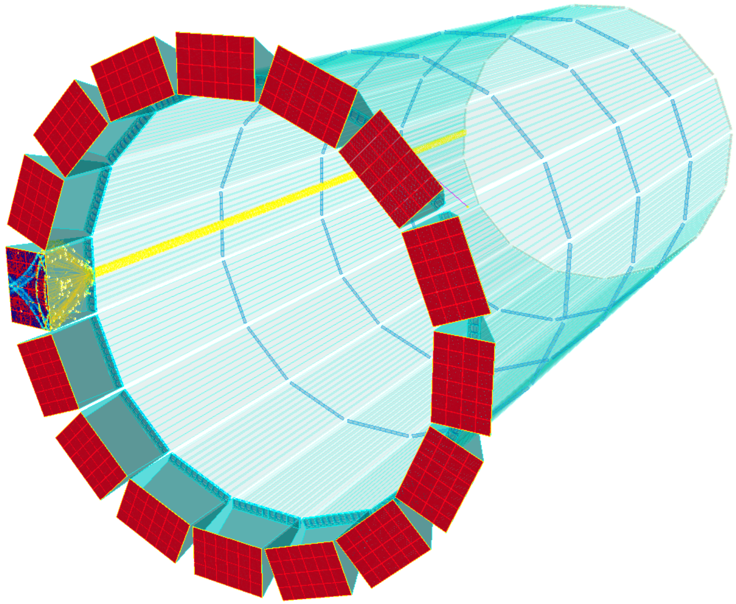
The High-Performance DIRC for the EIC



Jochen Schwiening

GSI Helmholtzzentrum für Schwerionenforschung GmbH

for the eRD14 hpDIRC group

- The hpDIRC Group
- Status of the hpDIRC Activity
- Plan for TDR-Readiness in 2023
- Schedule, Summary, and Outlook

hpDIRC Group

hpDIRC: part of the EIC Generic Detector R&D program since day one

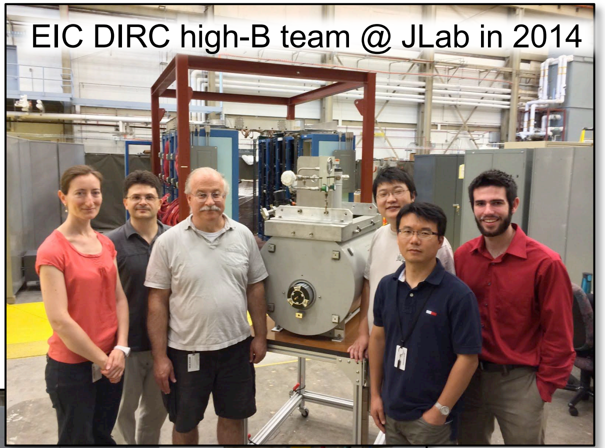
- 2011-2015: eRD4 - DIRC-based PID for the EIC
- 2015-now: hpDIRC activity in eRD14

Cooperation between groups from USA and Germany

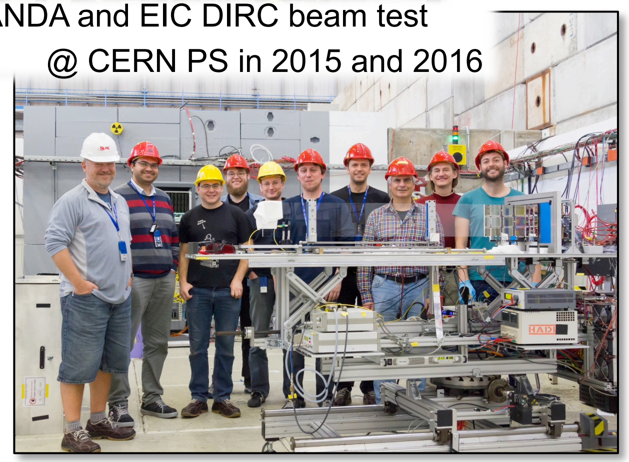
DIRC experience ranging from design, software development, R&D, and beam tests to assembly, installation, commissioning, and operation in:

Access to DIRC labs and facilities

laser labs: lens & bar measurements; monochromator, X-ray source: material tests; high-B test facility, psec laser pulser: sensor performance; PANDA/EIC DIRC prototype lab space; electronics lab, psec laser pulser: readout tests



EIC DIRC high-B team @ JLab in 2014



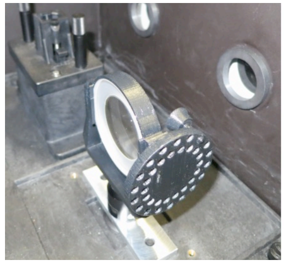
PANDA and EIC DIRC beam test @ CERN PS in 2015 and 2016

hpDIRC Team

Greg Kalicy co-PI, tenure track faculty, DIRC experience at GSI, ODU, and CUA since 2010

→ PANDA Barrel DIRC (2010-2014), hpDIRC (since 2013), GlueX DIRC (since 2015)

Optical tests of DIRC components*, Geant and ray-tracing simulation, prototype beam tests at GSI and CERN, radiation hardness tests, high-B tests, DIRC installation and commissioning

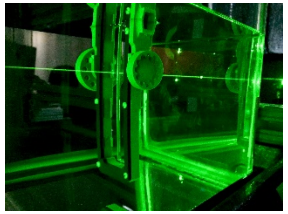


CUA facilities: X-ray source and monochromator

Former CUA hpDIRC members: T. Horn, M. Boer

Charles Hyde faculty, hpDIRC since 2011

DIRC design, EIC physics with PID focus, simulation, optical lab support, cosmic ray test facility



Thomas Hartlove laboratory specialist

Optical lab design and support

ODU facility: laser lab for lens measurements, picosecond laser pulser

Former ODU hpDIRC members: L. Allison, K. Park, H. Seraydaryan

**responsibilities within hpDIRC group highlighted in blue*

hpDIRC Team

Pawel Nadel-Turonski adjunct faculty, hpDIRC since 2011 at JLab and SBU

DIRC design, EIC physics with PID focus, mini-DIRC

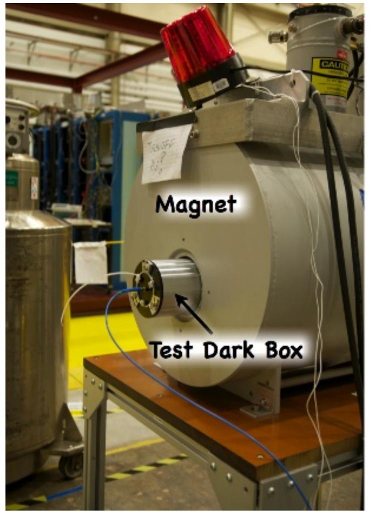
SBU facility: lab space for hpDIRC prototype preparation

Yordanka Ilieva faculty, hpDIRC since 2012

Photodetectors, high-B performance evaluation at JLab test facility

Former and current USC members involved in high-B tests at JLab:

T. Cao, C. Gleason, N. Zachariou plus undergraduate students



Carl Zorn senior scientist, hpDIRC since 2012

Photodetectors, high-B performance evaluation at JLab test facility

JLab facility: high-B sensor test setup, picosecond laser pulser

Former JLab hpDIRC members: J. Stevens, W. Xie

HPDIRC TEAM

Jochen Schwiening co-PI, senior scientist, DIRC experience at SLAC and GSI since 1995

→ BaBar DIRC (1995-2008), SuperB fDIRC (2001-2008), PANDA Barrel DIRC (since 2009), hpDIRC (since 2011), GlueX DIRC (since 2015)

DIRC design, optical properties and radiation hardness of DIRC bars, simulation and reconstruction, prototype beam tests at SLAC, GSI, and CERN, construction, installation, commissioning, operations and system management

Carsten Schwarz staff scientist, DIRC experience since 2004

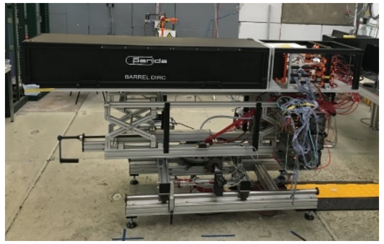
→ PANDA Barrel DIRC (since 2007), hpDIRC (since 2011)

Lens design, ray-tracing simulation, readout electronics, prototype beam tests at GSI and CERN

Roman Dzhygadlo staff scientist, DIRC experience since 2014

→ PANDA Barrel DIRC (since 2013), hpDIRC (since 2013), GlueX DIRC (since 2015)

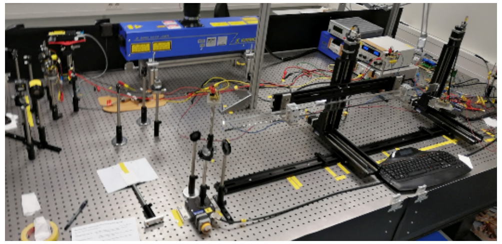
DIRC design, simulation and reconstruction, prototype beam tests at GSI and CERN, commissioning



Klaus Peters faculty and staff scientist, hpDIRC (since 2011), EIC physics

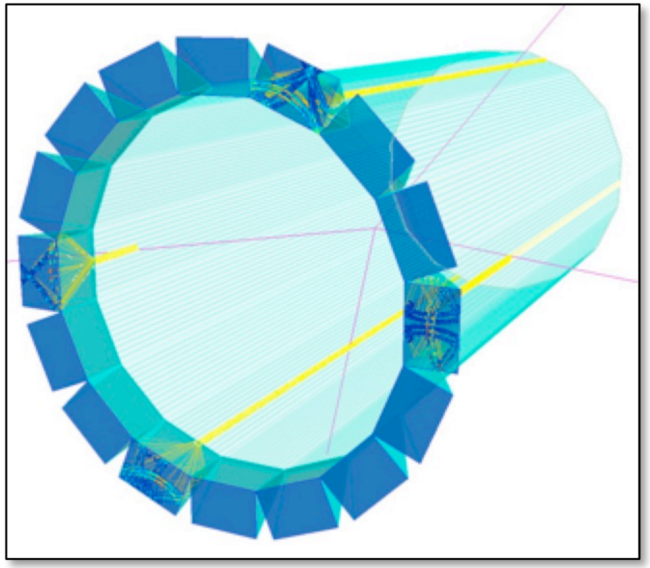
GSI facilities: optical lab, electronics lab, mechanical lab, PANDA Barrel DIRC prototype

Engineering support for prototype and beam tests: A. Gerhardt, D. Lehmann



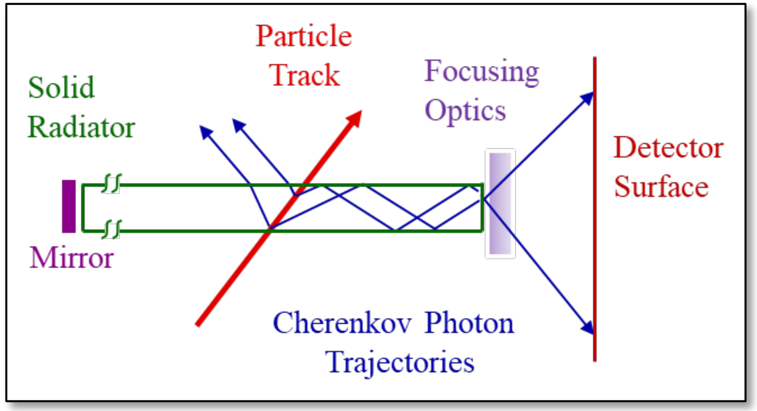
HPDIRC INTRODUCTION

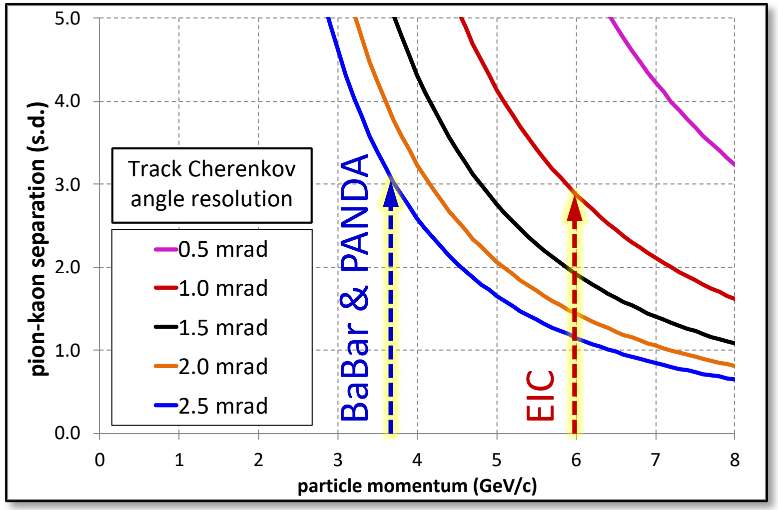
hpDIRC: a high-performance DIRC counter for radially compact hadronic PID in the barrel region of the future EIC experiments



- Designed to provide 3 s.d. separation for π/K up to 6 GeV/c, e/π up to 1.8 GeV/c, K/p up to 10 GeV/c
- Advancing DIRC PID performance by more than 50% beyond the state-of-the-art

Detection of Internally Reflected Cherenkov Light

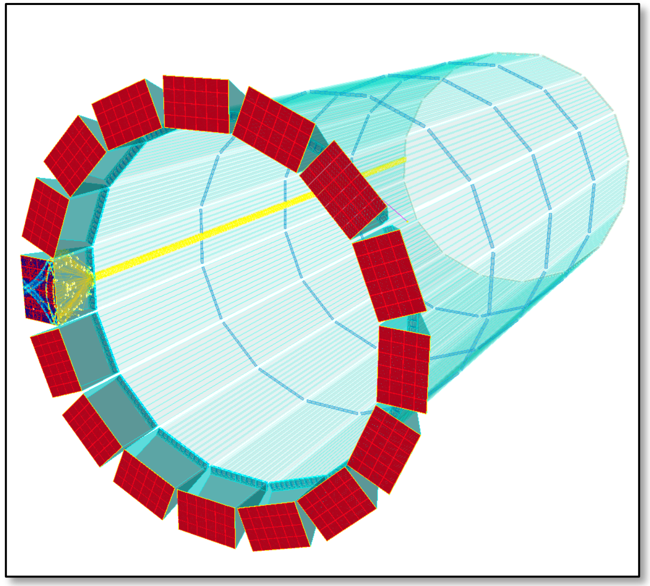


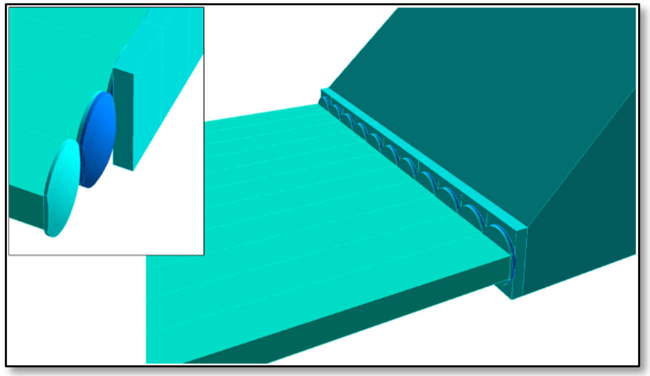


Concept: fast focusing DIRC

Inspired by design elements from BaBar, SuperB, Belle II, and PANDA

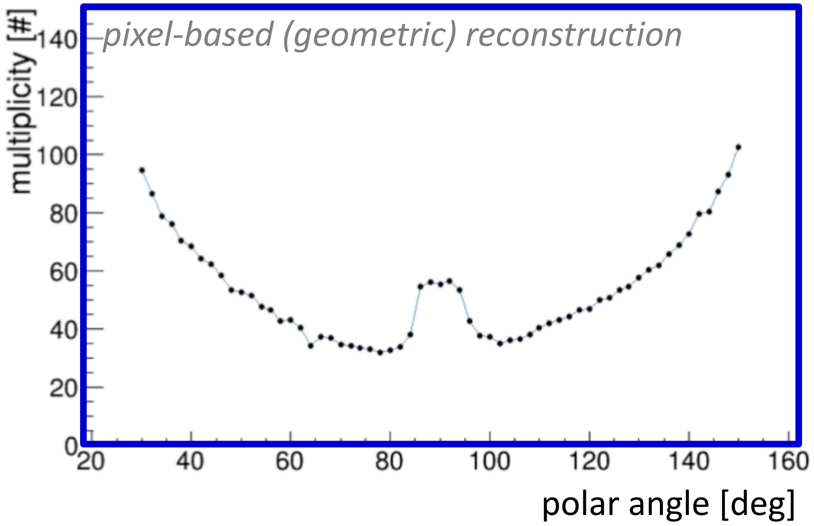
- Generic reference design: 1m barrel radius, 16 sectors
- 176 radiator bars (11 per sector), synthetic fused silica,
  17mm (T) × 35mm (W) × 4200mm (L)
- Focusing optics: innovative rad-hard 3-layer spherical lens
- Compact photon camera:
  30cm-deep solid fused silica prisms as expansion volumes
  lifetime-enhanced MCP-PMTs with $3x3mm^2$ pixels
  fast readout electronics (~100,000 channels , <100ps single photon timing)
- Expected performance (Geant4 simulation):
  30-100 detected photons per particle,
  ≥ 3 s.d. π/K separation at 6GeV/c



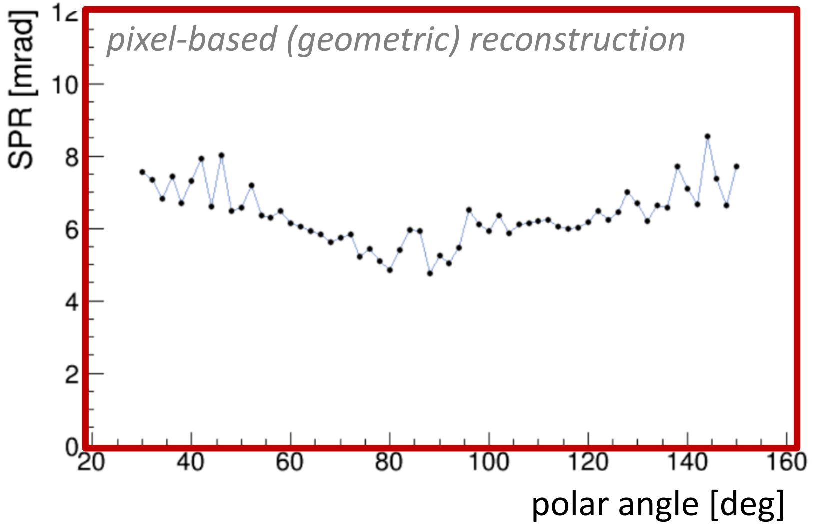


HPDIRC PERFORMANCE IN GEANT4

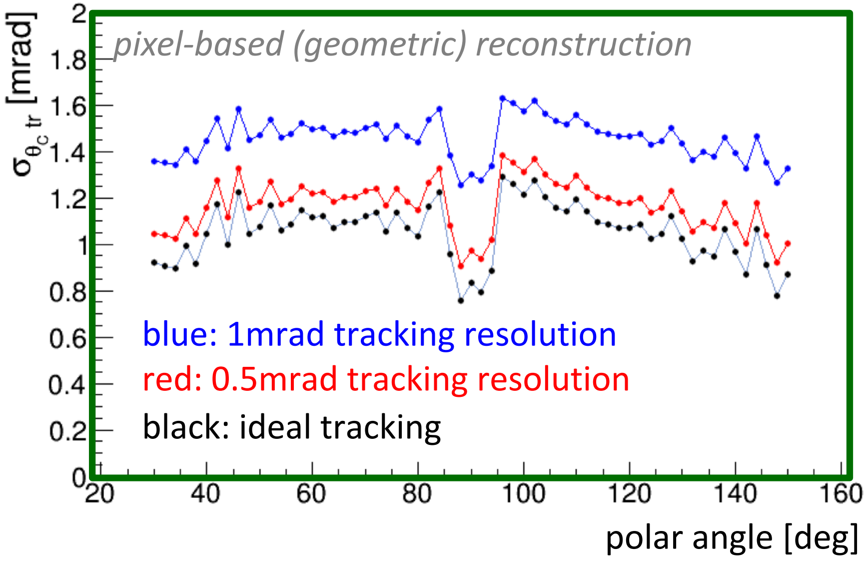
Photon yield per particle



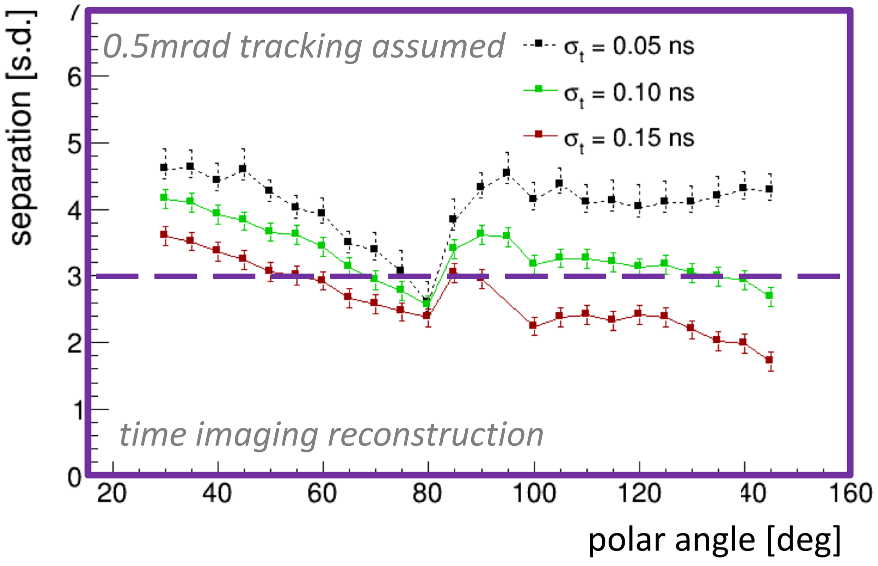
Cherenkov angle resolution per photon (SPR)



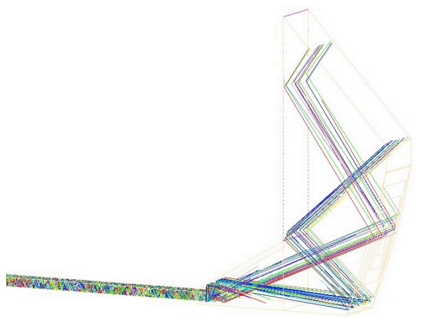
Cherenkov angle resolution angle per particle



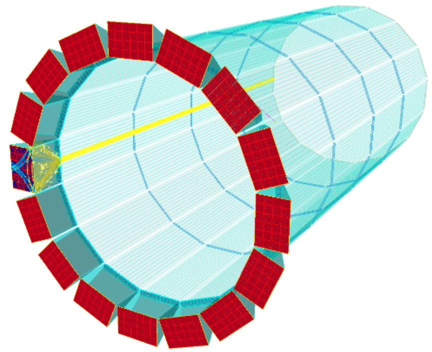
π/K separation power at 6 GeV/c



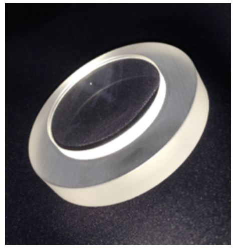
Key achievements:



- Implemented initial design in ray-tracing and Geant (2012)
- Developed innovative 3-layer lens concept (2013)
- Completed proof-of-principle in Geant4 – design meets EIC PID goal (2014)
- Validated detailed Geant4 simulation with particle beams at CERN (2015)
- Characterized prototype lens performance with laser setup (2016)
- Identified radiation-hard lens materials (2018)



Current activities:

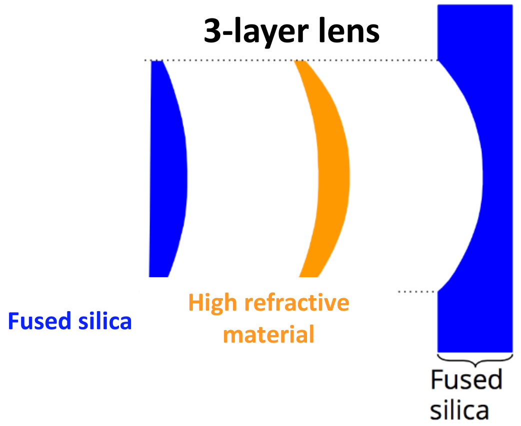


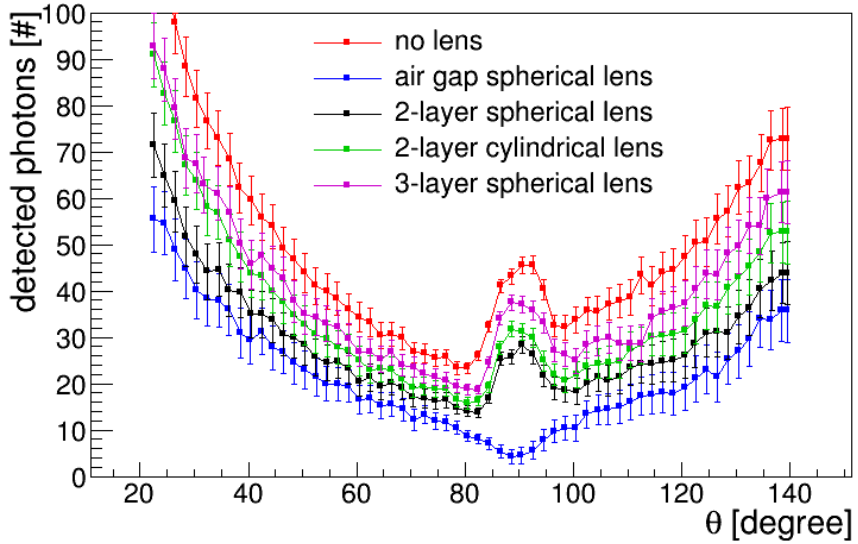
- Characterization of radiation hardness of lens materials
- Fabrication and evaluation of radiation-hard lens prototypes (PbF_2, Sapphire)
- Transfer of PANDA Barrel DIRC prototype to CUA/Stony Brook

Lens design

Conventional plano-convex lens with air gap limits DIRC performance

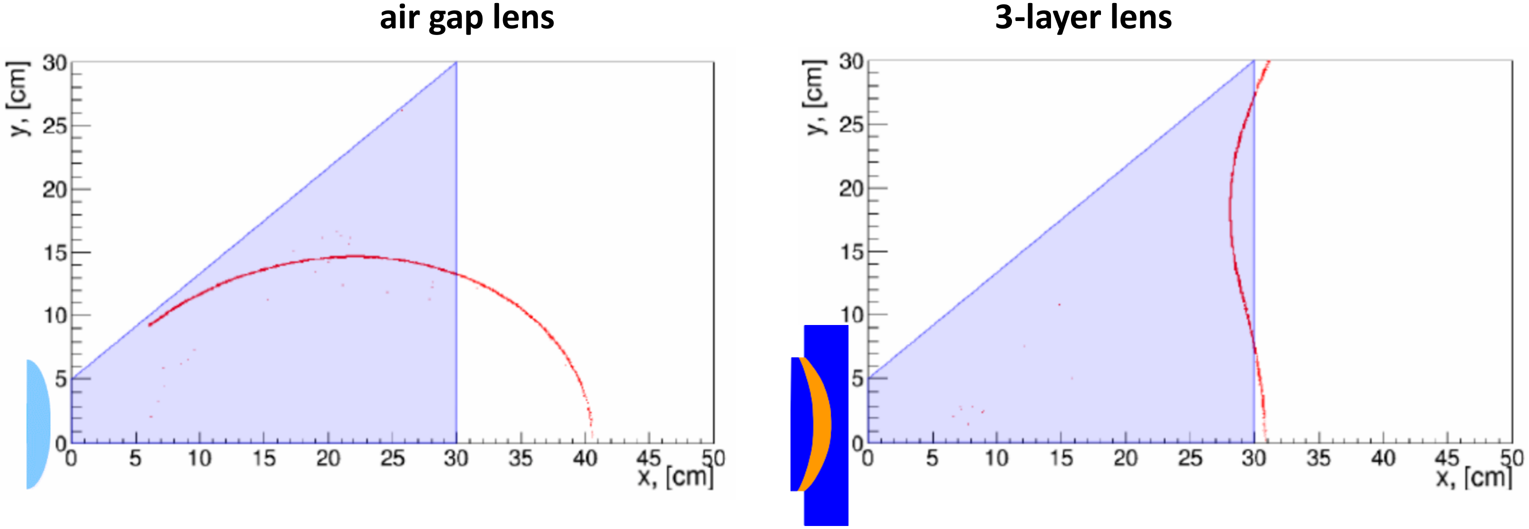
- Significant photon yield loss for particle polar angles around 90°
- Distortion of image plane for photons with steeper propagation angles
- Issues resolved by 3-layer lens with high-refractive index material for middle layer





From PANDA Barrel DIRC TDR: simulation

Geant4 simulation of focal plane:

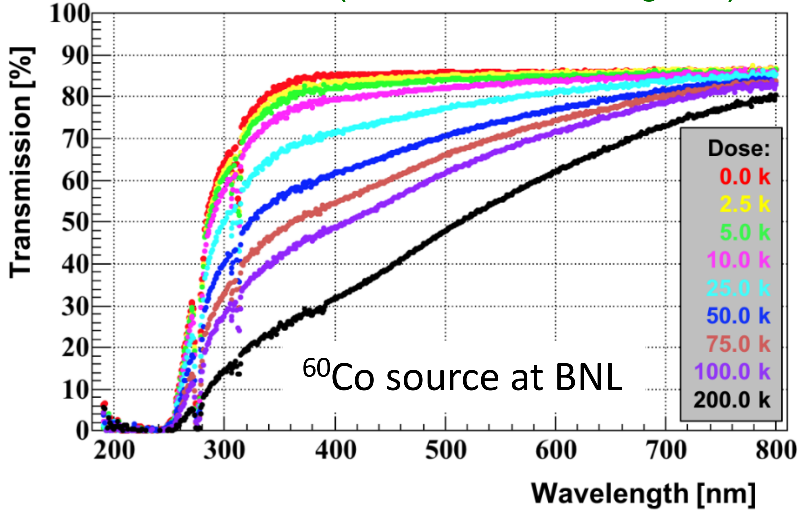


Geant Simulation

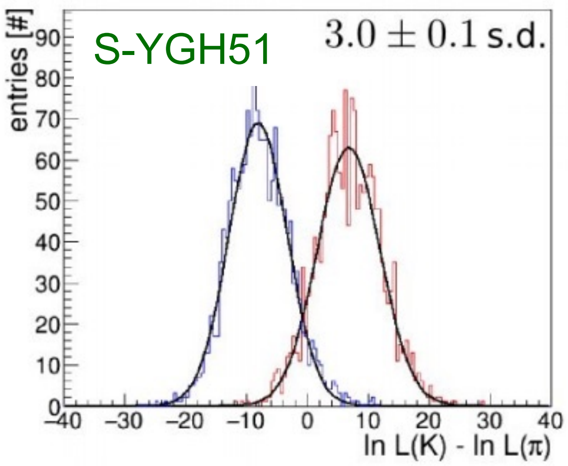
Lens material selection

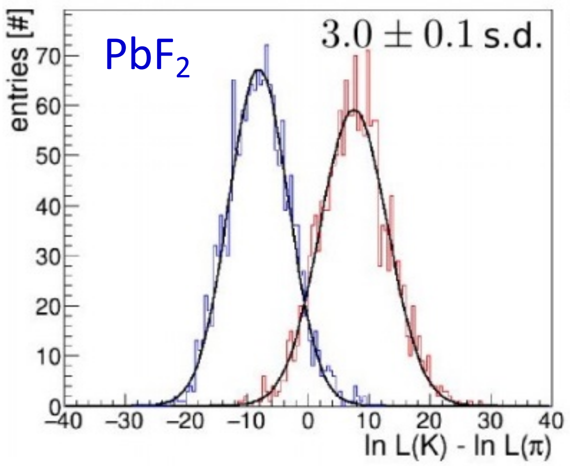
- Initial lens prototypes used lanthanum crown glass as the middle layer but this material was found to be insufficiently radiation hard
- Identified Sapphire and PbF_2 as possible alternatives (radiation-hard, good PID performance) but challenging for industry to process
- Two vendors currently building 3-layer lens prototypes with Sapphire and PbF_2 for us, expect delivery by October
- Upgrading ODU laser setup for improved speed, precision, and repeatability

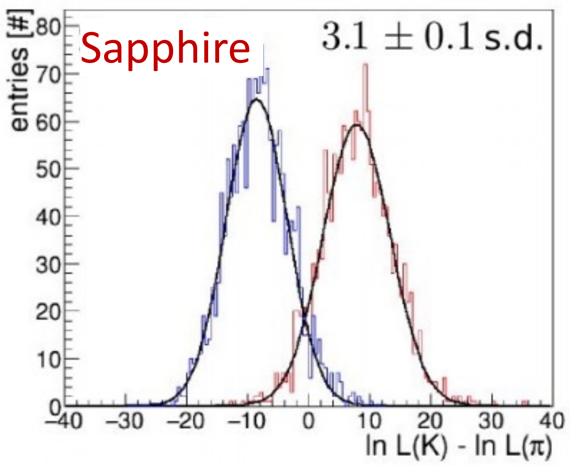
S-YGH51 (lanthanum crown glass)



Simulated π/K separation for charged pions and kaons with 6 GeV/c momentum and 30° polar angle, assuming a tracking resolution of 0.5 mrad.



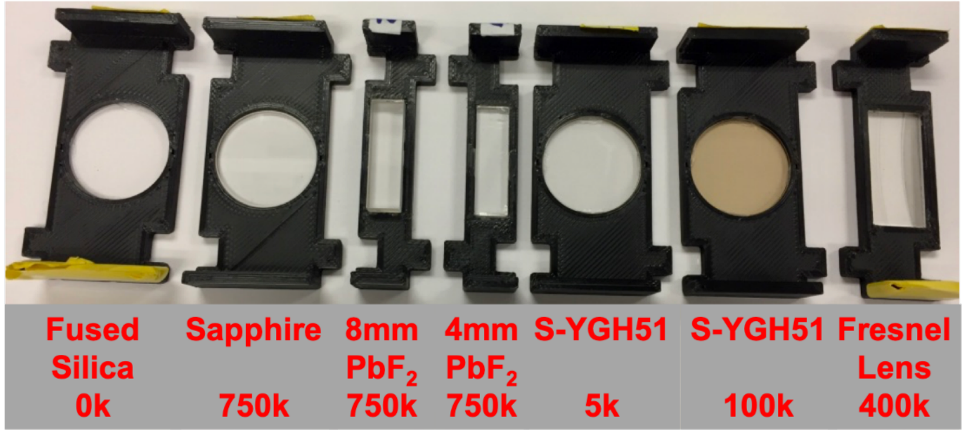




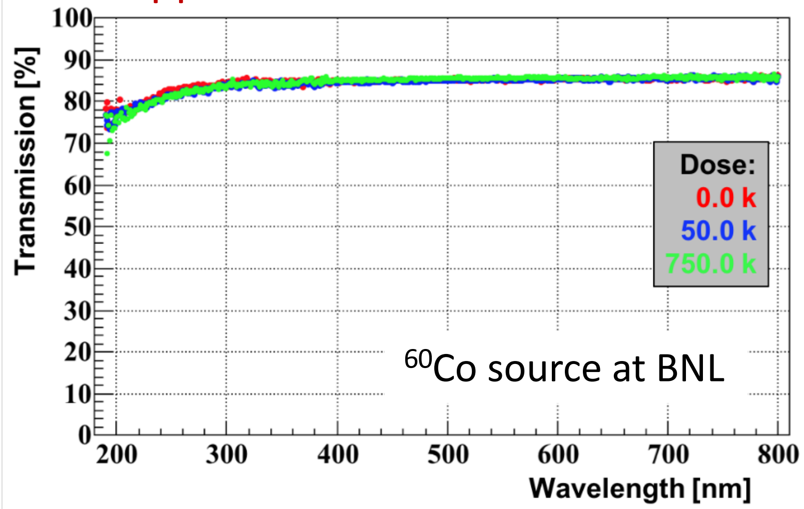
Radiation hardness study

- Seven materials studied with ^{60}Co source and monochromator at BNL
- Radiation hardness of Sapphire and PbF_2 confirmed
- Luminescence still to be investigated
- Neutron damage will be studied next

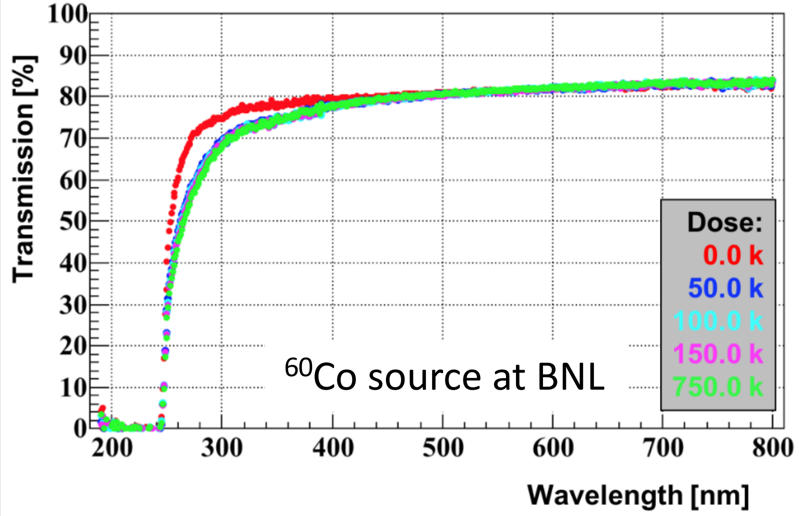
Tested samples



Sapphire



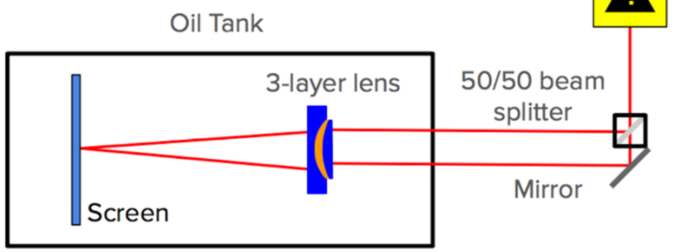
PbF_2

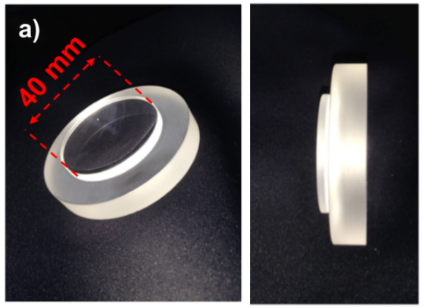


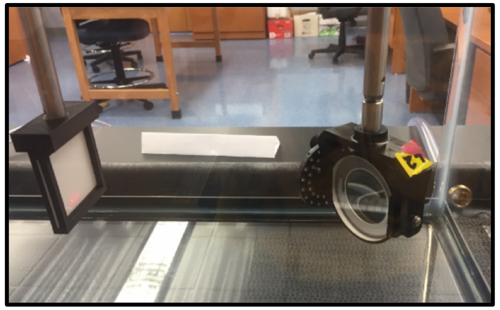
Lens measurements in ODU optical lab

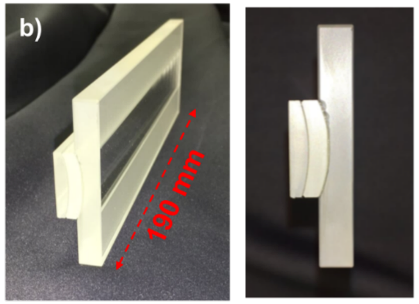
- Confirmed flat focal plane, matching prism shape
- Geant in excellent agreement with data

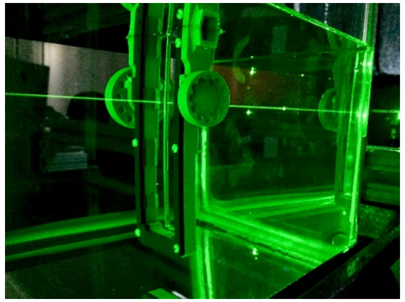
Laser setup to map the focal plane



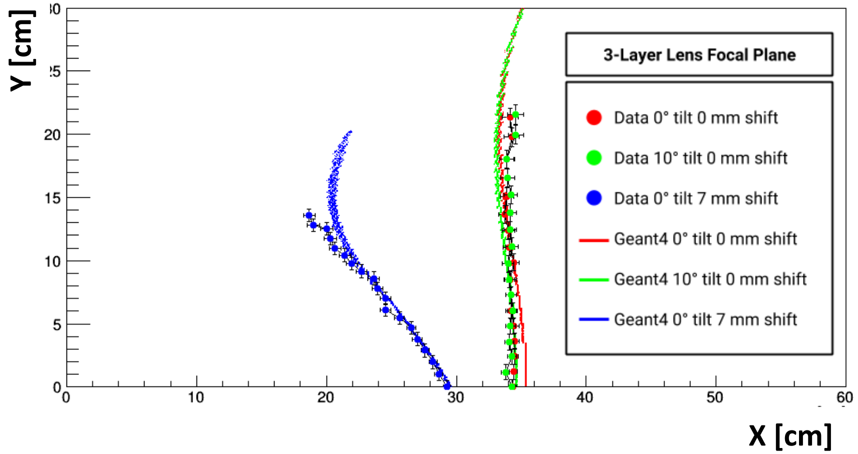




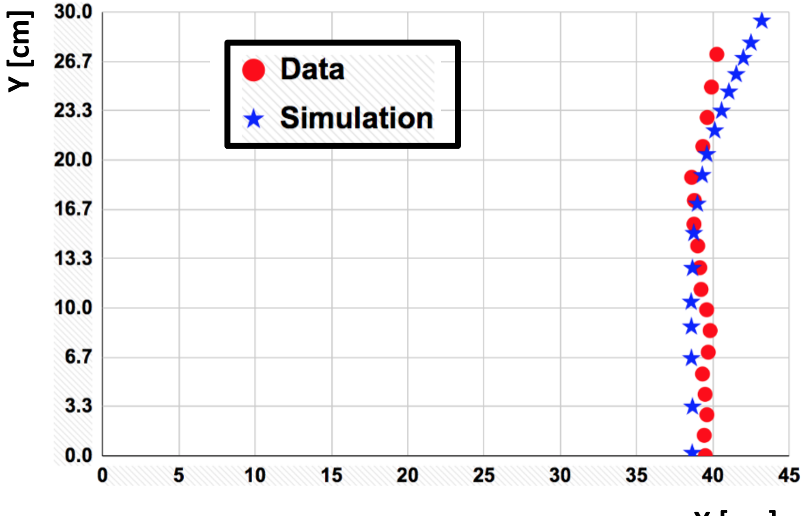




Spherical 3-layer lens prototype (a)



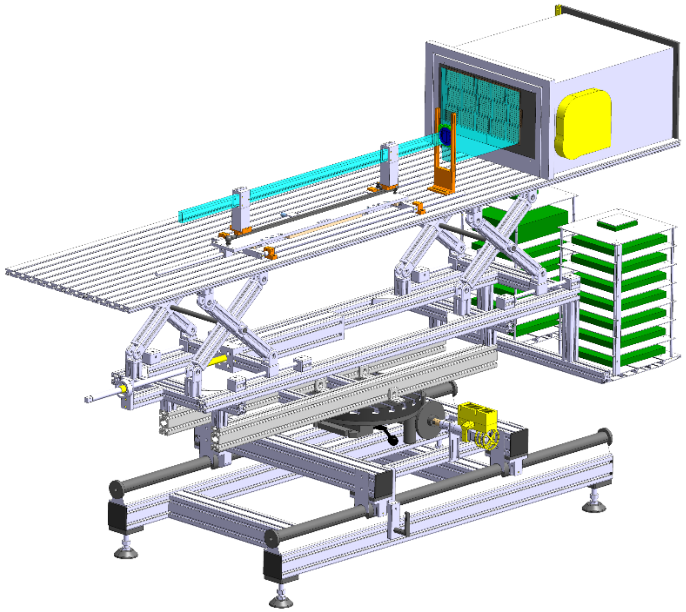
Cylindrical 3-layer prototype (b)



Experimental data vs. Geant

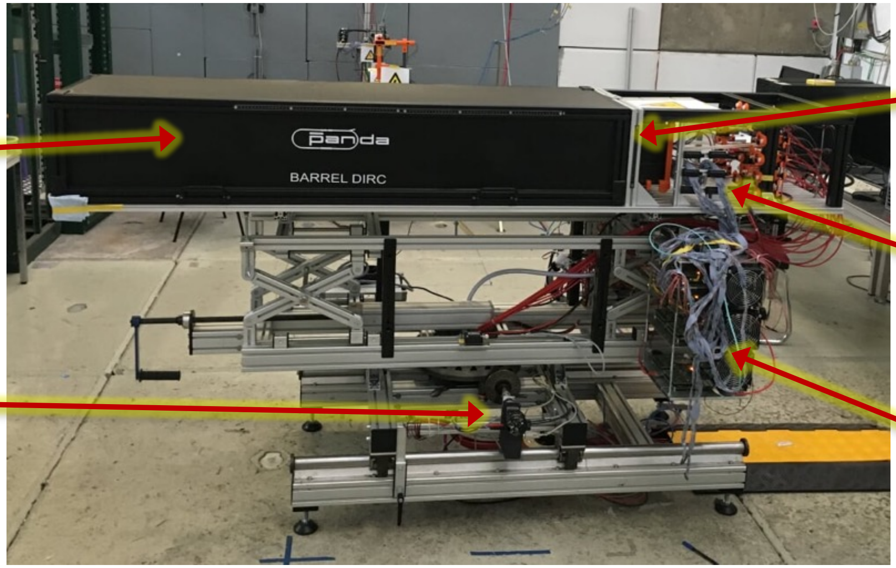
Transfer of the PANDA barrel DIRC prototype

- Modular design modified and improved over 11 years
- Achieved up to 4.8 s.d. π/K separation at 3.5 GeV/c and 20° polar angle in PANDA configuration (6mm pixels, 200ps photon timing)
- Available now due to conclusion of PANDA DIRC R&D
- Transfer will include support mechanics, bar, plate, prism, several MCP-PMTs (6mm pixels) and GSI readout electronics (~200ps photon timing)
- Start point for hpDIRC prototype, to be set up and tested at Stony Brook



Dark box for optics
(bar, lens, prism)

Rotation stage
(remote controlled)



MCP-PMT array

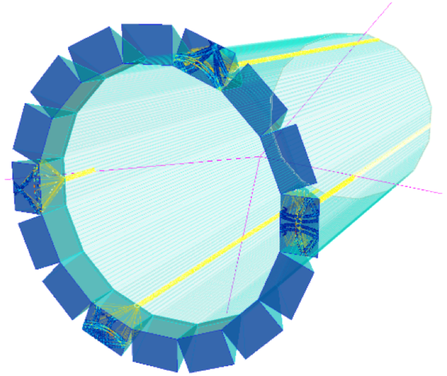
Frontend electronics (PADIWA)
(air-cooled)

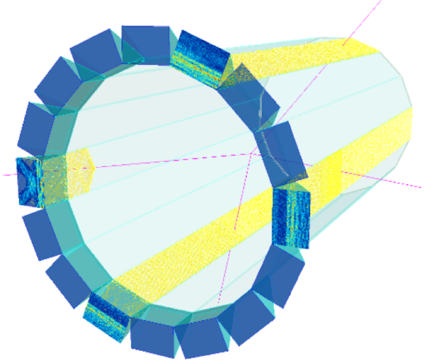
DAQ boards (TRB)

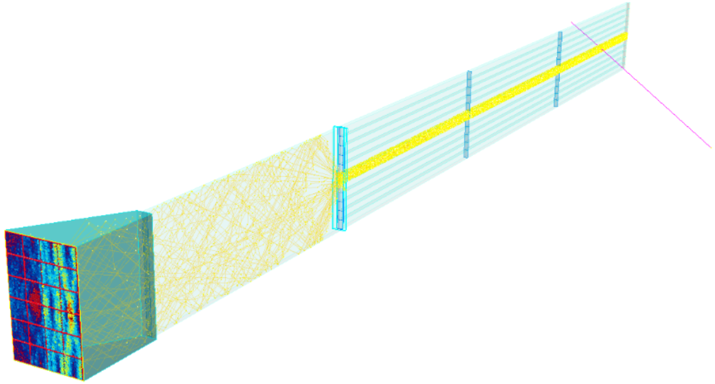
HPDIRC TDR TO DO LIST (1)

Achievements required for TDR readiness:

- Completion of hpDIRC design in simulation
  - Explore design options (bars vs. plates, hybrid combination of bars and plates, lens vs. focusing block)
  - Optimize design for cost and performance (number of bars and sensor pixels, expansion volume size)
  - Study PID performance in combination with other PID systems within the full detector frameworks and in the presence of expected backgrounds



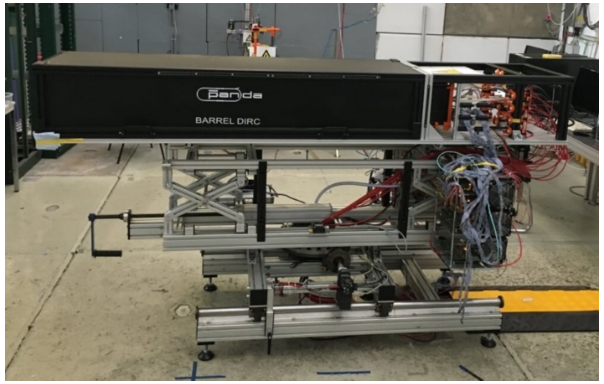




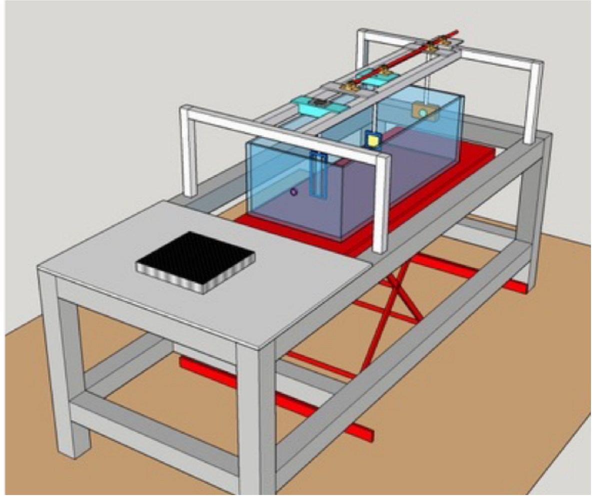
Geant4 examples of designs with: narrow bars | wide plates | hybrid design bars+plates

HPDIRC TDR TO DO LIST (2)

Achievements required for TDR readiness:



- Validation of PID performance with prototype in particle beams
  - Perform prototype/beamline simulation
  - Transfer PANDA Barrel DIRC prototype to CUA/Stony Brook
  - Acquire small-pixel sensors and fast readout electronics, set up DAQ/offline software
  - Perform initial beam test with PANDA components in 2021
  - Perform final/TDR beam test with small pixels and fast readout in 2022



- Validation of radiation-hard 3-layer spherical lens
  - Validate machinability of radiation-hard materials
  - Characterize focal plane in upgraded ODU laser setup

HPDIRC LIST OF REQUIREMENTS

Requirements to achieve TDR readiness by 2023:

- Financial support for PostDocs
  - FY20 request includes 50% PostDoc for prototype simulation and lab tests
  - Will need 100% PostDoc (or two 50% PostDocs) to perform hpDIRC simulation tasks and lead beam test activities in FY21-FY23, including analysis work
- Financial support for detector hardware
  - FY20 request includes funding (via USC budget) for 1024-channel Photonis Planacon XP85122 to start tests and to prepare SiREAD readout electronics at UHawaii.
  - FY20 request already includes funding for shipment of the PANDA Barrel DIRC prototype and instrumentation for prototype evaluation equipment
  - Will need to start procurement of MCP-PMTs (commercial or LAPPD) in FY21 for beam test in 2022
- Financial support for travel to beam tests in FY21 and FY22
- Beam time allocation at FermiLab in 2021 and 2022

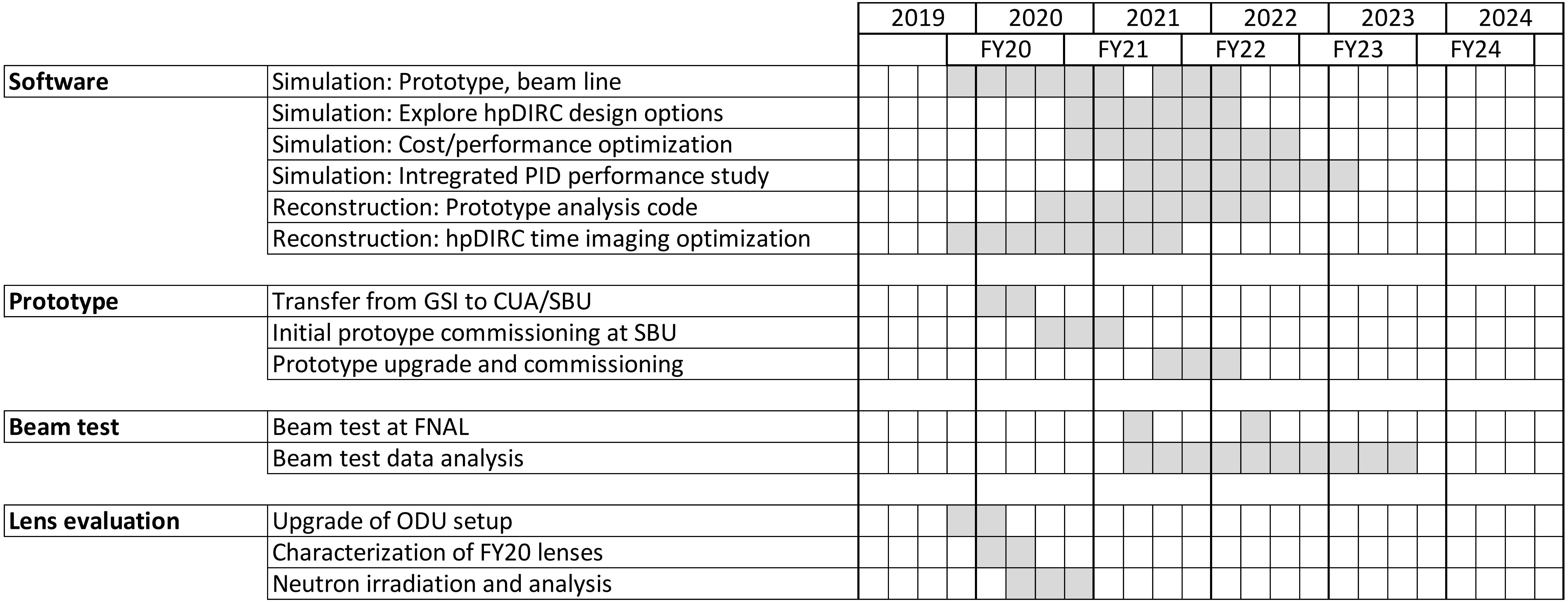
hpDIRC List of Requirements

Requirements to achieve TDR readiness by 2023:

R&D work package	FTE request	Invest/consumable request	Comment
Prototype/beamline simulation, lens measurements, radiation tests	0.5 ($60k/yr)		FY20-22
Design optimization	0.5 ($65k/yr)		FY21-23
Prototype setup and beam tests	0.5 ($65k/yr)		FY21-23
Lens validation		$25k	FY20
Prototype transfer & initial setup (shipping, equipment)		$39k	FY20
(Photonis Planacon XP85122 MCP-PMT)			FY20, part of high-B request
Sensors for 2022 beam test *(possibly also usable for mRICH/dRICH test)*		$200k	FY21/FY22, assumes commercial MCP-PMTs *(cost expected to be lower if LAPPDs are available)*
(Readout for 2022 beam test)			FY21/FY22, will be part of electronics request
Beam instrumentation, incidentals		$15k	FY21&FY22 each
Travel to 2021 and 2022 beam tests		$10k-$15k	FY21&FY22
Contingency: possible 2023 beam test (if needed)		$25k	FY23
Other travel (*measurements at ODU/CUA/BNL, annual meeting)*		$15k/yr	FY20-23
Other consumables, lab equipment, incidentals		$10k/yr	FY20-23

**FY21-23 items listed are without in-kind contributions from the hpDIRC institutions*

Schedule to achieve TDR readiness by 2023



HPDIRC SUMMARY

The hpDIRC activity is in a good position to achieve TDR readiness by 2023

but needs additional resources beyond current funding levels to accelerate the progress

- Initial generic design meets PID requirement in simulation
- Geant simulation has been validated with PANDA Barrel DIRC prototype at CERN

Remaining technical risks:

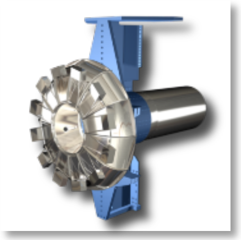
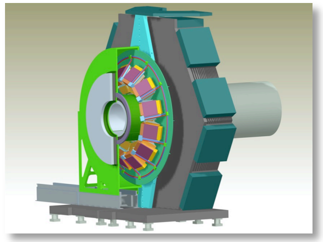
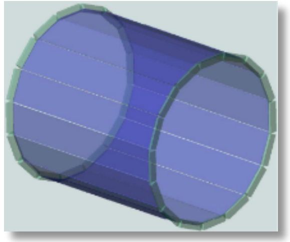
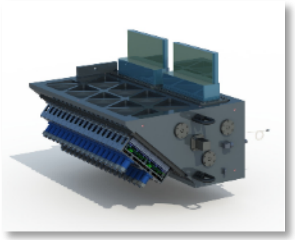
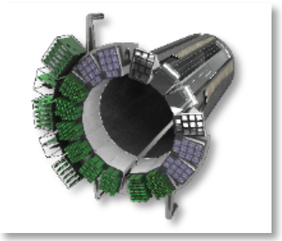
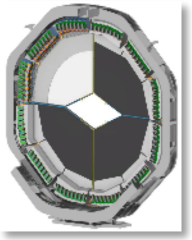
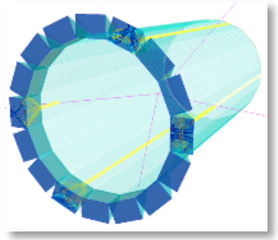
- Quality of radiation-hard lens prototypes (will be studied in FY20)
- Availability of sensor solution for possible 3T magnet configuration
  (smaller-pore MCP-PMTs and SiPM will be investigated in eRD14)
- Availability of fast high-density readout electronics for beam test

Requesting additional funding for PostDocs, invest, and travel to reach 2023 goal

Thank you for your attention

Extra Material

DIRC CONCEPT

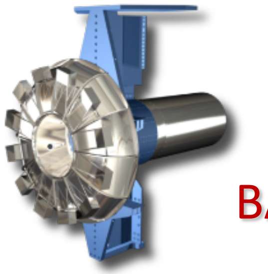








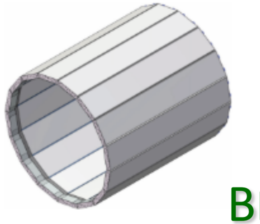
BaBar | SuperB | Belle II | GlueX | panda | panda | Electron Ion Collider

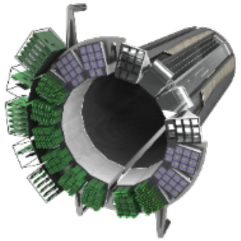
Detection of Internally Reflected Cherenkov Light

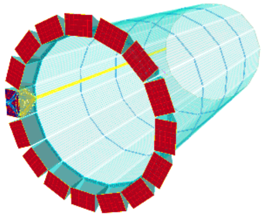
- DIRC counters have become a popular solution for hadronic PID over the past two decades.
- DIRCs are radially very compact, providing more space for calorimeters or tracking detectors.
- BaBar DIRC was the first DIRC, PID in barrel region, very successful, π/K up to ~4 GeV/c (1999-2008).
- Prompted DIRC interest by several experiments: Belle II, SuperB, PANDA, GlueX, and others;
  R&D to make DIRC readout more compact, expand momentum reach, use for endcap PID.
  Key technology: multi-pixels sensors, small pixels, fast timing, tolerance of high rates and B fields.
- Very active and complex R&D, applying advances in sensors, electronics, imaging, algorithms.

Barrel DIRC Counters







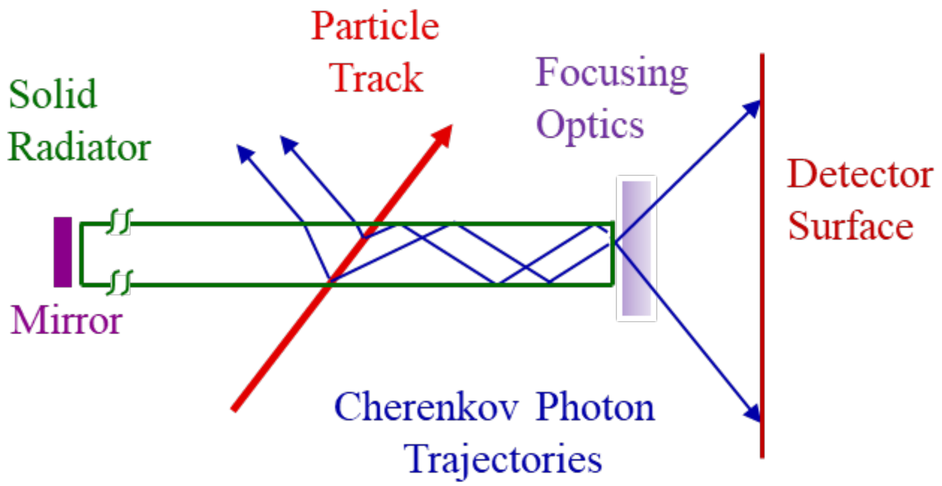


	BaBar DIRC	Belle II TOP	PANDA Barrel DIRC	EIC hpDIRC
Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*	Narrow bars *(35mm)*
Barrel radius	85cm	115cm	48cm	100cm
Bar length	490cm *(4×122.5cm)*	250cm *(2×125cm)*	240cm *(2×120cm)*	420cm *(4×105cm)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*	176 *(16×11 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	~11k MCP-PMT pixels	~100k 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	Installed 2016	Installation 2023/24	TDR-ready in 2023

DIRC CONCEPT

- Charged particle traversing radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.

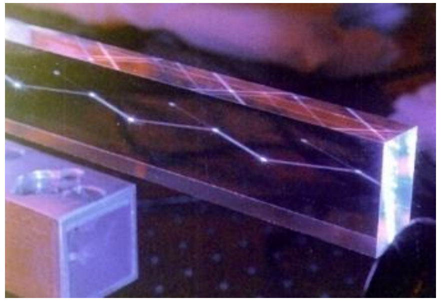
- For $n>\sqrt{2}$ some photons are always totally internally reflected for $\beta\approx 1$ tracks.



- Radiator and light guide: bar, plate, or disk made from Synthetic Fused Silica ("Quartz") or fused quartz or acrylic glass or …

- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

→ Major technological challenge for BaBar – is it really possible to efficiently and precisely conserve angle during up to 2000 reflections? ... and maintain that surface quality for 10+ years?



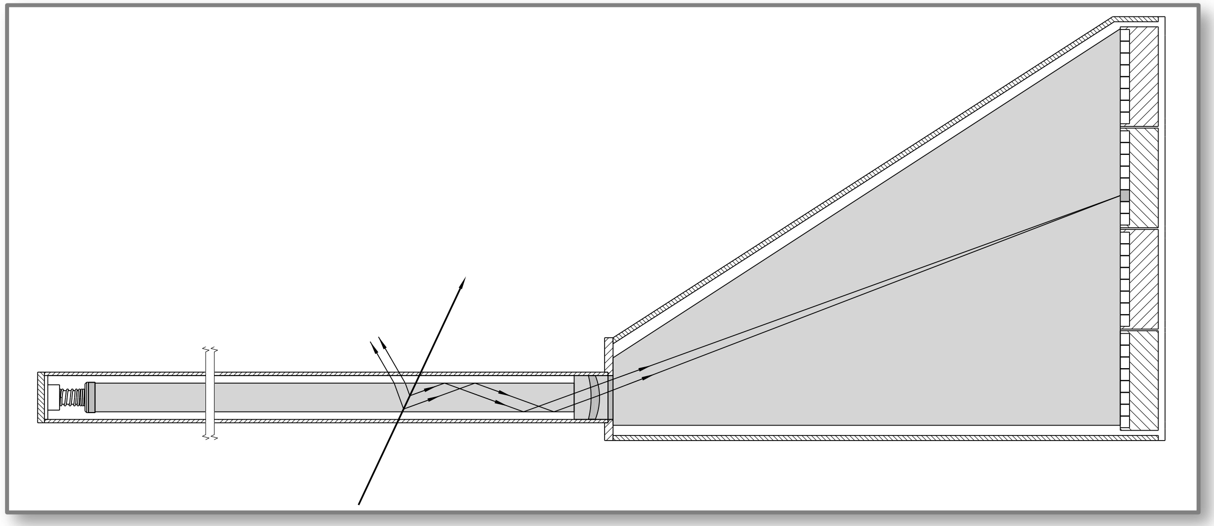
DIRC Concept

- Mirror attached to one bar end, reflects photon back to readout end.

- Photons exit radiator via optional focusing optics
  into expansion region, detected
  on photon detector array.

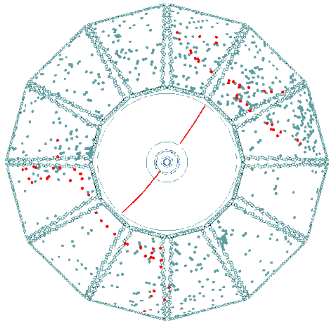
- DIRC is intrinsically a 3-D device,
  measuring: x, y, and time of Cherenkov
  photons, defining θ_c, ϕ_c, $t_{propagation}$.

- Ultimate deliverable for DIRC: PID likelihoods.

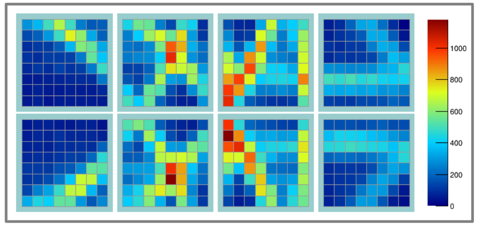


DIRC hit patterns are not typical Cherenkov rings.

Different DIRCs use different reconstruction approaches
to provide likelihood for observed hit pattern (in detector space or in
Cherenkov space) to be produced by e/μ/π/K/p plus event/track background.
DIRC requires momentum and position of particle measured by tracking system.



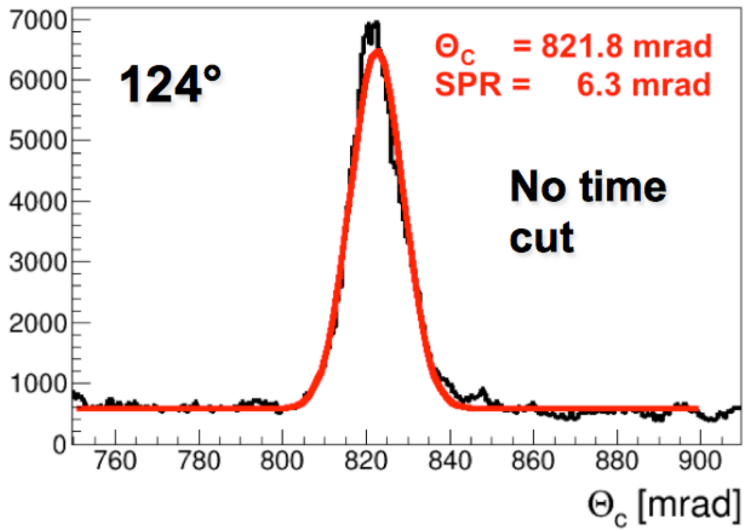
Typical event
BaBar DIRC

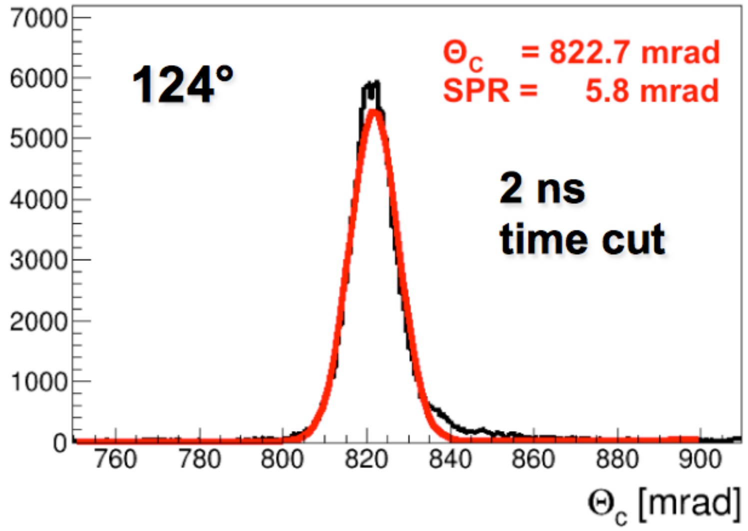


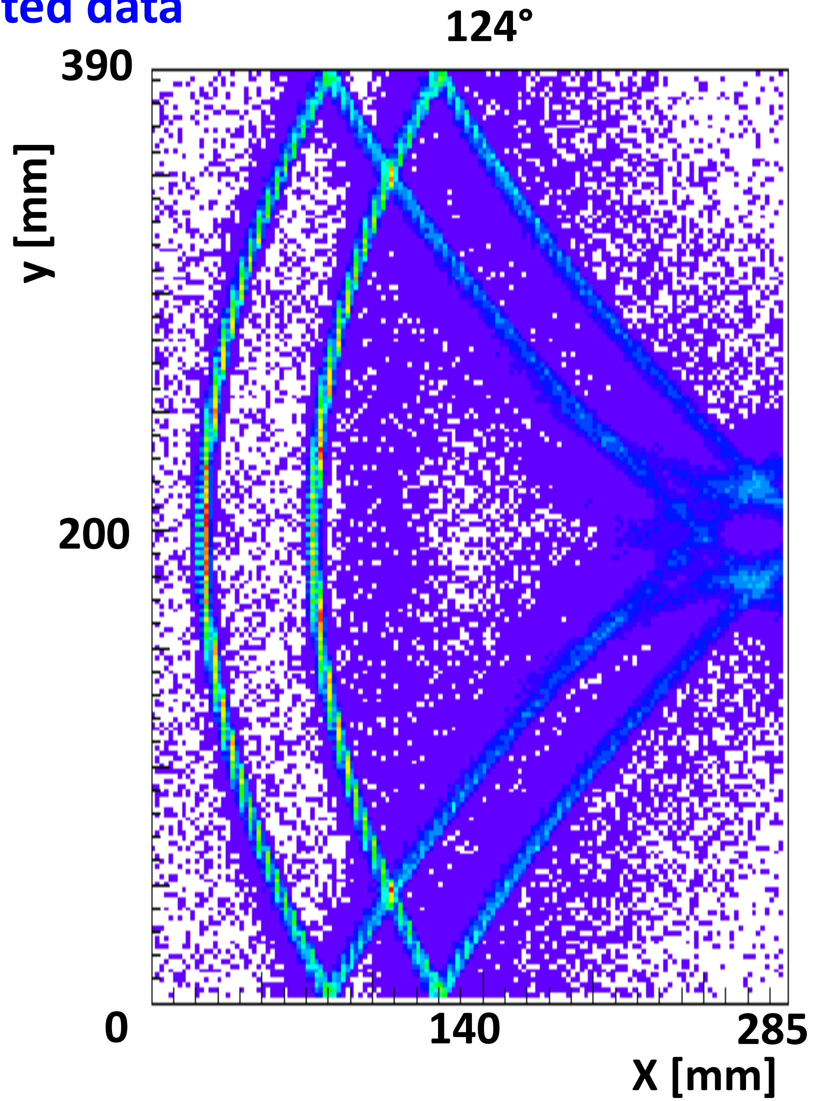
Accumulated hit pattern
PANDA Barrel DIRC

HPDIRC Simulation: Performance

Simulated data





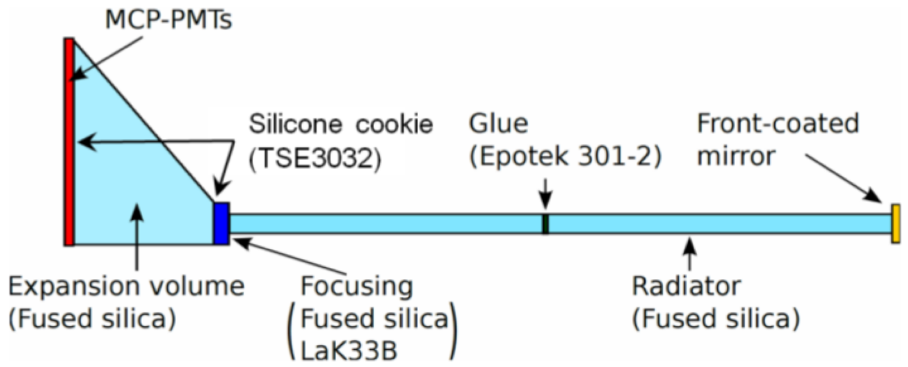


HPDIRC SIMULATION: DESIGN OPTIONS

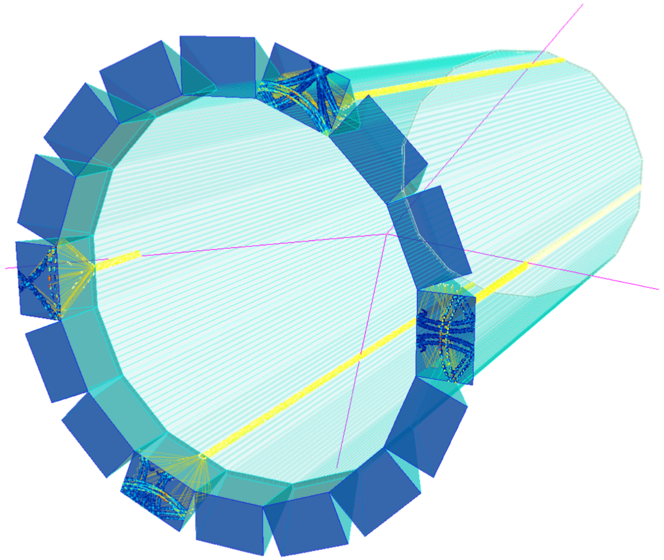
- Number of sectors and radius not final
- Bar width, pixel size to be optimized
- Prism size to be optimized: depth, opening angle
- Major decision between radiator bars and plates

  has to made, investigate hybrid “ultimate” design

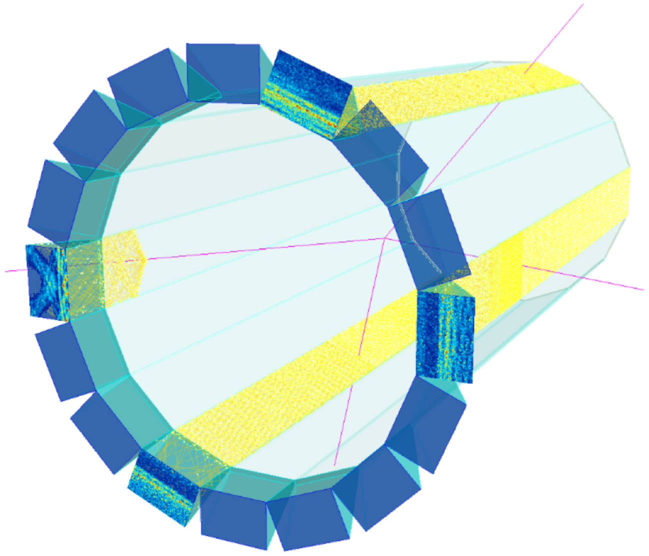
Simplified view of Geant components for one sector:



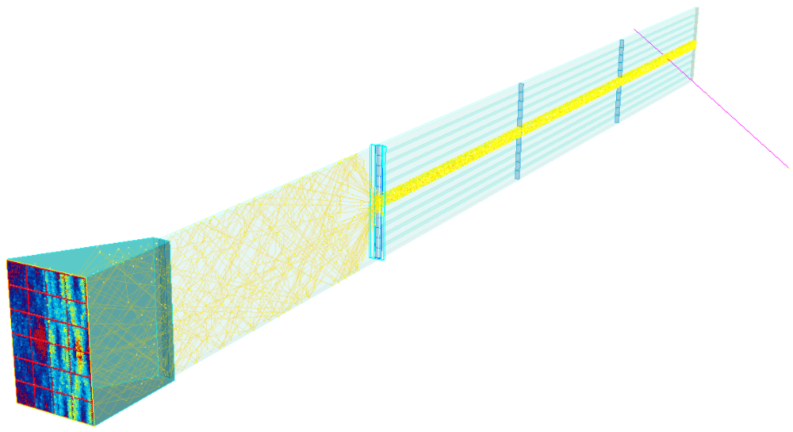
GEANT4 visualization of the designs:



11 narrow bars in each sector



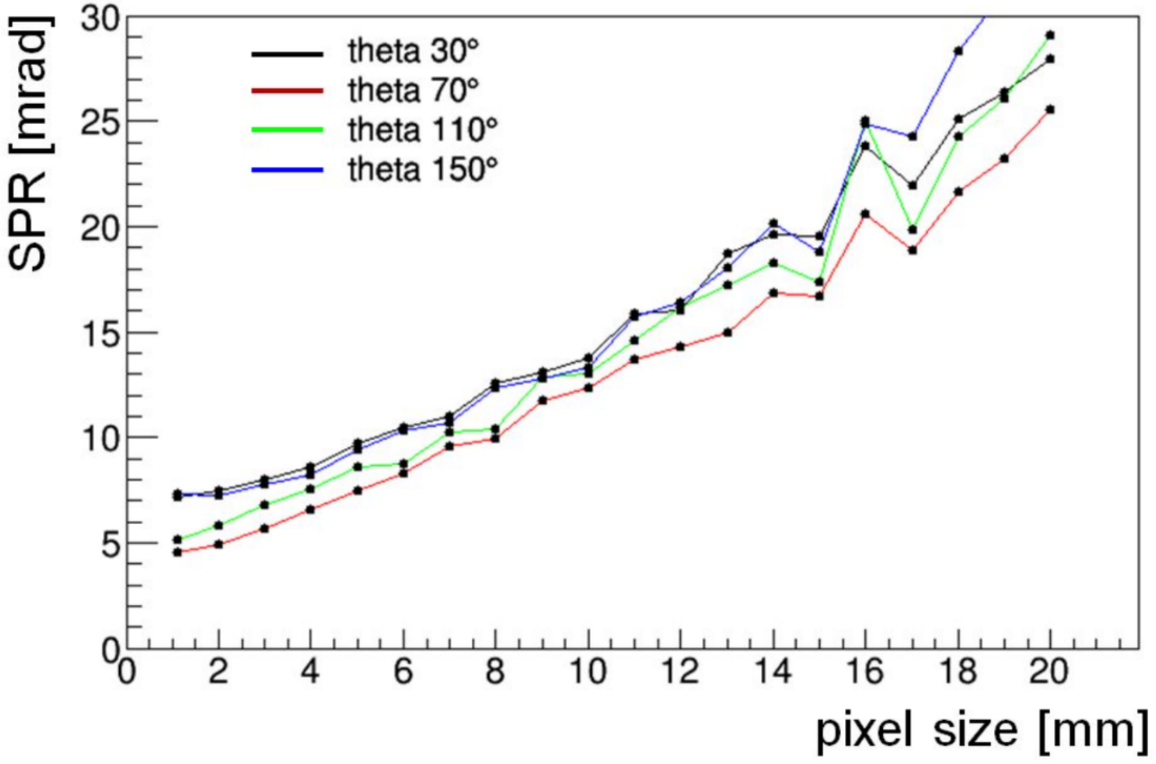
1 wide bar (plate) in each sector



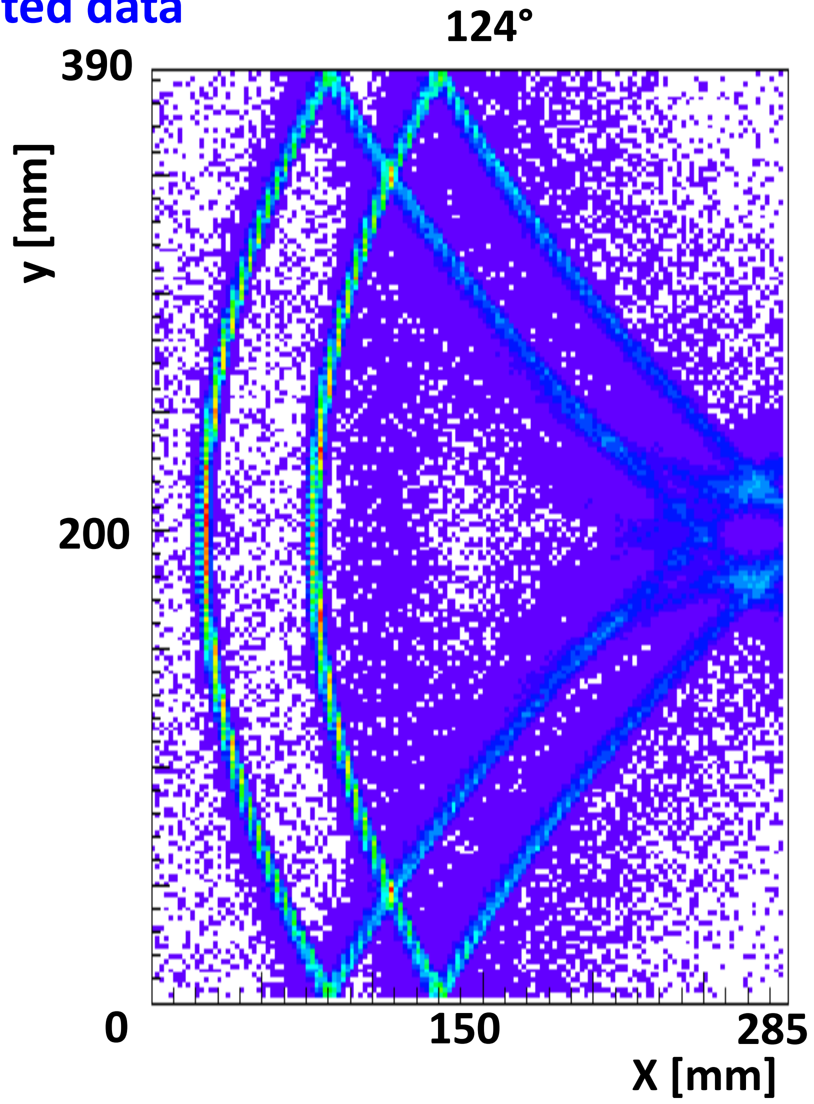
Hybrid of bars and plate in each sector

hpDIRC Simulation: Pixel Size

Influence of the pixel size on SPR for selected track polar angles

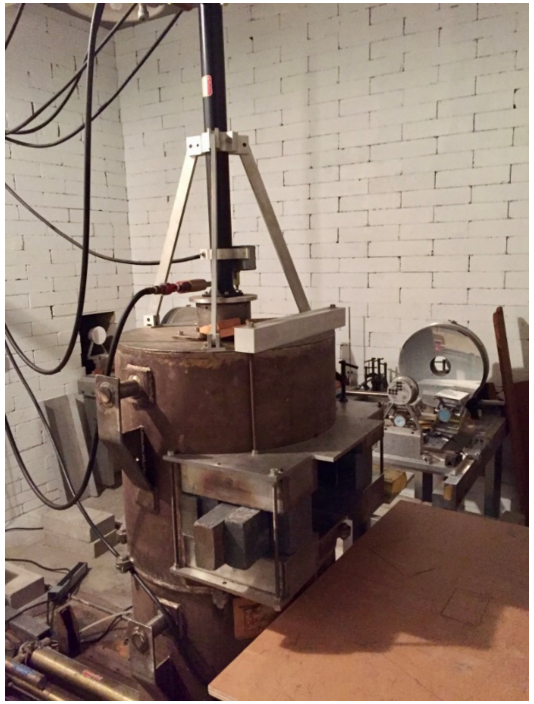


Simulated data

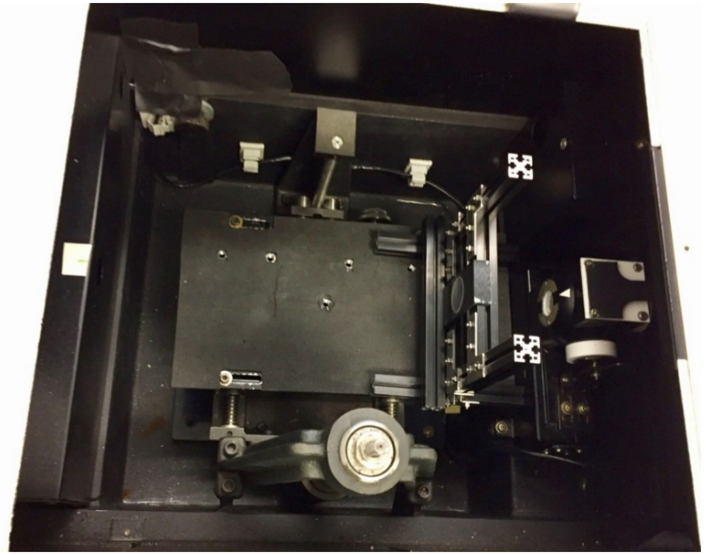


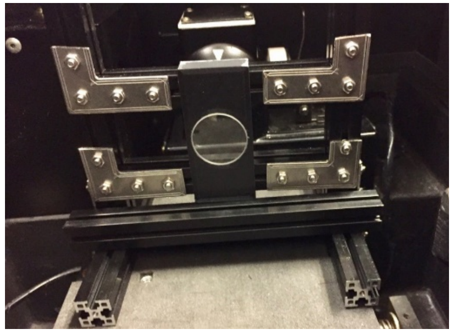
hpDIRC Radiation Tests

Co^{60} Chamber



Monochromator



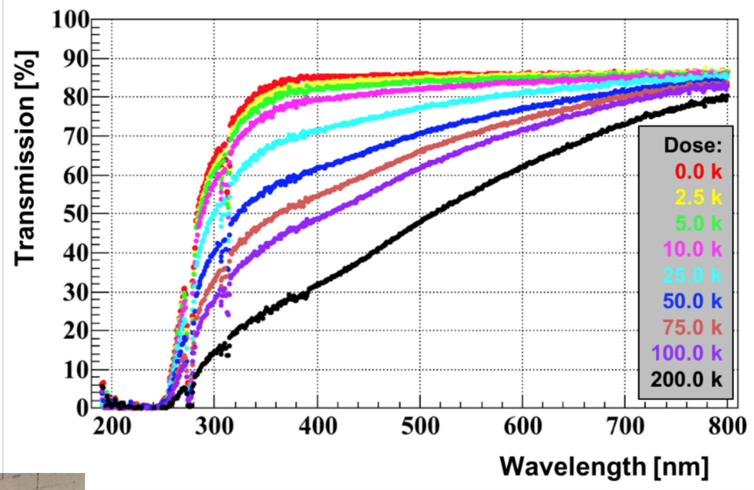


- ^{60}Co **irradiation results**

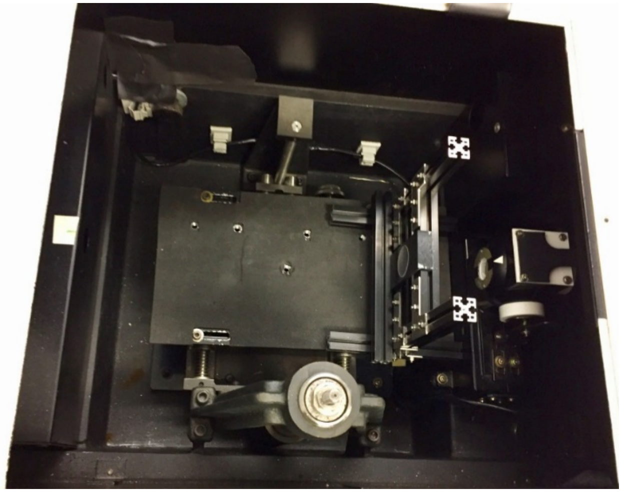
- Radiation damage quantified by measuring the transmission in the 190-800 nm range in a monochromator

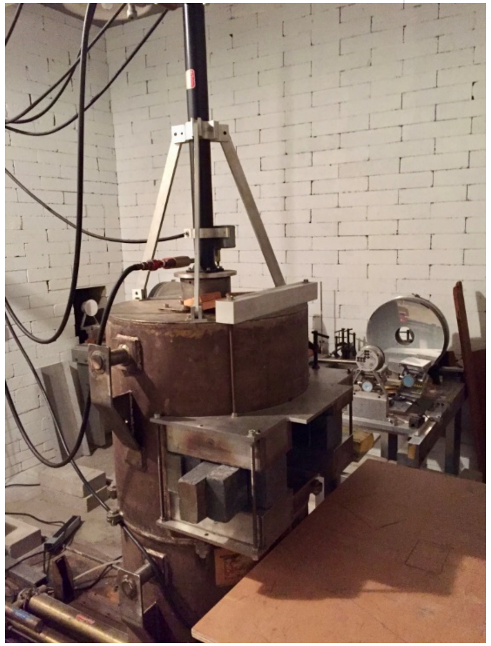
- Transmission loss of alternate lanthanum crown glass material (S-YGH51) confirmed

S-YGH51 (NLaK33 equivalent)



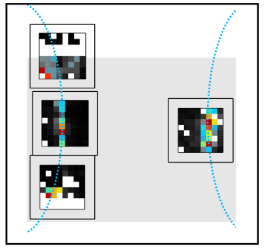
Monochromator

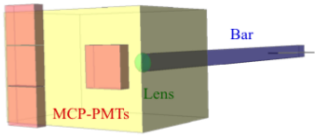




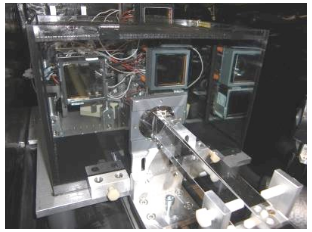
Co^{60} Chamber

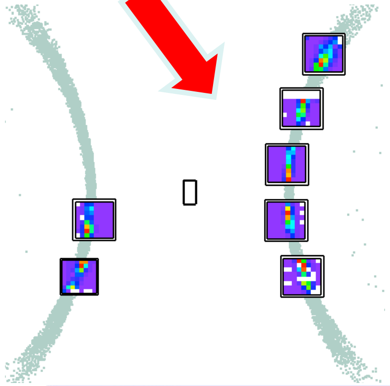
PANDA BARREL DIRC BEAM TESTS



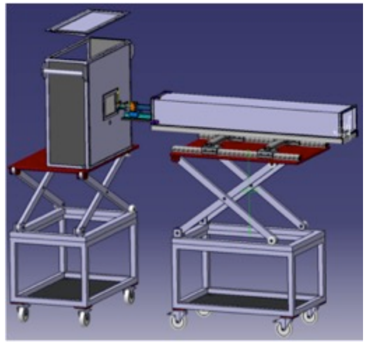


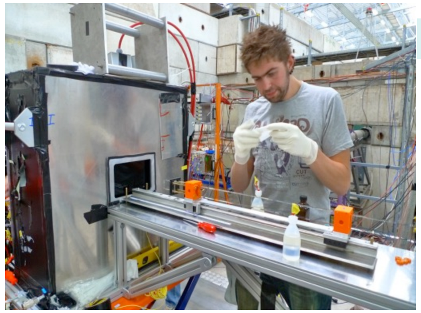
GSI
2008/2009

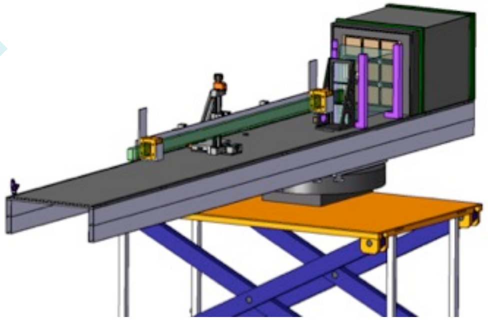




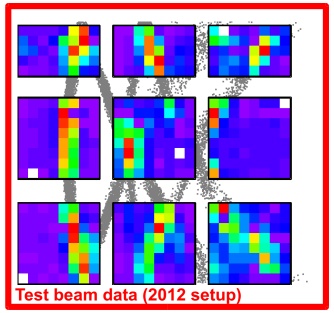
GSI, CERN
2011

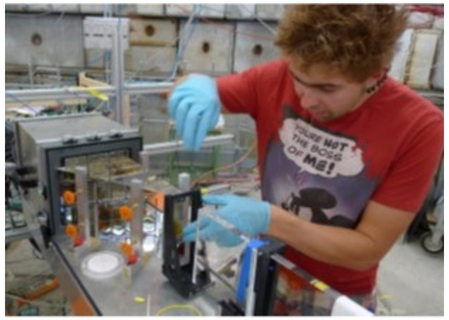


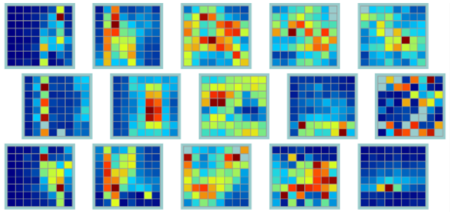




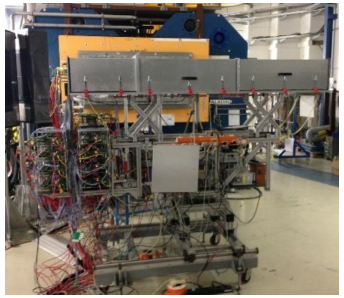
CERN
2012

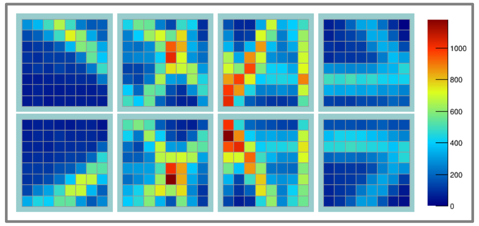




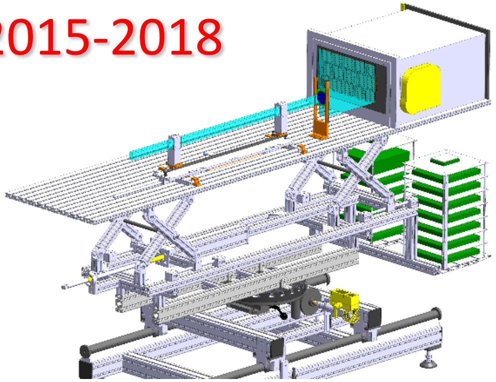


GSI 2014





CERN
2015-2018



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

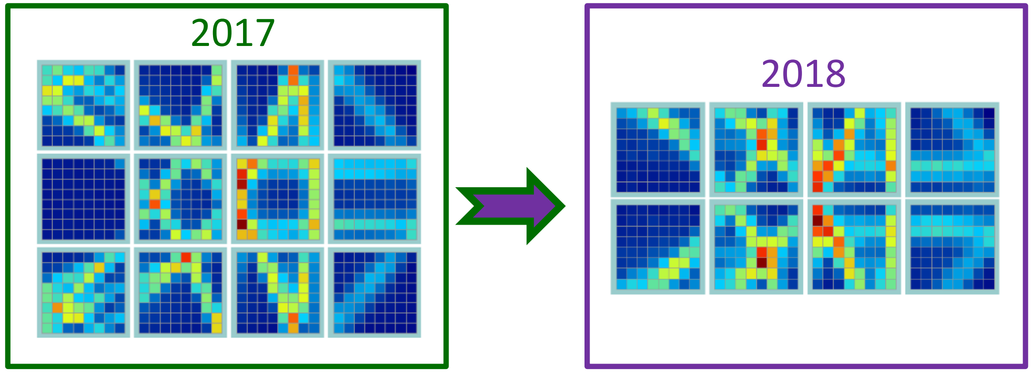
PANDA Barrel DIRC beam test at CERN in 2017 and 2018

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

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

no significant impact on PID ⟹ major cost savings.

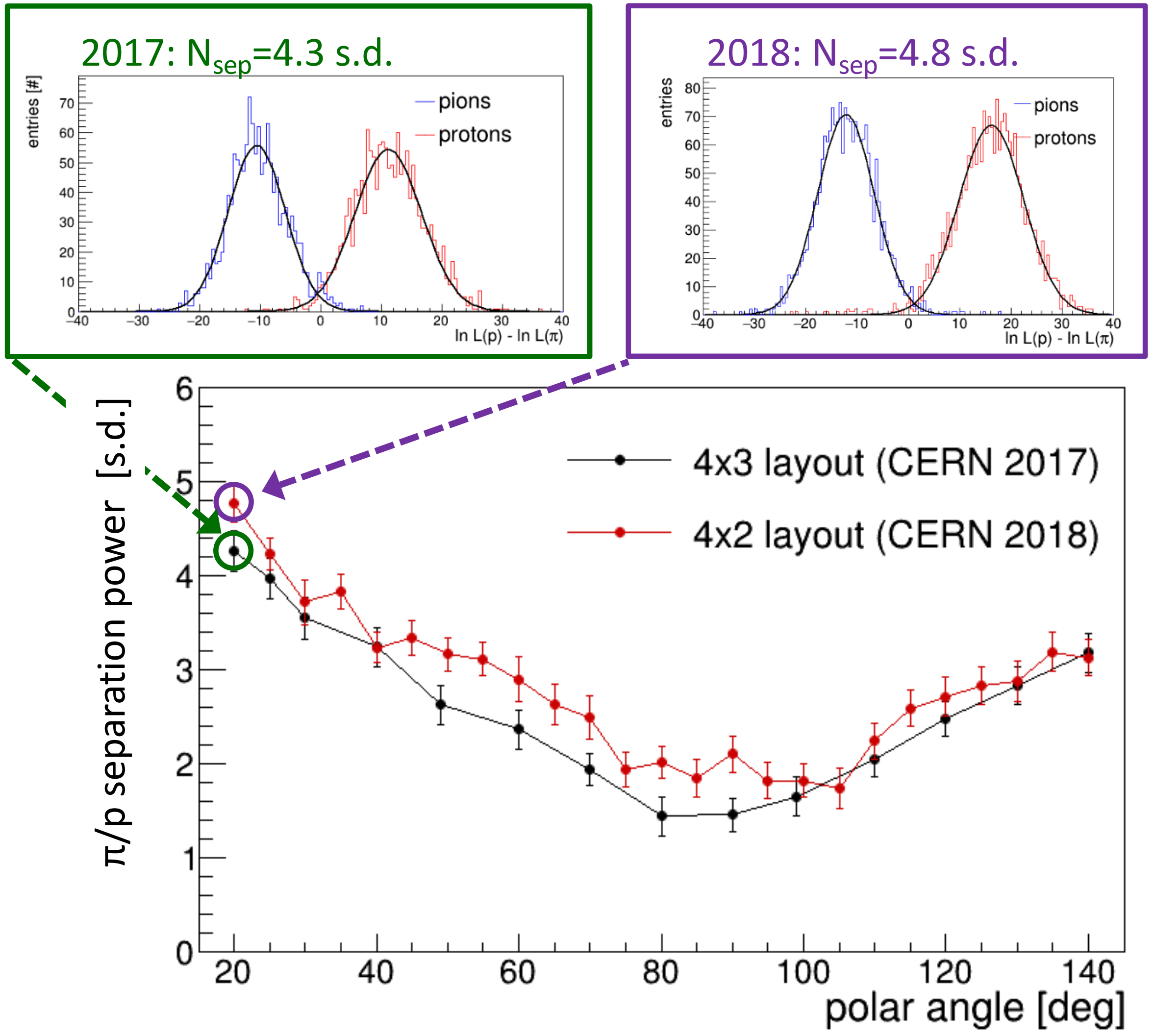
2018: beam test with reduced coverage to 8 MCP-PMTs (2x4)



accumulated hit pattern

beam data, 7 GeV/c

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



Found expected photon loss rate (30-40%)

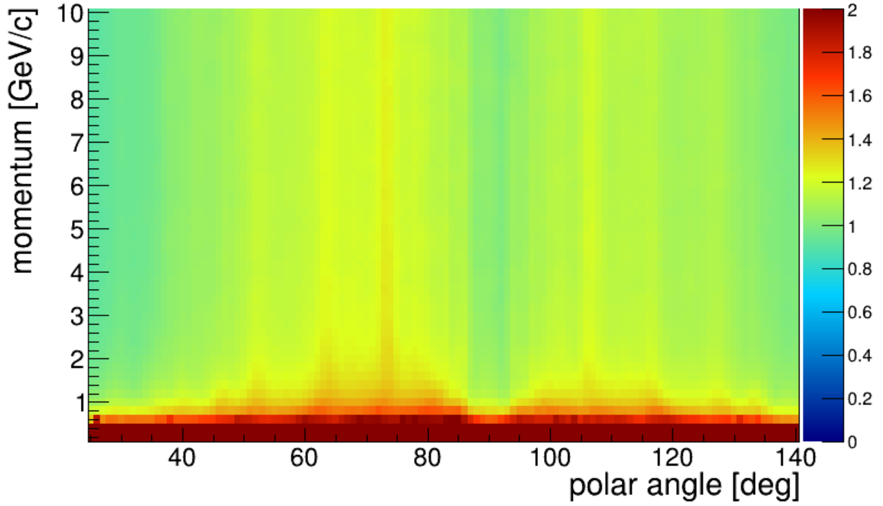
with no observable loss of PID performance.

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

High-performance DIRC: fast simulation

- A fast simulation C++ class was designed and released to the EIC software community
- It is available in github, may be of interest to the SCTF community
- Geant4 simulation of the current hpDIRC baseline design and a pixel-based reconstruction are used to determine
  - the Cherenkov angle resolution per photon
  - the number of detected Cherenkov photons per particle
- these values are used to calculate the Cherenkov angle resolution per particle and, in combination with the assumed tracking resolution, the separation power in units of standard deviations for (e, μ, π, K, p)

Geant4 Cherenkov angle resolution per particle



Example: derived π/K separation power
(tracking resolution of 0.5 mrad)