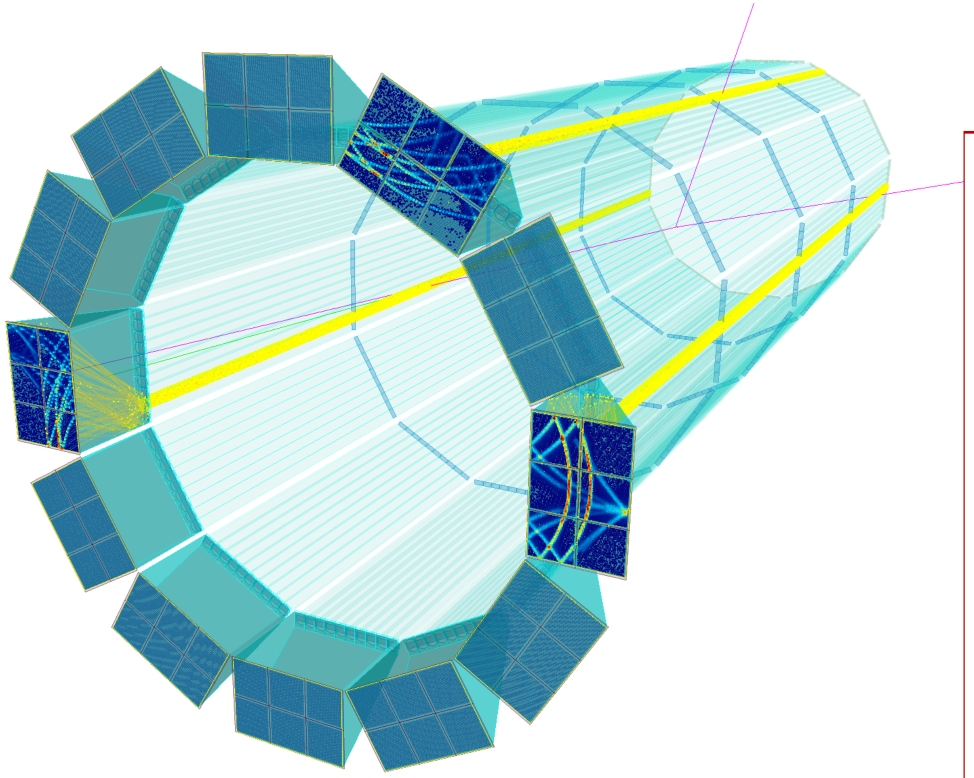
The hpDIRC Detector for the ePIC Experiment

Greg Kalicy CUA



- hpDIRC Concept & Design
- Performance Studies
- Mechanical Integration
- Radiator Bars
- Prototype
- Schedule
- DSC
- Plans for QA

July 28th, 2023

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

Wing ☺ Skrzydło

POLISH

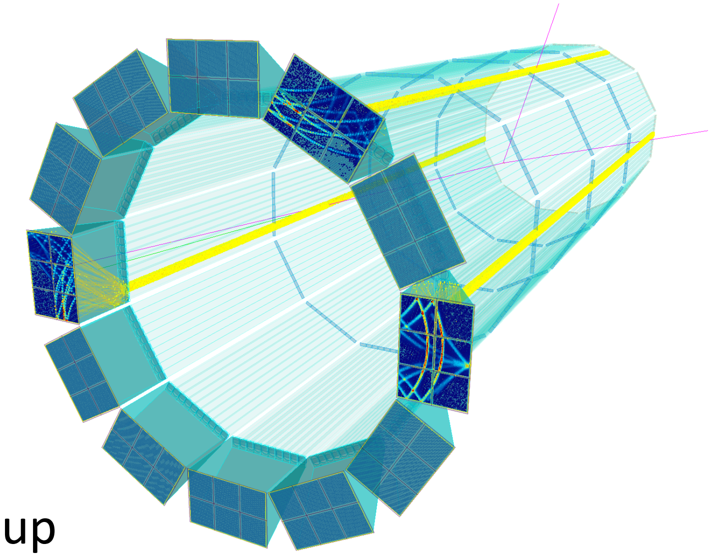
1. dwa
2. dwie
3. dwoje
4. dwóch
5. dwaj
6. dwiema
7. dwom
8. dwoma
9. dwojga
10. dwojgu
11. dwojgiem
12. dwójka
13. dwójki
14. dwójkę
15. dwójką
16. dwójce
17. dwójko

ENGLISH

1. Two
2. Second

English	Polish
Pardon?	Proszę?
Please.	Proszę.
Go ahead.	Proszę.
Here you are.	Proszę.
You're welcome.	Proszę.
Not at all.	Proszę.
Well, well!	Proszę, proszę!

Executive Summary



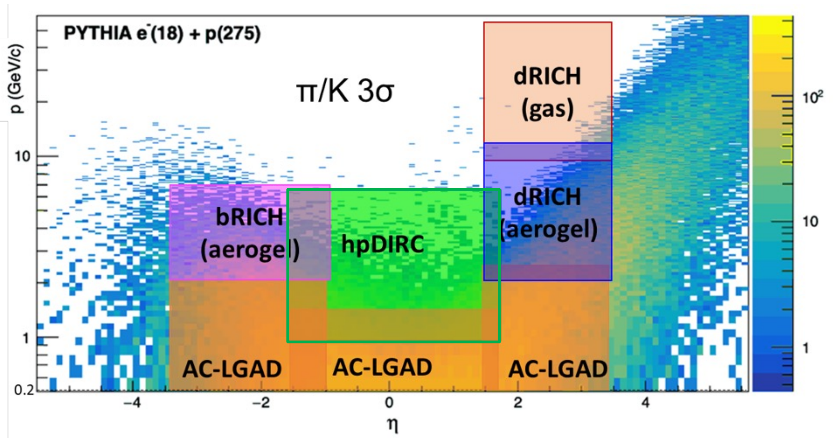
- hpDIRC Annual Meeting
  - Added new members to hpDIRC DSC, established liaisons
  - Reviewed and revaluated plans moving forward
  - Started preparations for positive PID review
- Keep on benefiting from collaboration and synergies with PANDA Barrel DIRC Group

  (Key elements, simulation and focusing lenses, validated in particle beams in 2018, mechanical design)
- Main remaining steps towards production readiness and TDR in Sep 2024:
  - Validation of reusing BaBar DIRC radiator bars
  - Evaluation of sensors and readout ASIC (synergy with bwRICH and project R&D)
  - Completion of mechanical design and integration
- hpDIRC DSC includes eight institutions with well-established expertise and interest in work packages
- Plans for remaining studies, QA, and construction match project schedule

hpDIRC is the baseline hadronic barrel PID system for ePIC

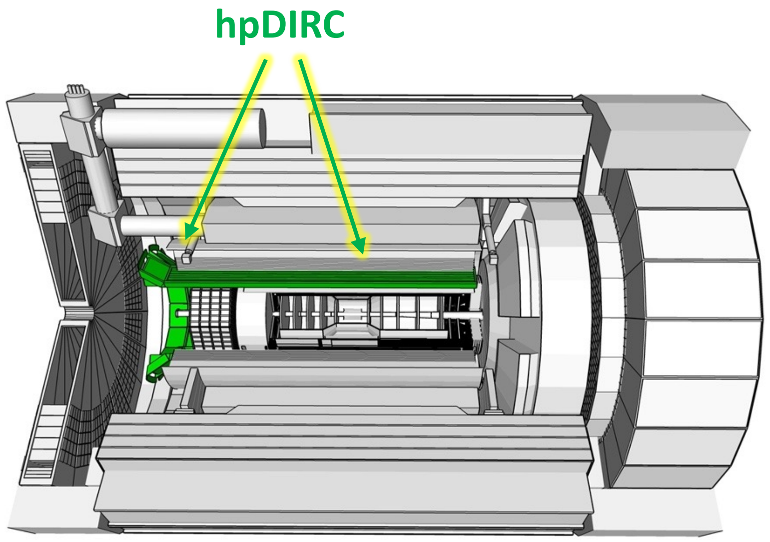
- Concept developed as part of previous Generic R&D program (eRD14)
- Finalizing design, validating components as part of Project R&D (eRD103)
- Future innovate optical DIRC configurations in new Generic R&D program (see Roman's talk on Sunday)

Summary of π/K PID requirements in ePIC



hpDIRC Concept:

- 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



3D model of ePIC central detector

hpDIRC

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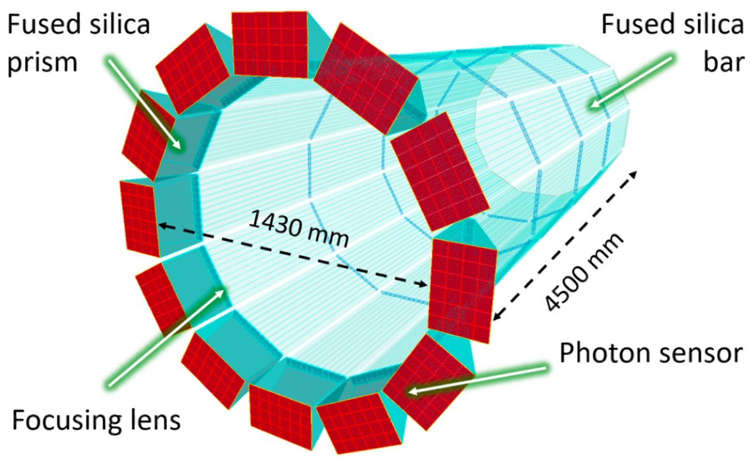

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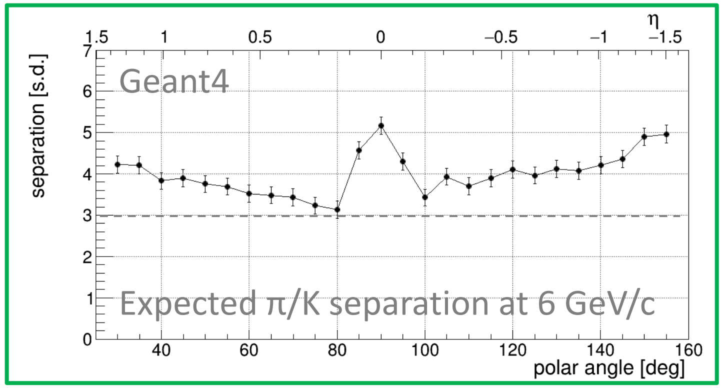
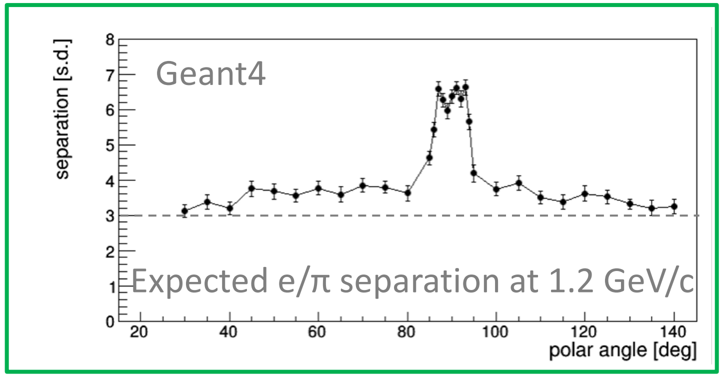




hpDIRC Preliminary Baseline Design

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

Focusing optics:

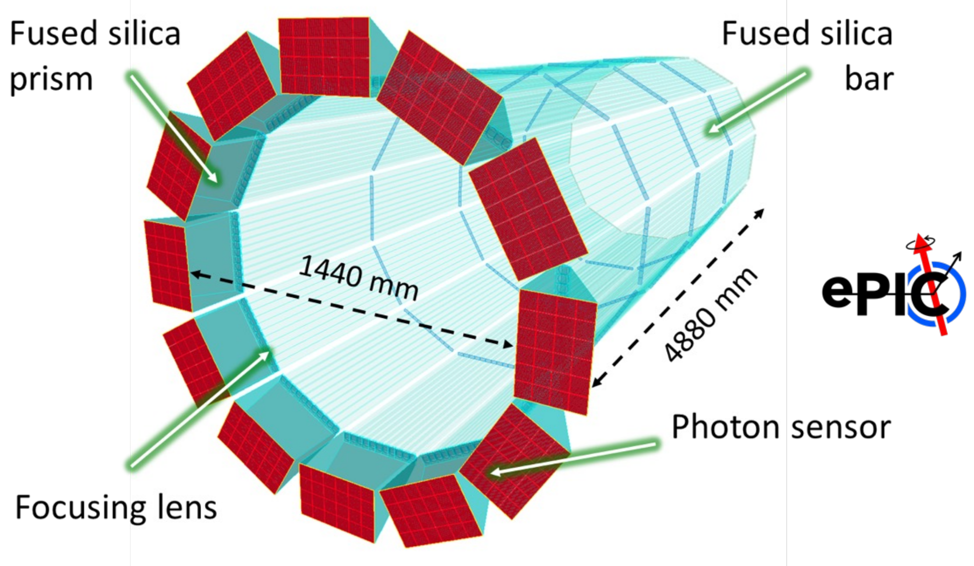
- Radiation-hard 3-layer spherical lens (sapphire or PbF_2)

Expansion volume:

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

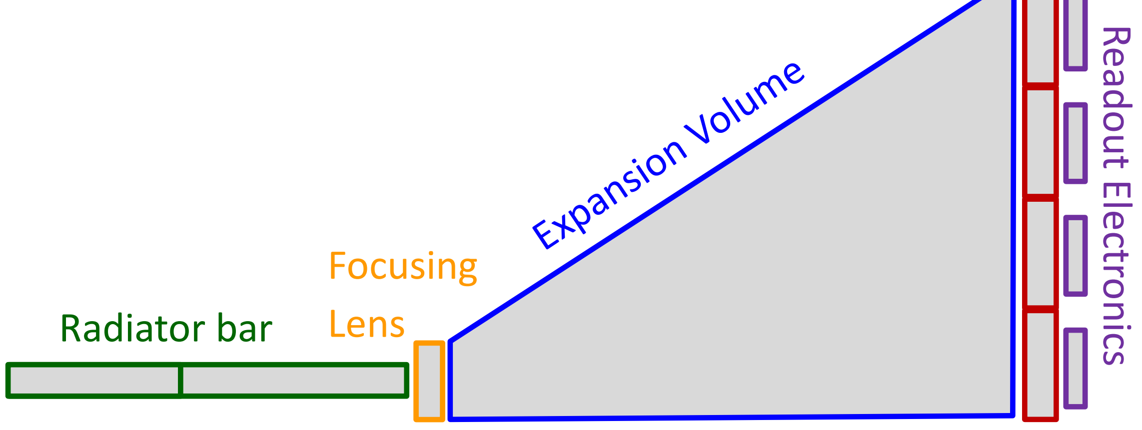
Readout system:

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



hpDIRC Components:

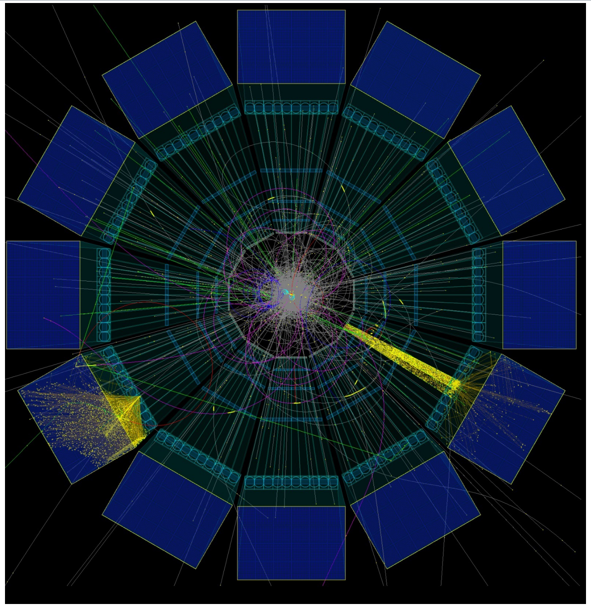
(CFRP bar box and readout box, flat mirror are not shown*)*



hpDIRC Simulation

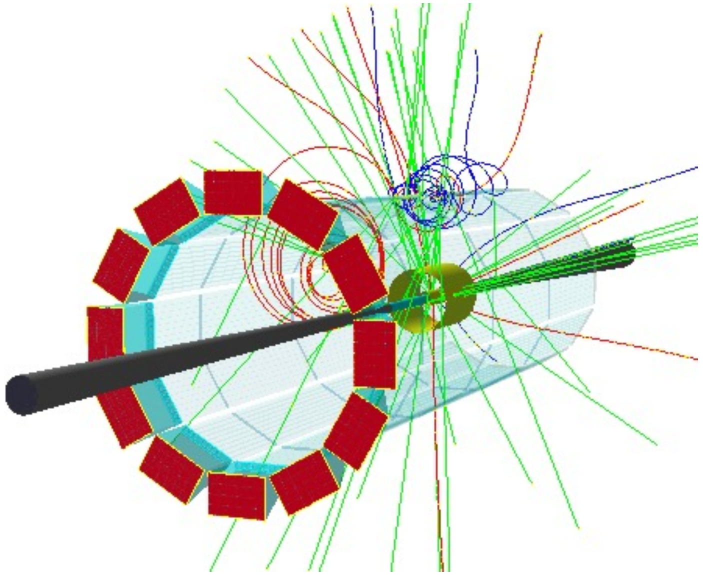
Stand-alone Geant4 Simulation

- 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

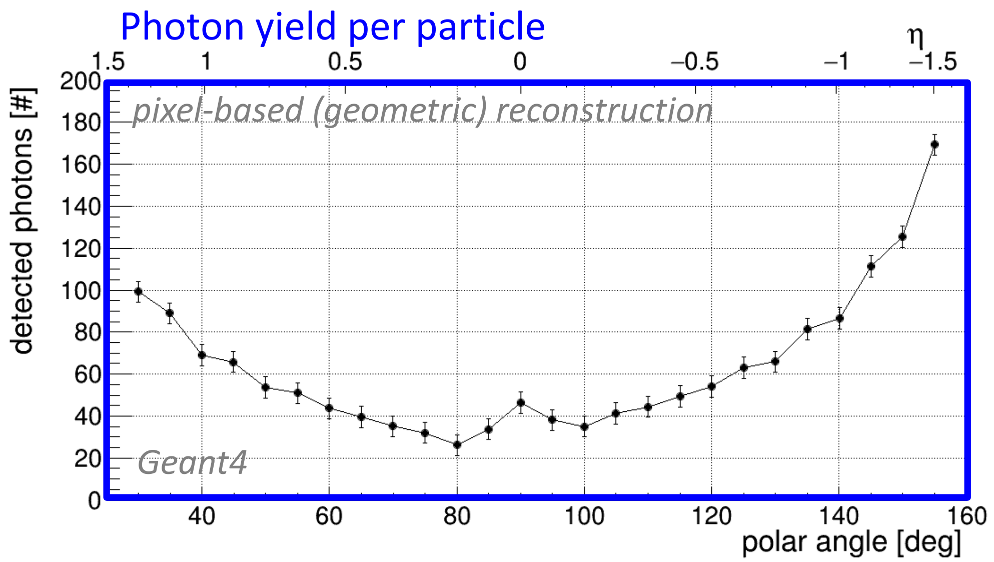


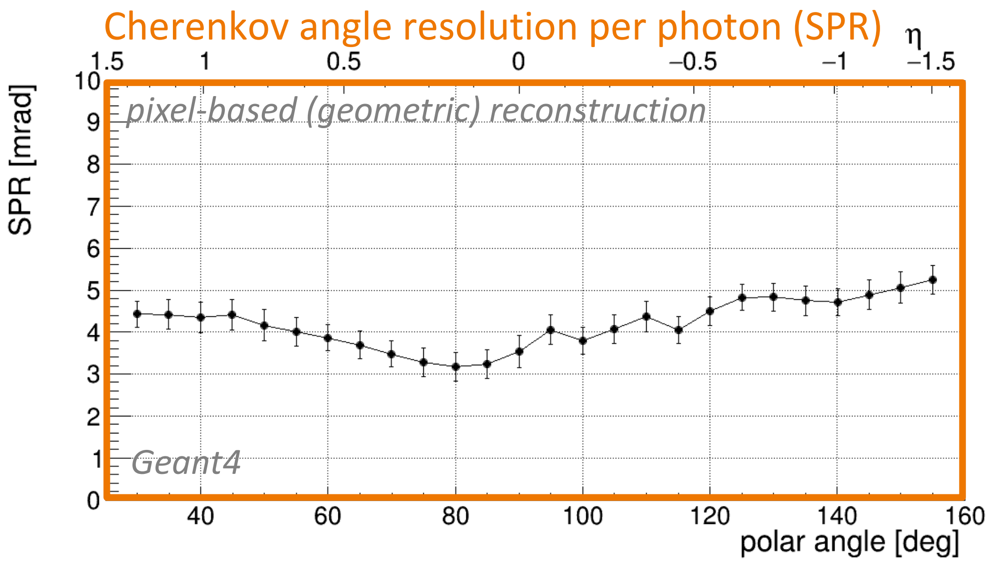
Full ePIC Simulation:

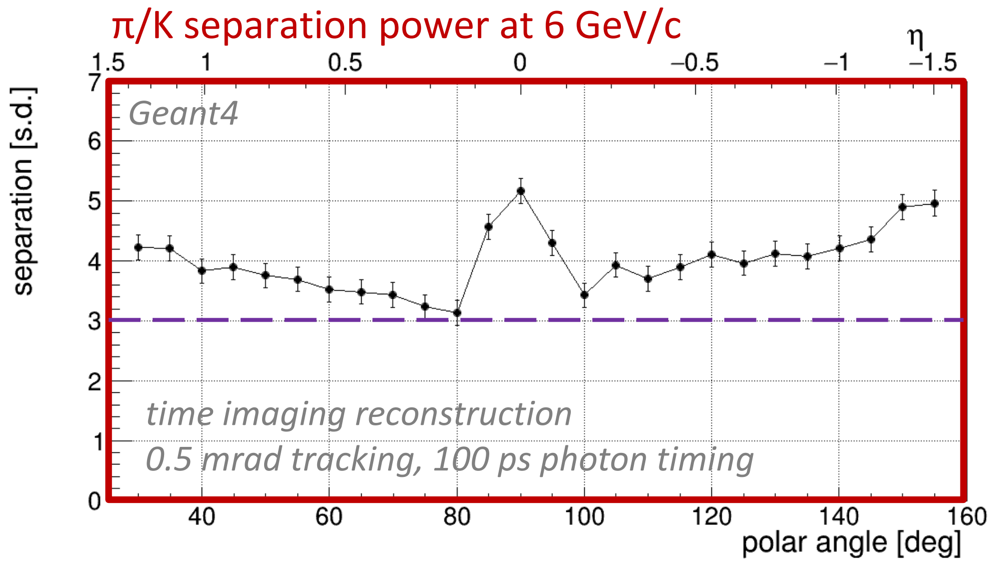
- Enables to study of the hpDIRC performance in magnetic field, using physics events (Pythia), including backgrounds and impact of other subsystems
- Imported and integrated stand-alone Geant4 package
- Implemented reconstruction, validating performance



Event in full ePIC simulation







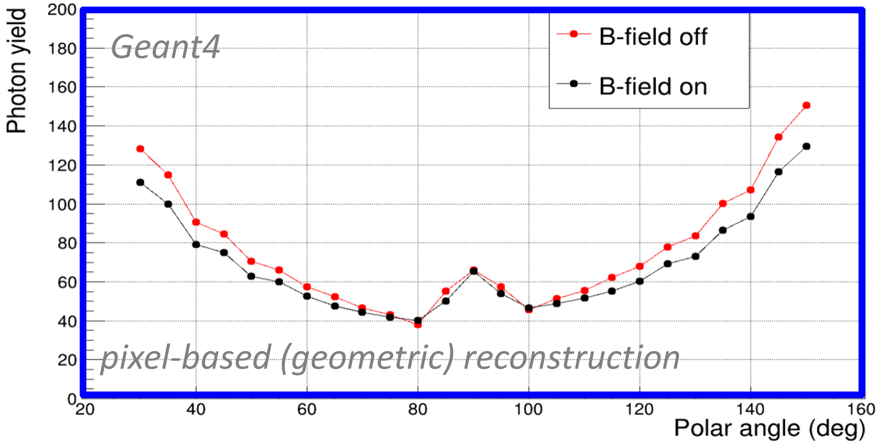
Simulation studies performed with

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

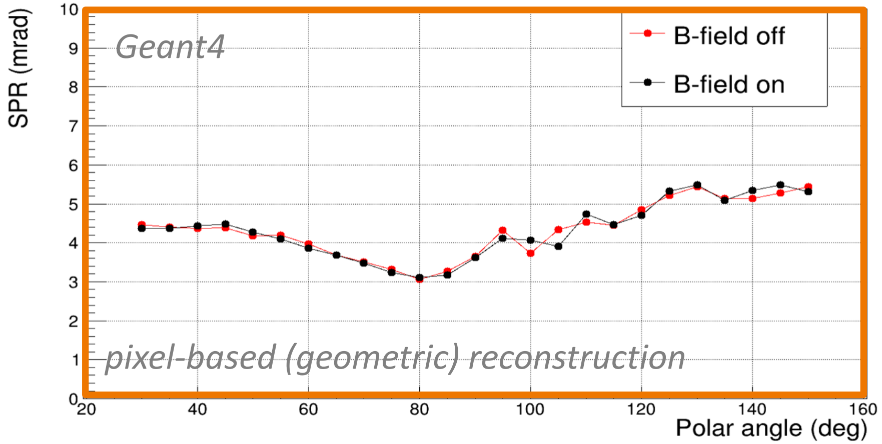
→ Performance requirements reached: ≥ 3 s.d. π/K separation at 6 GeV/c for all angles

Impact of magnetic field on hpDIRC performance

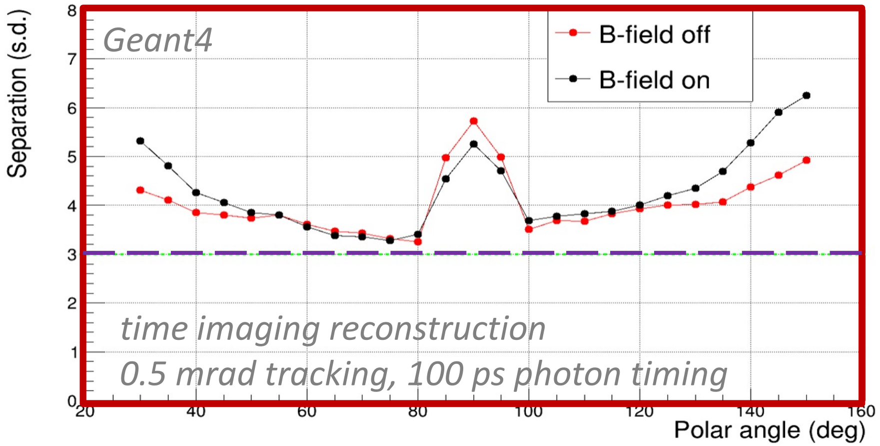
Photon yield per particle



Cherenkov angle resolution per photon (SPR)



π/K separation power at 6 GeV/c



Simulation studies performed with

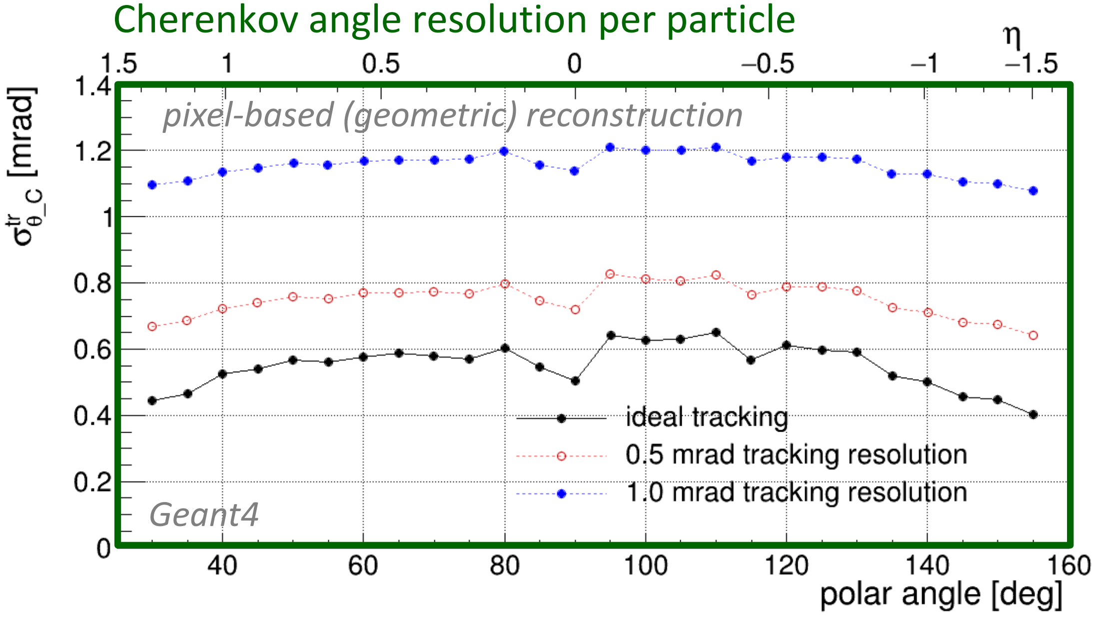
- ePIC software framework Fun4All (Geant4)
- Single particles from particle gun
- 6 GeV/c momentum
- MARCO: 1.7 T magnetic field

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

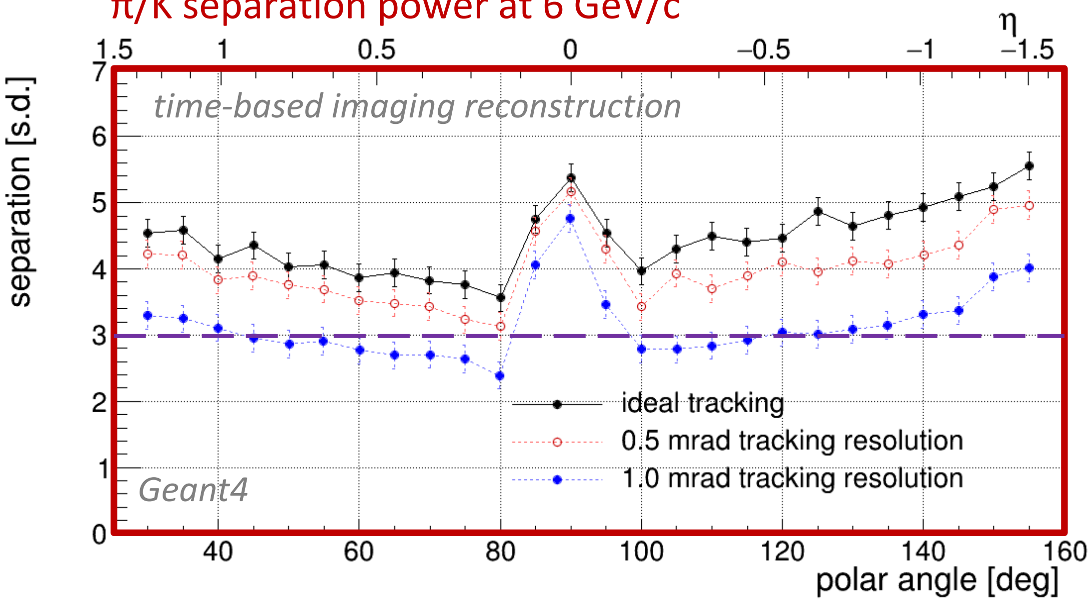
Expected hpDIRC Performance vs. Tracking

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

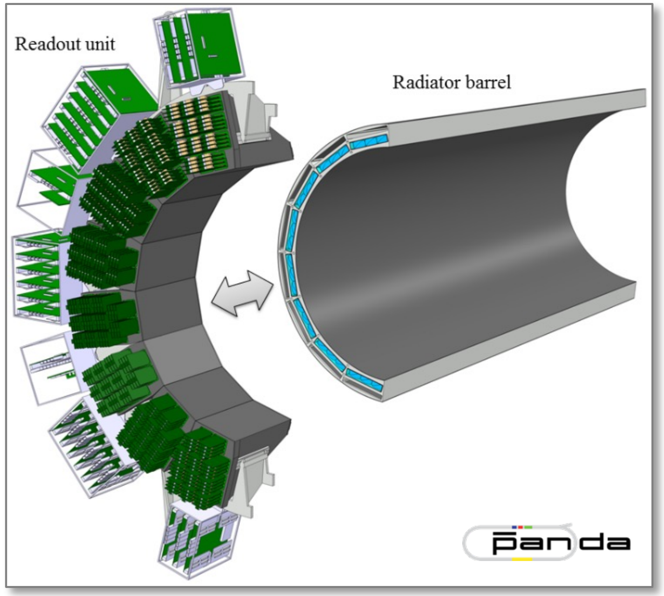
- Stand-alone Geant4 simulation
- Single particles from particle gun
- 6 GeV/c momentum
- No magnetic field, no other ePIC subsystems

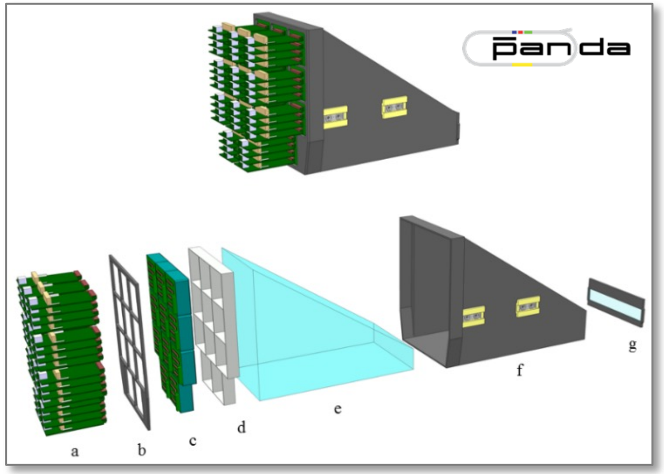
→ High-precision angular resolution crucial for reaching required hpDIRC performance

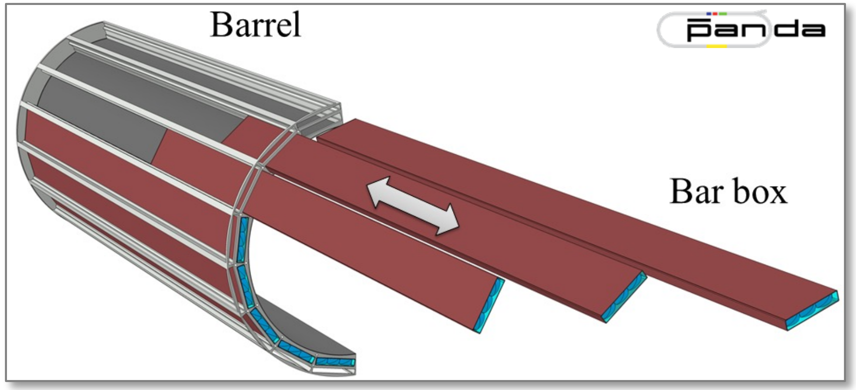
Mechanical Support and Integration

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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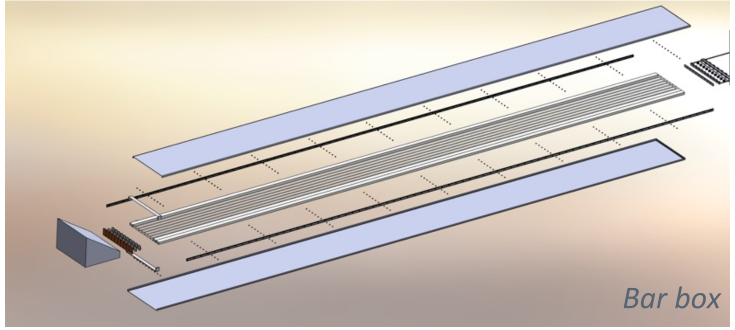
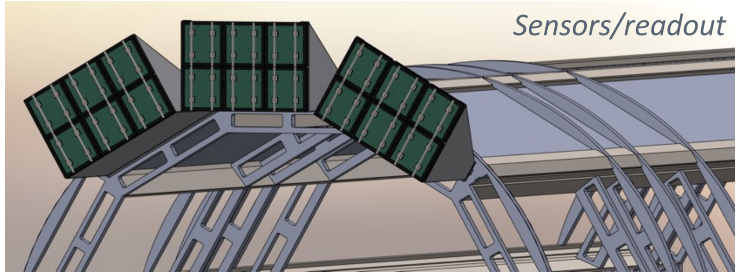
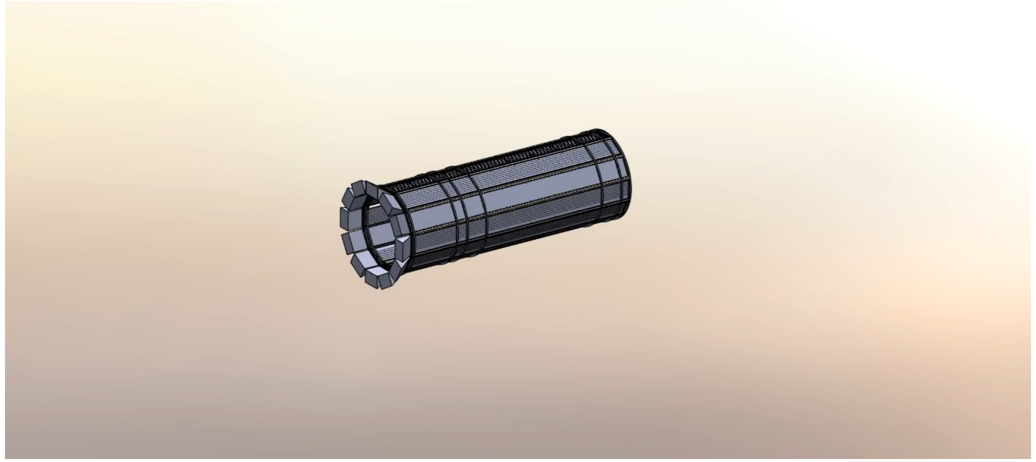
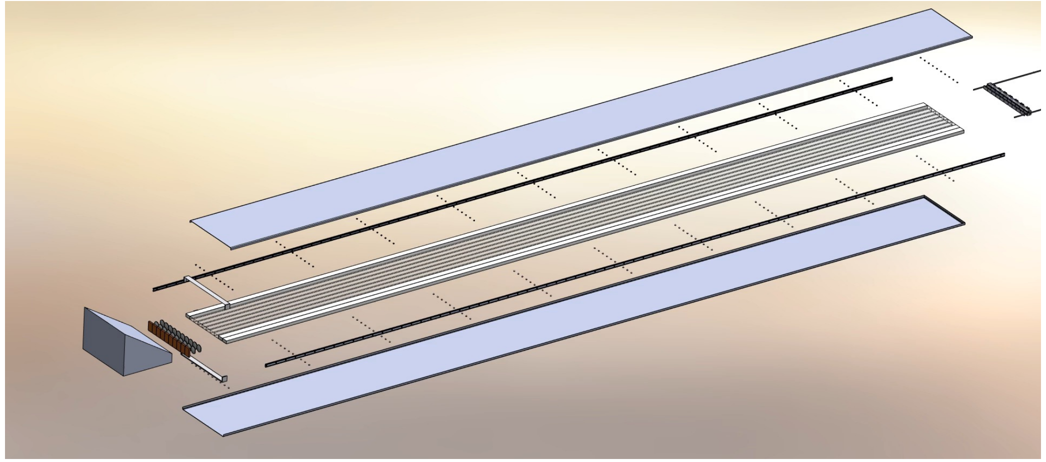
ePIC hpDIRC preliminary mechanical design





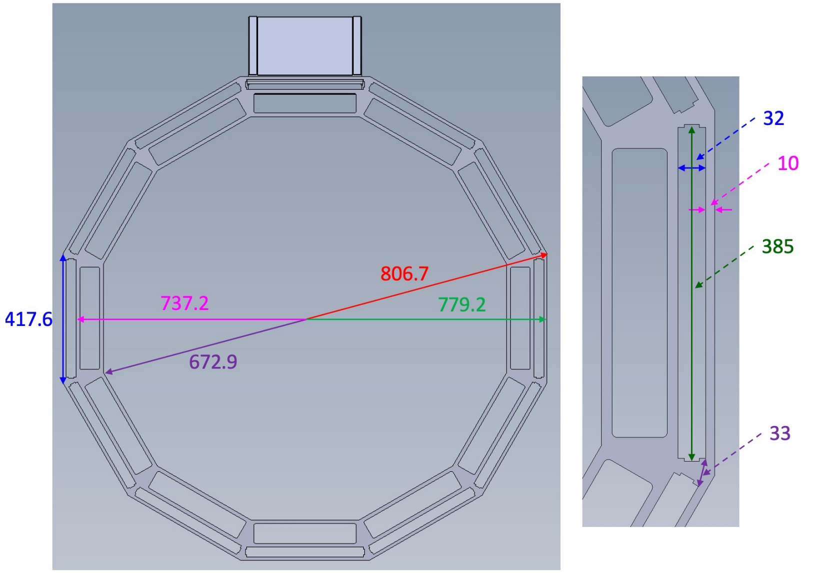


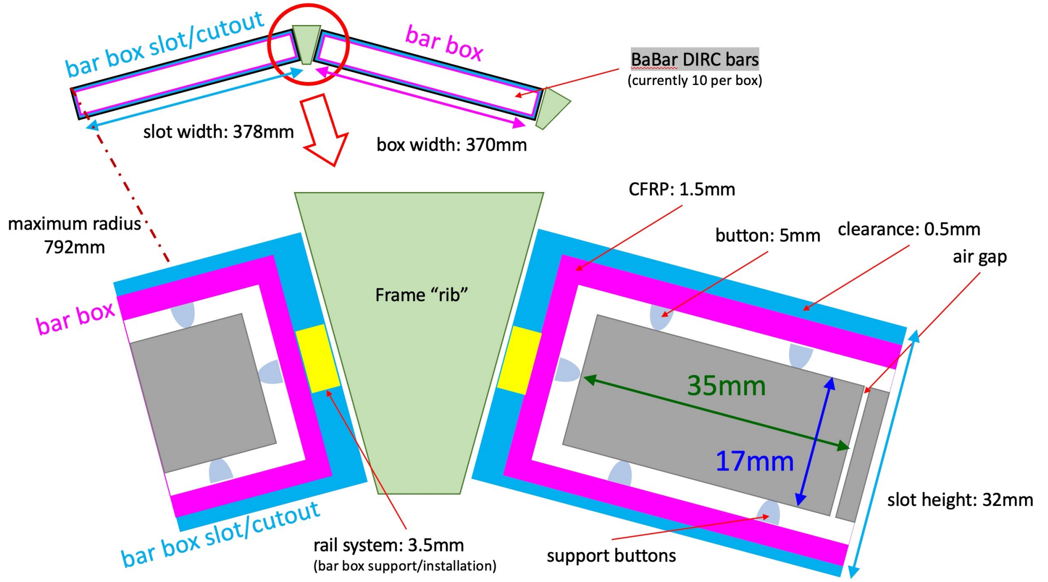


Two short MEC movies (only in Powerpoint version)

Impact of number of modules on performance and stability

- Current designs assumes 12 modules with 10 long bars in each module
- Discussions followed by simulation studies on increasing number of modules and changing radius
- Increasing number of modules:
  - Lower radial thickness of DIRC
  - Decrease azimuthal acceptance
  - Present potential challenges for sensor coverage of detector plane

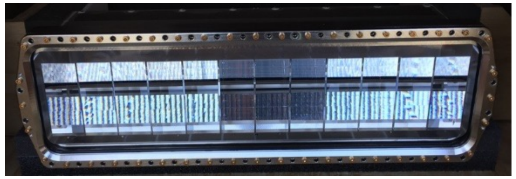
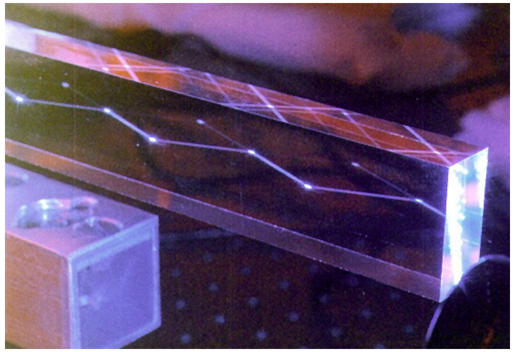




Reuse of BaBar DIRC Bars

- 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
- 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 $-1.65 \leq \eta \leq +1.65$ (360 bars needed)
- Quality of bar surfaces, 25 years after initial production and disassembly, to be verified
- Additional 120 ~80cm bars required for the light guide section, $\eta \leq -1.65$, to couple to lenses
- Procure new bars from industry or disassemble the 4 bar boxes from GlueX?

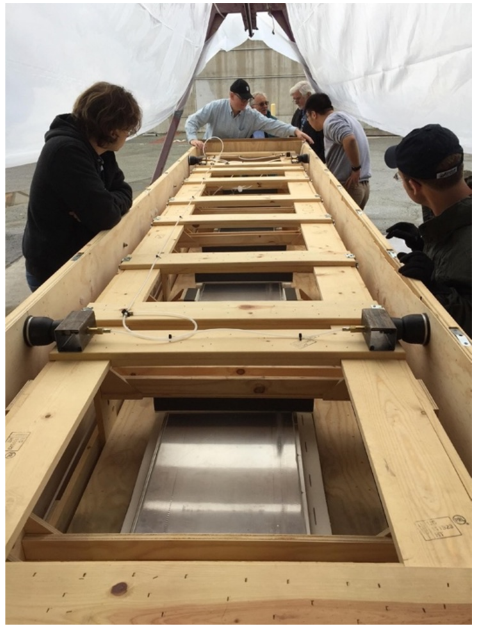


Reuse of BaBar DIRC Bars

- Transport of eight bar boxes from SLAC to JLab planned for later this summer
- 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 Lab will consist of three parts:
  - Cleaning/inspection station
  - Darkroom with laser setup to measure quality of DIRC bars
  - Storage (long and short-term)
- Reflection coefficient measurement to evaluate surface quality

BaBar DIRC bar box transportation for GlueX



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DIRC QA laser lab (completion date July)

DIRC labs under construction at JLab

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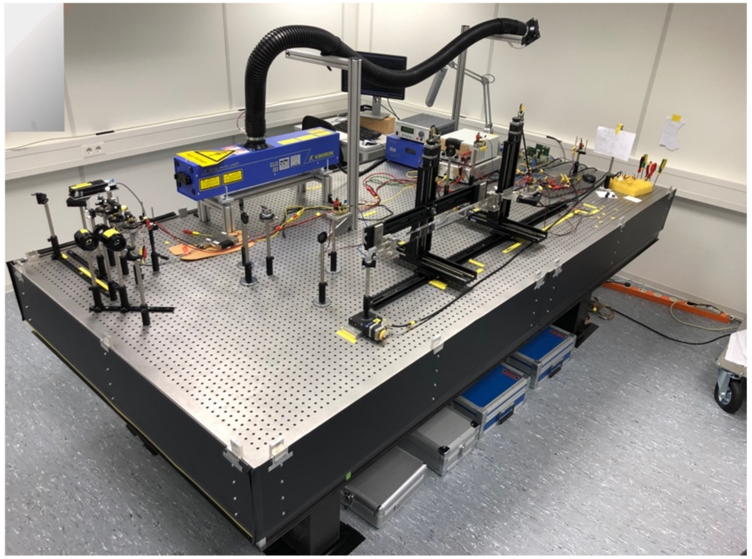
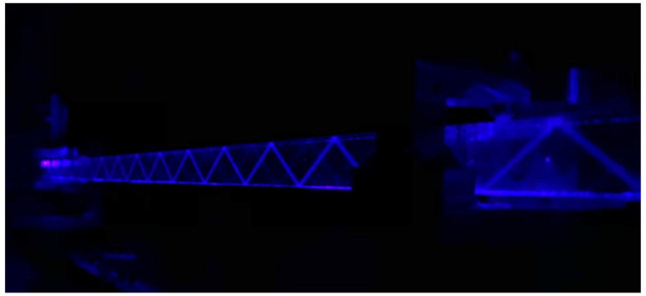
Laser lab at GSI



PANDA DIRC bar in GSI laser lab



HPDIRC PROTOTYPE IN CRT

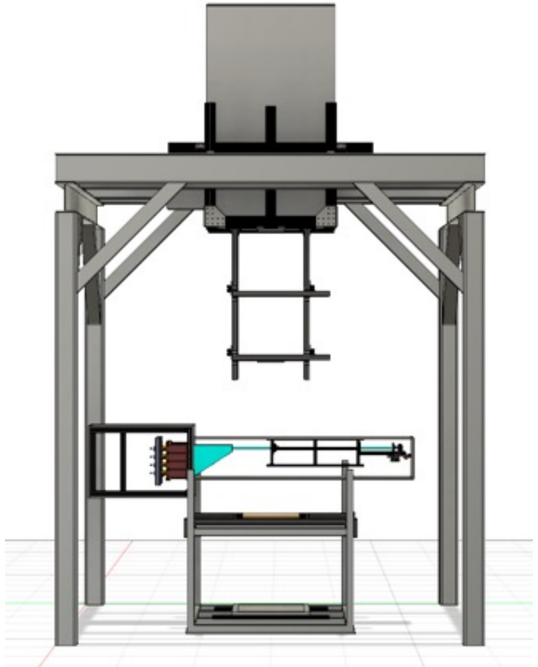
Cosmic Ray Telescope (CRT) is under construction at SBU

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, optimum placement of tracking and timing detectors
- Cherenkov tagger construction at ODU

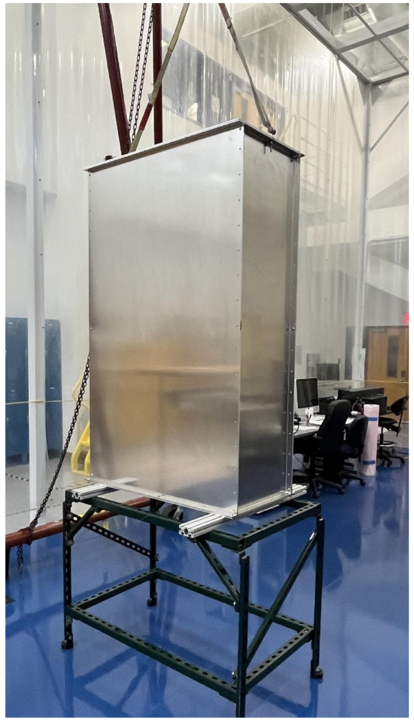
DIRC lab/CRT space at SBU

CRT setup schematic

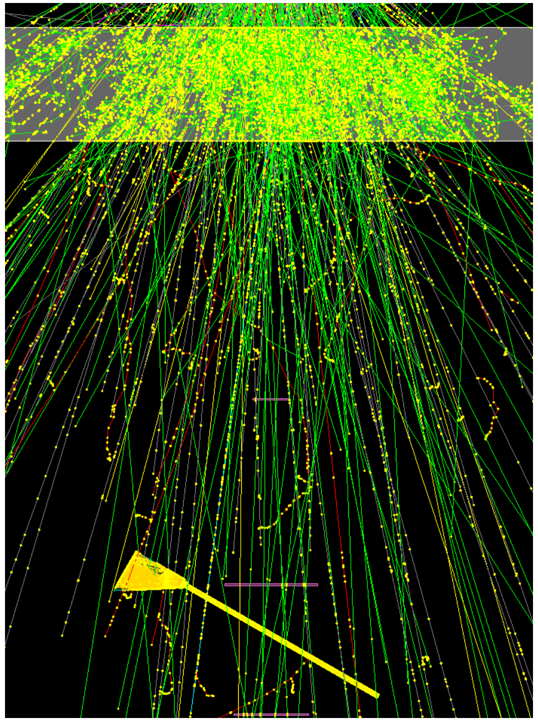


Prototype components from GSI at SBU

Cherenkov tagger under construction at ODU

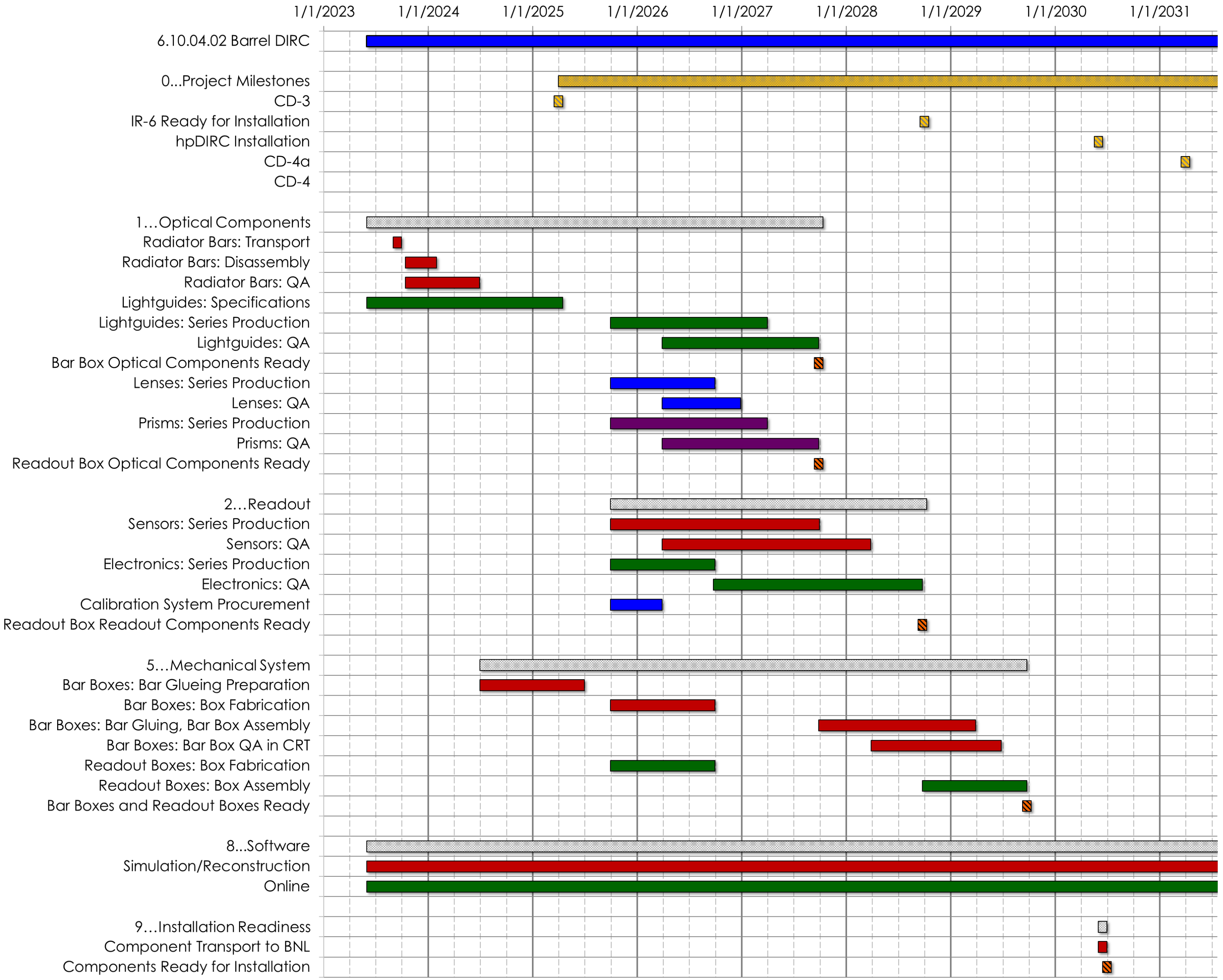


Geant simulation



Schedule

- hpDIRC technical schedule consistent with project schedule
- On track for TDR readiness next summer
- hpDIRC scheduled for installation into ePIC in June 2030
- Expect hpDIRC readiness for installation well before that date



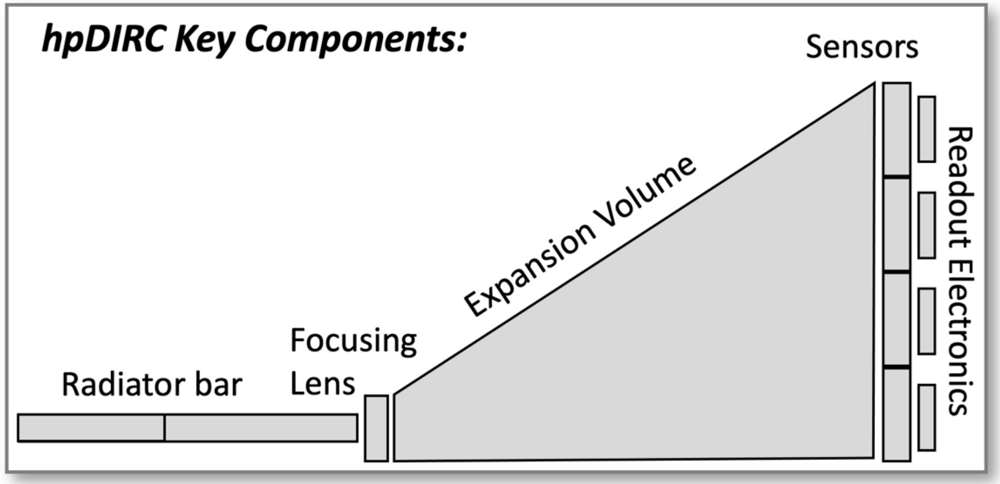
hpDIRC DSC

Recent formation of hpDIRC system collaboration (DSC)

- Core formed by groups that have been involved in the BaBar, GlueX, and PANDA DIRC counters, and in the EIC DIRC R&D program, for many years, some since 2011
- Expressions of interest (informal) in many work packages, continue to grow DSC
- Started process to match expertise and interest to system priorities

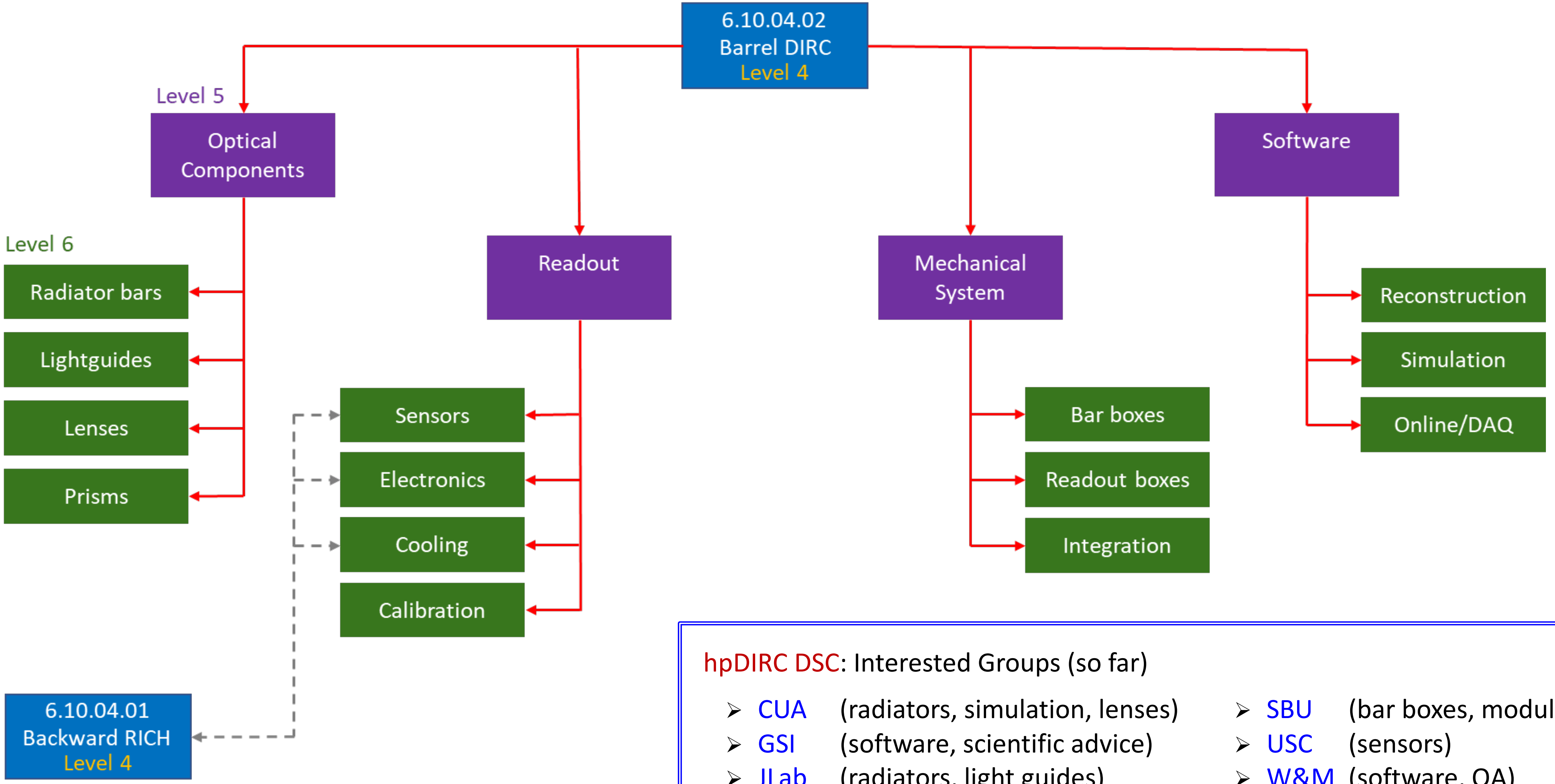
EoI examples:

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



WORK PACKAGES

Preliminary hpDIRC work package breakdown to level 6



hpDIRC DSC: Interested Groups (so far)

- CUA (radiators, simulation, lenses)
- GSI (software, scientific advice)
- JLab (radiators, light guides)
- ODU (lenses)
- SBU (bar boxes, module tests)
- USC (sensors)
- W&M (software, QA)
- WSU (readout boxes, simulation)

Example of preliminary hpDIRC work package breakdown to level 7 (with institutional interests)

6.10.04.02 Barrel DIRC (Level 4)

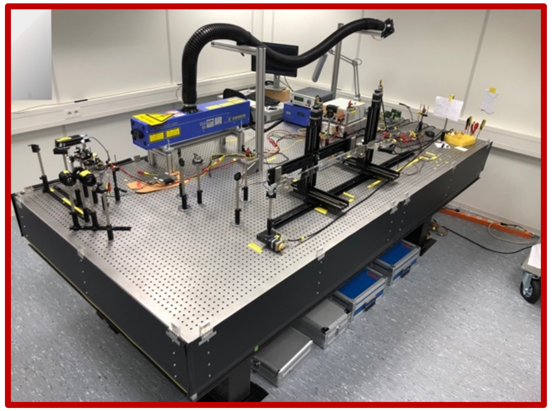
- **Level 5: Optical components**
  - **Level 6: Radiator bars**
    - **Level 7: Transport**: Jefferson Lab, CUA, Indiana
    - **Disassembly**: Jefferson Lab, CUA
    - **QA**: CUA, Jefferson Lab
  - **Light guides**
    - **Specifications**: GSI, CUA
    - **QA**: CUA, Jefferson Lab
  - **Lenses**
    - **Specifications**: GSI, CUA
    - **QA**: ODU, CUA
  - **Prisms**
    - **Specifications**: GSI, CUA, WSU
    - **QA**: WSU

QA Plan

Quality assurance plans for components and modules

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

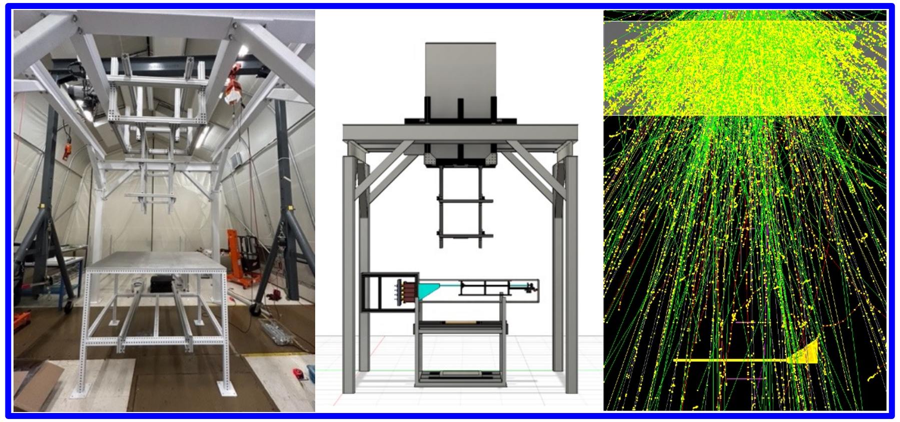
- Radiator bars and light guides: vendor QA for mechanical properties, laser scanning system at JLab to monitor internal photon transport efficiency of disassembled BaBar DIRC bars and/or new DIRC bars
- Sensors and electronics: laser pulser systems at CUA/JLab/USC (TBD) to measure gain, quantum and 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)



PID Review

Summary:

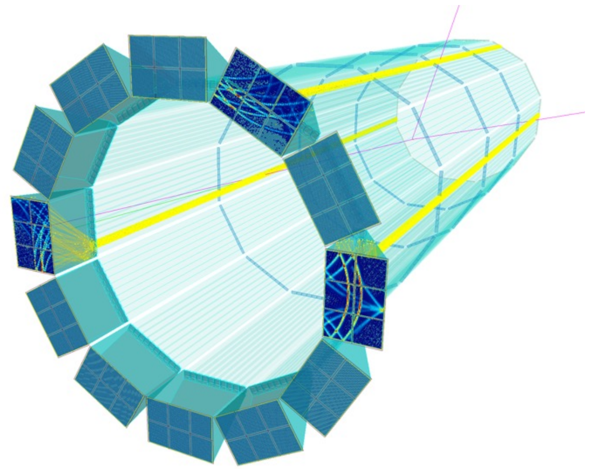
- The PID detector proponents provided excellent presentations and discussions during this review.
- We are very happy to see the state of the project and the very interesting R&D for the PID community, and encourage a continuation of R&D and beam tests to complete the designs.
- The PID detectors are fully on track for the CD2/3 review on the current project timeline.

	Charge Question	Conclusion
1	Are the technical performance requirements appropriately defined and complete for this stage of the project?	Yes, documentation of tracking requirements needed
2	Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?	Yes, advised parallel studies of HRPPDs and backup solution
3	Are the current designs and plans for detector and electronics readout likely to achieve the performance requirements with a low risk of cost increases, schedule delays, and technical problems?	Yes, more information needed
4	Are the fabrication and assembly plans for the various particle identification detector systems consistent with the overall project and detector schedule?	Yes, acknowledged proper handling of risk with bars reuse
5	Are the plans for detector integration in the EIC detector appropriately developed for the present phase of the project?	Yes
6	Have ES&H and QA considerations been adequately incorporated into the designs at their present stage?	Yes

SUMMARY

- ePIC hpDIRC: Fast focusing DIRC concept, developed over 10+ years of EIC R&D
- Positive feedback from recent PID review
- 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 ~1.2 GeV/c
- Key elements, simulation and focusing lenses, validated in particle beam in 2018
- Main remaining steps towards production readiness and TDR in Sep 2024:
  - Validation of reusing BaBar DIRC radiator bars
  - Evaluation of sensors and readout ASIC (synergy with bwRICH and project R&D)
  - Completion of mechanical design and integration
- hpDIRC system collaboration includes eight institutions with well-established expertise and interest in work packages
- Plans for remaining studies, QA, and construction match project schedule

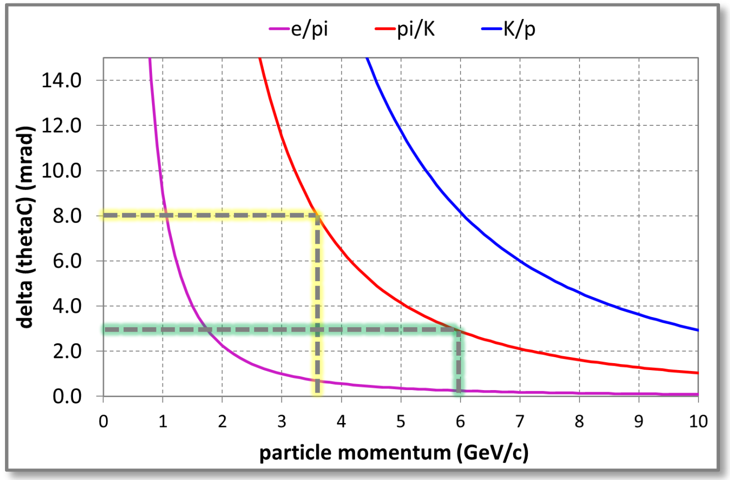
- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation
- legacy components (?)



Extra Slides

ADVANCING DIRC PERFORMANCE

DIRC Cherenkov angle difference vs. momentum



- Make DIRC less sensitive to background (main challenge for BABAR and SuperB)
  - decrease size of expansion volume, replace water as medium, add focusing optics;
  - find a way to place photon detector inside magnetic field.
- Investigate alternative radiator shapes (plates, disks), develop endcap device
- Push DIRC π/K separation to higher momentum

$$\sigma_{\theta_c}(particle) \approx \sqrt{\left(\frac{\sigma_{\theta_c}(photon)}{\sqrt{N_\gamma}}\right)^2 + \sigma^2_{correlated}}$$

  - improve angular resolution of tracking system, mitigate multiple scattering impact;
  - use photon detectors better PDE, improve Cherenkov angle resolution per photon.

$$\sigma_{\theta_c}(photon) \approx \sqrt{\sigma^2_{bar} + \sigma^2_{pix} + \sigma^2_{chrom}}$$

BABAR DIRC $\sigma_{\theta_c}(photon) = 9.6\text{ mrad}$

Limited in BABAR by:

- size of bar image ~4.1 mrad
- size of PMT pixel ~5.5 mrad
- chromaticity (n=n(λ)) ~5.4 mrad

Improve for future DIRCs via:

- focusing optics
- smaller pixel size
- better time resolution

SUPERB, BELLE II, PANDA & EIC

9.6 mrad → 5-6 mrad per photon → 1 mrad per particle (EIC goal) in reach

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

- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation
- legacy components (?)

➢ 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:

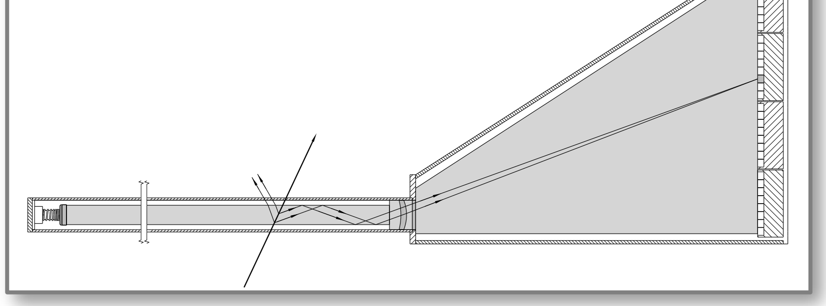
  ➢ high-precision tracking, expect 0.5mrad polar angle resolution;

  ➢ 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 ≤1mrad),

supplemental e/π separation up to 1.2 GeV/c.

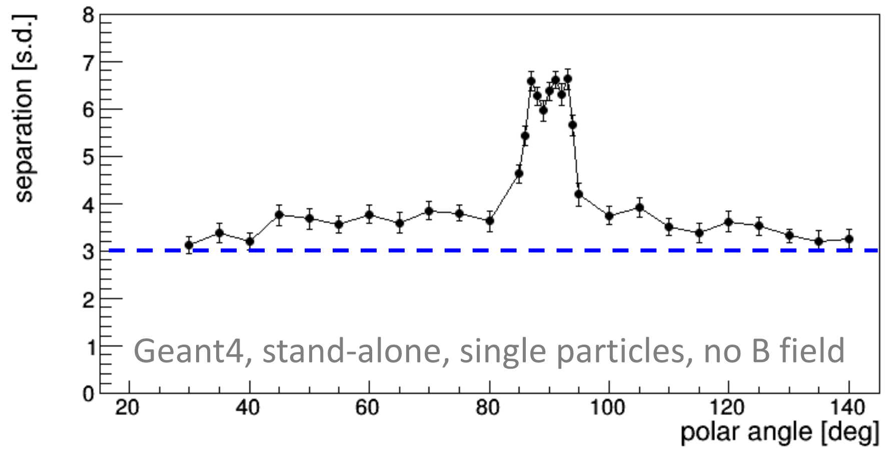


Schematic view of the EIC hpDIRC

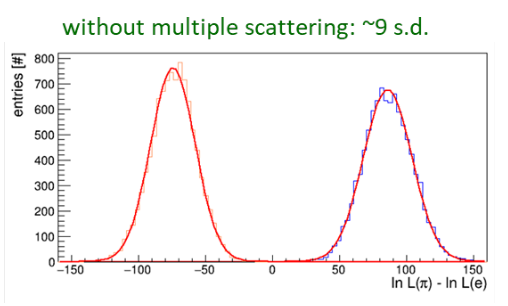
EXPECTED HPDIRC PERFORMANCE

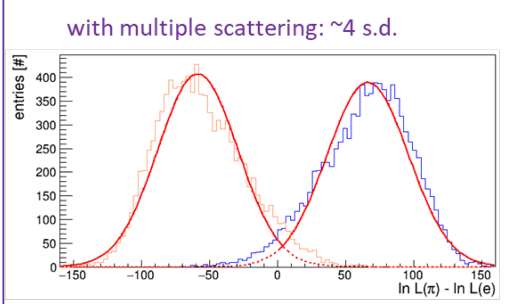
e/π separation at low momentum

- Yellow report effort identified need for supplemental e/π suppression from PID systems to support EM calorimeter at lower momentum
- hpDIRC e/π performance at low momentum very different from high-momentum domain, dominated by multiple scattering (MS) and EM showers in DIRC bars
- Expected performance (without any MS mitigation): ≥ 3 s.d. e/π separation at 1.2 GeV/c (caveat: non-Gaussian tails)
- Study of potential improvements from DIRC "ring center fit" and use of additional tracking point from AstroPix layer outside DIRC radius starting (also expected to further improve high-momentum π/K separation)



Example from Geant4
e/π log-likelihood difference
1 GeV/c momentum,
30° polar angle,
0.8mrad tracking resolution

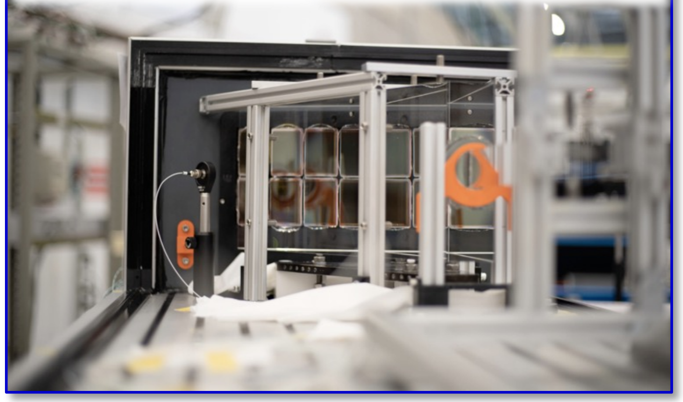




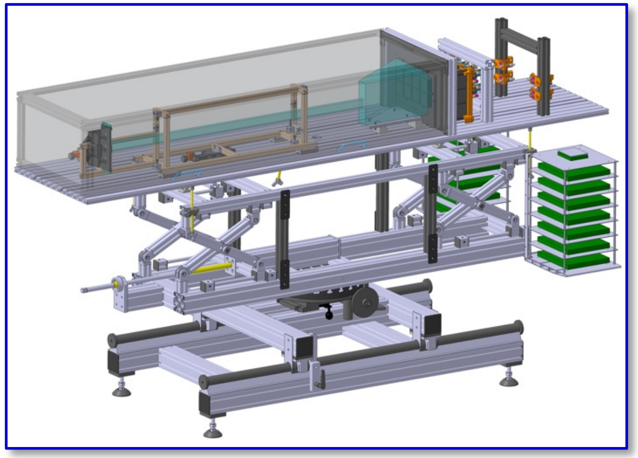
Performance validation: synergetic beam test with PANDA prototype at CERN PS in 2018

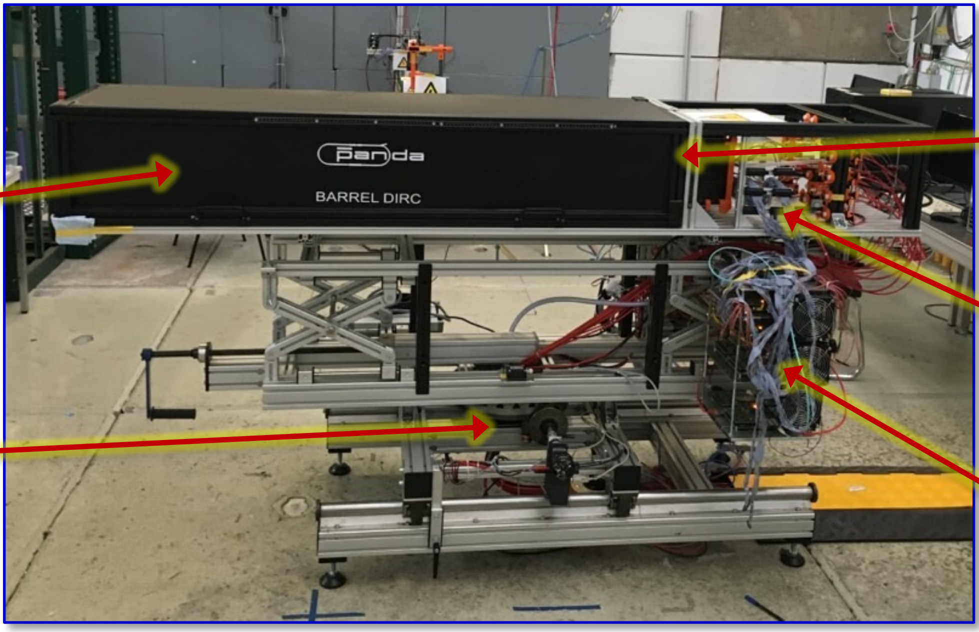
- Narrow fused silica bar, hpDIRC 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array (larger pixels, slower readout electronics than EIC)
- PiLas picosecond laser calibration system
- 7 GeV/c π/p beam equivalent to 3.5 GeV/c π/K
- MCP-TOF system to cleanly tag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

View from inside the Barrel DIRC dark box



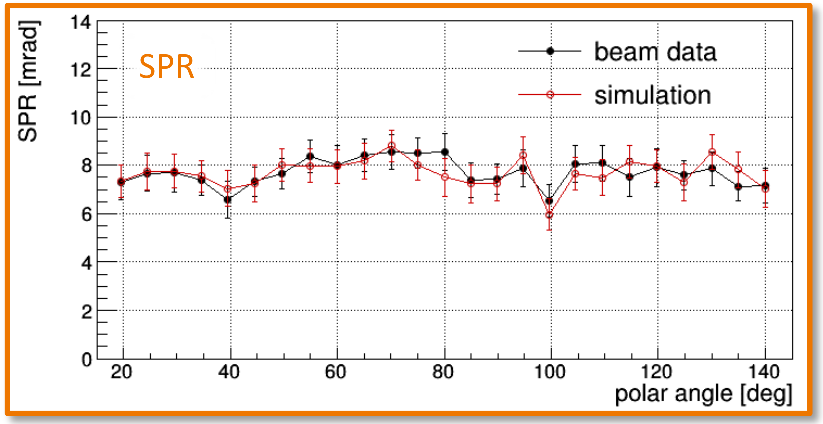
Schematic view of 2018 prototype

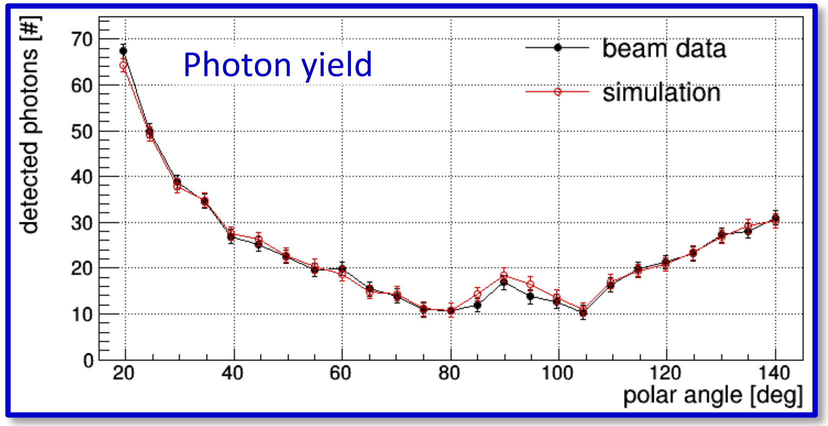




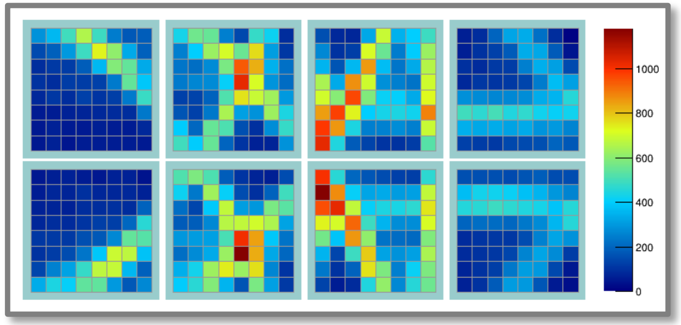
VALIDATION OF SIMULATION AND COMPONENTS

Performance validation: 2018 prototype at CERN PS

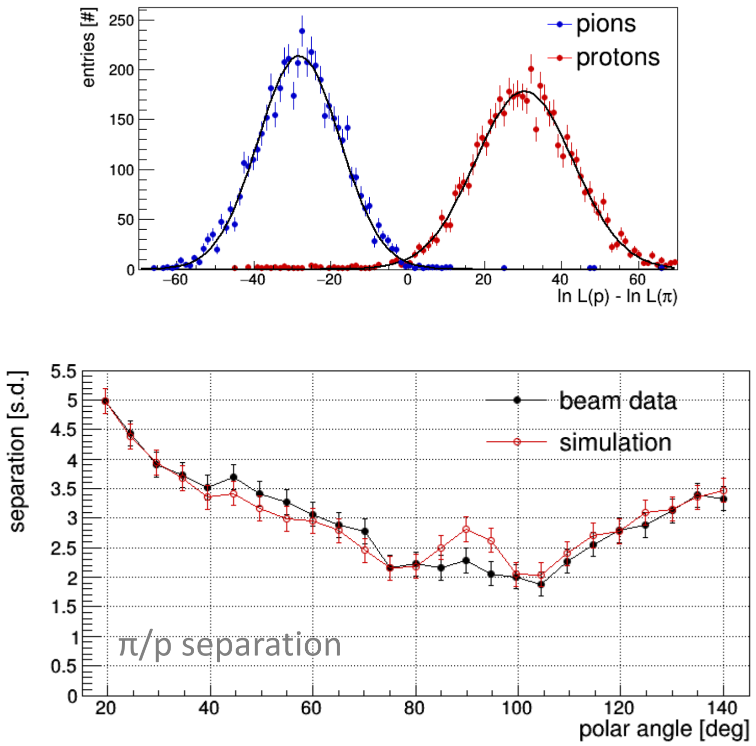




observed hit pattern at polar angle 20°



π/p separation power @ 7 GeV/c



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

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

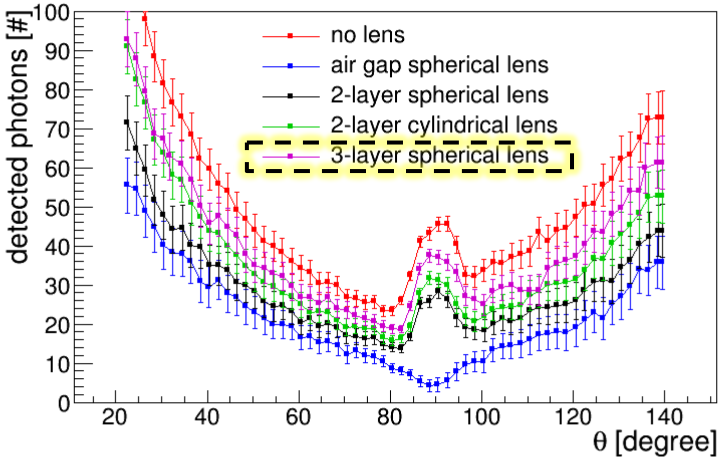
Innovative solution:

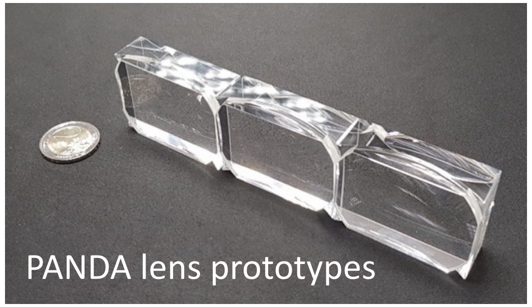
- 3-layer compound lens (without air gap):

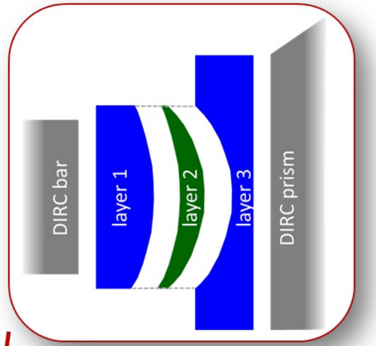
layer of high-refractive index material (focusing/defocusing) sandwiched between two layers of fused silica

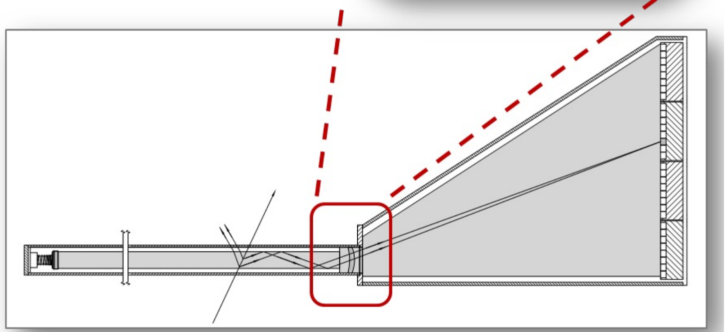
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Detailed radiation-hardness studies performed with ^{60}Co source, neutron irradiation next
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire or PbF_2 for EIC
- Industrial fabrication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

Geant4 simulation: photon yield









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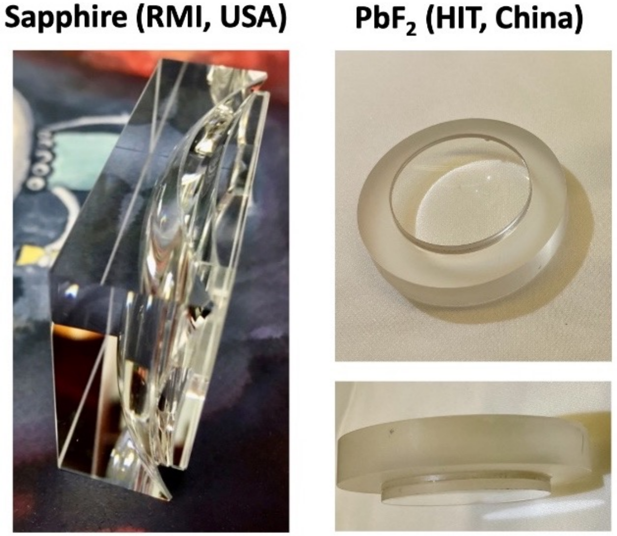
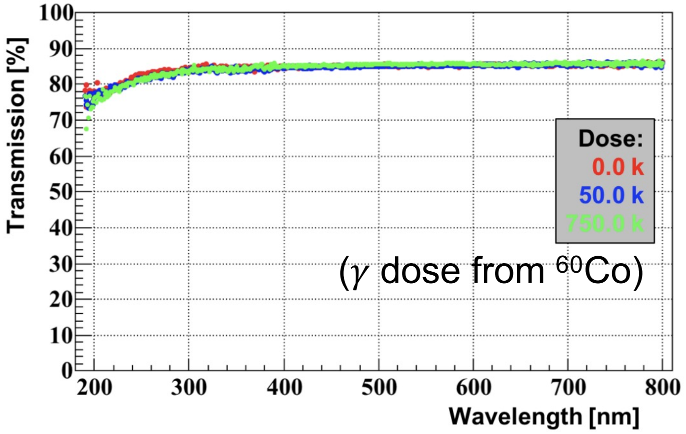
Radiation-hard 3-layer lens prototypes



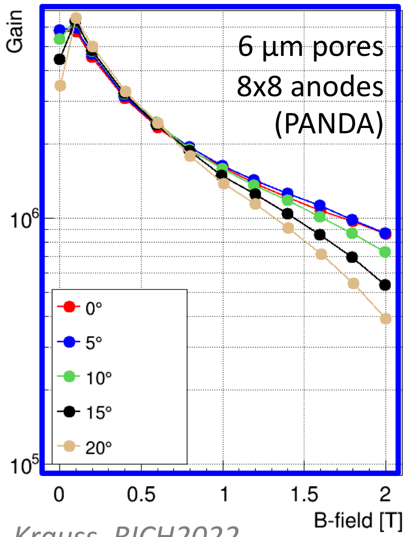
Radiation hardness of sapphire



hpDIRC sensor requirements

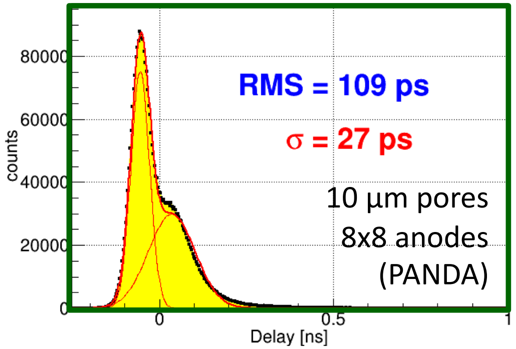
- Single photon sensitivity in ePIC magnetic field: 10^6 gain at ~ 1T
- Fast timing for single photons: timing precision (rms) < 100 ps
- Large active area ratio for tiled sensors: goal > 75%
- High PDE in visible range: goal > 25% at 400 nm
- Small pixels: anode pixel size < 3.5 mm
- Tolerance for high 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

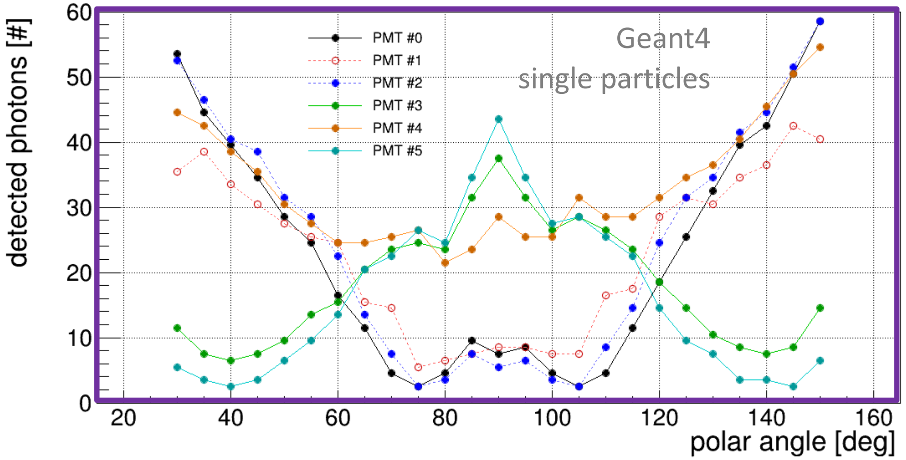


S. Krauss, RICH2022

PHOTONIS XP85012-S



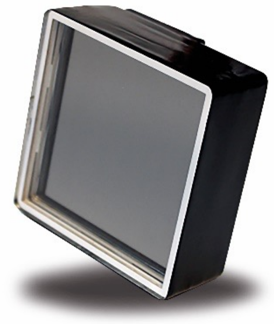
Expected number of photoelectrons per particle per 12 cm x 12 cm sensor



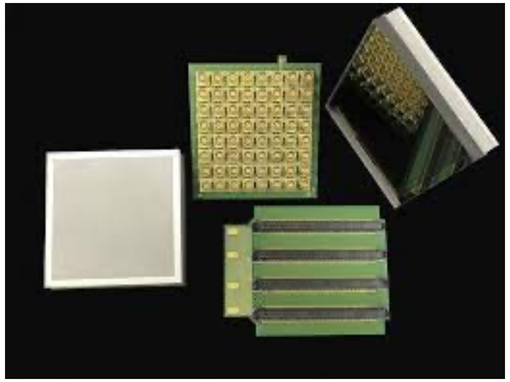
hpDIRC sensor: Microchannel-Plate PMT

- 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: DC-coupled Incom HRPPD Making use of synergy with bwRICH, optimizing cost and workforce Fallback solution: 2’’ MCP-PMTs from Photonis or Photek

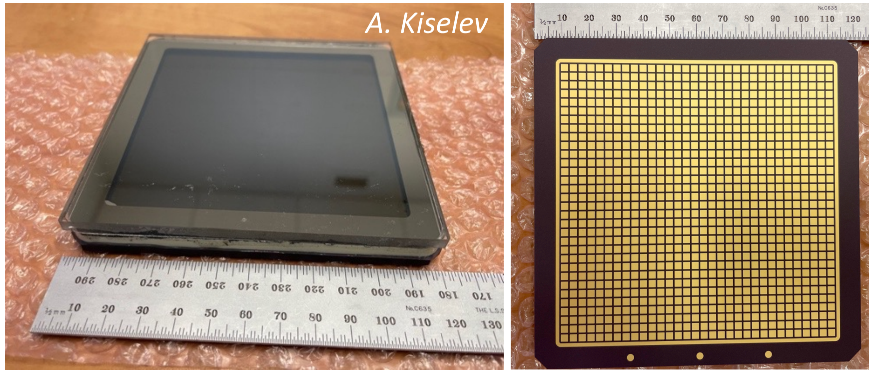
PHOTONIS XP85122-S



Photek MAPMT 253



INCOM Gen III HRPPD prototype (front/back view)



READOUT CHAIN

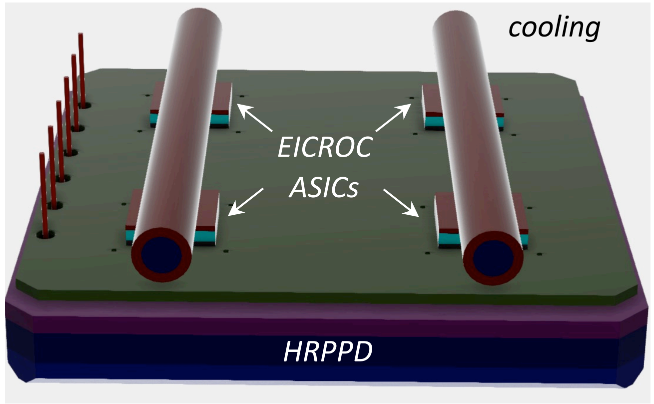
Front-end board (FEB) requirements for hpDIRC

- 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

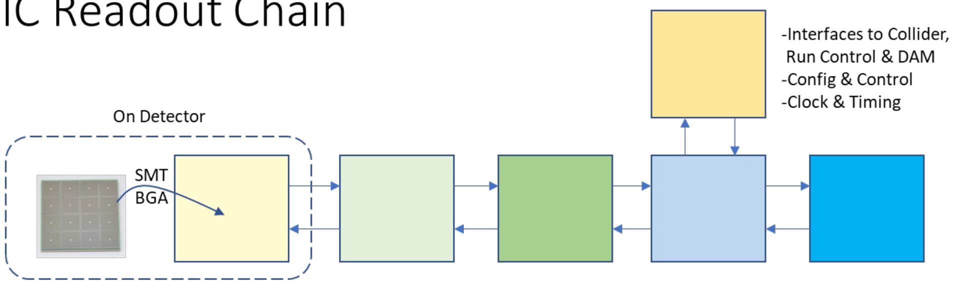
Baseline front-end board for hpDIRC: EICROC

- 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

A. Kiselev, preliminary



ePIC Readout Chain



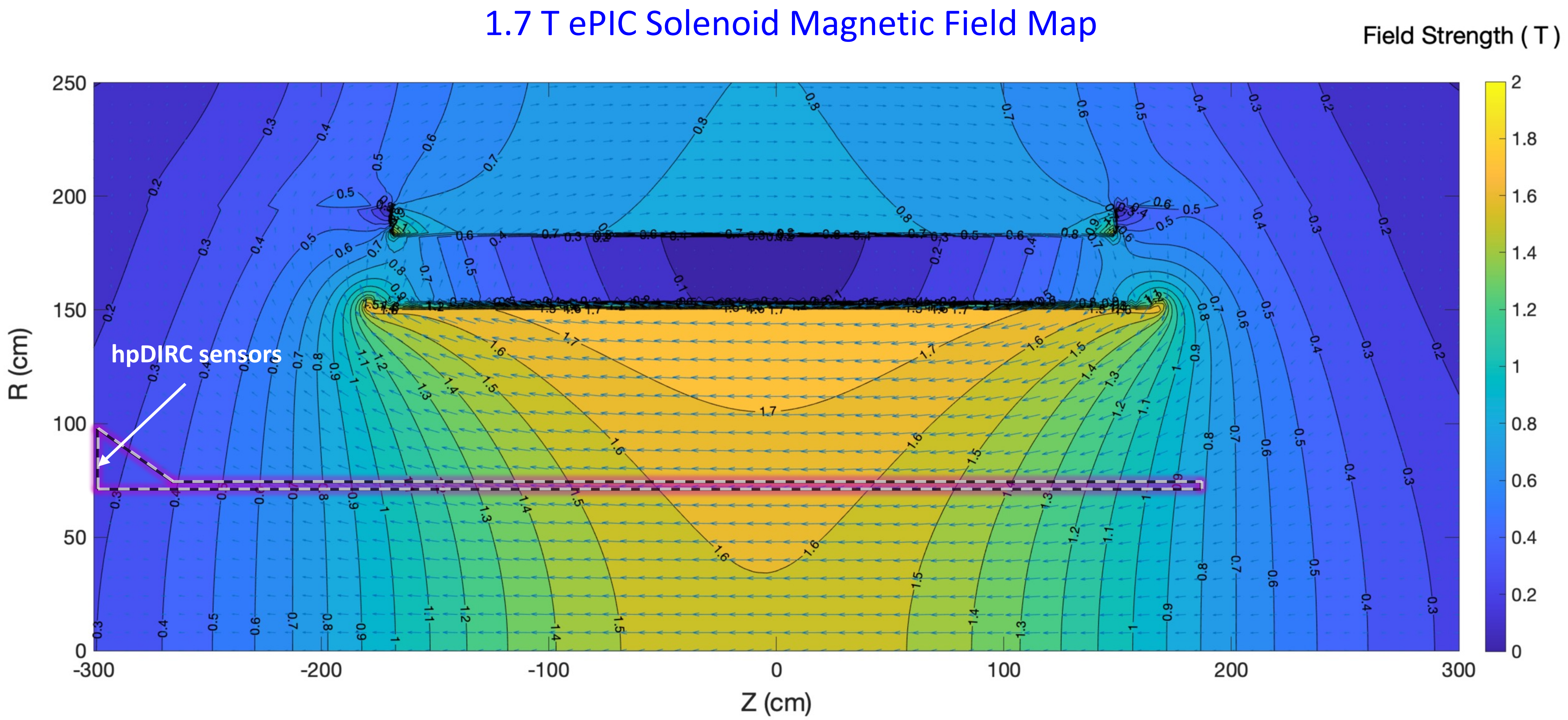
Name	Sensor	Adapter	Front End Board (FEB)	Readout Board (RDO)	Data Aggregation Module (DAM)	Computing
Design	**Detector Specific**	**Detector Specific**	**Detector Specific**	**Few Variants**	**Common**	**Common**
Function	-Multi-Channel Sensor	-HV/Bias Distribution -HV divider -Interconnect Routing	-Amplification -Shaping -Digitization -Zero Suppression -Bias Control & Monitoring	-Communication -Aggregation -Formatting -Data Readout -Config & Control -Clock & Timing	-Computing Interface -Aggregation -Software Trigger -Config & Control -Clock & Timing	-Data Buffering and Sinking -Calibration Support -QA/Scalers -Collider Feedback -Event ID/Building -Software Trigger -Monitoring
Attributes	-MAPS -AC-LGAD -MPGD -MCP-PMT -SiPM -LAPPD/HRPPD	-Sensor Specific -Passive	-ASIC/ADC -Discrete -Serial Link	-FPGA -Fiber Link	-Large FPGA -PCIe -Ethernet	-COTS -Ethernet

REQUIREMENTS FROM YELLOW REPORT

Table 3.1: This matrix summarizes the high level performance of the different subdetectors and a 3 T Solenoid. The interactive version of this matrix can be obtained through the Yellow Report Detector Working Group (https://physdiv.jlab.org/DetectorMatrix/).

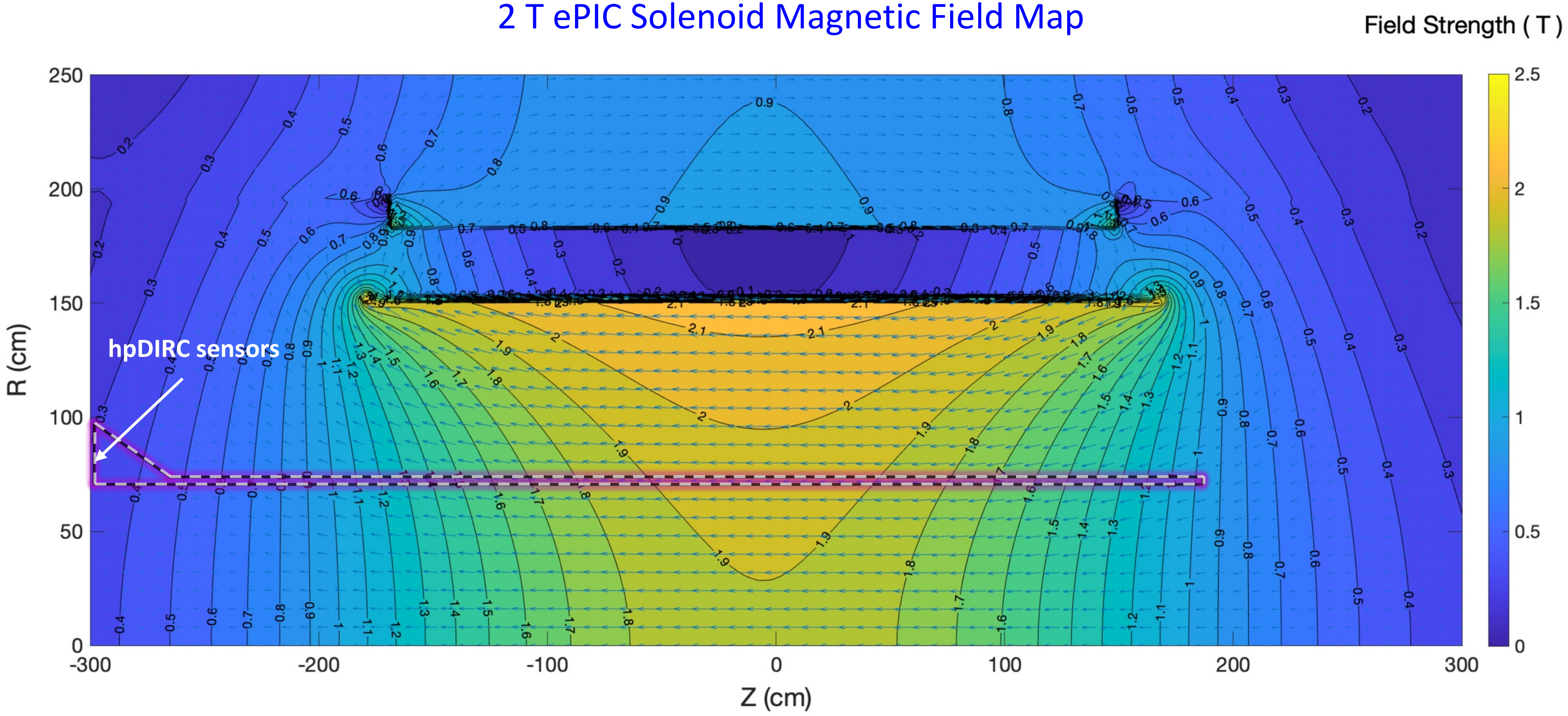
η	Nomenclature	Tracking						Electrons and Photons			$\pi/K/p$		HCAL		Muons
		Resolution	Relative Momentum	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range	Separation	Resolution σ_E/E	Energy	
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300			$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$	π suppression up to $1:10^{-4}$	20 MeV	≤ 10 GeV/c		$50\%/\sqrt{E} \oplus 10\%$	~500MeV	Muons useful for background suppression and improved resolution
-3.0 to -2.5															
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ µm ⊕ 10 µm	dca(z) ~ $100/p_T$ µm ⊕ 20 µm	$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$	π suppression up to $1:(10^{-3}\text{-}10^{-2})$	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	dca(xy) ~ $30/p_T$ µm ⊕ 5 µm	dca(z) ~ $30/p_T$ µm ⊕ 5 µm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to $1:10^{-2}$	100 MeV	≤ 6 GeV/c	≥ 3σ	$100\%/\sqrt{E} \oplus 10\%$		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	dca(xy) ~ $40/p_T$ µm ⊕ 10 µm	dca(z) ~ $100/p_T$ µm ⊕ 20 µm	$2\%/E \oplus (4^*\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		$50\%/\sqrt{E} \oplus 10\%$		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer														
	Zero Degree Neutral Detection														

R. Abdul Khalek et al., Science Requirements and Detector Concepts for the Electron-Ion Collider : EIC Yellow Report, doi:10.1016/j.nuclphysa.2022.12447



→ hpDIRC detector plane located in modest magnetic field of less than 0.5 T

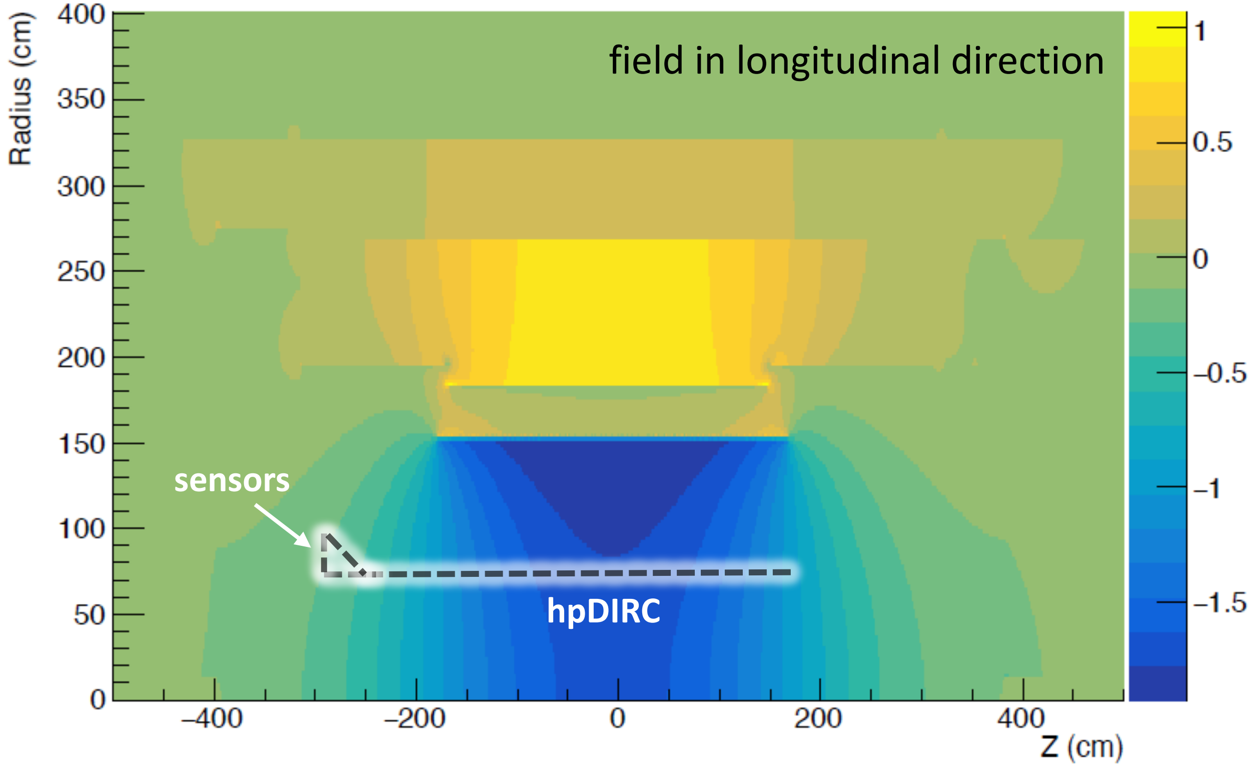
2 T ePIC Solenoid Magnetic Field Map

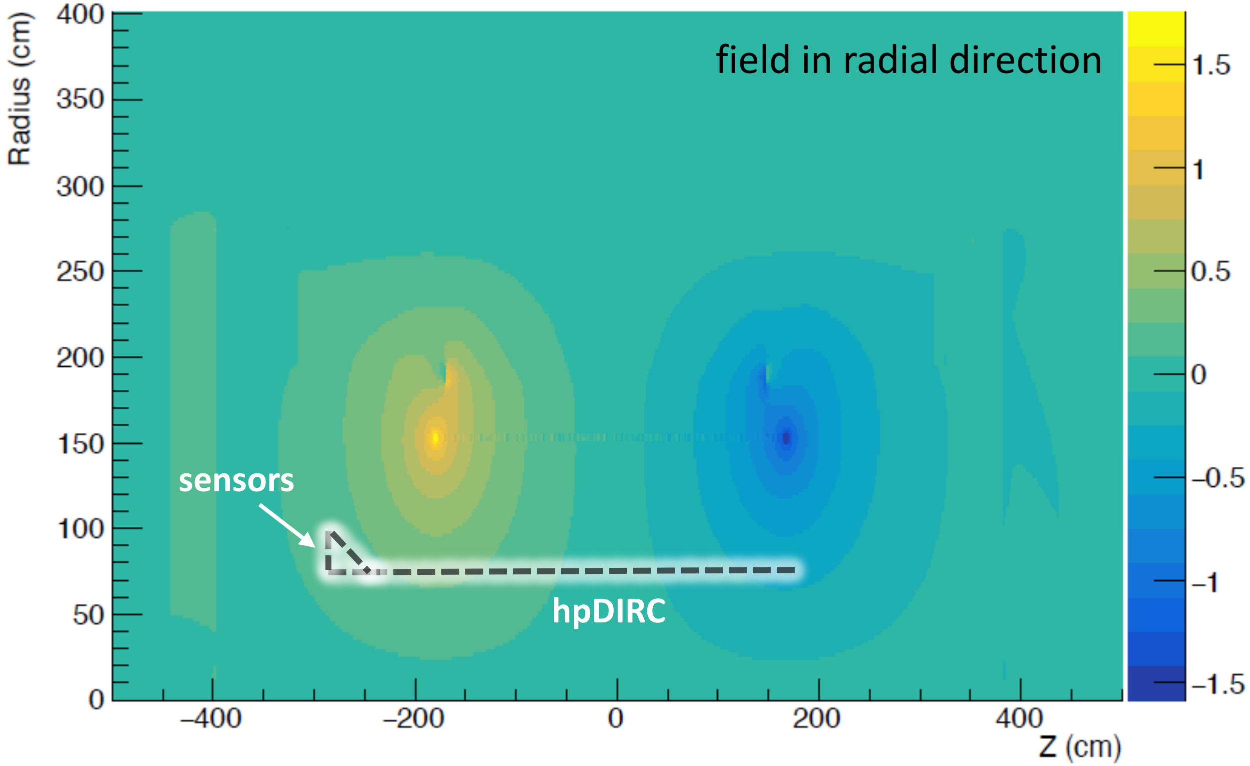


→ hpDIRC detector plane located in modest magnetic field of less than 0.5 T

https://wiki.bnl.gov/EPIC/index.php?title=Experimental_Solenoid

1.7 T ePIC Solenoid Magnetic Field Map



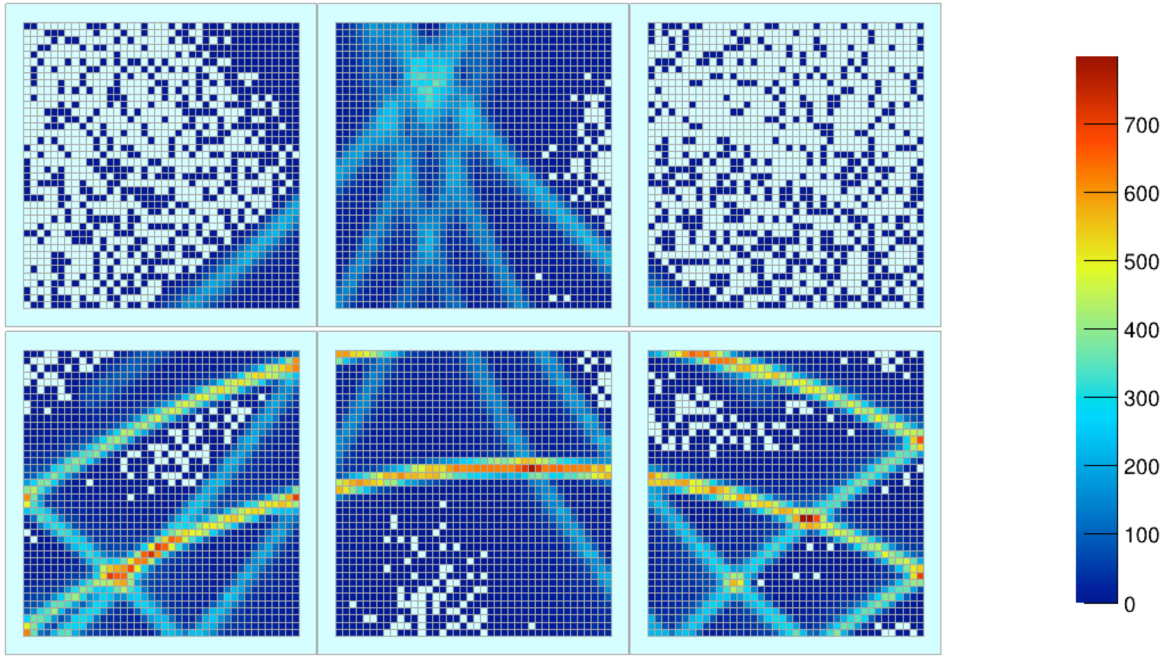


→ hpDIRC detector plane located in modest magnetic field of less than 0.5 T

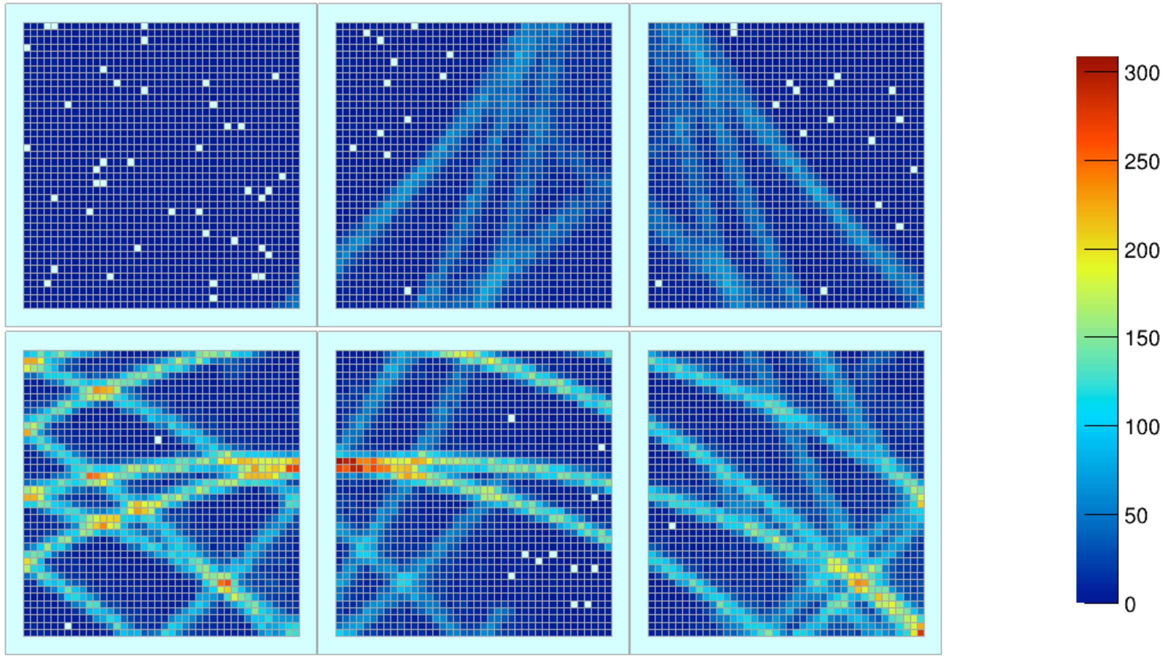
Impact of magnetic field on hit pattern

(accumulated hit pattern, 5000 charged pions, 6 GeV/c, 30° polar angle)

without magnetic field



with magnetic field



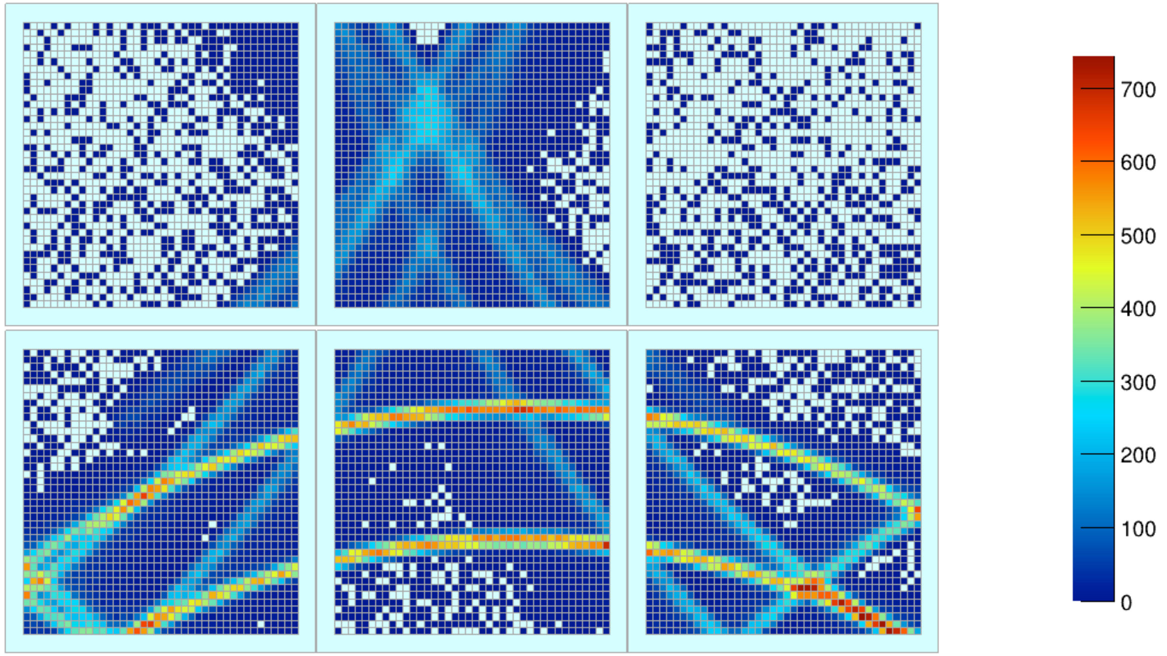
→ hpDIRC hit pattern spread out over larger area, more pixels, in ePIC magnetic field

hpDIRC in ePIC Magnetic Field

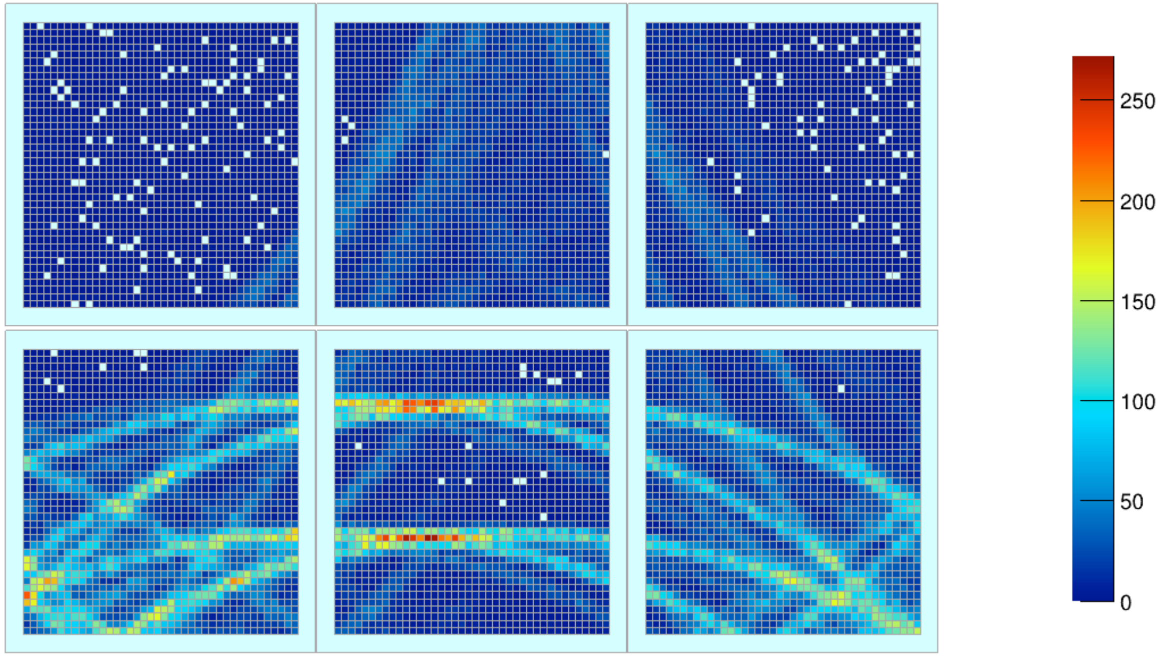
Impact of magnetic field on hit pattern

(accumulated hit pattern, 5000 charged pions, 6 GeV/c, 35° polar angle)

without magnetic field



with magnetic field



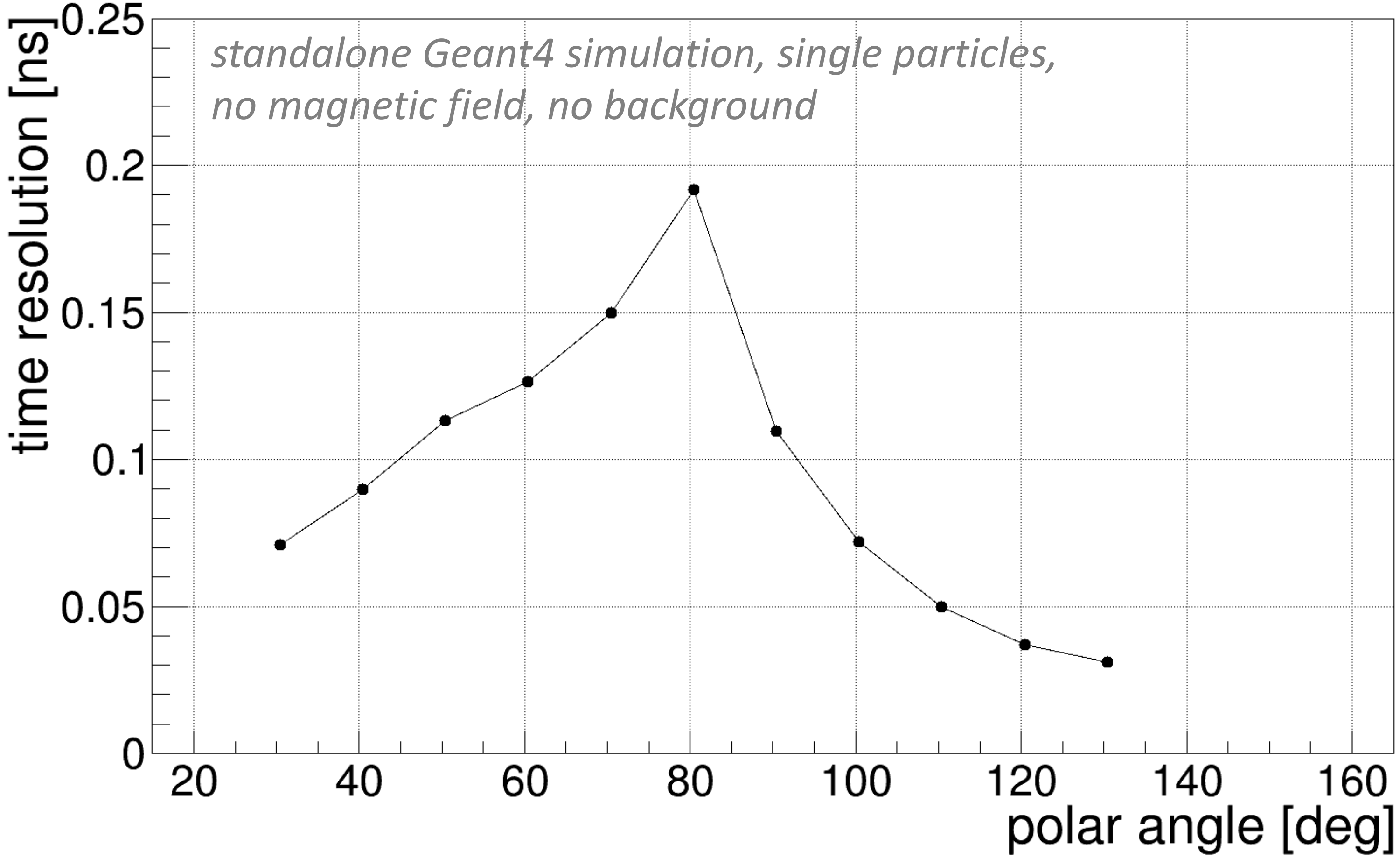
→ hpDIRC hit pattern spread out over larger area, more pixels, in ePIC magnetic field

HPDIRC TIMING

Calculate average time of Cherenkov light emission per particle

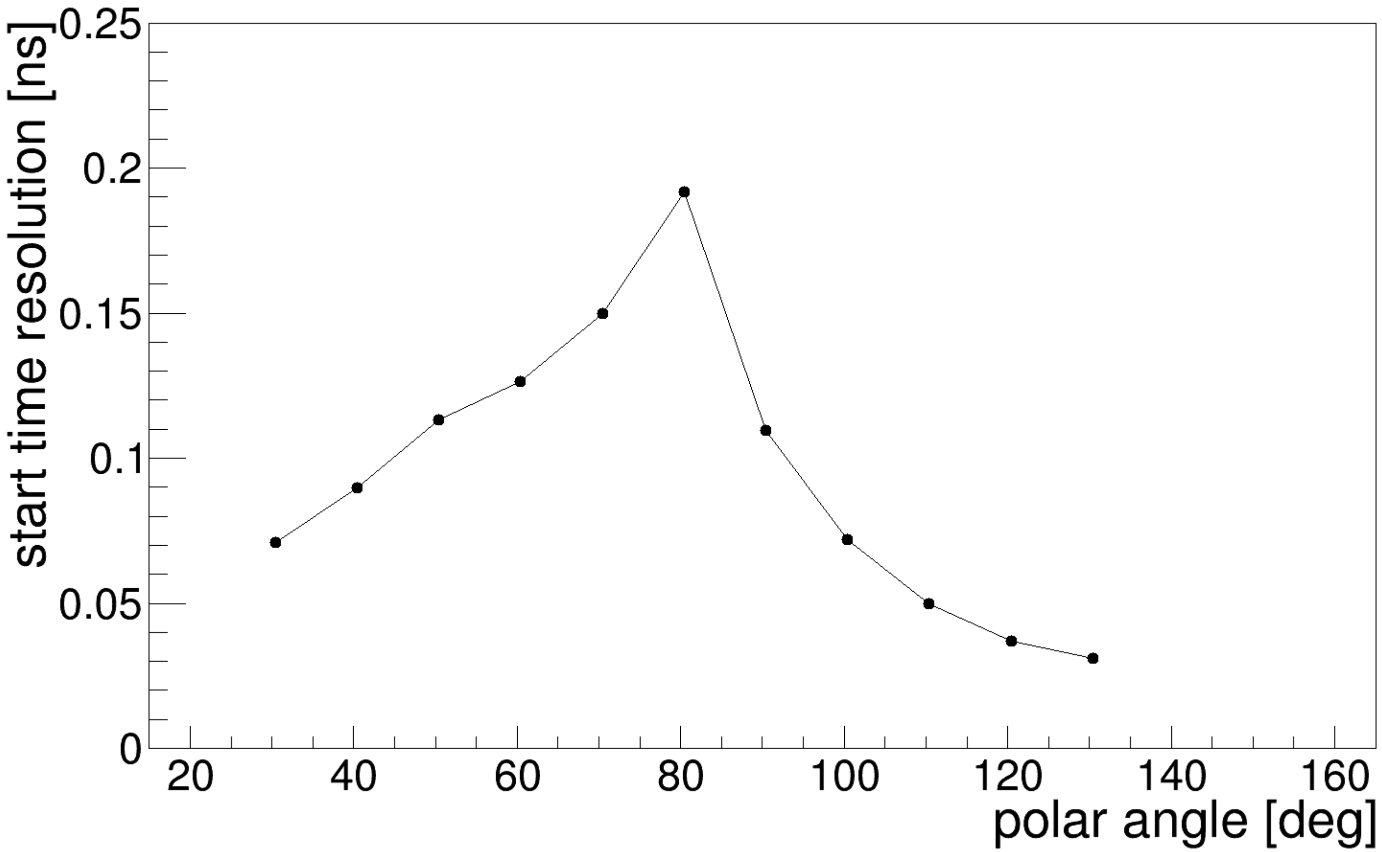
from difference between measured and calculated arrival time for each detected photon

Good precision for large number of photoelectrons, can be useful as TOF “stop time” if event T_0 is known



hpDIRC in ePIC Magnetic Field

Impact of magnetic field on hit pattern

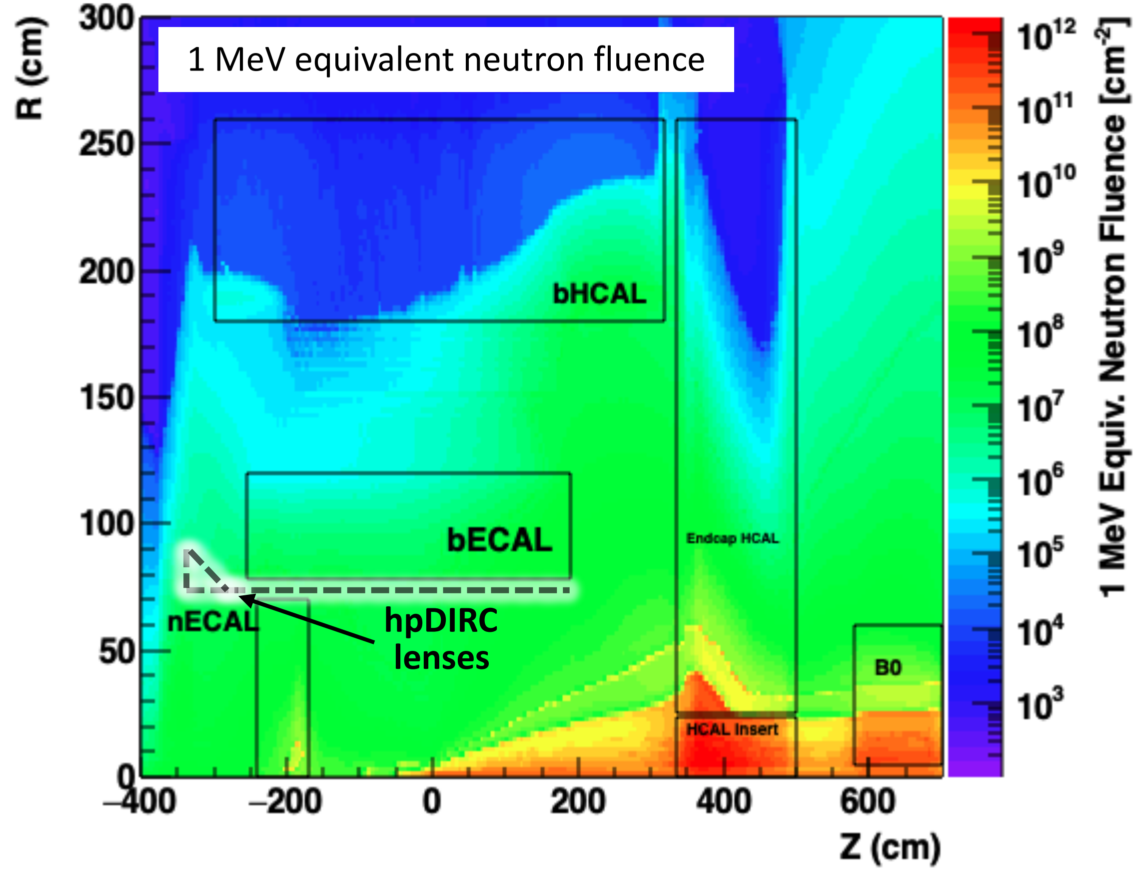


with magnetic field

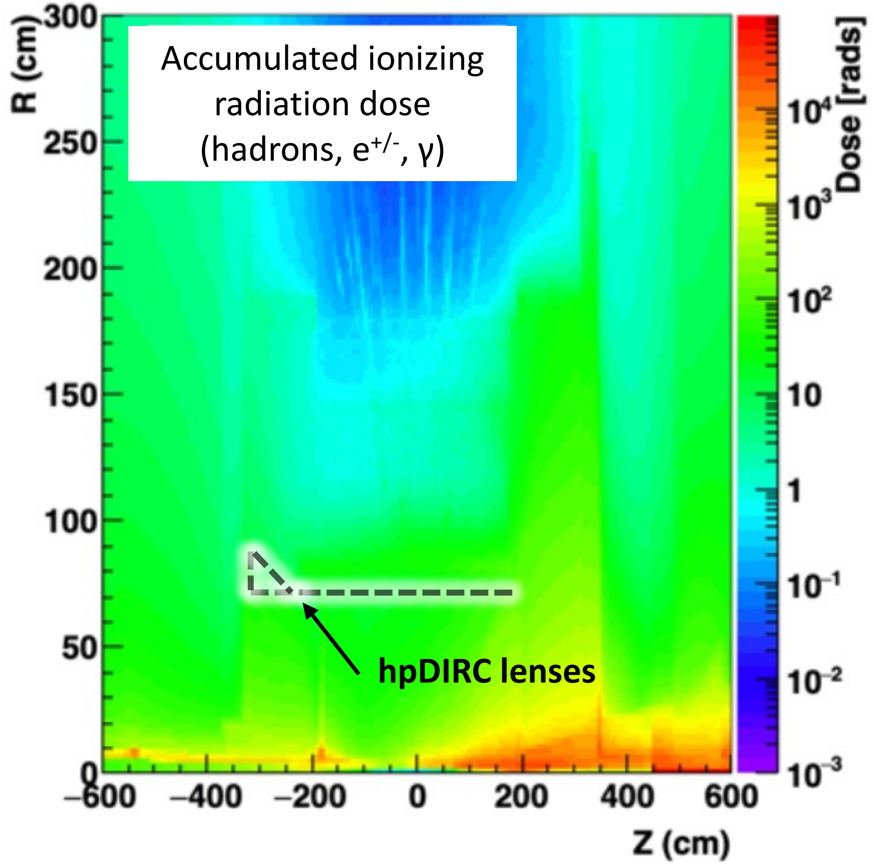
→ hpDIRC hit pattern spread out over larger area, more pixels, in ePIC magnetic field

https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses

Radiation Dose and Neutron Flux from Minimum-Bias e+p events



1 MeV equivalent neutron fluence - PYTHIA 18x275 GeV e+p minimum bias events at top luminosity (500 kHz min-bias rate, 6-month run)

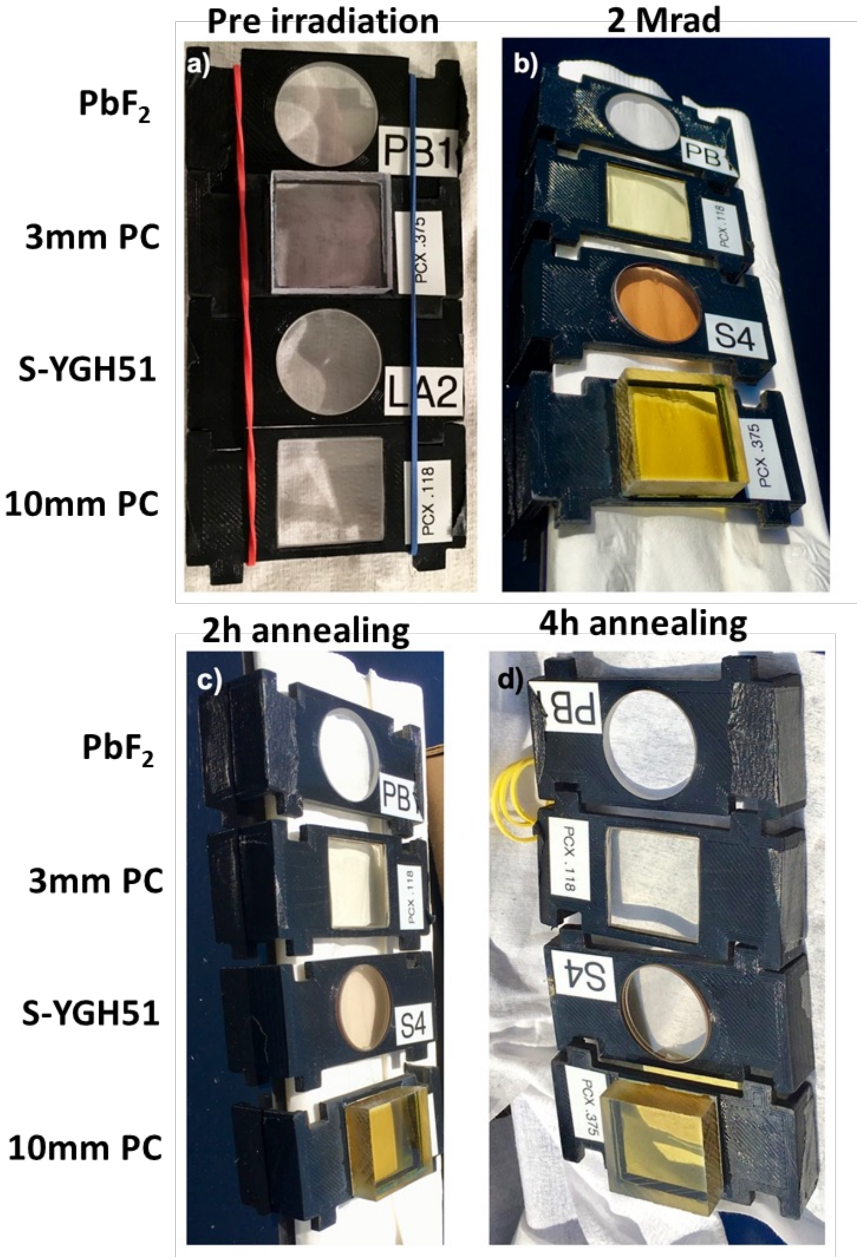


Accumulated ionizing radiation dose - PYTHIA 18x275 GeV e+p minimum bias events at top luminosity (500 kHz min-bias rate, 6-month run)

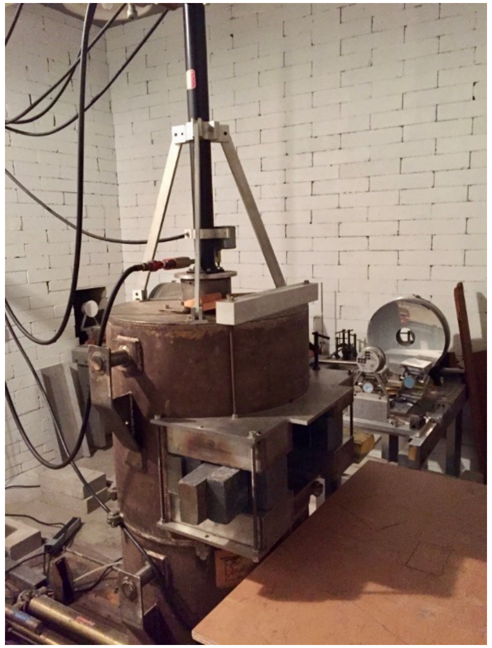
→ Expect less than 10^{9} neutrons cm^{-2} and less than 0.1krad per year at DIRC lens location

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.

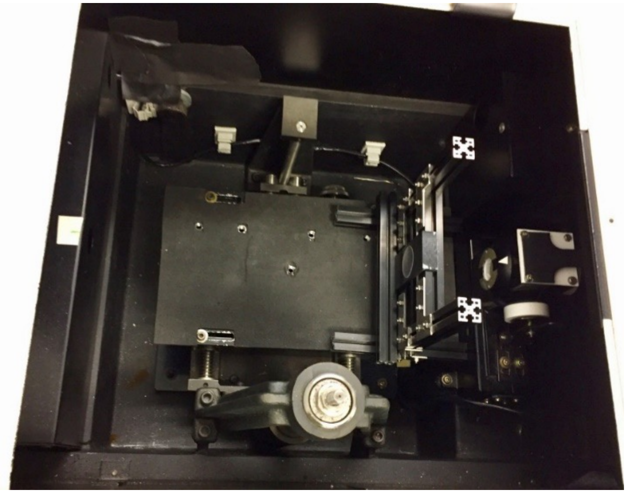


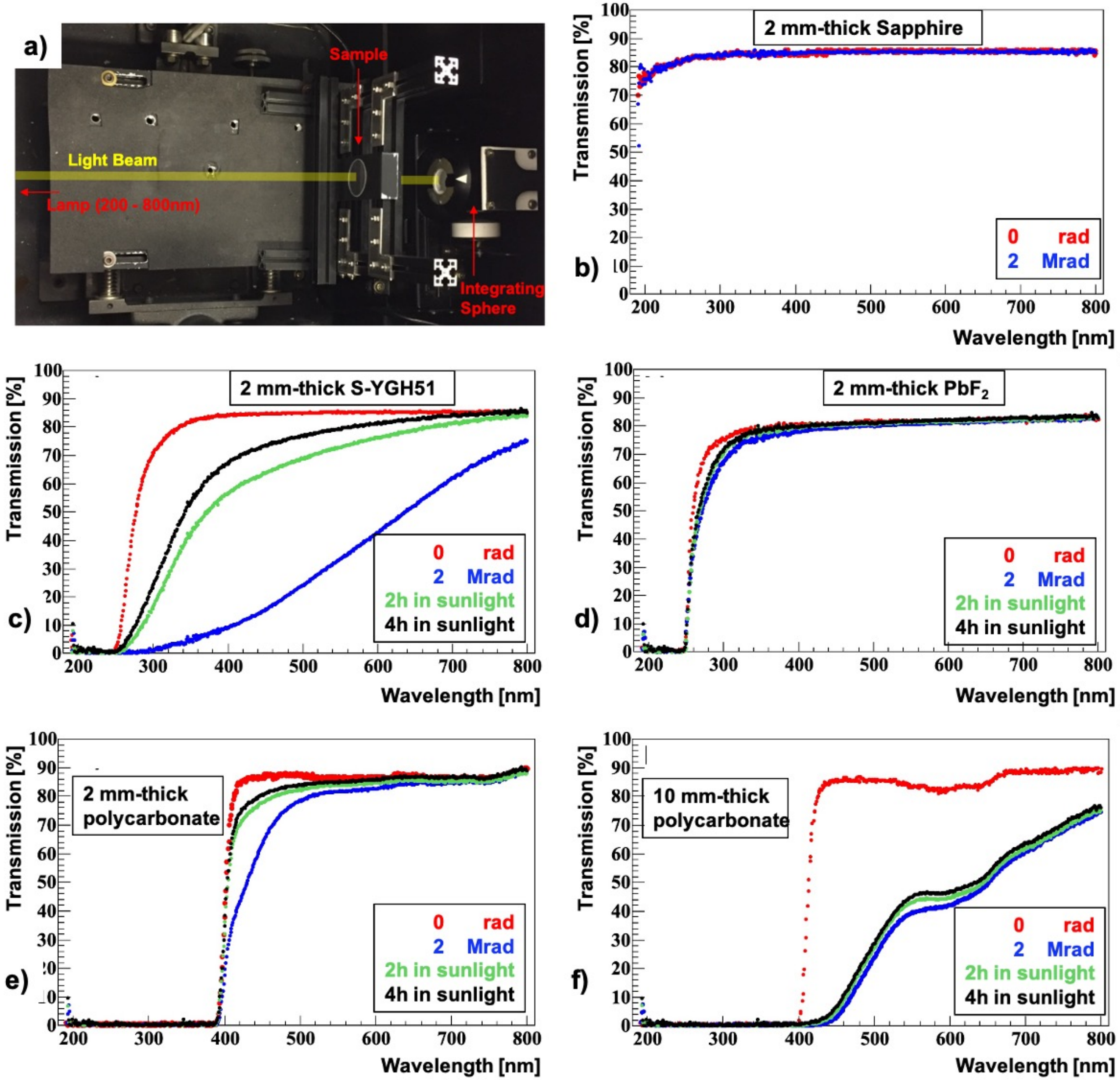
hpDIRC Radiation Tests



Co^{60} Chamber

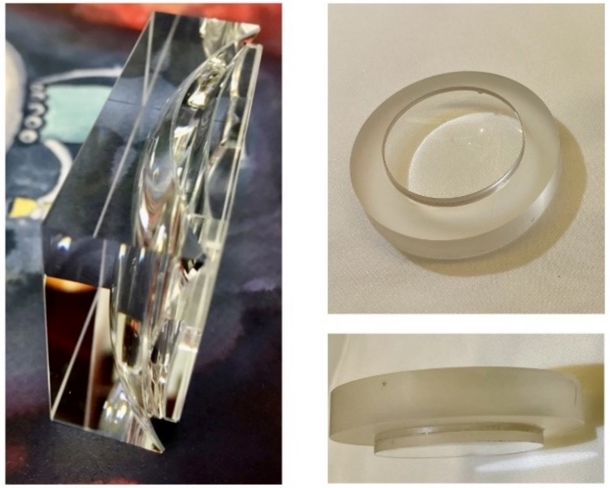
Monochromator

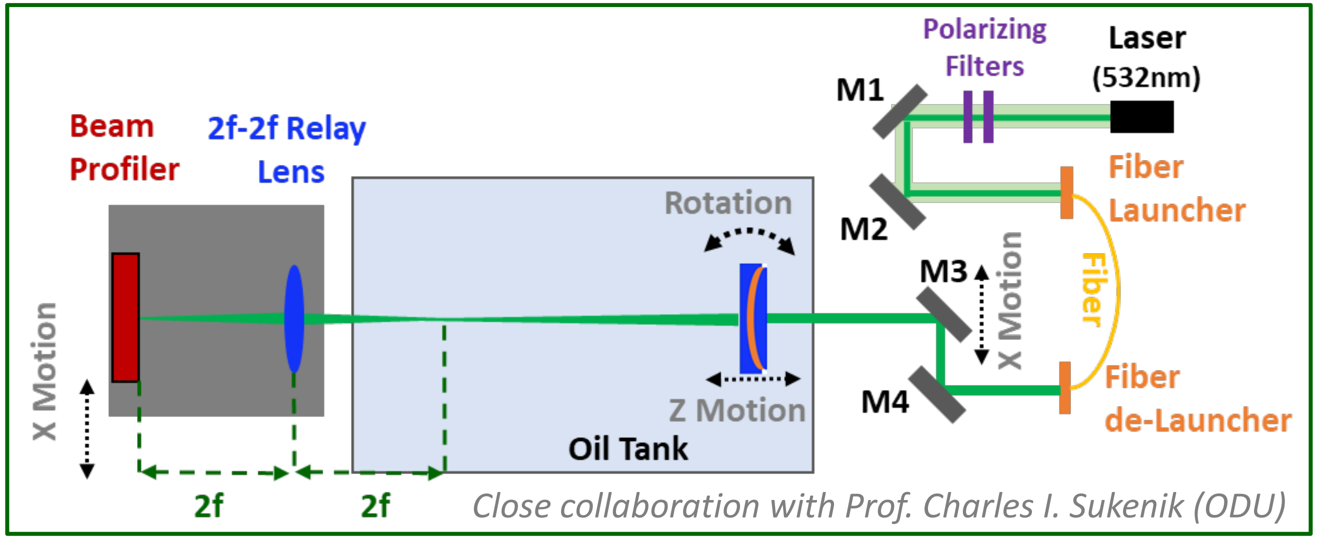




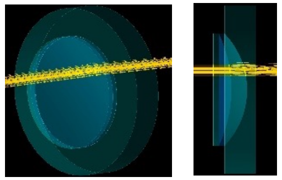
- Detailed scans of lens focusing properties with laser in optical lab at ODU

Radiation-hard 3-layer lens prototypes

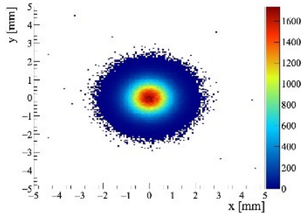




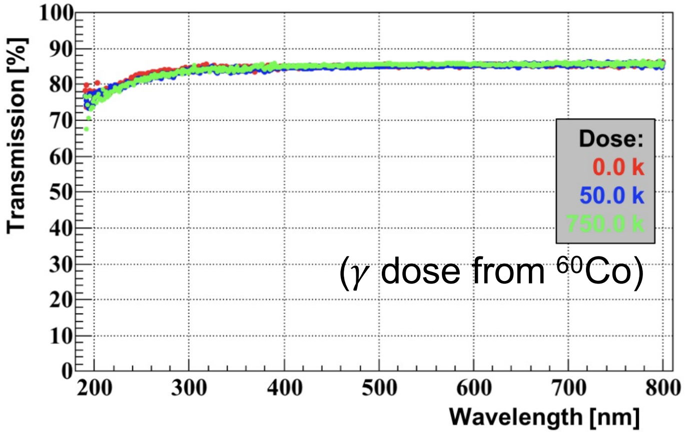
Close collaboration with Prof. Charles I. Sukenik (ODU)



Geant4 simulation



Radiation hardness of sapphire



Remaining Studies

Validation of the BaBar DIRC bar reuse:

- BaBar bar box transfer from SLAC to JLab and disassembly
- Validation of mechanical and optical bar quality in QA laser setup

hpDIRC studies in simulation:

- Study of the hpDIRC performance with background

Evaluating components and prototypes in DIRC labs (ODU, JLab, GSI, BNL)

hpDIRC prototype program:

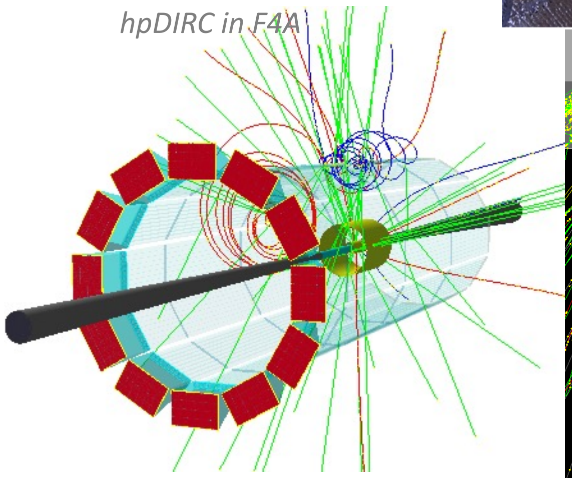
- Modular hpDIRC prototype in Cosmic Ray Telescope at SBU
- Incremental hpDIRC optical components integration and evaluation
- Adaptation and evaluation of sensors and readout electronics in hpDIRC prototype

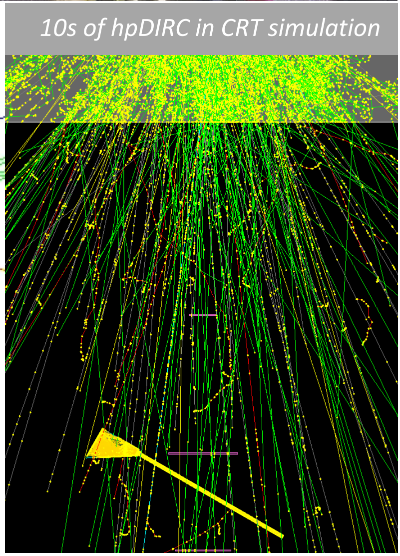
Generic DIRC R&D explores innovate optical DIRC configurations to create opportunities for cost reduction, performance improvement, and complementarity

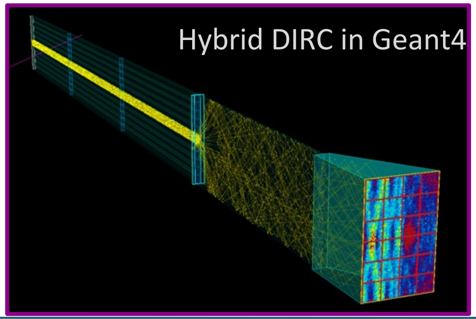
BaBar DIRC bars

DIRC barboxes in SLAC

hpDIRC in F4A





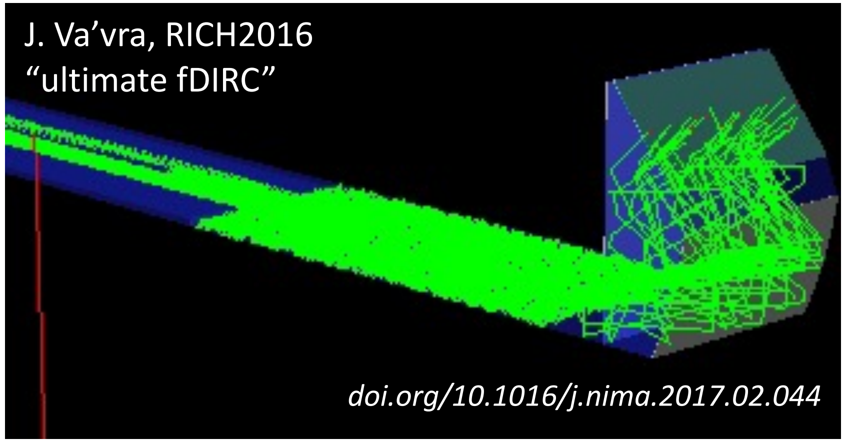


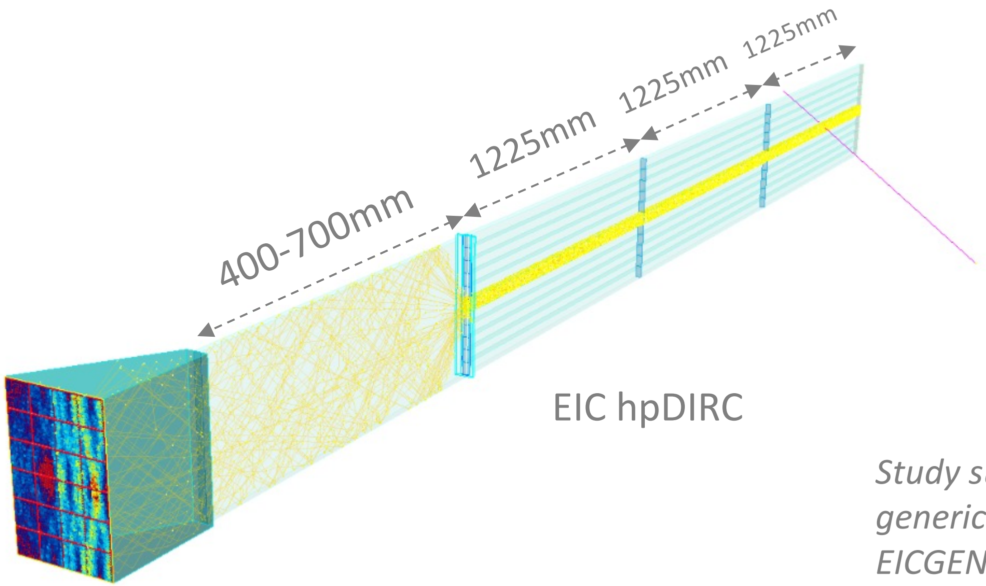
DIRC lab/CRT space at SBU

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

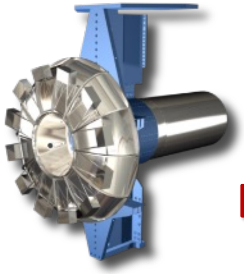




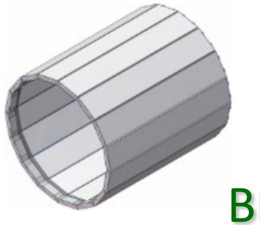
Study supported via generic R&D as EICGENRandD2022_12

GEANT4 visualization of hybrid of bars and plate in each sector

Barrel DIRC Overview

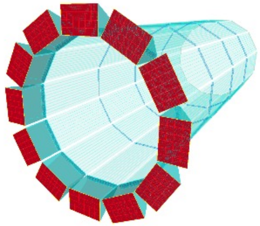


BaBar DIRC



Belle II TOP

PANDA Barrel DIRC



EPIC hpDIRC *

	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)*	488cm *(3×122.5 + 1x90.5)*
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)	TDR in 2017	TDR-ready in 2024

**Preliminary design*