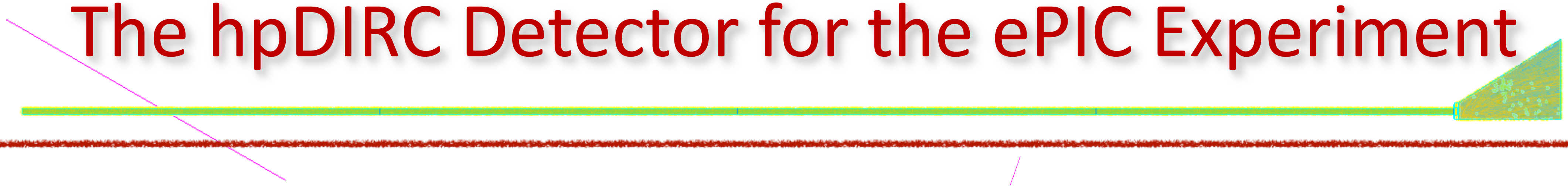
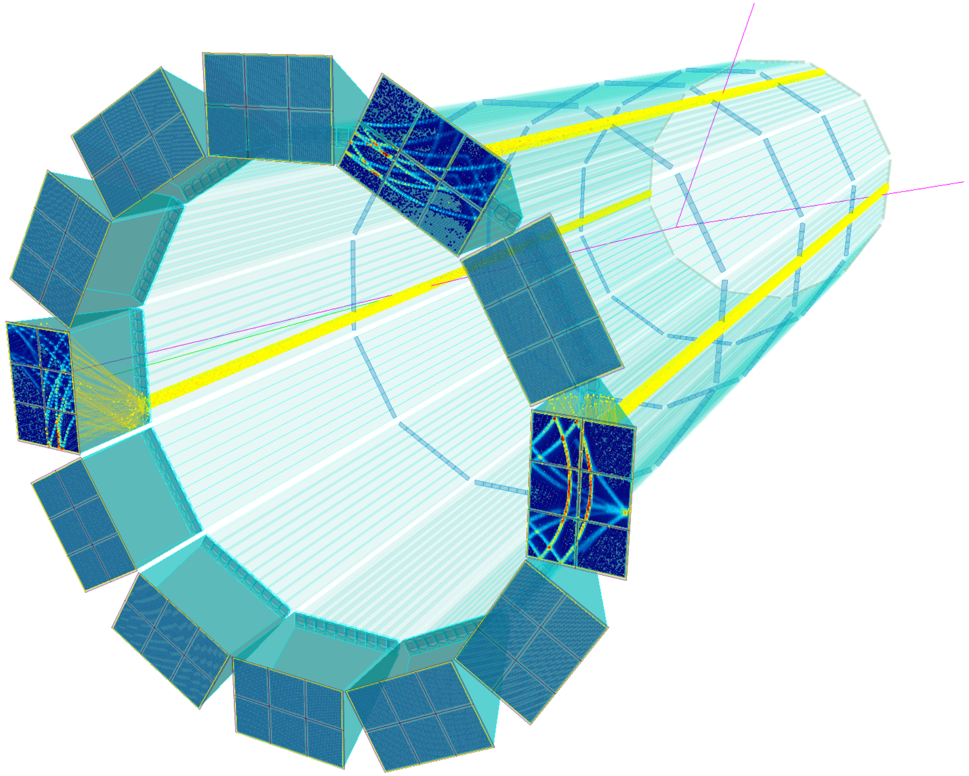
The hpDIRC Detector for the ePIC Experiment





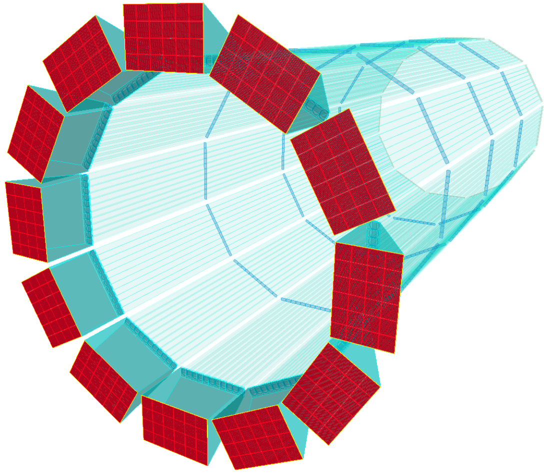
Greg Kalicy CUA

EIC Project PID Review

July 5th, 2023

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

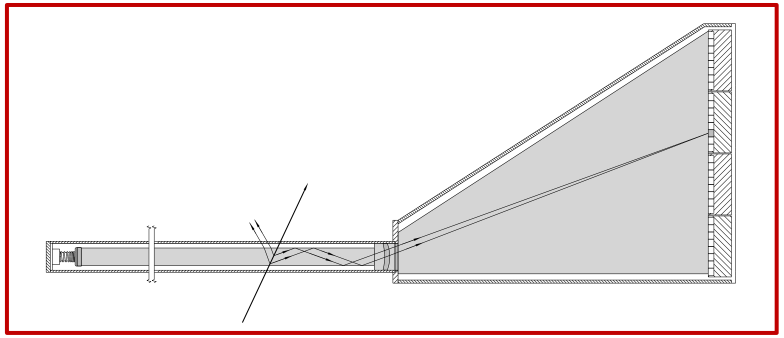
EXECUTIVE SUMMARY

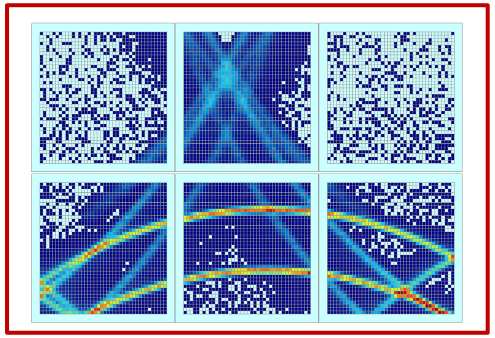


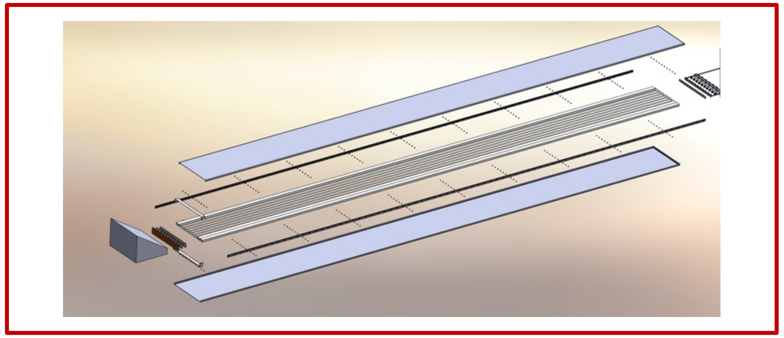
- The hpDIRC has been selected for the barrel PID of the EIC ePIC Detector
- Expected PID performance meets ePIC requirements (Yellow Report), separation: 3 ≥ s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
- Key elements, simulation and focusing lenses, validated in particle beams in 2018
- Main 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
- No challenges expected for ES&H and QA
- hpDIRC DSC includes eight institutions with well-established expertise and interest in work packages
- Plans for remaining studies, QA, and construction match project schedule

OUTLINE

- Introduction………………………………………………………………… Charge Question 1
  - ePIC requirements for hadronic barrel PID
  - DIRC principle
- High-performance DIRC for ePIC……………………………… Charge Question 1, 2, 3
  - R&D milestones
  - Preliminary design
  - Simulation and expected performance
  - Validation with prototype in particle beams
- Main components……………………………………………………… Charge Question 3, 4
  - Specifications, validation plans
- Mechanical design and detector integration……………… Charge Question 5
- ES&H and QA…………………………………………………………… Charge Question 6
- Detector system collaboration and work packages…… Charge Question 4
- Schedule……………………………………………………………………… Charge Question 4





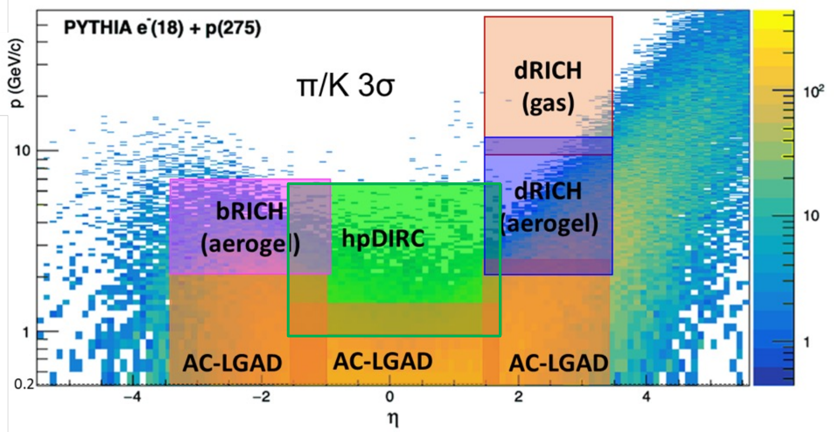


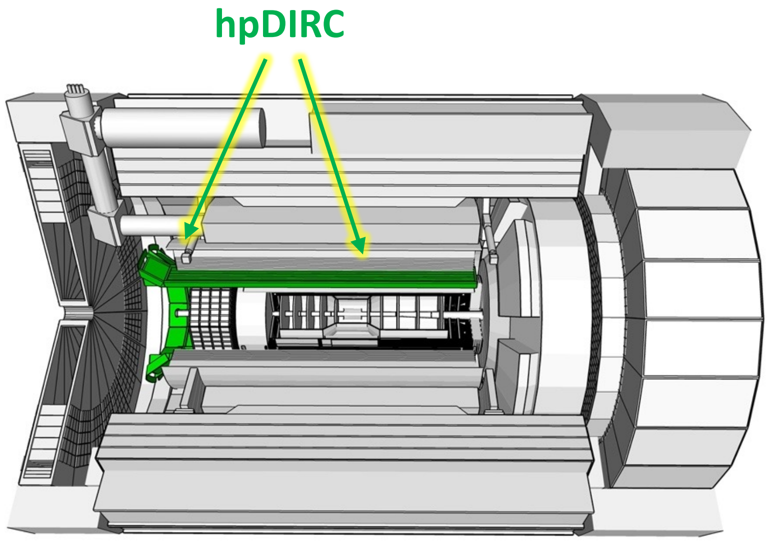
CHARGED PID REQUIREMENTS IN EPIC

Charge Question 1
Performance requirement definition

- EIC physics requires clean and efficient PID over a wide angular range
- Hadronic PID required to separate:
  - Electrons from charged hadrons -> electron ID mostly provided by calorimeters, supplemented for lower momenta by DIRC/RICH detectors
  - Charged pions, kaons, and protons from each other
- Requirements for barrel PID ($-1 \leq \eta \leq +1$):
  - Main separation power requirement: ≥ 3 s.d. π/K up to 6 GeV/c
  - System needs to be radially compact (impact on cost of outer systems)
  - Design needs to be flexible (sensor in B-field and detector integration)
  - Low demand on detector services (simplified integration and operation)

Summary of π/K PID requirements in ePIC



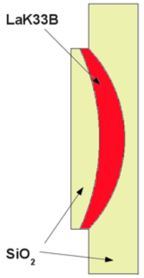


3D model of ePIC central detector

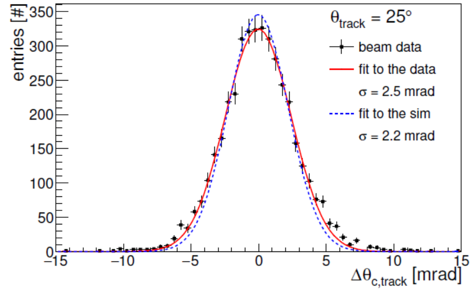
HIGH-PERFORMANCE DIRC R&D

- 10+ years ago: DIRC good candidate for hadronic particle in EIC detector barrel – if π/K momentum coverage achieved by BaBar DIRC is increased by 50%
- R&D for a high-performance EIC DIRC started in 2011 (synergetic with PANDA DIRC) *(Funded by DOE/BNL/JLab as RD2011-3, eRD4, eRD14, eRD103, EICGENRandD2022_12)*
- EIC DIRC R&D Milestones:
  - 2012: First multi-layer high-refractive index lens concept to avoid photon loss at air gaps
  - 2012: First 2-layer and 3-layer prototype lenses produced by industry
  - 2014: Simulation showed that lens-based design is expected to reach 1mrad Cherenkov angle resolution, equivalent to 3 s.d. π/K separation at 6 GeV/c
  - 2015: First successful CERN beam test with muti-layer spherical lens
  - 2017: Identified sapphire and PbF_2 as radiation-hard material candidates for lenses
  - 2018: Validated 3-layer spherical lens performance and Geant4 simulation with PANDA DIRC prototype with particle beam at CERN
  - 2019: First radiation-hard lens prototypes fabricated by industry
- hpDIRC selected as barrel PID solution for EIC detector in 2022

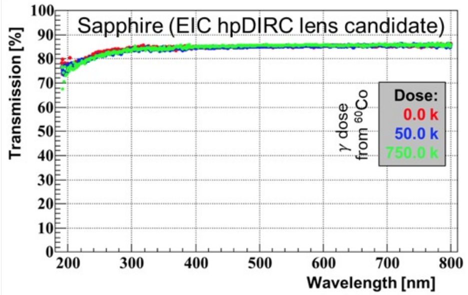
Initial 3-layer lens concept



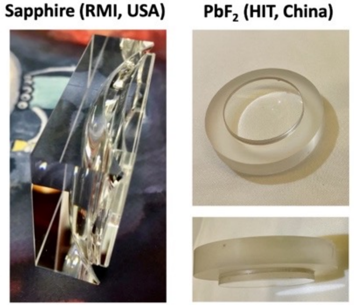
Cherenkov angle per particle, CERN 2015



radiation hardness of sapphire



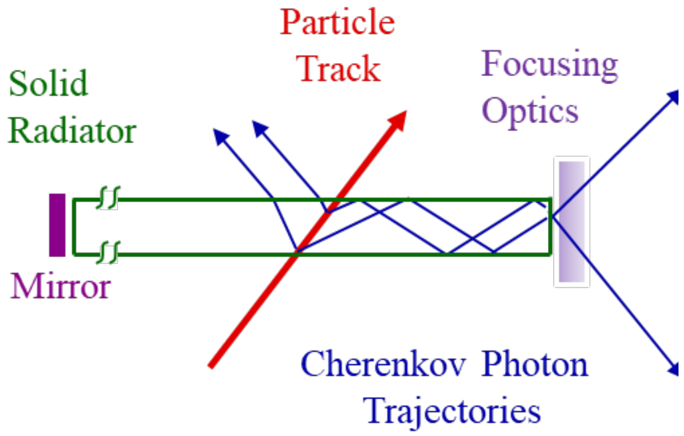
radiation hard lens prototypes



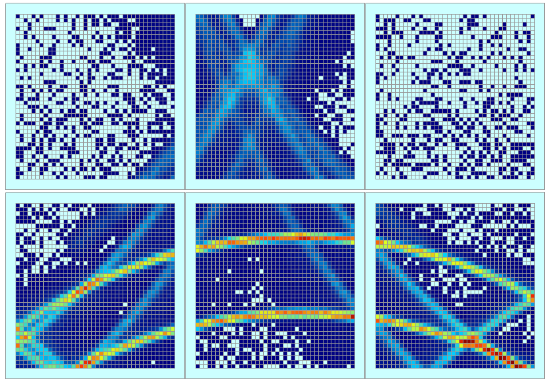
DIRC CONCEPT

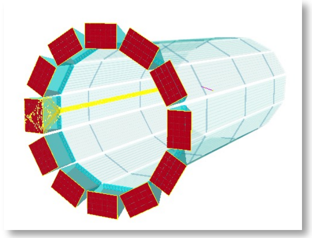
Detection of Internally Reflected Cherenkov Light

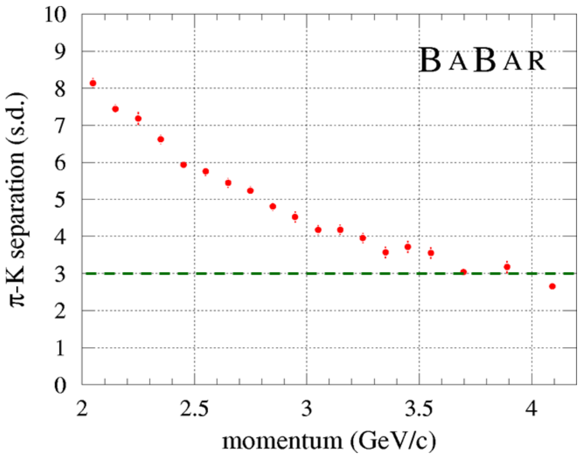
- Pioneered by the BaBar experiment
  at the SLAC National Accelerator Laboratory
- Fused silica bars or plates used as radiator and light guide
- Detector surface is outside active volume
- Cherenkov angle is conserved during internal reflections
  and reconstructed from detected photons
- Ultimate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



Accumulated ePIC
hpDIRC hit pattern
(Geant4)

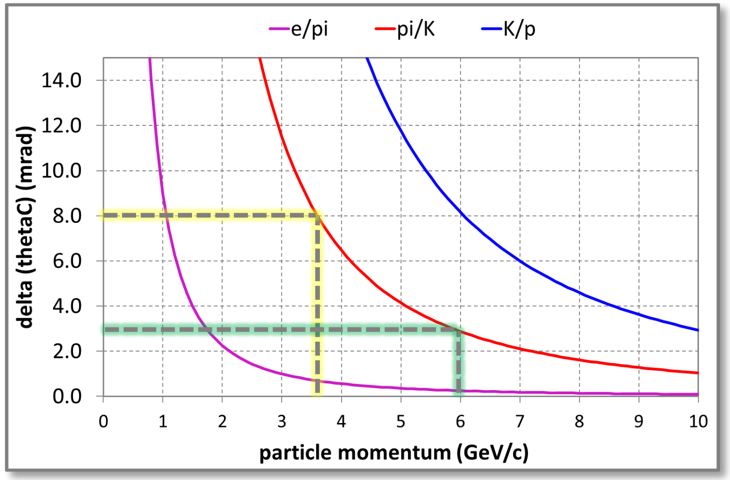






ADVANCING DIRC PERFORMANCE

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 $\sigma_{\theta_c}(photon) = 9.6\ \mathrm{mrad}$

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

SUPERB, BELLE II,
PANDA & EIC

HIGH-PERFORMANCE DIRC OVERVIEW

Charge Question 3
Detector and readout design

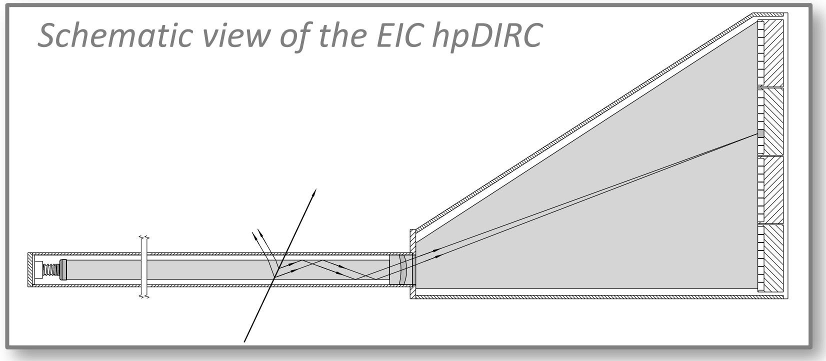
- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation
- legacy components (?)

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

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

  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

HPDIRC PRELIMINARY BASELINE DESIGN

Charge Question 3
Detector and readout 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:

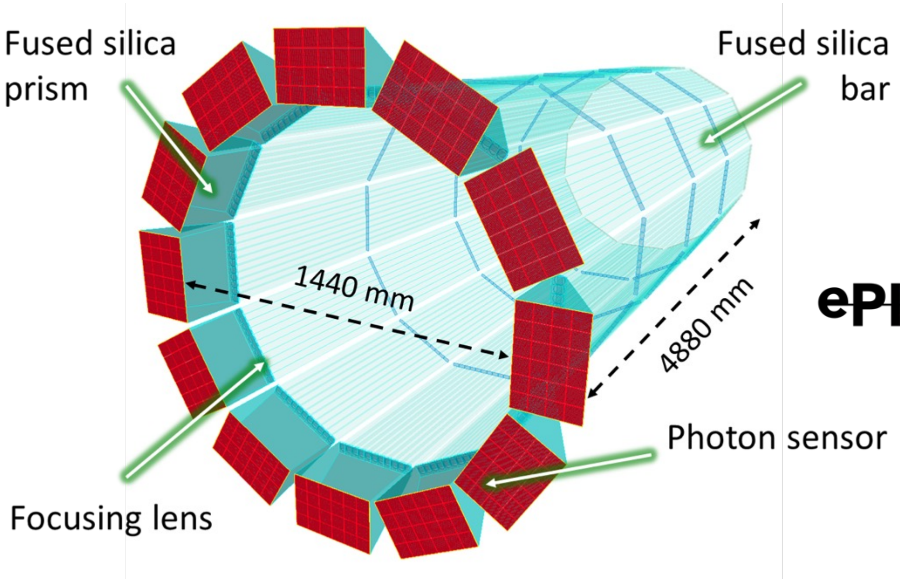
- Radiation-hard 3-layer spherical lens (sapphire or PbF_2)

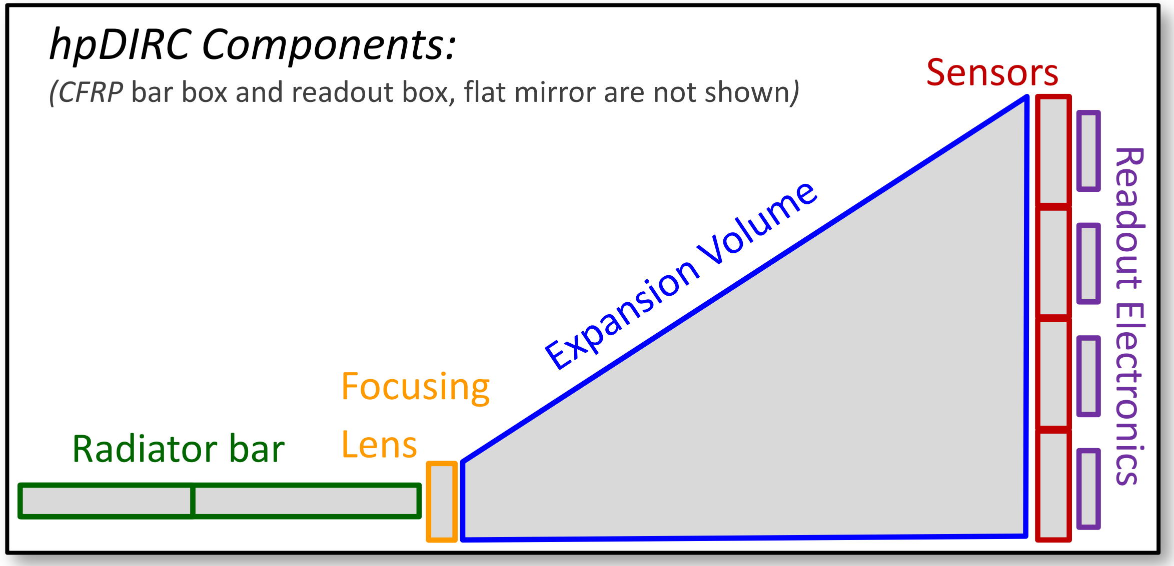
Expansion volume:

- 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)



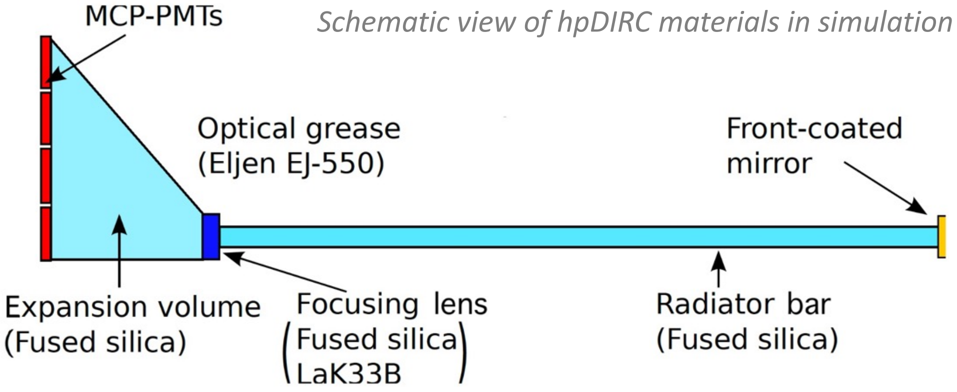


HPDIRC SIMULATION

Stand-alone Geant4 Simulation

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

Schematic view of hpDIRC materials in simulation

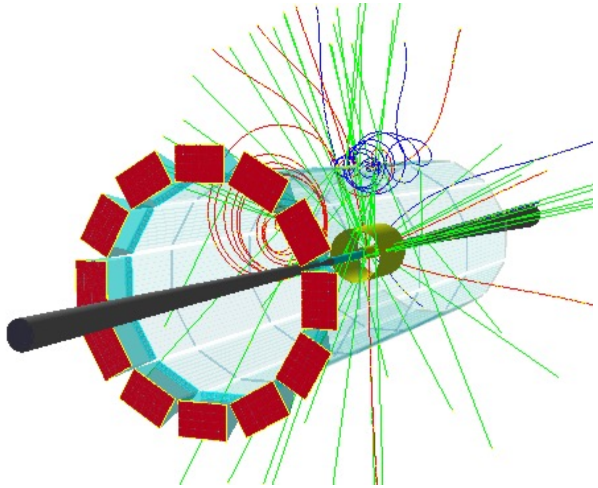


Full ePIC Simulation:

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

Reconstruction and PID methods:

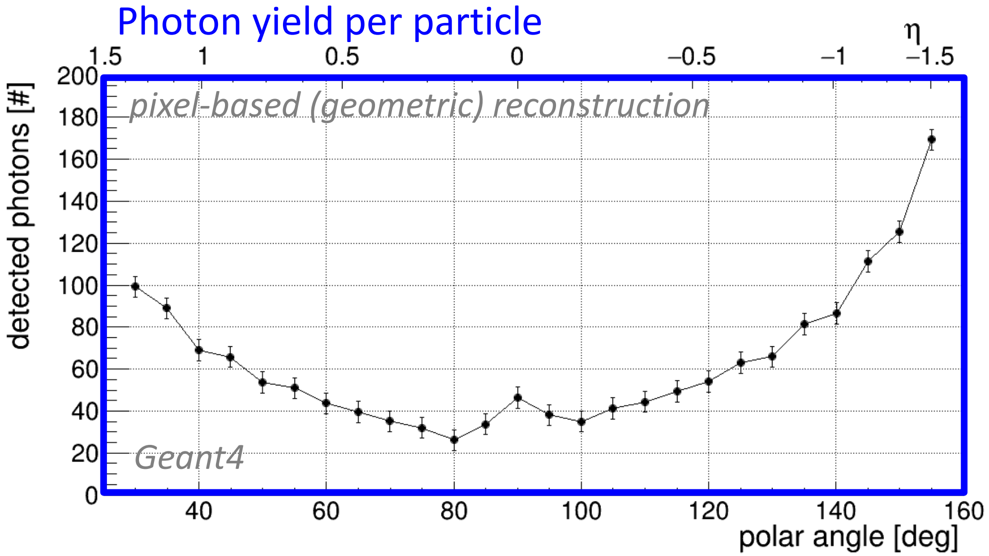
- Geometrical (BABAR-like), robust and fast method based on Look-Up Tables, delivers Cherenkov angle per particle and Single Photon Resolution (useful for calibration and in prototype tests), does not depend on precise time measurement
- Time Imaging (Belle II TOP-like), uses Probability Density Functions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

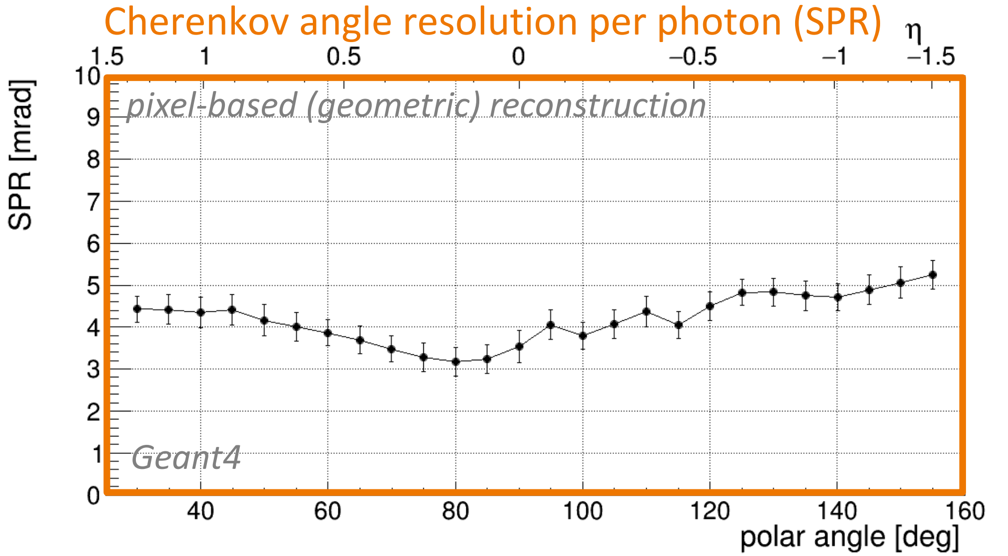


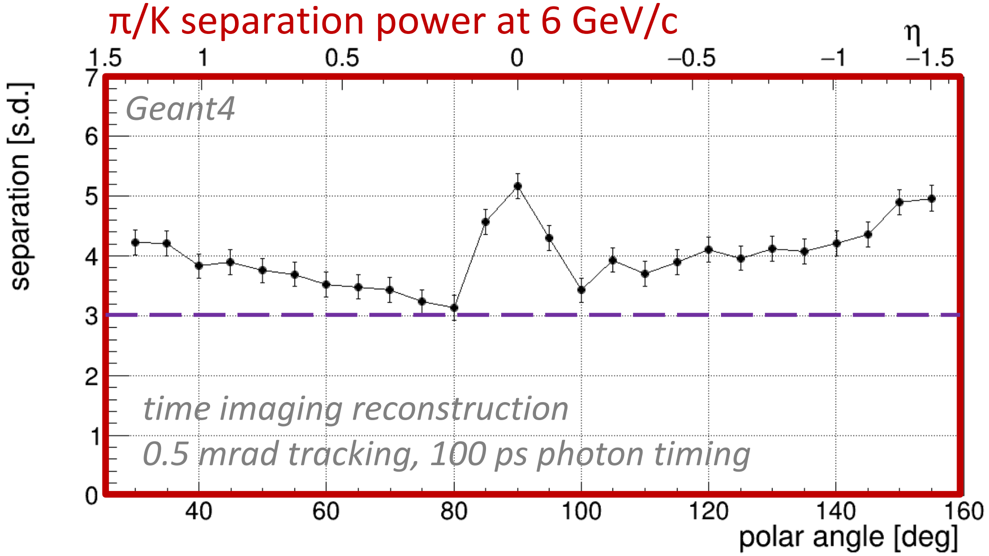
Event in full ePIC simulation

EXPECTED HPDIRC PERFORMANCE

Charge Question 2
Performance and construction plans







Simulation studies performed with

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

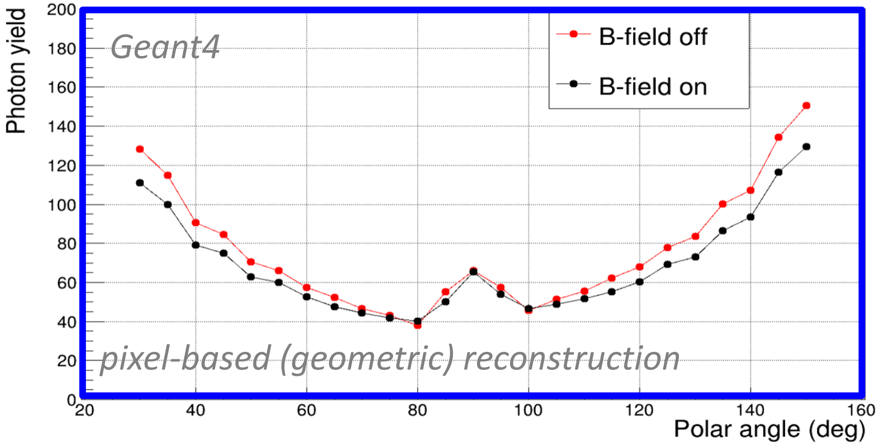
→ Performance requirements reached: ≥ 3 s.d. π/K separation at 6 GeV/c for all angles

Expected hpDIRC Performance vs. B Field

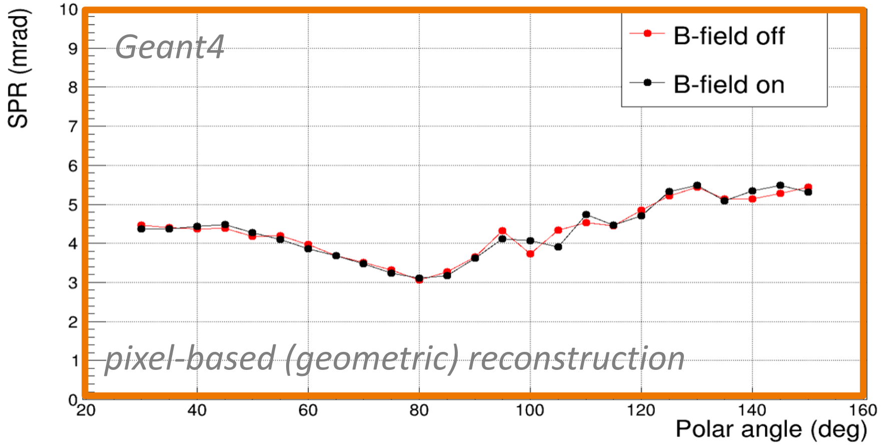
Charge Question 2
Performance and construction plans

Impact of magnetic field on hpDIRC performance

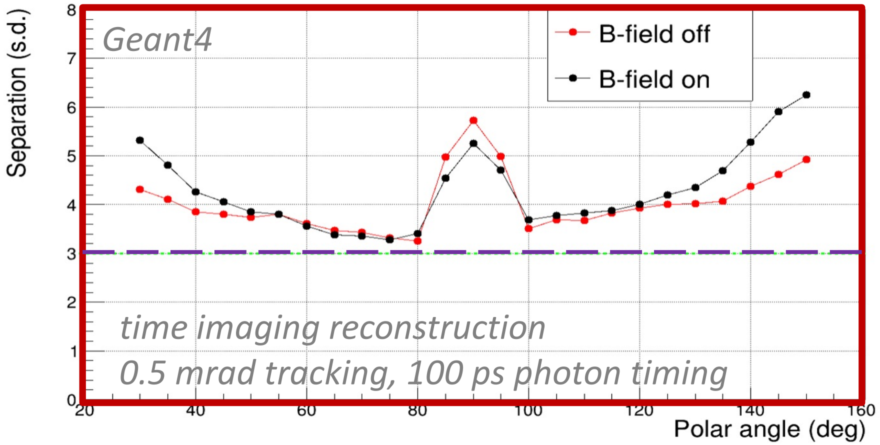
Photon yield per particle



Cherenkov angle resolution per photon (SPR)



π/K separation power at 6 GeV/c



Simulation studies performed with

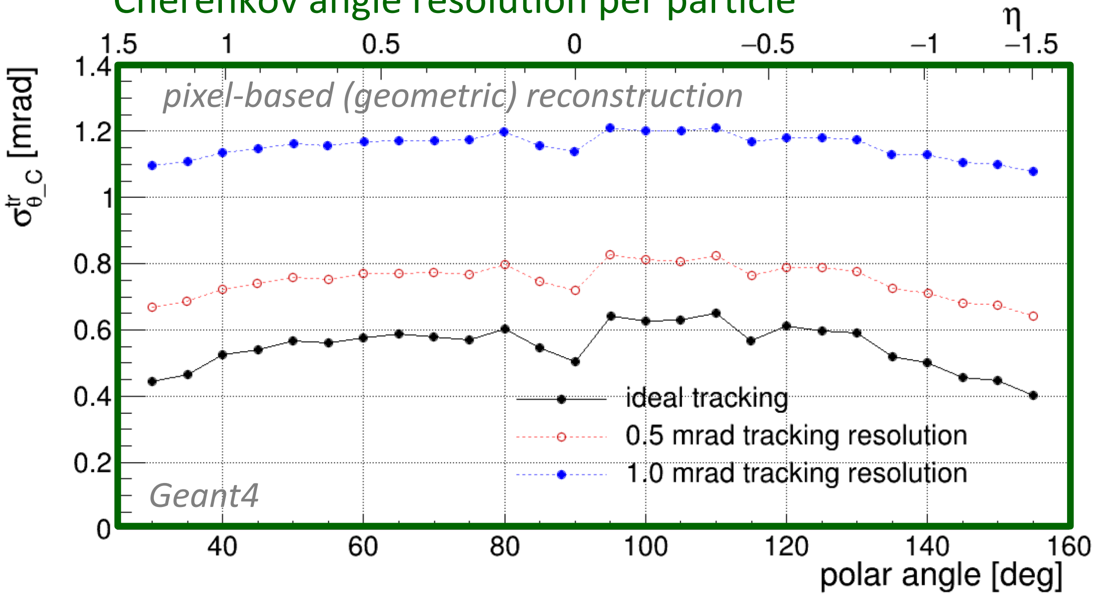
- ePIC software framework Fun4All (Geant4)
- Single particles from particle gun
- 6 GeV/c momentum
- MARCO: 1.7 T magnetic field

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

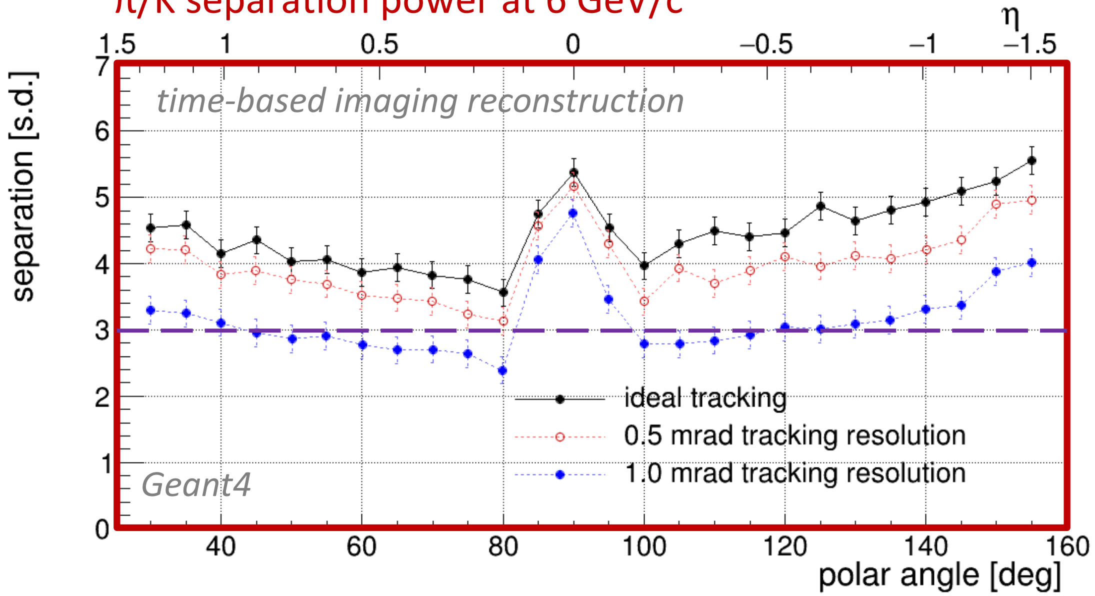
Expected hpDIRC Performance vs. Tracking

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

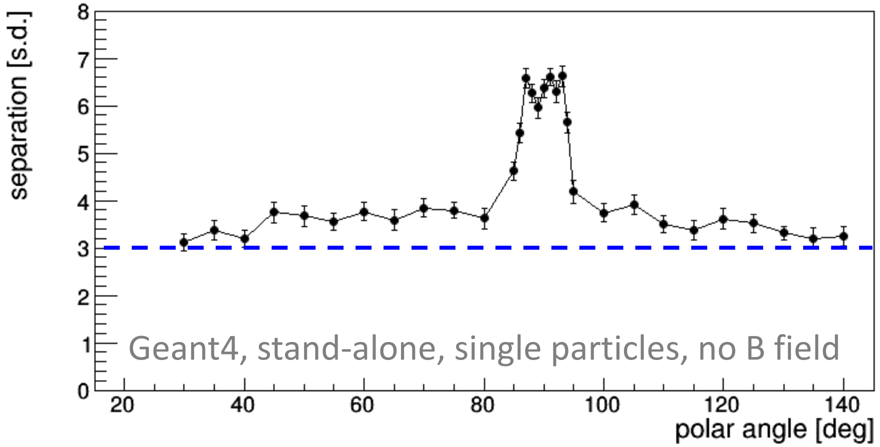
→ High-precision angular resolution crucial for reaching required hpDIRC performance

EXPECTED HPDIRC PERFORMANCE

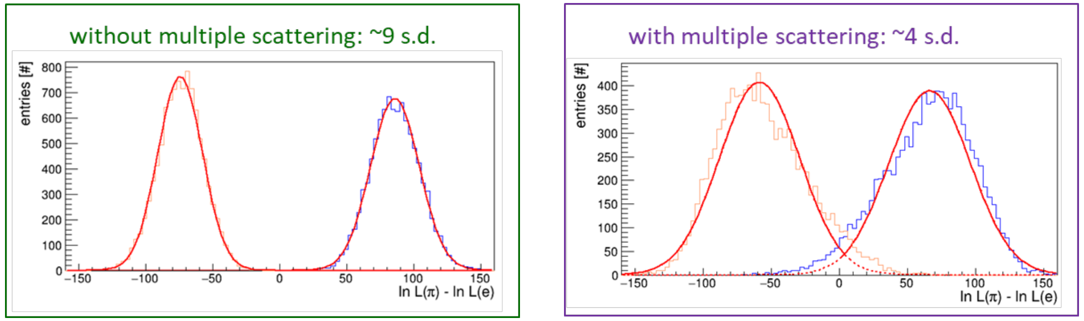
e/π separation at low momentum

- 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)

hpDIRC expected e/π separation at 1.2 GeV/c
without MS mitigation



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


without multiple scattering: ~9 s.d.

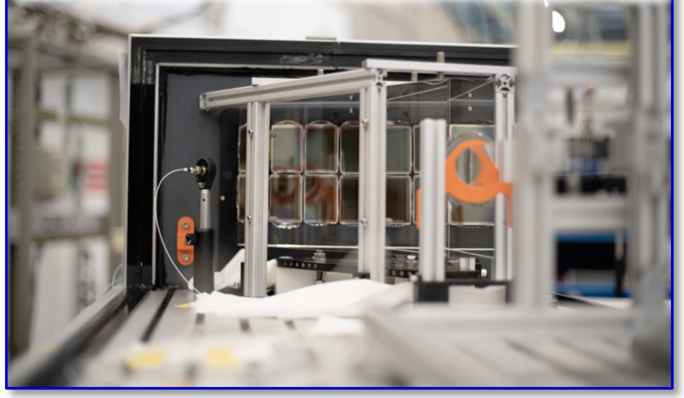
with multiple scattering: ~4 s.d.

VALIDATION OF SIMULATION AND COMPONENTS

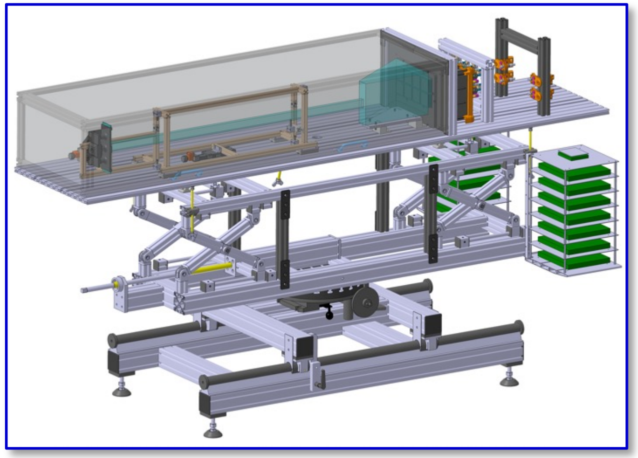
Performance validation: synergetic beam test with PANDA prototype at CERN PS in 2018

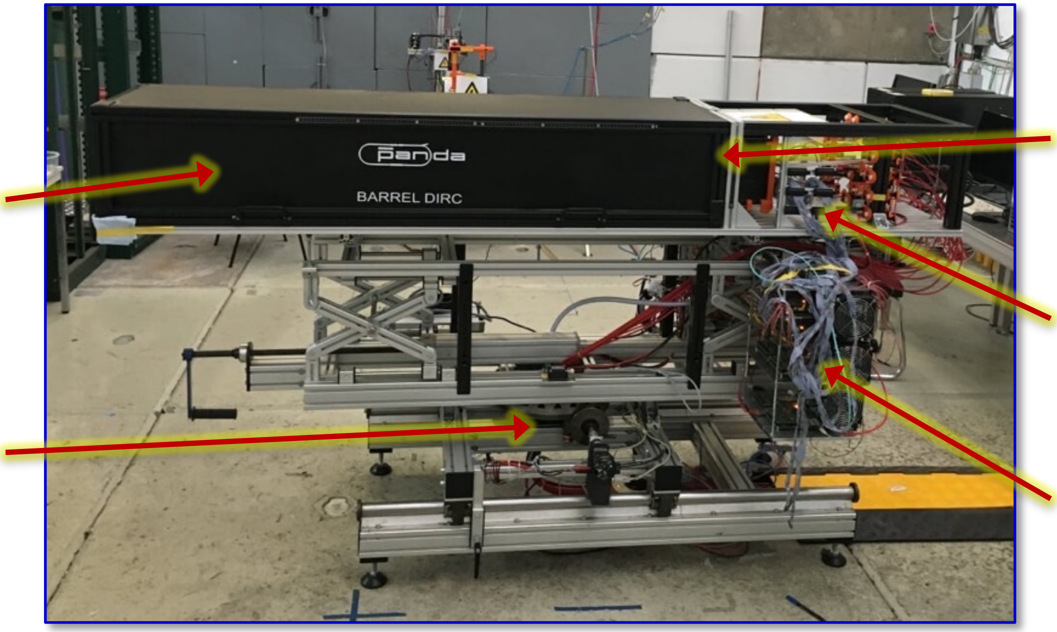
- Narrow fused silica bar, hpDIRC 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array (larger pixels, slower readout electronics than EIC)
- PiLas picosecond laser calibration system
- 7 GeV/c π/p beam equivalent to 3.5 GeV/c π/K
- MCP-TOF system to cleanly tag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

View from inside the Barrel DIRC dark box



Schematic view of 2018 prototype





Dark box for optics (bar, lens, prism)

Rotation stage (remote controlled)

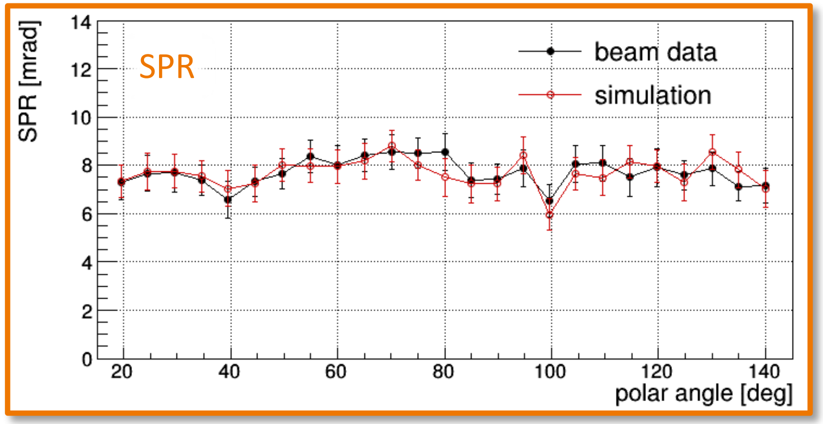
MCP-PMT array

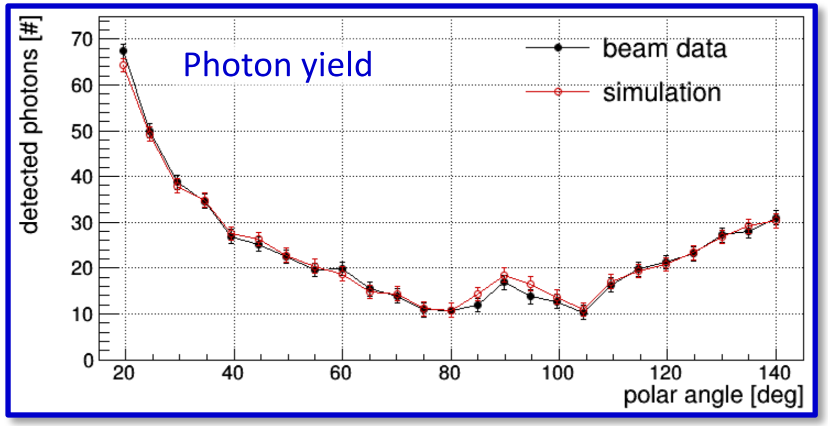
Frontend electronics (PADIWA) (air-cooled)

DAQ boards (TRB)

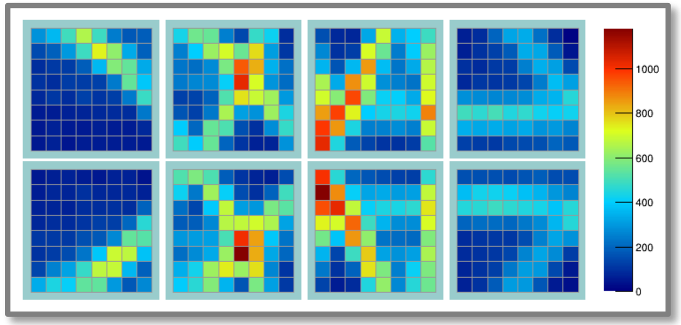
VALIDATION OF SIMULATION AND COMPONENTS

Performance validation: 2018 prototype at CERN PS

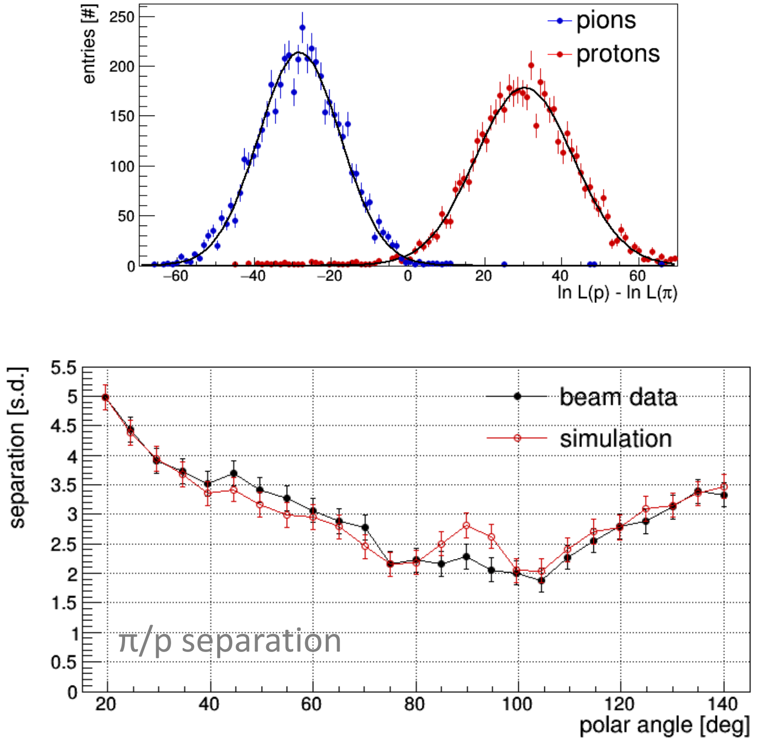




observed hit pattern at polar angle 20°



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

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:

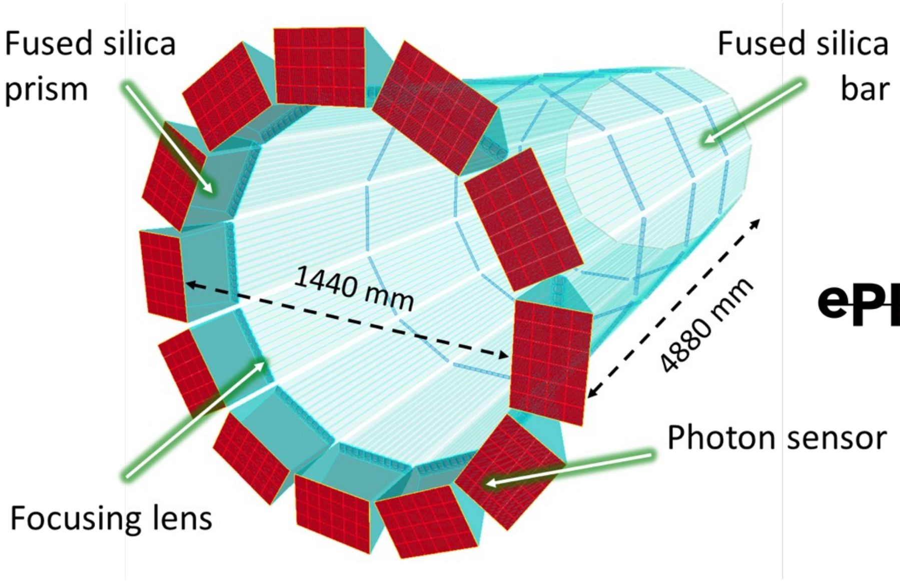
- Radiation-hard 3-layer spherical lens (sapphire or PbF_2)

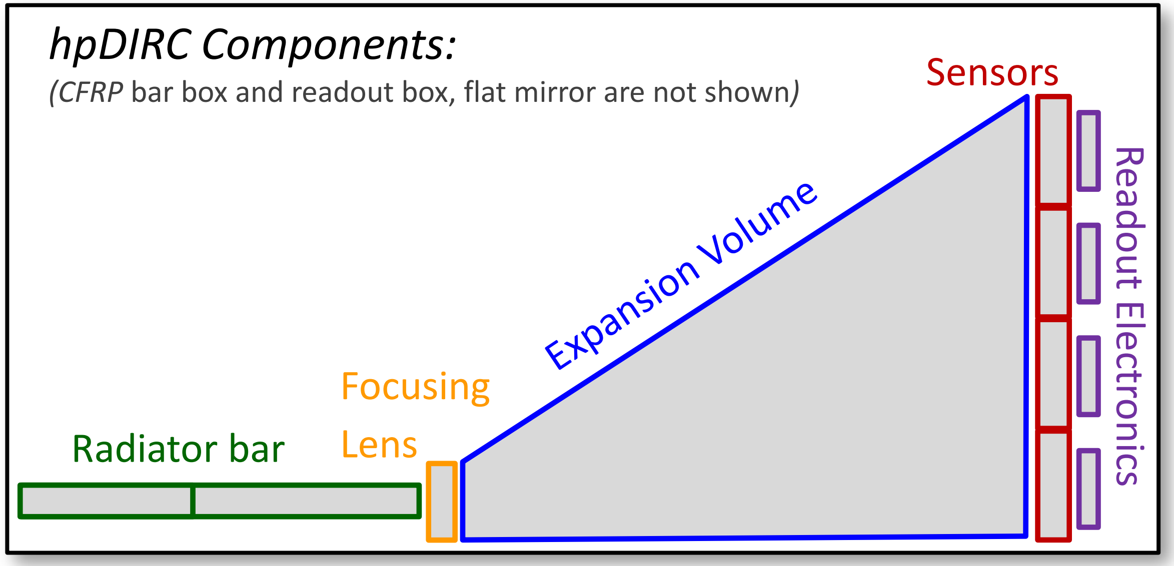
Expansion volume:

- 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:

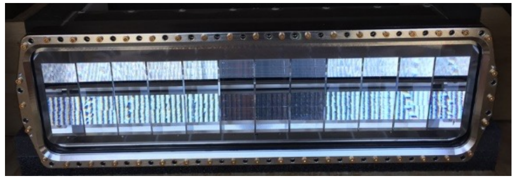
(CFRP bar box and readout box, flat mirror are not shown*)*

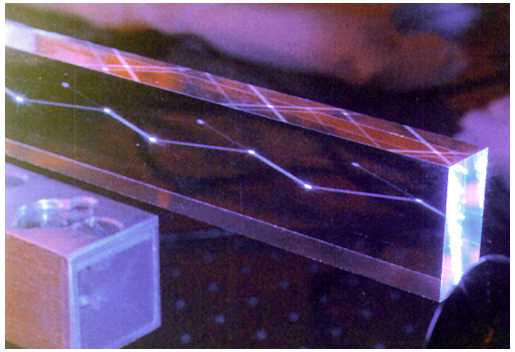
REUSE OF BABAR DIRC BARS

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 ≤ η ≤ +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, η ≤ -1.65, to couple to lenses
- Procure new bars from industry or disassemble the 4 bar boxes from GlueX?



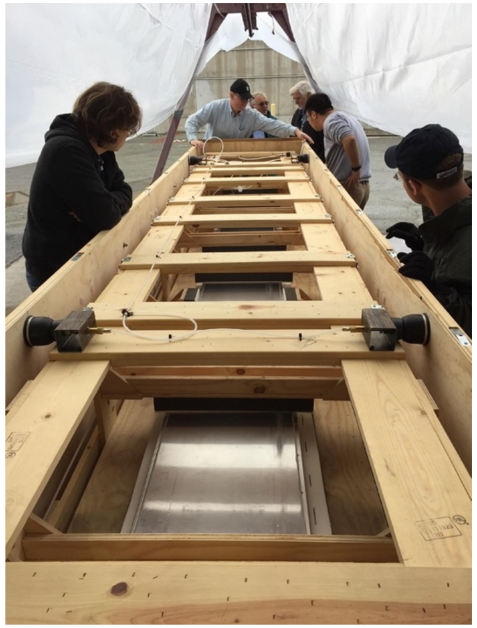


REUSE OF BABAR DIRC BARS

Charge Question 4
Fabrication and assembly plans

- 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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- Reflection coefficient measurement to evaluate surface quality

DIRC QA laser lab (completion date July)

DIRC labs under construction at JLab

REUSE OF BABAR DIRC BARS

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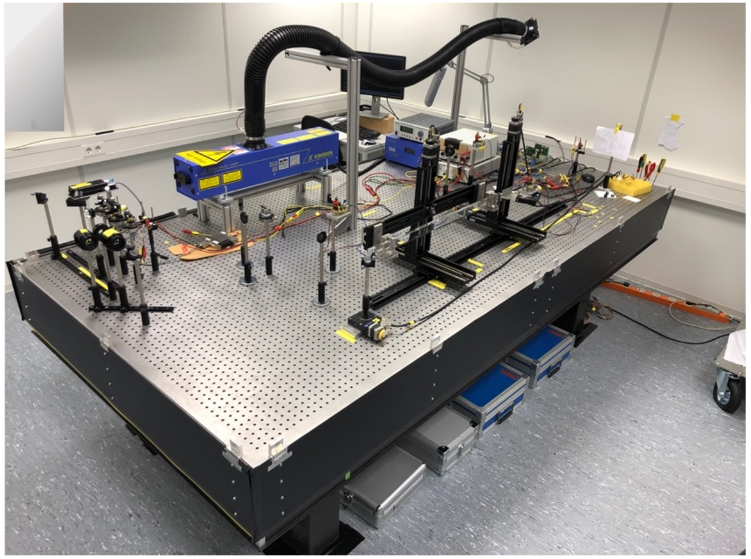
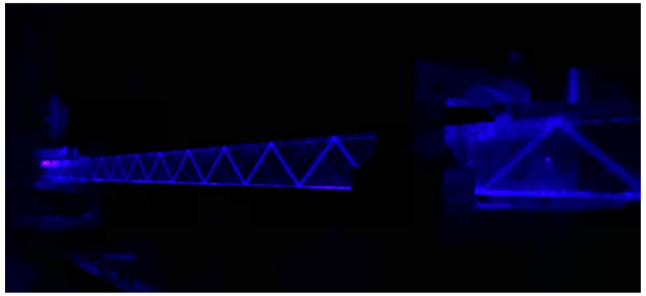
Laser lab at GSI



PANDA DIRC bar in GSI laser lab



FOCUSING OPTICS

Charge Question 4
Fabrication and assembly plans

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

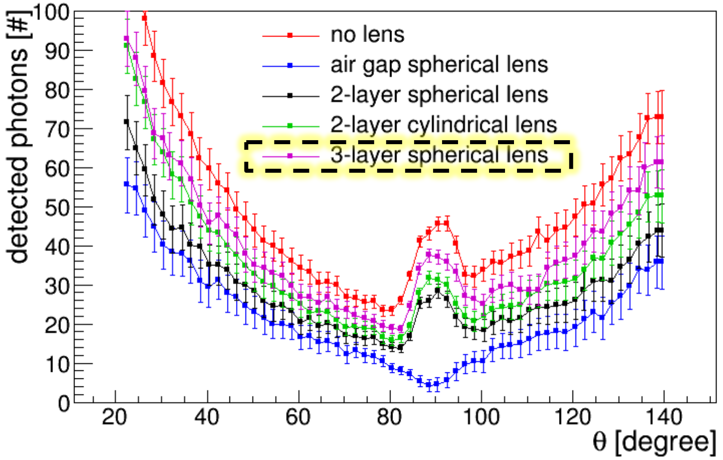
Innovative solution:

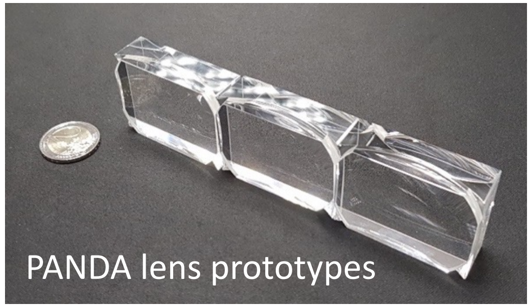
- 3-layer compound lens (without air gap):

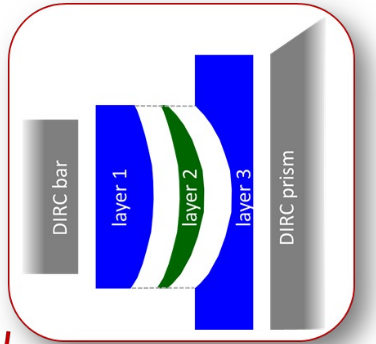
layer of high-refractive index material (focusing/defocusing)
sandwiched between two layers of fused silica

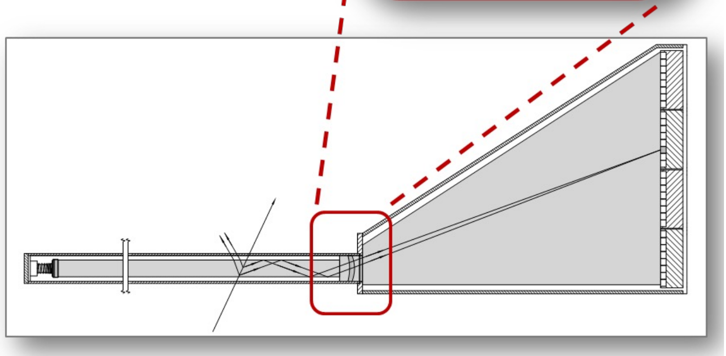
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Detailed radiation-hardness studies performed with ^{60}Co source, neutron irradiation next
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire or PbF_2 for EIC
- Industrial fabrication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

Geant4 simulation: photon yield




PANDA lens prototypes





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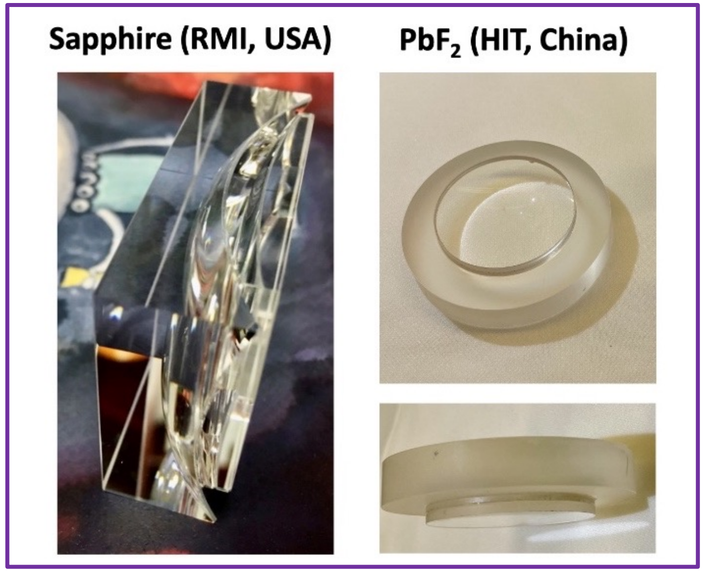
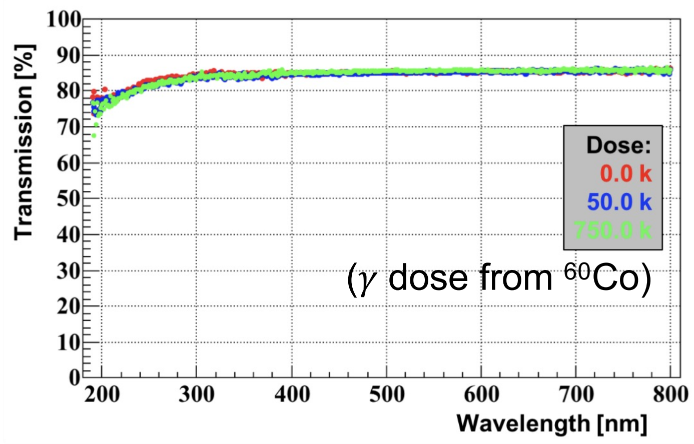
Radiation-hard 3-layer lens prototypes



Radiation hardness of sapphire

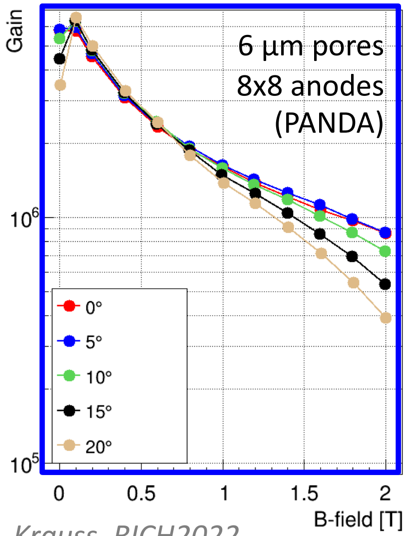


PHOTOSENSORS

hpDIRC sensor requirements

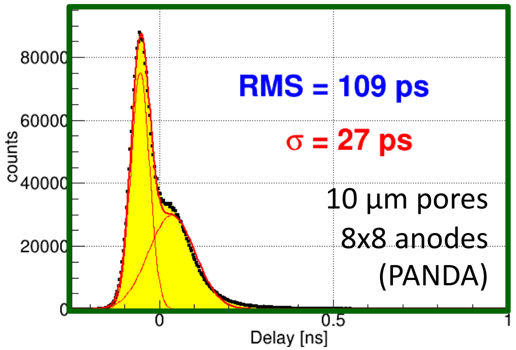
- Single photon sensitivity in ePIC magnetic field: 10^6 gain at ~ 1T
- Fast timing for single photons: timing precision (rms) < 100 ps
- Large active area ratio for tiled sensors: goal > 75%
- High PDE in visible range: goal > 25% at 400 nm
- Small pixels: anode pixel size < 3.5 mm
- Tolerance for high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

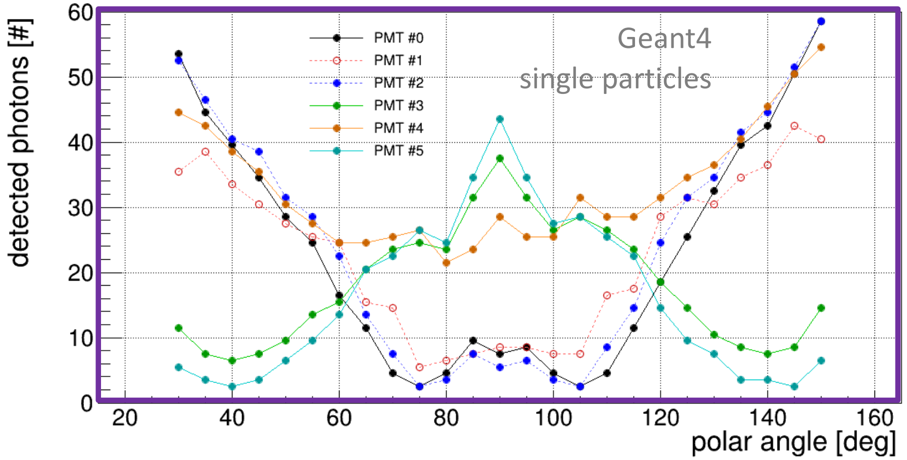


S. Krauss, RICH2022

PHOTONIS XP85012-S



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



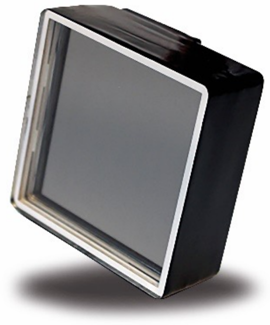
PHOTOSENSORS

Charge Question 3
Detector and readout design

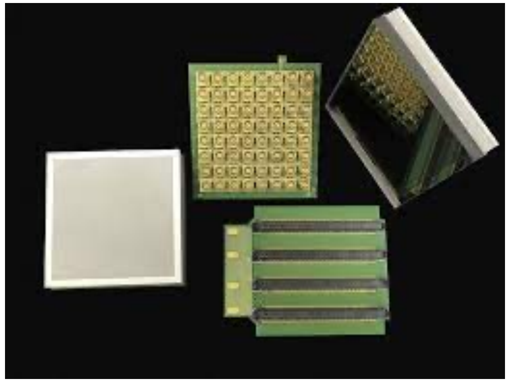
hpDIRC sensor: Microchannel-Plate PMT

- 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
    - See sensor and readout presentation tomorrow

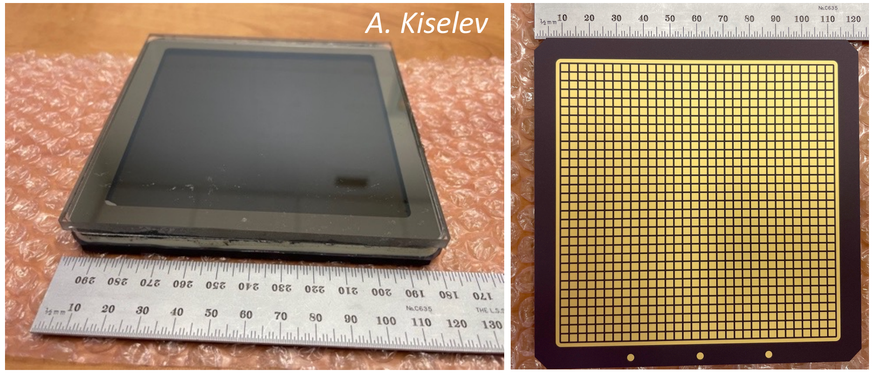
PHOTONIS XP85122-S



Photek MAPMT 253



INCOM Gen III HRPPD prototype (front/back view)



READOUT CHAIN

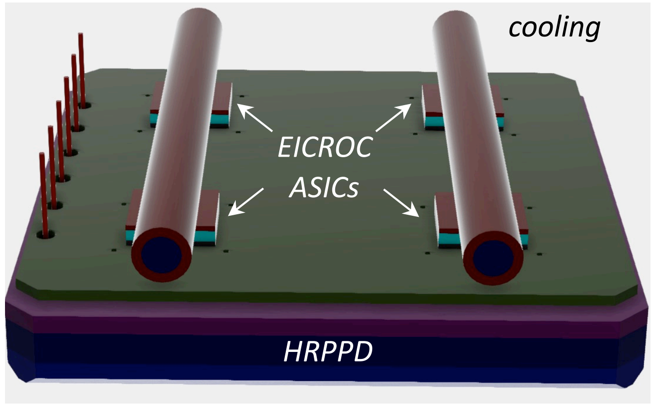
Charge Question 3
Detector and readout design

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

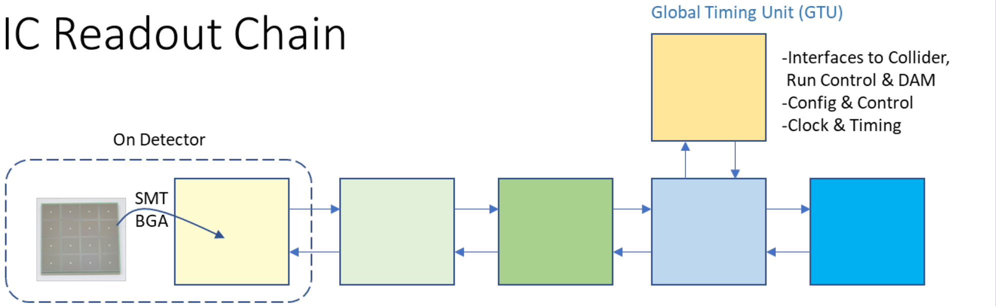
Baseline front-end board for hpDIRC: EICROC

- 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
    - See DAQ, sensor and, readout presentations tomorrow



A. Kiselev, preliminary

ePIC Readout Chain



Global Timing Unit (GTU):
-Interfaces to Collider, Run Control & DAM
-Config & Control
-Clock & Timing

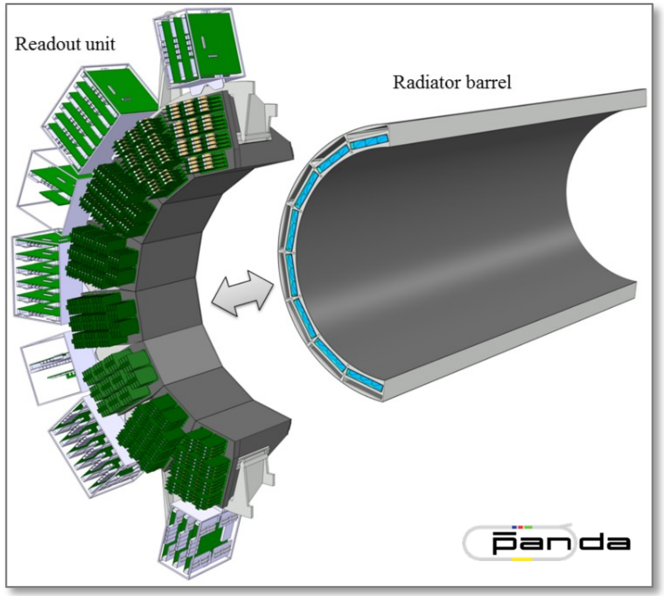
Name	Sensor	Adapter	Front End Board (FEB)	Readout Board (RDO)	Data Aggregation Module (DAM)	Computing
Design	**Detector Specific**	**Detector Specific**	**Detector Specific**	**Few Variants**	**Common**	**Common**
Function	-Multi-Channel Sensor	-HV/Bias Distribution -HV divider -Interconnect Routing	-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

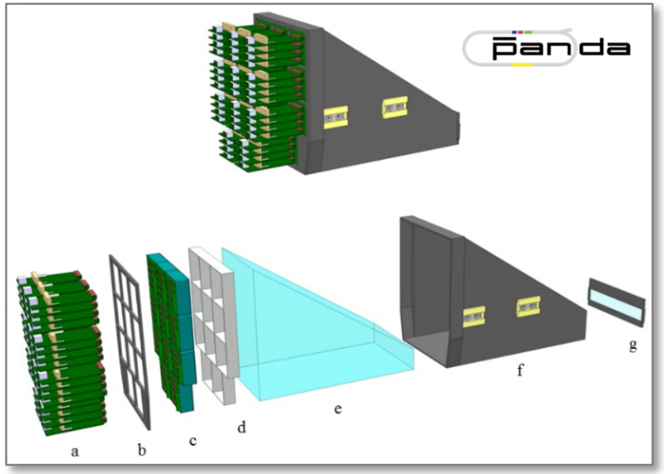
MECHANICAL SUPPORT AND INTEGRATION

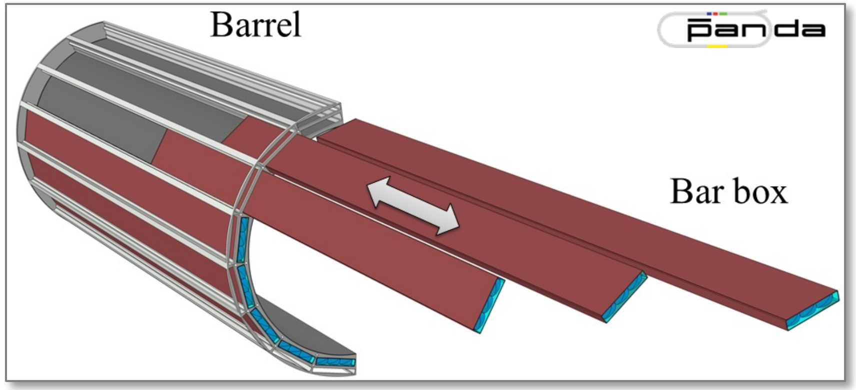
Charge Question 5
Detector integration plans

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)
- See separate presentation on ePIC Detector Integration Status and CAD Design







PANDA Barrel DIRC example of DIRC mechanical design

MECHANICAL SUPPORT AND INTEGRATION

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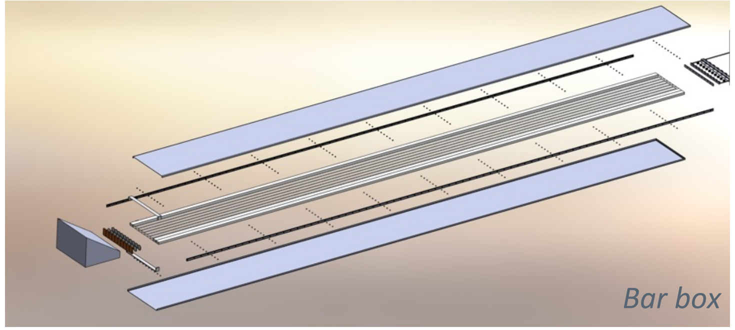
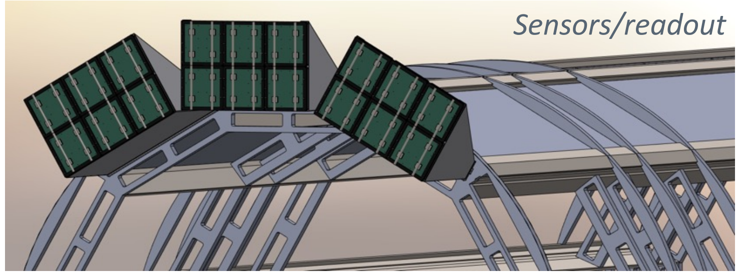
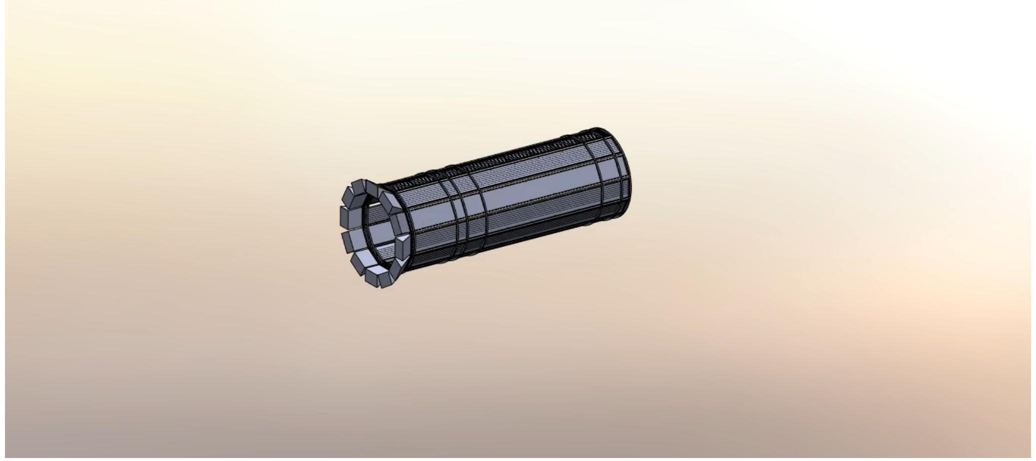
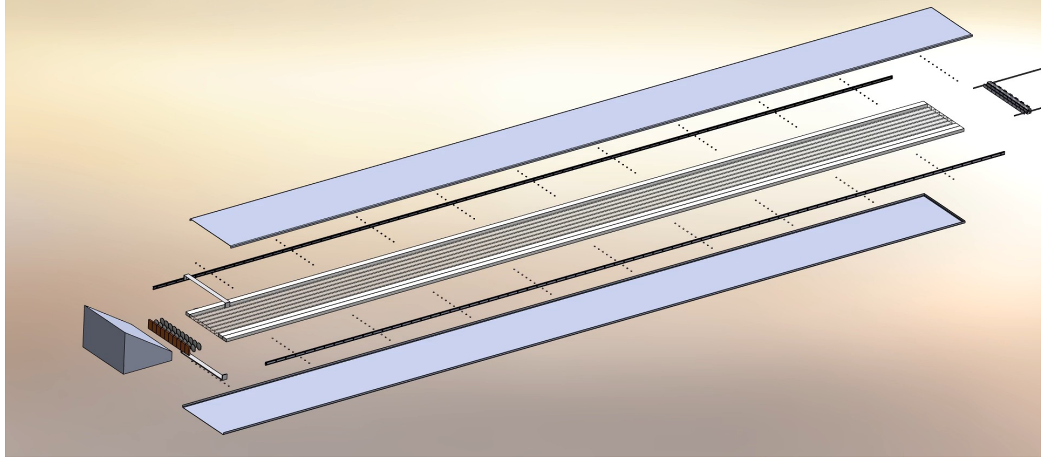
ePIC hpDIRC preliminary mechanical design







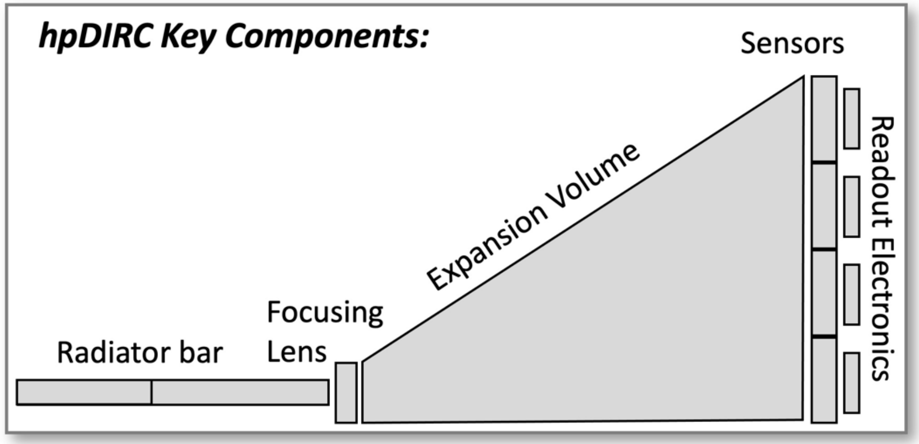


Two short MEC movies
(only in Powerpoint version)

ES&H

Charge Question 6
ES&H and QA

- The system does not use any flammable gases or cryogenic liquids
- The bar boxes and readout boxes will be purged by boil-off dry nitrogen at a flow rate of a few liters per hour per box
- Hazard: electrical shock
  Sensors require high voltages (up to 2.5 kV)
  → HV connections are not accessible in normal operation mode;
  HV module will be keyed off, operation only by trained personnel
- Hazard: laser radiation
  The hpDIRC will use a class 3B HeCd laser pulser to calibrate sensors and electronics
  → laser will be fully contained in optical fibers, operation only by trained personnel
- Hazard: chemical leak
  Readout electronics to be cooled by chilled liquid (details TBD)
  → Cooling liquid will circulate at sub-atmospheric pressure
- The hpDIRC system will comply with all applicable ES&D and OSHA regulations

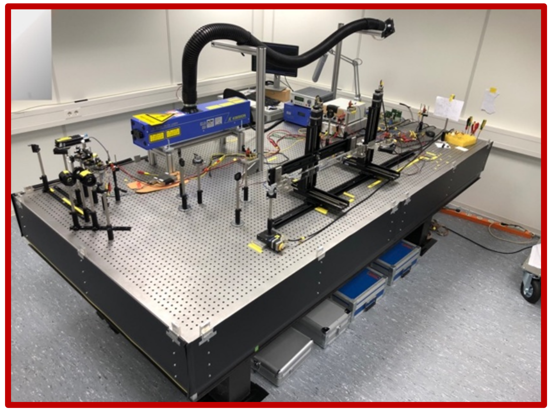


QA PLAN

Quality assurance plans for components and modules

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

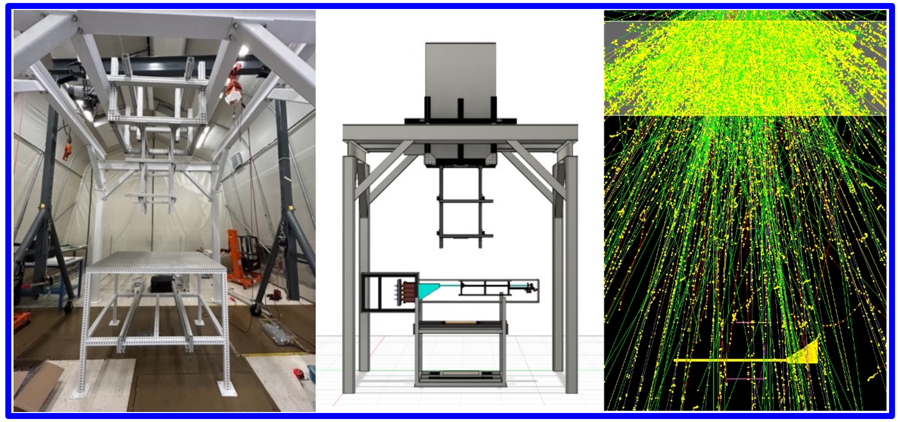
- Radiator bars and light guides: vendor QA for mechanical properties, laser scanning system at JLab to monitor internal photon transport efficiency of disassembled BaBar DIRC bars and/or new DIRC bars
- Sensors and electronics: laser pulser systems at CUA/JLab/USC (TBD) to measure gain, quantum and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

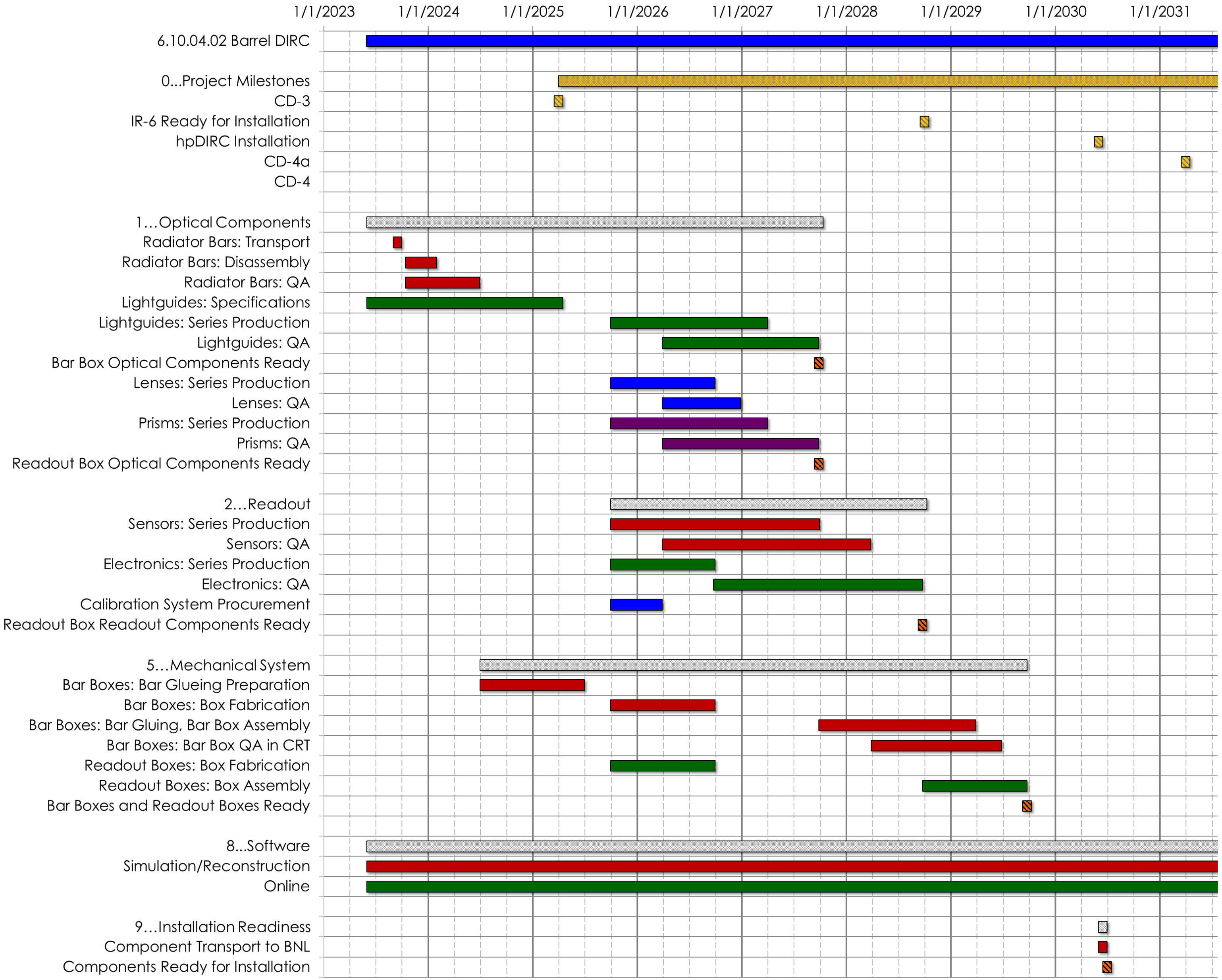
DIRC lab and Cosmic Ray setup at SBU (photo, CAD, Geant4)



SCHEDULE

Charge Question 4
Fabrication and assembly plans

- 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

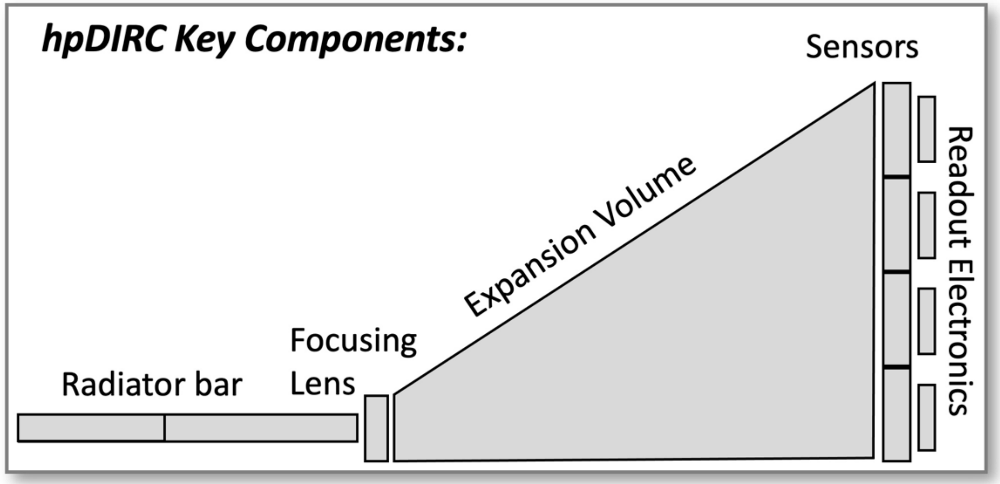
Charge Question 4
Fabrication and assembly plans

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

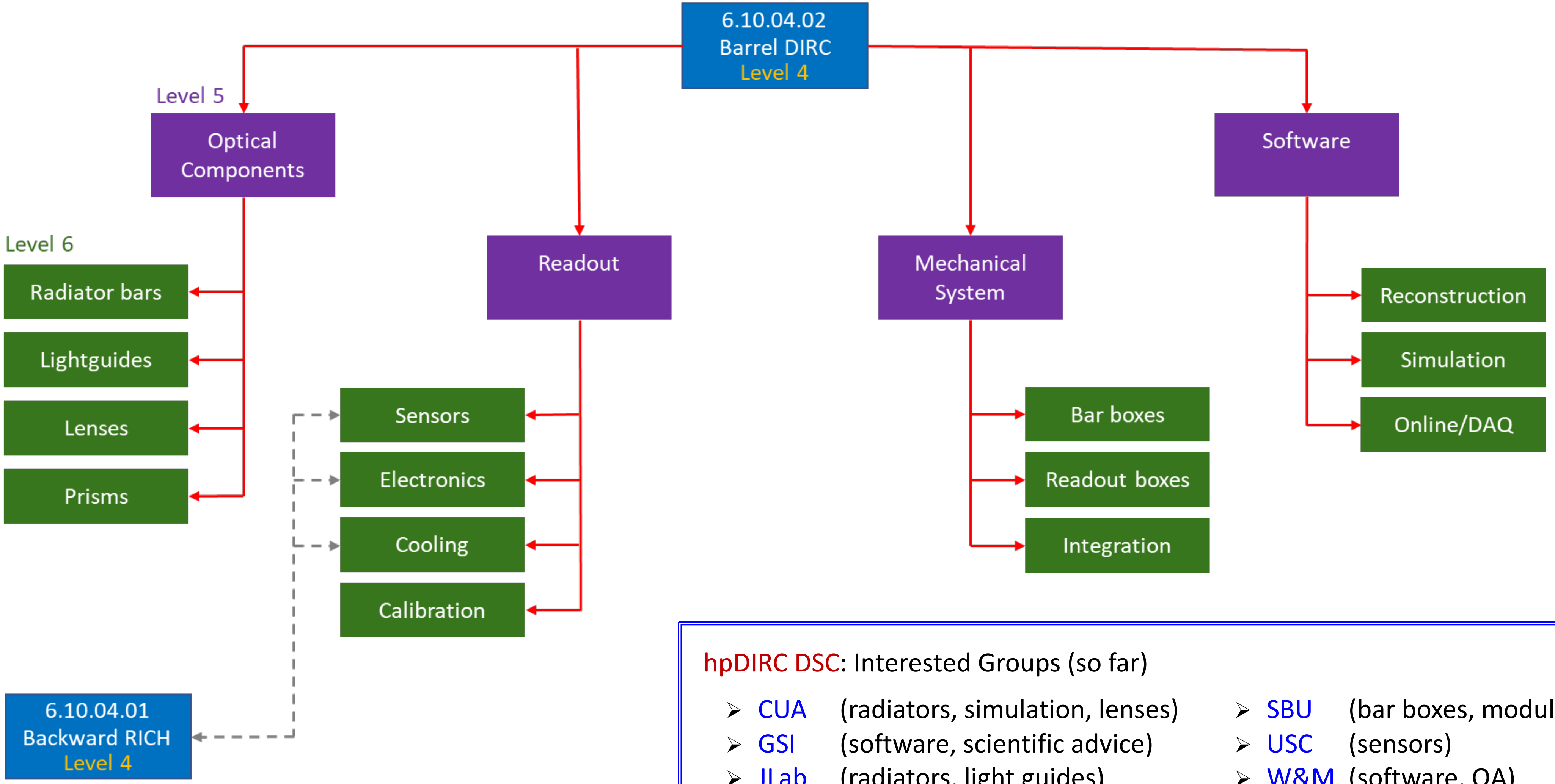
EoI examples:

- 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

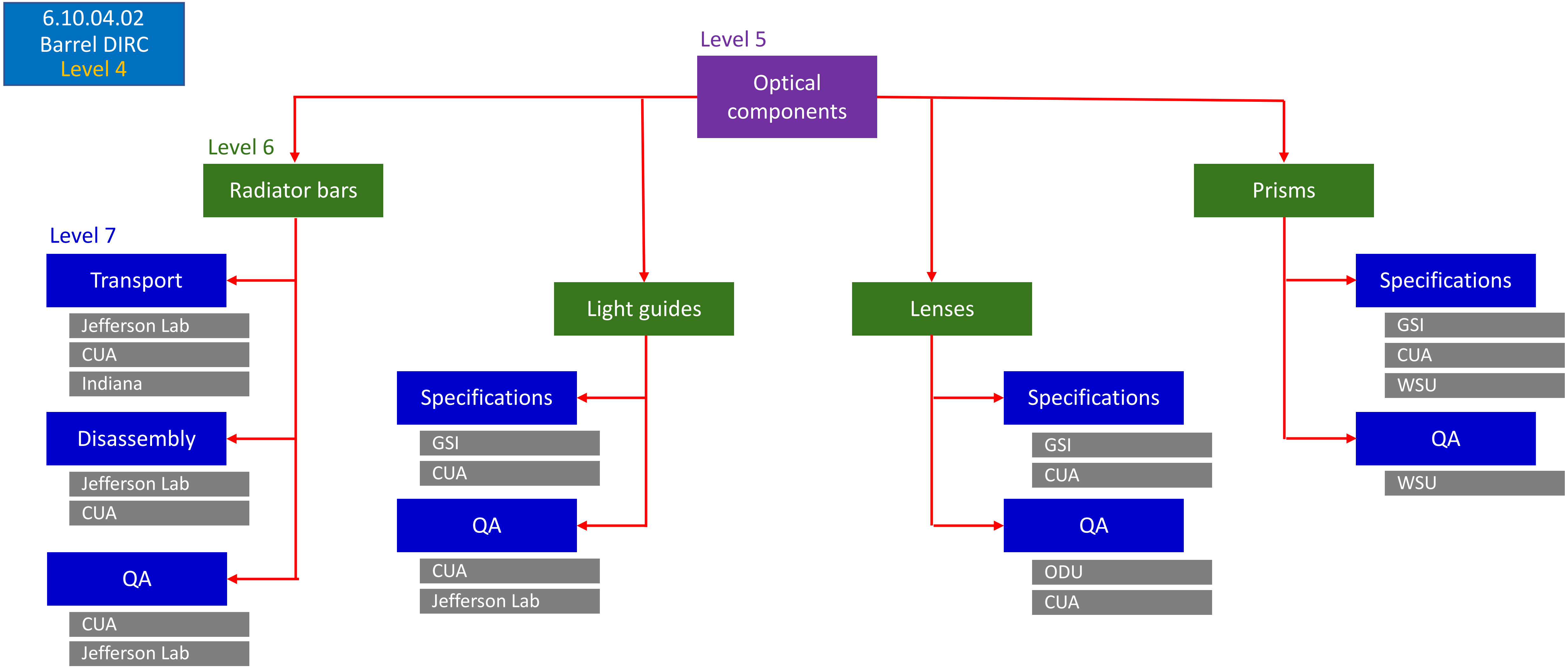


hpDIRC DSC: Interested Groups (so far)

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)

WORK PACKAGES

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

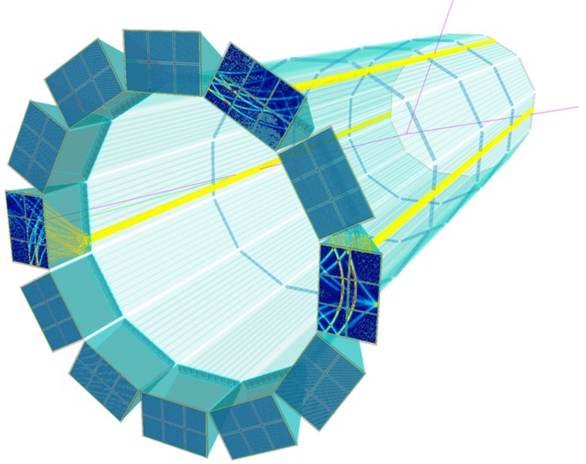
Level 6

- 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

SUMMARY

- ePIC hpDIRC: Fast focusing DIRC concept, developed over 10+ years of EIC R&D
- Expected PID performance meets ePIC requirements (Yellow Report), separation: 3 ≥ s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 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
- Presented plans for ES&H and QA, modular integration concept
- 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 (?)



CHARGE QUESTION ROADMAP

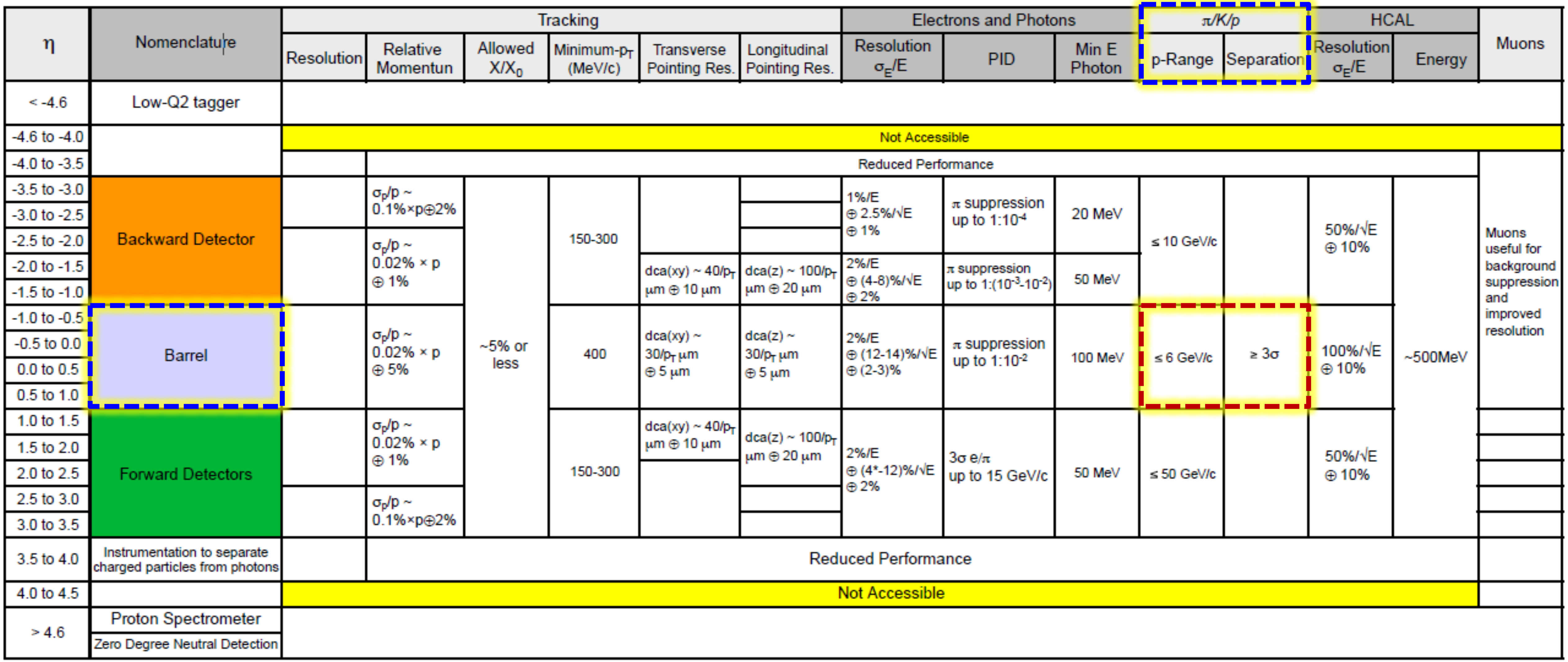
	Charge Question	Slide Number
1	Are the technical performance requirements appropriately defined and complete for this stage of the project?	4
2	Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?	11-16
3	Are the 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?	5, 8-9, 17, 24-26
4	Are the fabrication and assembly plans for the various particle identification detector systems consistent with the overall project and detector schedule?	18-21, 31-34
5	Are the plans for detector integration in the EIC detector appropriately developed for the present phase of the project?	27-28
6	Have ES&H and QA considerations been adequately incorporated into the designs at their present stage?	29-30

Thank you all for your attention.

Extra Slides

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/).

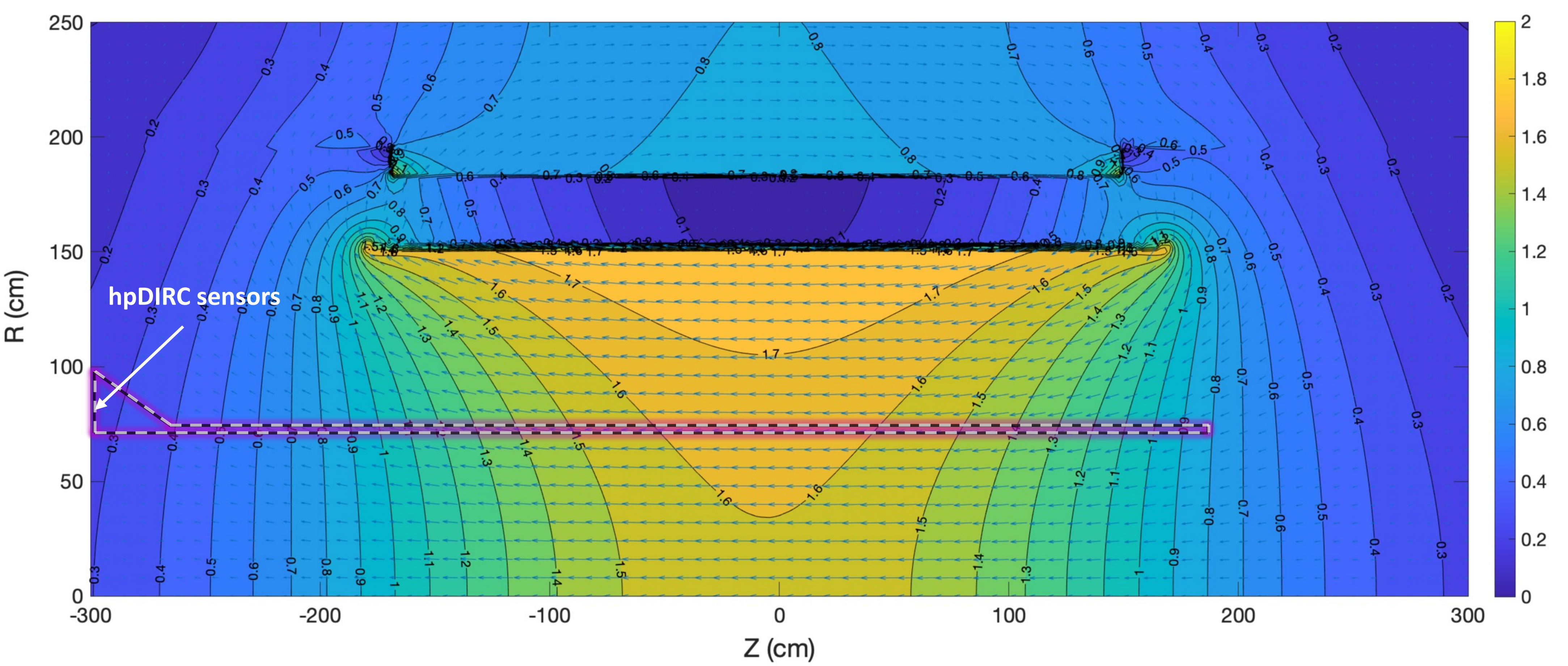


η	Nomenclature	Tracking						Electrons and Photons			$\pi/K/p$		HCAL		Muons
		Resolution	Relative Momentun	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range	Separation	Resolution σ_E/E	Energy	
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												Muons useful for background suppression and improved resolution
-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	$\leq$ 10 GeV/c		$50\%/\sqrt{E} \oplus 10\%$	~500MeV	
-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 $\oplus$ 10 μm	dca(z) ~ $100/p_T$ μm $\oplus$ 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 $\oplus$ 5 μm	dca(z) ~ $30/p_T$ μm $\oplus$ 5 μm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to $1:10^{-2}$	100 MeV	$\leq$ 6 GeV/c	$\geq 3\sigma$	$100\%/\sqrt{E} \oplus 10\%$		
-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 $\oplus$ 10 μm	dca(z) ~ $100/p_T$ μm $\oplus$ 20 μm	$2\%/E \oplus (4^{*}\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	$\leq$ 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

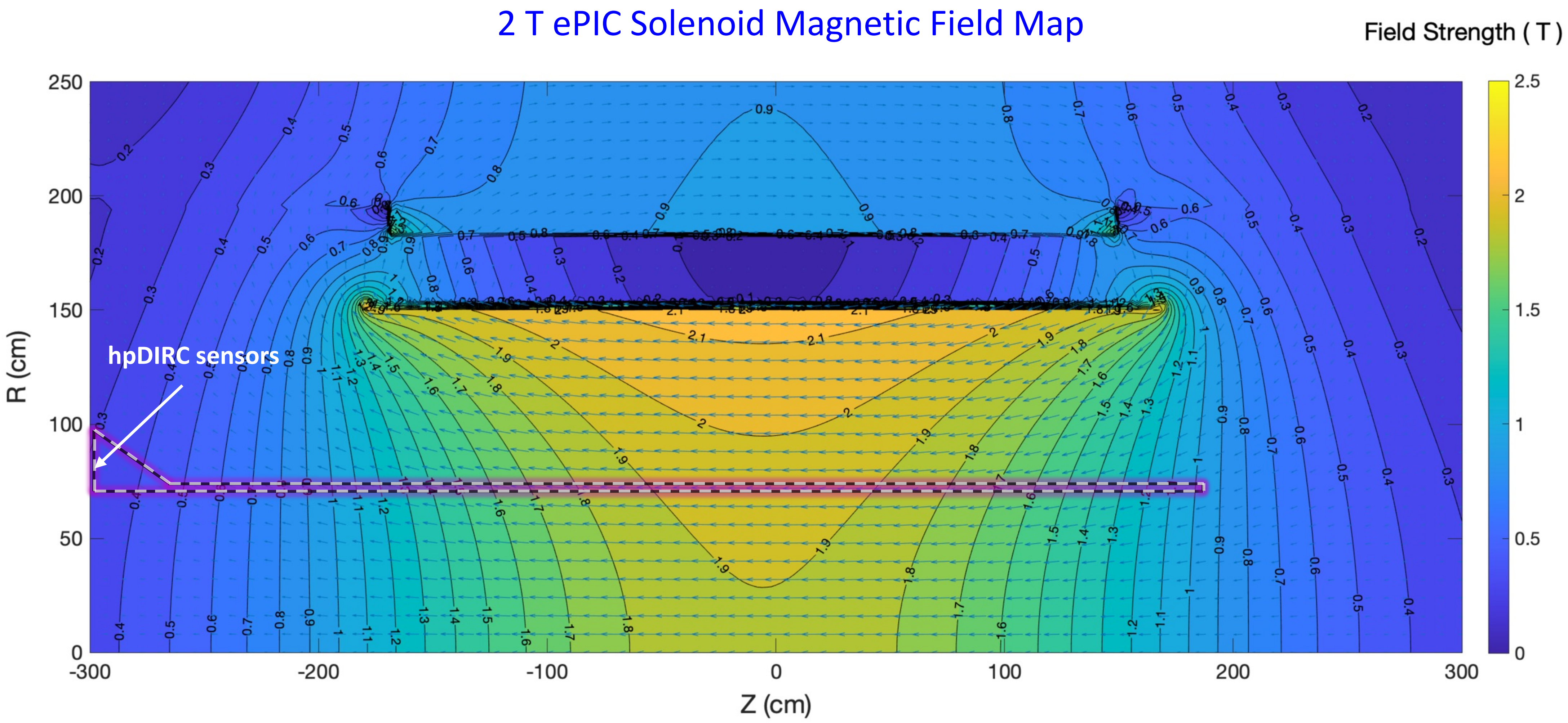
HPDIRC IN EPIC MAGNETIC FIELD

1.7 T ePIC Solenoid Magnetic Field Map



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

HPDIRC IN EPIC MAGNETIC FIELD

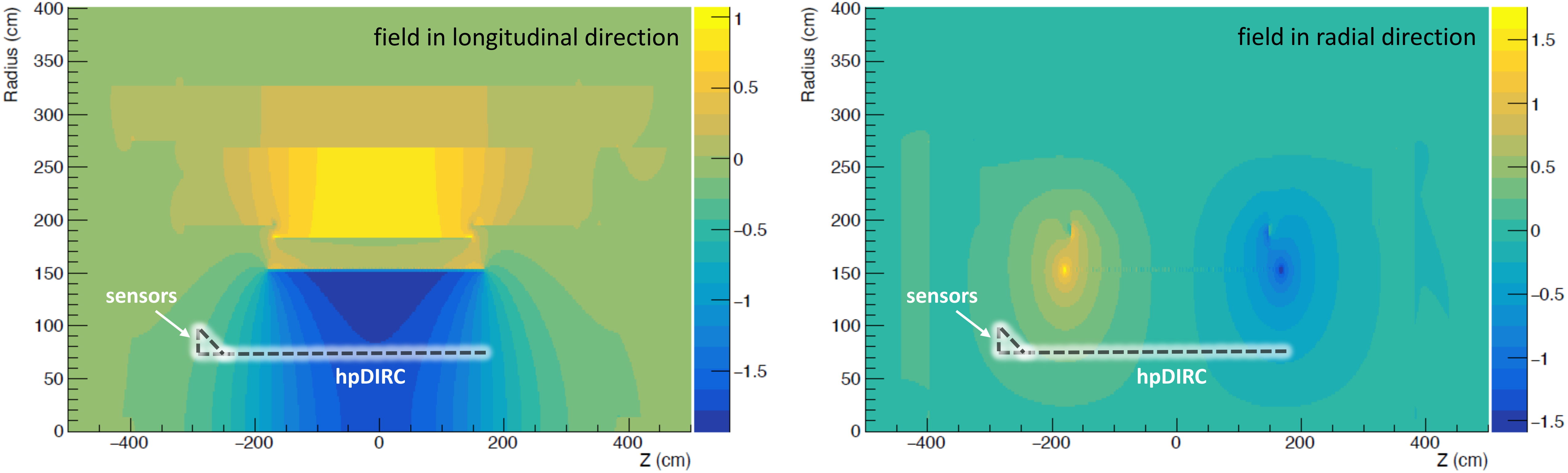


→ hpDIRC detector plane located in modest magnetic field of less than 0.5 T

hpDIRC in ePIC Magnetic Field

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

1.7 T ePIC Solenoid Magnetic Field Map



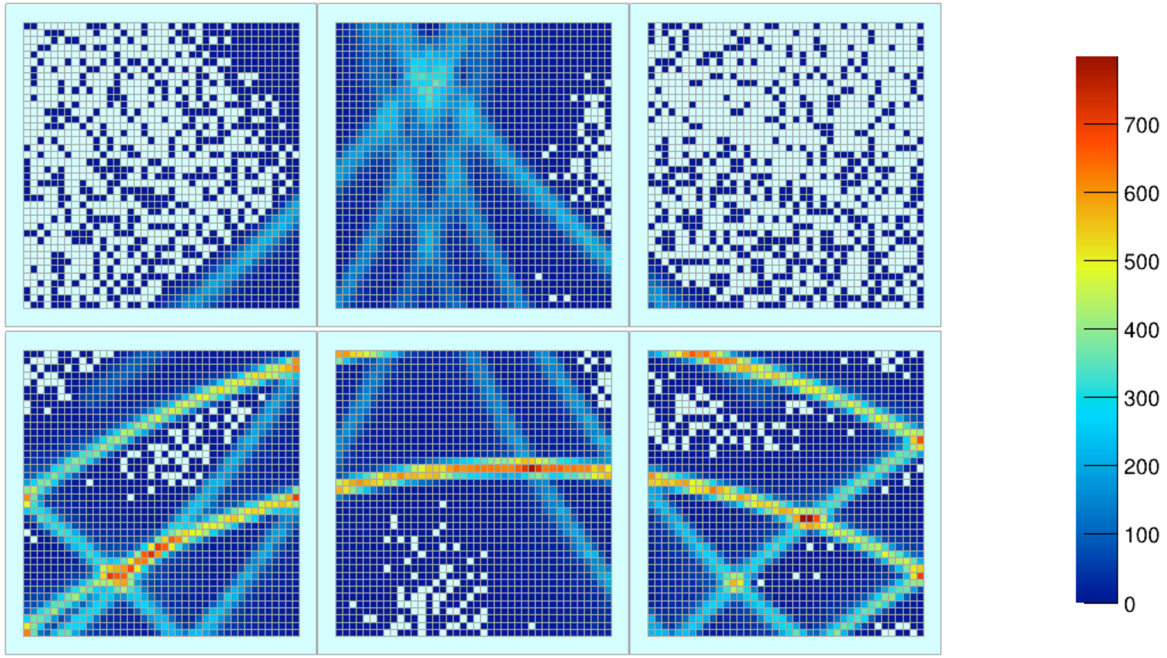
→ hpDIRC detector plane located in modest magnetic field of less than 0.5 T

HPDIRC IN EPIC MAGNETIC FIELD

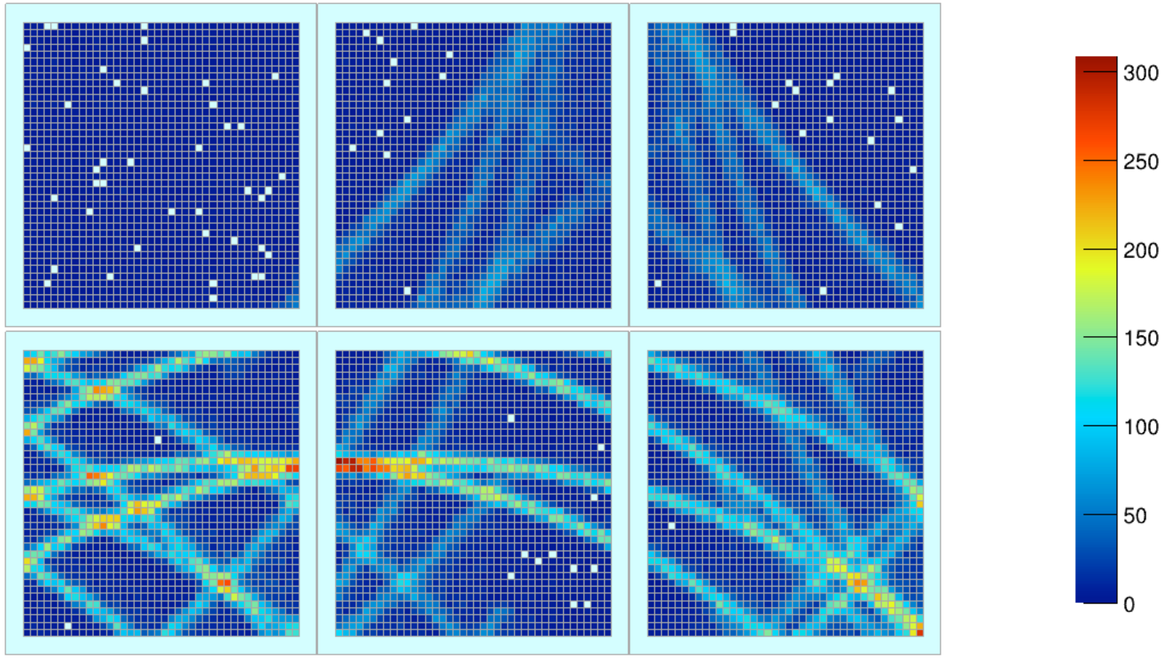
Impact of magnetic field on hit pattern

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

without magnetic field



with magnetic field



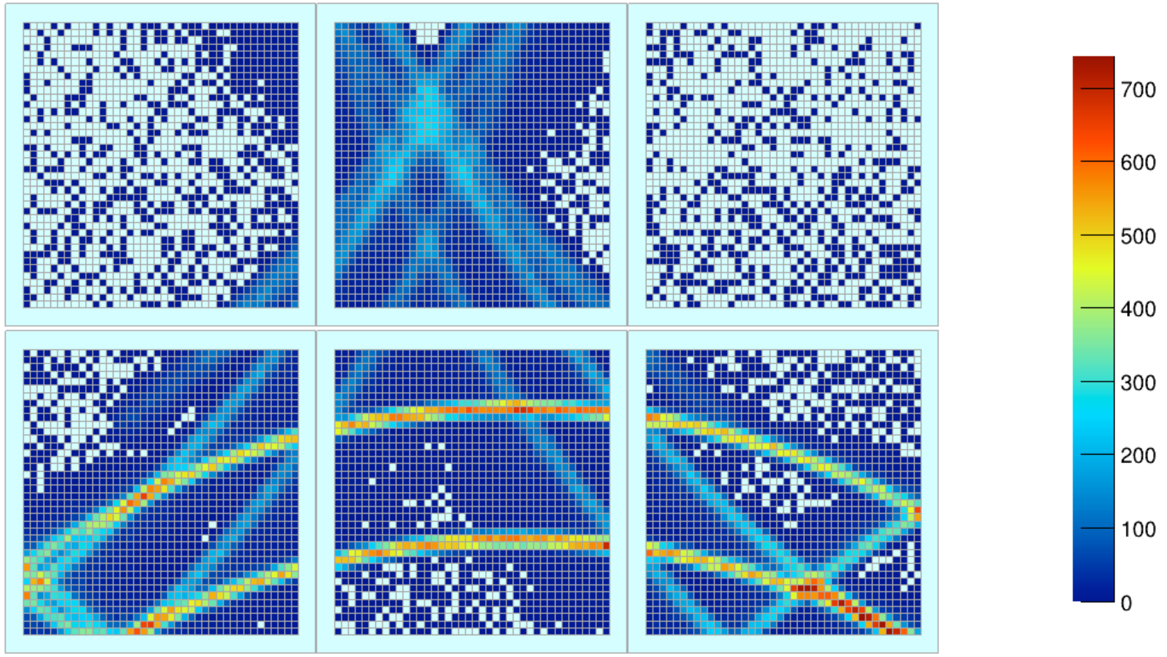
→ hpDIRC hit pattern spread out over larger area, more pixels, in ePIC magnetic field

HPDIRC IN EPIC MAGNETIC FIELD

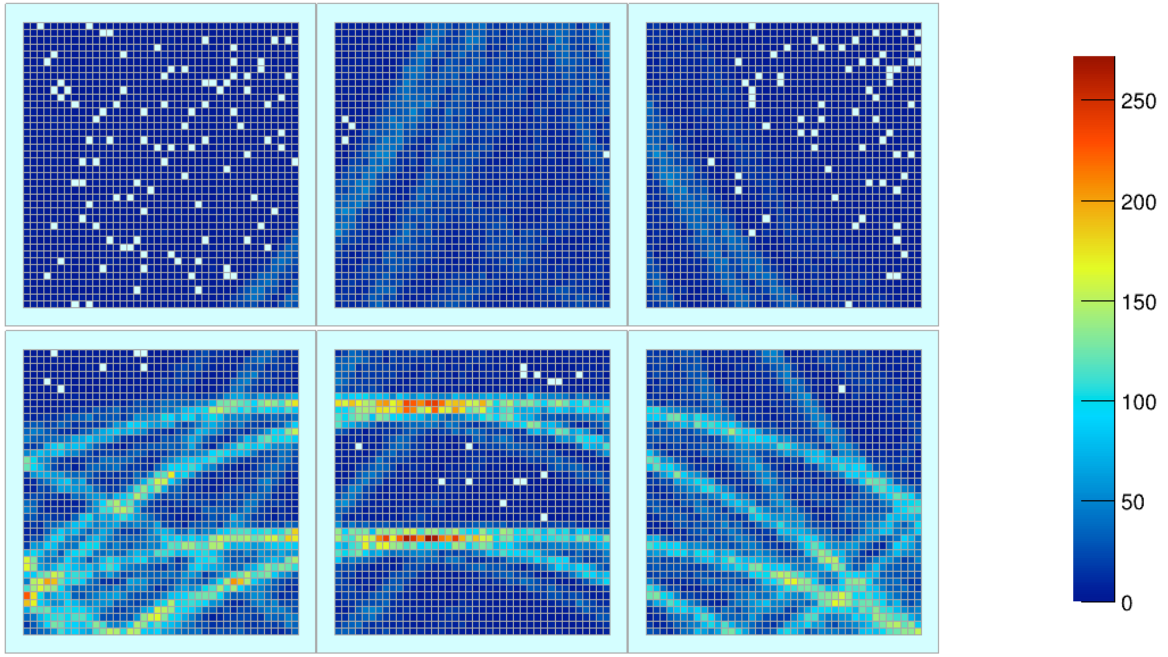
Impact of magnetic field on hit pattern

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

without magnetic field



with magnetic field

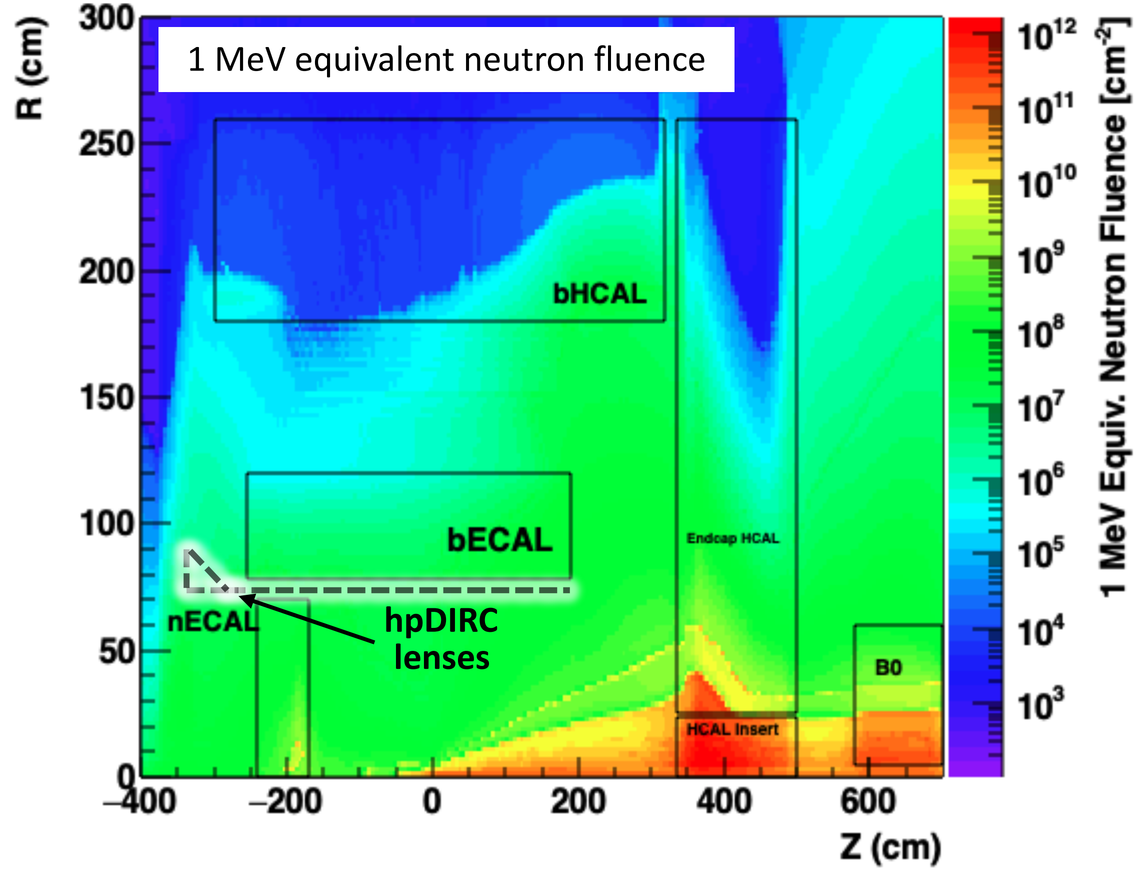


→ hpDIRC hit pattern spread out over larger area, more pixels, in ePIC magnetic field

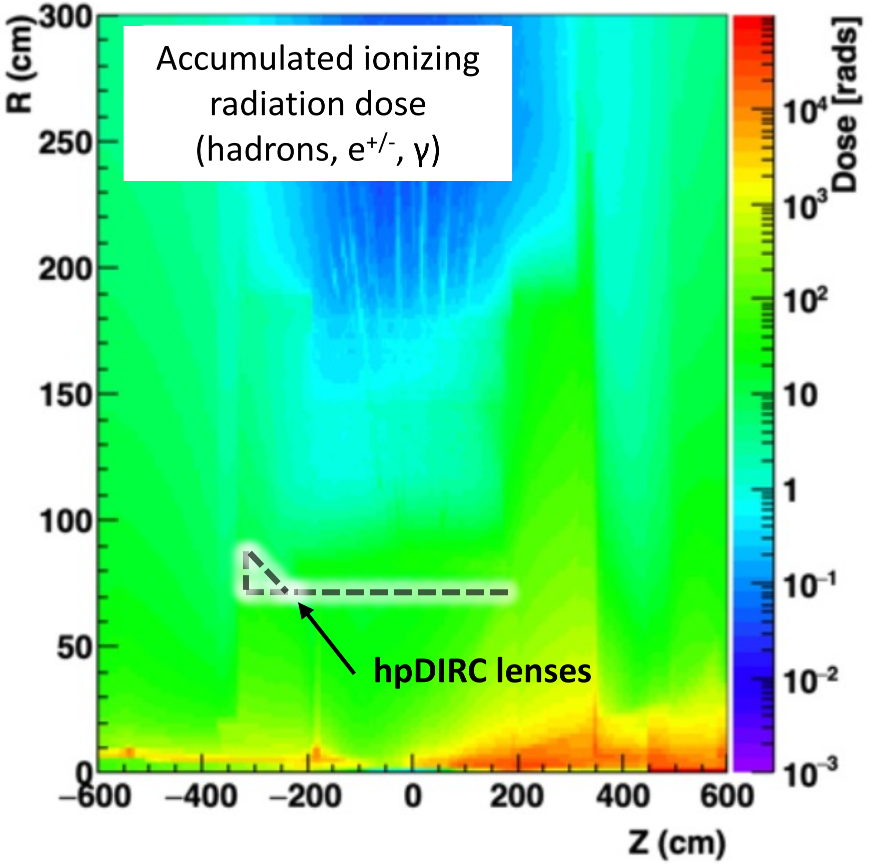
HPDIRC IN EPIC RADIATION ENVIRONMENT

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)

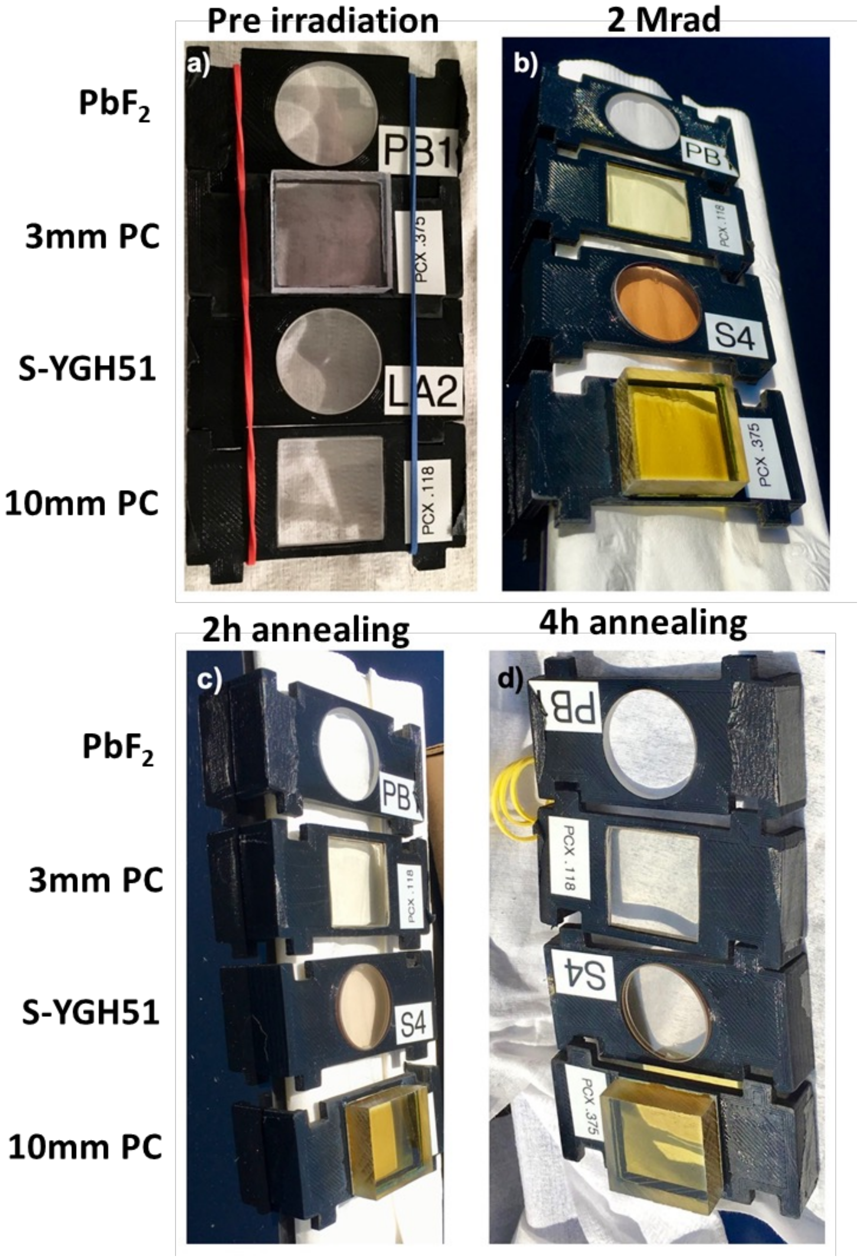


Accumulated ionizing radiation dose - PYTHIA 18x275 GeV e+p minimum bias events at top luminosity (500 kHz min-bias rate, 6-month run)

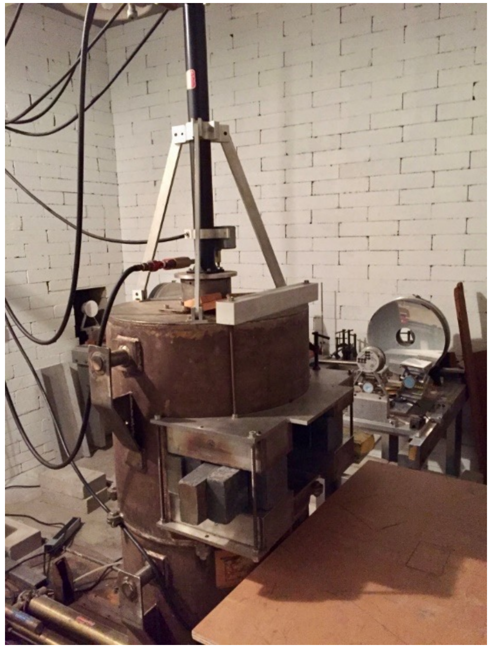
→ Expect less than 10^9 neutrons cm^{-2} and less than 0.1krad per year at DIRC lens location

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.

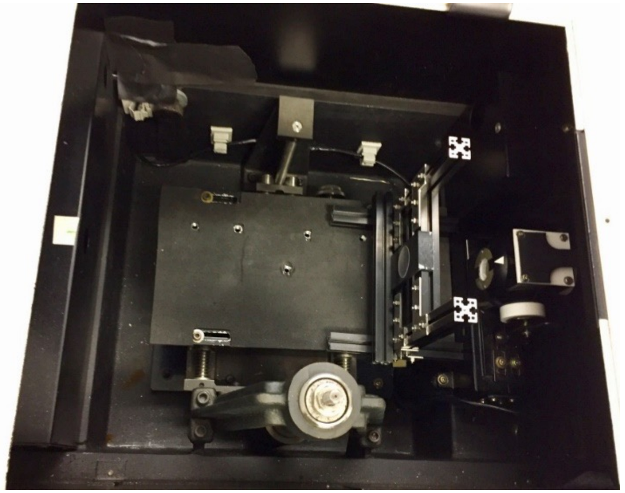


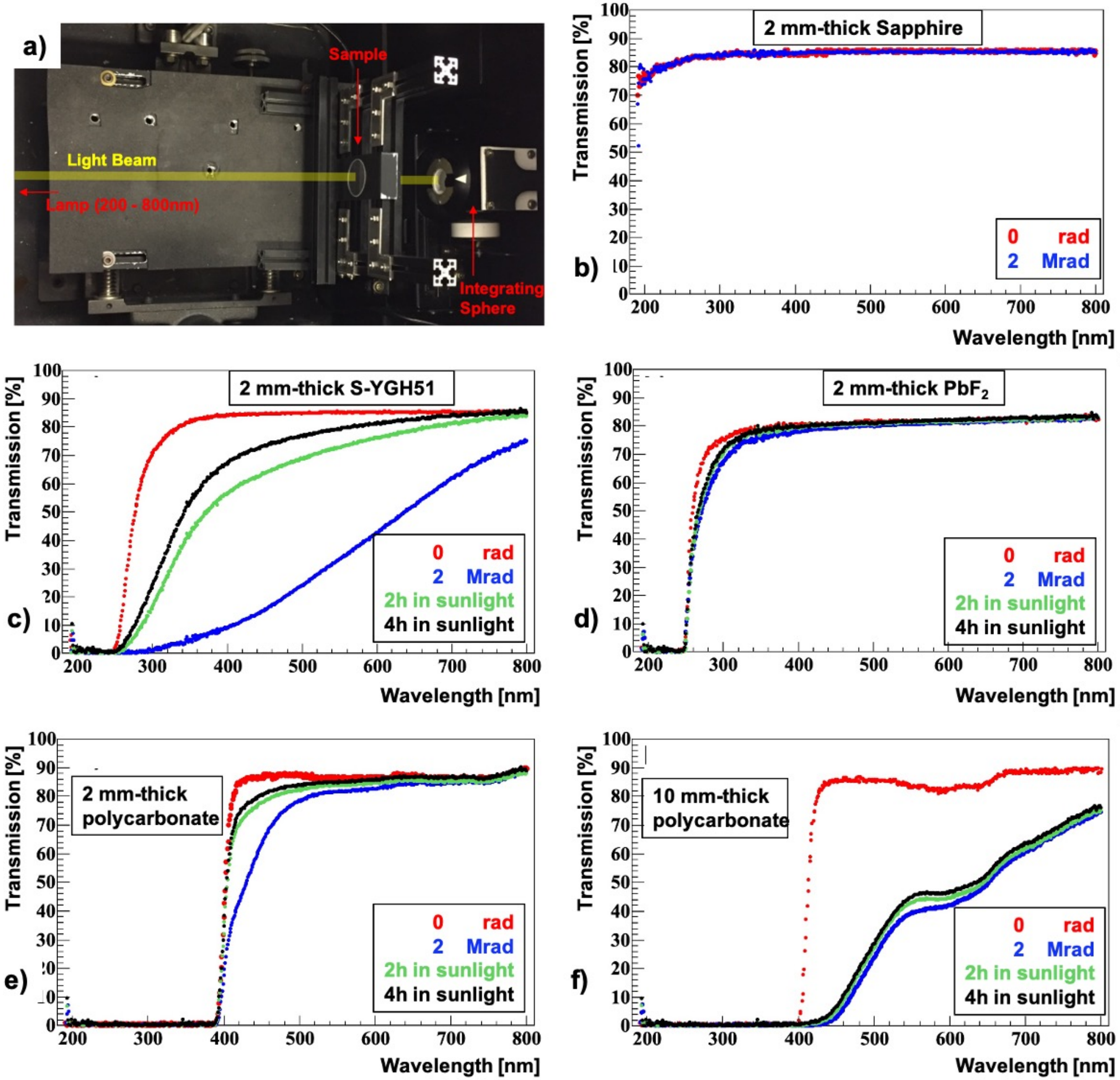
HPDIRC RADIATION TESTS



Co^{60} Chamber

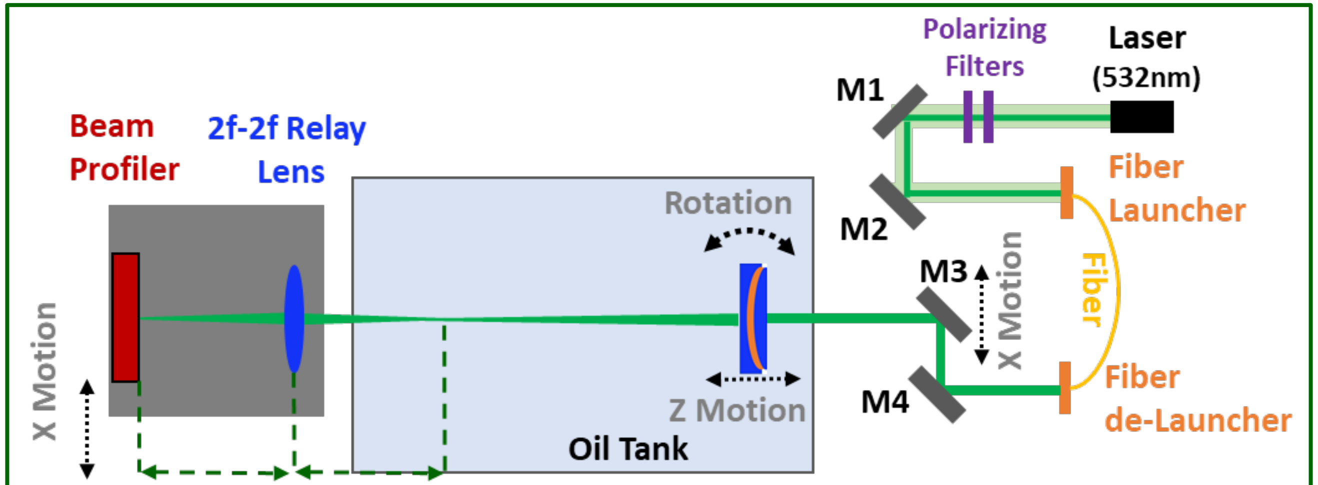
Monochromator



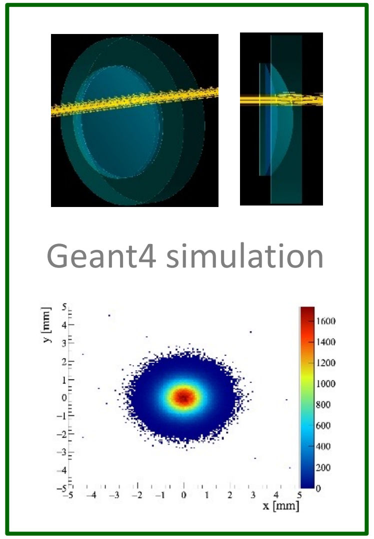


LENS FOCUSING

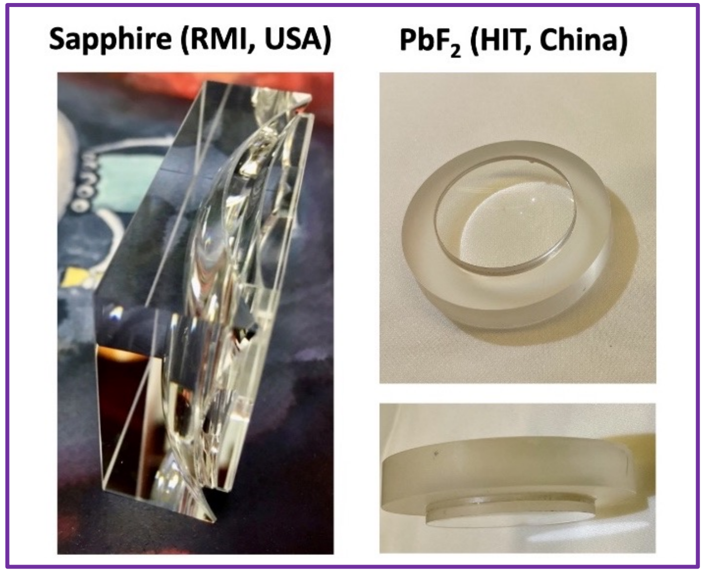
- ➢ Detailed scans of lens focusing properties with laser in optical lab at ODU



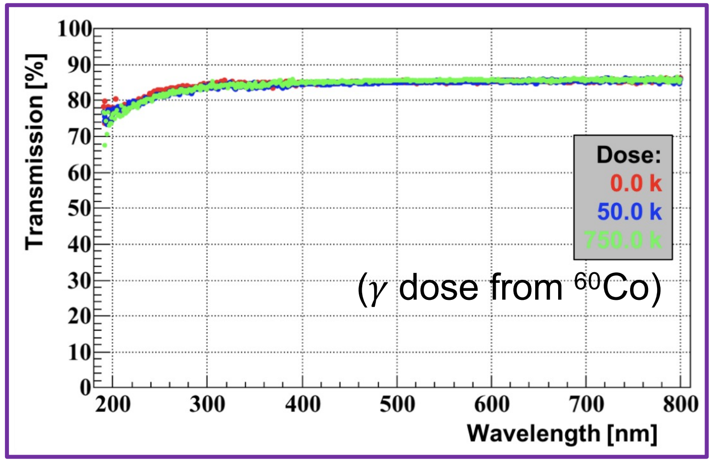
Close collaboration with Prof. Charles I. Sukenik (ODU)



Radiation-hard 3-layer lens prototypes



Radiation hardness of sapphire



(γ dose from ^{60}Co)

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:

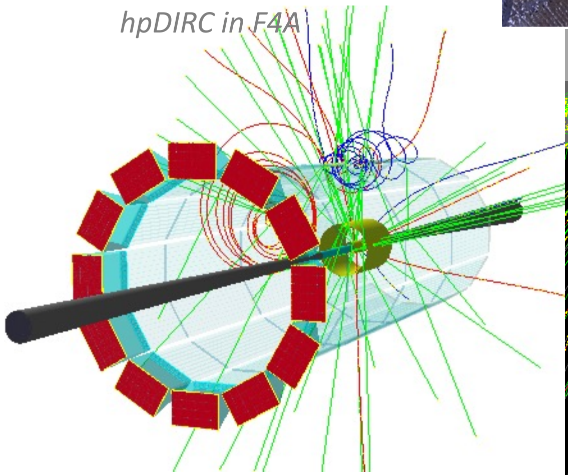
- Modular hpDIRC prototype in Cosmic Ray Telescope at SBU
- Incremental hpDIRC optical components integration and evaluation
- Adaptation and evaluation of sensors and readout electronics in hpDIRC prototype

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

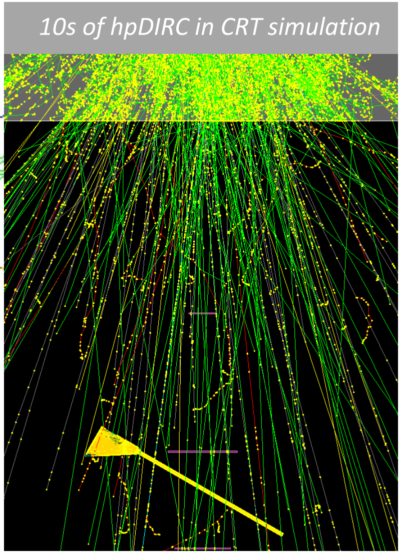
BaBar DIRC bars

DIRC barboxes in SLAC

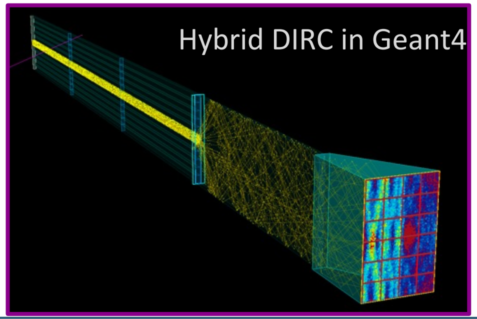
hpDIRC in F4A



10s of hpDIRC in CRT simulation



Hybrid DIRC in Geant4



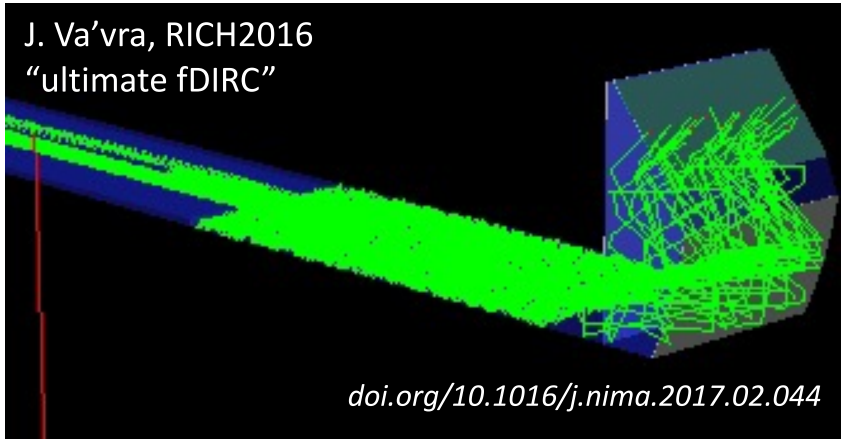
DIRC lab/CRT space at SBU

LIGHT GUIDE SECTION

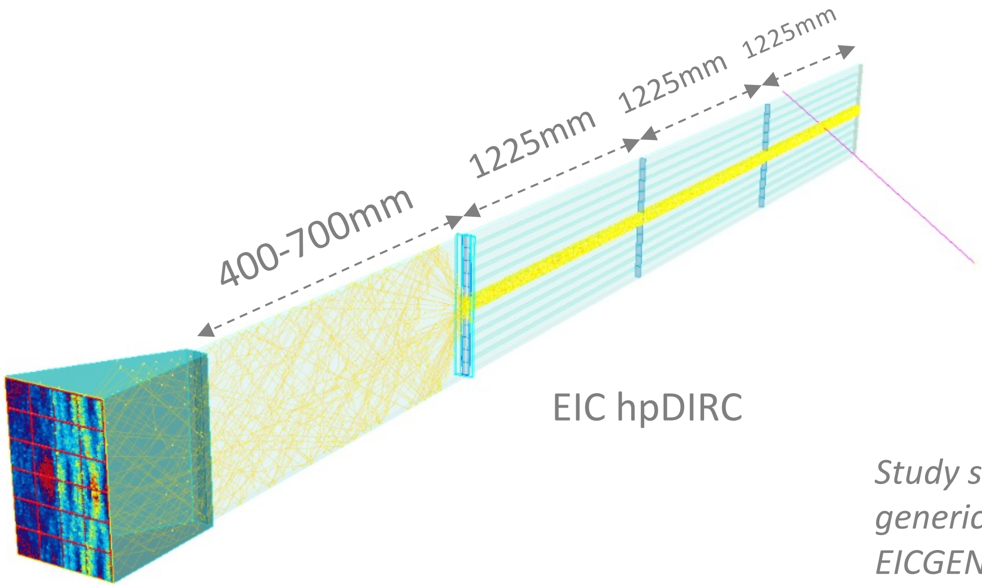
Performance improvement

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

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


J. Va'vra, RICH2016
"ultimate fDIRC"

doi.org/10.1016/j.nima.2017.02.044

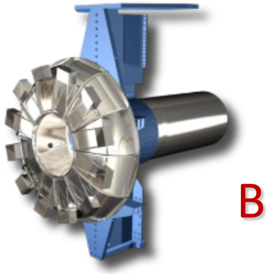


EIC hpDIRC

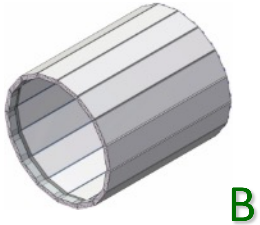
Study supported via generic R&D as EICGENRandD2022_12

GEANT4 visualization of hybrid of bars and plate in each sector

BARREL DIRC OVERVIEW

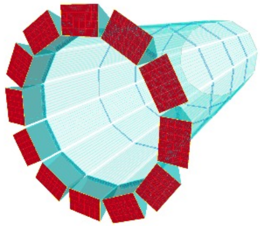


BABAR DIRC



BELLE II TOP

PANDA BARREL DIRC



EPIC HPDIRC *

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*