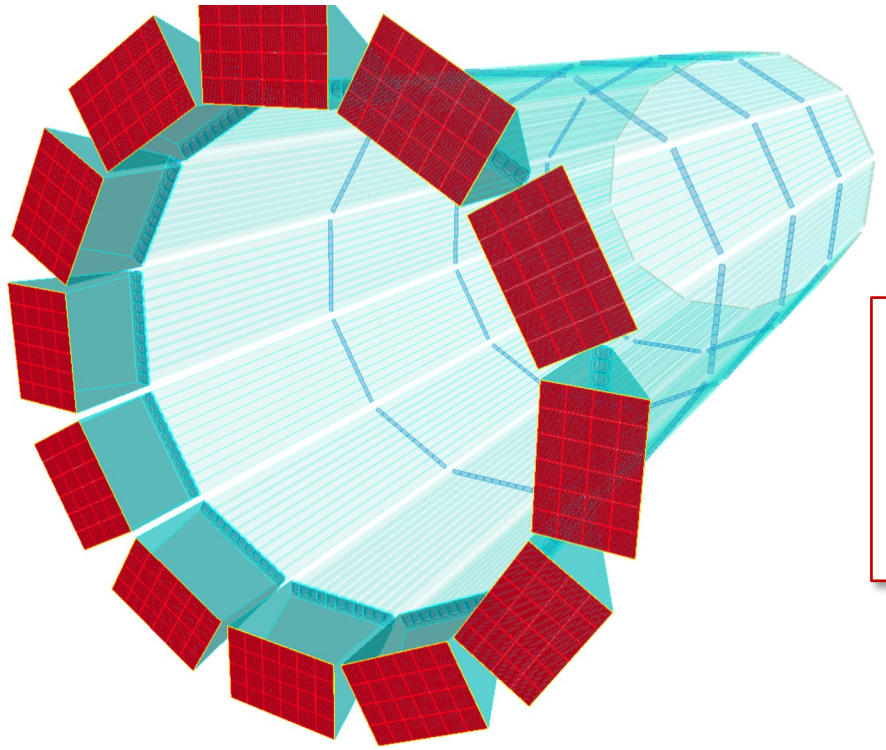
The hpDIRC Detector for the ePIC Experiment

Greg Kalicy

CUA



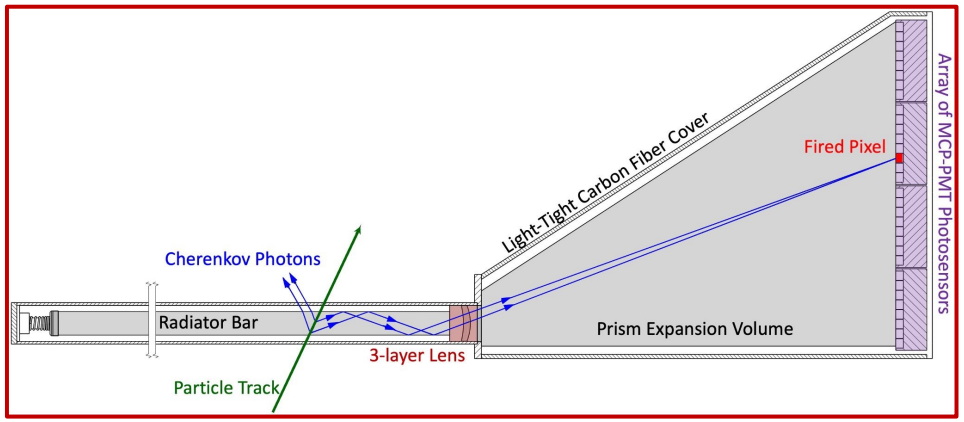
XII International Workshop on Ring Imaging Cherenkov Detectors – RICH 2025

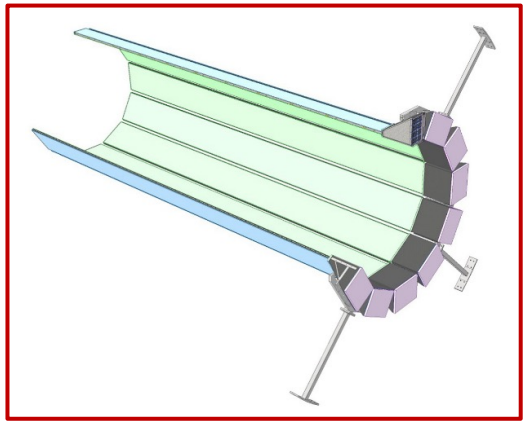
September 18th, 2025

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

Outline

- Introduction
  - ePIC requirements for hadronic barrel PID
  - hpDIRC detector for Electron-Ion Collider
- High-performance DIRC for ePIC
  - Concept
  - Design
  - Mechanical design and integration
  - Simulation and expected performance
- Main components and their validation
  - 3-layer lenses
  - Sensors and readout electronics
  - DIRC bars
  - Full chain tests with cosmic rays
- Summary



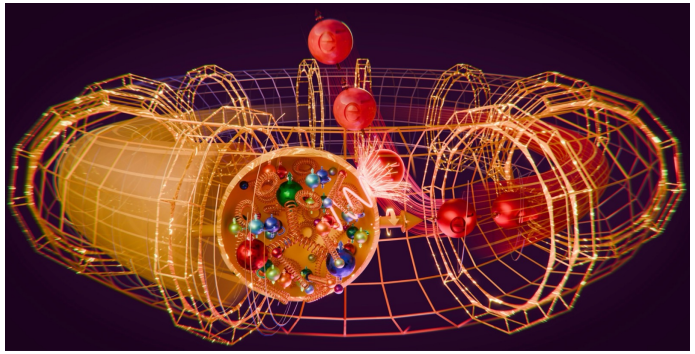


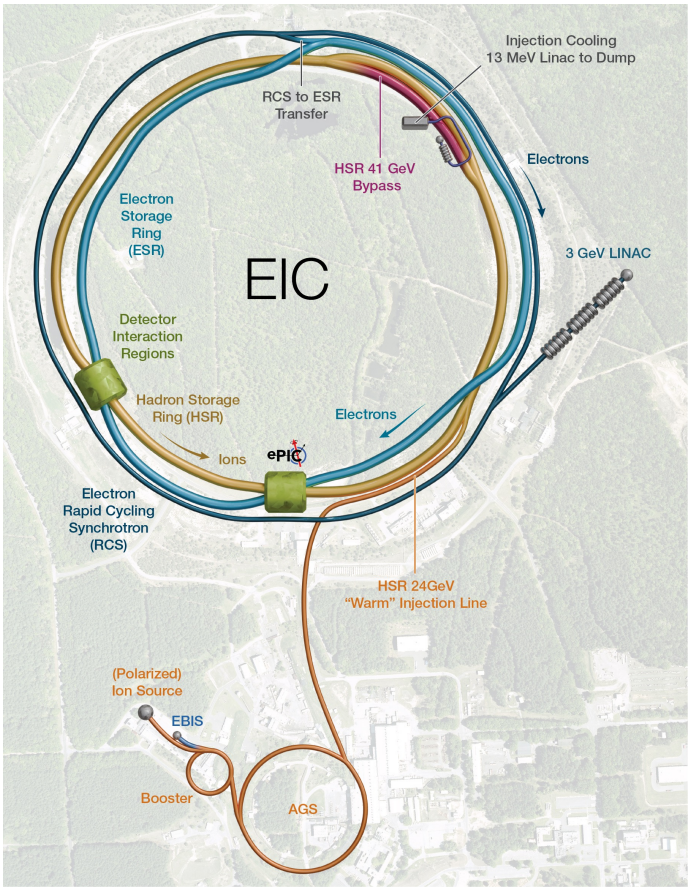
Electron-Ion Collider

- EIC: A high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV
- Factor 100 to 1000 higher luminosity as HERA

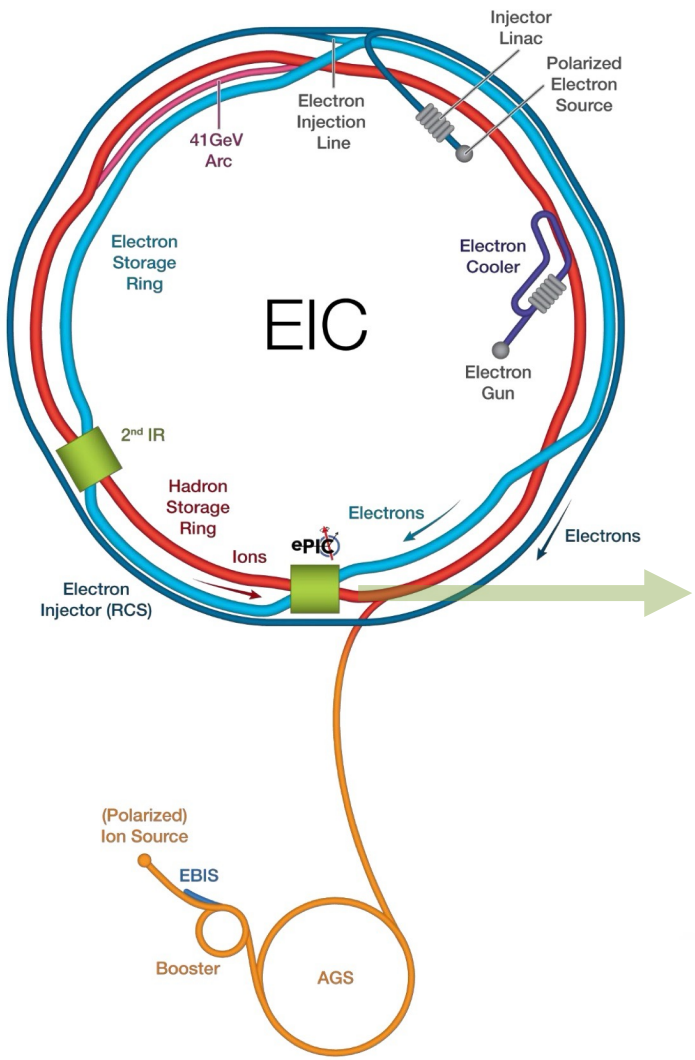
  both electrons and protons / light nuclei polarized,

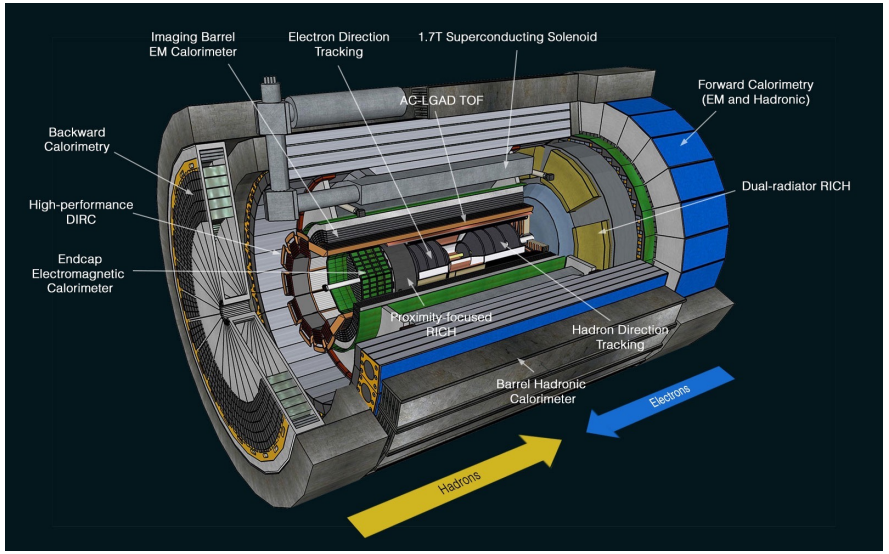
  nuclear beams: d to U
- Science Program: EIC can uniquely address profound questions about nucleons and how they are assembled to form the nuclei and atoms
- ePIC: State of the art general purpose collider detector
- Status: System Collaborations and Working groups finalizing preparations for construction, advanced stage of editing preTDR
- 2nd Interaction Region and potential for 2nd Detector



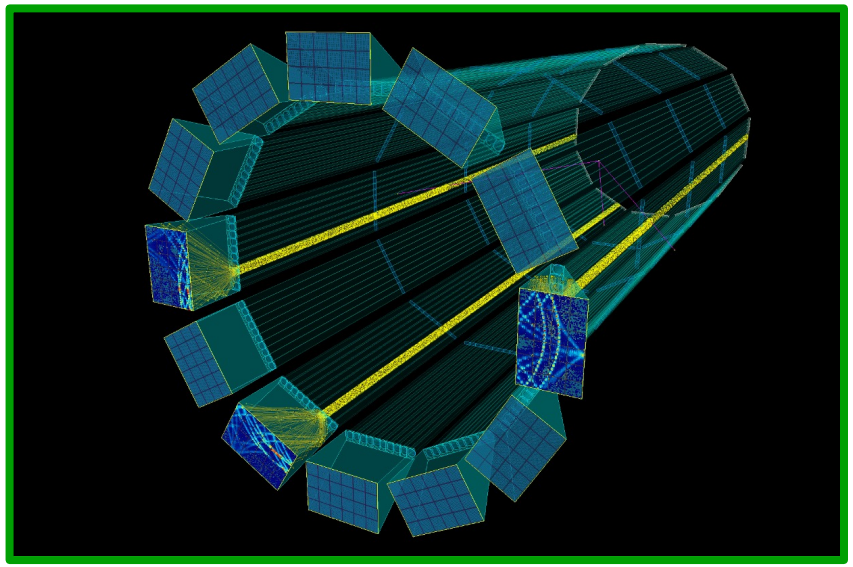


hpDIRC for Electron-Ion Collider



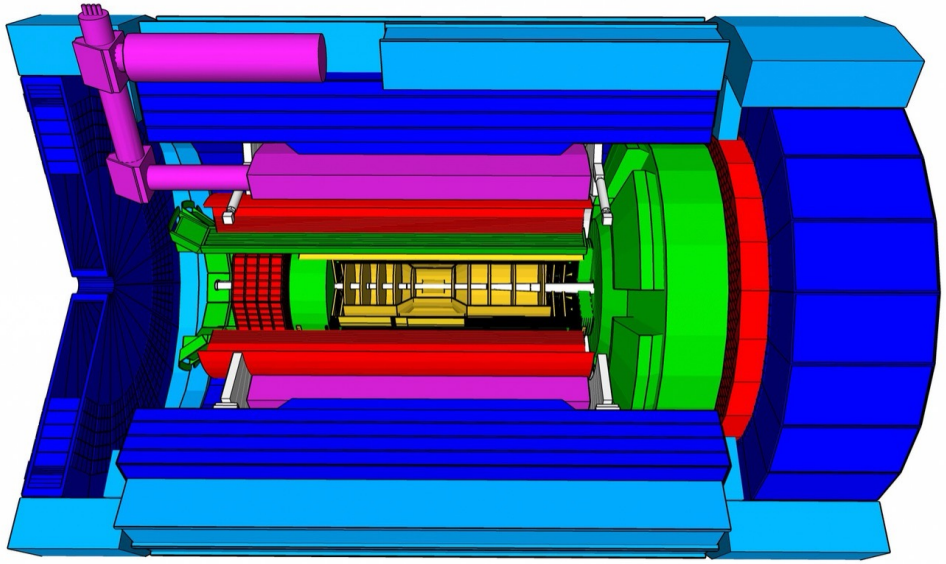


ePIC EIC hpDIRC



ePIC

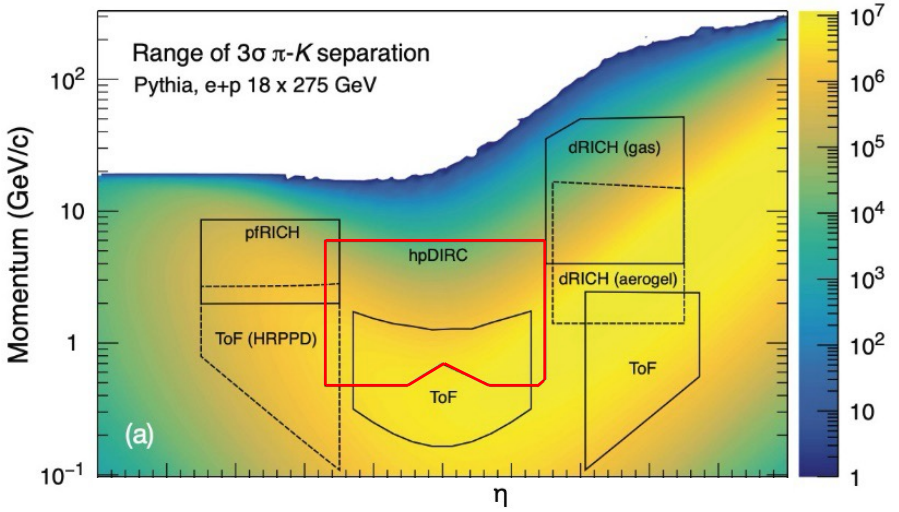
- hadronic calorimeters
- Solenoidal Magnet
- e/m calorimeters (ECal)
- Time.of.Flight, DIRC, RICH detectors
- MPGD trackers
- MAPS tracker



CHARGED PID REQUIREMENTS IN EPIC

- 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 ($-1 \leq \eta \leq +1$):
  - 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



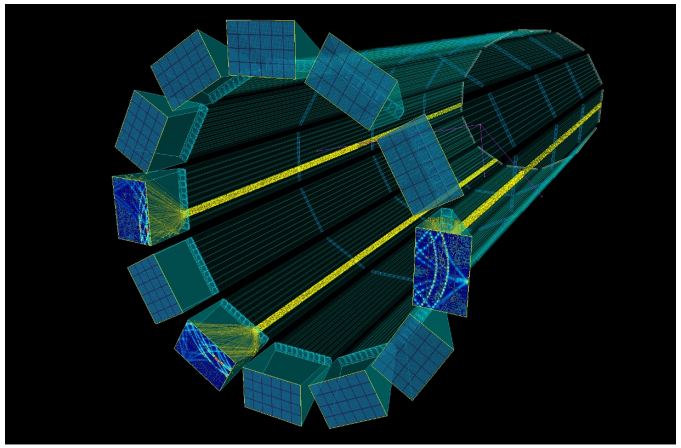
HIGH-PERFORMANCE DIRC OVERVIEW

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

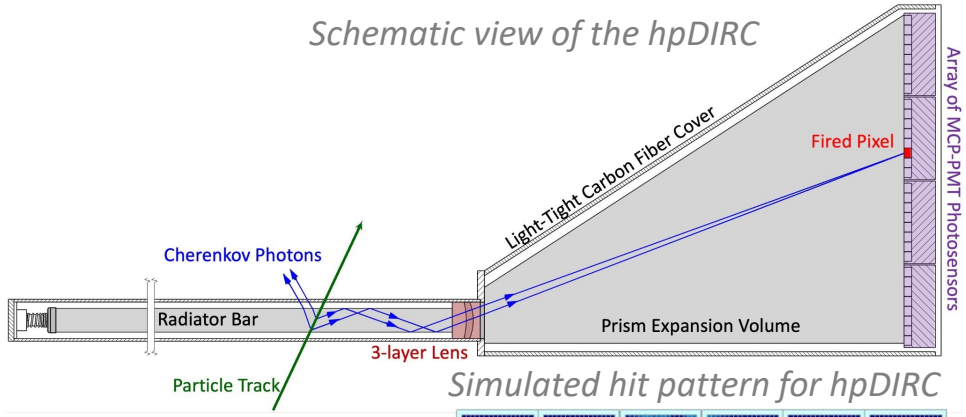
- Concept: fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction.
- Radiation-hard 3-layer spherical lens to reduce bar image size and shape imaging plane;
- Lifetime-enhanced MCP-PMTs with fine anode segmentation to reduce pixel size;
- Fast photon timing for chromatic dispersion mitigation 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.

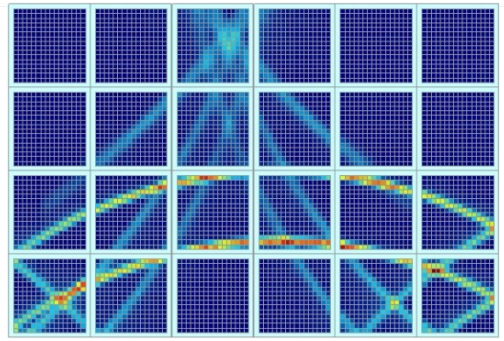
ePIC EIC hpDIRC in DIRC Geant4 Simulation



Schematic view of the hpDIRC



Simulated hit pattern for hpDIRC



HPDIRC DESIGN

DIRC 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:

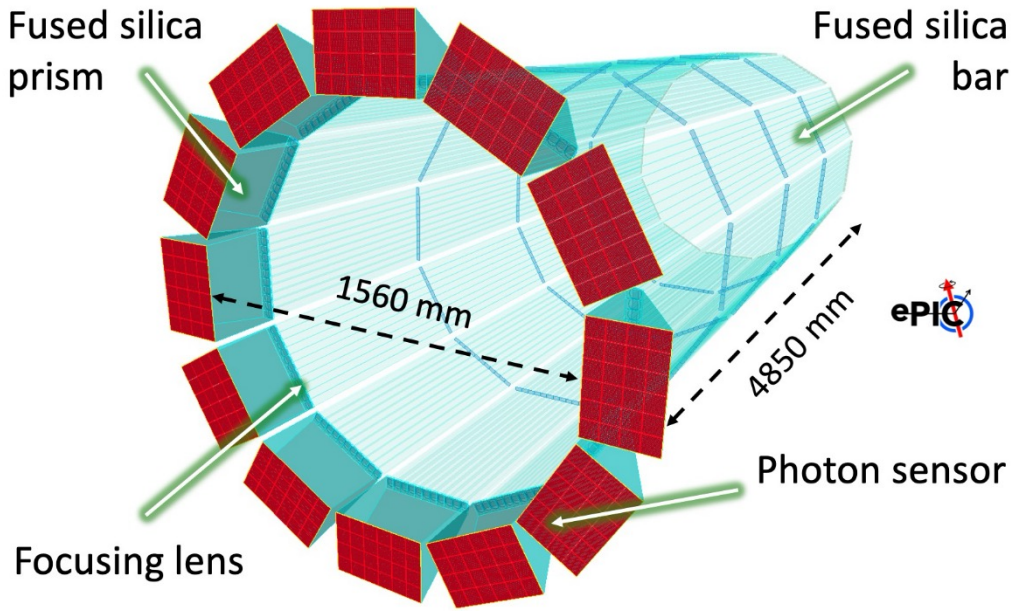
- Radiation-hard 3-layer spherical lens (sapphire)

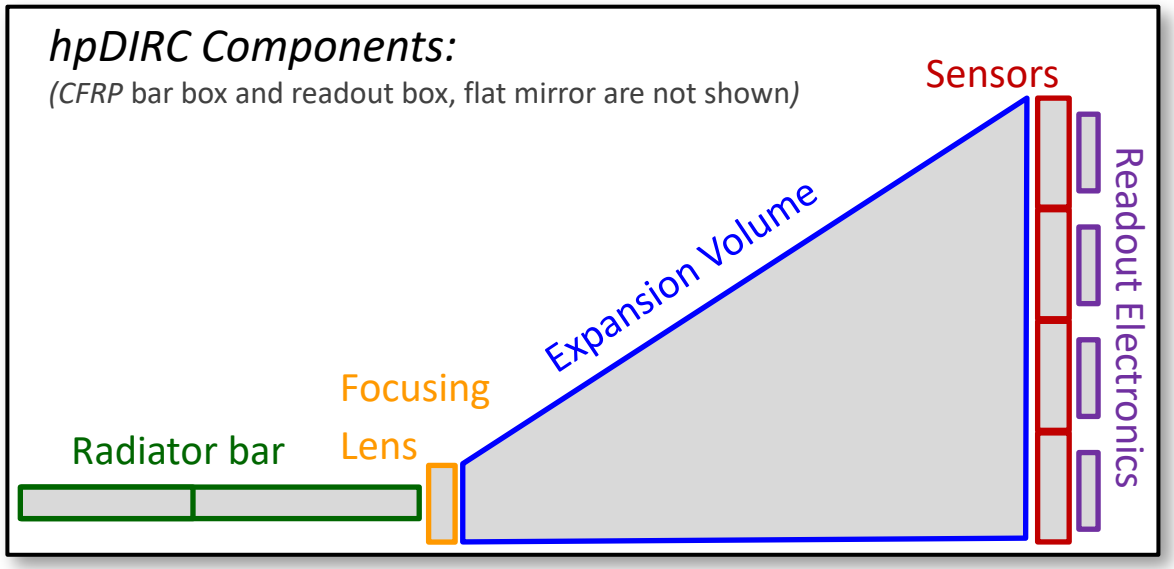
Expansion volume:

- 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)





HPDIRC SIMULATION

Geant4 DIRC Simulation Software

- Realistic optics, geometry, and wavelength-dependent material properties
- Validated with test beam data (PANDA Barrel DIRC prototype at CERN)

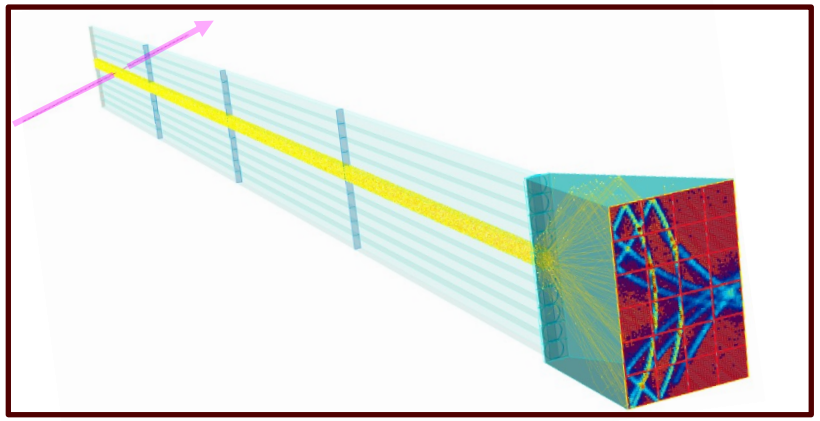
hpDIRC Performance

- Expected PID performance meets ePIC requirements (Yellow Report), separation: 3 ≥ s.d. π/K up to 6 GeV/c
- Confirmed robust performance in magnetic field, using physics events (Pythia) to include backgrounds, multiple tracks per bar

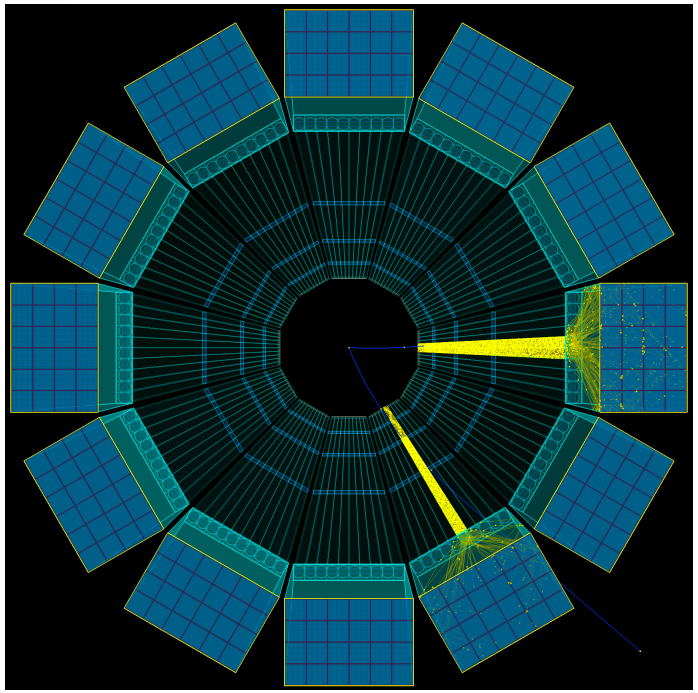
Ongoing Studies

- Effects of bar/lens misalignments and realistic tracking angular resolution, and their mitigation
- Full integration into the global ePIC software and reconstruction
- Machine Learning approach to reconstruction

Single particle gun events to map hpDIRC performance



Pythia events in hpDIRC simulation



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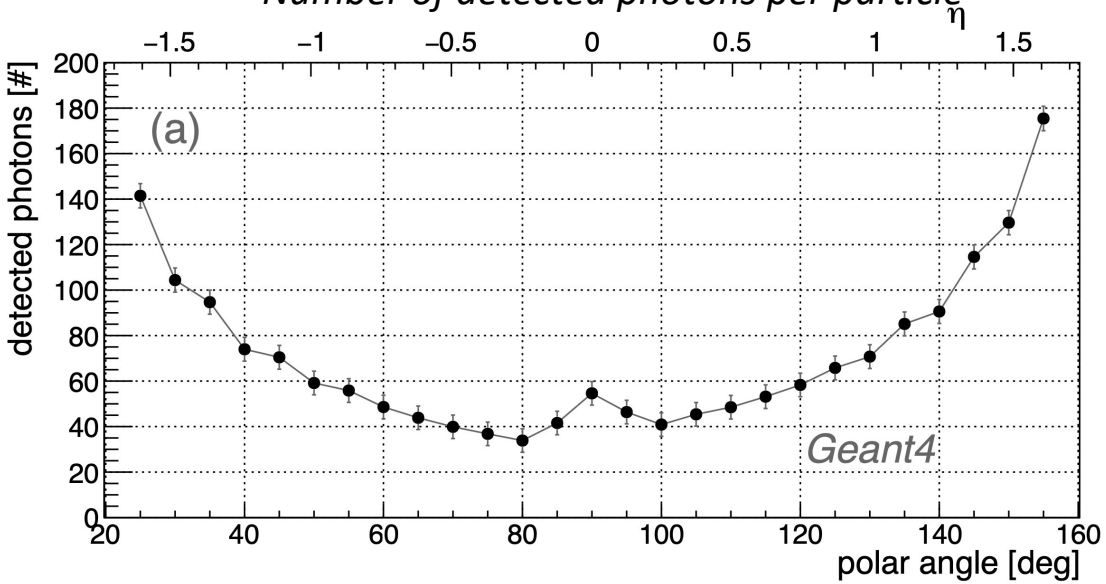
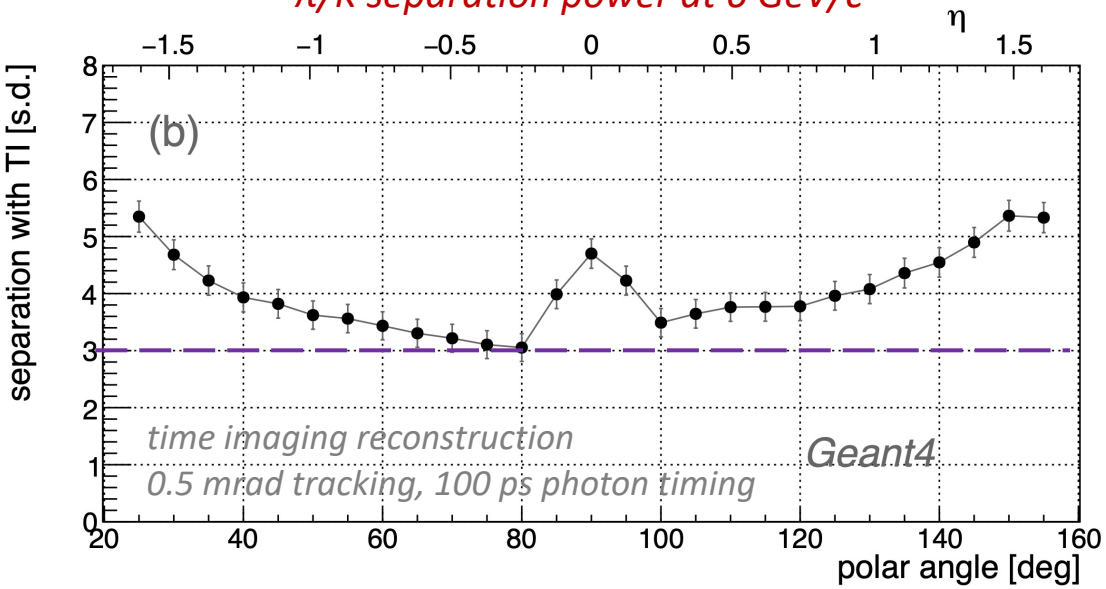
Number of detected photons per particle



π/K separation power at 6 GeV/c



3-Layer Focusing Lens

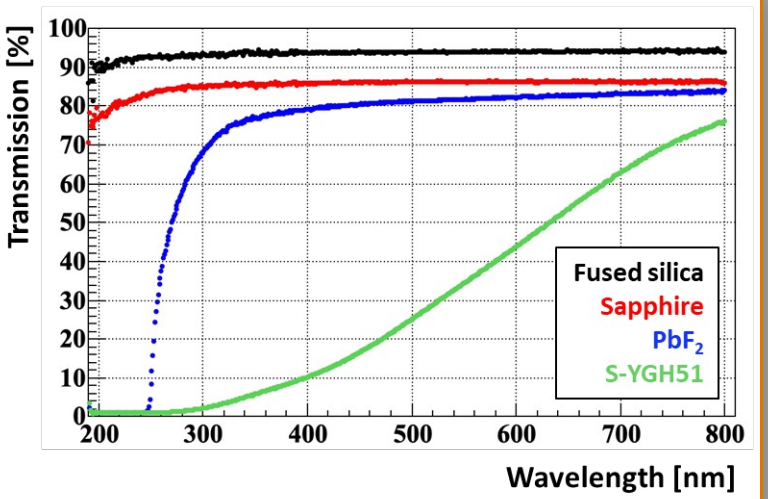
- 3-layer compound lens (without air gap):

  layer of high-refractive index material (focusing/defocusing)
  sandwiched between two layers of fused silica

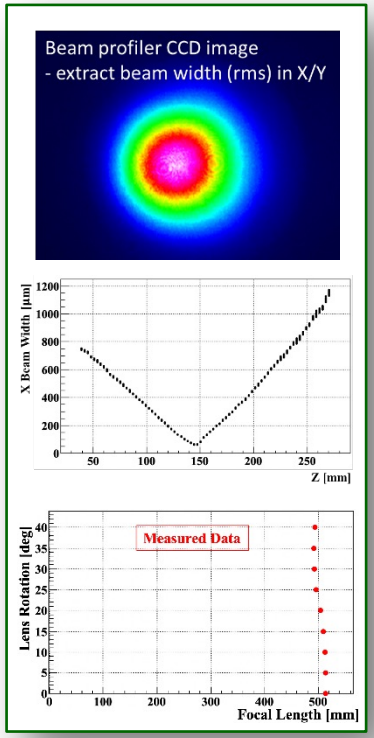
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Detailed radiation-hardness studies performed with ^{60}Co source
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire for ePIC
- Industrial fabrication of lenses demonstrated
- Performance of spherical 3-layer lenses validated with PANDA Barrel DIRC prototype

Laser lab in ODU

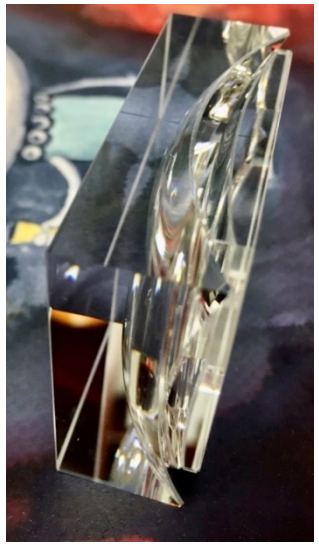
Transmission after 2Mrad dose (^{60}Co source)



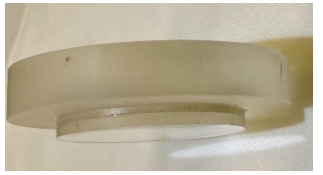
Work supported by Jim Kierstead (BNL)



Sapphire (RMI, USA)



PbF_2 (HIT, China)

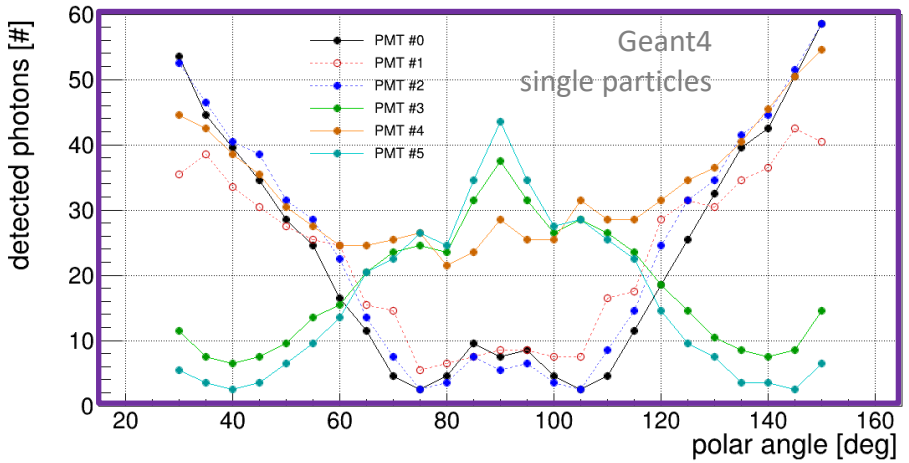


READOUT

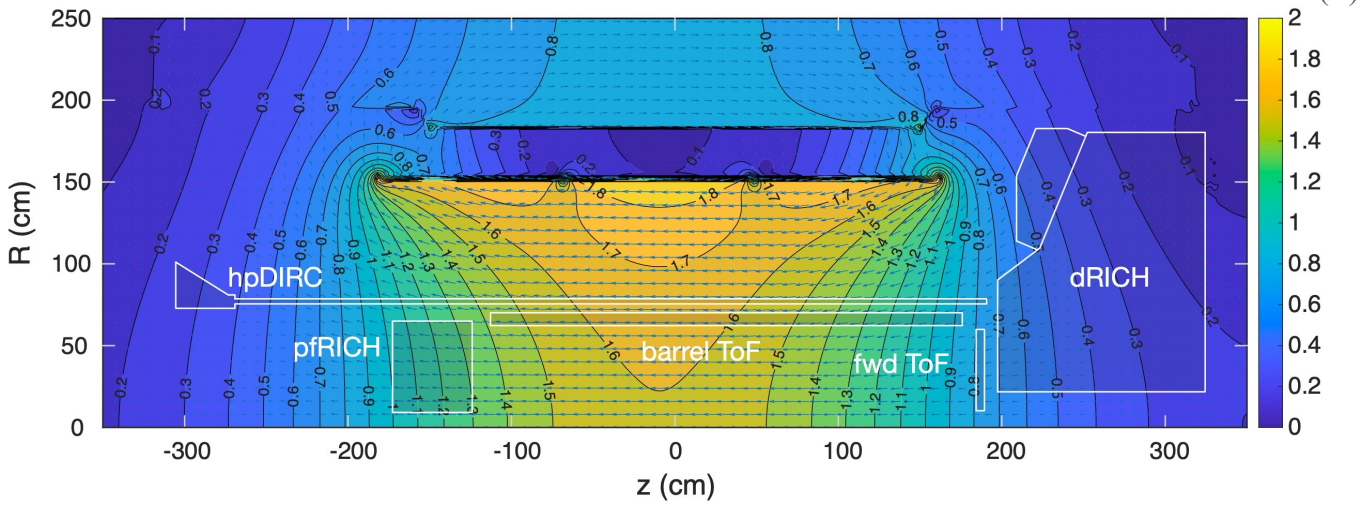
hpDIRC sensor requirements

- Tolerance for high occupancies: up to 150+ photoelectrons per particle, need DC-coupled anodes
- Single photon sensitivity in ePIC magnetic field
- Fast timing for single photons: timing precision (rms) < 100 ps
- Large active area ratio for tiled sensors: goal > 75%
- High PDE in visible range: goal > 25% at 400 nm
- Small pixels: anode pixel size < 3.5 mm
- Tolerance for high photon rates: goal > 100 kHz/cm^2
- Long lifetime: goal > 3 C/cm^2

Expected number of photoelectrons per particle per 12 cm x 12 cm sensor



ePIC magnetic field map with the PID detector envelopes overlaid



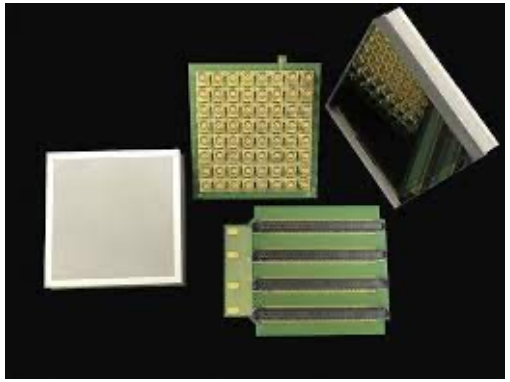
READOUT

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

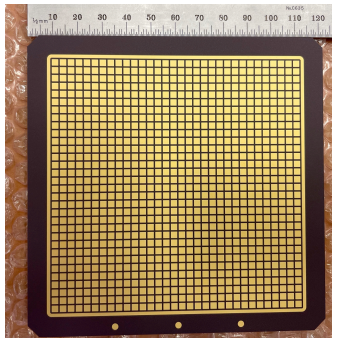
- MCP-PMTs capable of meeting all hpDIRC requirements *(A. Kiselev talk on Wed Sep 17th)*
- Baseline sensor for hpDIRC: 2'' Photek MAPMT 253 MCP-PMT
- Potential alternative: DC-coupled Incom HRPPD

  Making use of synergy with pfRICH, optimizing cost and workforce
  - See pfRICH presentation and dedicated photosensors talks for more HRPPD and MCP-PMTs details
- Setups in US and Glasgow are ready for side-by-side comparison and evaluation of key performance parameters (decision on sensor expected before TDR)

Photek MAPMT 253



INCOM Gen III HRPPD prototype (front/back view)

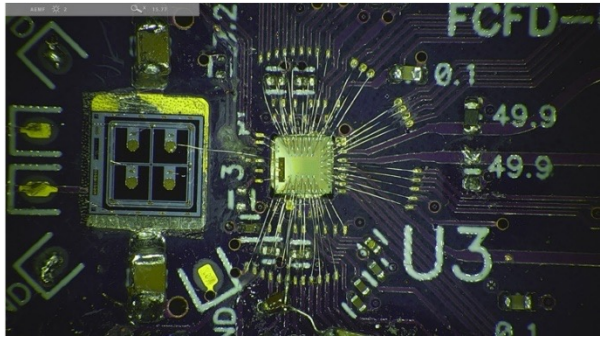


Baseline front-end board:

FCFD: Fermilab Constant Fraction Discriminator Readout Chip

- Synergetic development with ePIC AC-LGAD and pfRICH systems
- Low-power and high time precision ASIC, 128 channels per board

FCFDv0



BARS

- Potential reuse of BaBar DIRC bars can provide significant cost saving, reduces technical and schedule risk
- 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 finished
- 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 $-1.65 \leq \eta \leq +1.65$
- Additional 120 bars required for the light guide section, $\eta \leq -1.65$, to couple to lenses
- Quality of bar surfaces, 25 years after initial production and disassembly, is being verified

BaBar DIRC bar boxes stored in SLAC

First BaBar DIRC bar box opened in JLab

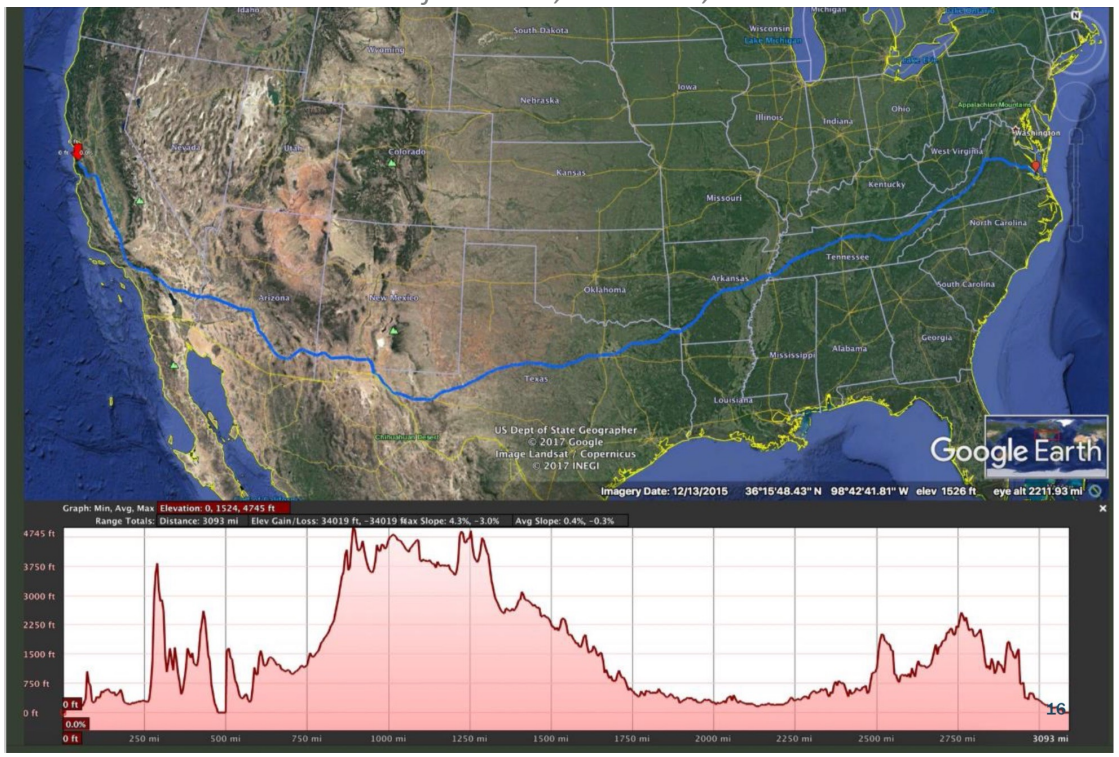
Moving BaBar DIRC Bars

Successful transport of 8 DIRC bar boxes in April 2024

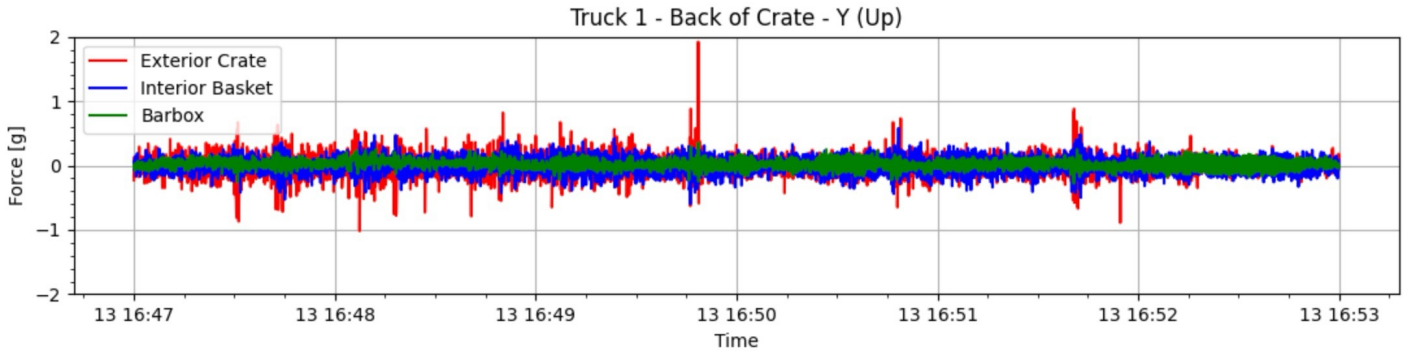
- Followed procedure from bar box transfer for GlueX in 2017/2018
- Low altitude road from SLAC, CA to JLab, VA
- Goal: Kept shocks on Bar box below 1g

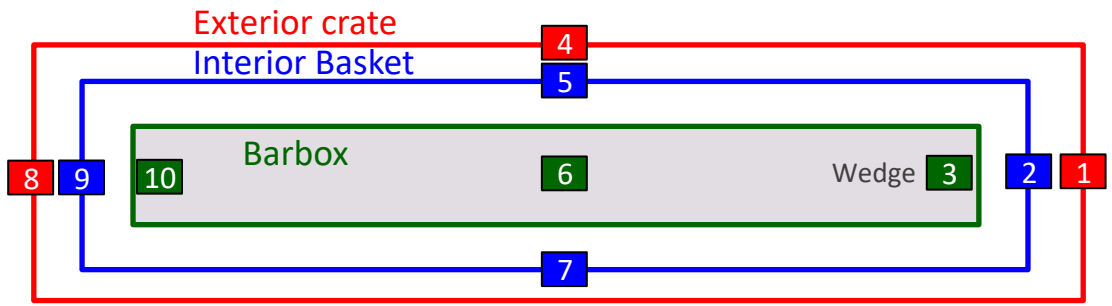
(Transportation crates with inner suspension, shock-absorbing foam, hydraulic shocks, air shocks, shock-absorbing donuts, air-ride and temperature control trucks)

Road from SLAC, CA to JLab, VA



Sample of vibrations during transport and location of accelerometers





Andrew Lumanog, Tyler Lemon, Random guy from Poland, Jochen Schwiening

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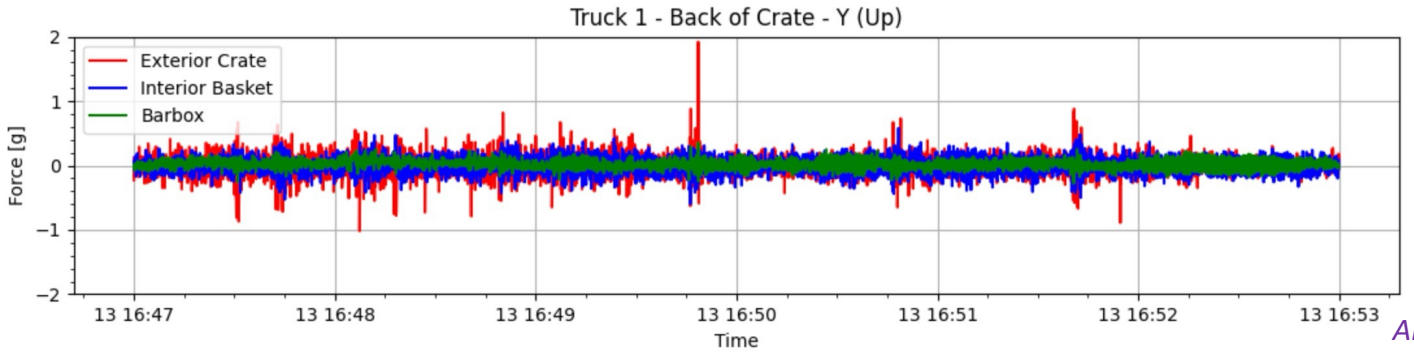
Inside of transportation crates

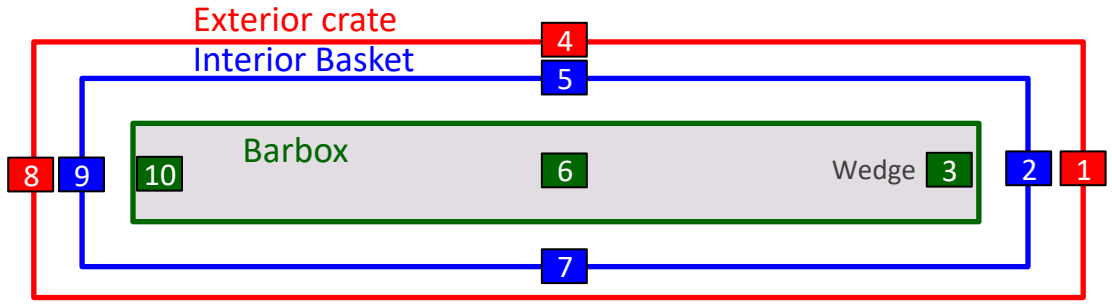
Loaded bar boxes ready for transport

8 bar boxes in two trucks

Bar boxes in Jlab ready for disassembly

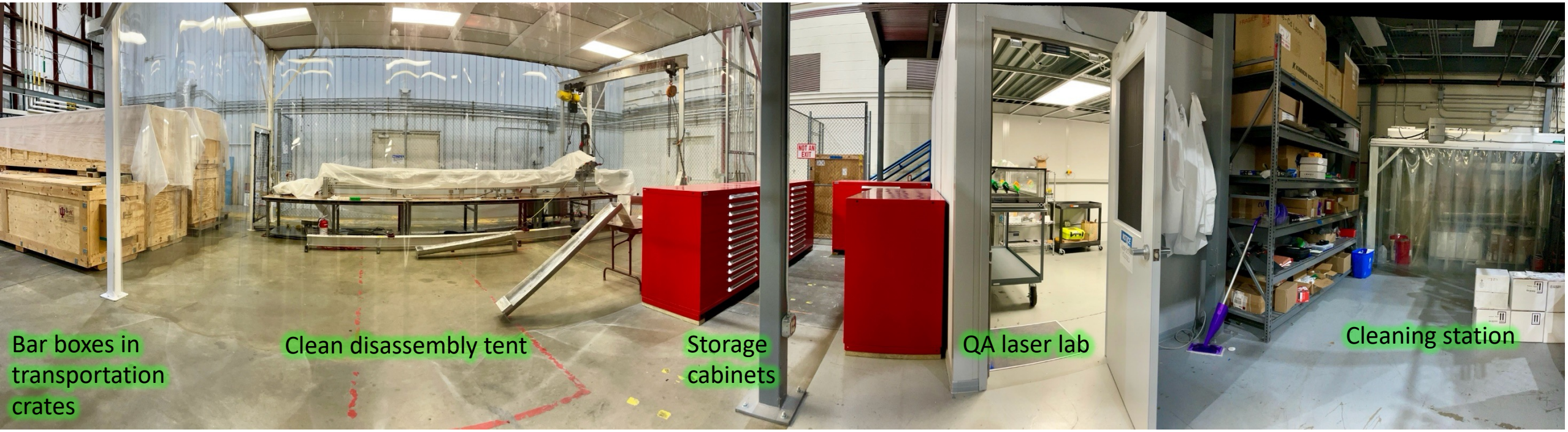
Sample of vibrations during transport and location of accelerometers





Andrew Lumanog (JLab), Tyler Lemon (JLab), Greg Kalicy (CUA), Jochen Schwiening (GSI)

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

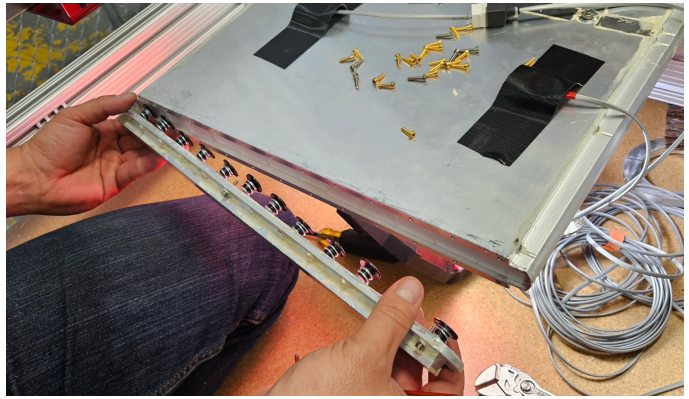
Status:

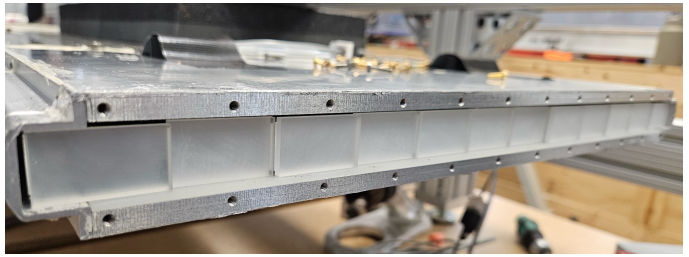
- Aluminium shells removed from two bar boxes
- First bar box fully disassembled, 48 short bars separated, QA started
- Second bar box disassembly in progress

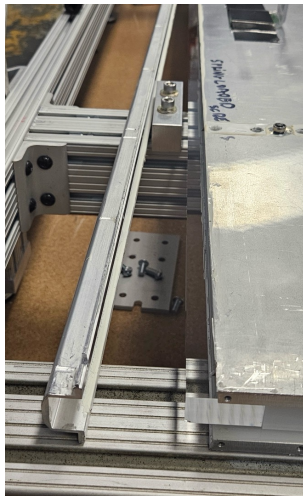
Reuse of BaBar DIRC Bars

Bar box on CNC

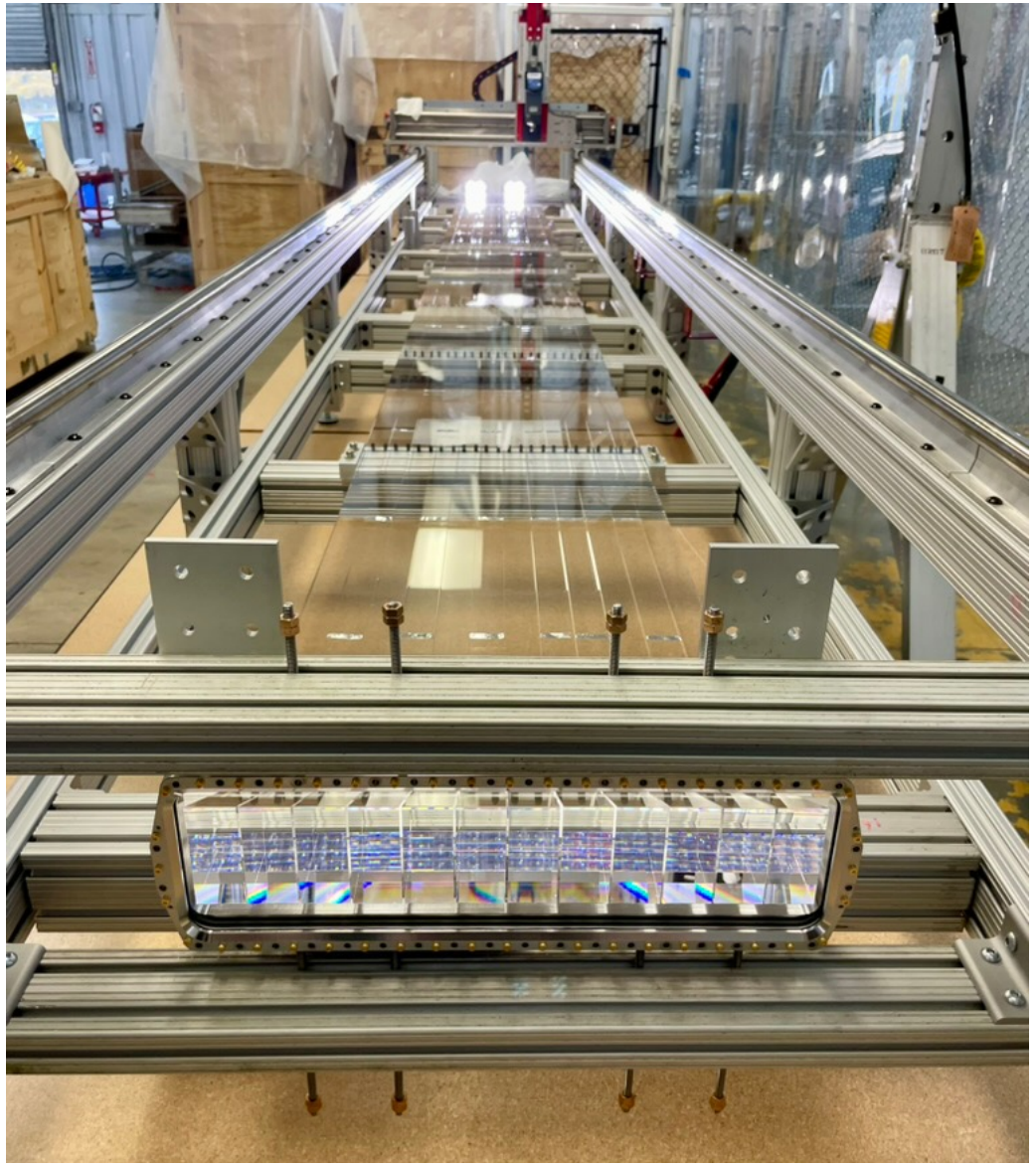
Removing aluminum shell







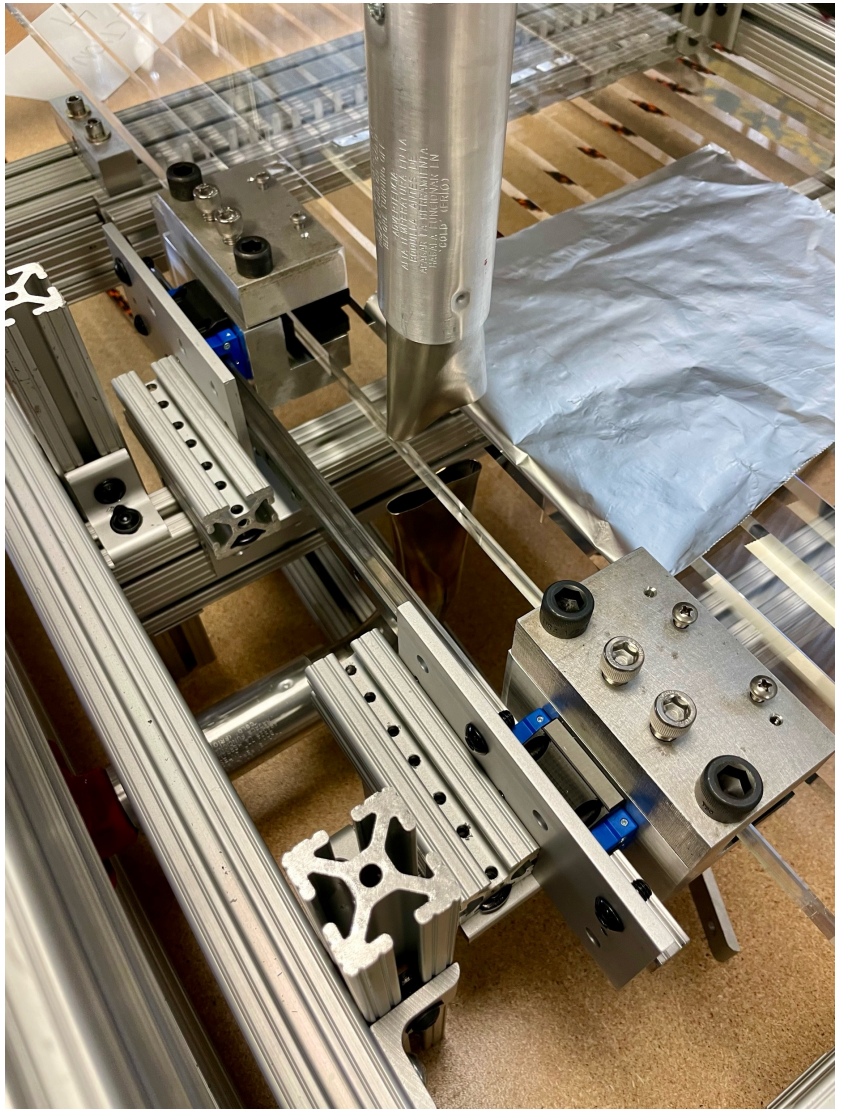
Bar box with disassembled aluminum shell



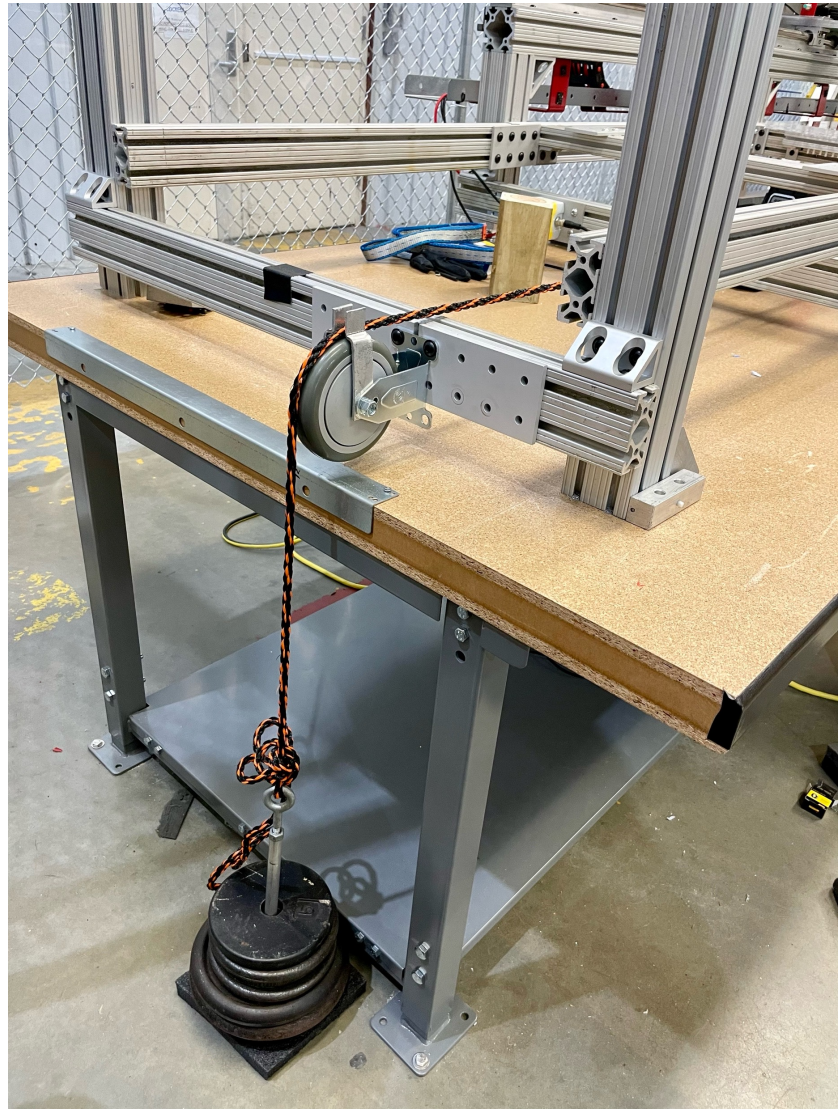
Reuse of BaBar DIRC Bars

Heat guns softening glue joints between bars

Highly adjustable clamps to separate bars



Weight with short travel pulling on clamp

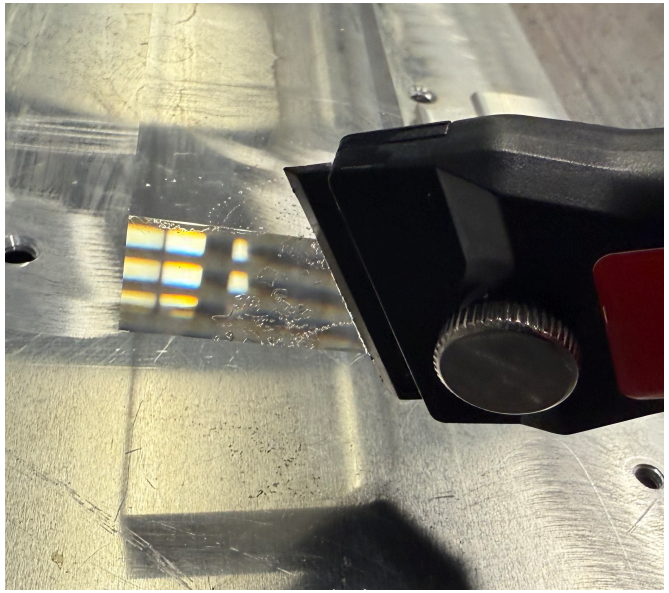


Reuse of BaBar DIRC Bars

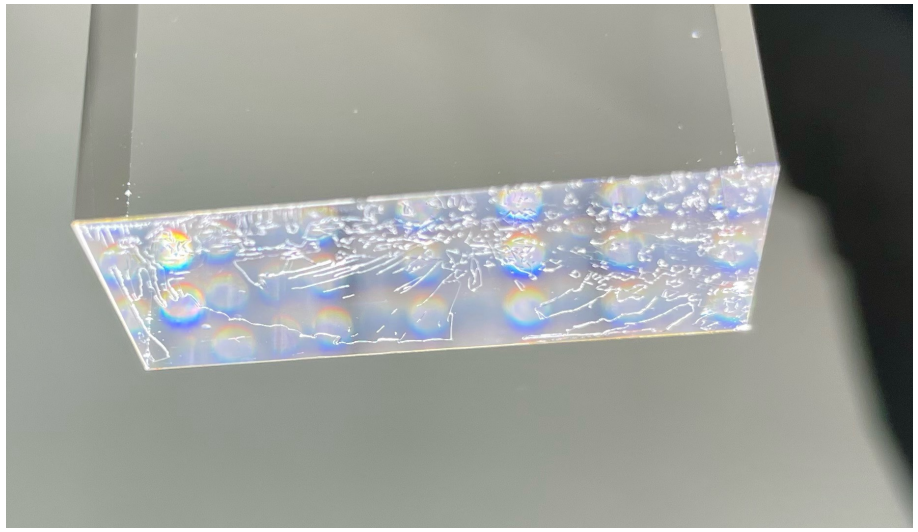
Bar end immersed in acetone bath

"Bathtub" in position for glue removal

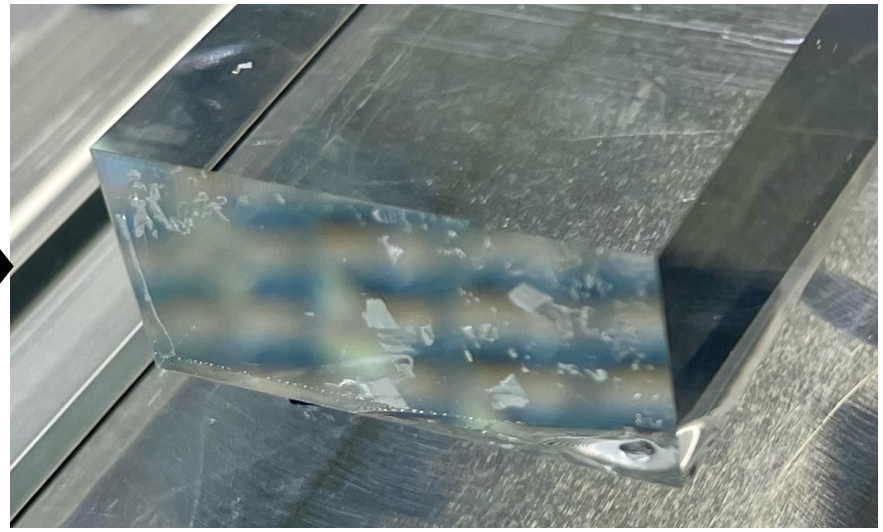
Glue removal



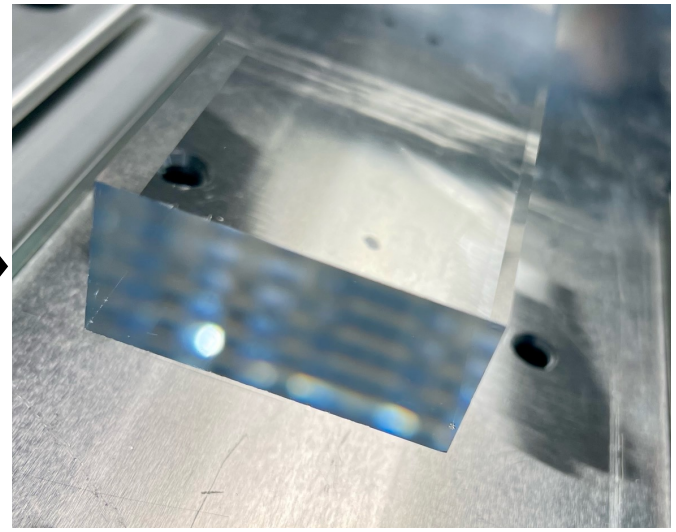
Glue residue after separation



Glue residue mid-way through cleaning

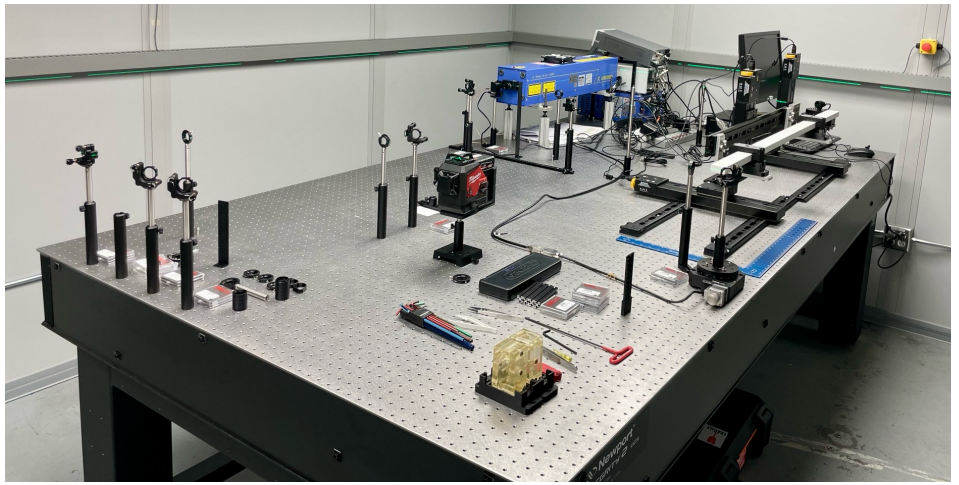


Cleaned bar end

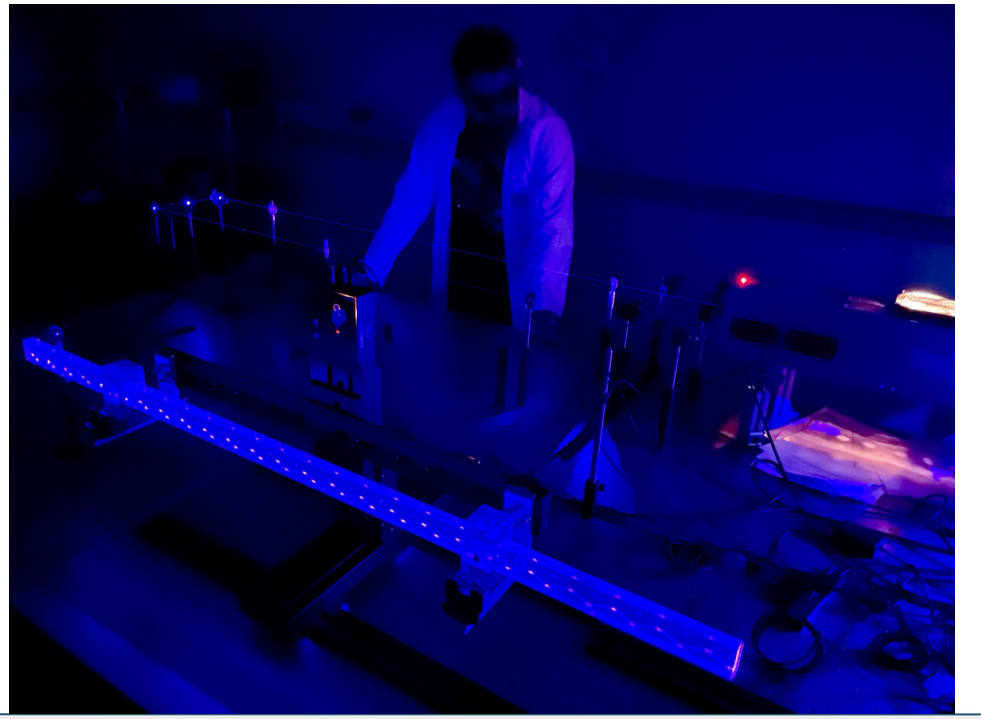


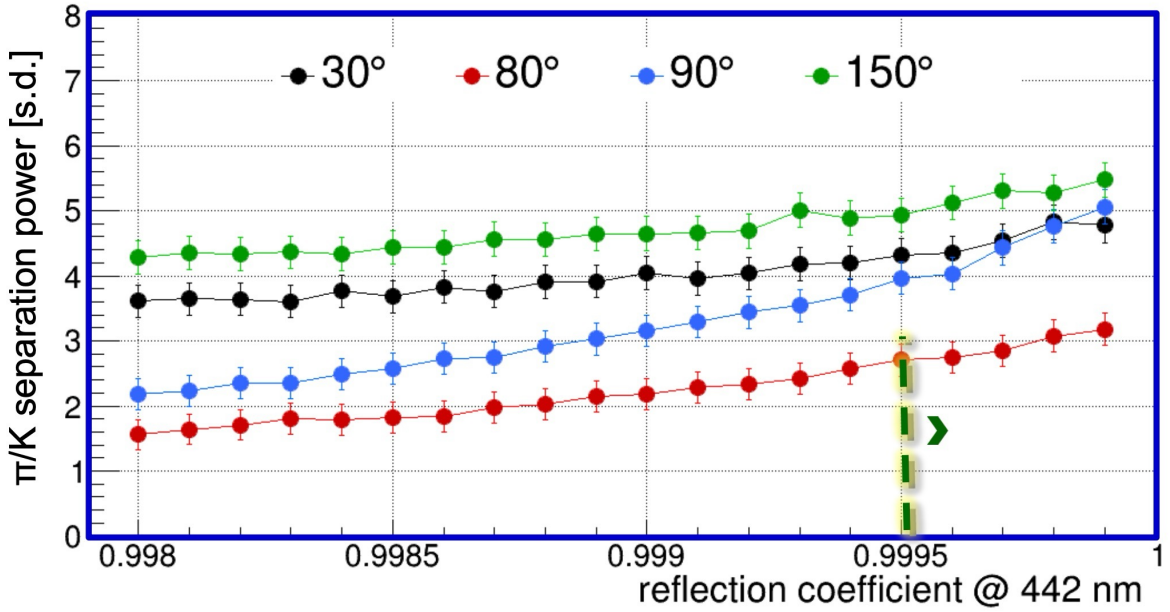
Reuse of BaBar DIRC Bars

- Laser setup similar to the one used at GSI for the PANDA Barrel DIRC
- HeCd laser with two wavelengths is used (325 nm, 442 nm)
- Reflection coefficient measurement allows to evaluate surface quality of the bars with sub nm precision and compare it to data from BaBar DIRC pre-construction
- Initial measurements of separated bars match R = 0.9995 goal, consistent with the SLAC measurement for other BaBaR DIRC bars



Measurement with 442 nm laser





Validation of Components

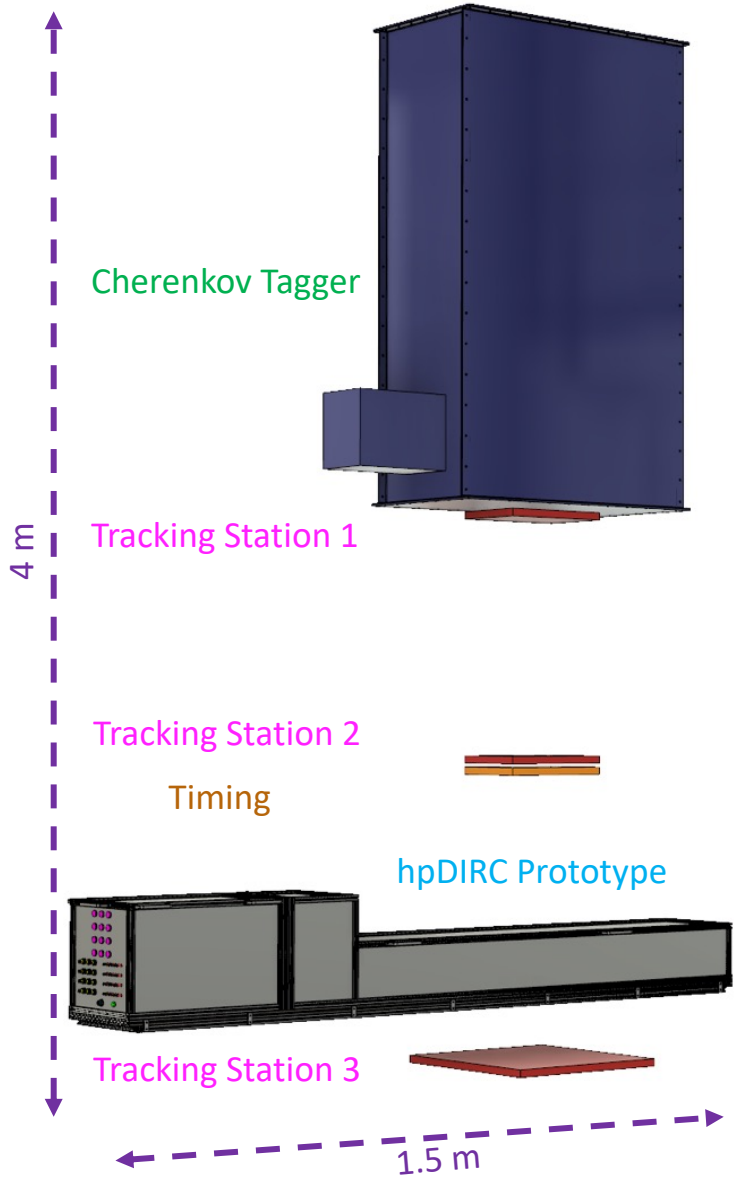
Cosmic Ray Telescope (CRT) at SBU

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/scintillator + SiPMs for event timing
- DIRC Geant4 simulation used to optimize setup arrangement

Ultimate CRT goal: test of assembled ePIC hpDIRC modules

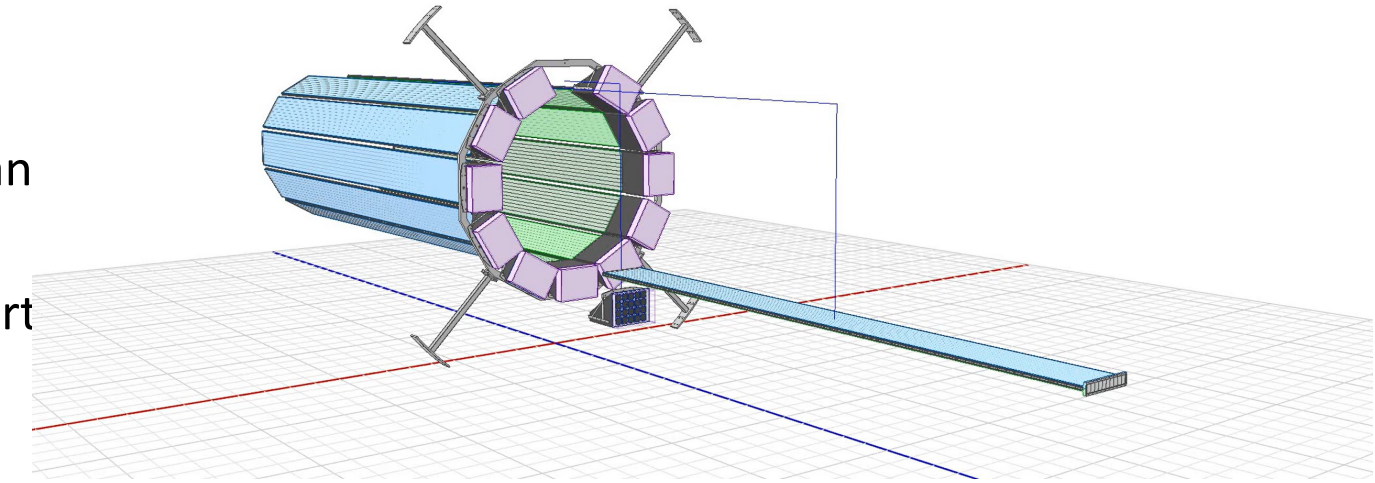
CRT setup CAD schematic

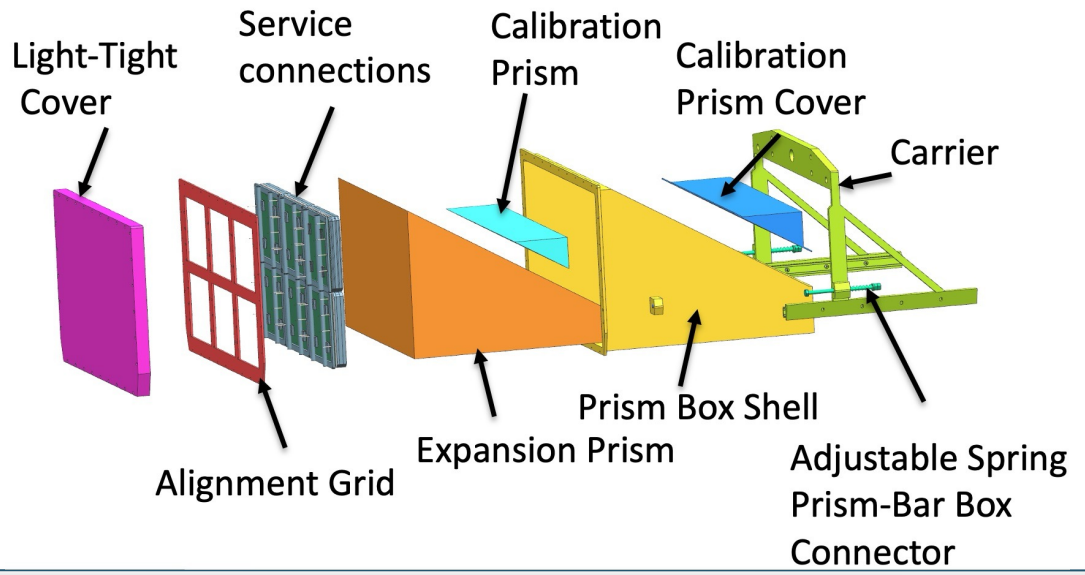


Mechanical Support and Integration

Bar and Readout Boxes

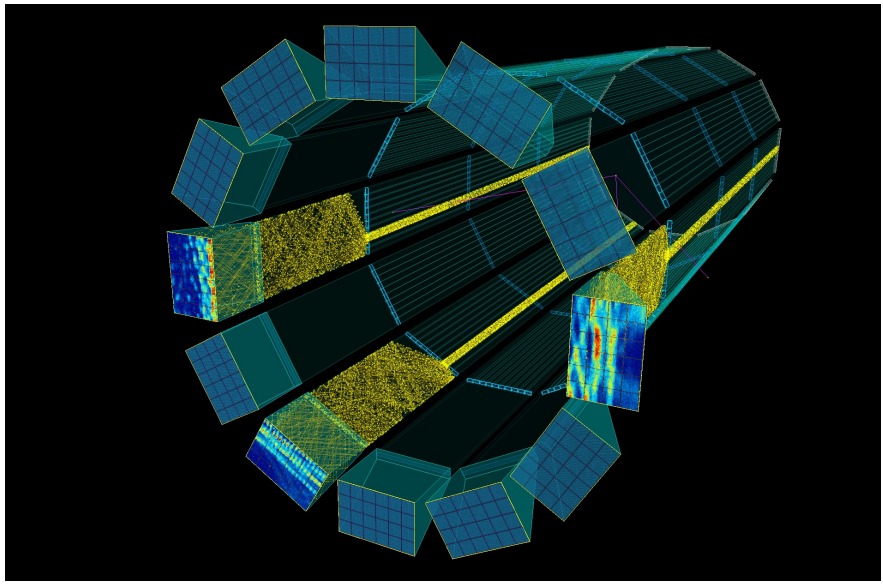
- Modular CFRP enclosures (3 mm thick shells)
- Bar boxes
  - House DIRC bars, mirror, focusing lenses, and an optically transparent readout window
  - Installed first using guided rollers on the support structure
- Readout boxes
  - Contain prism expansion volume, photon sensors, readout electronics, and calibration system
  - Designed to accommodate both sensor options
  - Installed after bar boxes and precisely aligned to each unit
- Full module matching performed prior to installation





OUTLOOK

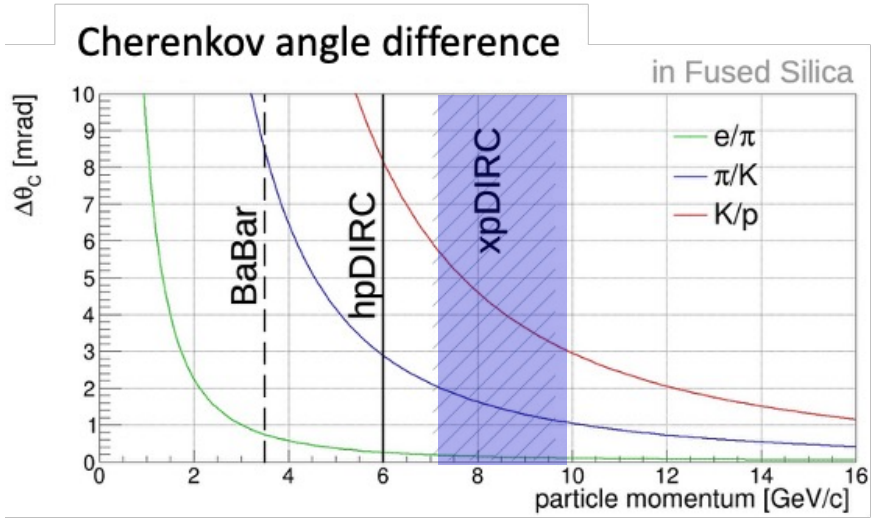
xpDIRC for EIC Detector2

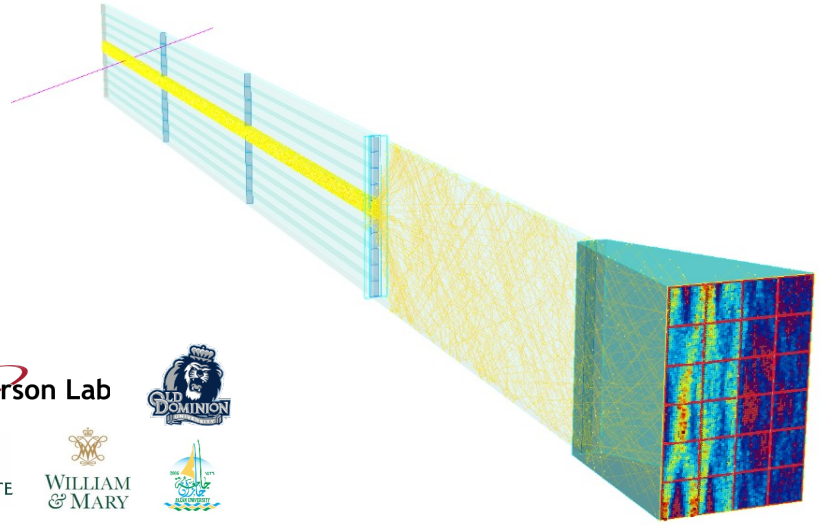


- New Generic EIC R&D program with Detector2 in mind aims to advance the DIRC performance reach beyond 8 GeV/c

- xpDIRC concept - hybrid of bars and plate in each sector with improved focussing

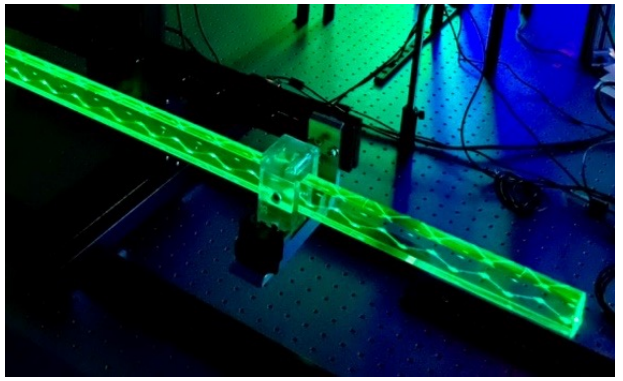
- See Roman Dzhygadlo poster

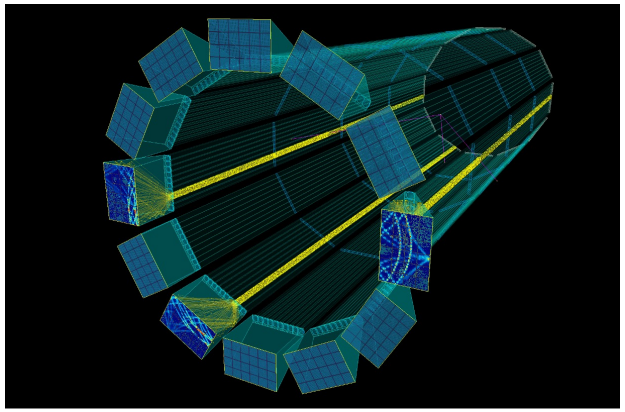




SUMMARY

- ePIC hpDIRC: Fast focusing DIRC concept, developed over 14+ 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
- hpDIRC components fabrication start in 2027
- Bar box assembly planed to start in 2028
- hpDIRC scheduled for installation into
  ePIC in June 2031, expect hpDIRC readiness for installation well before that date





π/K separation power at 6 GeV/c