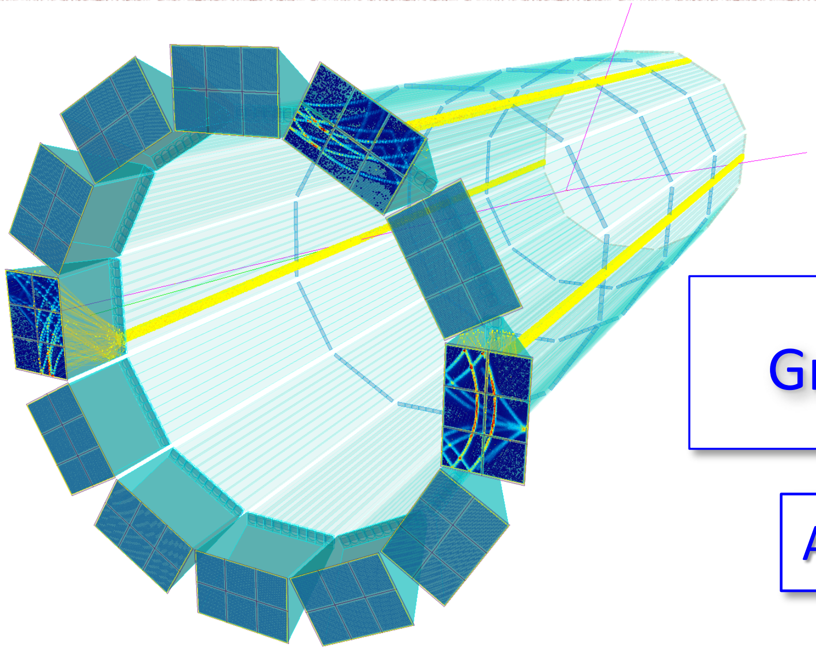
eRD103: The High-Performance DIRC

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

- hpDIRC overview
- FY23 progress, and milestones
- FY24 plans, activities, and milestones
- Roadmap towards TDR/Production readiness



Greg Kalicy CUA

August 31th, 2023

eRD103 hpDIRC Group

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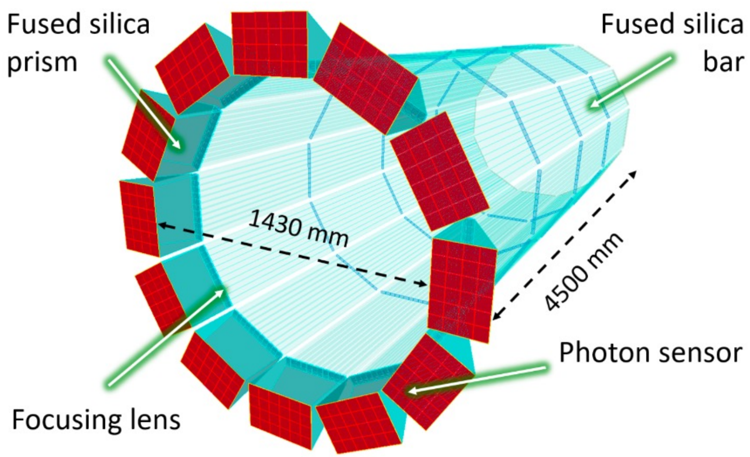
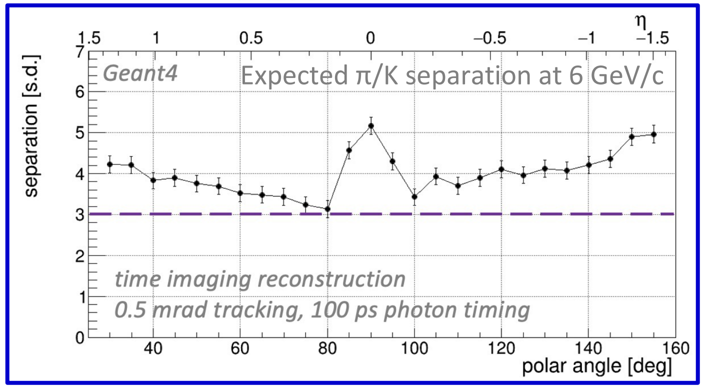
High-performance DIRC Concept

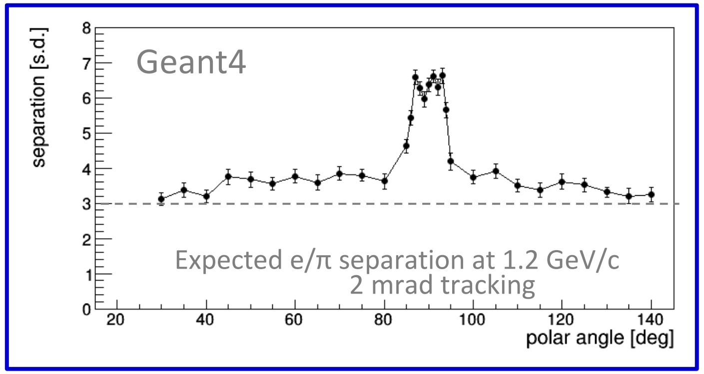
- Concept developed as part of Generic R&D program (eRD14)
- Finalizing design, risk mitigation as part of Project R&D (eRD103)
- Future DIRC R&D in new Generic R&D program (EICGENRandD12)



Key Features:

- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Design based on BaBar DIRC, R&D for SuperB FDIRC, PANDA Barrel DIRC
- Radiator/light guide: narrow fused silica bars (radius/length flexible)
- Innovative 3-layer spherical lenses
- Compact fused silica prisms as expansion volumes
- Fast photon detection: small-pixel MCP-PMTs and high-density readout electronics
- Detailed Geant4 simulation: ≥ 3 s.d. π/K separation at 6 GeV/c,
  ≥ 3 s.d. e/π separation at 1.2 GeV/c





Radiator bars:

- Barrel radius: 720 mm, 12 sectors
- 10 long bars per sector, 4880 mm x 35 mm x 17 mm (L x W x T)
- Long bar: 4 bars, glued end-to-end,
  3 BaBar bars + new short bars for "light-guide" section
- Flat mirror on far end

Focusing optics:

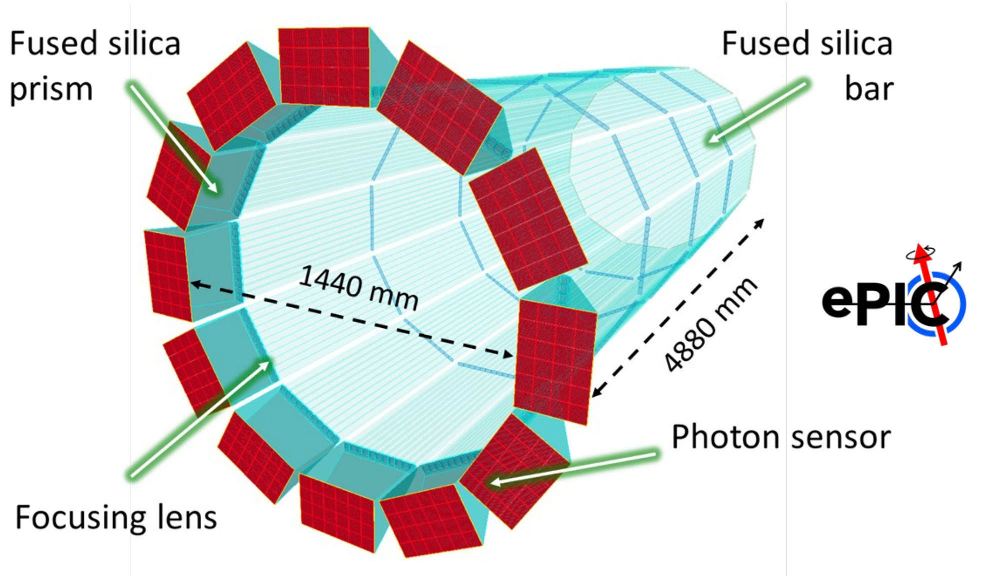
- Radiation-hard 3-layer spherical lens (sapphire or PbF_2)

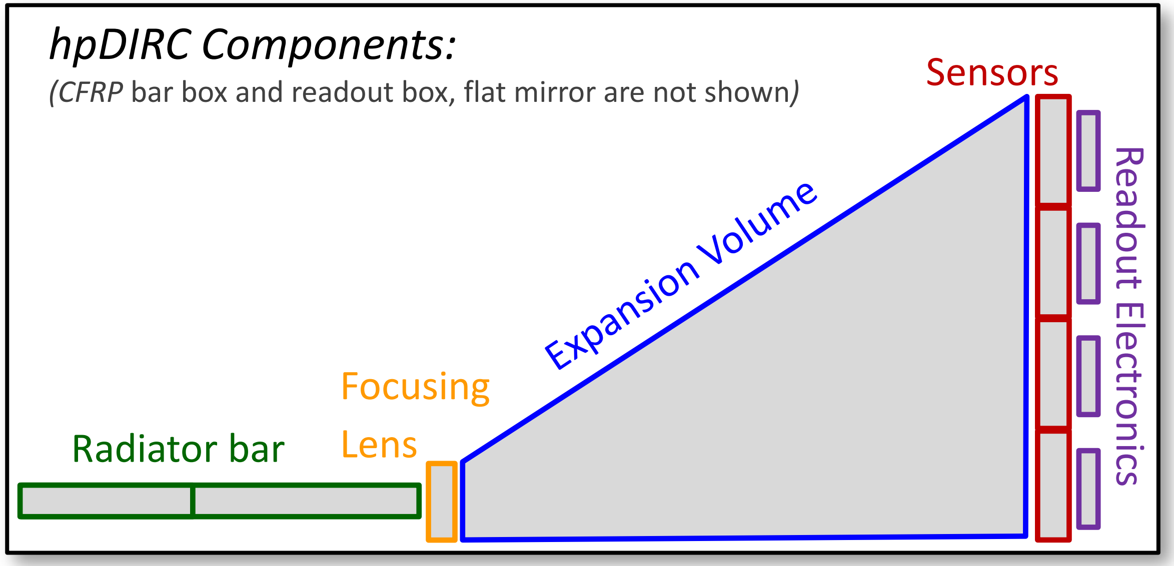
Expansion volume:

- Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)

Readout system:

- MCP-PMT Sensors (e.g. Photek/Photonis/Incom)
- ASIC-based Electronics (e.g EICROC)





hpDIRC Baseline Design

Radiator bars:

- Barrel radius: 720 mm, 12 sectors
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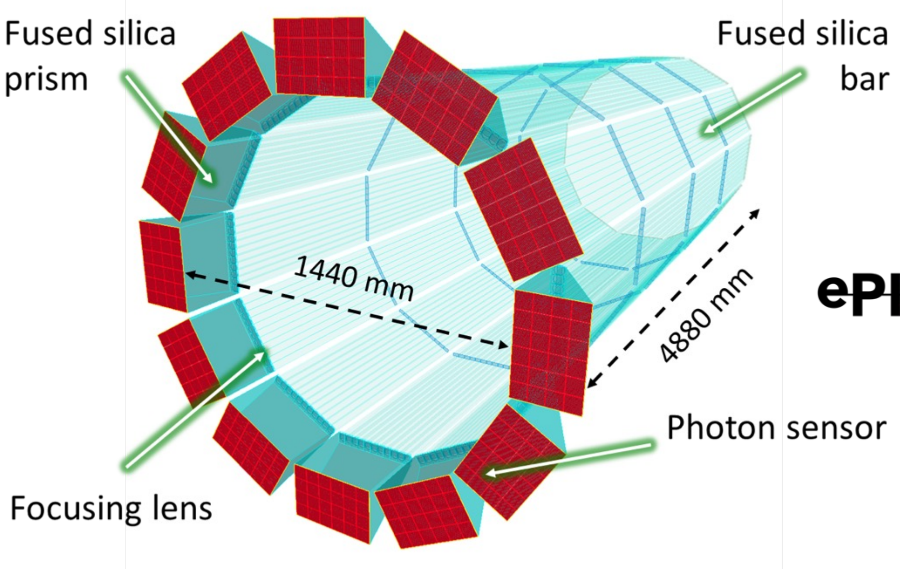
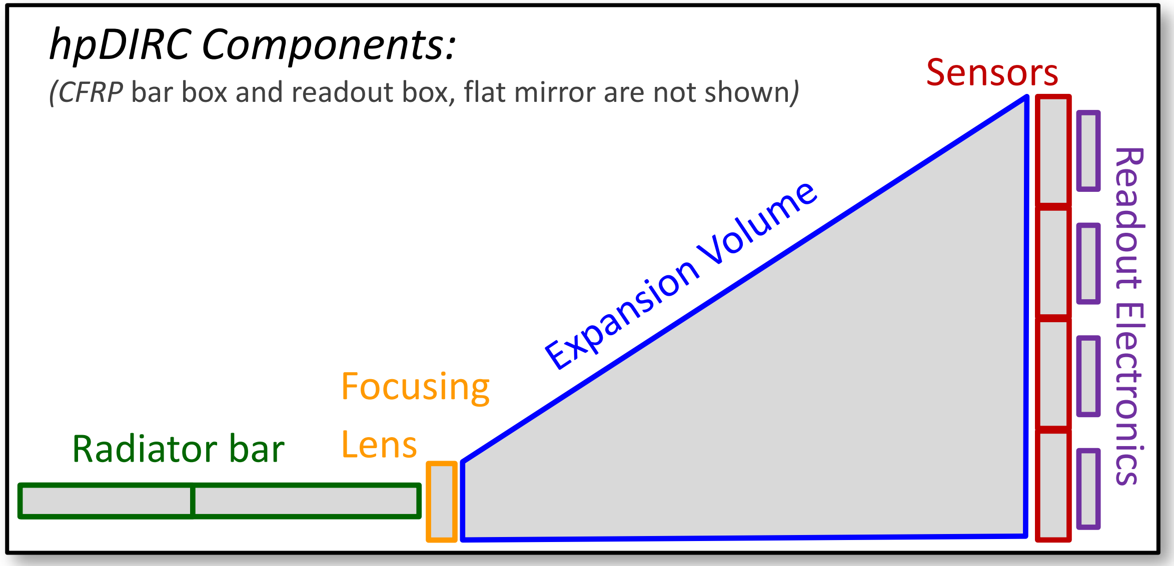


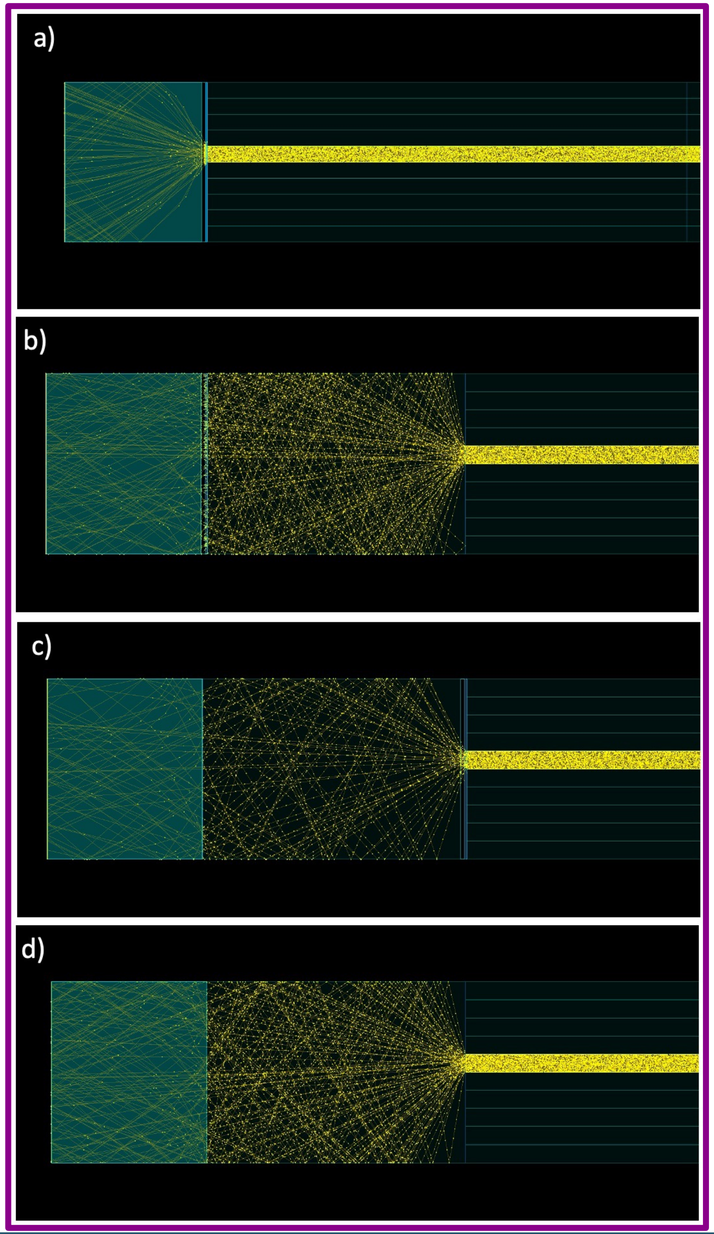
ePIC

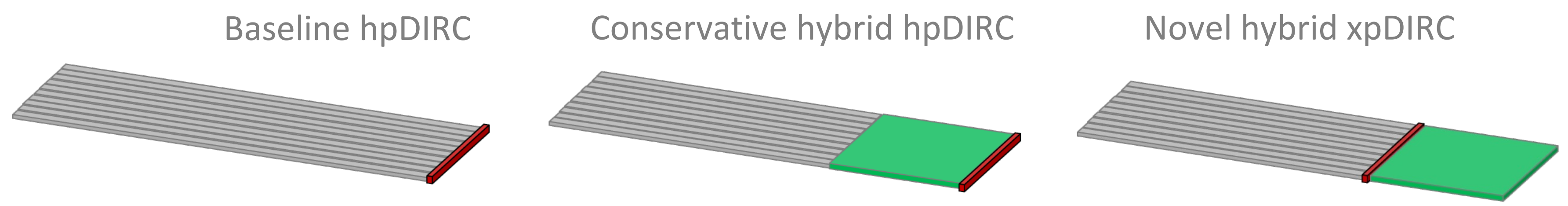


Example of EICGENRandD12 geometry study

- Hybrid optics (narrow bars in active area, wide plates as light guides) could mitigate focusing errors and reduce cost
  - Expansion volume effectively starts at end of narrow bar, improving angular resolution, possible use of cylindrical lens
  - Longer expansion in plate in plate could make shorter prism possible, with smaller sensor area, possibly enabling use of SiPM
  - Addressing "light-guide" section options for ePIC hpDIRC

EICGENRandD12 DIRC Geant4 Simulations



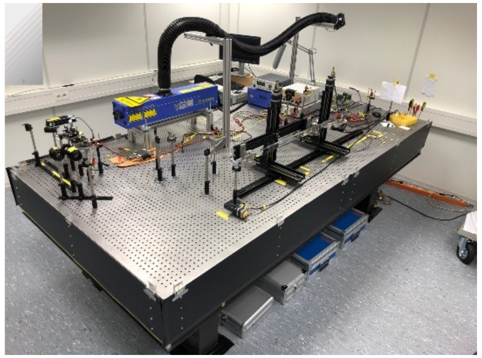


R&D FY23 Highlights

Validation of the BaBar DIRC bar reuse (JLab activity):

- Building and commissioning QA laser setup to measure mechanical and optical quality of the bars (In final stage)
- Prepared for transport (7/2023)
- Bar box transfer from SLAC to JLab (before end of 2023)

Laser lab at GSI

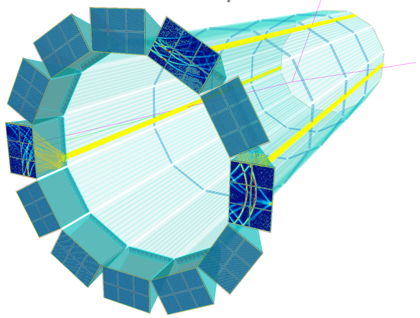


BaBar DIRC bars

hpDIRC studies in simulation:

- Initial study of the hpDIRC performance with magnetic field (done)
- Study of the hpDIRC azimuthal acceptance and preliminary performance with HRPPDs (done)
- Study of the hpDIRC performance with physical events (in progress, continued in 2024)

hpDIRC



hpDIRC prototype:

- Set up initial Cosmic Ray Telescope at SBU, start hpDIRC prototype integration (12/2023)
- Transfer of DIRC prototype components from GSI to SBU (done)
- Simulation studies of hpDIRC prototype with cosmic rays (done, continued in 2024)

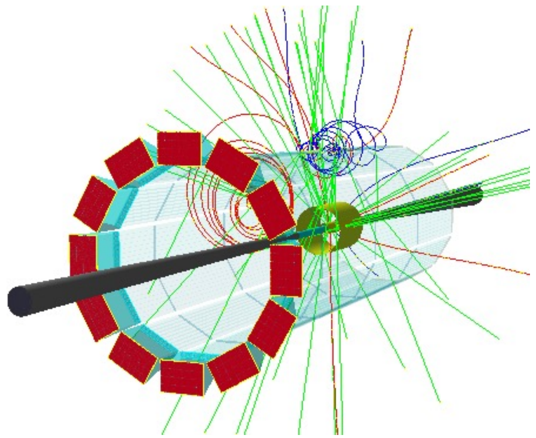
DIRC lab/CRT space at SBU

eRD103 R&D FY24 Plans

hpDIRC design studies in simulation (hpDIRC DSC activity):

- Optimize hpDIRC geometry (radiator bar positioning, focusing, prism shape, MCP-PMT/HRPPD arrangement)
- Complete study of the hpDIRC performance with physical events in the full ePIC simulation
- Continue study of impact of post-DIRC tracking layer

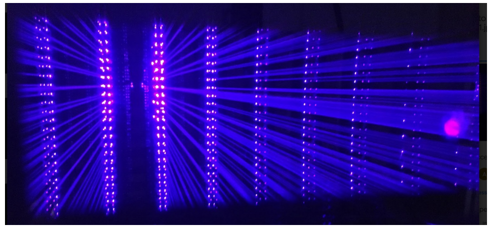
hpDIRC with physical event



Validation of the BaBar DIRC bar reuse (JLab activity):

- Measure mechanical and optical quality of the disassembled bars
- Determine impact of optical quality of the bars on hpDIRC performance

DIRC bar in HeCd laser at GSI



Milestones:

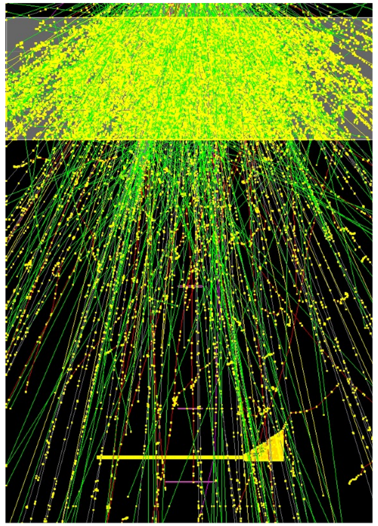
- Complete QA of bars from first disassembled BaBar DIRC bar box, decision about reusability and further disassembly strategy (JLab/CUA, Q4/2023-Q1/2024)
- Completed evaluation and parametrisation of cost/performance optimized EIC DIRC design options in simulation (CUA/GSI/WSU, Q1/2024)

eRD103 R&D FY24 Plans

Incremental development of hpDIRC prototype:

- Commission the CRT setup and initial hpDIRC prototype
- Finish Cherenkov Tagger with updated photosensors
- Evaluate the expected performance with cosmic rays
- Integrate single/double BaBar bars into hpDIRC prototype

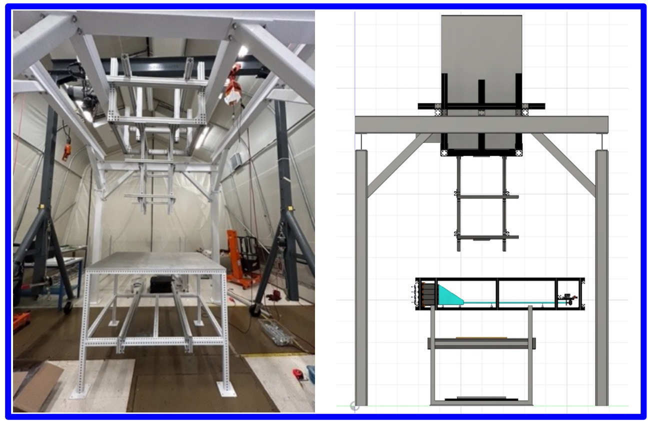
hpDIRC in CRT simulation



Milestones:

- Evaluated initial hpDIRC prototype with cosmic rays (CUA/GSI/SBU, Q1/2024)
- Cherenkov Tagger finished and integrated in CRT (CUA/ODU, Q1-Q2/2024)
- Commissioning of full CRT setup completed (CUA/ODU/SBU, Q2/2024)
- Functional hpDIRC prototype with single bar (CUA/SBU Q3 2024)
- Upgraded hpDIRC setup with two bars and radiation hard 3-layer lenses (Q4/2024)

DIRC lab and Cosmic Ray setup at SBU



eRD103 R&D Schedule

FY 22

- Preparation of the QA DIRC lab in JLab for BaBar bars
- Design and plans for CRT assembly
- hpDIRC performance studies and integration in full ePIC Sim.

FY 23

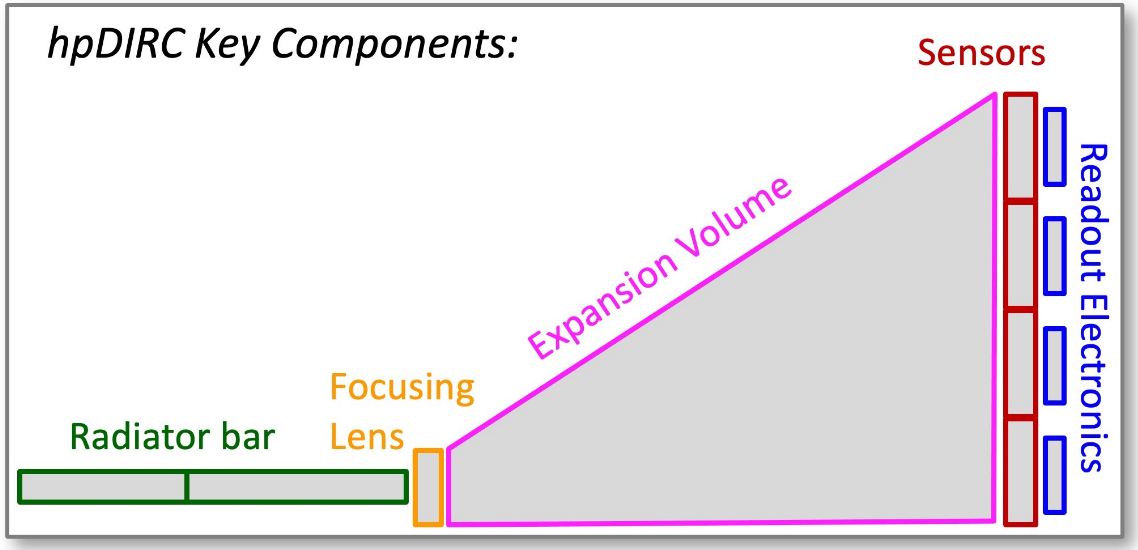
- Transfer of DIRC prototype components from GSI to SBU
- Development of CRT and prototype DAQ
- Cost/performance optimization of design in simulation

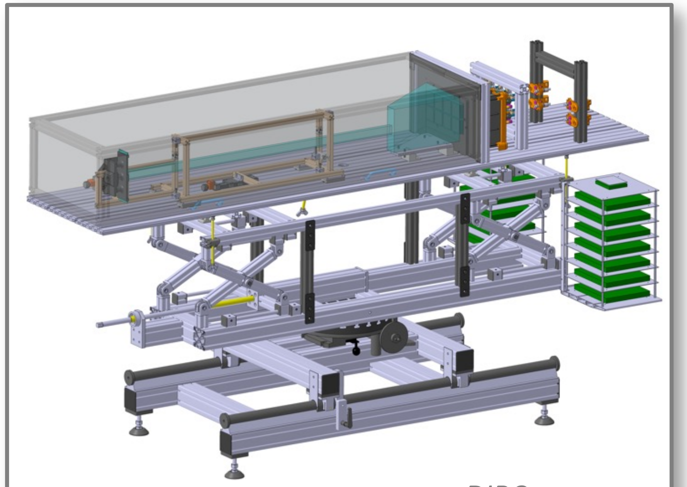
FY 24

- Validation of BaBar DIRC radiator bar reuse option
- Assembly and integration of initial hpDIRC prototype into CRT with tracking and timing detectors
- Incremental upgrade of hpDIRC prototype

FY 25

- Adaptation and evaluation of sensors and readout electronics in hpDIRC prototype
- Conclusion of prototype program with final cost/performance-optimized design
- Remaining technical, schedule, and cost risks, as well as on production readiness



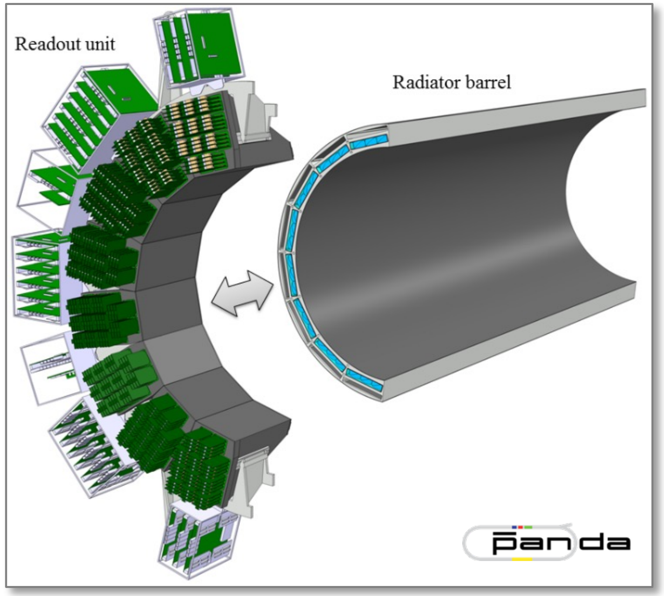


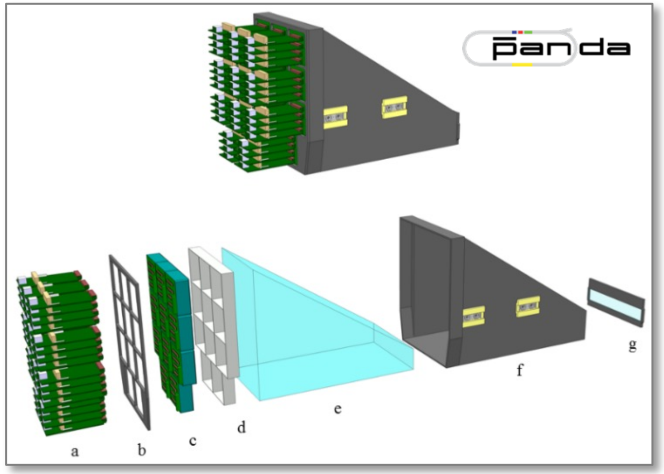
DIRC prototype

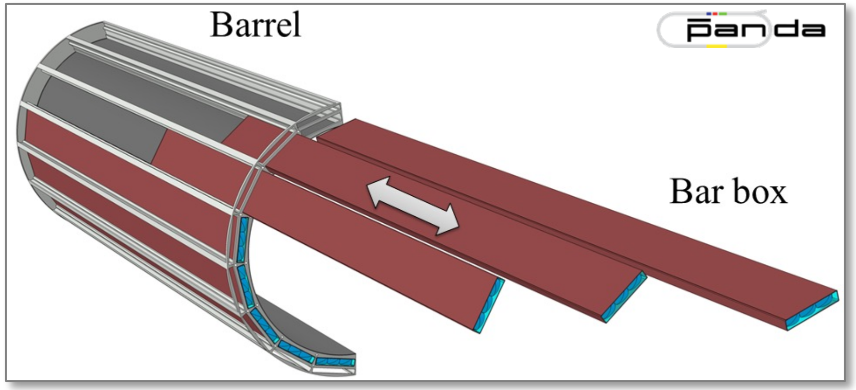
MECHANICAL SUPPORT AND INTEGRATION

Synergy with PANDA Barrel DIRC has helped to tackle many questions

- Integration into ePIC detector, modular concept, dry nitrogen purge
- Bar boxes slide into support frame, readout boxes removable
- Engineering/integration support for hpDIRC from EIC project (Avishay Mizrahi, MIT)
- Material used for bar boxes and readout boxes: CFRP
  - Light-weight solution, makes thinner bar boxes possible.
    Studying material stiffness, mechanical properties, and potential
    long-term impact of material outgassing on the bar surfaces (PANDA synergy)







PANDA Barrel DIRC example of DIRC mechanical design

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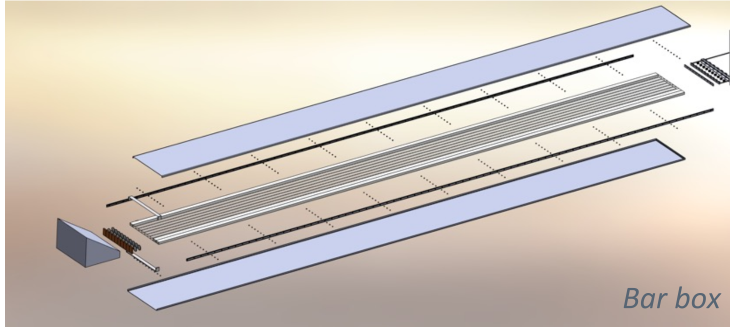
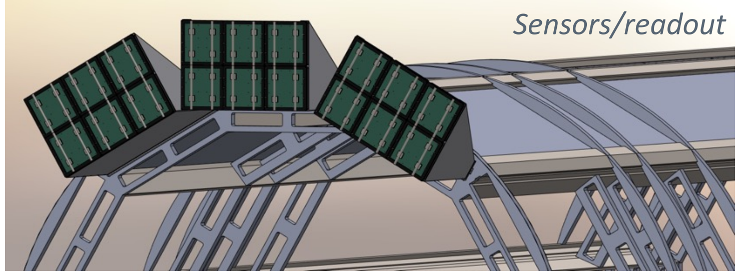
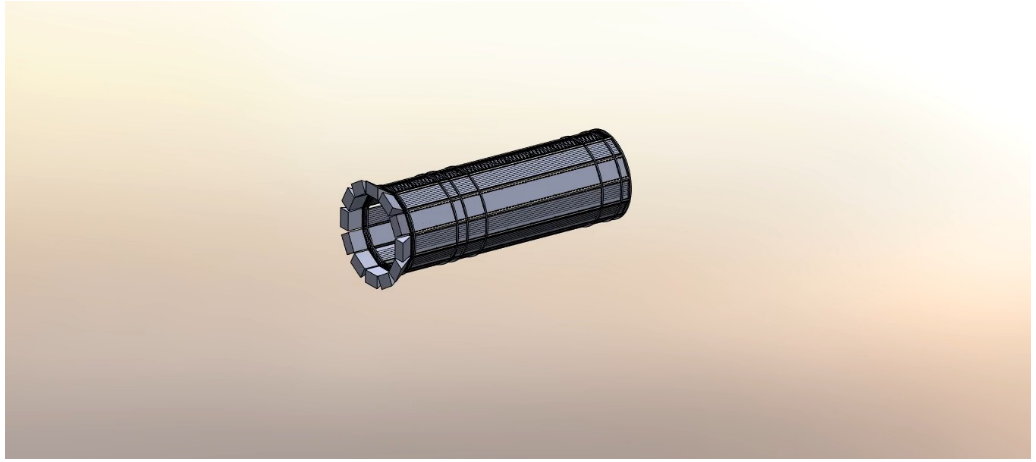
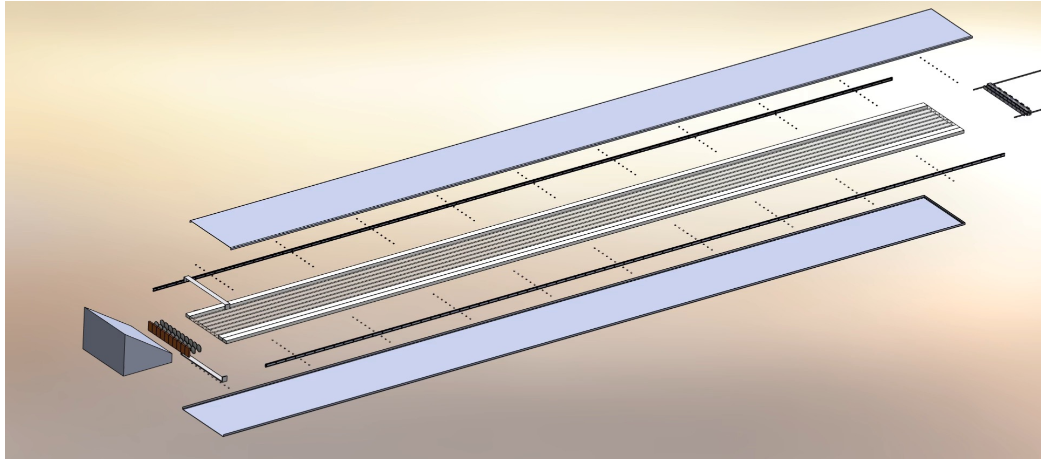
ePIC hpDIRC preliminary mechanical design









Two short MEC movies (only in Powerpoint version)

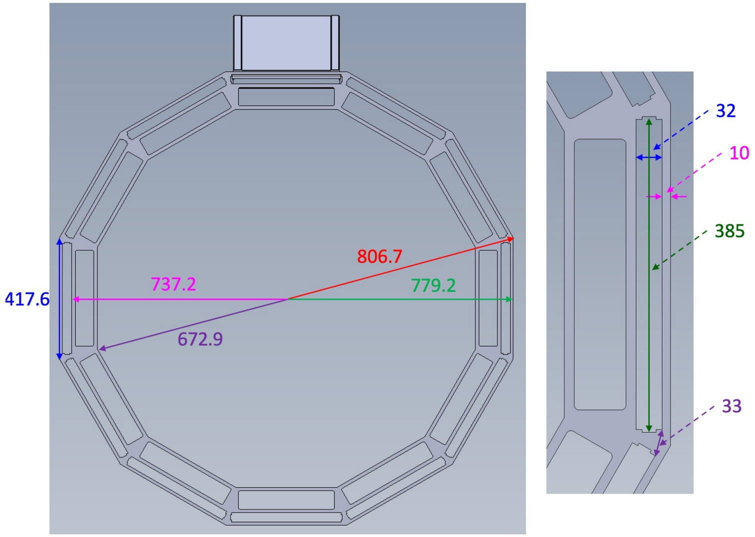
Impact of number of modules on performance and stability

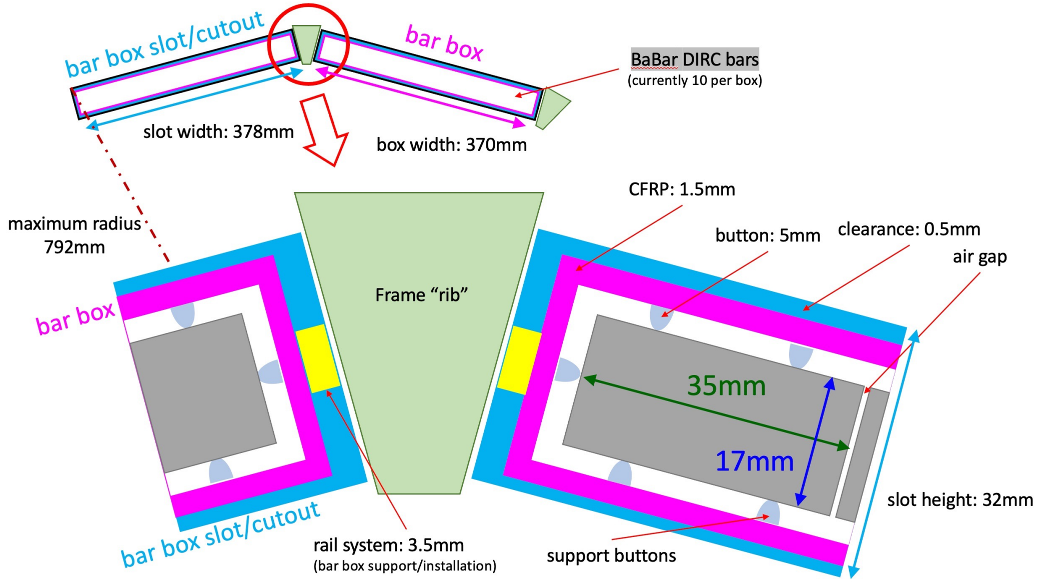
Current designs assumes 12 modules with 10 long bars in each module

Project requested studies on increasing number of modules and/or changing radius (using full G4 simulations)

Changing number of modules impacts:

- radial thickness of DIRC
- azimuthal acceptance
- radial location
- sensor coverage of detector plane





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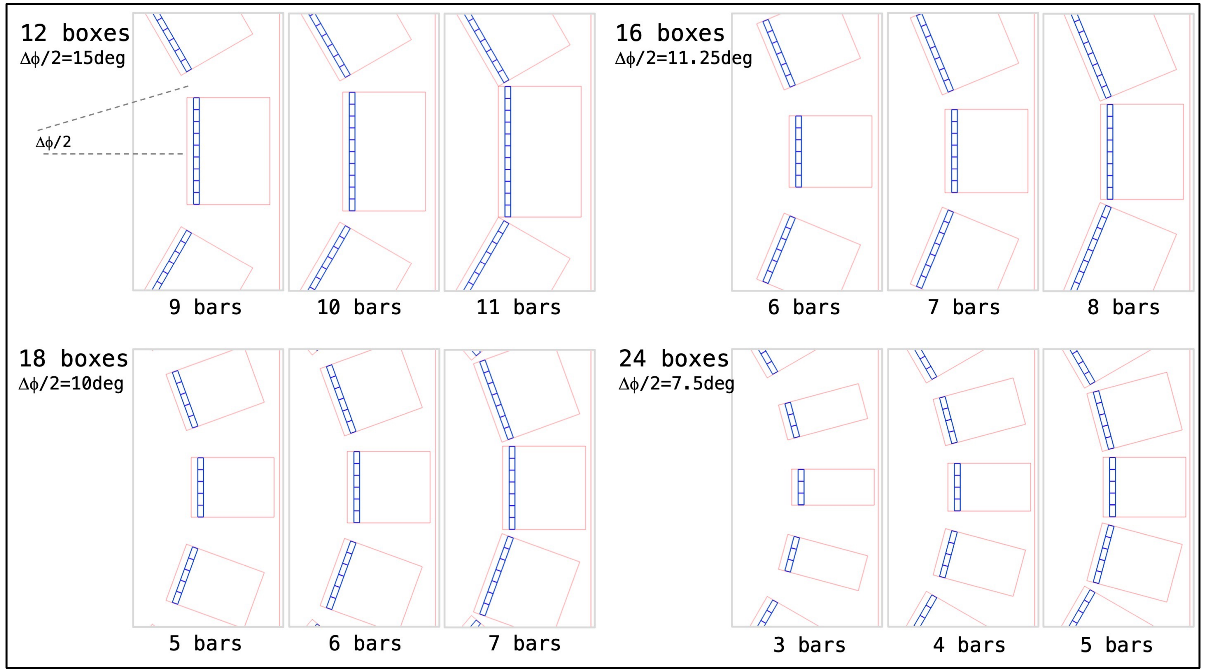
G4 Simulation study of number of modules and bars



Changing number of modules impacts:

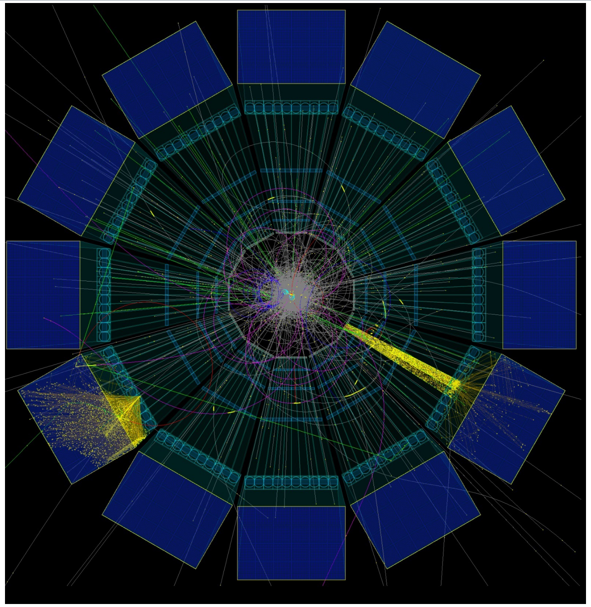
- radial thickness of DIRC
- azimuthal acceptance
- radial location
- sensor coverage of detector plane

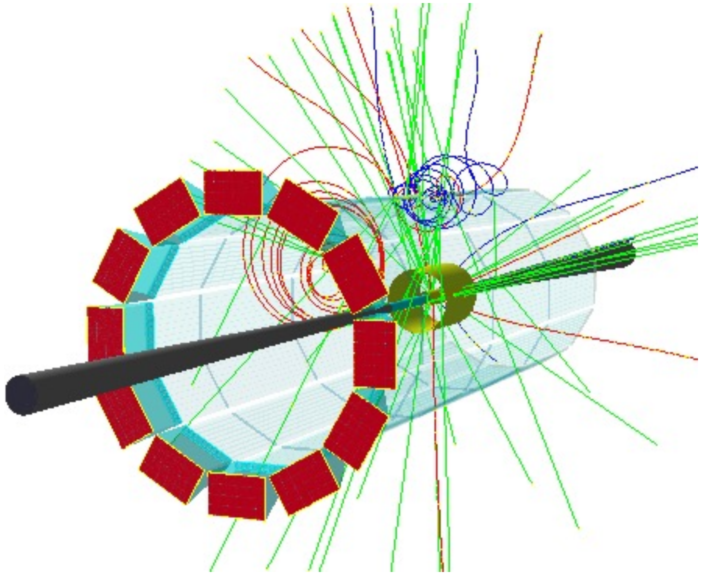
Stand-alone Geant4 Simulation

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

Full ePIC Simulation:

- Enables to study of the hpDIRC performance in magnetic field, using physics events (Pythia), including backgrounds and impact of other subsystems
- Imported and integrated stand-alone Geant4 package
- Implemented reconstruction, validating performance
- Started studies on tracks multiplicity in single event (tracks separated in polar angle by more then 5° easily manageable in reconstruction)

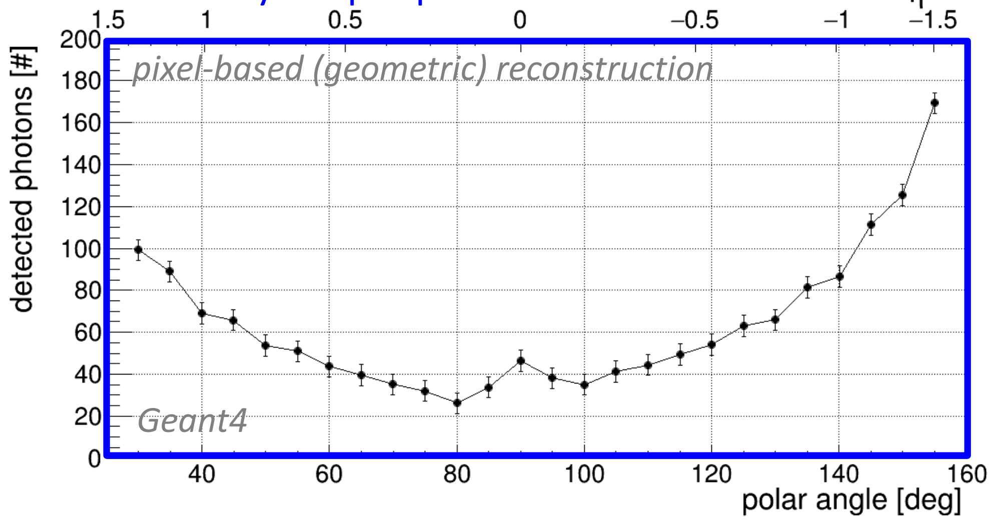




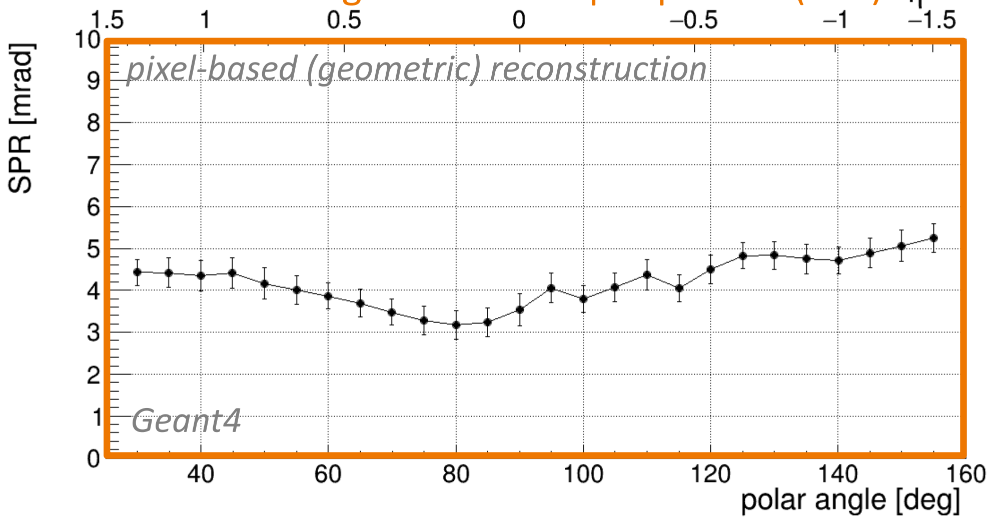
Event in full ePIC simulation

Expected hpDIRC Performance

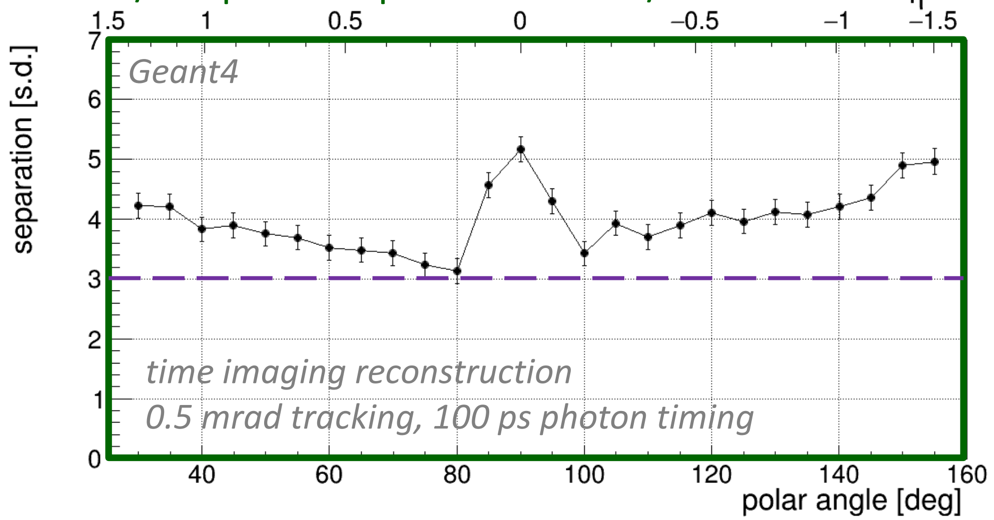
Photon yield per particle



Cherenkov angle resolution per photon (SPR)



π/K separation power at 6 GeV/c



Simulation studies performed with

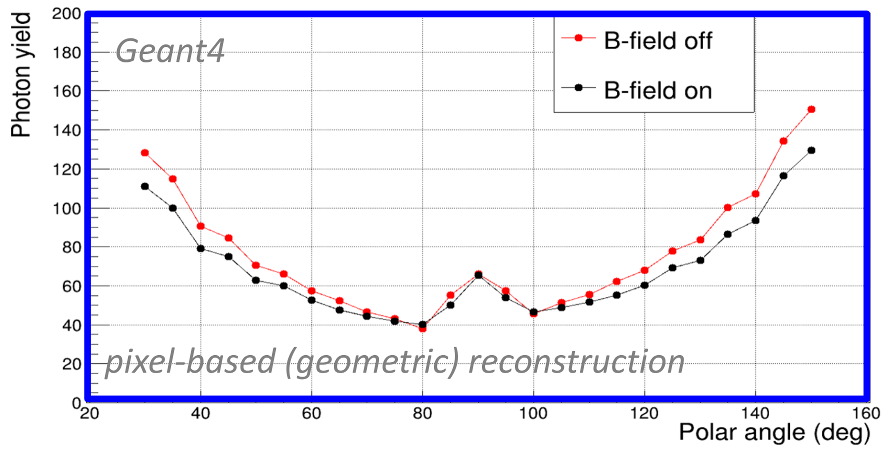
- Stand-alone Geant4 simulation
- Single particles from particle gun
- 6 GeV/c momentum
- No magnetic field, no other ePIC subsystems

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

EXPECTED HPDIRC PERFORMANCE VS. B FIELD

Impact of magnetic field on hpDIRC performance

Photon yield per particle



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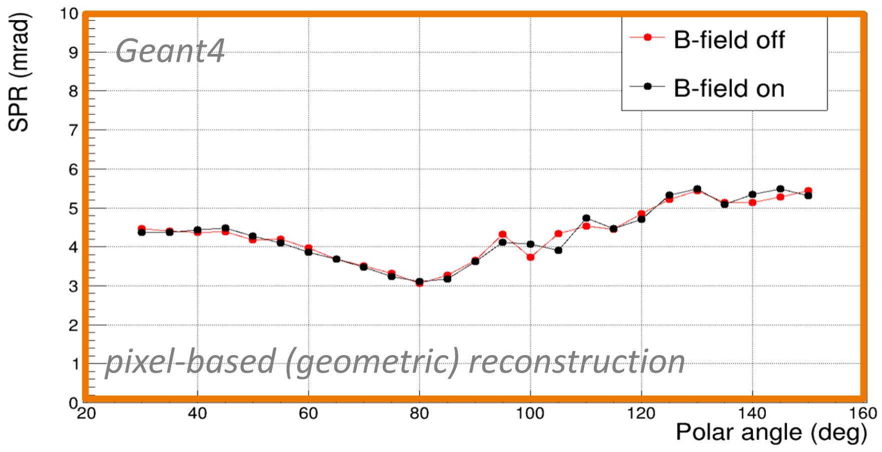
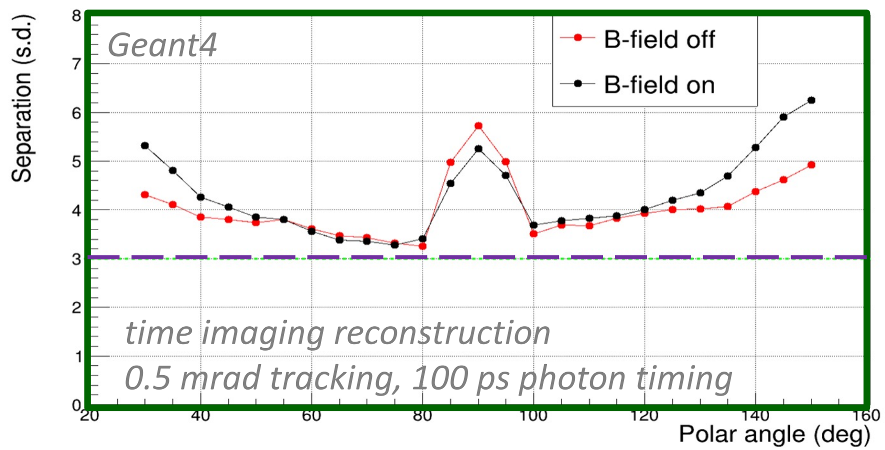


π/K separation power at 6 GeV/c



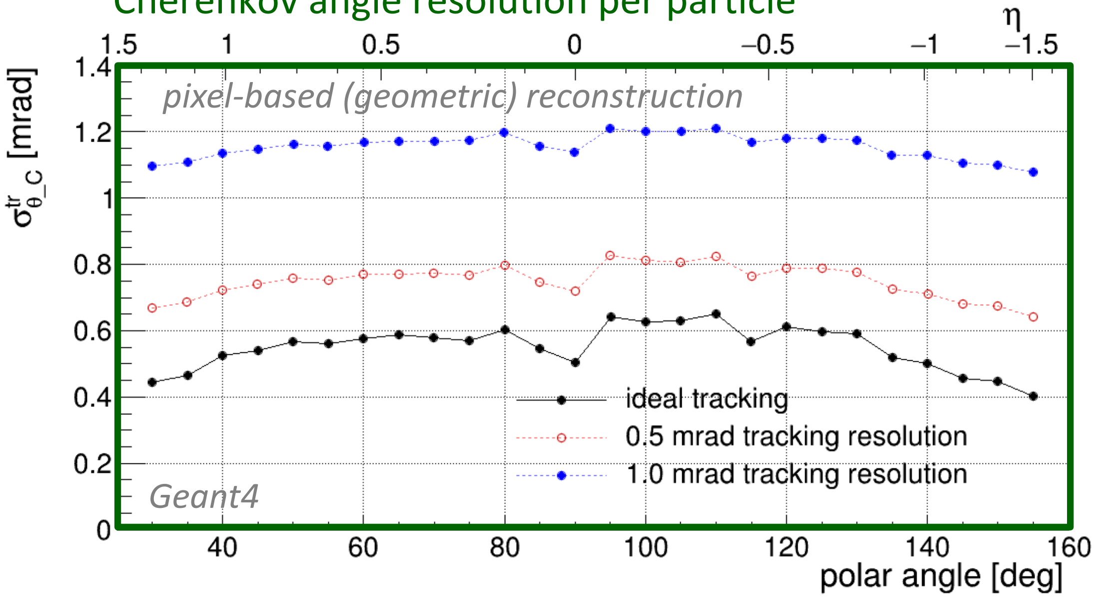
Simulation studies performed with

- ePIC software framework Fun4All (Geant4)
- Single particles from particle gun
- 6 GeV/c momentum
- MARCO: 1.7 T magnetic field

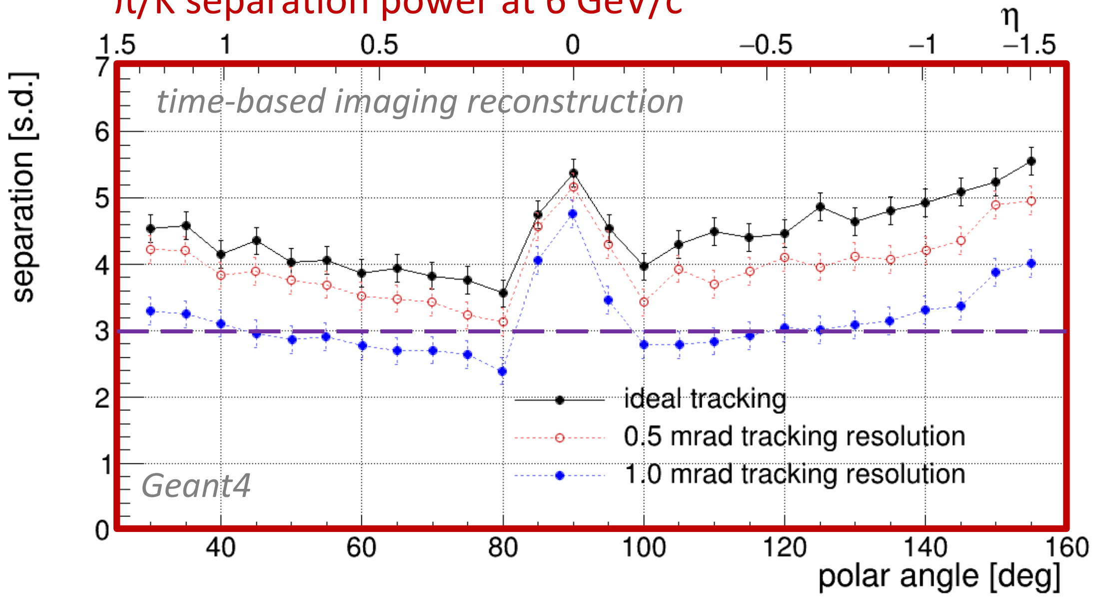
→ No significant impact of magnetic field on hpDIRC performance at 6 GeV/c

Impact of tracking angular resolution on hpDIRC performance

Cherenkov angle resolution per particle



π/K separation power at 6 GeV/c



Note:

- *π/K Cherenkov angle difference at 6 GeV/c: $\Delta\Theta_c \approx 3$ mrad*
- *Yellow Report tracking requirement: 0.5 mrad resolution 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

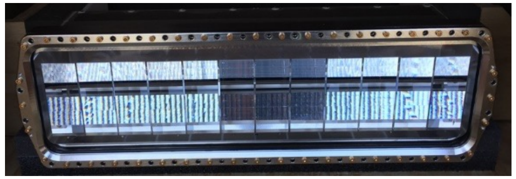
→ High-precision angular resolution crucial for reaching required hpDIRC performance

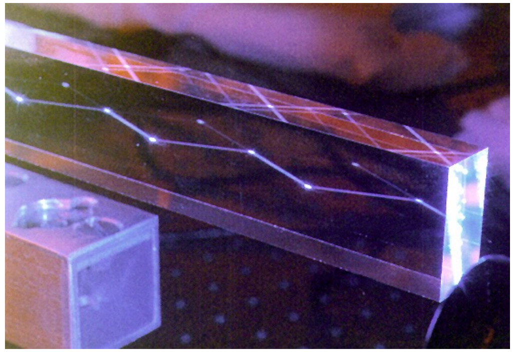
Reuse of BaBar DIRC Bars

Experience with bar/plate production in BaBar and Belle-II was challenging

→ can we reuse available BaBar DIRC bars in ePIC?

- 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
- Potentially saves up to $10M in cost, reduces technical and schedule risk
- Full-size bar boxes are too long, do not fit into EIC central detector,
  wedges deteriorate resolution: need to disassemble bar boxes for reuse
- hpDIRC barrel requires total of 480 short bars (1-1.2 m length)
- Eight bar boxes currently located at SLAC could yield up to 384 short bars,
  sufficient to cover rapidity range $-1.65 \le \eta \le +1.65$ (360 bars needed)
- Quality of bar surfaces, 25 years after initial production and disassembly, to be verified
- Additional 120 bars required for the light guide section, $\eta \le -1.65$, to couple to lenses
- Procure new bars from industry or disassemble the 4 bar boxes from GlueX?



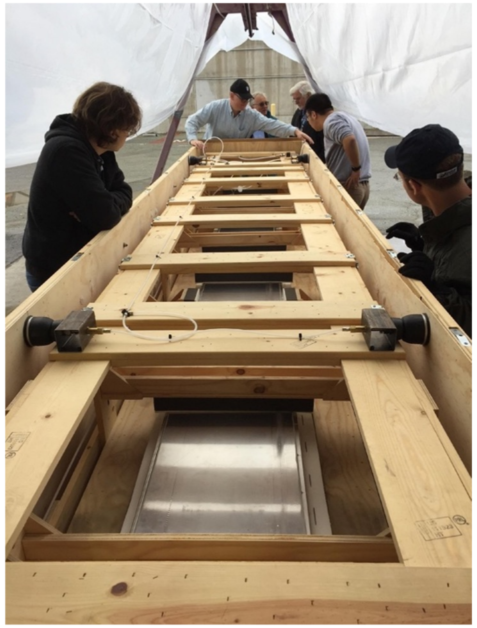


Reuse of BaBar DIRC Bars

- Transport of eight bar boxes from SLAC to JLab planned before end of the 2023 (coordination with SLAC, DOE)
- We will use similar method (wooden crates and shock absorption trays) as for the successful GlueX bar box transport in 2017/2018 (GlueX experts will participate)
- Bar boxes to be disassembled into individual bars at JLab (start in the fall)
- Optical quality of bars after disassembly will be evaluated in QA DIRC lab, located next to disassembly tent
- QA DIRC lab close to ready to start test measurements
- Reference DIRC bars (never used in BaBar) from SLAC available for commissioning
- QA space will accommodate Cleaning/Inspection, Laser quality measurements and storage
- Reflection coefficient measurement to evaluate surface quality

BaBar DIRC bar box transportation for GlueX

New transportation crates for EIC



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DIRC QA laser lab (completion date August)

DIRC labs under construction at JLab

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- We will use similar method (wooden crates and shock absorption trays) as for the successful GlueX bar box transport in 2017/2018 (GlueX experts will participate)
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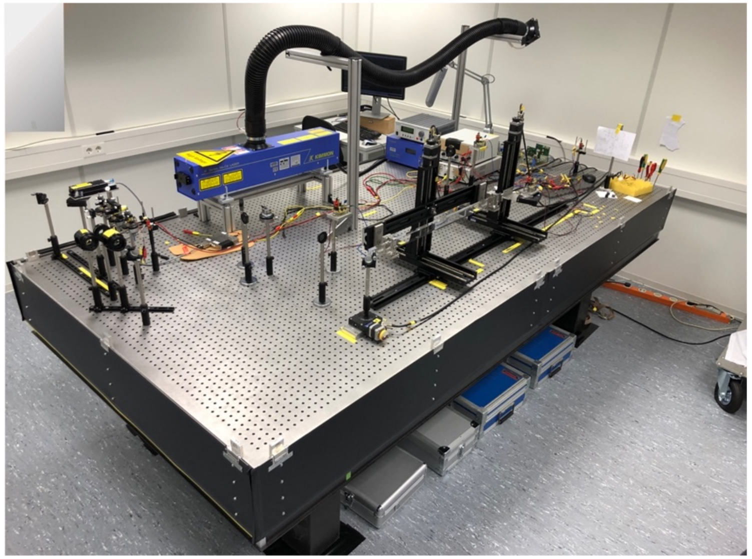
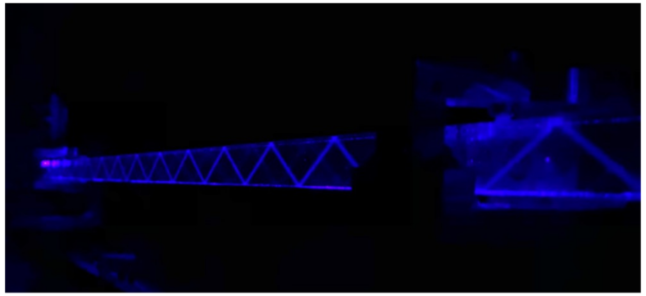
- Optical quality of bars after disassembly will be evaluated in QA DIRC lab, located next to disassembly tent
- QA DIRC lab close to ready to start test measurements
- Reference DIRC bars (never used in BaBar) from SLAC available for commissioning
- QA space will accommodate Cleaning/Inspection, Laser quality measurements and storage
- Reflection coefficient measurement to evaluate surface quality

Laser lab at GSI

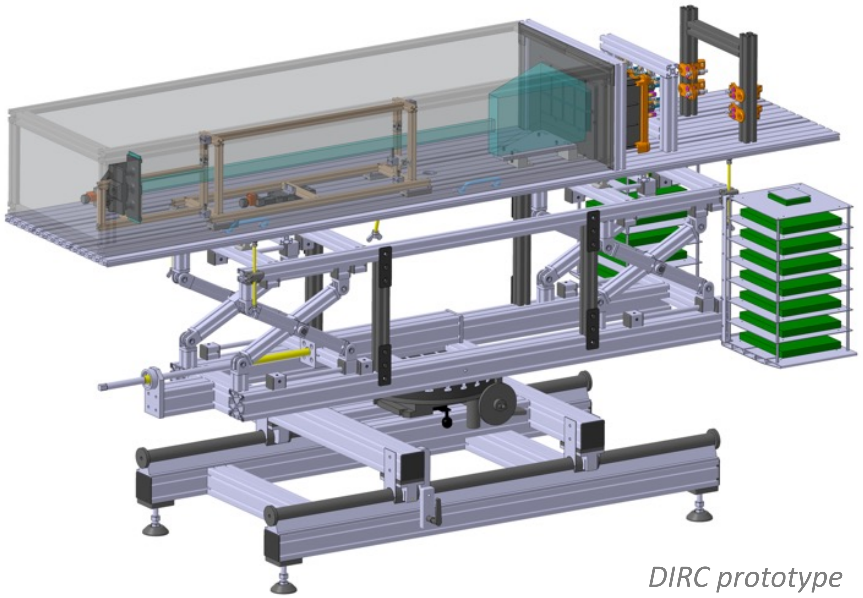


PANDA DIRC bar in GSI laser lab

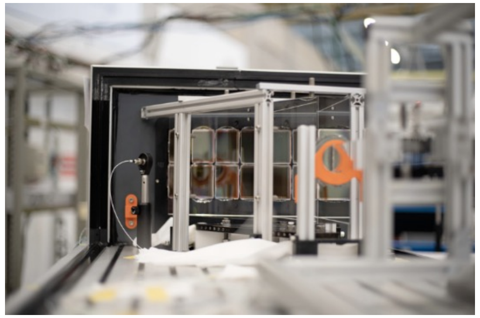


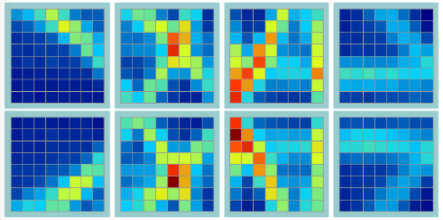
Technical risk: hpDIRC PID design validation

- Many aspects of hpDIRC already validated in particle beams
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18)
  (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)



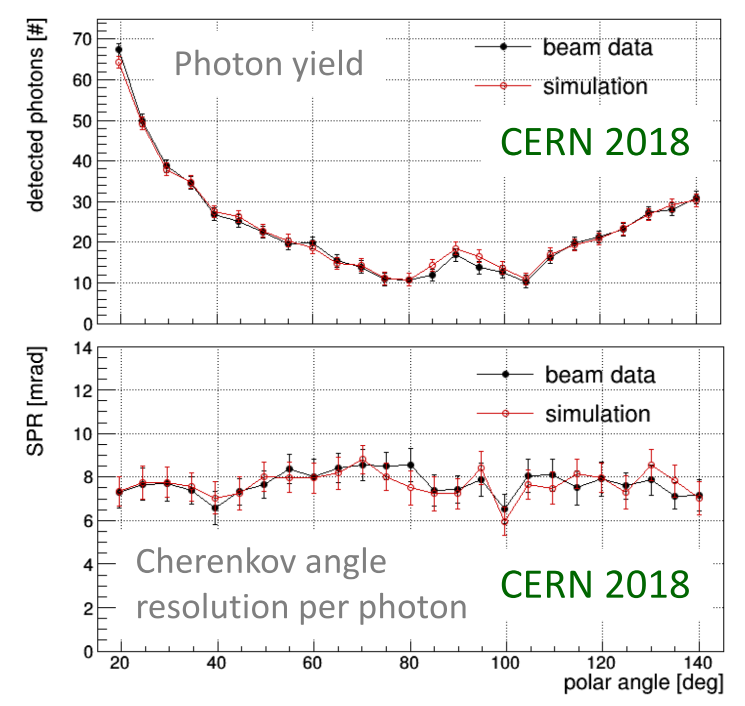
DIRC prototype





Hit pattern

CERN 2018



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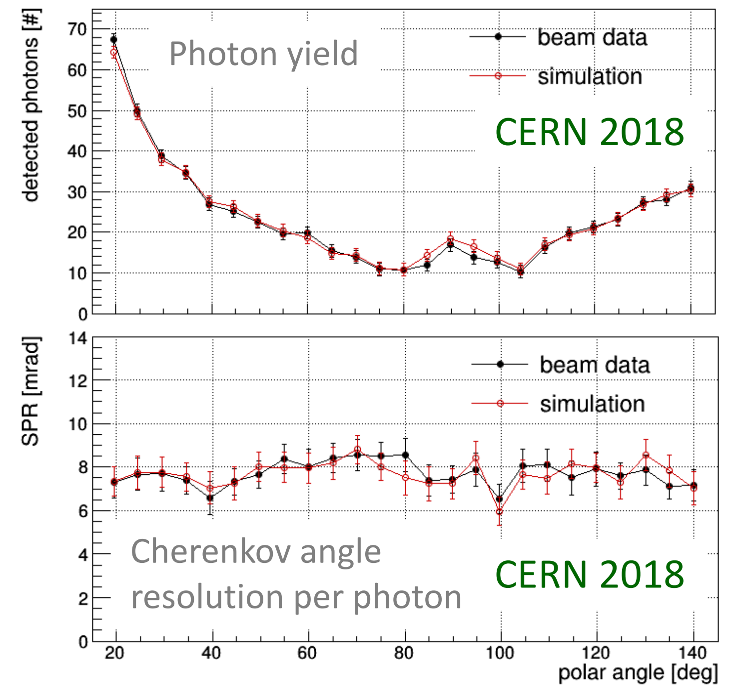
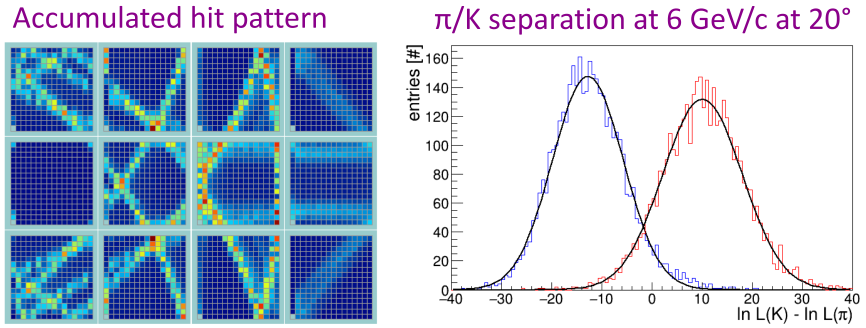
- Excellent agreement with simulation (same simulation used for hpDIRC)

- Used this simulation to predict PID performance of upgraded hpDIRC prototype
  (new MCP-PMTs and electronics, 3mm pixels, improved PDE, 100ps timing)
- Expected π/K separation at 6 GeV/c at 20°: 3.1 s.d.
- Upgraded PANDA Barrel DIRC prototype (new sensors, new electronics) capable of hpDIRC PID performance validation in particle beams



Geant simulation of upgraded prototype



HPDIRC PROTOTYPE IN CRT

Cosmic Ray Telescope (CRT) is under construction at SBU

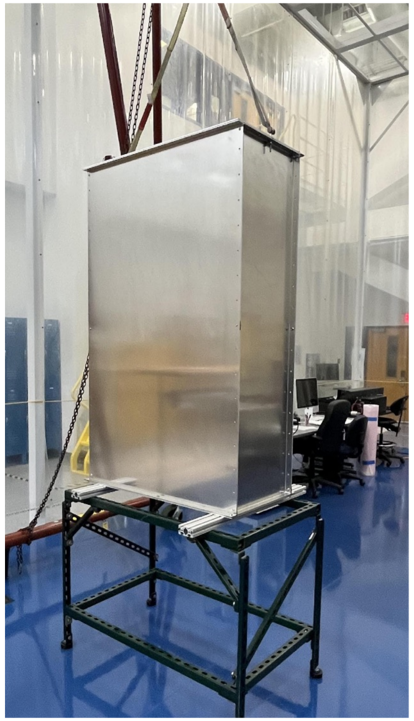
Facility to test incremental upgrades of prototype components, performance evaluation

- PANDA Barrel DIRC prototype components arrived in April, ready to be installed
- Advanced construction of mechanical support (rotation and translation of prototype)
- Simulation studies: 3D tracking, optimal placement of tracking and timing detectors
- Cherenkov tagger construction at ODU

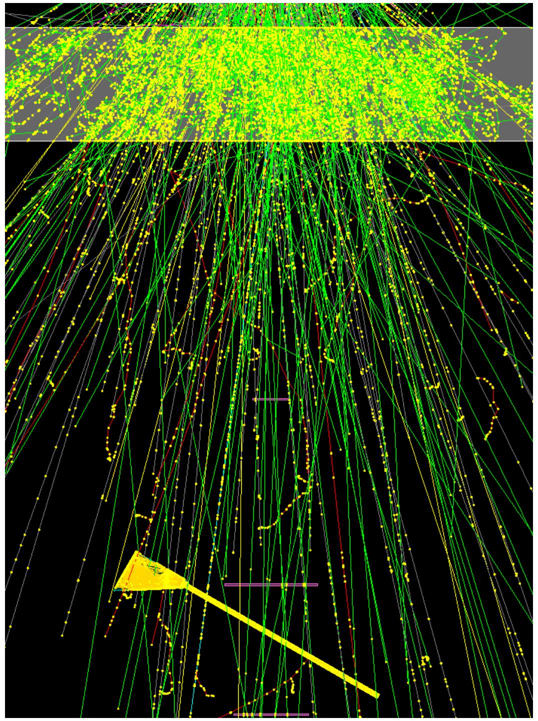
DIRC lab/CRT space at SBU

Prototype components from GSI at SBU

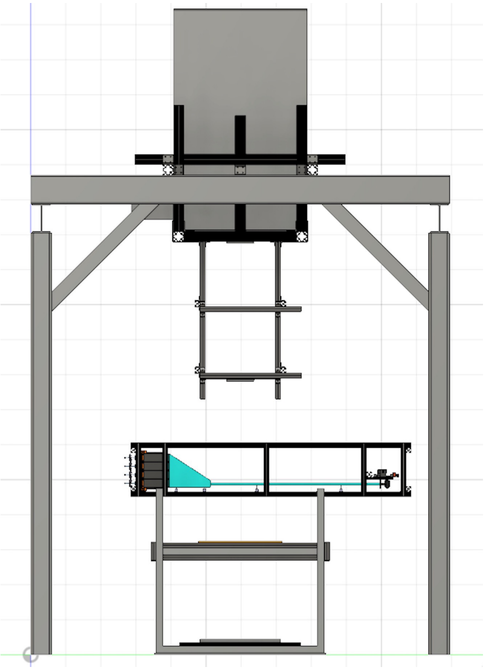
Cherenkov tagger at ODU



Geant4 simulation



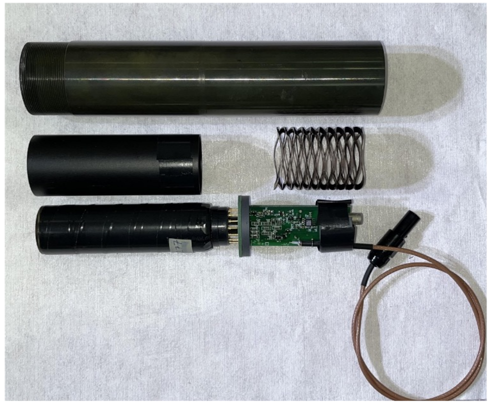
CRT setup schematic



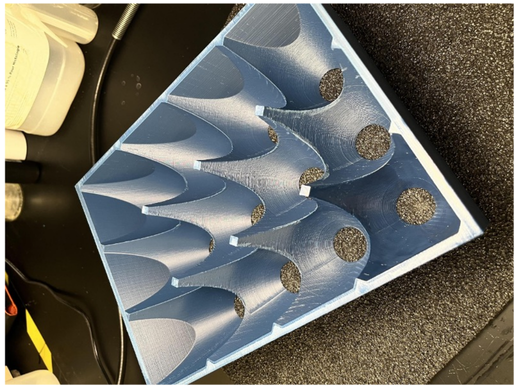
CRT Development: Cherenkov Tagger

- Cherenkov tagger is being developed and constructed at ODU (C. Hyde et al.)
- Tested legacy photosensors proved to be insufficient, require upgrade ($10k)
- CUA will help with finishing and transporting of tagger to SBU

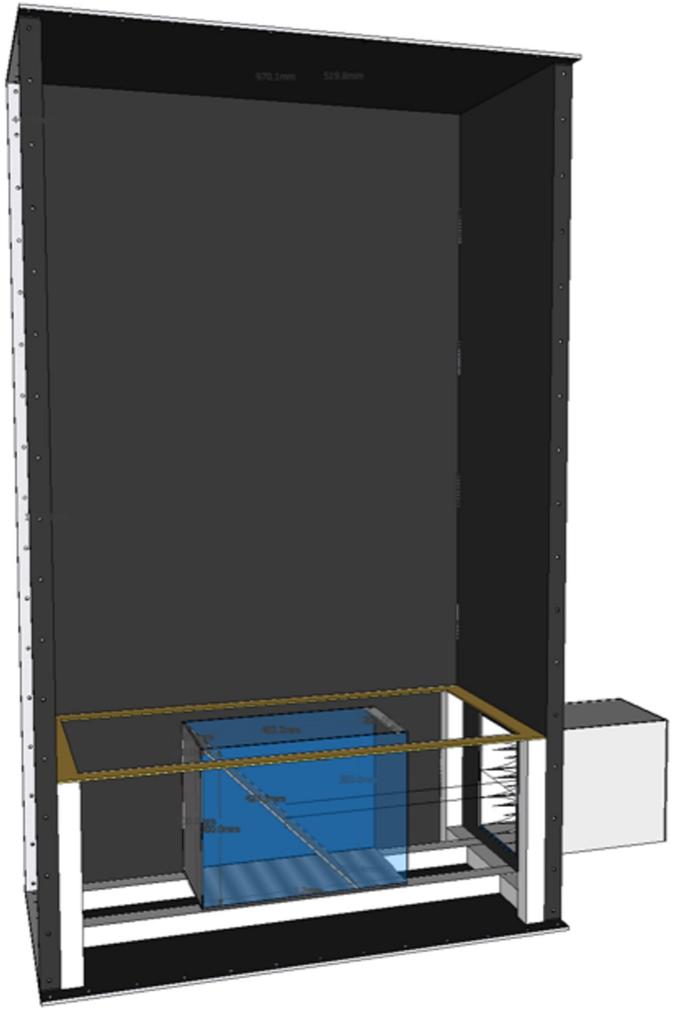
PMT



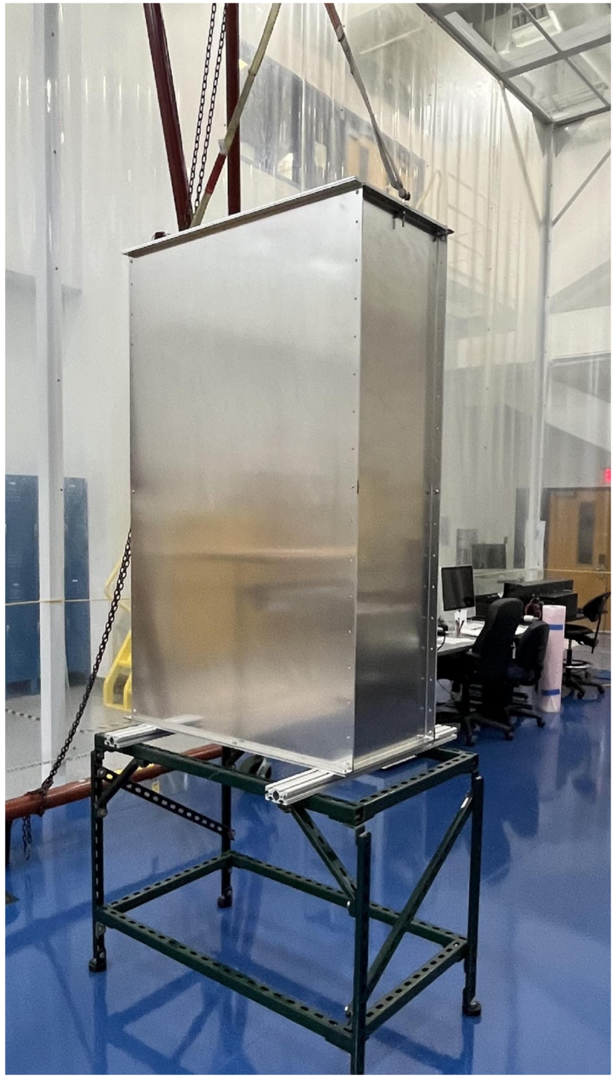
Light catcher



CAD drawing of Cherenkov tagger



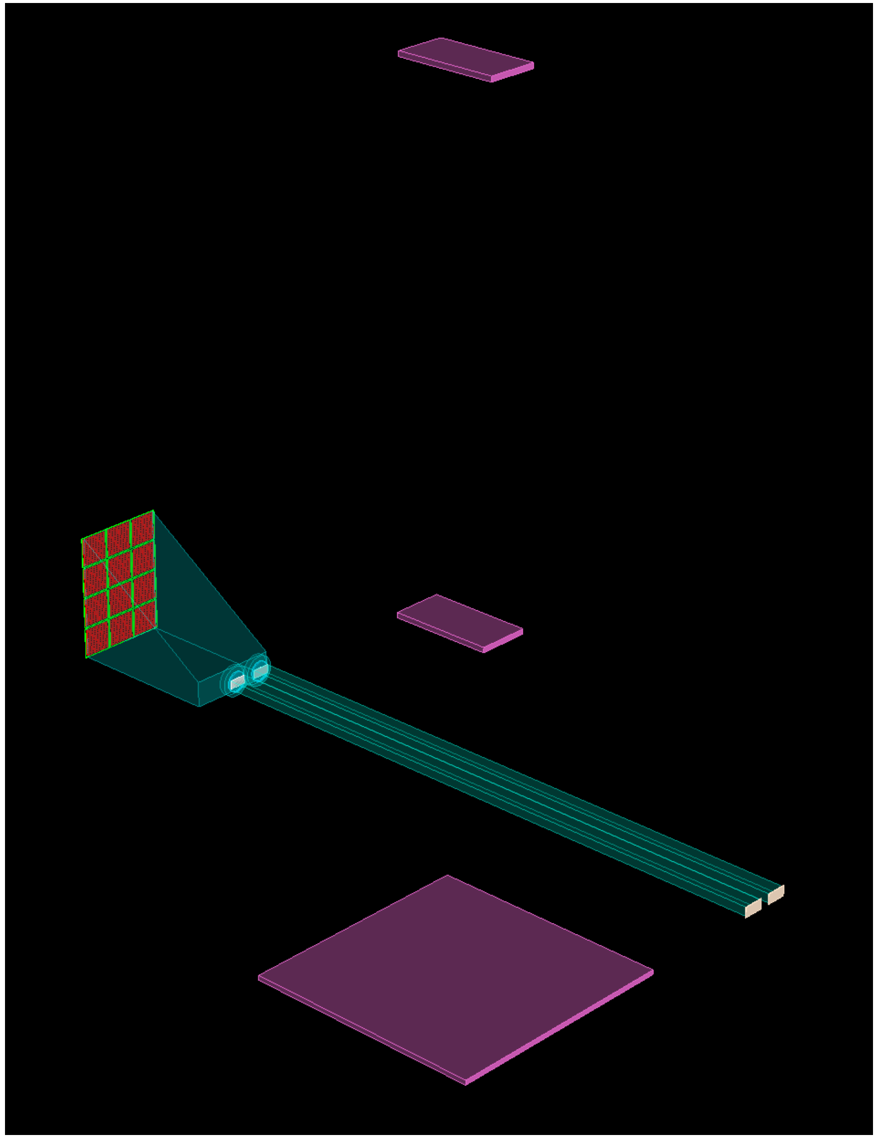
Cherenkov tagger in construction at ODU



hpDIRC Prototype: Plans for FY24

- Geant4 (CRY generator) Simulation used for optimization
  - Realistic material budget above CRT
  - Detailed hpDIRC prototype
  - Optimization of tracking detectors in progress
- Initial prototype with bar from PANDA Barrel DIRC
- Disassembled BaBar DIRC bars can be tested in the prototype
- Prototype with two bars simultaneously will allow to study additional aspects of performance, increase statistics
- Two radiation-hard 3-layer lenses are in hand and will be tested for the first time in prototype
- Ultimate CRT goal: test of fully assembled ePIC hpDIRC modules (gluing of bars and assembly of hpDIRC barboxes planned at SBU)

Simulation of hpDIRC Prototype with 2 bars in CRT



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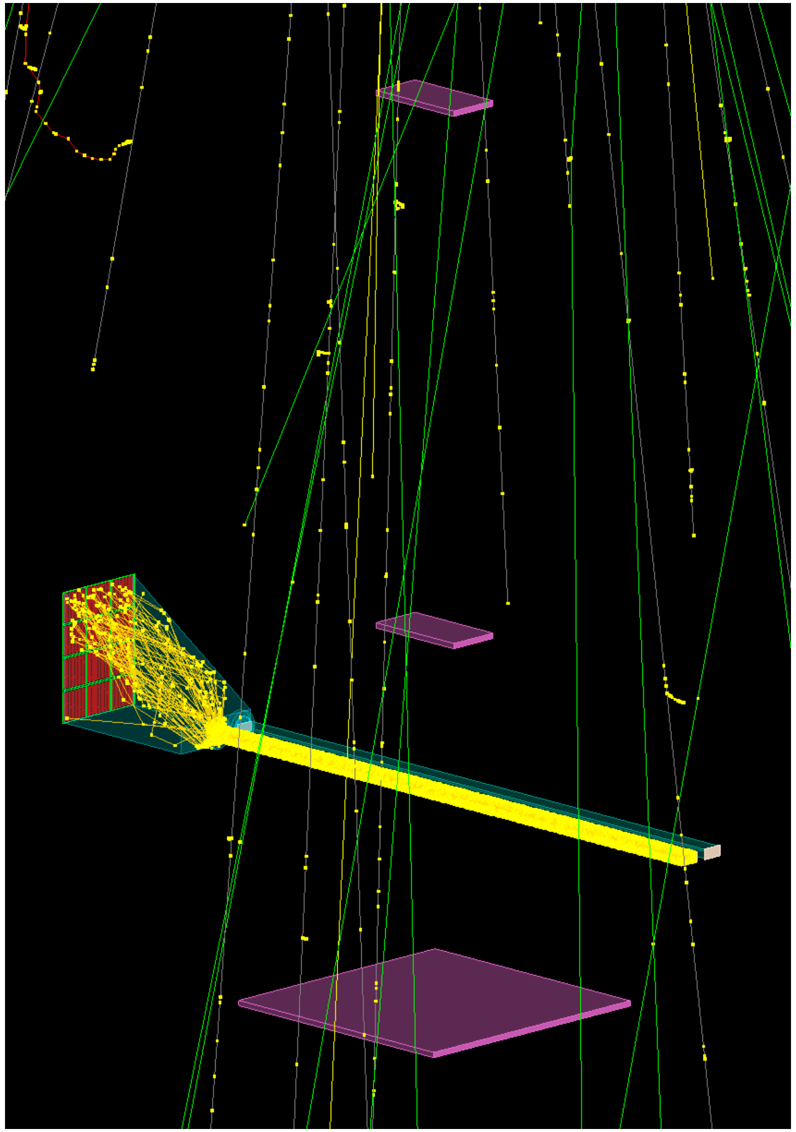
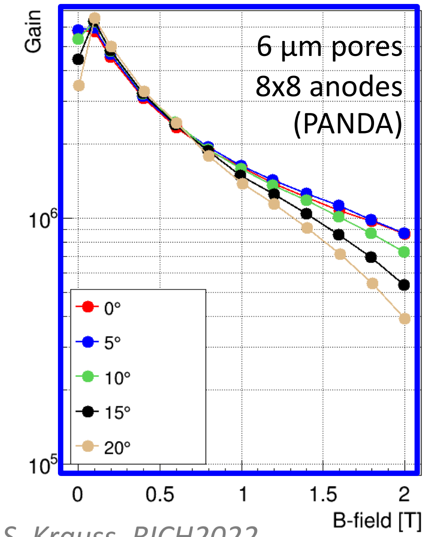


hpDIRC sensor requirements

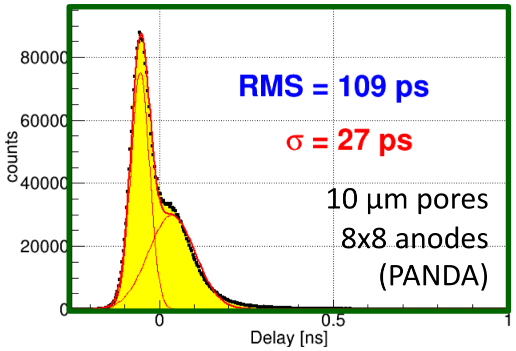
- Single photon sensitivity in ePIC magnetic field: 10^6 gain at ~ 1T
- Fast timing for single photons: timing precision (rms) < 100 ps
- Large active area ratio for tiled sensors: goal > 75%
- High PDE in visible range: goal > 25% at 400 nm
- Small pixels: anode pixel size < 3.5 mm
- Tolerance for high photon rates: goal > 0.5 MHz/cm^2
- Tolerance for high occupancies: up to 200+ photoelectrons per particle, need DC-coupled anodes
- Long lifetime: goal > 10 C/cm^2

PHOTONIS MAPMT 253

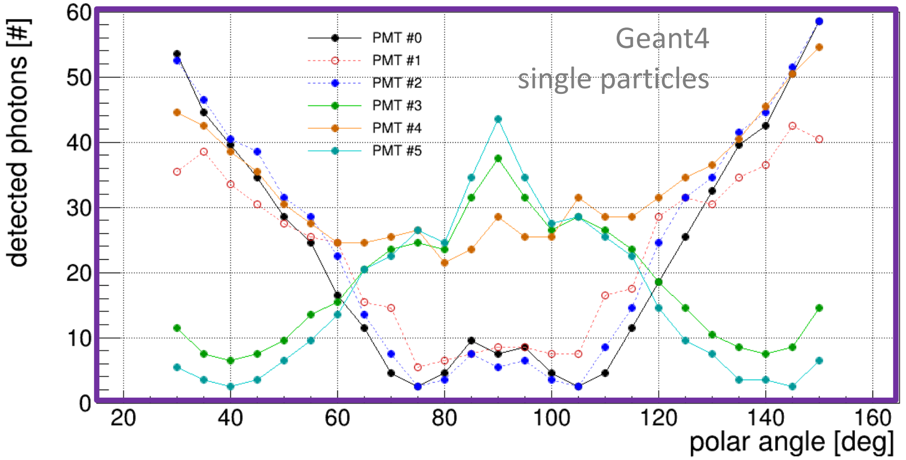


S. Krauss, RICH2022

PHOTONIS XP85012-S



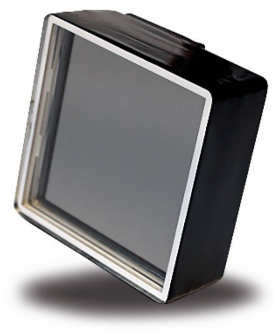
Expected number of photoelectrons per particle per 12 cm x 12 cm sensor



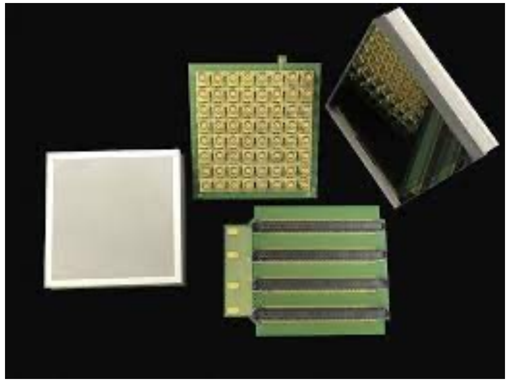
hpDIRC sensor: Microchannel-Plate PMT

- MCP-PMTs capable of meeting all hpDIRC requirements *(A. Lehmann review talk at RICH2022)*
- Successful application in Belle-II TOP (Hamamatsu 1'' MCP-PMTs) and PANDA/EIC DIRC beam tests (Photonis 2'' MCP-PMTs)
- Lifetime-enhanced 2'' MCP-PMTs commercially available from Photonis and Photek with suitable DC-coupled anode configurations
- Good performance of 8x8 anode versions in PANDA MCP-test stands *(see S. Krauss, RICH2022),* configuration with smaller anodes to be validated
- Ongoing development at Incom: 12 cm-sized Gen III HRPPDs, 32x32 anodes Active project, supported by EIC PED funds, baseline sensor for ePIC bwRICH
- Baseline sensor for hpDIRC: 2'' MCP-PMTs from Photonis or Photek Potential solution: DC-coupled Incom HRPPD
  - Evaluation studies needed for both solutions, submitted as part of eRD110
  - hpDIRC Prototype at CRT can be used for prototype sensor studies

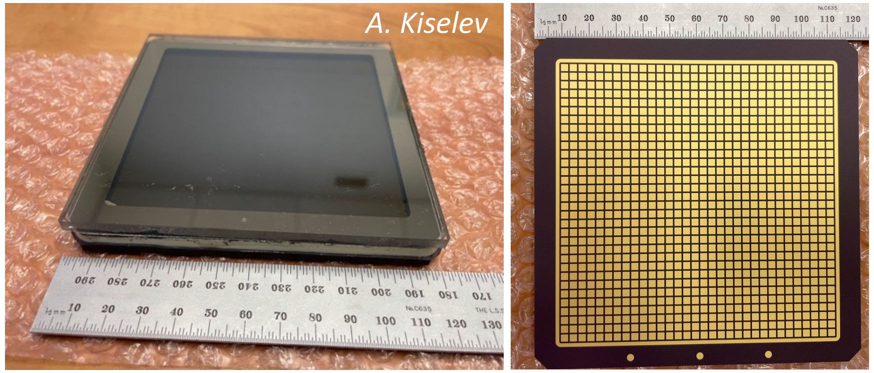
PHOTONIS XP85122-S



Photek MAPMT 253



INCOM Gen III HRPPD prototype (front/back view)



PHOTOSENSORS

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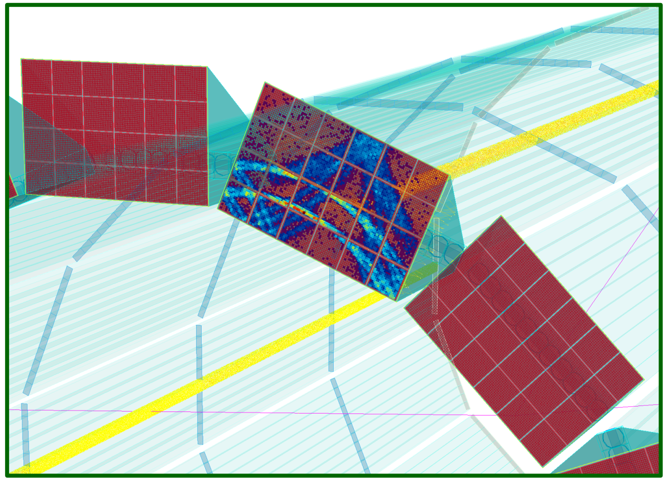
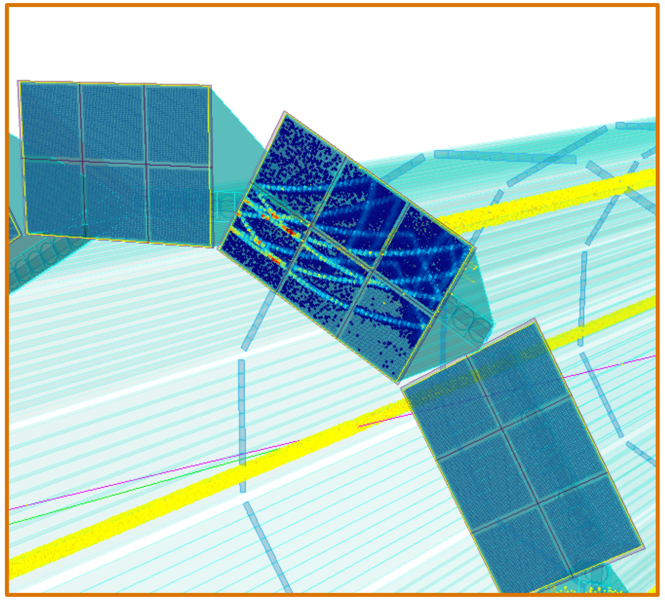
hpDIRC Simulation with baseline 2'' MCP-PMTs



hpDIRC Simulation with Incom HRPPD



Readout Chain

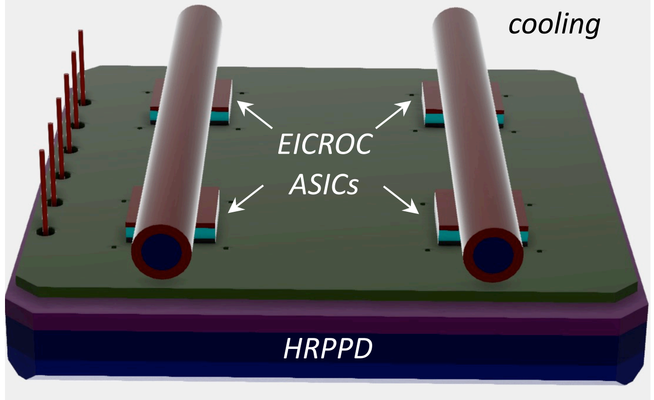
Front-end board (FEB) requirements for hpDIRC

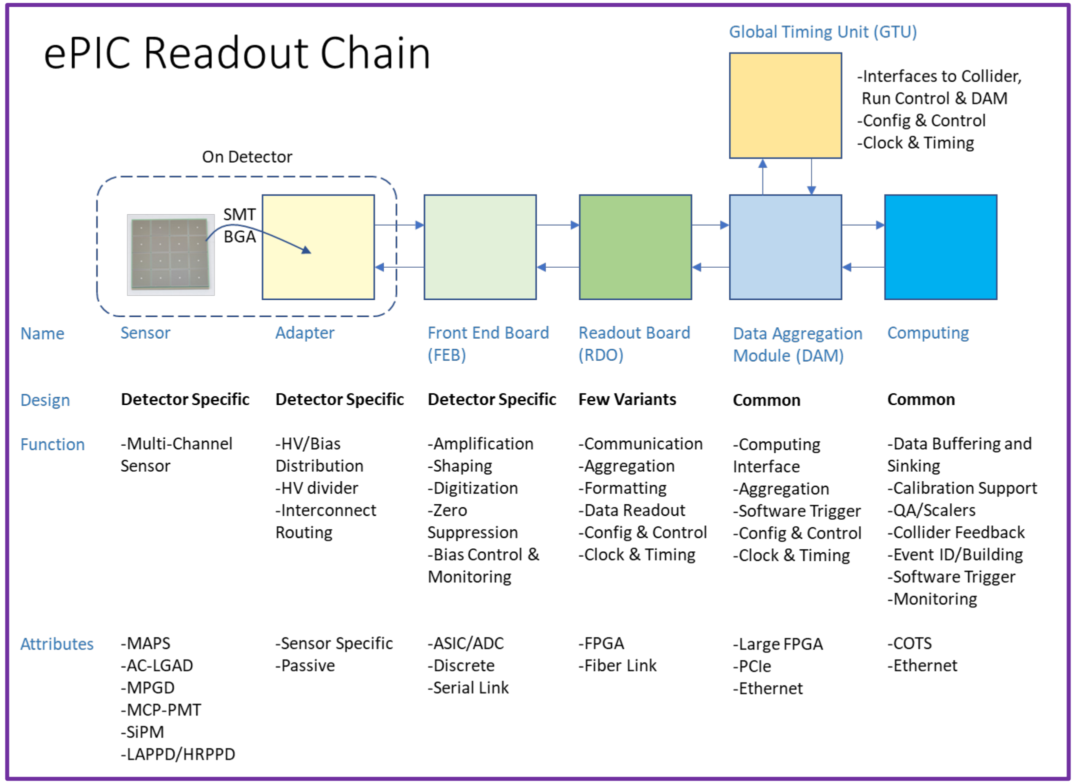
- Sensitive to small (few mV) MCP-PMT pulses
- Maintain excellent single photon timing precision
- Match sensor footprint and channel density
- High rate, high occupancy, streaming readout

Baseline front-end board for hpDIRC: EICROC

- Synergy development with ePIC AC-LGAD and bwRICH systems
- Low-power ASIC, 256+ channels per board
- Will deliver hit time, time over threshold
- EICROC will be mounted directly to HRPPD via interposer/adapter
- Readout Boards will be located on readout box, near EICROC
  - Developed as part of eRD109
  - hpDIRC Prototype at CRT can be used for sensor-readout studies

A. Kiselev, preliminary





FY24 Budget Request

FY 24 Plan:

- hpDIRC prototype in CRT:
  - Finishing Cherenkov Tagger
  - Installation, commissioning, and operation of CRT
  - Operating and upgrading prototype
- Validation of the BaBar DIRC bar reuse
- hpDIRC Cost/Performance design optimization

Budget request:

- ⇨ Materials for CUA
- ⇨ Materials, graduate student, and senior support for SBU
- ⇨ Travel for DIRC experts (CUA/GSI)
- ⇨ No eRD funding requested (Jlab supported)
- ⇨ No eRD funding requested (hpDIRC DSC)

Notes

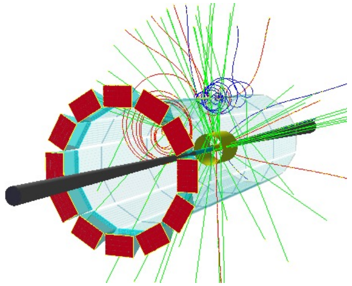
- JLab DSG supports QA lab and bar measurement
- Software studies picked up by hpDIRC DSC

Item	**Institution**	**Requested**
PostDoc/Senior (50%) CRT	SBU	$60k
Prototype Equipment	CUA	$15k
Travel to DIRC lab at SBU	CUA/GSI	$30k
CRT Graduate student	SBU	$61.5k
CRT Materials	SBU	$15k
Total		$181.5k

SUMMARY/OUTLOOK

- Important eRD103 progress in 2023, close to meeting declared milestones
- Positive feedback from recent PID review
- Adjusted eRD103 program fits perfectly hpDIRC multi-program R&D effort with clearly defined roadmap towards TDR and ultimately construction readiness
- Continuation of program in 2024 with focus on Cosmic ray telescope (CRT), validation of BaBar bars reuse option, and completion of cost optimized hpDIRC design
- Preparing the way for future incremental upgrade of the hpDIRC prototype when bars, sensors, and readout electronics become available
- The ultimate goal for CRT to test the full hpDIRC module well aligned with SBU plans and ePIC schedule

hpDIRC in simulation



Transportation crates

CRT space at SBU

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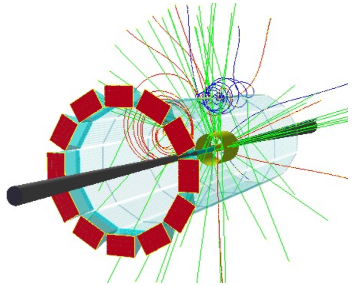


Transportation crates

CRT space at SBU

Thank you all for your attention

Extra Material

HIGH-PERFORMANCE DIRC R&D

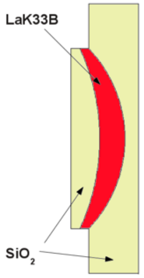
- 10+ years ago: DIRC good candidate for hadronic particle in EIC detector barrel – if π/K momentum coverage achieved by BaBar DIRC is increased by 50%

- 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)

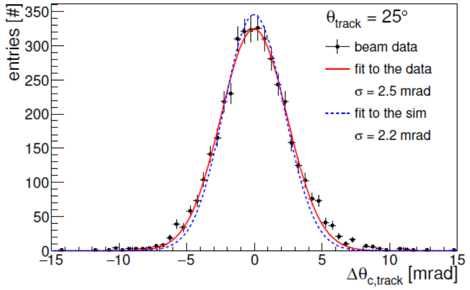
- EIC DIRC R&D Milestones:
  - 2012: First multi-layer high-refractive index lens concept to avoid photon loss at air gaps
  - 2012: First 2-layer and 3-layer prototype lenses produced by industry
  - 2014: Simulation showed that lens-based design is expected to reach 1mrad Cherenkov angle resolution, equivalent to 3 s.d. π/K separation at 6 GeV/c
  - 2015: First successful CERN beam test with multi-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

- hpDIRC selected as barrel PID solution for EIC detector in 2022

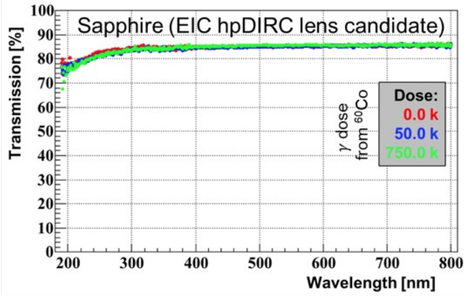
Initial 3-layer lens concept



Cherenkov angle per particle, CERN 2015

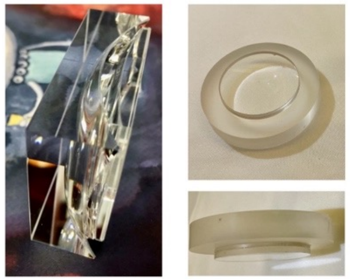


radiation hardness of sapphire



radiation hard lens prototypes

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

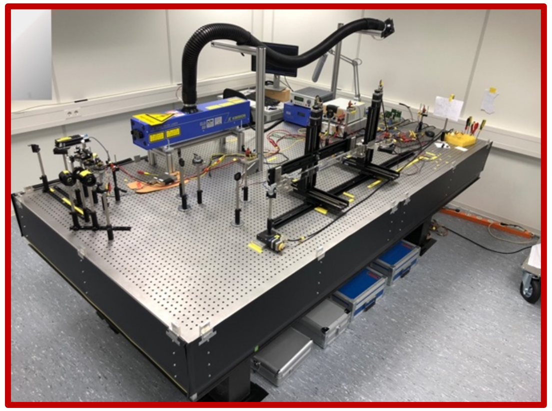


QA Plan

Quality assurance plans for components and modules

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

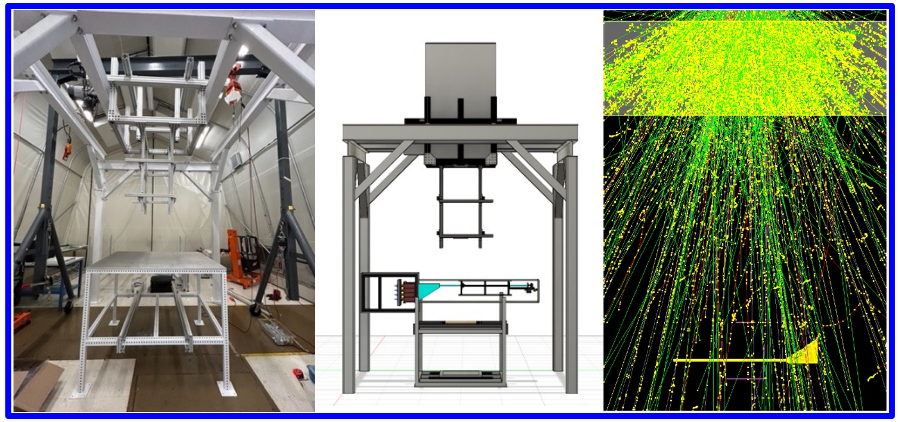
- Radiator bars and light guides: vendor QA for mechanical properties, laser scanning system at JLab to monitor internal photon transport efficiency of disassembled BaBar DIRC bars and/or new DIRC bars
- Sensors and electronics: laser pulser systems at CUA/JLab/USC (TBD) to measure gain, quantum and 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 SBU
- Assembled DIRC module (bar box coupled to readout box, vertical slice): Cosmic Ray Telescope at SBU
- Installed DIRC module in ePIC: picosecond laser pulser calibration system, cameras to monitor optical coupling between sensors, prisms, lenses



DIRC laser lab at GSI

Lens evaluation setup at ODU

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



HPDIRC DESIGN: NUMBER OF PHOTOSENSORS

Example of validated cost/performance optimization, based on simulation study:

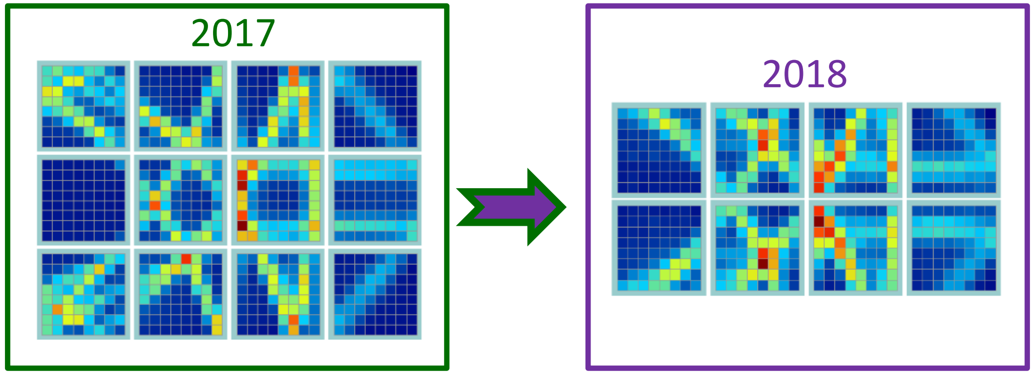
PANDA Barrel DIRC beam test at CERN in 2017 and 2018

2017: prism covered with 12 MCP-PMTs (3x4)

Simulation: 1/3 of the MCP-PMTs can be removed with

no significant impact on PID ⟹ major cost savings

2018: beam test with reduced coverage to 8 MCP-PMTs (2x4)



accumulated hit pattern

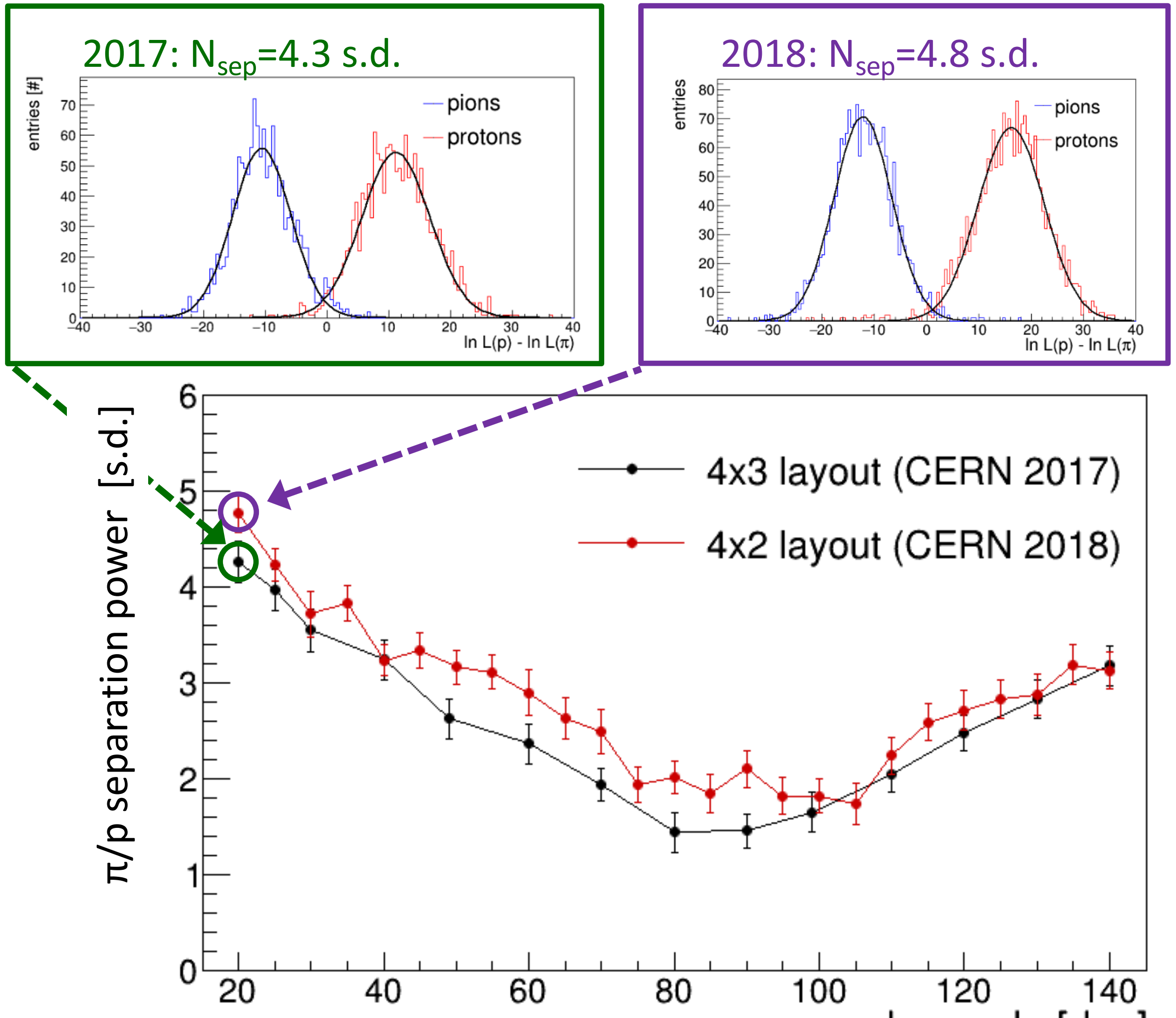
Found expected photon loss rate (30-40%)

with no observable loss of PID performance

(Small improvement is due to better timing precision in 2018)

beam data, 7 GeV/c

Note: π/p at 7 GeV/c ≈ π/K at 3.5 GeV/c



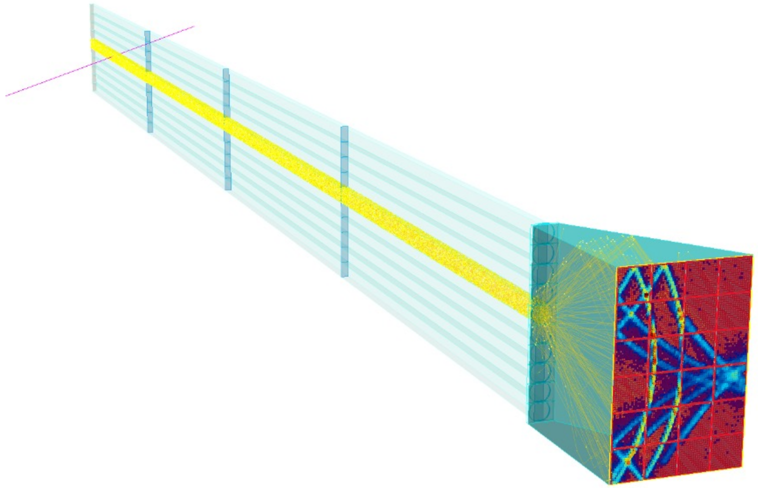
Preliminary analysis from 2020

hpDIRC Prototype: Hybrid Radiator Design

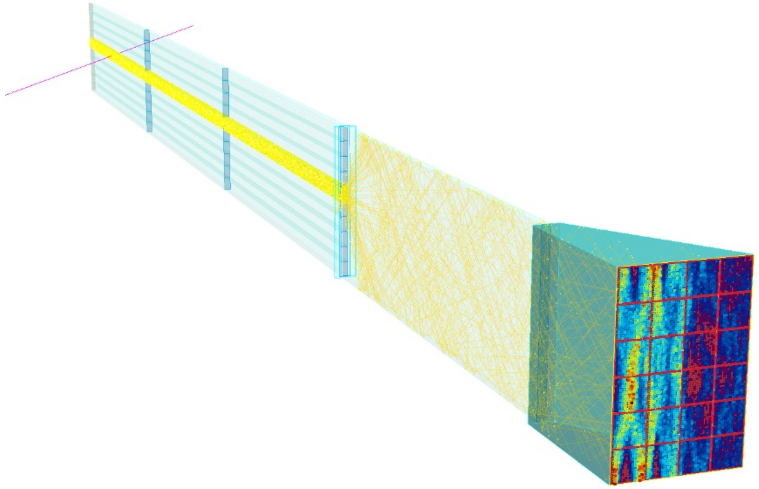
Opportunity: Cost saving and performance improvement

- EIC detector barrel length requires additional fused silica bars or plate ("light guide") to connect BaBar DIRC bars to prism
- Narrow bars could be ordered from industry or, possibly, produced by cutting and repolishing BaBar DIRC bars
- Alternative: one single short wide plate as transition light guide between BaBar DIRC bars and prism
- Would significantly reduce cost compared to new narrow bars and potentially improve hpDIRC performance
- Performance of plate/bar "hybrid" design needs to be studied in simulation → topic of hpDIRC generic R&D proposal

Geant4 visualization of the two options



Narrow bars in each sector



Hybrid of bars and plate in each sector

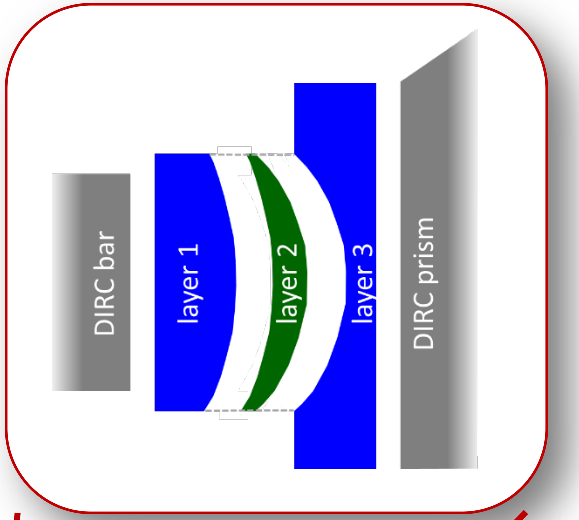
HPDIRC COMPONENTS: 3-LAYER LENS

Technical risk: hpDIRC PID design validation

- Radiation hardness and focusing performance of 3-layer lens

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

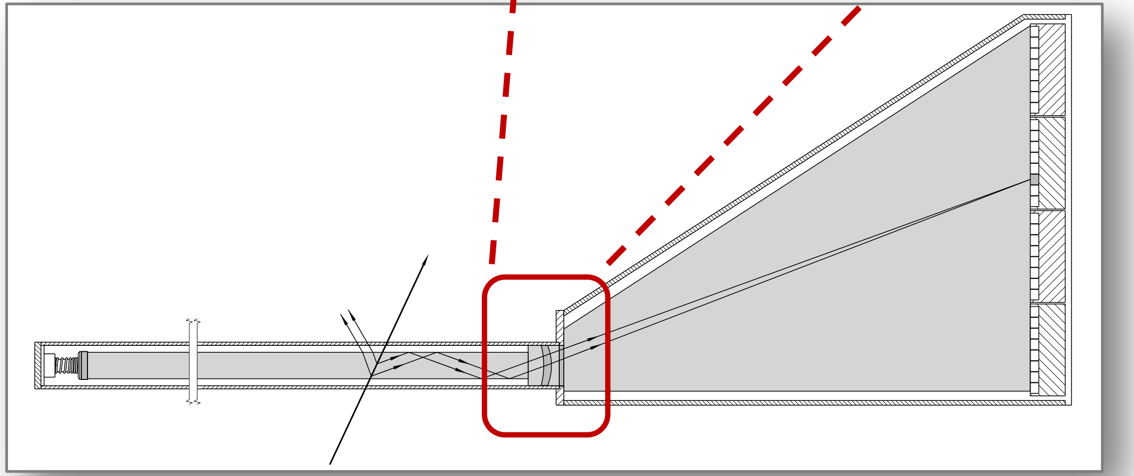


Key element of hpDIRC design:

- 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
- Successfully produced prototype lenses and validated performance in PANDA Barrel DIRC prototype with particle beams at CERN and GSI



3-Layer Lens

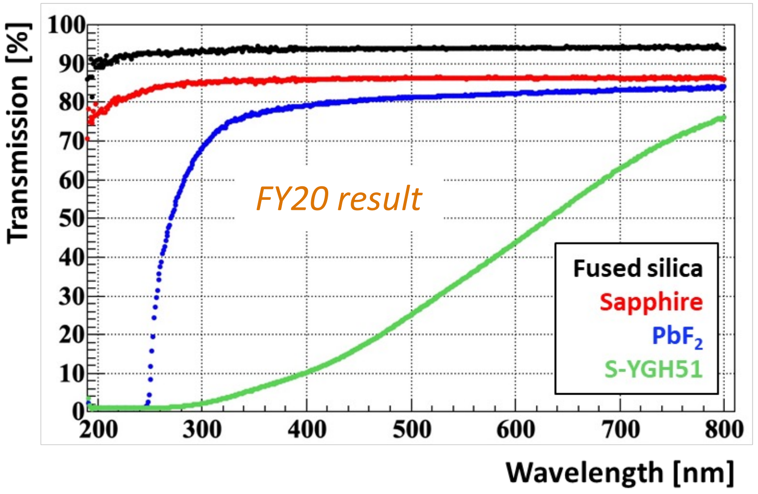
Technical risk: hpDIRC PID design validation

- Radiation hardness and focusing performance of 3-layer lens

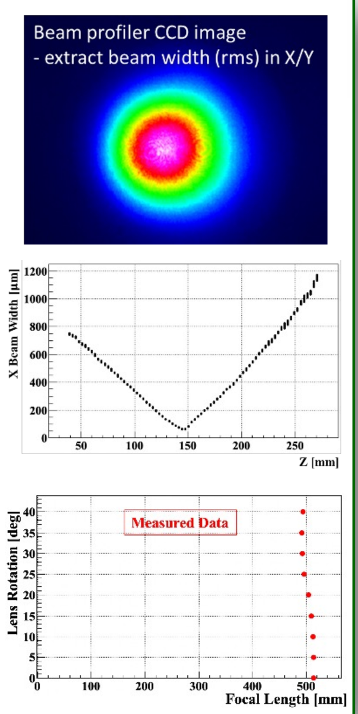
hpDIRC R&D activities (eRD14 and eRD103):

- Identified radiation-hard material for middle layer (^{60}Co study complete, neutrons next)
- Demonstrated that rad-hard material is suitable for lens fabrication by industry
  (New sapphire and PbF_2 lens prototypes produced, ready for tests)
- Validated focusing properties/flat focal plane
- Optical aberrations included in hpDIRC simulations

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

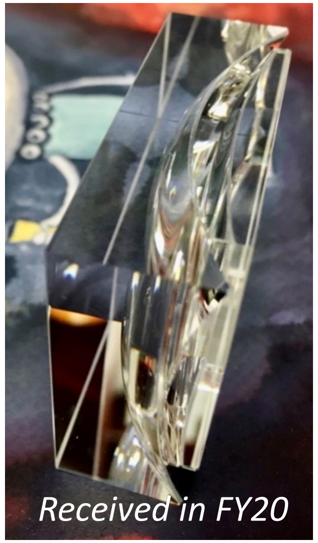


Work supported by Jim Kierstead (BNL)



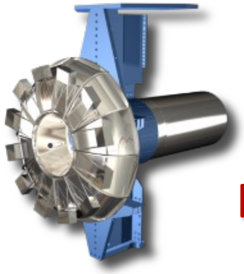
Laser lab in ODU

Sapphire (RMI, USA)

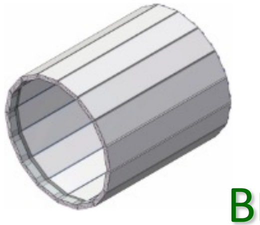


PbF_2 (HIT, China)

Barrel DIRC Overview

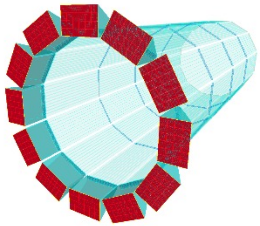


BaBar DIRC



Belle II TOP

PANDA Barrel DIRC



ePIC hpDIRC *

Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*	Narrow bars *(35mm)*
Barrel radius	85cm	115cm	48cm	72cm
Bar length	490cm *(4×122.5)*	250cm *(2×125)*	240cm *(2×120)*	420cm *(3×122.5 + 1x52.5)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*	120 *(12×10 bars)*
Expansion volume	110cm, ultrapure water	10cm, fused silica	30cm, fused silica	30cm, fused silica
Focusing	None (pinhole)	Mirror (for some photons)	Spherical lens system	Spherical lens system
Photodetector	~11k PMTs	~8k MCP-PMT pixels	~8k MCP-PMT pixels	~74k MCP-PMT pixels
Timing resolution	~1.5ns	<0.1ns	~0.1ns	~0.1ns
Pixel size	25mm diameter	5.6mm×5.6mm	6.5mm×6.5mm	3.2mm×3.2mm
PID goal	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 3.5 GeV/c	3 s.d. π/K to 6 GeV/c
Timeline	1999 - 2008	Running (installed 2016)	Installation ~2025	TDR-ready in 2024

**Preliminary design*

DIRC RESOLUTION

I. Adam et al., Nucl. Instr. Meth. A, 538, 2005.

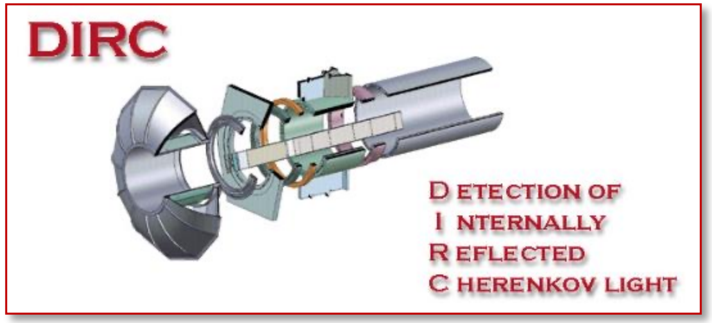
$$\sigma^2_{\theta_c}(particle) = \sigma^2_{\theta_c}(photon)\Big/ N_\gamma + \sigma^2_{correlated}$$

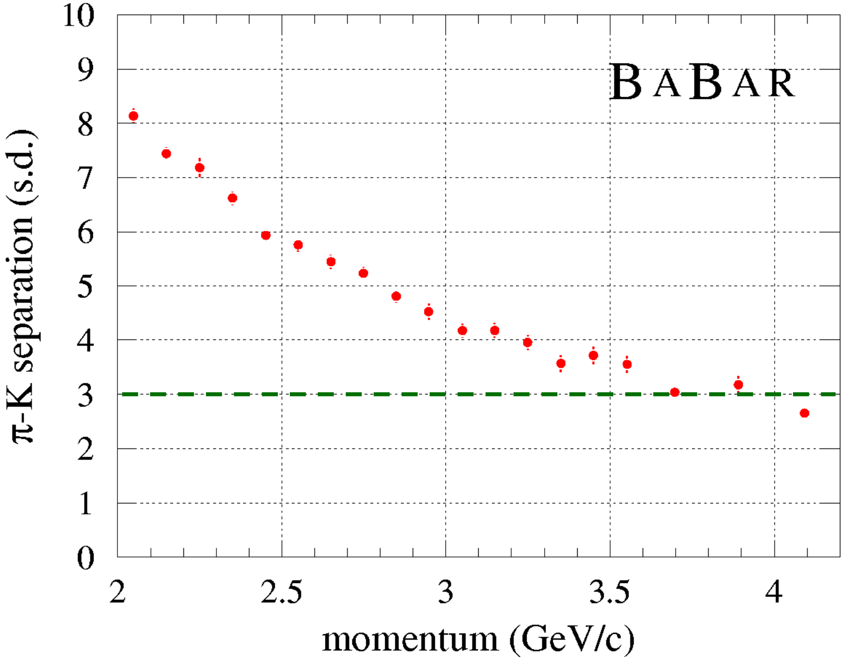
$\sigma_{\theta_c}(particle)$ Cherenkov angle resolution per particle

$\sigma_{\theta_c}(photon)$ Cherenkov angle resolution per photon
(bar size, pixel size, chromatic, bar imperfections)

N_γ Number of detected photons per particle
(bar size, bar imperfections, Photon Detection Efficiency)

$\sigma_{correlated}$ Contribution from external sources
(tracking, multiple scattering, etc.)



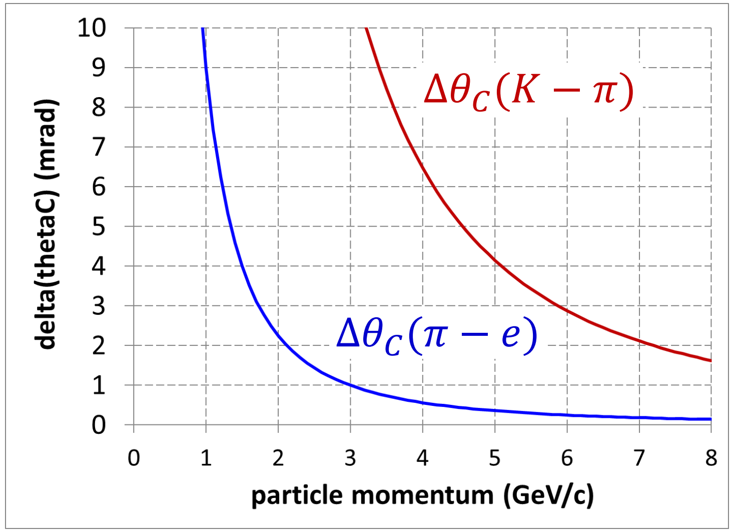


BaBar DIRC achieved 2. 4 mrad θ_C resolution at 3-4 GeV/c,

3 s.d. π/K separation at 4 GeV/c

How can we push this performance to higher momentum?

Improving on the BaBar DIRC



PID performance largely driven by track Cherenkov angle (θ_C) resolution.

Required resolution defined by refractive index of radiator.

Example: π/K separation in synthetic fused silica <n>≈1.473

→ 2.9 mrad π/K difference in θ_C at 6 GeV/c;

→ need ~1 mrad resolution per particle for 3 s.d. separation.

Approach:

Smaller track angular error (better tracking detector)

Higher photon yield (modern sensors with better PDE)

Improve Cherenkov angle resolution per photon

BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon, 2.4 mrad per particle

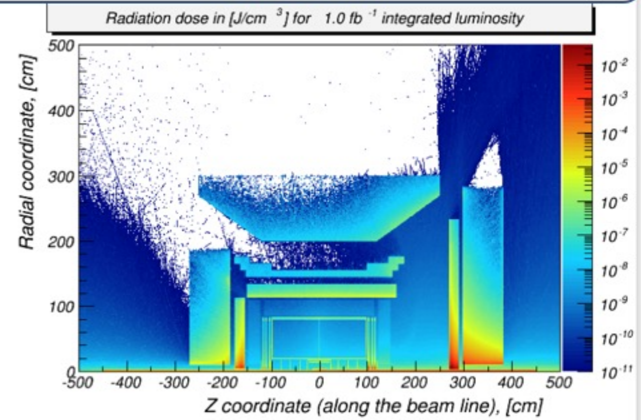
Limited in BABAR by:			Improve for future DIRCs via:
▪ size of bar image	~4.1 mrad	→	▪ focusing optics
▪ size of PMT pixel	~5.5 mrad	→	▪ smaller pixel size
▪ chromaticity (n=n(λ))	~5.4 mrad	→	▪ better time resolution
	9.6 mrad	→	5-7 mrad per photon → 1 mrad per particle

SuperB, Belle II, PANDA & EIC

Background/radiation

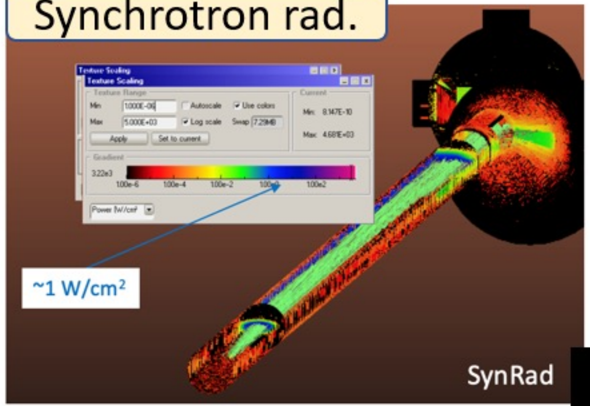
- The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance
- There are several background/radiation sources :
  - primary collisions
  - beam-gas induced
  - synchrotron radiation
- The design of absorbers and masks must be modeled thoroughly

Primary collisions/ionizing radiation

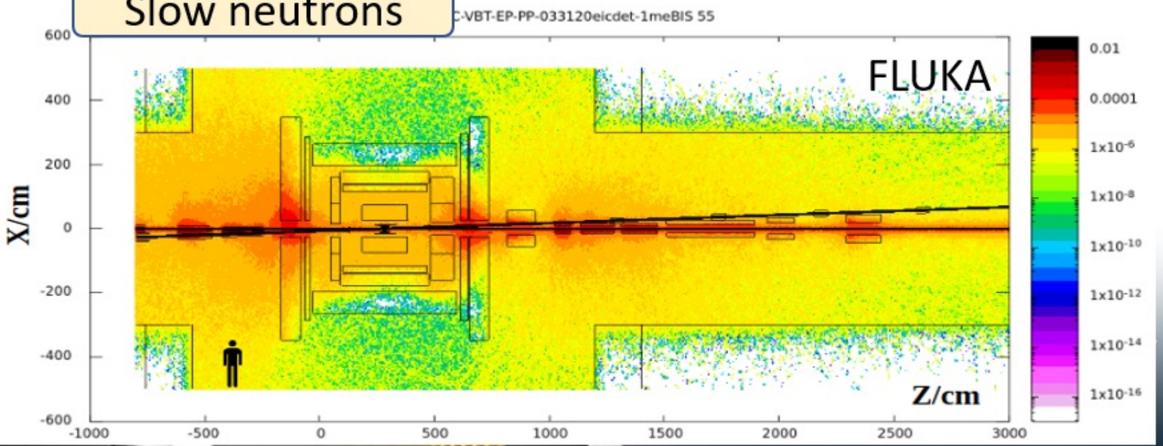


-> backward EmCal: ~250 rad/year (at a "nominal" luminosity ~10^{33} cm^{-2} s^{-1})

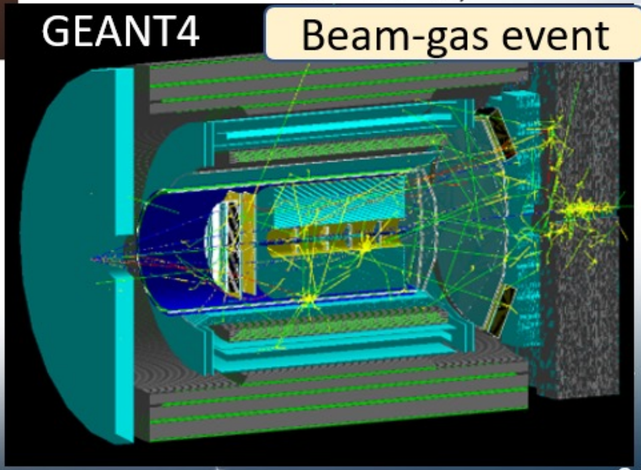
Synchrotron rad.



Slow neutrons



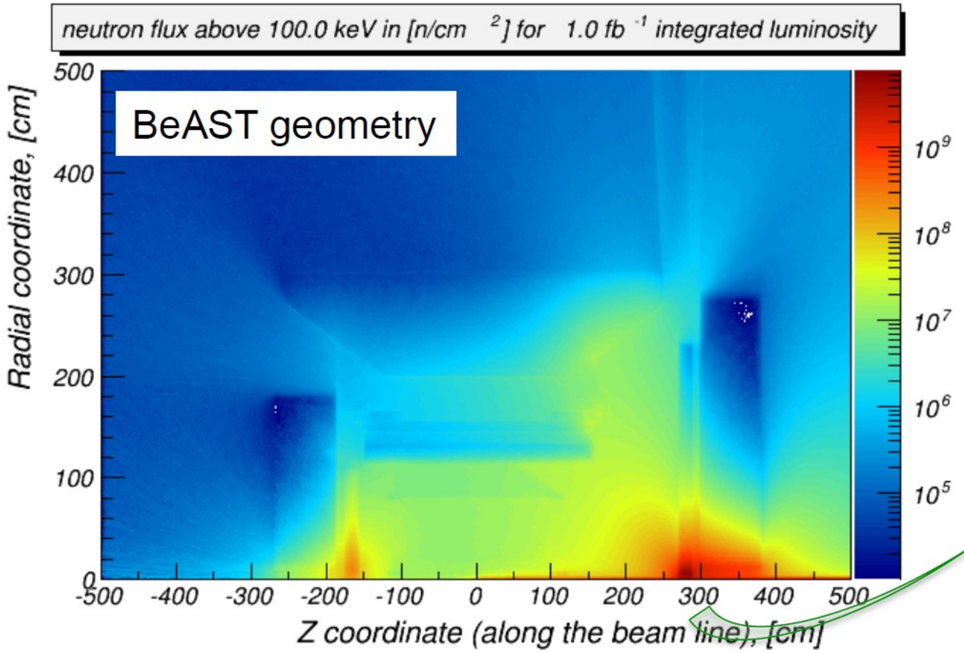
Beam-gas event

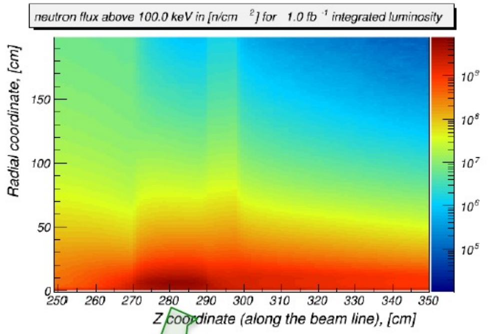


EIC Detector Radiation Map

Neutron fluence from primary interactions

<u>The quantity</u>: Fluence = "a sum of neutron path lengths"/"cell volume" for N events





-> forward EmCal: up to ~5*10^9 n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location;

NB: "standard" EIC run at ~10^{33} cm^{-2}s^{-1} luminosity is 10 fb^{-1}

<u>The numbers look OK, but:</u>

- Beam line elements not incorporated in the simulation
- Thermal neutrons are not accounted
- Close to beam line: ~10^{34} cm^{-2}s^{-1} over ~10 years would exceed ~10^{11} n/cm^2

Simulation for primary interactions

EicRoot Monte Carlo, PYTHIA, BeAST geometry

No beam-gas, no synchrotron radiation, no thermal neutrons

Fluence from 2D color map to be scaled by factor 100 for 10 year running at high luminosity.

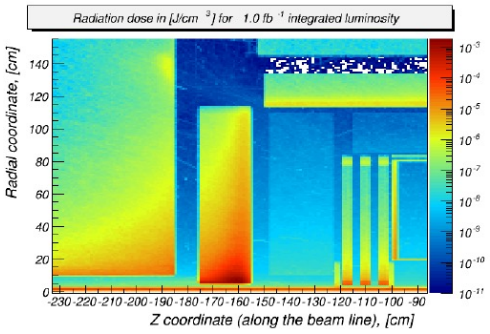
Expect less than 10^9 neutrons cm^{-2} per year at potential DIRC lens locations.

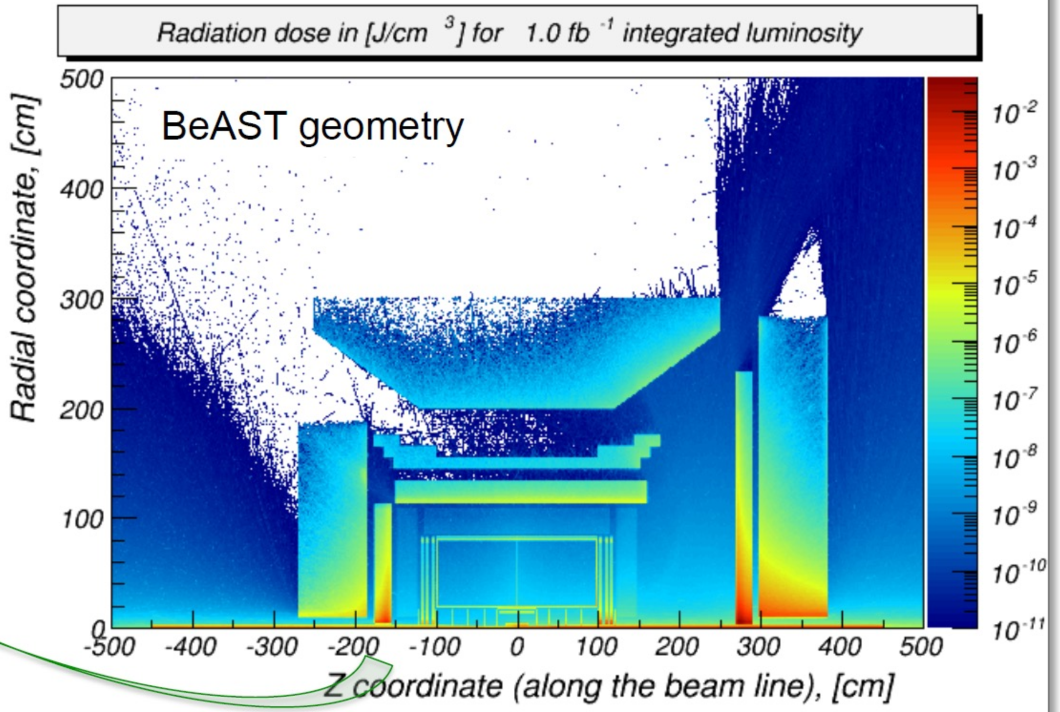
Will use safety factor 100 – 10,000 for neutron irradiation campaign this fall.

Slide presented by
Yulia Furletova (JLab) and <u>Alexander Kiselev</u> (BNL)
EICUG Yellow Reports Kick-off Meeting, MIT December 2019

Radiation dose from primary interactions

The (primary) quantity: E_{sum} = "a sum of dE/dx"/"cell volume" for N events





-> crystal EmCal: up to $\sim 2*10^{-3}$ J/cm^3 per fb^{-1} (close to beam line)

1 rad = 0.01 Gy & [Gy] = [J/kg] & PWO density ~8g/cm^3 -> ~250 rad/year

(at "nominal" luminosity ~10^{33} cm^{-2} s^{-1})

-> looks OK?

Simulation for primary interactions

EicRoot Monte Carlo, PYTHIA, BeAST geometry

No beam-gas, no synchrotron radiation

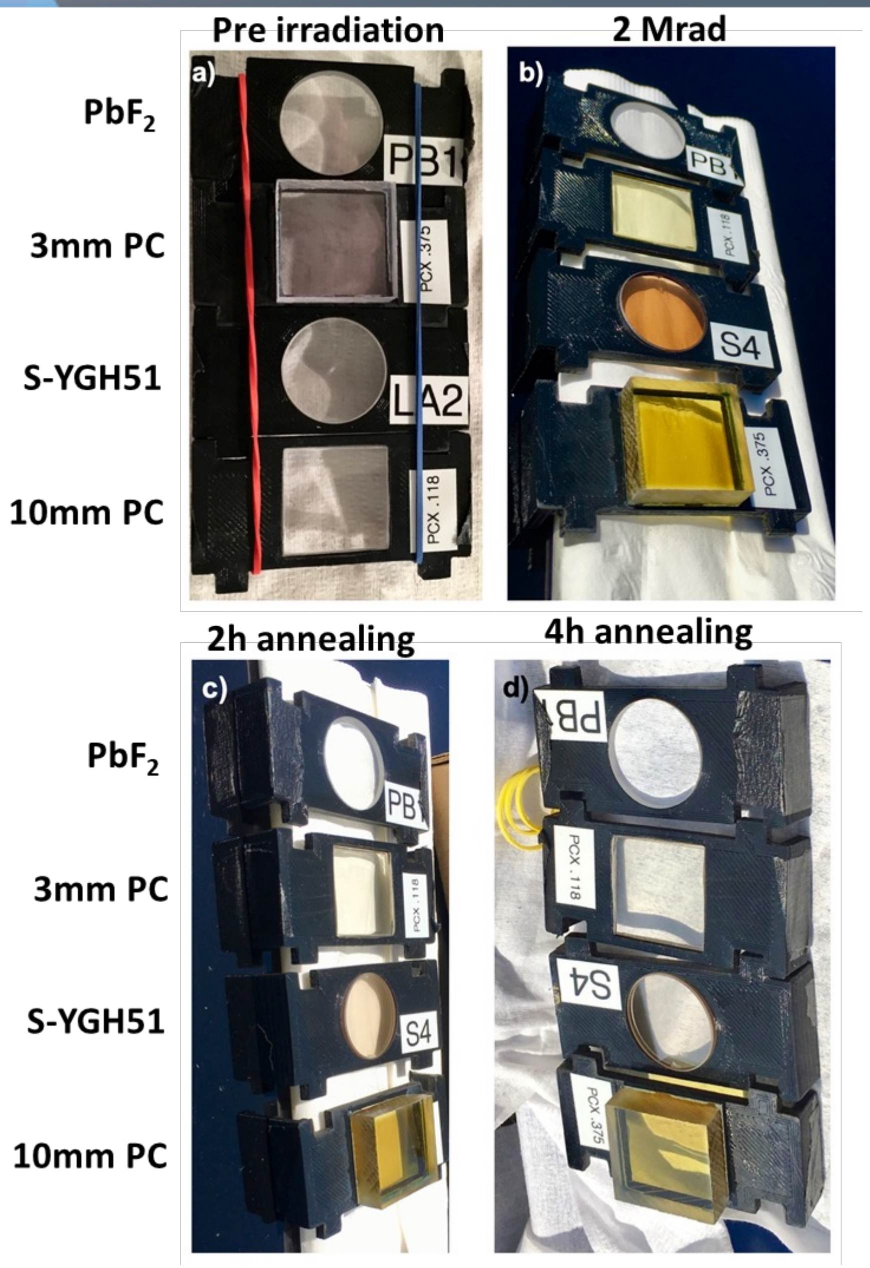
Dose from 2D color map to be scaled by factor 100 for 10 year running at high luminosity

Expect less than 100 rad/year at potential DIRC lens locations.

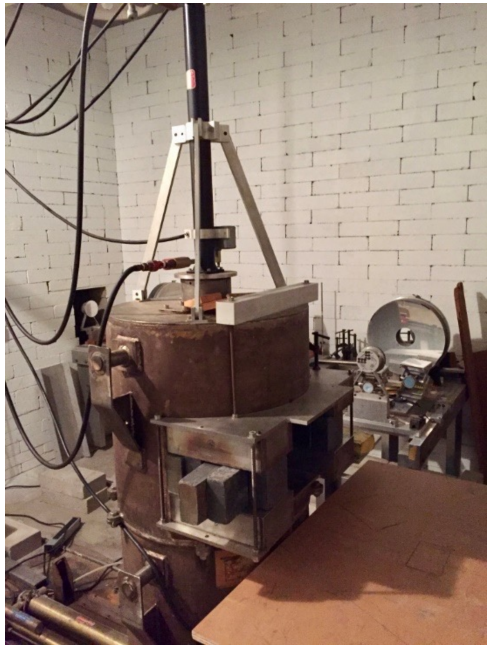
Slide presented by
Yulia Furletova (JLab) and Alexander Kiselev (BNL)
EICUG Yellow Reports Kick-off Meeting, MIT December 2019

HPDIRC RADIATION TESTS

- Four materials studied up to 2 Mrad:
  - sapphire
  - lead fluoride (PbF_2)
  - lanthanum crown glass (S-YGH51)
  - polycarbonate (PC)
- Sapphire confirmed to be extremely radiation hard. PbF_2 showed very small deterioration.
- Initial photo-annealing and luminescence tests.



HPDIRC RADIATION TESTS



Co^{60} Chamber

Monochromator