eRD103: The High-Performance DIRC

Directed R&D Program to Mitigate Key Risks for the ePIC DIRC Detector

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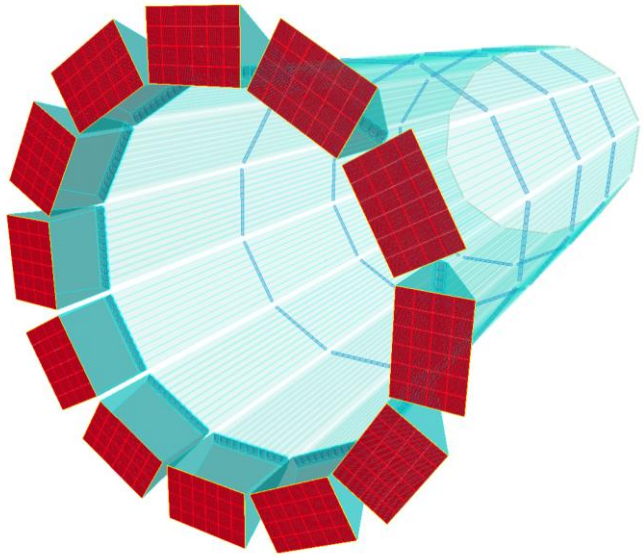


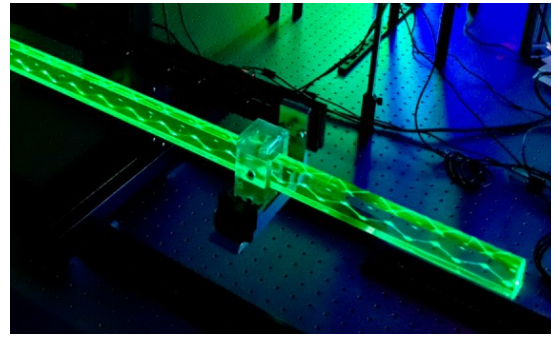
eRD103

April 16th, 2025

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

MILESTONE

- 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.
  - End-to-end system validation of the complete hpDIRC setup will be performed in the CRT before entering the construction phase.



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 short bars, glued end-to-end
- Short bars made from highly polished synthetic fused silica
- Flat mirror on far end

Focusing optics:

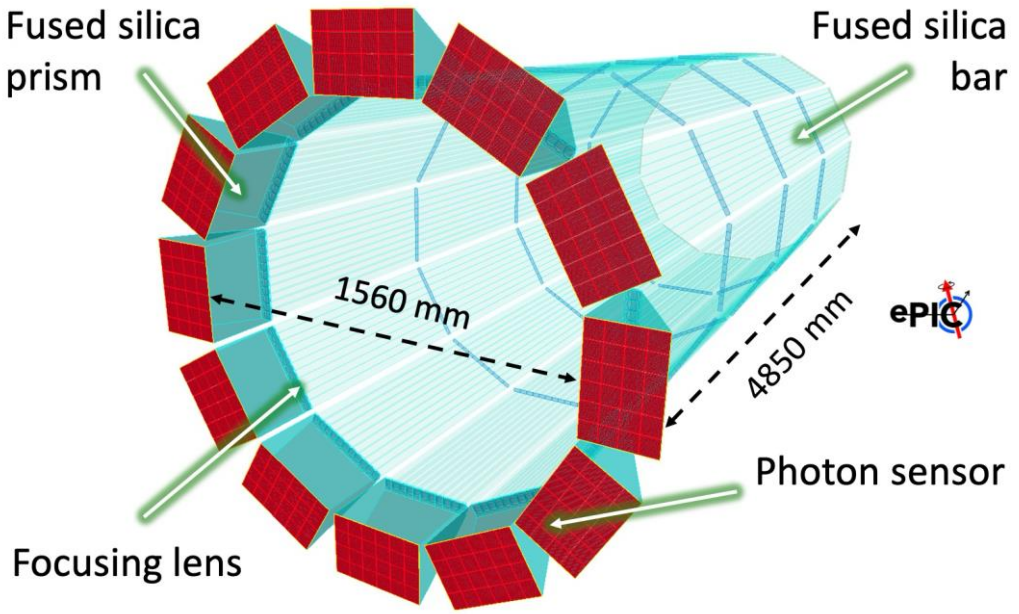
- Radiation-hard 3-layer spherical lens (sapphire)

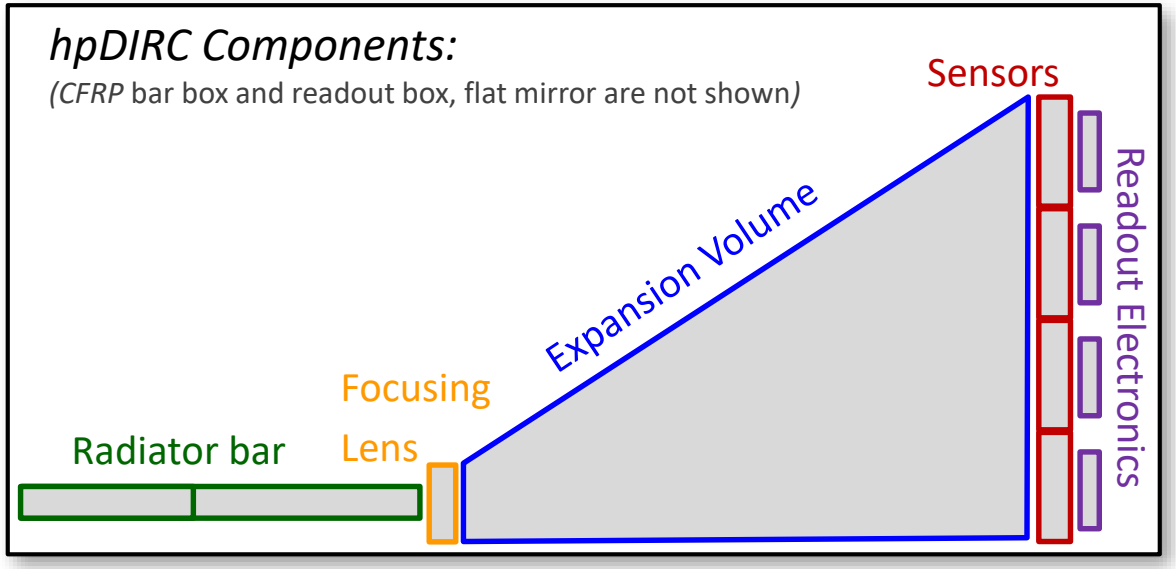
Expansion volume:

- 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)





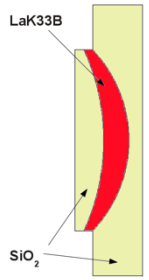
HIGH-PERFORMANCE DIRC R&D

- 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%

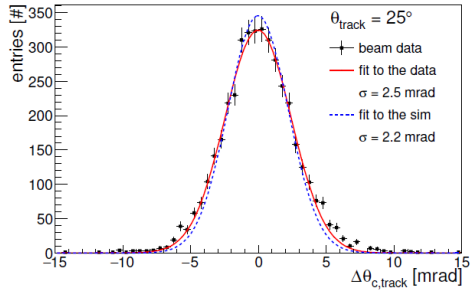
- R&D for a high-performance EIC DIRC started in 2011 (synergetic with PANDA DIRC)
  (Funded by DOE/BNL/JLab as RD2011-3, eRD4, eRD14, eRD103, EICGENRandD2022_12)

- 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 1mrad 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 disassembly, separation of first bar

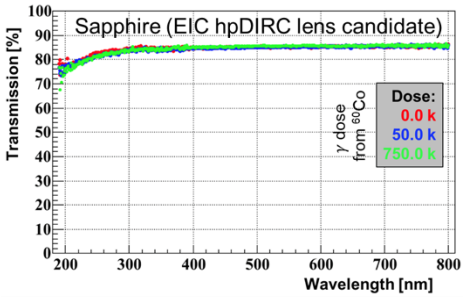
Initial 3-layer lens concept



Cherenkov angle per particle, CERN 2015

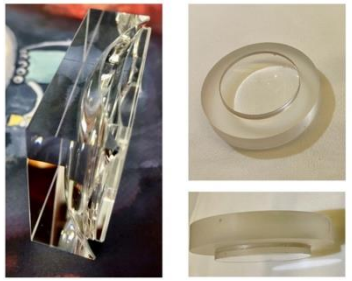


radiation hardness of sapphire



radiation hard lens prototypes

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



HPDIRC RECENT ACTIVITIES

hpDIRC prototype in Cosmic Ray Telescope (CRT):

- CRT commissioning in progress at SBU to become test bench for incremental upgrades of new components (bars, sensors, readout electronics, eventually full hpDIRC modules)

Validation of the BaBar DIRC bar reuse:

- Bar boxes transferred from SLAC to JLab in April 2024
- Disassembly and QA at JLab are in progress
- Decision on reuse of bars expected this summer

Ongoing hpDIRC studies in simulation:

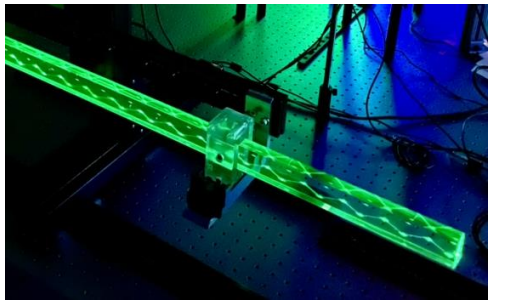
- Design optimization and challenging performance

New generic R&D:

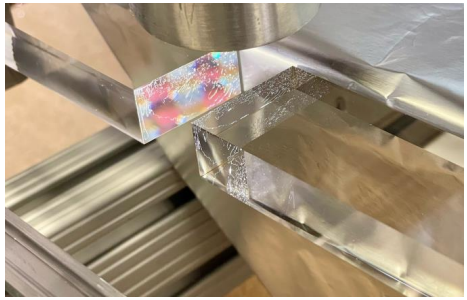
- New ideas for light guide
- Further improved focusing
- Possible use of SiPM

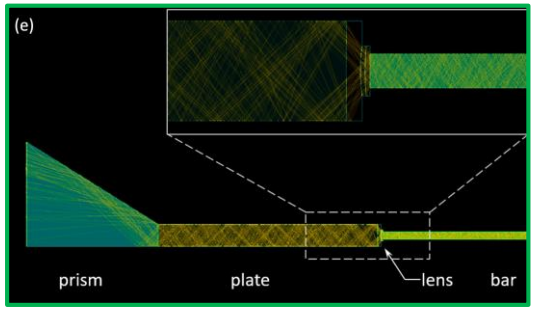
hpDIRC prototype at SBU

QA at JLab



First separated bars at JLab





Simulation studies to improve the performance

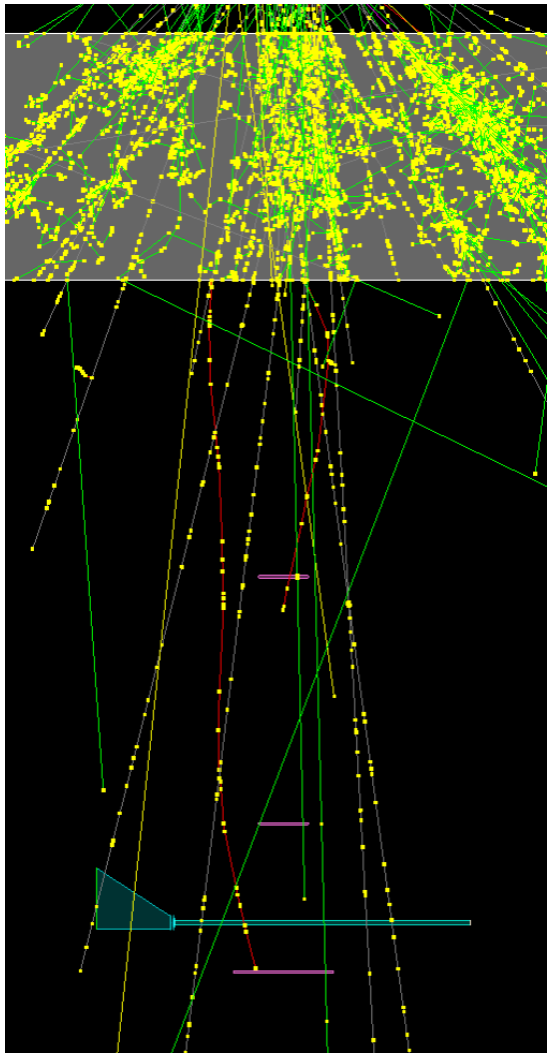
Validation of Components

Cosmic Ray Telescope (CRT) at SBU

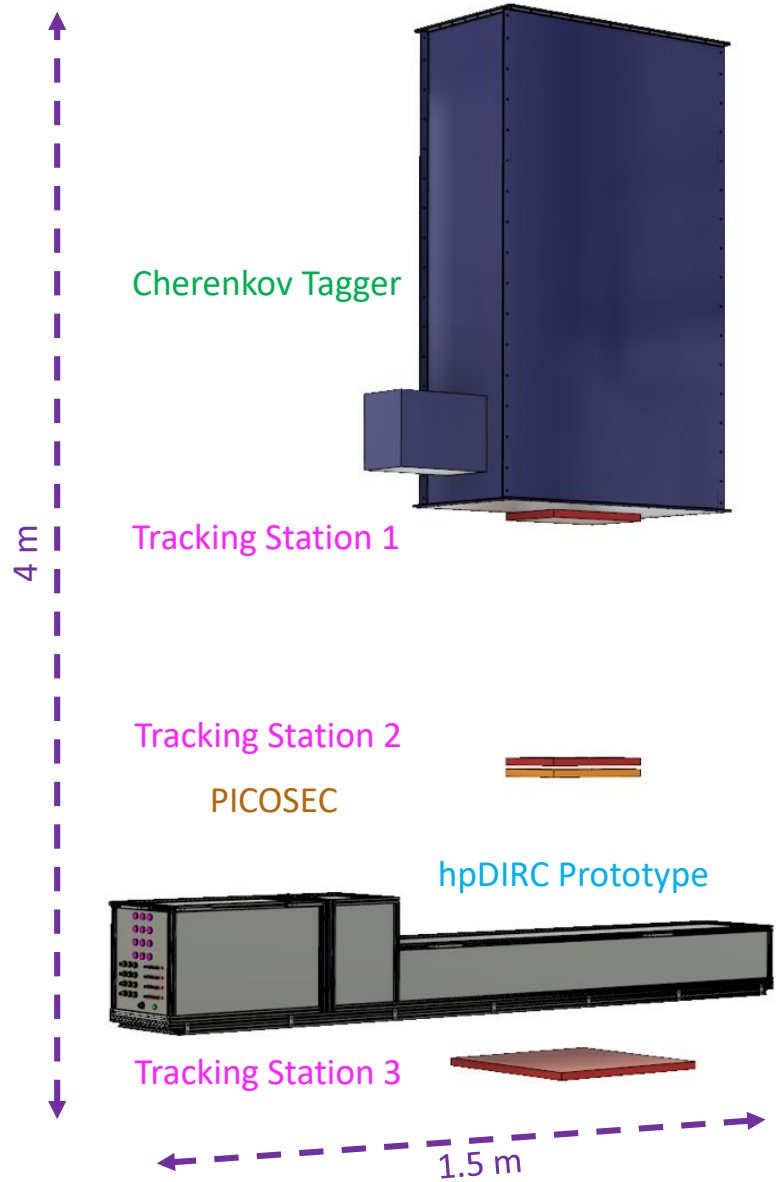
Facility to test incremental upgrades of components, performance evaluation

- Initial PANDA Barrel DIRC-based configuration to commission setup
- 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 optimise setup arrangement

Geant4 simulation of CRT setup

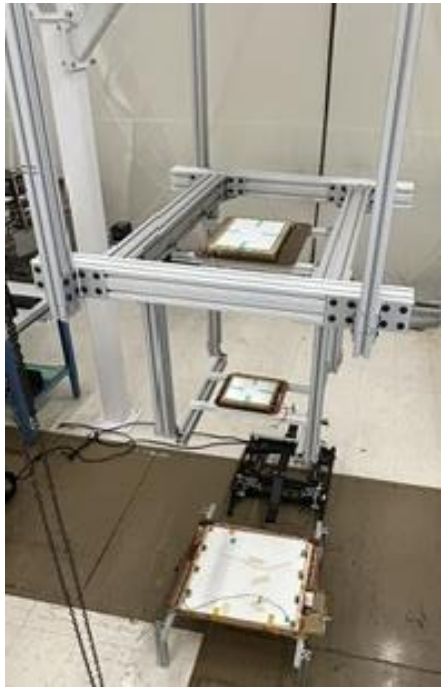


CRT setup CAD schematic

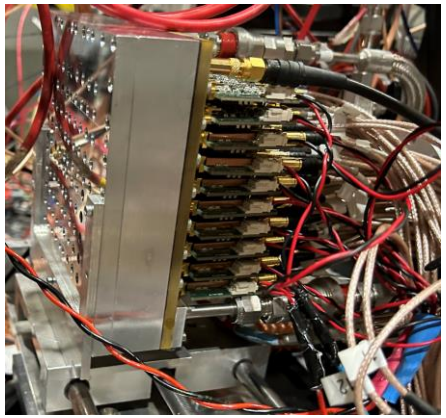


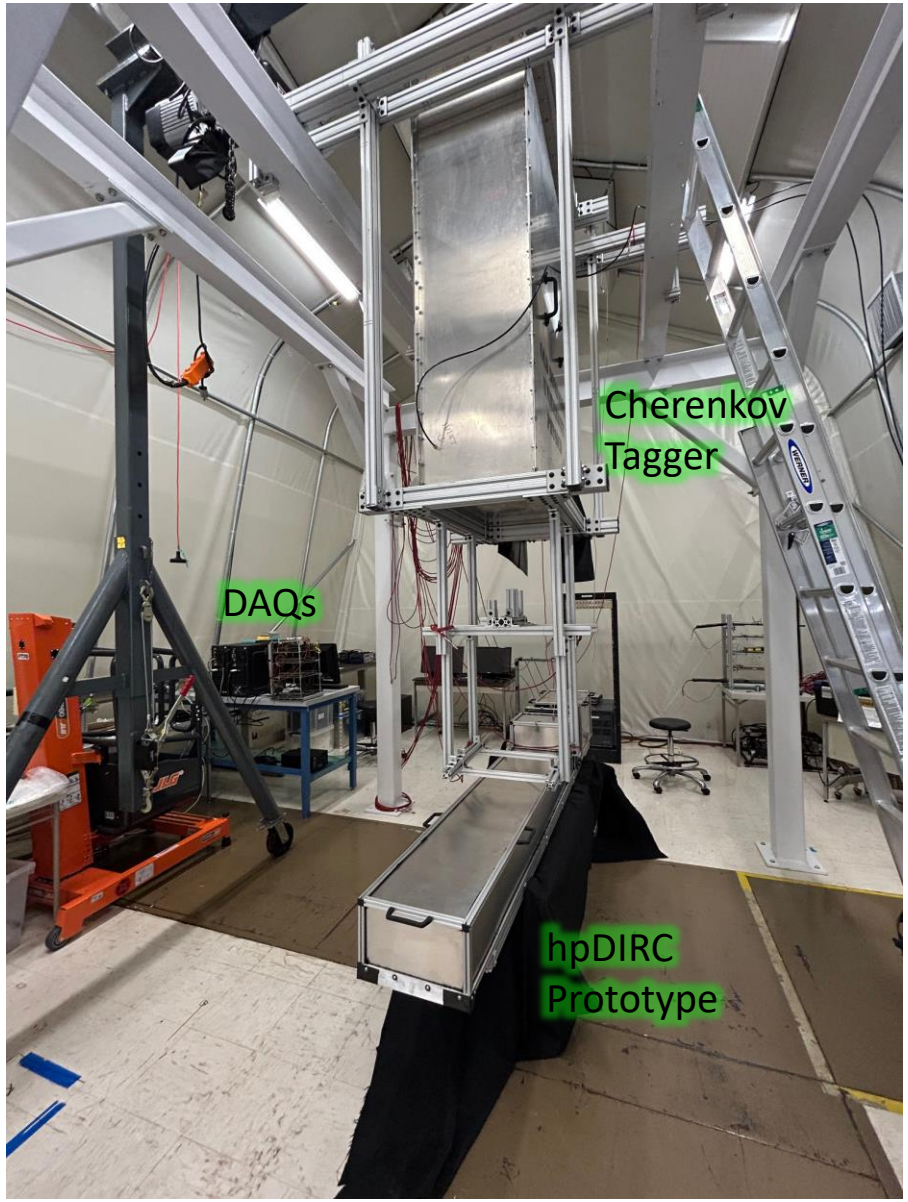
VALIDATION OF COMPONENTS

Trackers in the CRT



Large area PICOSEC

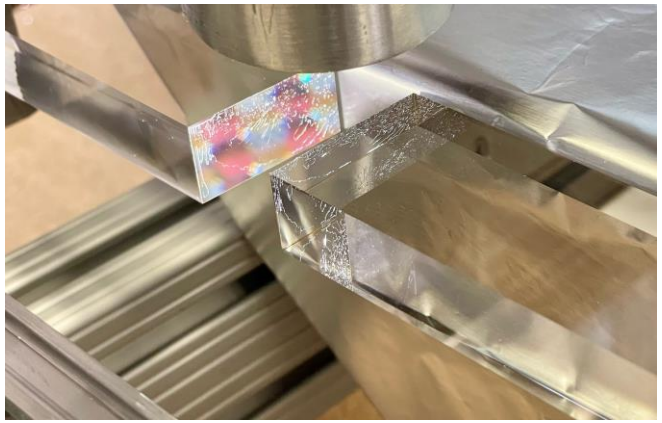




Reuse of BaBar DIRC Bars

- 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

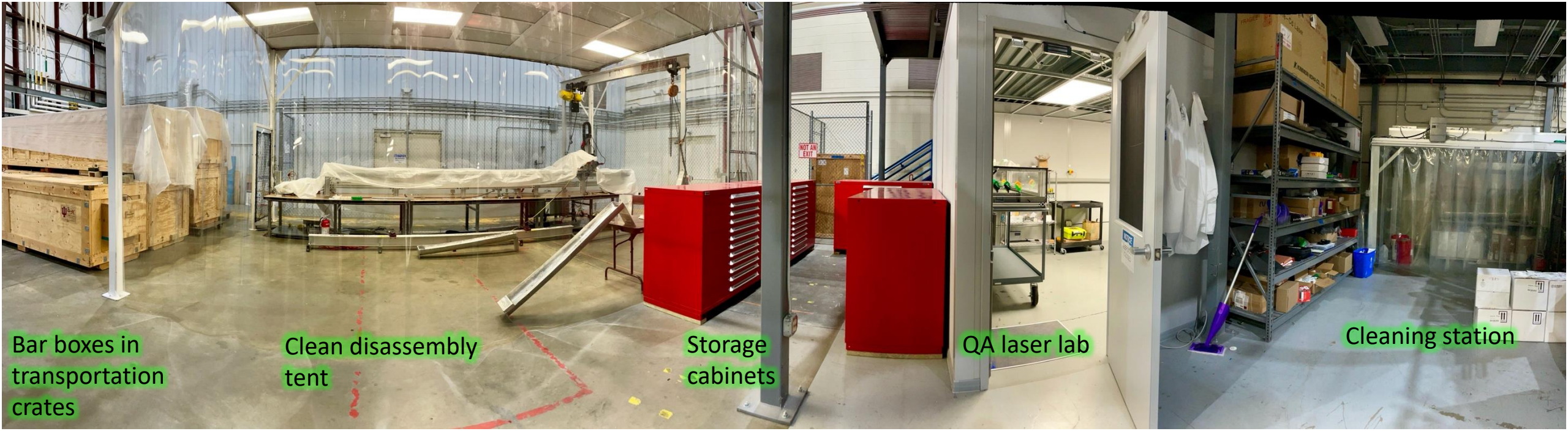
- Full-size bar boxes are too long, do not fit into EIC central detector, wedges deteriorate resolution: need to disassemble bar boxes for reuse
  - Facility, setups, and tools developed, disassembly of first bar box in progress



- 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 $-1.57 \leq \eta \leq +1.57$
- Additional 120 bars required for the light guide section, $\eta \leq -1.57$, to couple to lenses
- Quality of bar surfaces, 25 years after initial production and assembly, to be verified
  - QA of first disassembled bars in underway

Reuse of BaBar DIRC Bars

Panoramic view of hpDIRC lab space in the EEL building



Refurbishing process at JLab:

- Clean tent for removal of bar box shells and debonding of bars
- Cleaning station in tent to remove glue/pollution, visually inspect bars
- QA laser lab to inspect quality of the bars (transmission, reflection coefficient)
- Measured bars are wrapped, tagged, and stored in four storage cabinets
- Spreadsheet keeps track of bar tag ID, Boeing/SLAC data, QA results, location

Team currently working on disassembly:

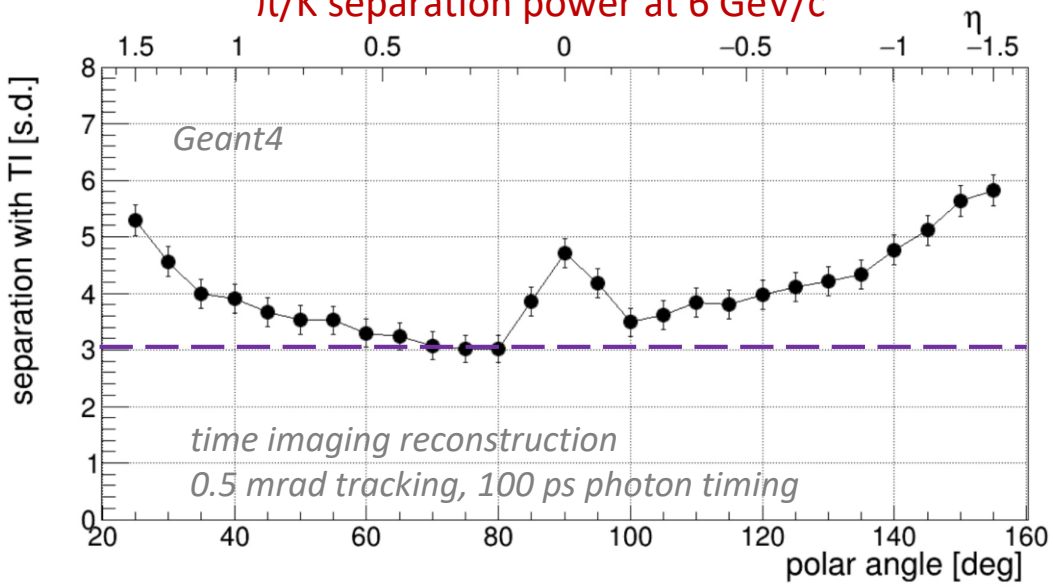
- 3 JLab Technicians:
  Andrew Lumanog, Caleb Graham, David Edwards
- 2 Scientists:
  Greg Kalicy (CUA), Sourav Tarafdar (JLab)
- JLab DSG Group:
  Tyler Lemon, George Jacobs, Mindy Leffel
- Graduate Student: Shelby Arrigo (W&M)

HPDIRC SIMULATION

Recent hpDIRC related studies:

- Confirmed robust performance in magnetic field, and using physics events (Pythia) to include backgrounds, multiple tracks per bar (WSU)
- Performance with new iterations of ePIC angular track resolution maps (GSI)
- Verifying optimal sensor coverage (CUA, GSI)
- Study of bar imperfections impact on the performance relevant for the BaBar bars qualification (GSI)
- Impact of bars misalignments on performance (Jazan)
- Machine Learning approach to reconstruction (W&M)
- Preparations for hpDIRC prototype 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
- 6 GeV/c momentum
- No magnetic field, no other ePIC subsystems
- 0.5 mrad tracking resolution

→ hpDIRC capable of reaching required performance at 6 GeV/c for 0.5 mrad tracking angular precision

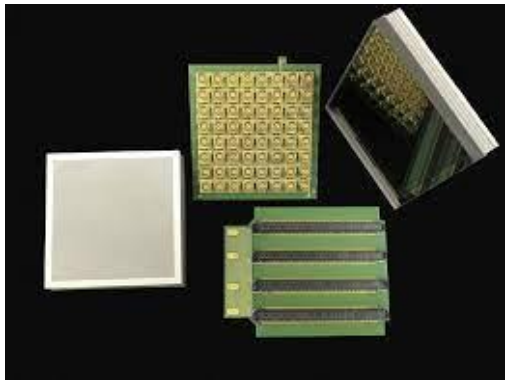
READOUT

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

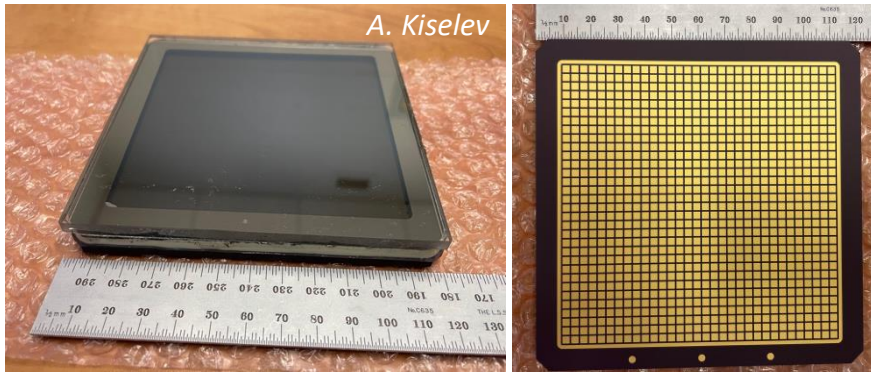
- MCP-PMTs capable of meeting all hpDIRC requirements *(A. Lehmann review talk at RICH2022)*
- Baseline sensor for hpDIRC: 2'' Photek MAPMT 253 MCP-PMTs
- Potential solution: DC-coupled Incom HRPPD

  Making use of synergy with pfRICH, optimizing cost and workforce
  - See sensor and readout presentation tomorrow

Photek MAPMT 253



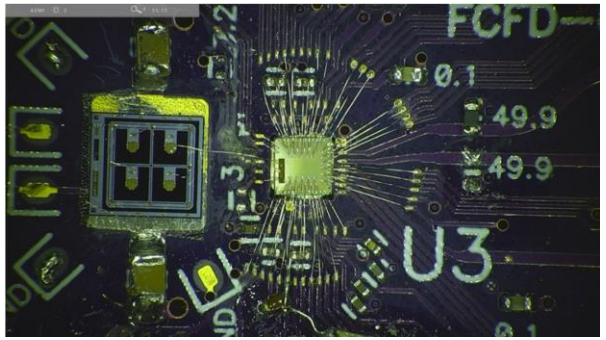
INCOM Gen III HRPPD prototype (front/back view)



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 eRD110 and eRD109 presentations tomorrow

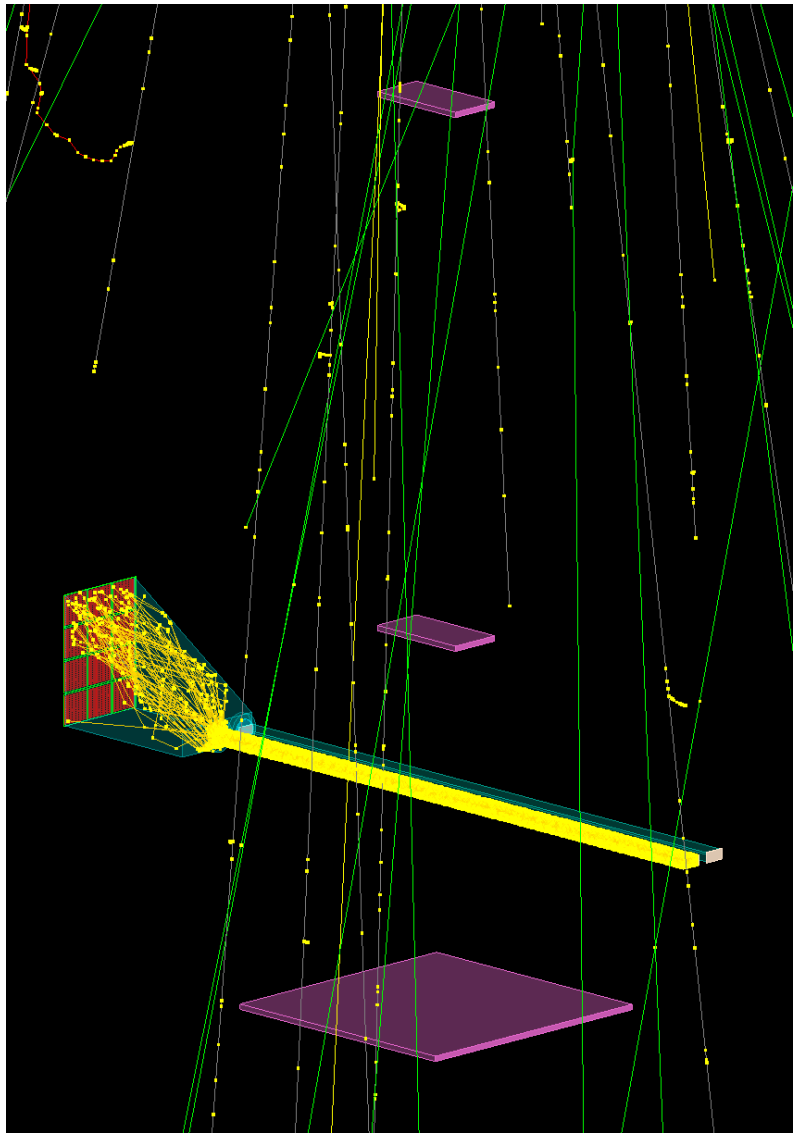
FCFDv0



Upcoming Activities

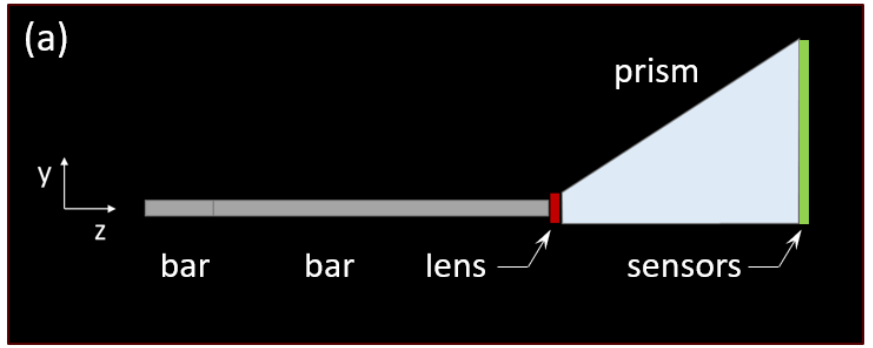
- Integration and commissioning of full setup
  - Initial configuration with bar from PANDA Barrel DIRC
  - Two radiation-hard 3-layer lenses are in hand and will be tested for the first time in full chain DIRC setup
- Disassembled BaBar DIRC bars will be used once available
- Setup with two bars arranged side-by-side will increase statistics enabling studies of additional aspects of performance
- Readout box designed to allow easy addition of small-pixel sensors once they become available
- Ultimate CRT goal: test of fully assembled ePIC hpDIRC modules

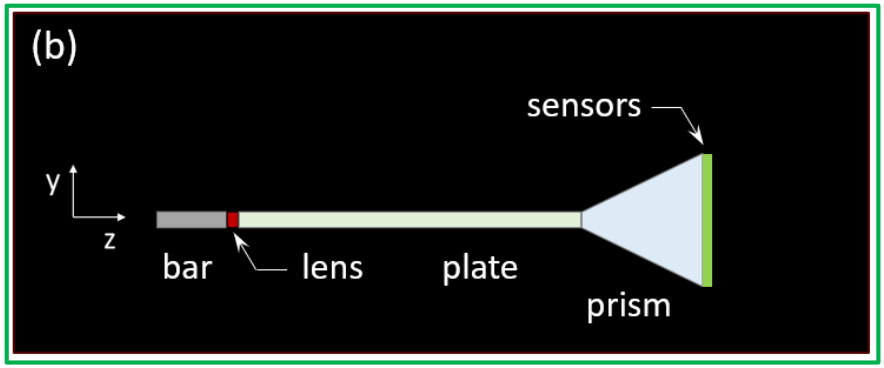
Simulation of hpDIRC Prototype with 2 bars in CRT

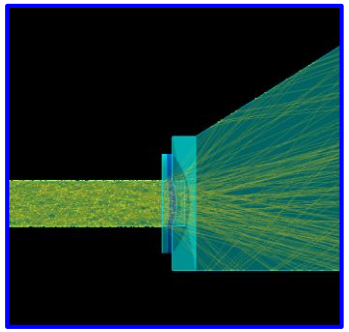


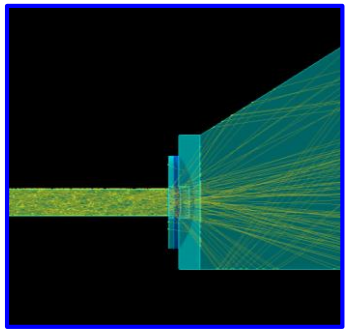
Future Plans

- Proposal submitted to DOE for xpDIRC R&D
- Hybrid optics (mitigate focusing errors and reduce cost)
  - Configuration where the cylindrical lens is positioned between the wide plate and the expansion volume comes close to achieving the desired 3 s.d. separation power at 6 GeV/c
  - Alternative cylindrical lens positions require additional optimization to determine if their performance can be enhanced
  - Study of plate configuration with spherical lenses
  - Optimize lens properties for longer expansion in plate
  - Study shorter prism, two half-width prisms, possibly with SiPM readout (cost reduction, reduce sensor area of prism by factor 3-4)
  - Optimize "Thick plate" hybrid design (avoids photon loss in the lens)
- Thinner bars (mitigate multiple scattering effects in DIRC bars)
  - Study potential combination with "Thick plate" hybrid design









SUMMARY/OUTLOOK

- hpDIRC full chain setup at Cosmic ray telescope (CRT):
  - hpDIRC setup, trackers, and Cherenkov tagger are installed and in progress of commissioning/integration.
  - Preparing the way for future incremental upgrade of the hpDIRC setup when bars, sensors, and readout electronics become available
  - The ultimate goal for the CRT, to test full hpDIRC module is well-aligned with ePIC schedule
- Validation of BaBar bars reuse option is in progress
- Simulation being carried out to study effect of different practical conditions on hpDIRC performance
- New Generic DIRC R&D explores innovative optical DIRC configurations to create opportunities for cost reduction and performance improvement and fits well into the schedule of ePIC hpDIRC components tests

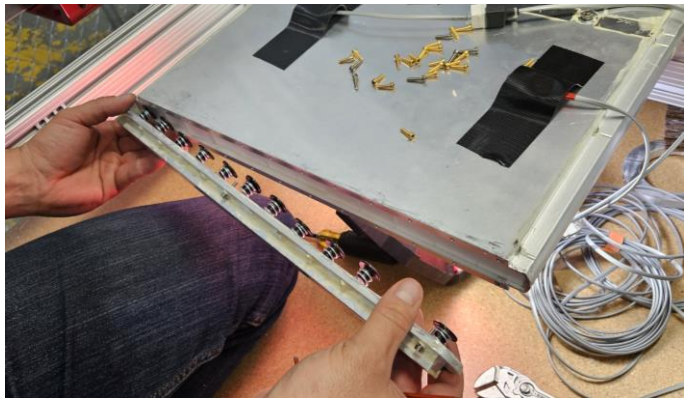
hpDIRC prototype

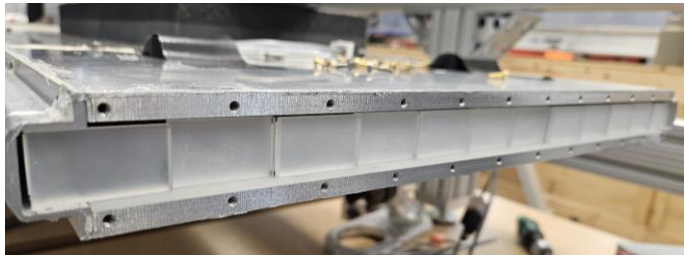
Extra Slides

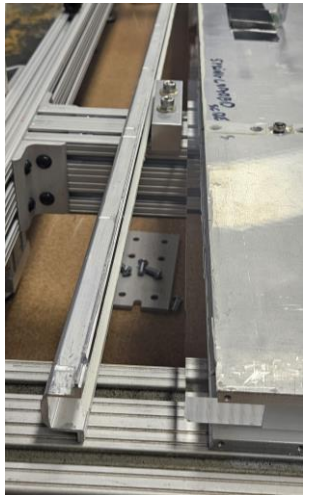
Reuse of BaBar DIRC Bars

Bar box on CNC

Removing aluminum shell





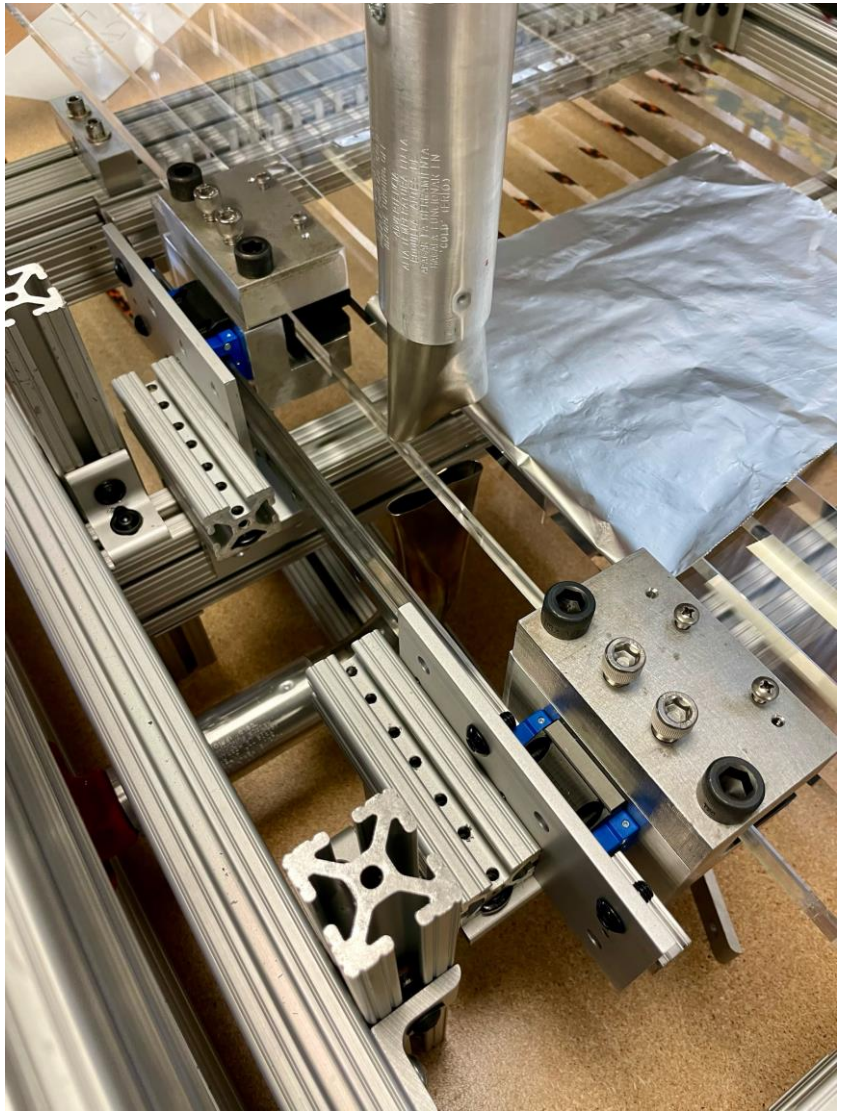


Bar box with disassembled aluminum shell

Reuse of BaBar DIRC Bars

Heat guns softening glue joints between bars

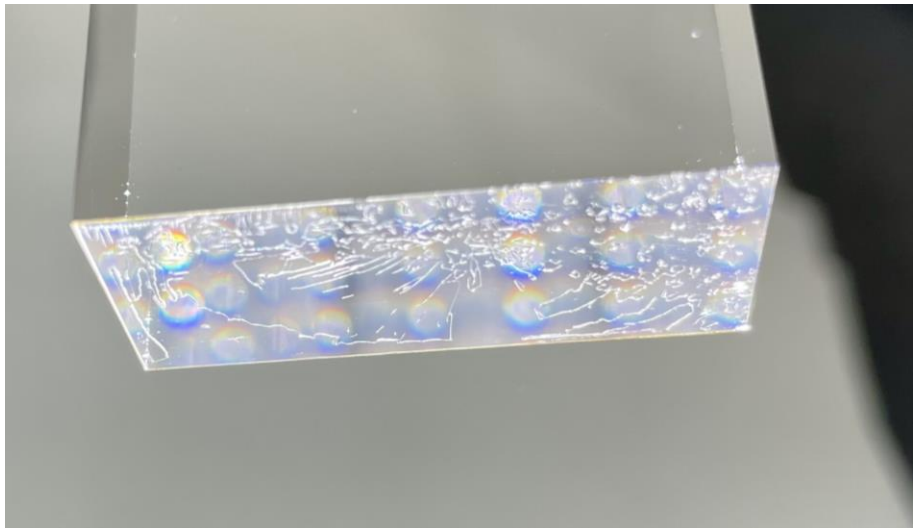
Highly adjustable clamps to separate bars



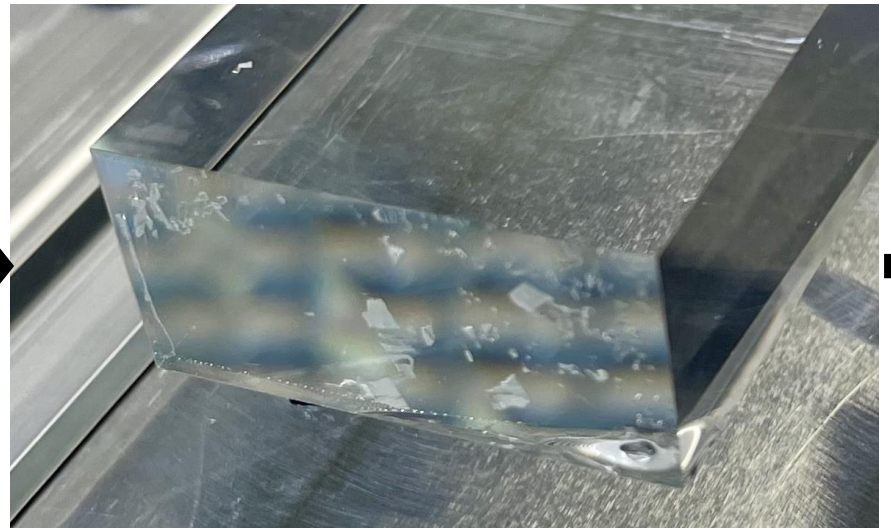
Weight with short travel pulling on clamp

Reuse of BaBar DIRC Bars

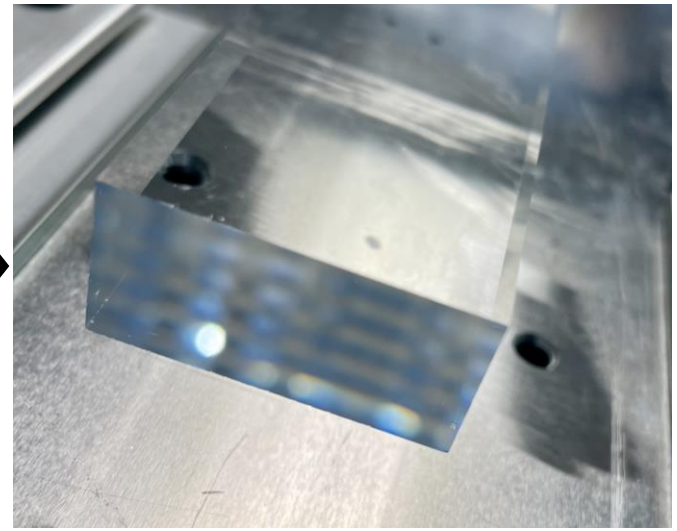
Glue residue after separation



Glue residue mid-way through cleaning



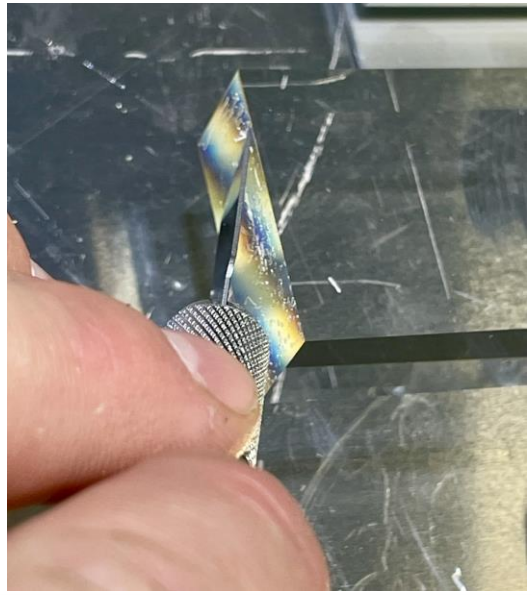
Cleaned bar end



Bar end immersed in acetone bath

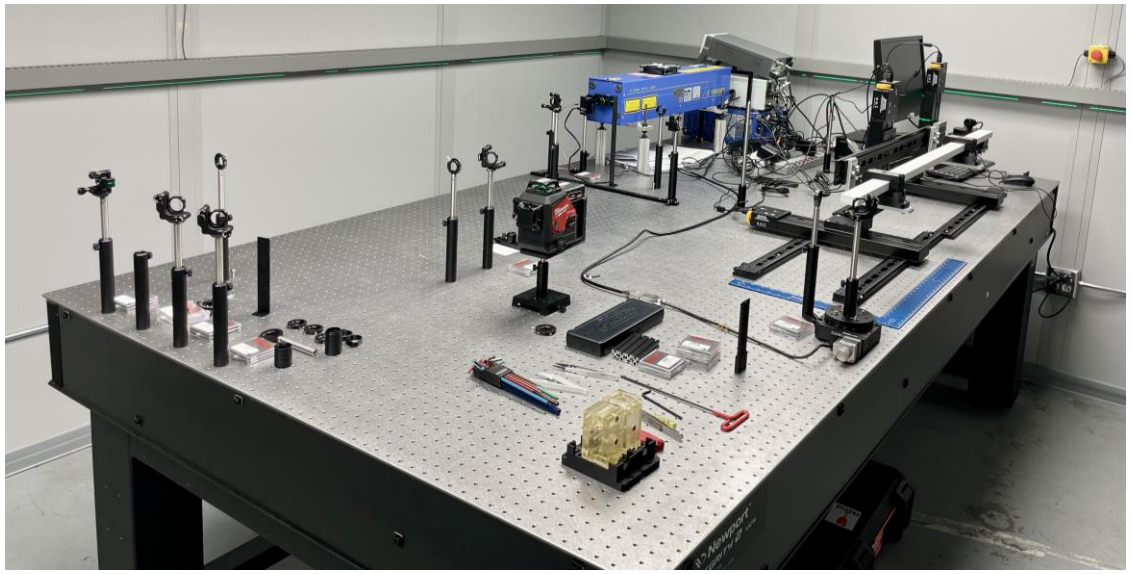
"Bathtub" in position for glue removal

Glue removal

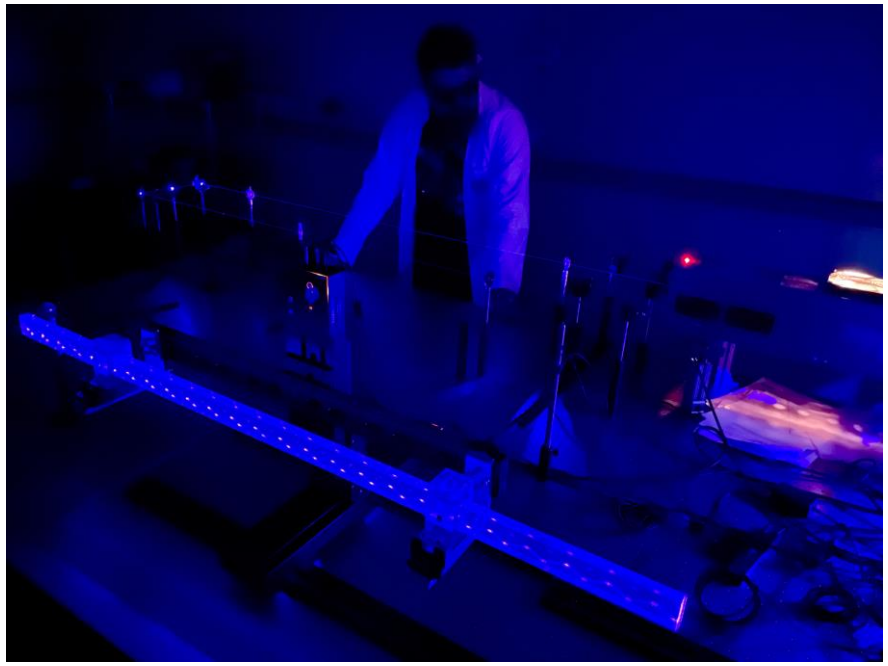


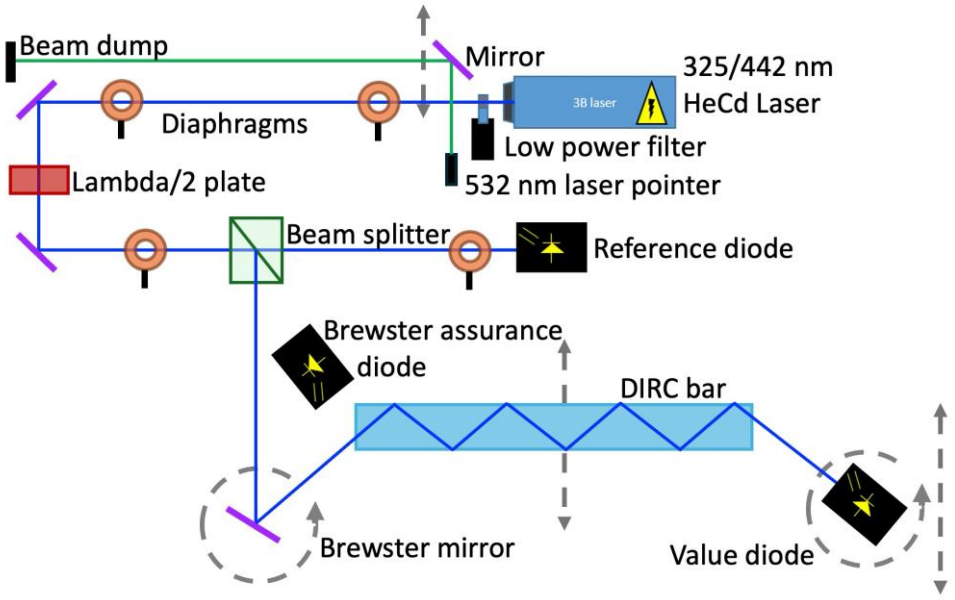
Reuse of BaBar DIRC Bars

- Laser setup built at JLab based on similar setup at GSI for PANDA Barrel DIRC
- Reflection coefficient measurement allows to evaluate surface quality of the bars with sub nm precision
- HeCd laser with two wavelengths is used (325 nm, 442 nm)



Measurement with 442 nm laser





Focusing Optics

Barrel DIRC counters (PANDA, EIC) require focusing for wide range of photon angles

Conventional plano-convex lens with air gap limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°, gap in DIRC PID
- Distortion of image plane, PID performance deterioration

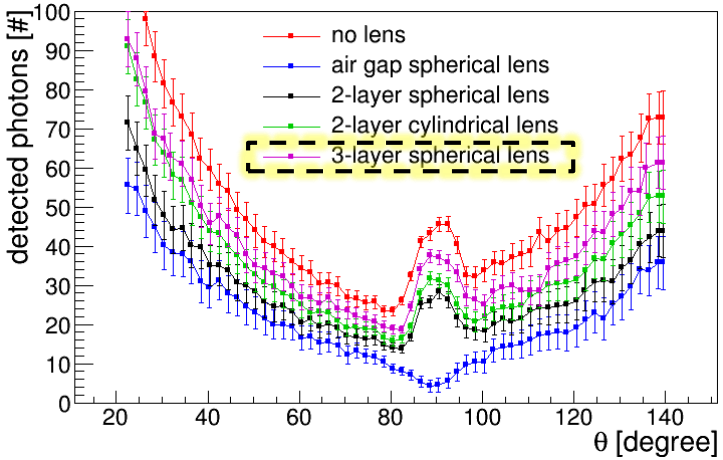
Innovative solution:

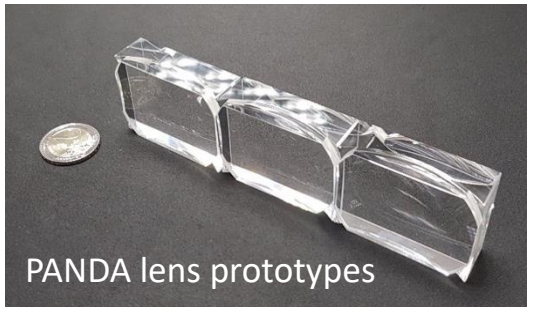
- 3-layer compound lens (without air gap):

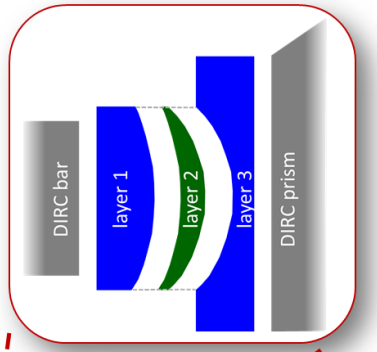
layer of high-refractive index material (focusing/defocusing)
sandwiched between two layers of fused silica

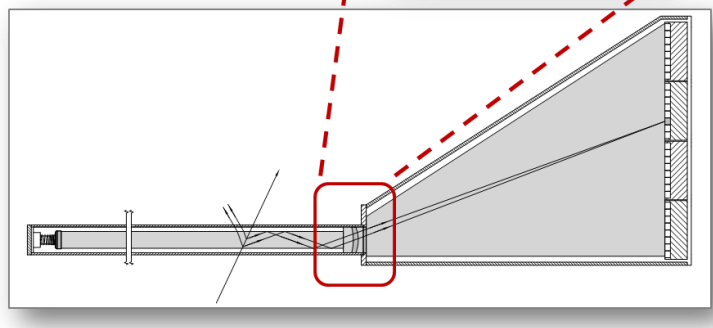
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Detailed radiation-hardness studies performed with ^{60}Co source, neutron irradiation next
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire or PbF_2 for EIC
- Industrial fabrication of lenses demonstrated
- Performance of spherical 3-layer lenses validated with PANDA Barrel DIRC prototype

Geant4 simulation: photon yield





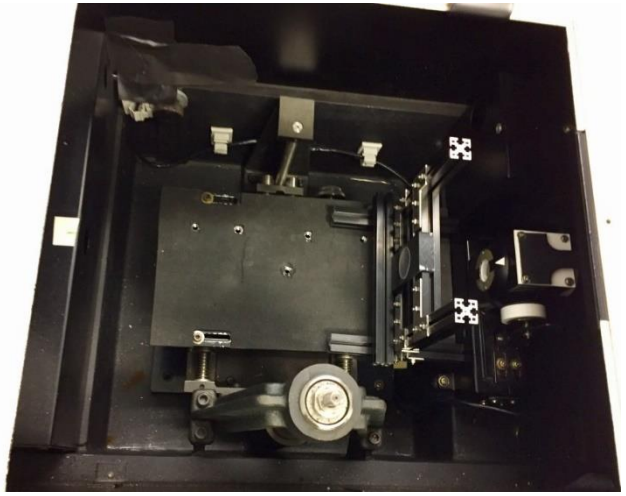


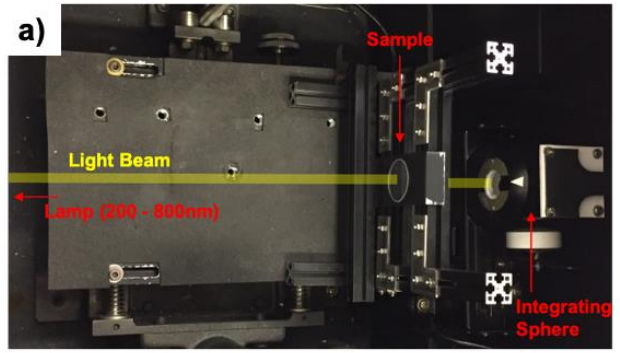


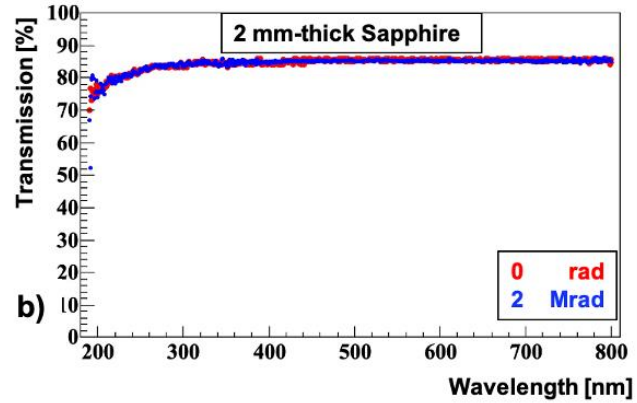
HPDIRC RADIATION TESTS

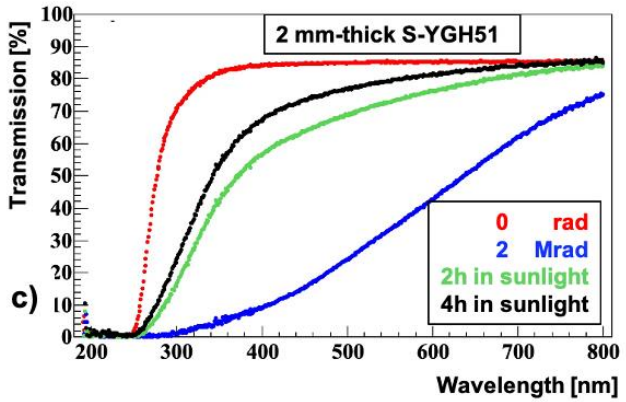
Co^{60} Chamber

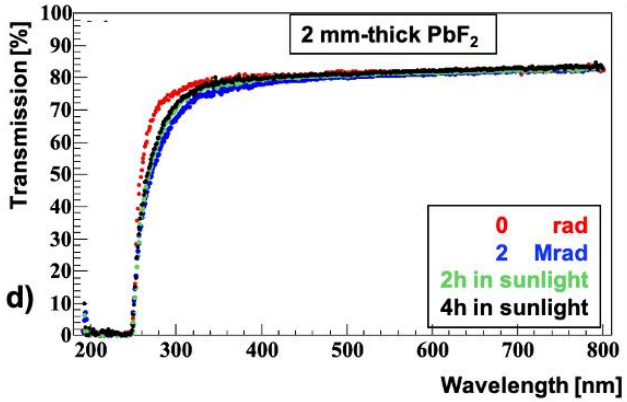
Monochromator

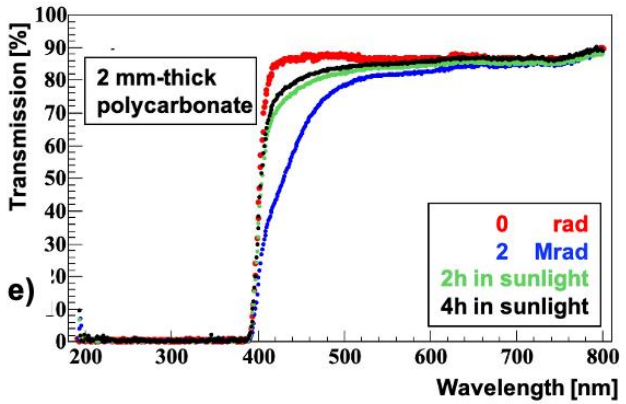


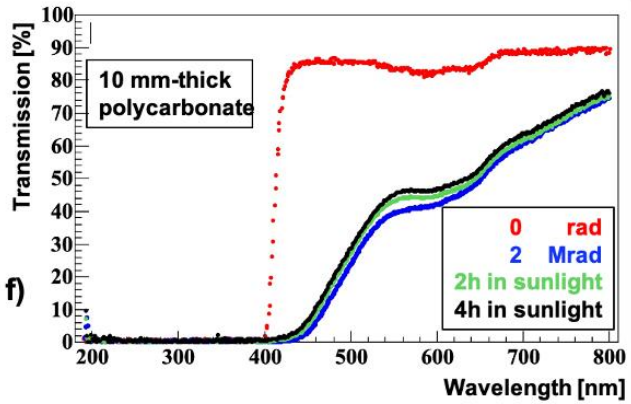










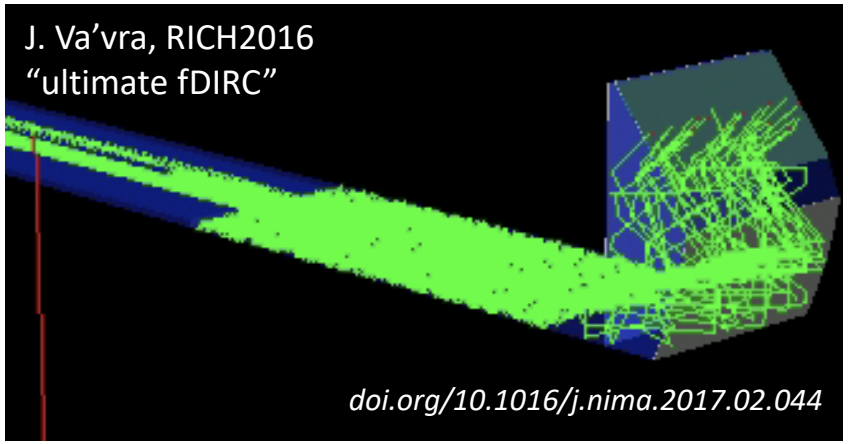


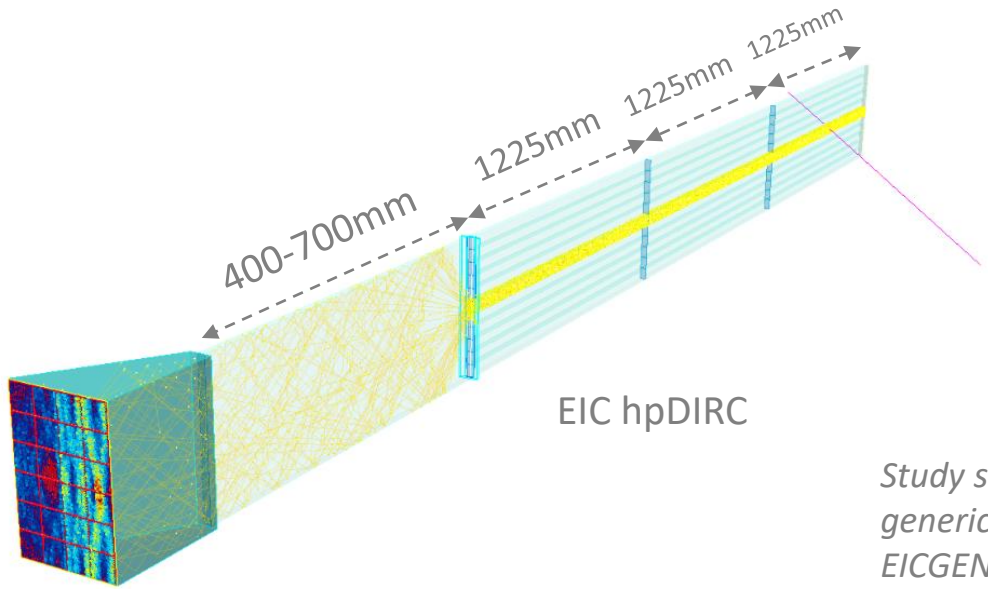
Light Guide Section

Performance improvement

- EIC detector barrel length requires additional fused silica bars or plate to connect BaBar DIRC bars to prism
- Narrow bars could be obtained by cutting and repolishing BaBar DIRC bars or by ordering new bars from industry
- At RICH 2016 J. Va'vra showed the "ultimate fDIRC" concept for SuperB with then best-in-class predicted DIRC performance

  Concept: use single short wide plate as transition light guide between BaBar DIRC bars and expansion volume
- For EIC hpDIRC design: use plate as light guide between BaBar DIRC bars and prism, combine with lens focusing
- Would significantly reduce cost compared to new narrow bars and potentially improve hpDIRC performance





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GEANT4 visualization of hybrid of bars and plate in each sector