eRD4: DIRC-based PID for the EIC central detector

— Progress Report eRD4.1, eRD4.2

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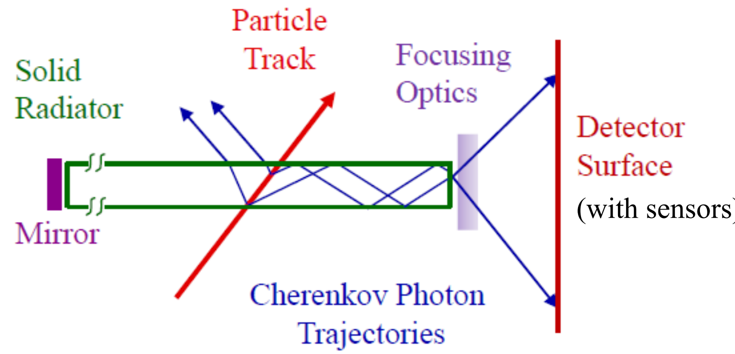
Generic Detector R&D for an Electron Ion Collider
Advisory Committee Meeting, BNL, July 9-10, 2015

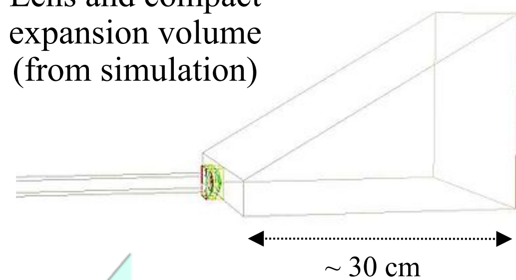
DIRC summary, eRD4.1

- A DIRC can provide a radially compact particle identification solution for the EIC central detector
- The goal of this R&D is to adapt the DIRC technology to the EIC requirements (performance and integration)
- Simulations, supported by beam tests, show that using novel lenses and a compact expansion volume one could reach a resolution of 1 mrad, corresponding to a 3σ K/π separation at 6 GeV/c (and greater at lower momenta)

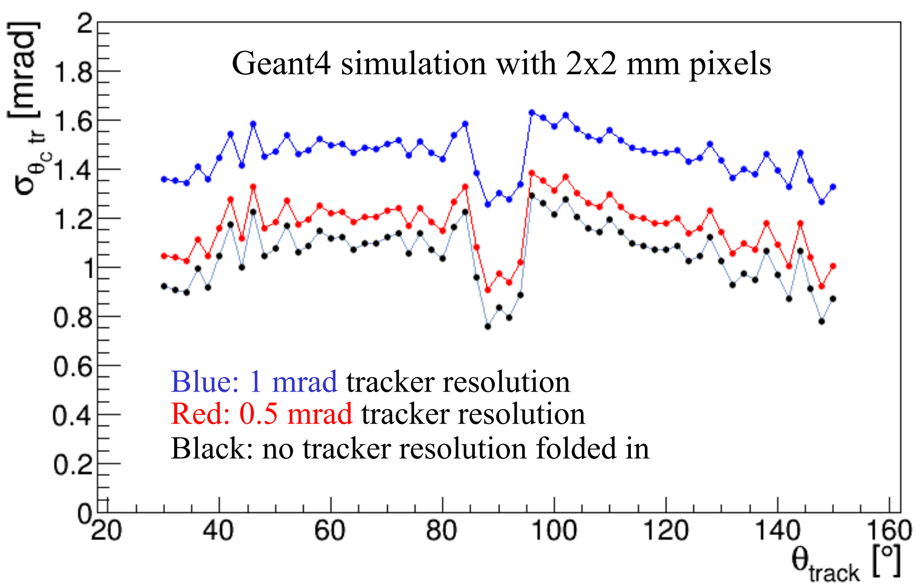
General layout of a DIRC with lens focusing

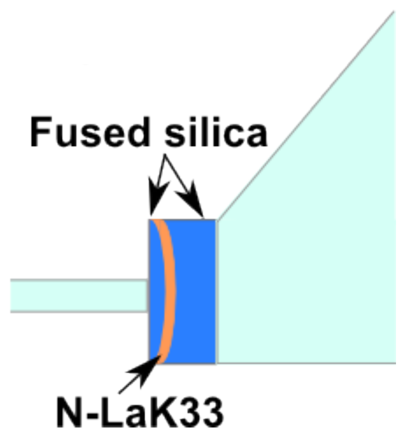


Lens and compact expansion volume (from simulation)

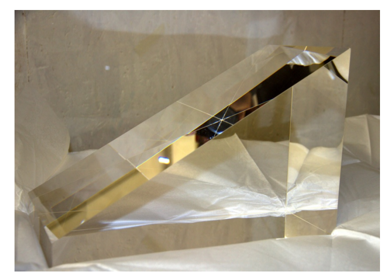


Cherenkov angle resolution (for each track)





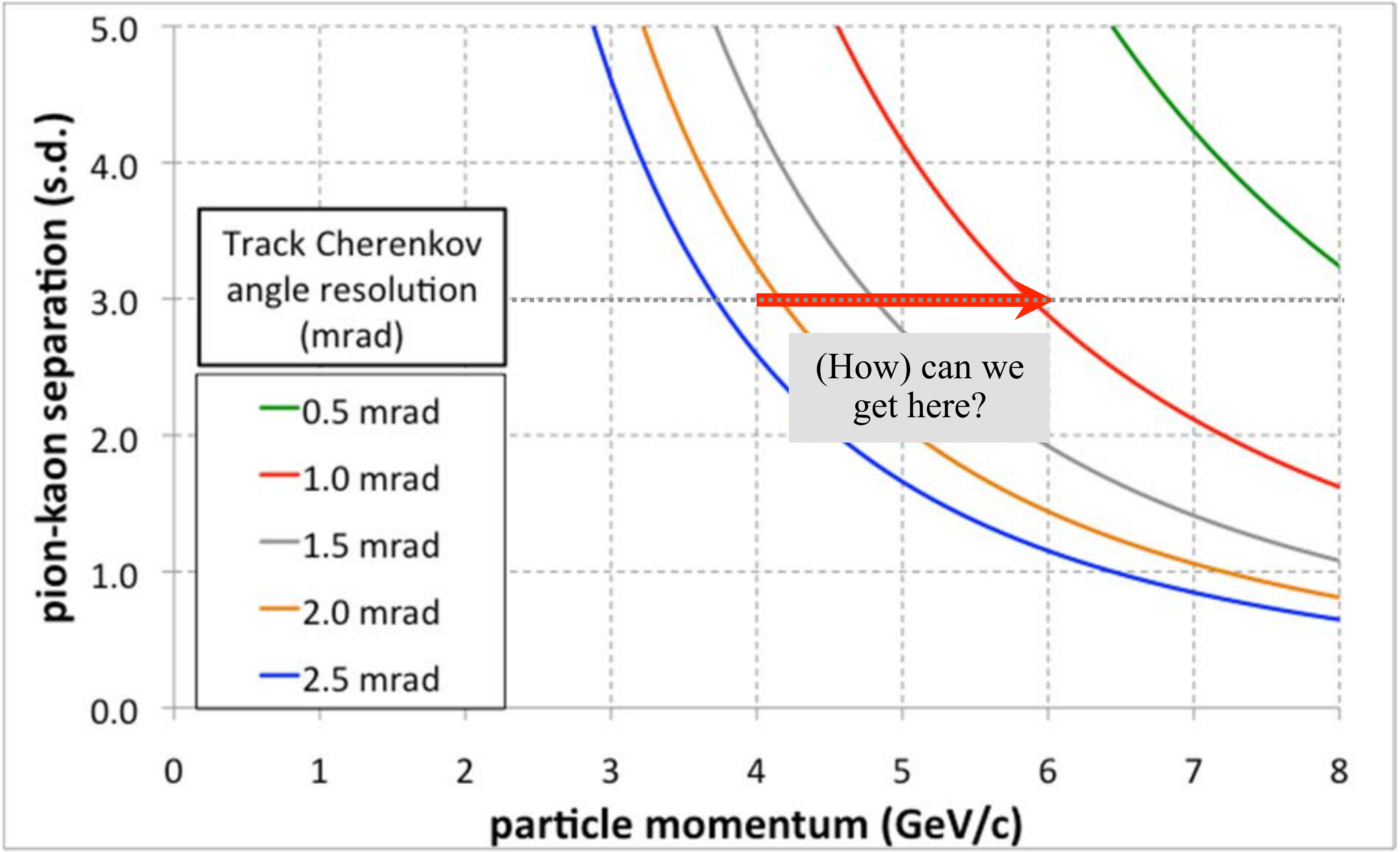
Novel high index of refraction lens (with no air gaps)



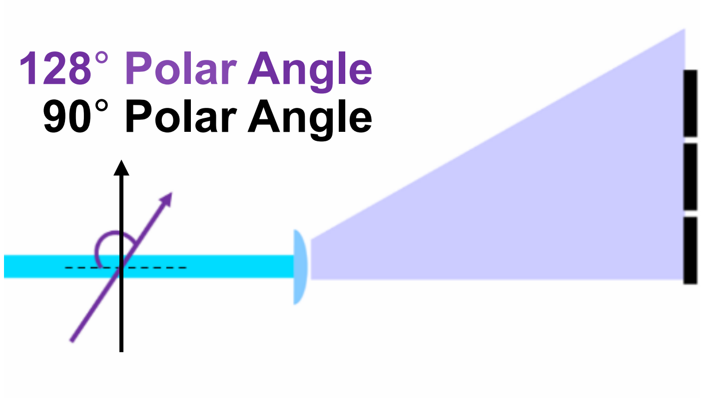
Compact expansion volume of fuzed silica (quartz)

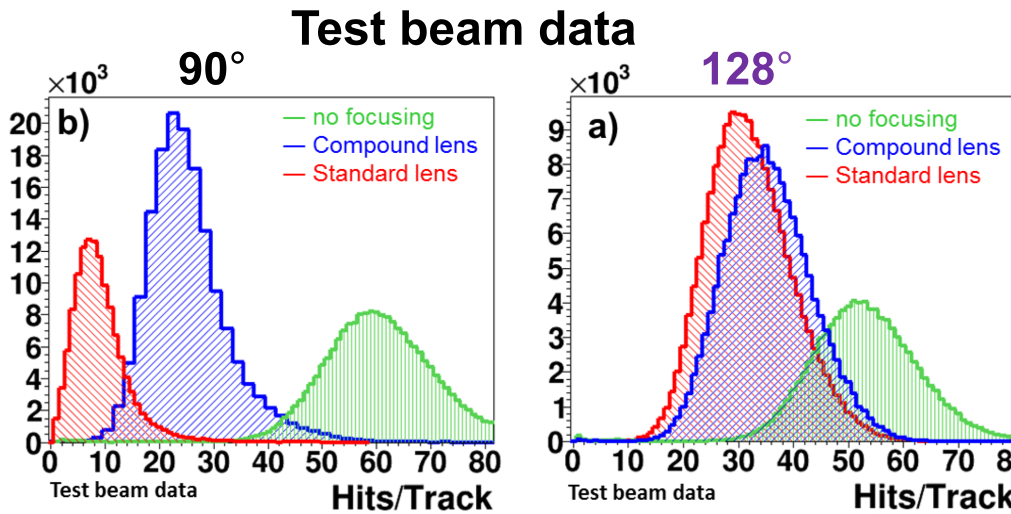
Tentative performance goal for DIRC@EIC

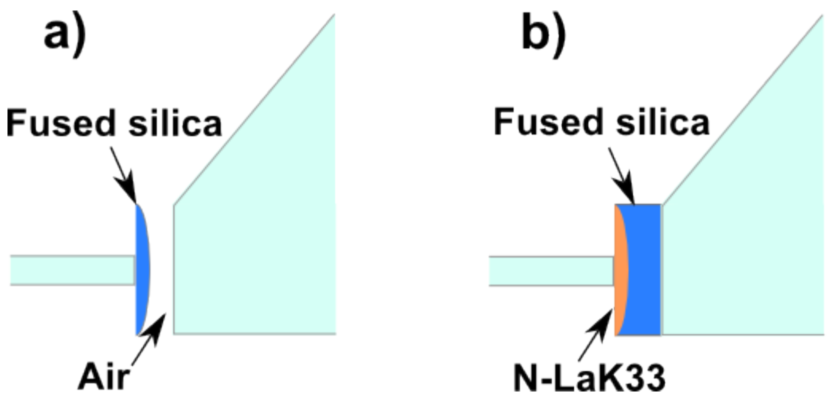
- π/K ID as a function of the θ_c resolution

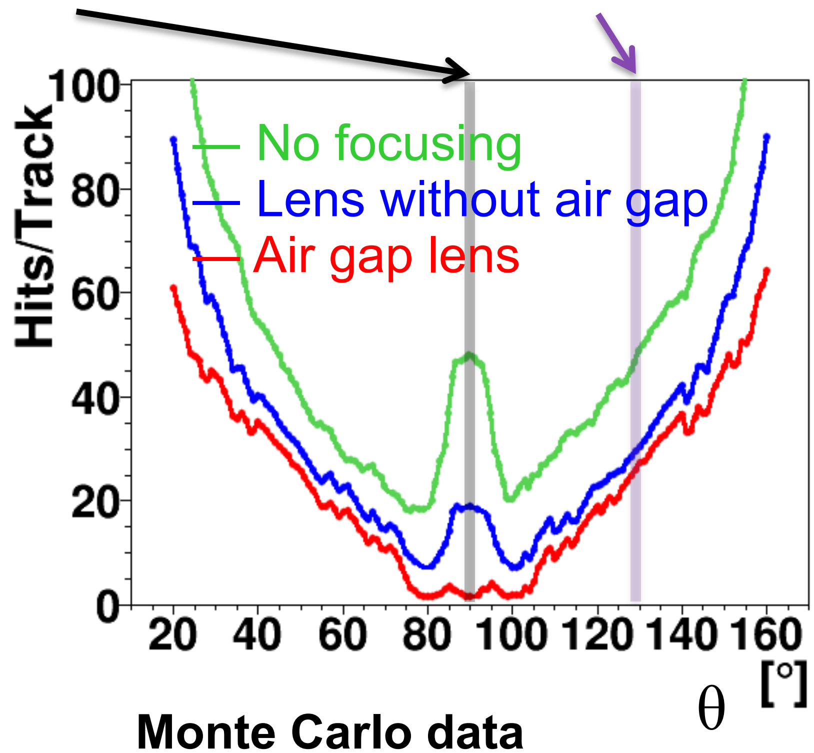


Early lenses with and without air gap



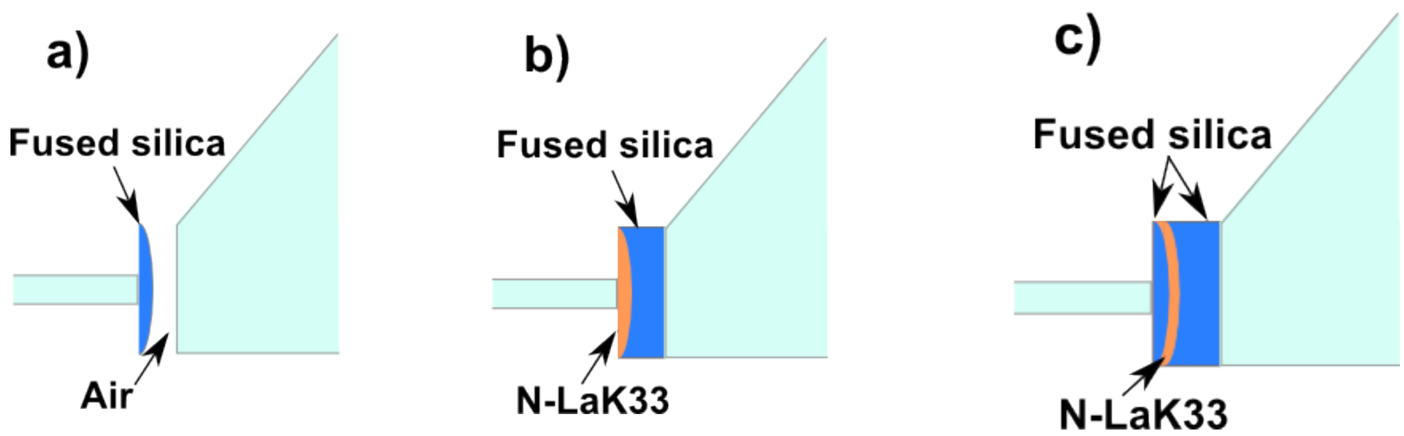




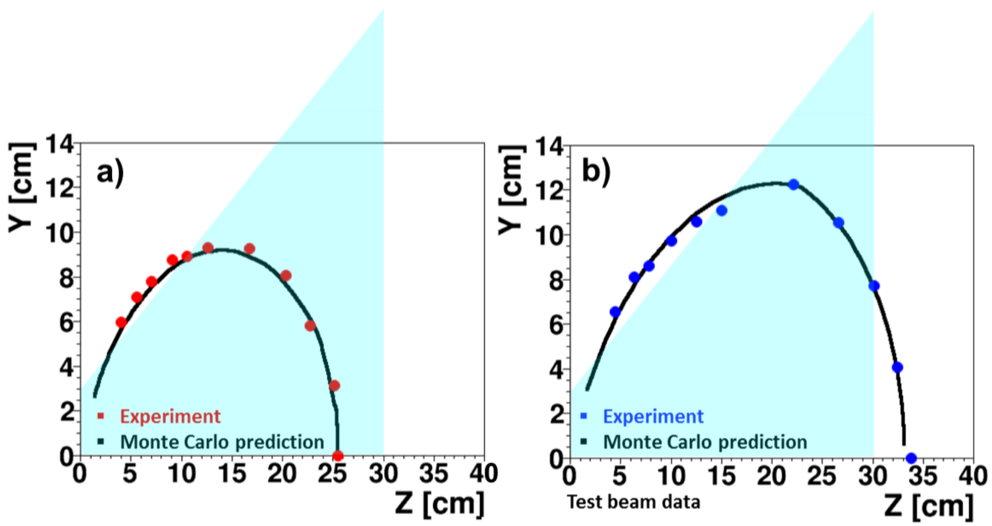


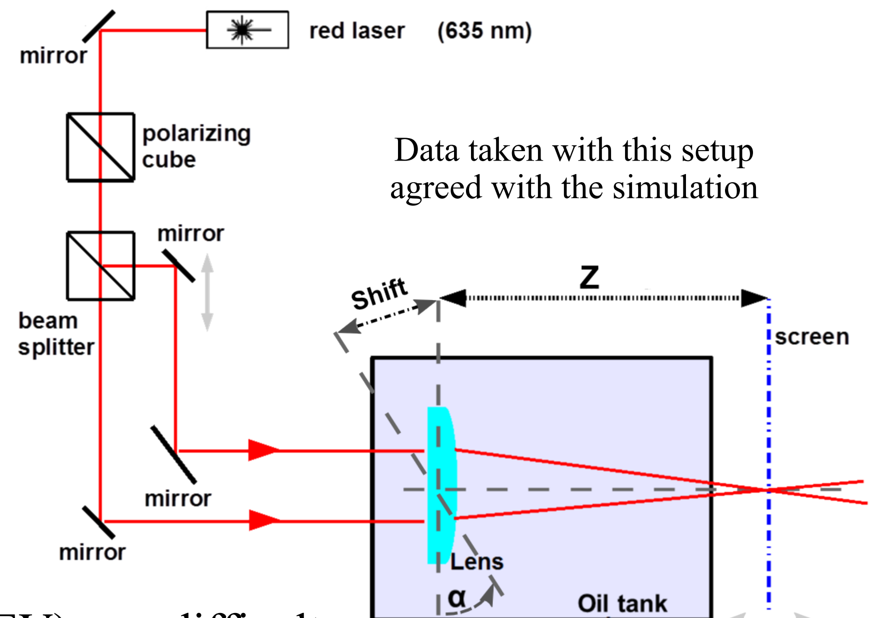
- A 2-layer lens without an air gap could addressed the photon yield at 90°, but the resolution (incl. the kaleidoscopic effect) was not satisfactory for steeper angles
  - A 3-layer lens with a flat focal plane was needed!

Lens evolution aimed to catch photons around 90°



- c) is a 3rd generation lens developed as part of the EIC R&D
- It resolves photon yield issues and improves single-photon resolution

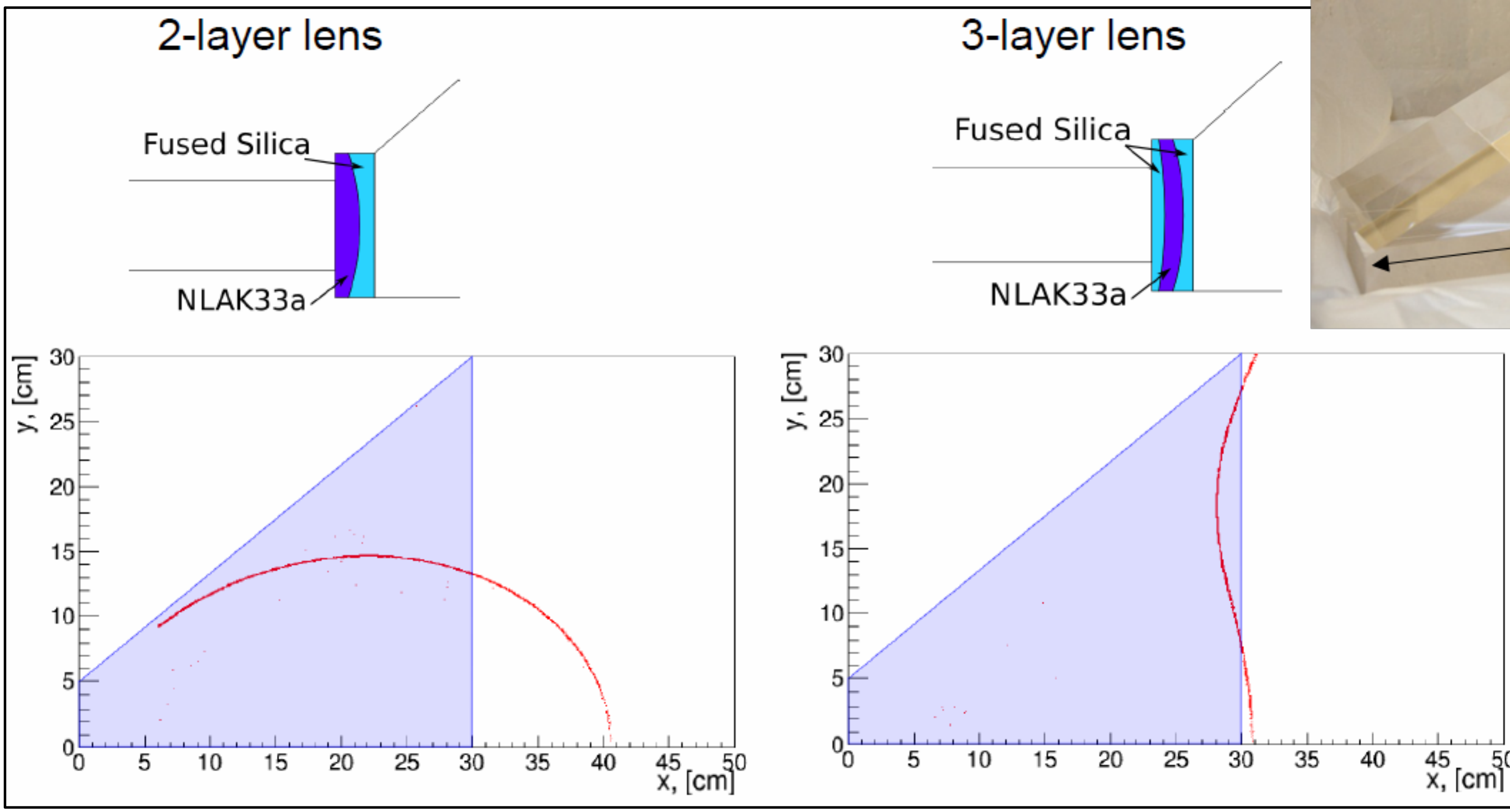


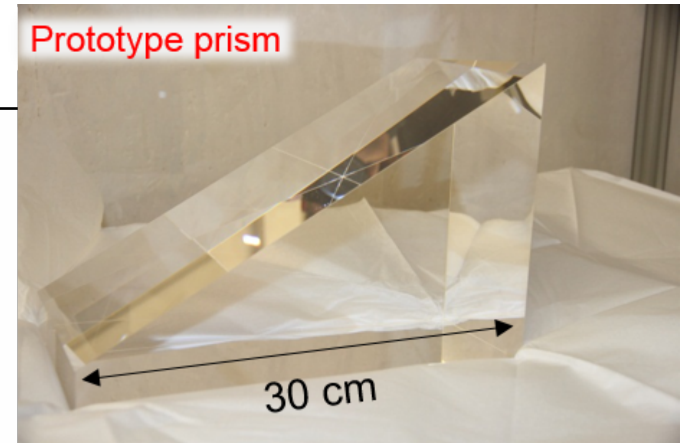


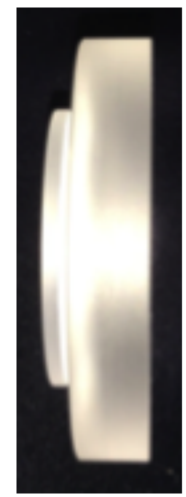
Data taken with this setup agreed with the simulation

- Early lenses had a complicated focal planes
- Matching of optics, sensors, and expansion volume (EV) was difficult
- c) was designed to have a ***flat*** focal plane (in both x and y): **no need to develop a special EV!**

3-layer spherical lens with flat focal plane

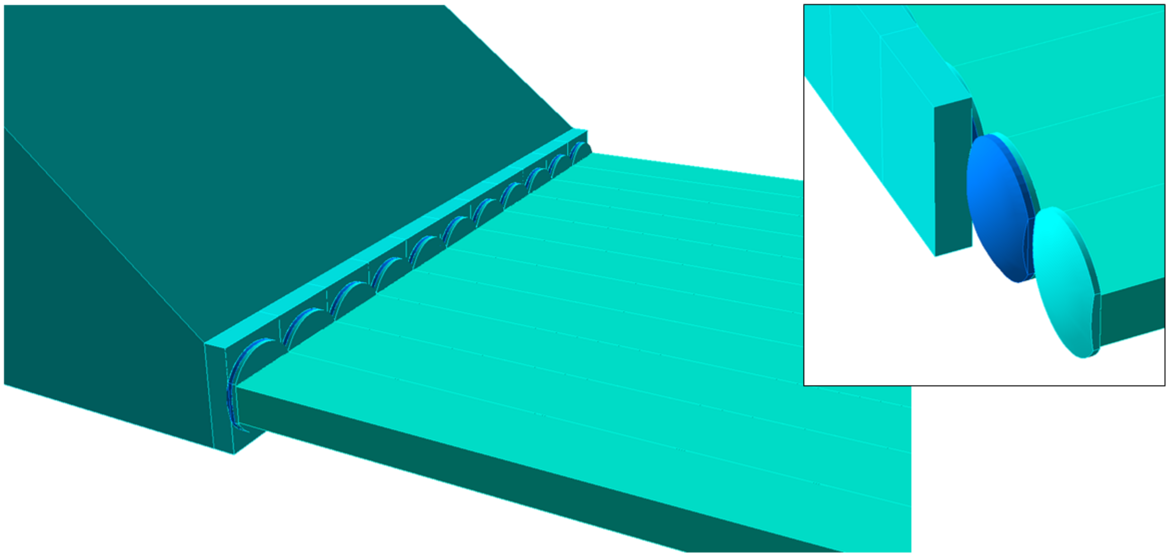


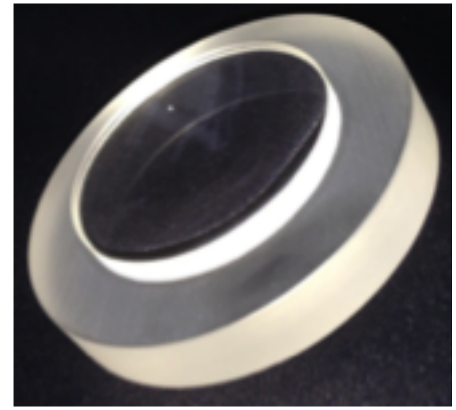




- The prototype lens was matched to the existing GSI prototype prism
  – The focal plane can at any angle making it possible to align the sensors with the B-field.
- In the simulation, a wider prism would be used, covering an entire bar box

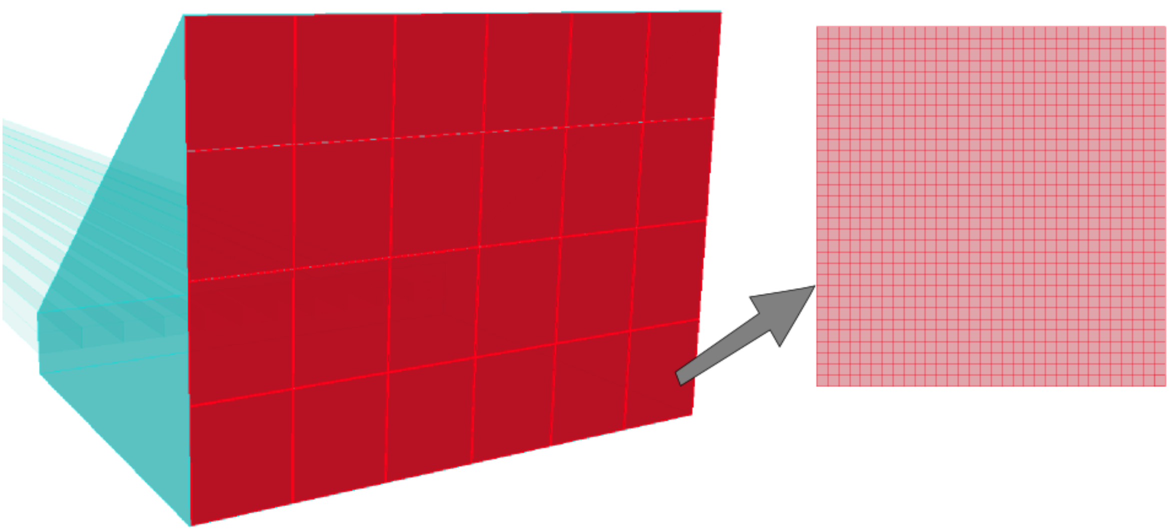
Lens-based readout "camera" in Geant4





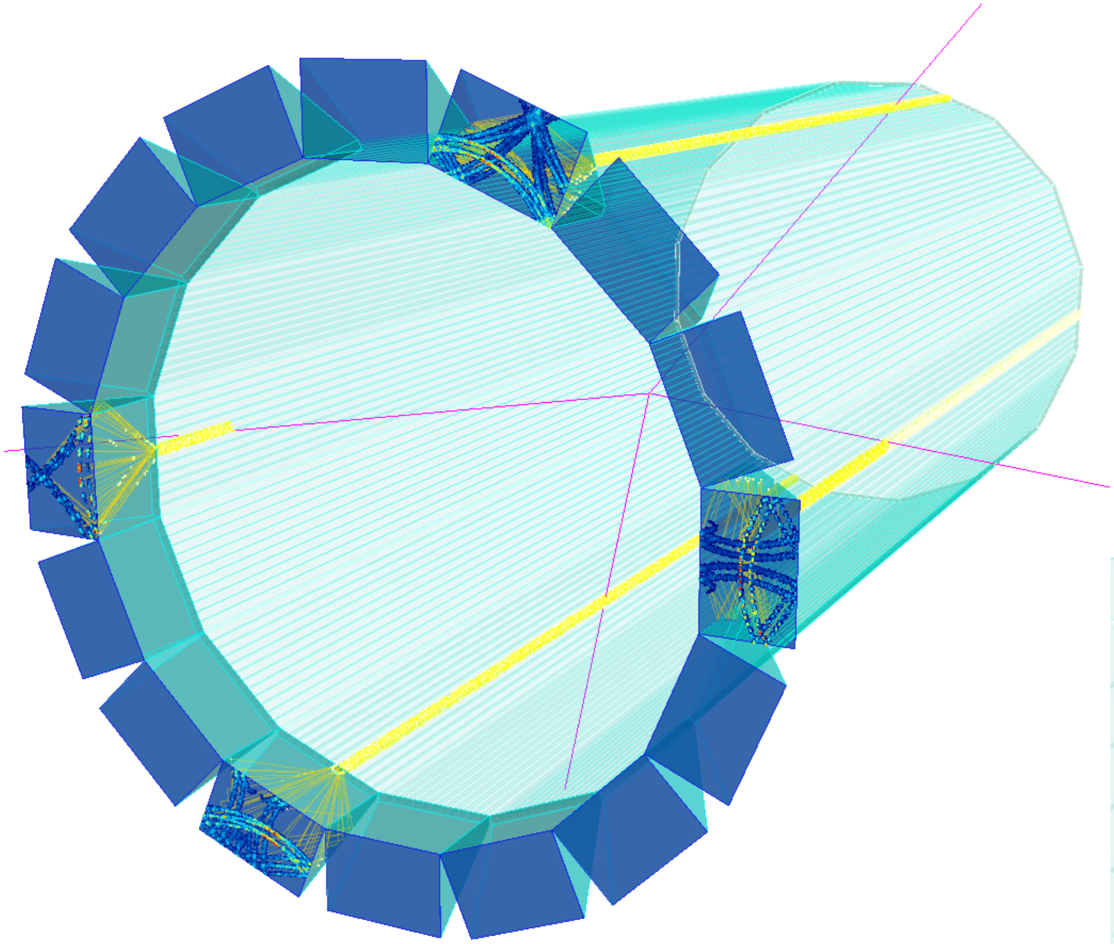
Actual prototype lens

- An array of spherical lenses, on one side attached to individual radiator bars, and on the other a common, 30 cm deep expansion volume prism



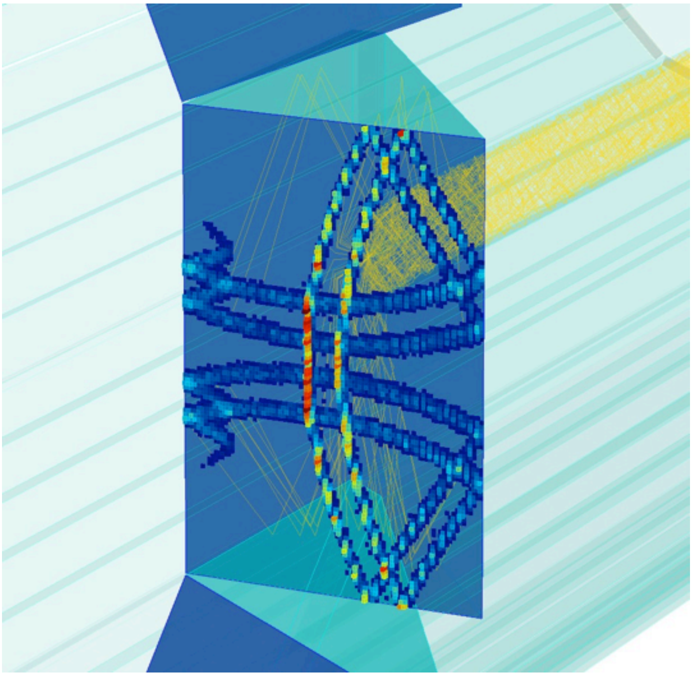
- 6x4 photosensors on the focal plane of the EV
- In the simulation, each sensor had 32x32 pixels with a size of 2x2 mm^2

Geant4 simulation with narrow radiator bars



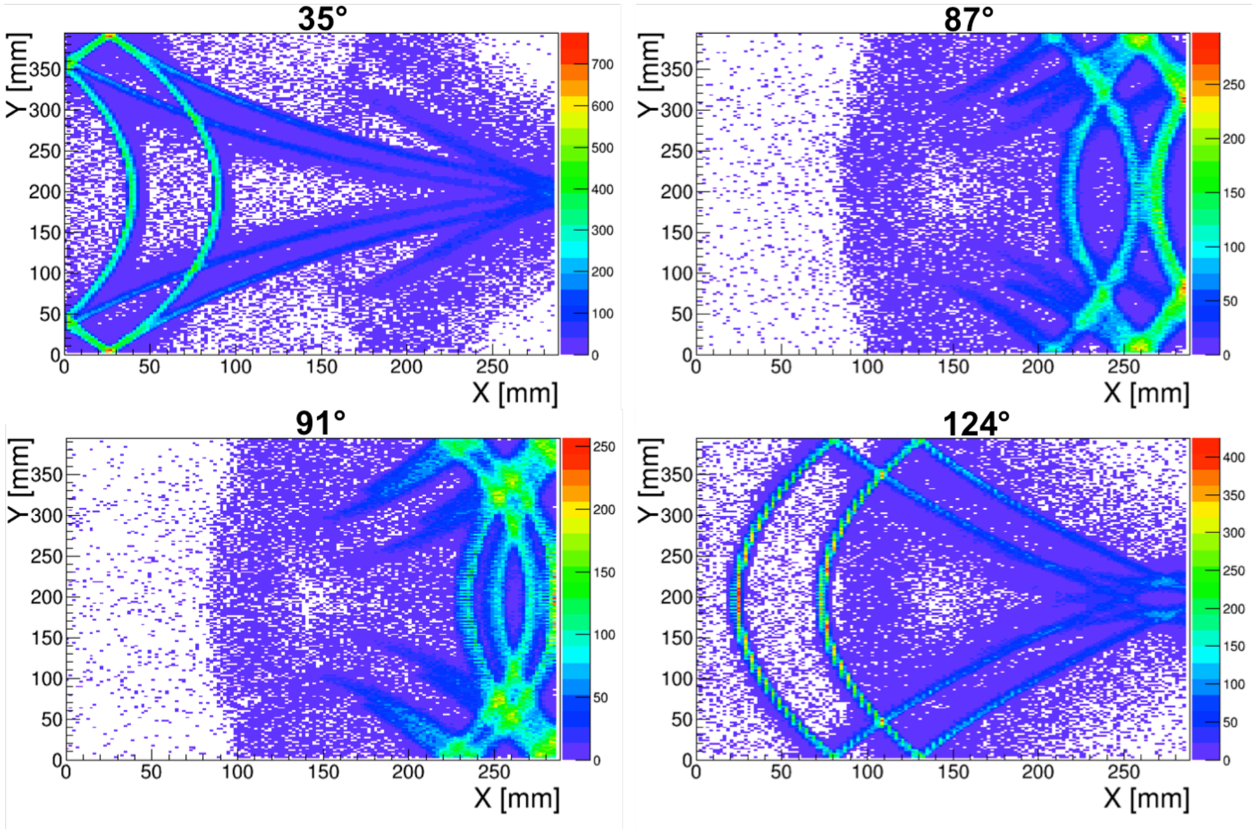
- Standalone Geant4 simulation
  - Developed at GSI
  - Can be integrated with various frameworks (GEMC, eicROOT)

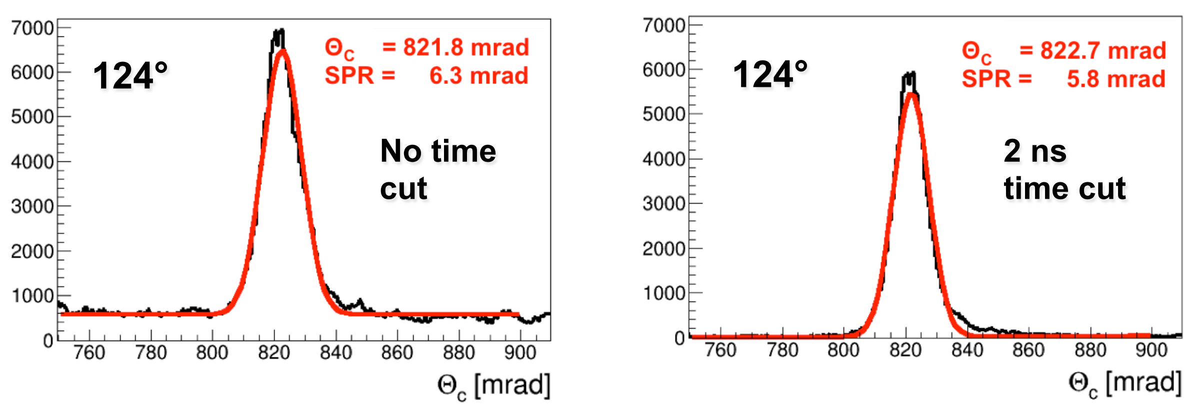
- Close-up view of the spherical 3-layer lens without air gap



- 16 bar boxes are shown, but this can be adjusted as needed to the specific EIC detector layout.

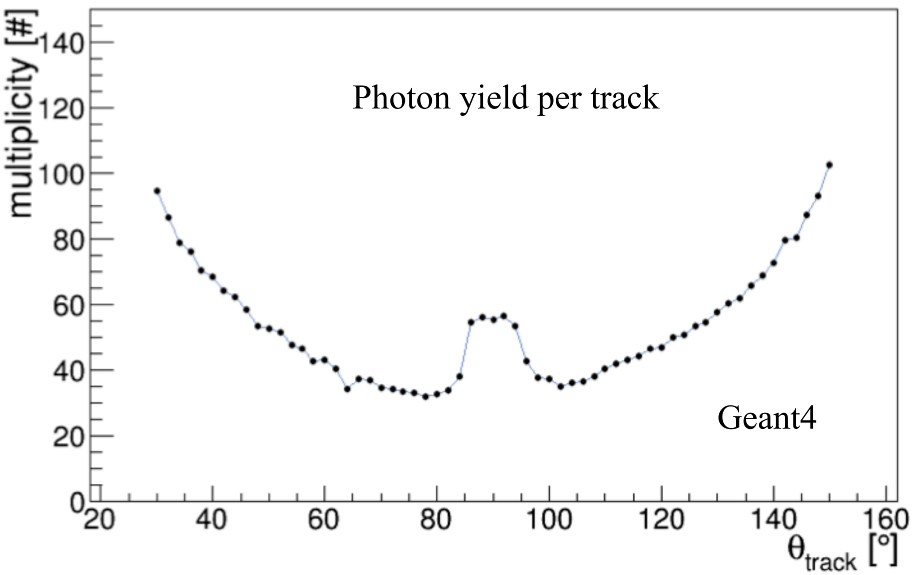
Hit patterns at different angles and reconstructed θ_c

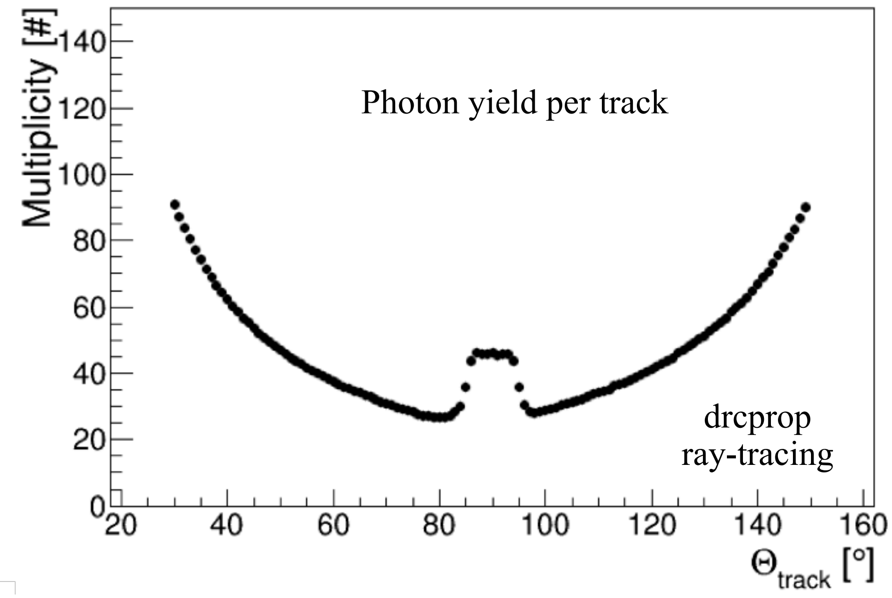


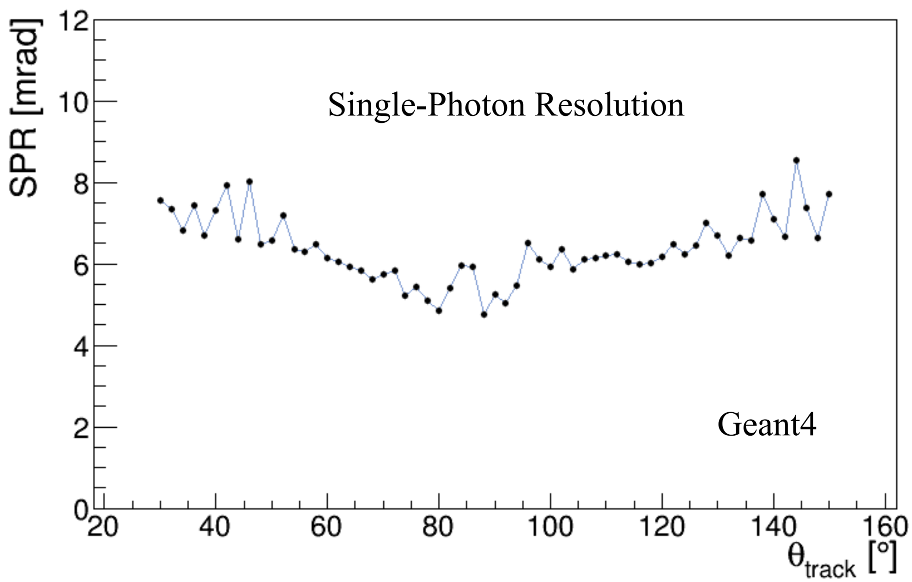


- Hit patterns in the common expansion volume of a bar box for different angles of the incident particle
  - Plots are summed over many events.
- The reconstruction shows the Single-Photon Cherenkov angle resolution on top of a combinatorial background, which can be suppressed by a timing cut.
  - The actual sensor timing resolution will be < 100 ps rather than 2 ns.

Photon yield and Single-Photon Resolution

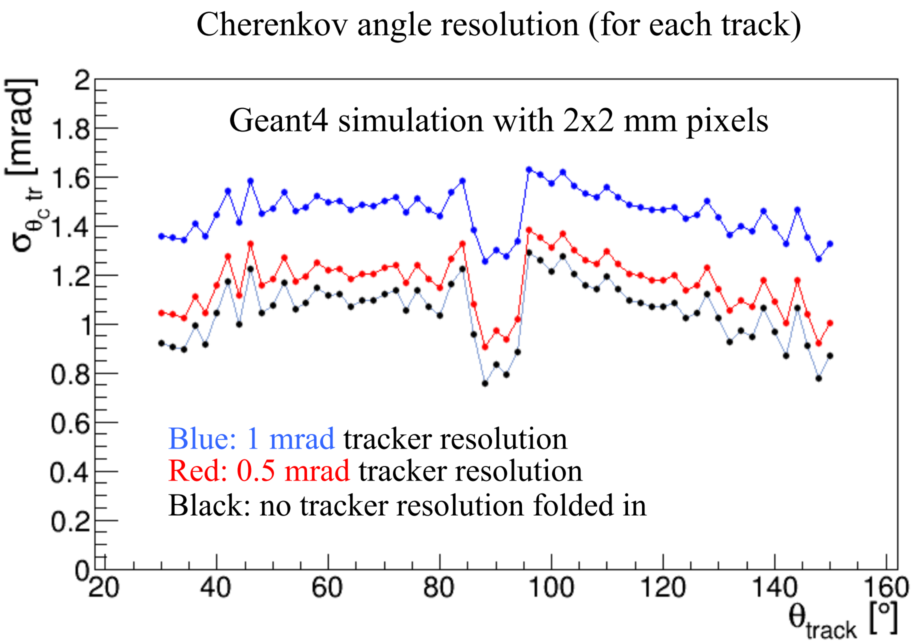


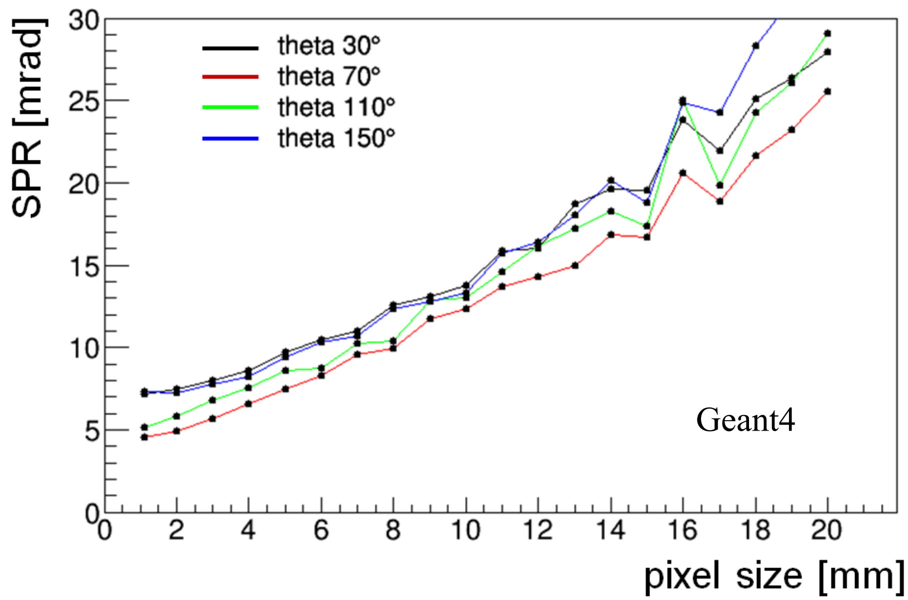




- The photon yields are largest when the bar is traversed at an angle, but the 3-layer lens ensures good yields also a normal incidence.
  - The yields results from Geant4 and drcprop (ray-tracing) agree!
- The Cherenkov angle resolution (per track) is ~SPR/√multiplicity

Cherenkov angle resolution for a track



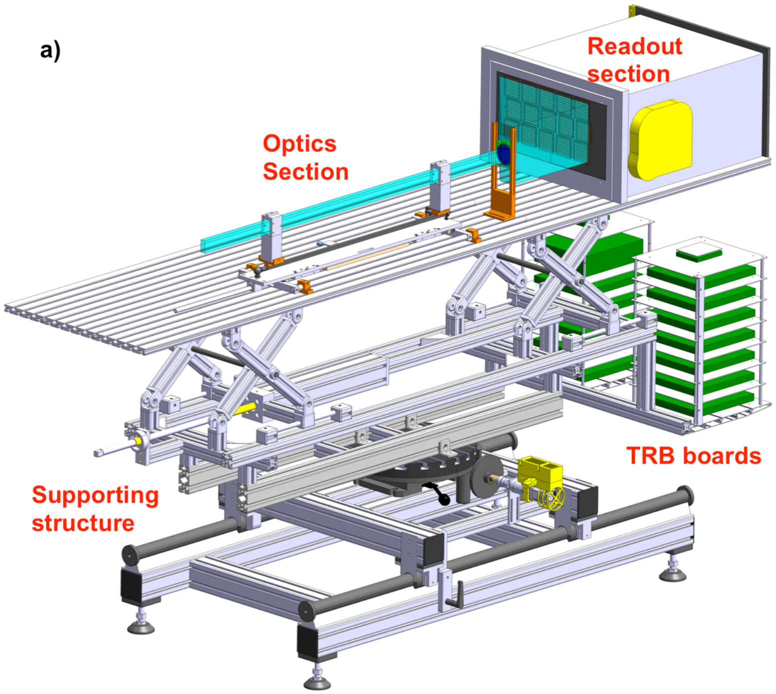


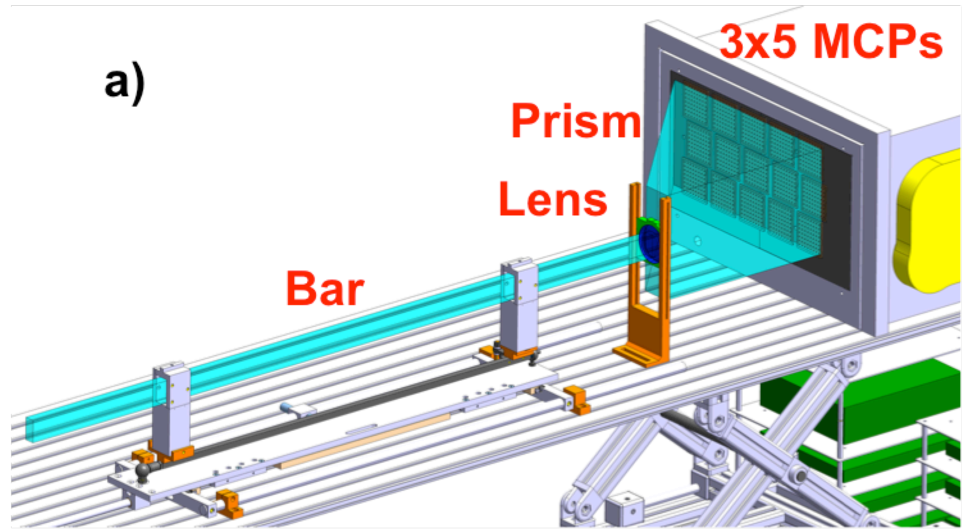
- (Upper panel): The per-track resolution of the readout camera depends on how well the angle of incidence on the bar is determined by the central tracker.
- (Lower panel): The resolution also depends on the pixel size of the sensors on the focal plane.
- With a tracker angular resolution of 0.5-1 mrad and a sensor pixel size of 2-3 mm, the lens-based EIC DIRC will be able to reach the Cherenkov angle resolutions close to 1 mrad corresponding to a π/K separation of 6 GeV/c.

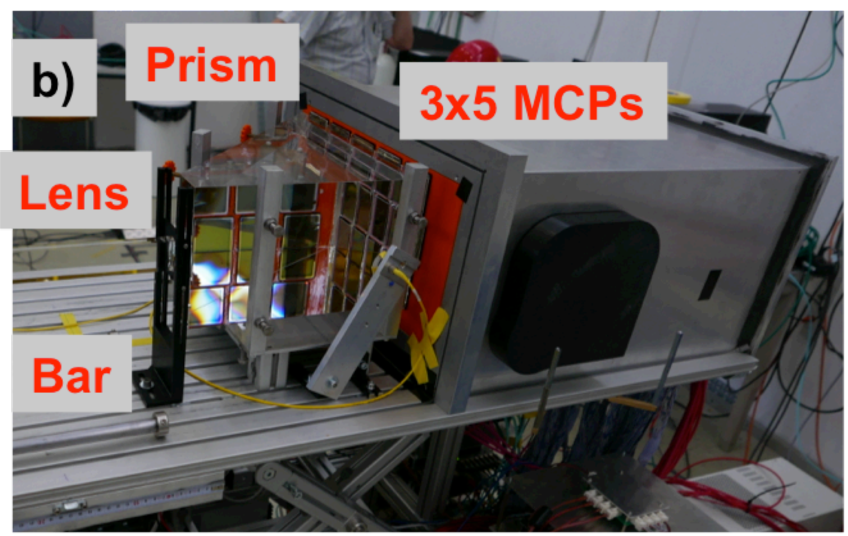
Milestone reached: The feasibility of a high-performance EIC DIRC has been demonstrated and using a compact readout "camera."

Verification of simulation results with new lens in test beams at CERN and GSI

Prototyping – synergies with PANDA DIRC R&D

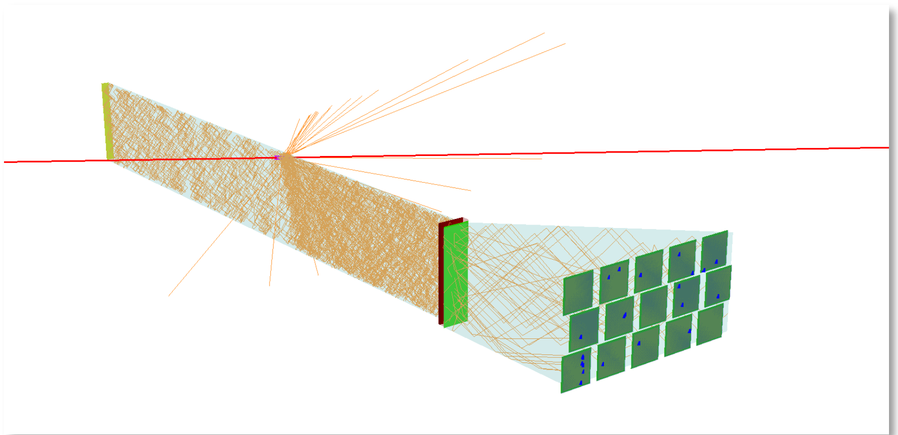




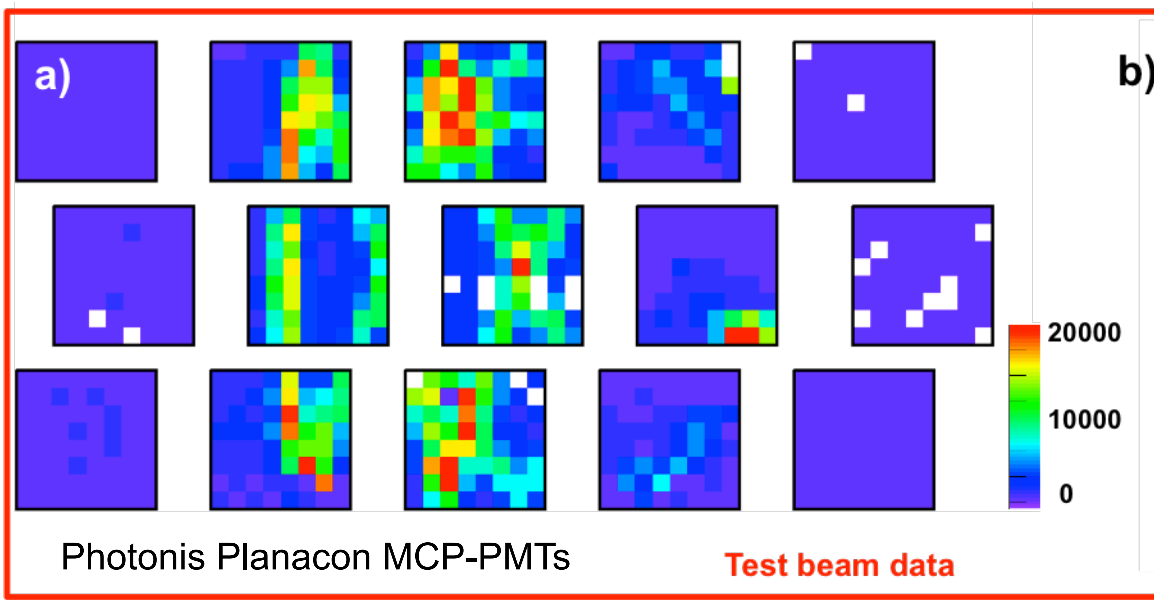


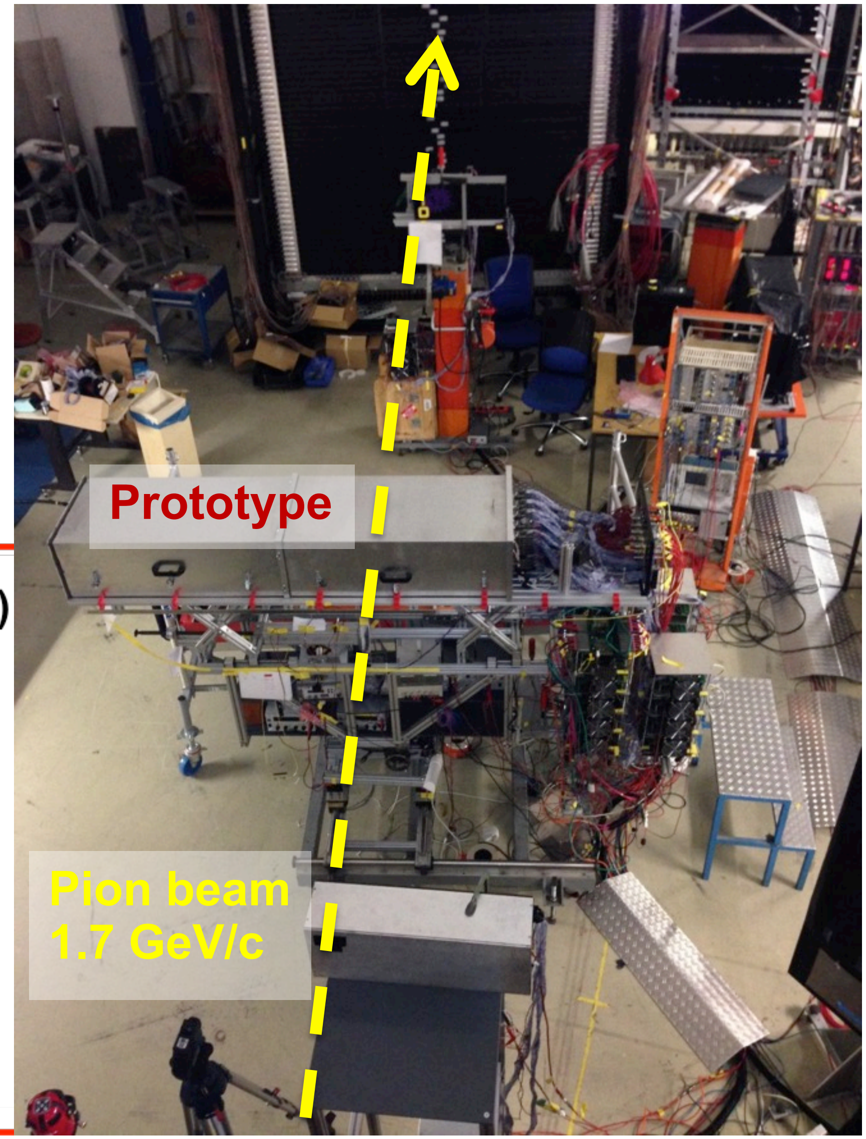
- The PANDA DIRC prototype is ideal for in-beam testing of the new 3-layer lens designed and procured for the EIC R&D
- The Photonis MCP-PMTs in the prototype have 6 mm pixels, so separate simulations are required to validate the test results and projections for the high-performance DIRC

Beam tests at GSI in the summer of 2014



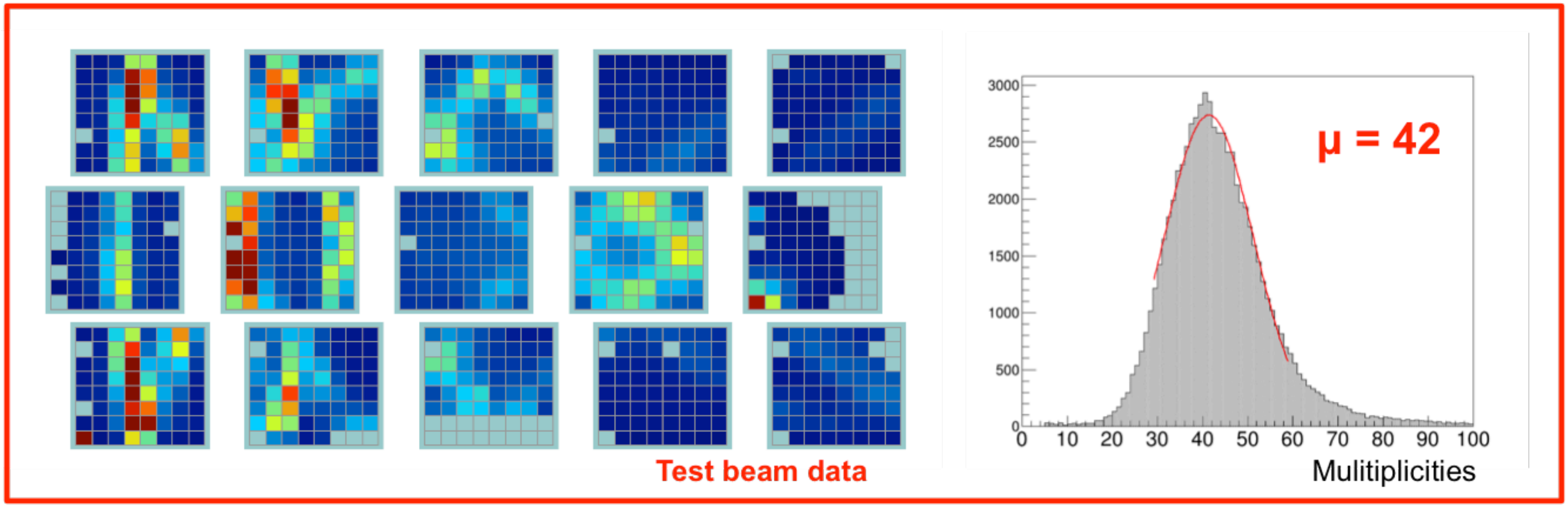
- First data with new 3-layer lens (36 mm bar)

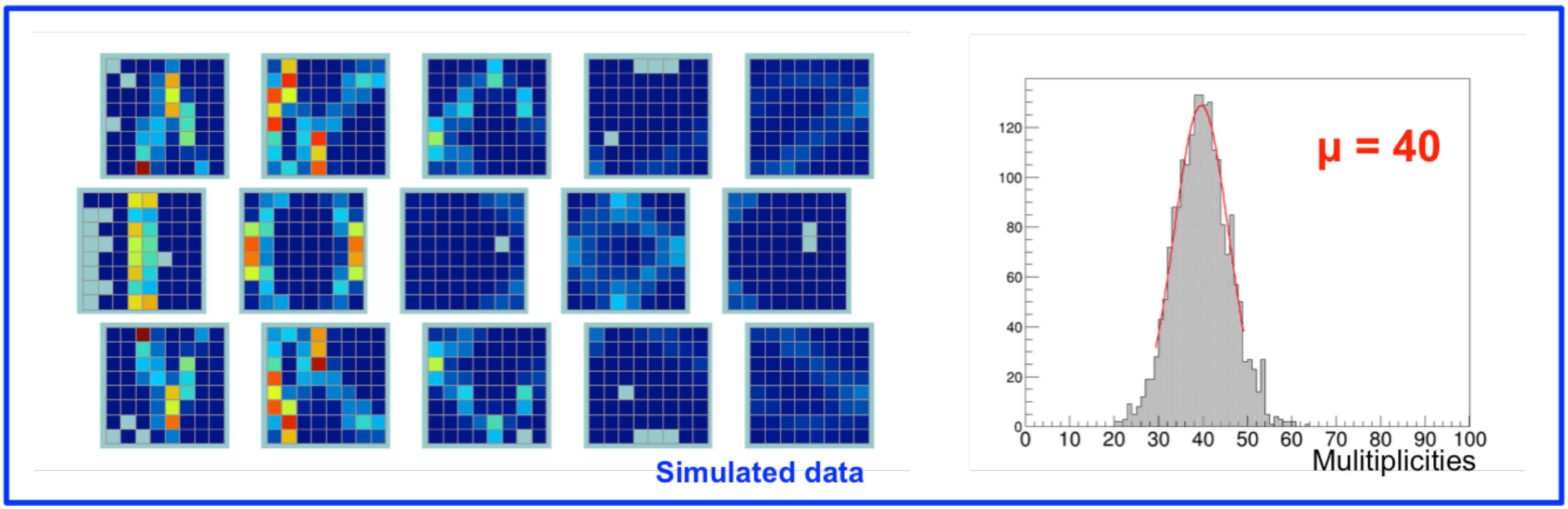




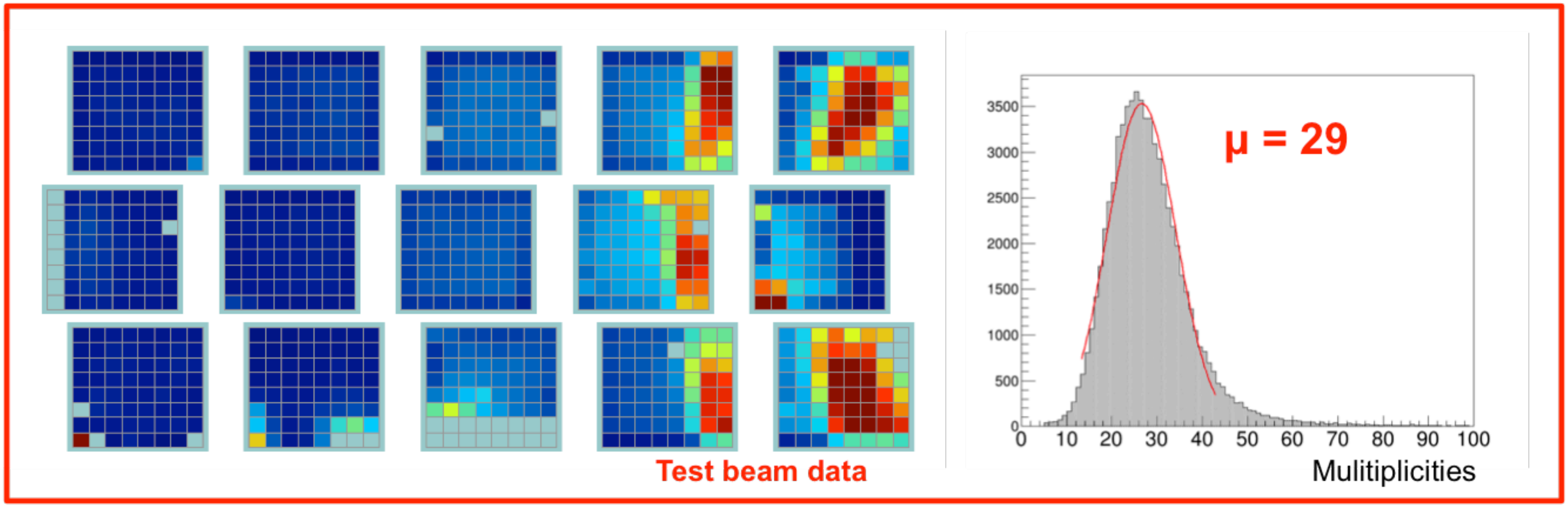
Beam incident at 125°

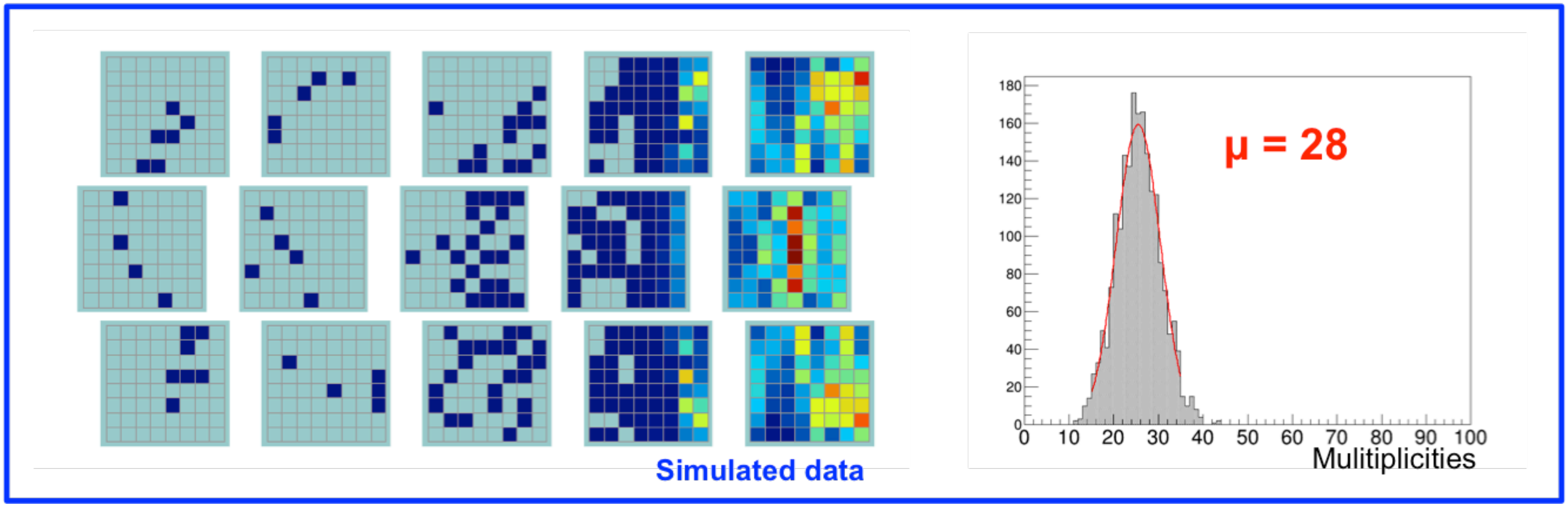
2015 CERN test beam data and simulation - 125°



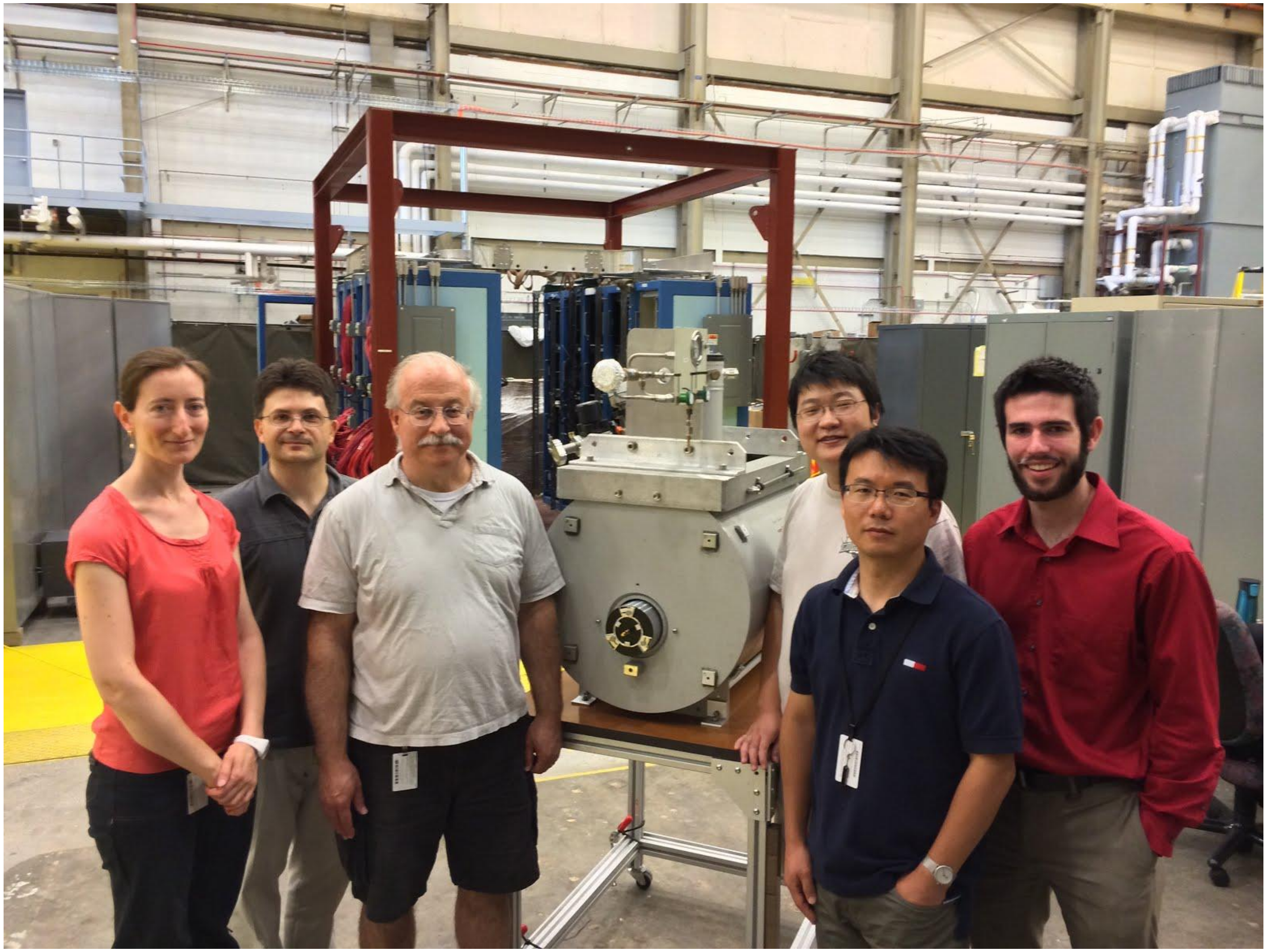


2015 CERN test beam data and simulation - 90°



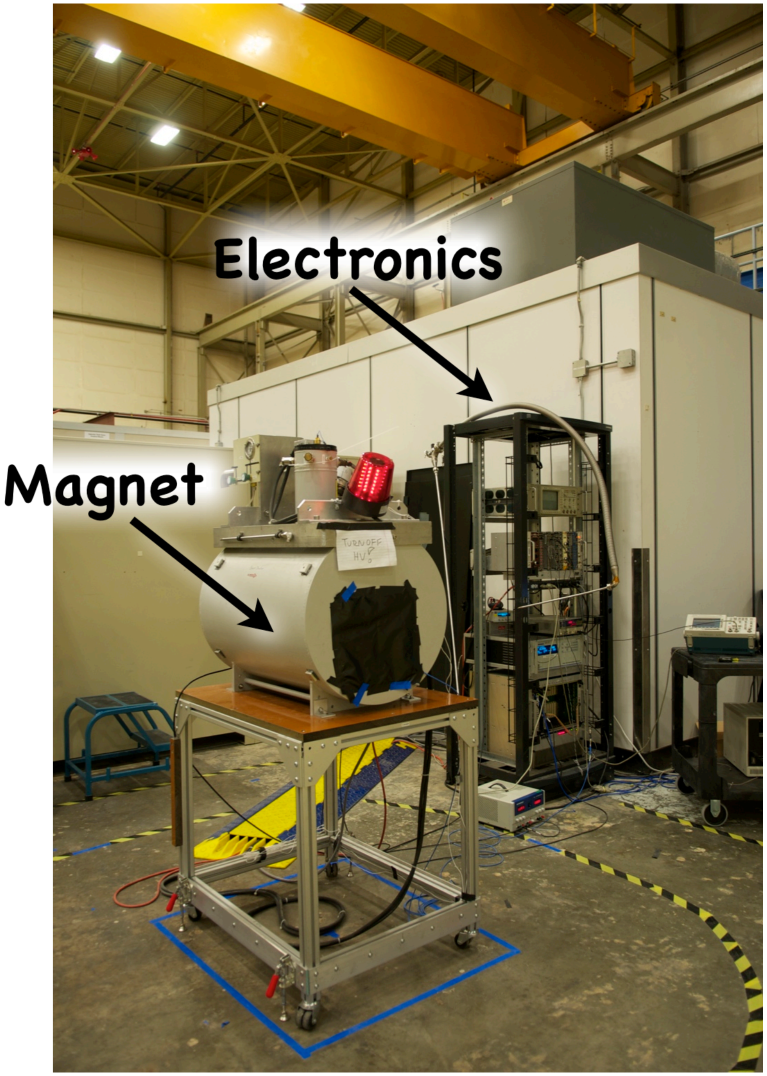


eRD4.2 Photosensors in high magnetic fields



Y. Ilieva (USC), P. Nadel-Turonski (JLab), C. Zorn (JLab), T. Cao (USC), K. Park (ODU), and E. Bringley (USC) in front of the 5T FROST magnet in the permanent test area at JLab. Note the sensor test tube inside the 5” magnet bore.

High-B field test facility taking production data

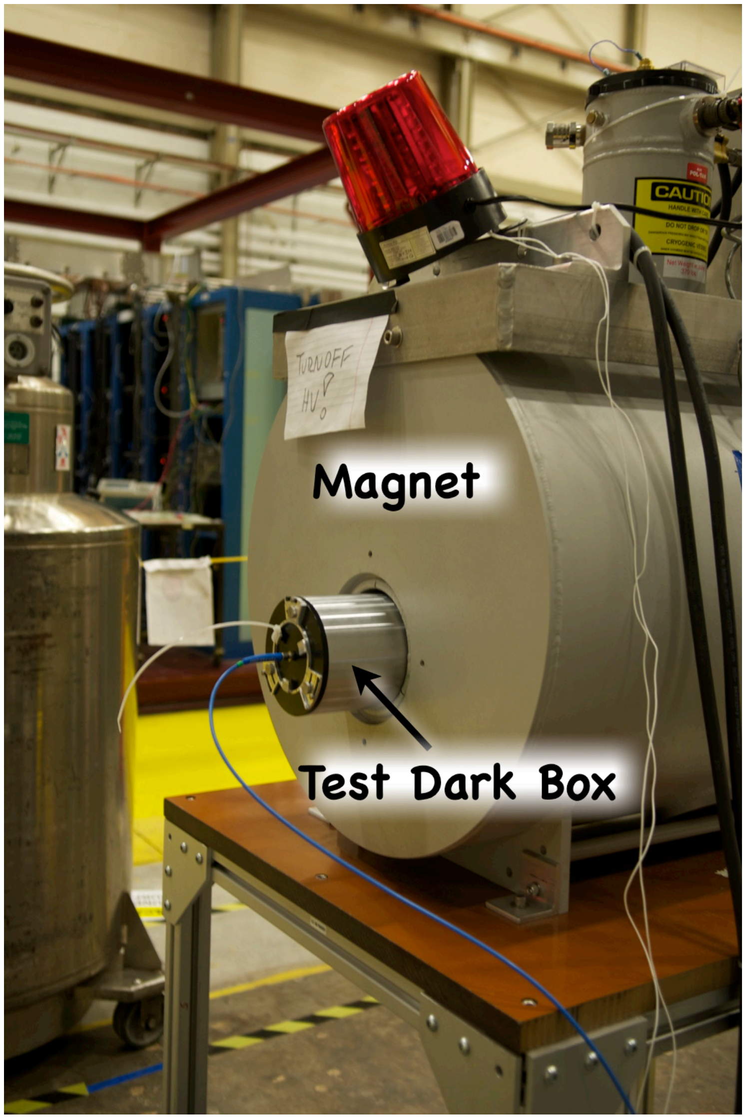


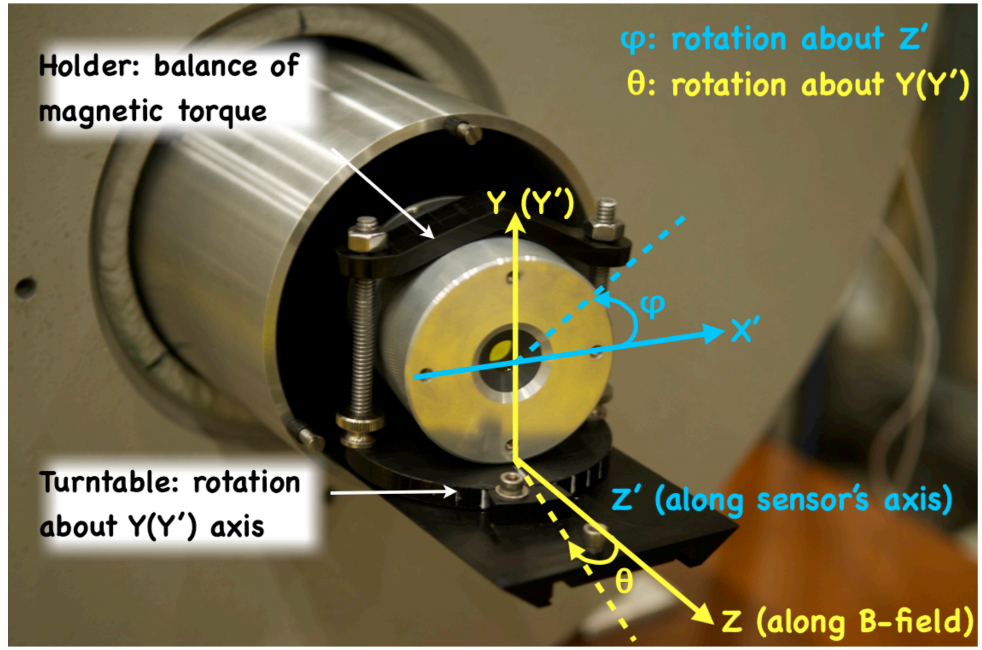
T. Cao and G. Kalicy during cooldown (LHe dewar is visible)

FY14: facility commissioned
FY15: two production runs – one completed and one starting next week

One run per semester is planned during years 4 and 5

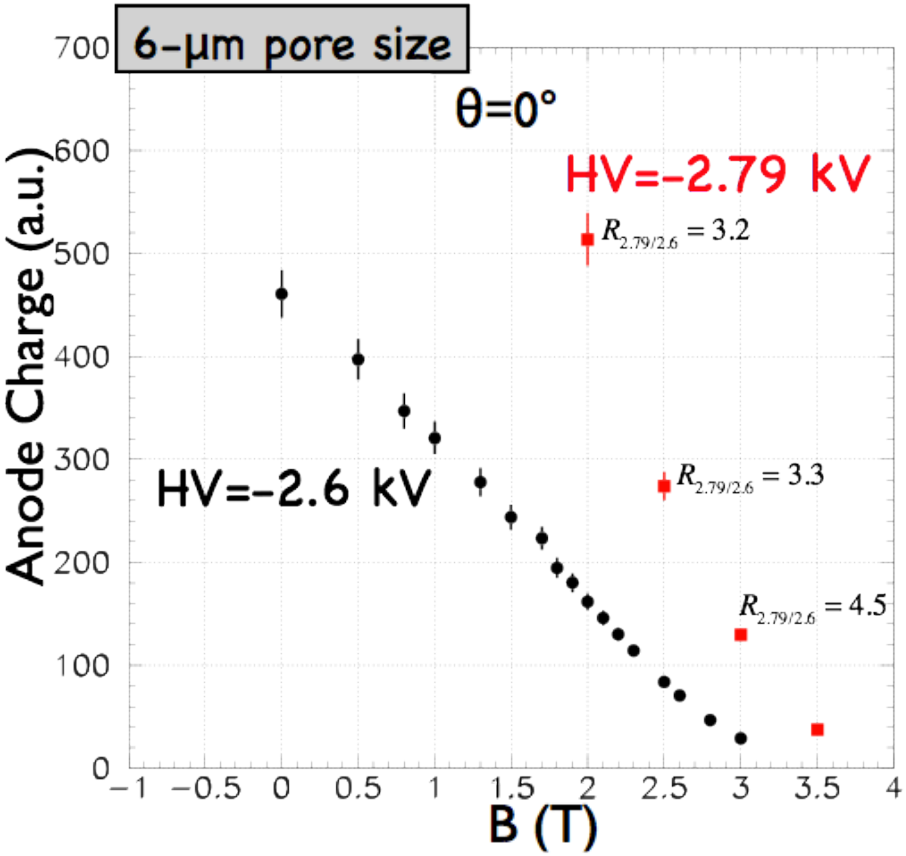
First sensors tested in B field up to 5 T

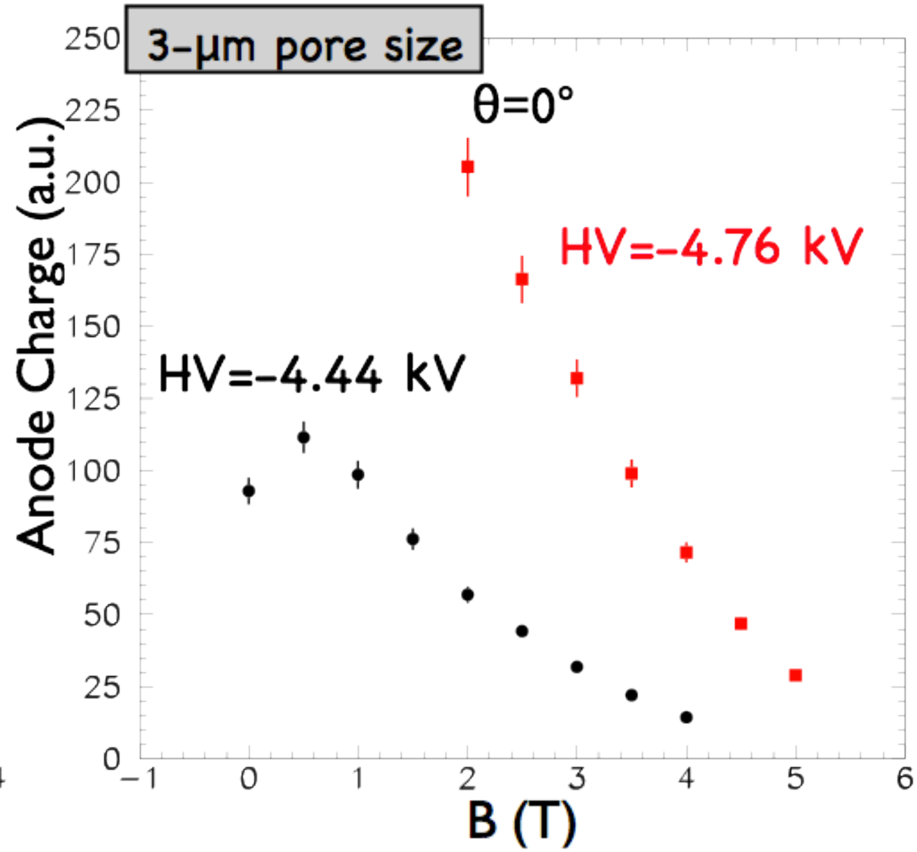




- The pictures show the dark tube which is inserted into the FROST 5 T solenoid and the Photek PMT210 mounted in the rotatable holder
- In addition to the PMT210, the Photek PMT240 and Photonis PP0365G MCP-PMTs were also tested during the November run.

Gain as function of B and high voltage

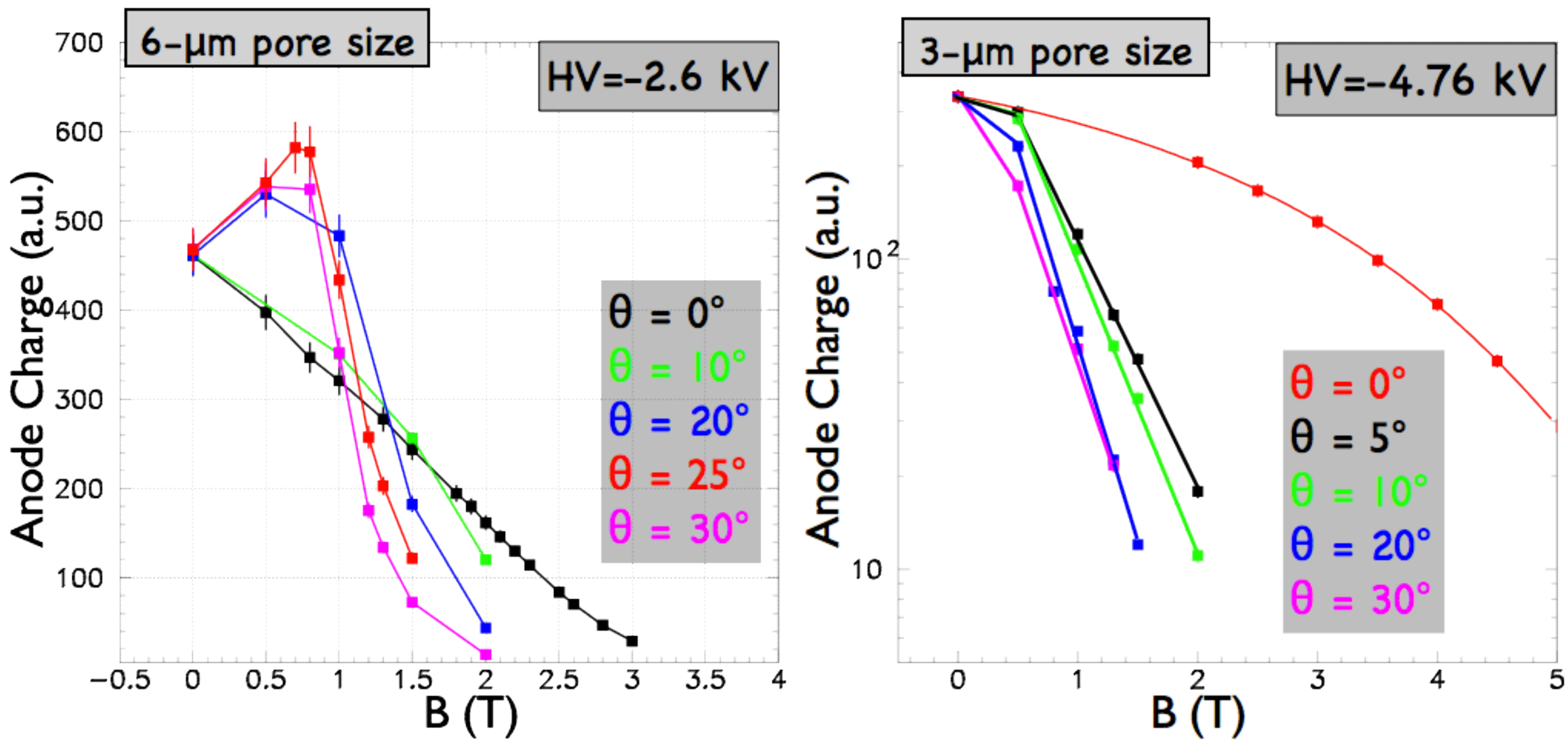




- Gain Drops with Field
  - Anode current drops
  - Raise HV on μCP
  - Restore Gain!

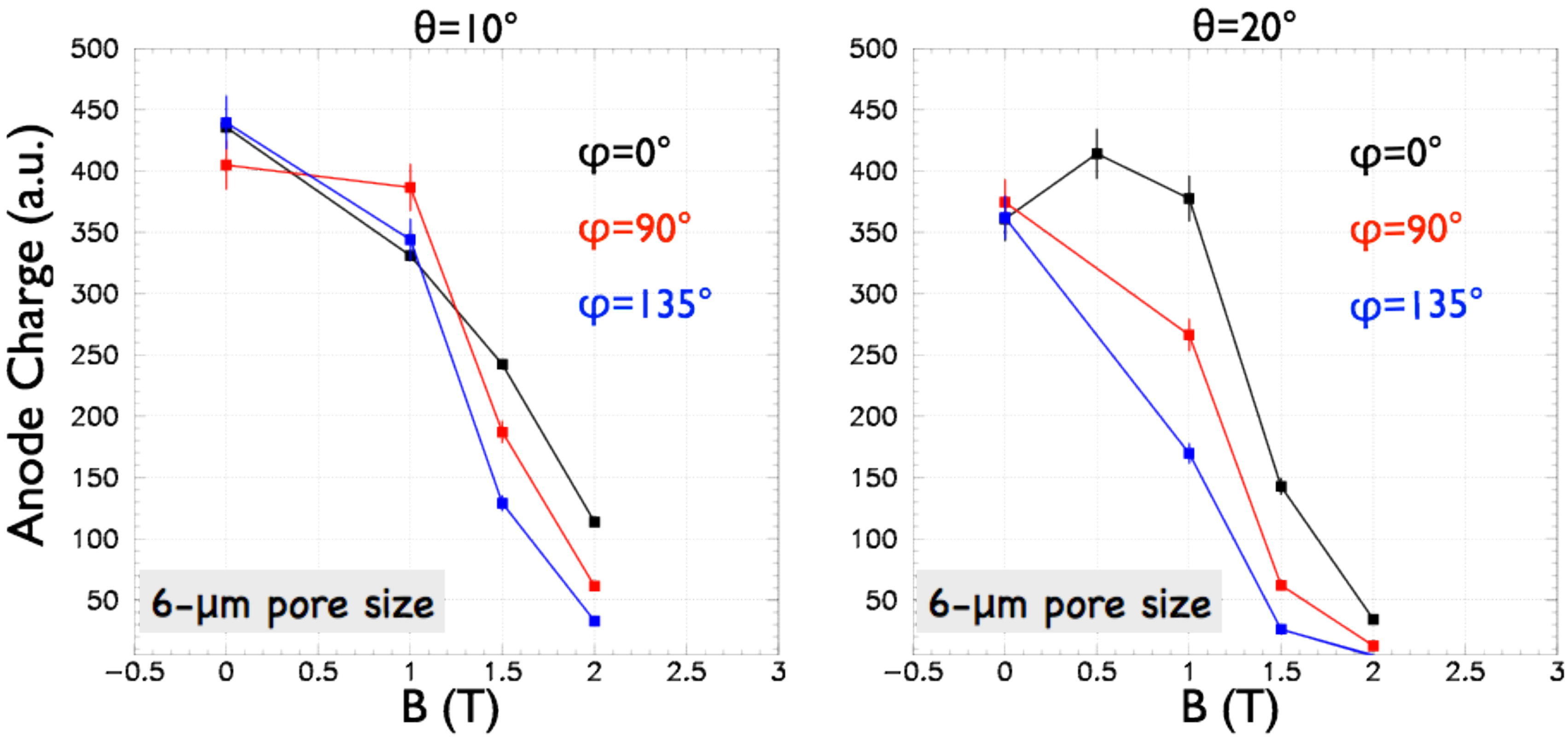
- Smaller Pore size
  - Better High-B performance!

Gain as function of B and polar angle



- Very strong dependence of B-field response w.r.t. angle θ between **B** and direction perpendicular to face of μCP ☹
- This needs more study

Gain as function B, polar, and azimuthal angles



- Two layer μCP in chevron pattern
- Pores at angle $\alpha \approx 10°$ to surface normal
- Azimuthal dependence non-trivial
- Optimize potential distribution K-μCP, μCP, μCP-μCP, μCP-Anode?
- Effects of non-uniform Magnetic field at sensor.

Conclusions

RD4.1: Fundamental Milestone Achieved!

- 1 mrad Cherenkov angular resolution is, in-principle, achievable.
  - Compact, simple, Expansion Volume
  - 3-layer spherical lens (no air-gap).

RD4.2: MicroChannelPlate PMTs show promise, but also challenges for operation in high magnetic fields.

See Pawel N-T's talk for outlook for R&D of practical realization of high performance DIRC

Backup

Budget summary

Budget	Year 1	Year 2	Year 3	Year 4	*Total*
Postdoc (50%)	$53,290	$54,000	$55,200	$52,305	*$214,795*
Students	$8,300	$13,764	$13,764	$13,784	*$49,592*
Hardware	$41,970	$58,630	$24,000	$30,000	*$154,600*
Travel	$11,440	$13,606	$22,036	$18,931	*$66,013*
Total	*$115,000*	*$140,000*	*$115,000*	*$115,000*	*$485,000*

Budget	Year 1	Year 2	Year 3	Year 4	*Total*
Old Dominion University (ODU)	$53,290	$54,000	$55,200	$52,305	*$214,795*
Catholic University of America (CUA)	$9,800	$8,300	$8,300	$8,300	*$34,700*
University of South Carolina (USC)		$7,606	$12,646	$12,646	*$32,898*
JLab and GSI (through MoU)	$51,910	$70,094	$38,854	$41,749	*$202,607*
Total	*$115,000*	*$140,000*	*$115,000*	*$115,000*	*$485,000*

- Postdoc salary matched by ODU funds (50%)
- Synergies with GSI: hardware for beam tests and optics studies
- In-kind contributions from JLab: two 5T solenoids, lab space, etc, for high-B test facility
- Free sensor loans from Photonis, Photek, and Hamamatsu: 6 MCP-PMTs
- *Note that in Year 2 this proposal merged with the sensor radiation hardness one (C. Zorn)*

Meetings and travel in the fall of 2014

Postdoc travel to and from GSI

- Participation in the 2014 test beam and later simulation / analysis work

Travel for University of South Carolina for High-B tests

- Extensive participation!

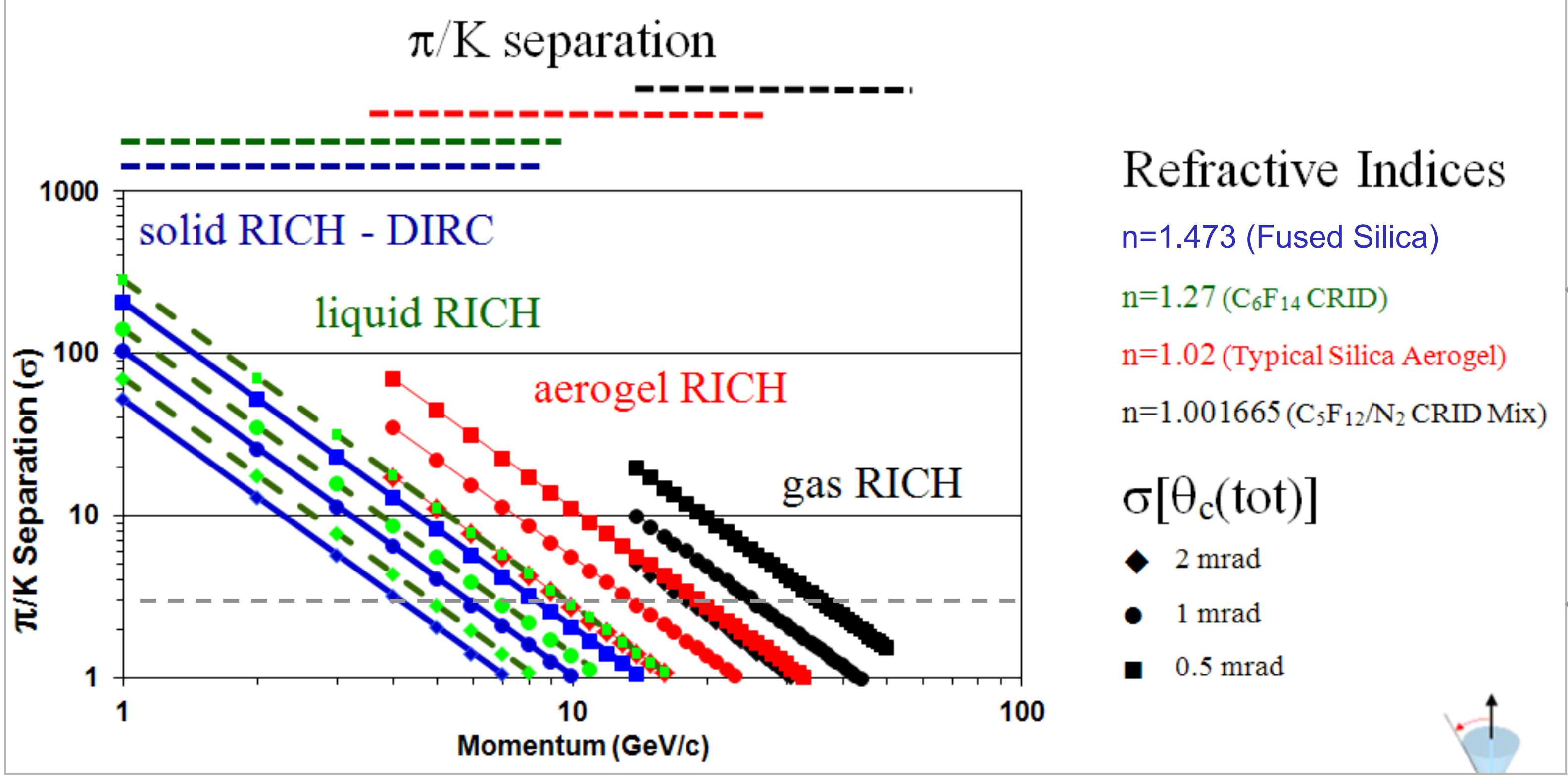
Travel to BNL for meetings with the advisory committee

- Car pooling in JLab van!

DIRC performance limits

$$N_\sigma \approx \frac{\left(m_1^2 - m_2^2\right)}{\left(2p^2\sqrt{n^2-1}\,\sigma[\theta_c(tot)]\right)}.$$

(For momenta well above threshold.)



radiator materials

angular error per track

In principle a DIRC can provide a 3σ π/K separation significantly beyond what was achieved at BaBar (4 GeV/c) – perhaps as high as 10 GeV/c

based on B. Ratcliff RICH2002

General strategies for improving the θ_c resolution

$$\sigma_{\theta_c}^{track} = \frac{\sigma_{\theta_c}^{photon}}{\sqrt{N_{p.e.}}} \otimes \sigma^{correlated}$$

Correlated term:
tracking detectors, multiple scattering, etc

$$\sigma_{\theta_c}^{photon} = \sqrt{\sigma_{bar-size}^2 + \sigma_{pixel-size}^2 + \sigma_{chromatic}^2 + \sigma_{bar-imperfection}^2}$$

BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon → 2.4 mrad per track

Limited in BABAR by:			Could be improved 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	----▸	4-5 mrad (?) per photon
· number of photons	15-50	----▸	· photocathode/SiPM

topics for R&D proposal (→ focusing optics, smaller pixel size, better time resolution, photocathode/SiPM)

- DIRC bar thickness can in principle also be increased beyond the 17 mm (19% r.l.) used in Babar
- Excellent 3D imaging (2 spatial + time) essential for pushing performance beyond state-of-the-art

Primary responsibilities

1. Simulations of DIRC performance and design of prototype

- Old Dominon University

2. Lens and expansion volume prototype construction and testing

- GSI Helmholtzzentrum für Schwerionenforschung

3. Sensor tests in high magnetic fields

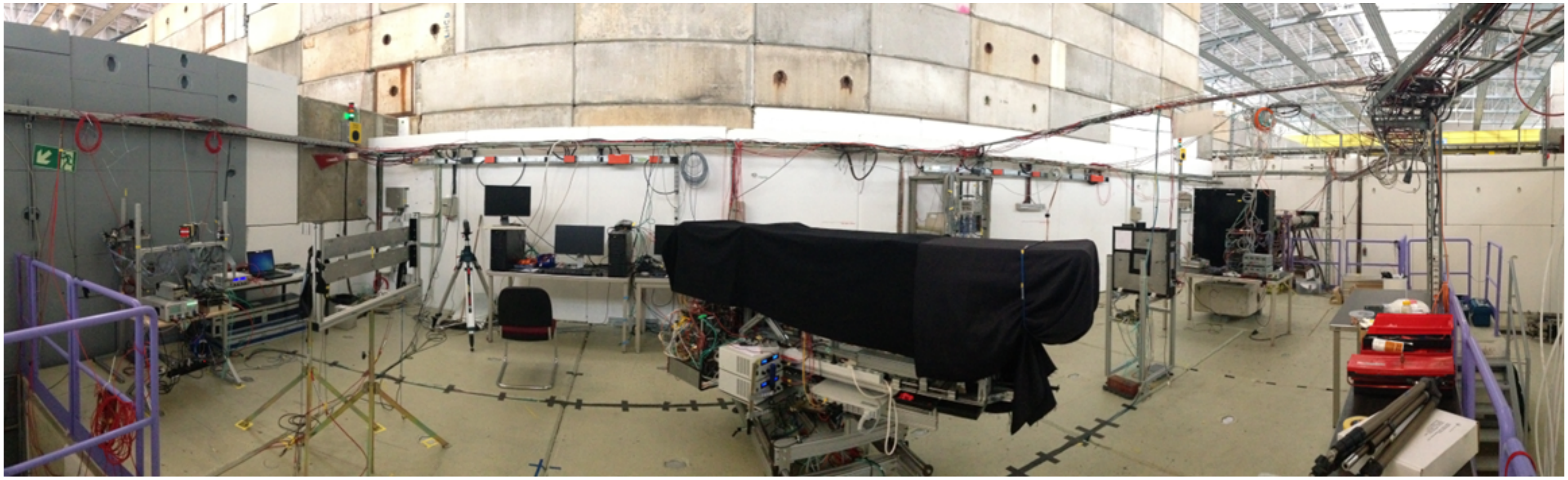
- University of South Carolina and Jefferson Lab

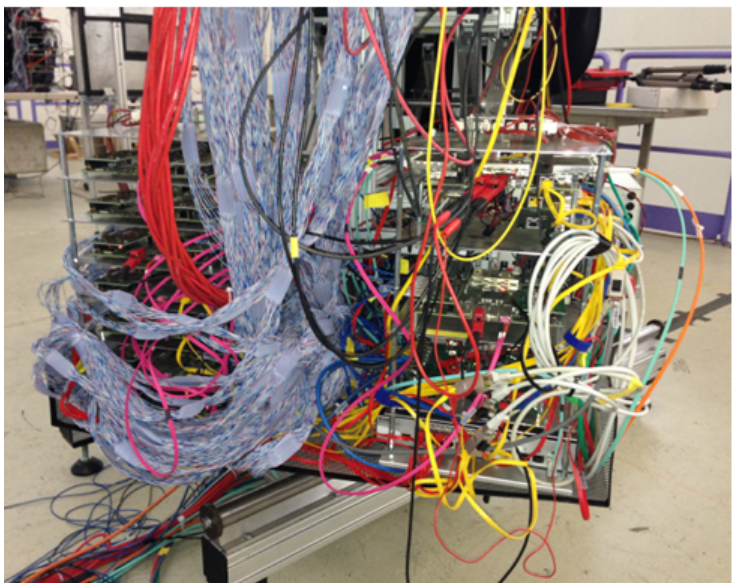
4. Detector integration

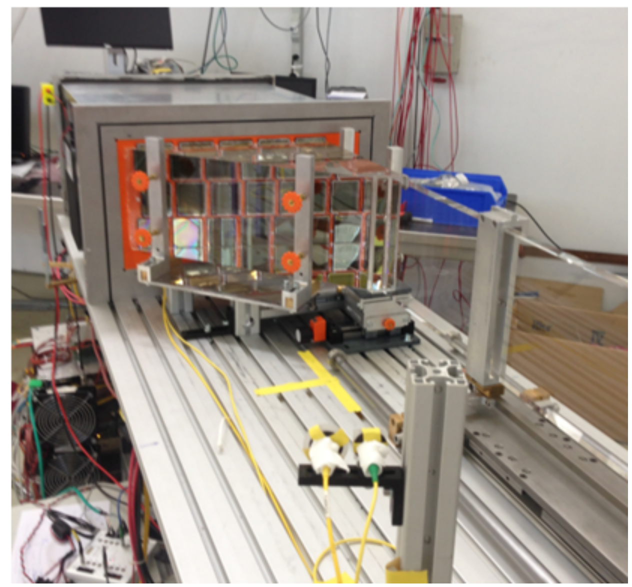
- Catholic University of America

Note: **The proposal is a collaborative effort and most institutions will contribute to more than one of the areas above regardless of their primary responsibility**

Setup at CERN in 2015

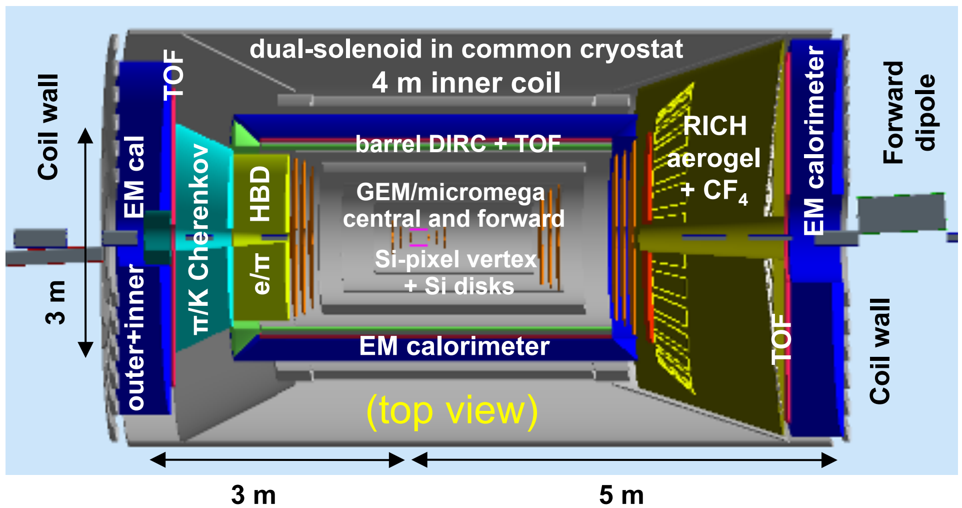






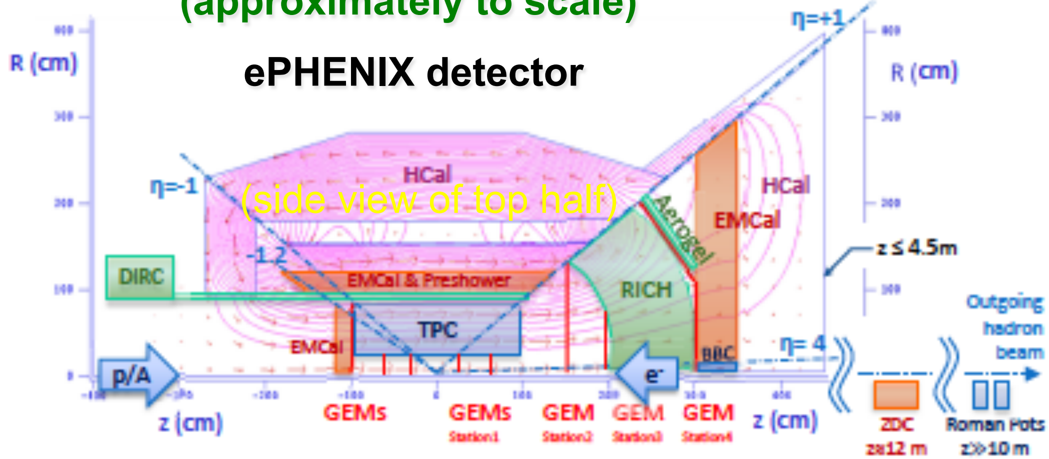
Integration with EIC detector concepts

MEIC IP1 detector



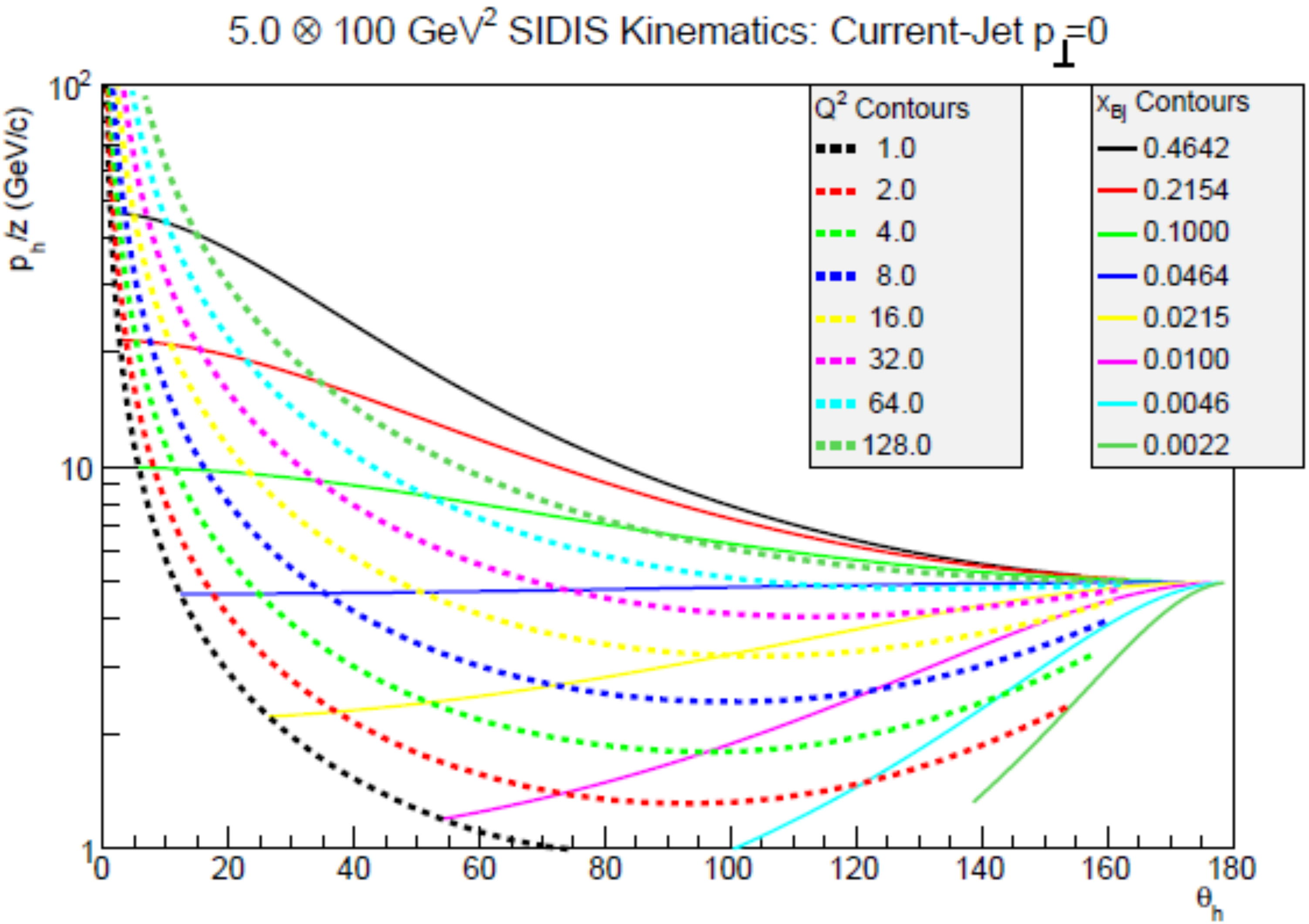
(approximately to scale)

ePHENIX detector



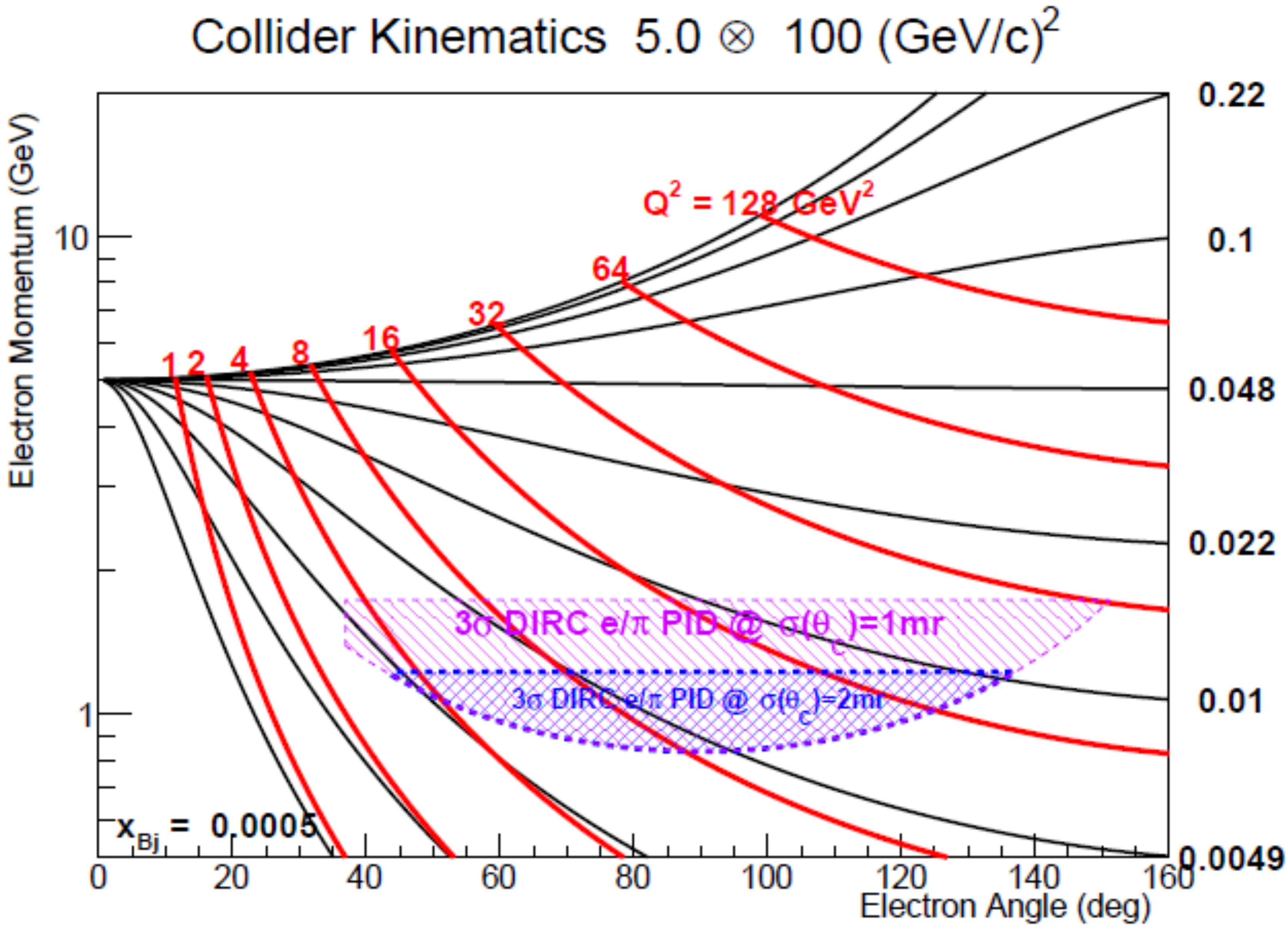
- The central detector concepts developed at JLab and BNL, exemplified by MEIC IP1 and ePHENIX, both offer plenty of space for the DIRC readout.
  - **Sensors easily accessible!**
- Internal vs external "camera"
  - Placement of sensors outside of the field is possible, but requires long bars (plates)
  - Would require integration with the EM calorimeter
- Integration of the DIRC into the global EIC detector simulations
  - Integration of the DIRC with the general EIC detector simulations has started.

Example: π/K identification in semi-inclusive DIS



- Need high momentum coverage – especially at forward barrel angles!

Example: e/π identification in DIS at low *x*



- High-Q^2, low-x electrons have low momenta and require good pion suppression

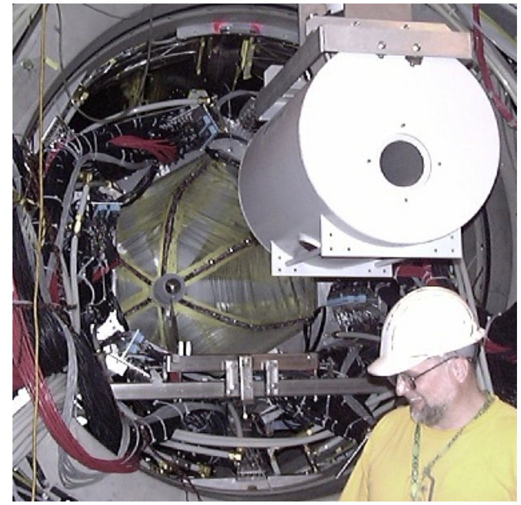
High-B field – magnets

Initial tests will use FROST magnet

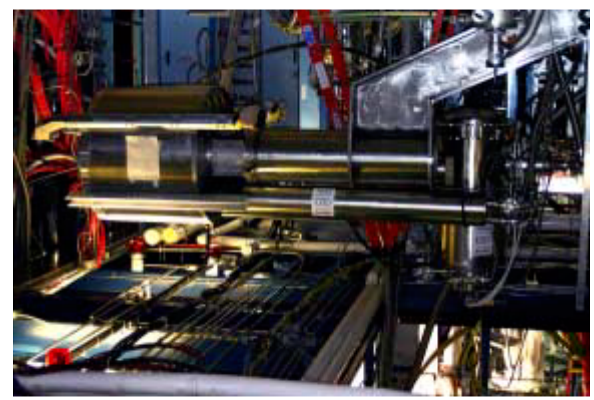
- Two magnets formerly used with CLAS are dedicated for the high-B field test facility – the larger DVCS and smaller FROST solenoids
- Both magnets can reach 5 T, but the FROST one is cheaper to set up and operate (requires less LHe)

Long-term strategy for facility

- Perform first series of tests using smaller magnet.
- In the future, a larger bore can be needed to accommodate larger sensors (LAPPDs) or provide more space for rotations
- Test boxes have been built for both magnets (C. Zorn)
- Both magnets will be part of the facility and can be used for future measurements as required



CLAS FROST solenoid
with 5 inch bore

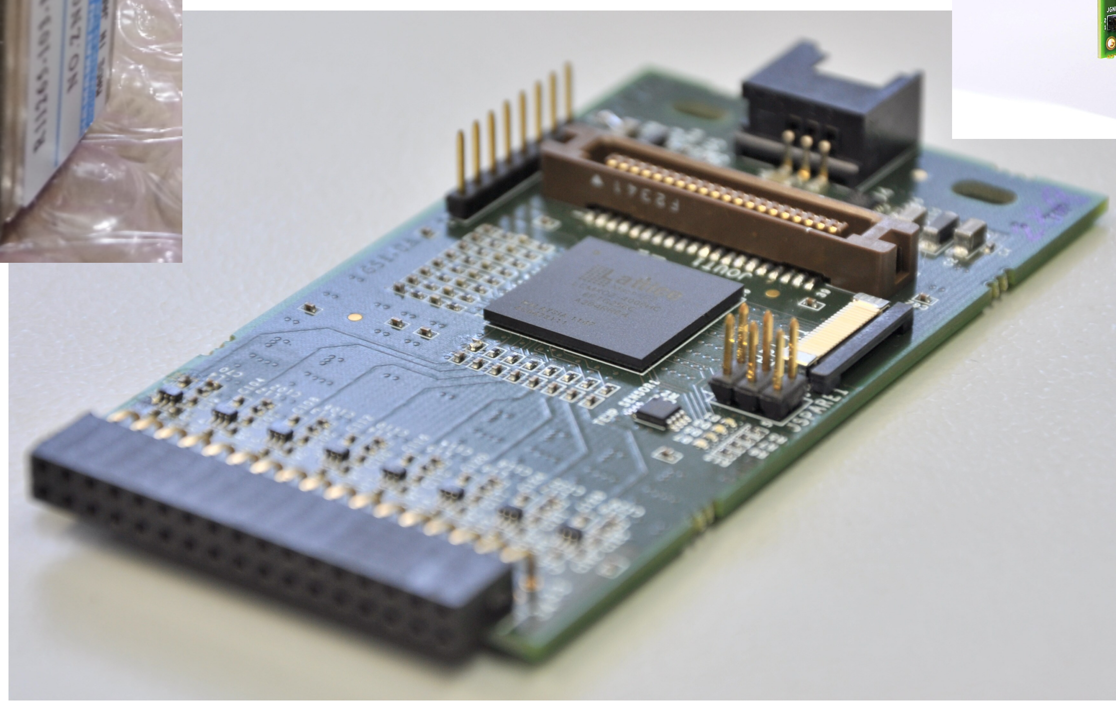


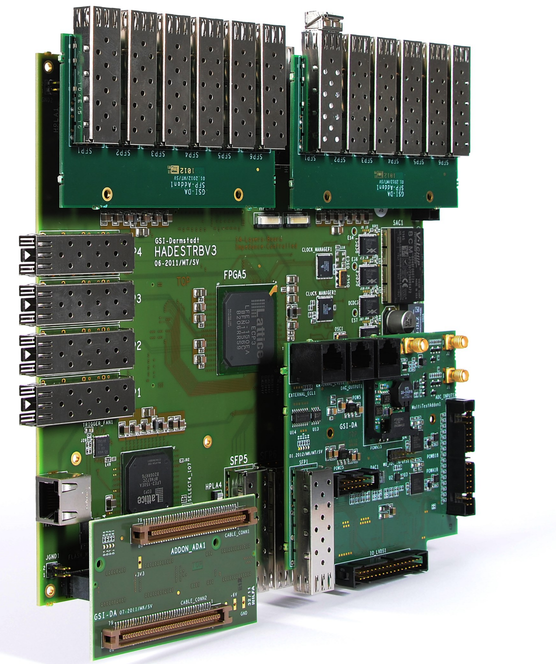
CLAS DVCS solenoid with 9 inch bore

Procurements for test at GSI

Hamamatsu R11265-103-64 small-pixel MaPMTs
256 channels total (4 MaPMTs).
Photo taken in transit at JLab

PaDiWa interface card for connecting the procured MaPMTs (via Hamamatsu E11906 sockets) to the TRBv3 DAQ card (right).





TRBv3 DAQ card
with AddOns

The new three-layer lens was delivered for the August/September test beam!