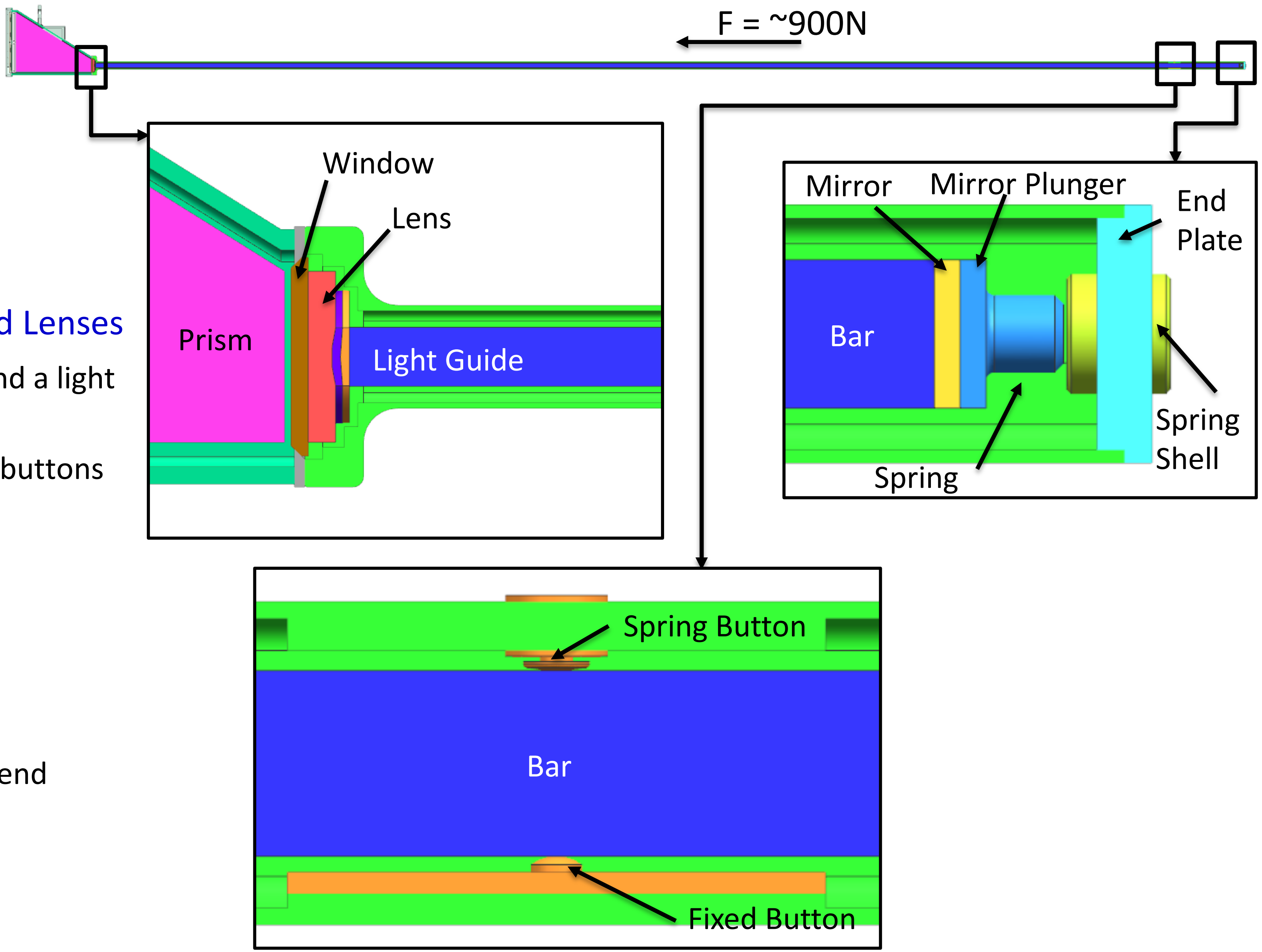




Mechanical Support and Integration

Bar Boxes:

- CFRP Shell
  - Approximately 4.6m Long
  - Thickness: 1.5 mm – 3 mm
    (thicker in key locations)
- Contains Quartz Radiator Bars, Mirrors, and Lenses
  - 10 long bars each formed by 3 short bars and a light guide section
  - Radiator bars supported on rounded nylon buttons to minimize losses
- Capped on each end
  - Spring End Plate at Forward End
  - Adjustable spring assemblies for each bar
  - Maintain compression in glue joints
  - Optically transparent window at backward end
  - Counters force from springs at forward end
  - Provides gas-tight boundary

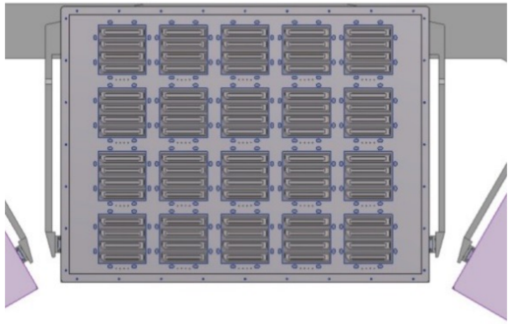


Mechanical Support and Integration

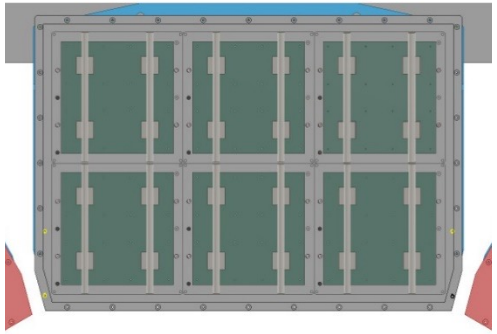
Readout Box

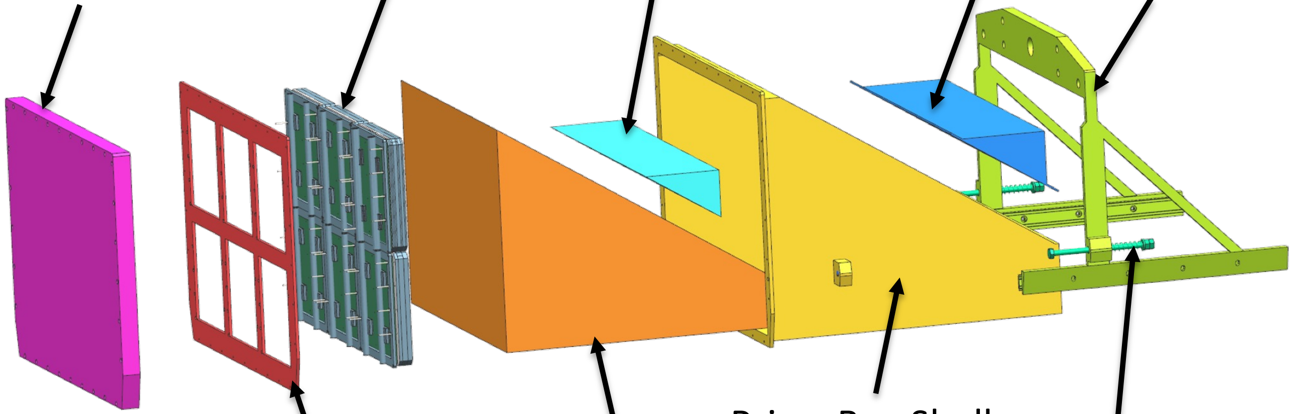
- Box shell
  - Current material: CFRP
  - Current thickness: 5 mm
- Contains expansion prism, calibration laser system
- Supports sensors, readout electronics, and associated services
- Mechanical design solutions for two sensor options:
  - MCP-PMT (baseline)
  - HRPPD
- Optical cookie connection between prism and bar box window

MCP-PMT



HRPPD



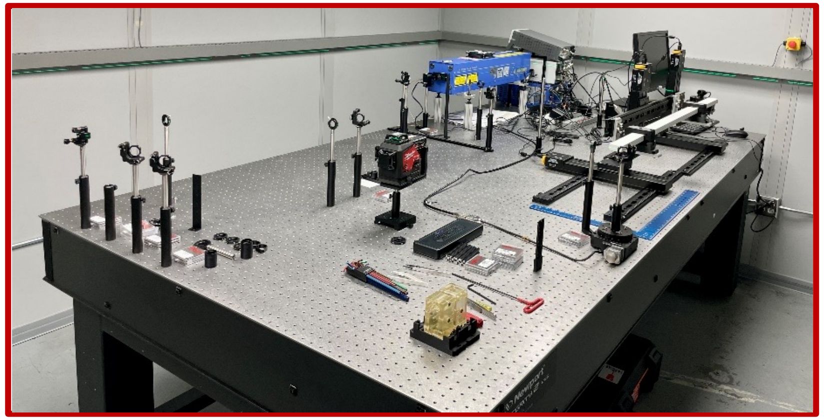


QA PLAN

Quality assurance plans (100% components will be verified/tested)

Combination of process control/QA at vendor site and lab measurements

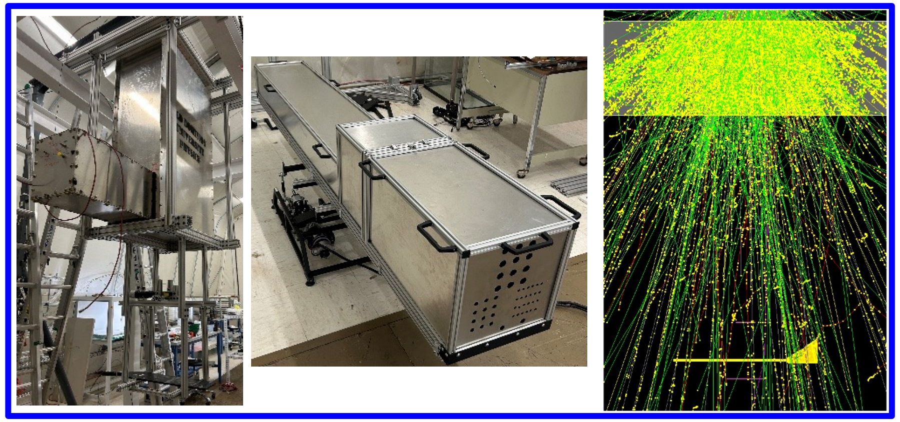
- Radiator bars and light guides: vendor QA for mechanical properties, laser scanning system at JLab to monitor internal photon transport efficiency of disassembled BaBar DIRC bars and/or new DIRC bars
- Sensors and electronics: laser pulser systems at CUA/JLab/USC (TBD) to measure gain, quantum and collection efficiency, dark count rate, etc
- Lenses: laser lab at ODU to evaluate shape of focal plane
- Prisms: vendor QA, checks at WSU
- Bar boxes, prism boxes: vendor QA, checks at CRT (SBU or JLab)
- Assembled DIRC module (bar box coupled to readout box, vertical slice): Cosmic Ray Telescope at SBU or JLab
- Installed DIRC module in ePIC: picosecond laser pulser calibration system, cameras to monitor optical coupling between sensors, prisms, lenses



DIRC laser lab at JLab

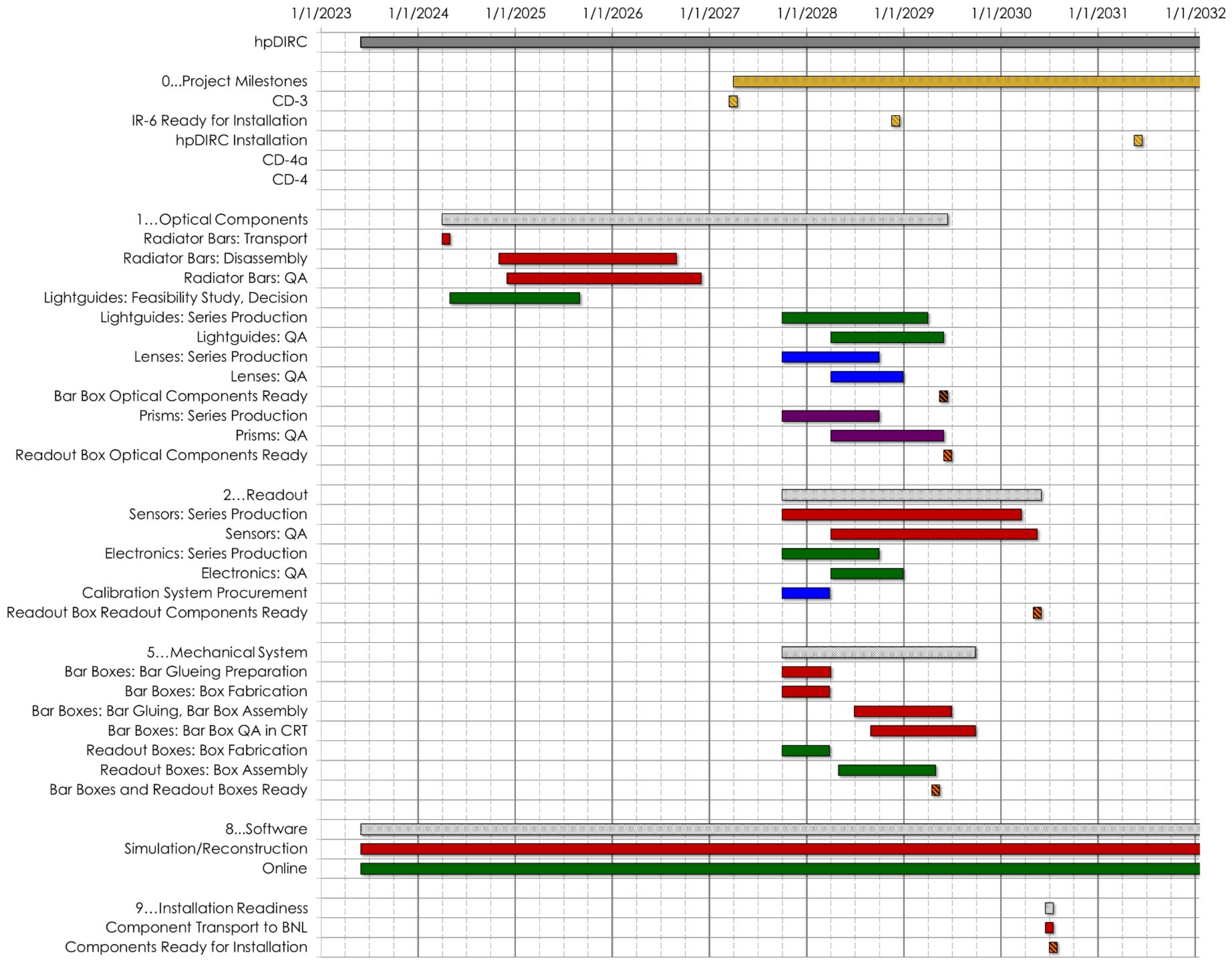
Lens evaluation setup at ODU

DIRC lab and Cosmic Ray setup at SBU (photos, Geant4)



SCHEDULE

- hpDIRC technical schedule consistent with project schedule
- hpDIRC scheduled for installation into ePIC in June 2031, expect hpDIRC readiness for installation well before that date

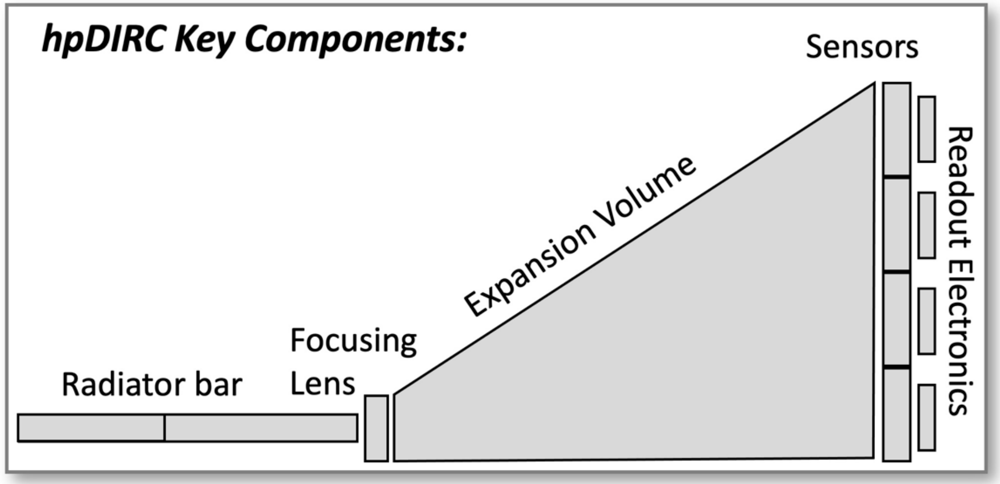


ePIC hpDIRC group (DSC)

- Core formed by groups that have been involved in the BaBar, GlueX, and PANDA DIRC counters, and in the EIC DIRC R&D program, for many years, some since 2011
- Current number of people across all institutions actively involved is 25

Responsibility examples:

- Radiators: transport and disassembly of BaBar DIRC bar boxes, validation quality of disassembled bars, optional QA of new bars/plates for light guide section – JLab, CUA, W&M
- Bar boxes: gluing of bars and lenses, assembly of bar boxes, QA in Cosmic Ray Telescope – SBU, JLab
- Lenses: evaluation of focal plane, QA – ODU, CUA
- Sensors: QA, readout chain tests – USC, Glasgow
- Readout boxes: assembly, QA – WSU
- Simulation, reconstruction – CUA, GSI, W&M, WSU, Jazan



SUMMARY

- ePIC hpDIRC: Fast focusing DIRC concept, developed over 10+ years of EIC R&D
- Expected PID performance meets ePIC requirements (Yellow Report), separation: 3 ≥ s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.1 GeV/c
- Key elements, simulation and focusing lenses, validated in particle beam in 2018
- Main remaining steps towards production readiness and TDR:
  - Validation of reusing BaBar DIRC radiator bars
  - Evaluation of sensors and readout ASIC (synergy with pfRICH)
  - Completion of mechanical design and integration
- ePIC hpDIRC group includes nine institutions, 23 active participants with well-established expertise
- Plans for remaining studies, QA, and construction match project schedule
- Passed 60% Design review in April 2025
- Passed Final Design Review of BaBar DIRC bar refurbishment in April 2025