DIRC-based PID for the EIC

— Mid-Year Progress Report

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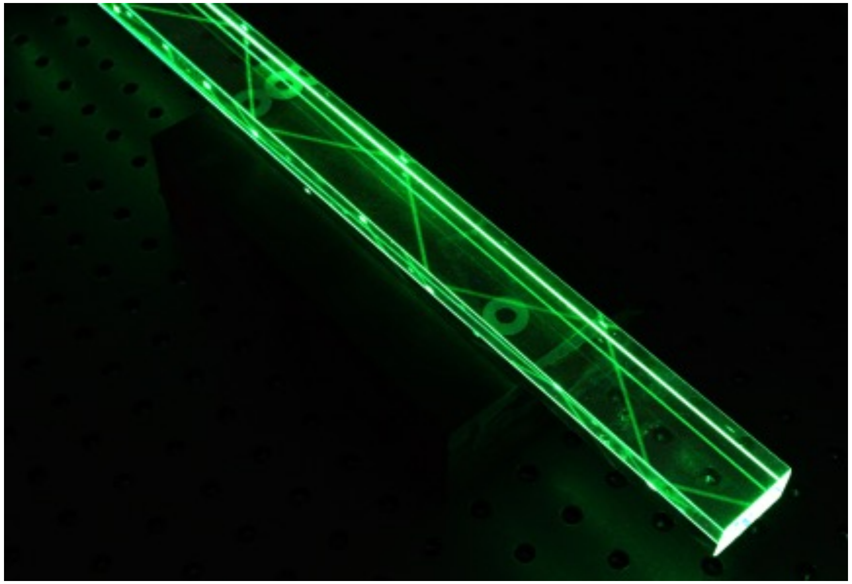
Generic Detector R&D for an Electron Ion Collider
Advisory Committee Meeting, BNL, January 22, 2015

Outline



1. Introduction

2. DIRC simulations, prototyping, and beam tests

3. High-B field test facility – first runs

R&D goals and progress summary

1. Investigate possibility of pushing state-of-the-art performance

- Extend 3σ π/K separation beyond 4 GeV/c, maybe as high as 6 GeV/c
  - also improves e/π and K/p separation

Accomplished. Proof of concept simulations done! Beam test with new lens!

2. Demonstrate feasibility of using a DIRC in the EIC detector

- Compact readout "camera" (focusing + expansion volume + sensors)
  - simulations, lens and EV design, prototyping, test beams
- Operation in high magnetic fields (up to 3 T)
  - sensor tests up to 5T

Ongoing. Lots of progress!

Ongoing. High-B facility taking production data!

3. Study integration of the DIRC with other detector systems

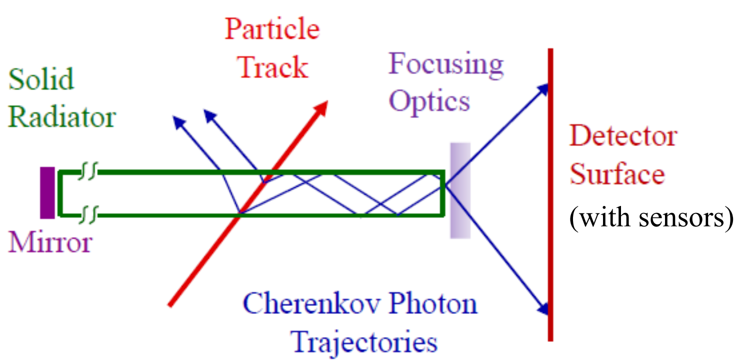
- Supplementary Cherekov? Internal or external readout? Bars or plates?
- Impact on endcap design and barrel calorimeter? New configurations?

Some progress. Understanding if improving as detector concepts evolve

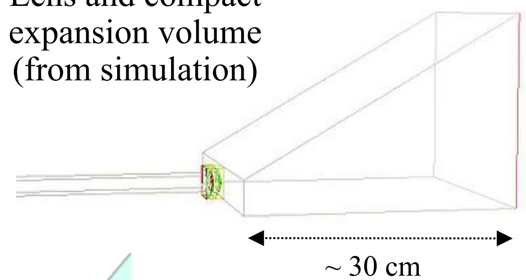
DIRC summary

- A DIRC can provide a radially compact particle identification solution for the EIC central detector
- The goals of this R&D are to adapt the DIRC technology to the EIC requirements (performance and integration)
- Simulations show that using novel lenses and a compact expansion volume one could improve the resolution at forward angles of 1 mrad at 30°, corresponding to a 3σ K/π separation at 6 GeV/c (and greater at lower momenta)

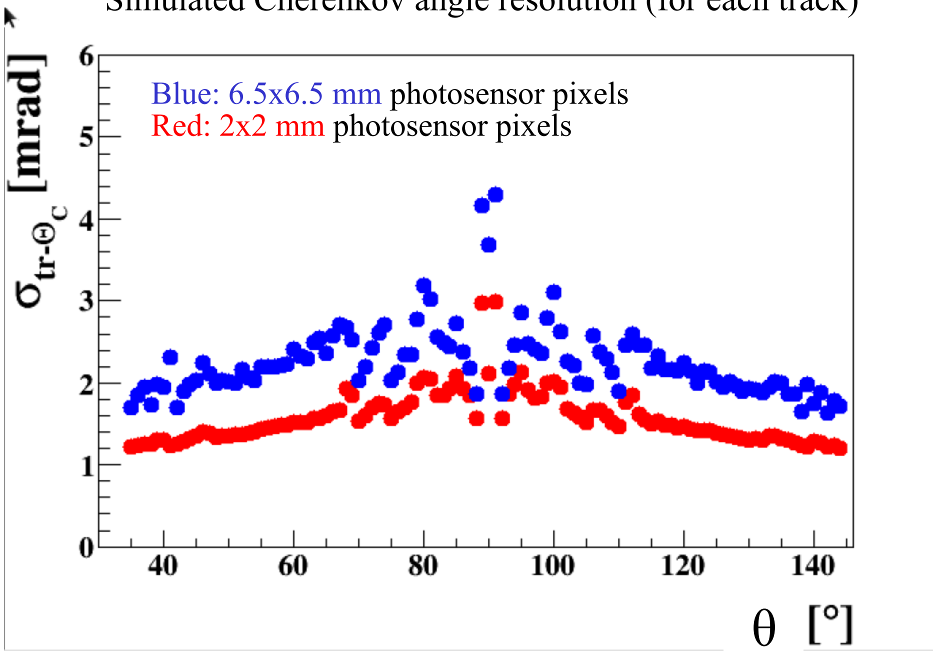
General layout of a DIRC with lens focusing

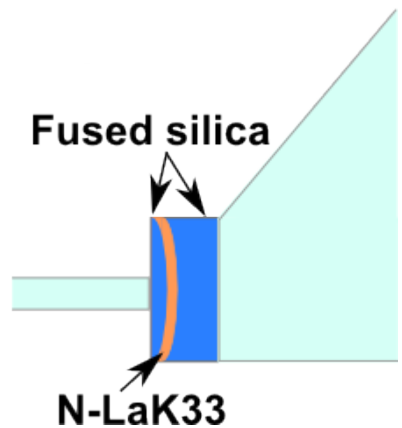


Lens and compact expansion volume (from simulation)

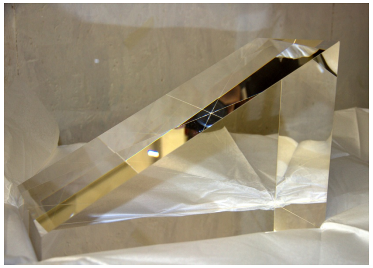


Simulated Cherenkov angle resolution (for each track)





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

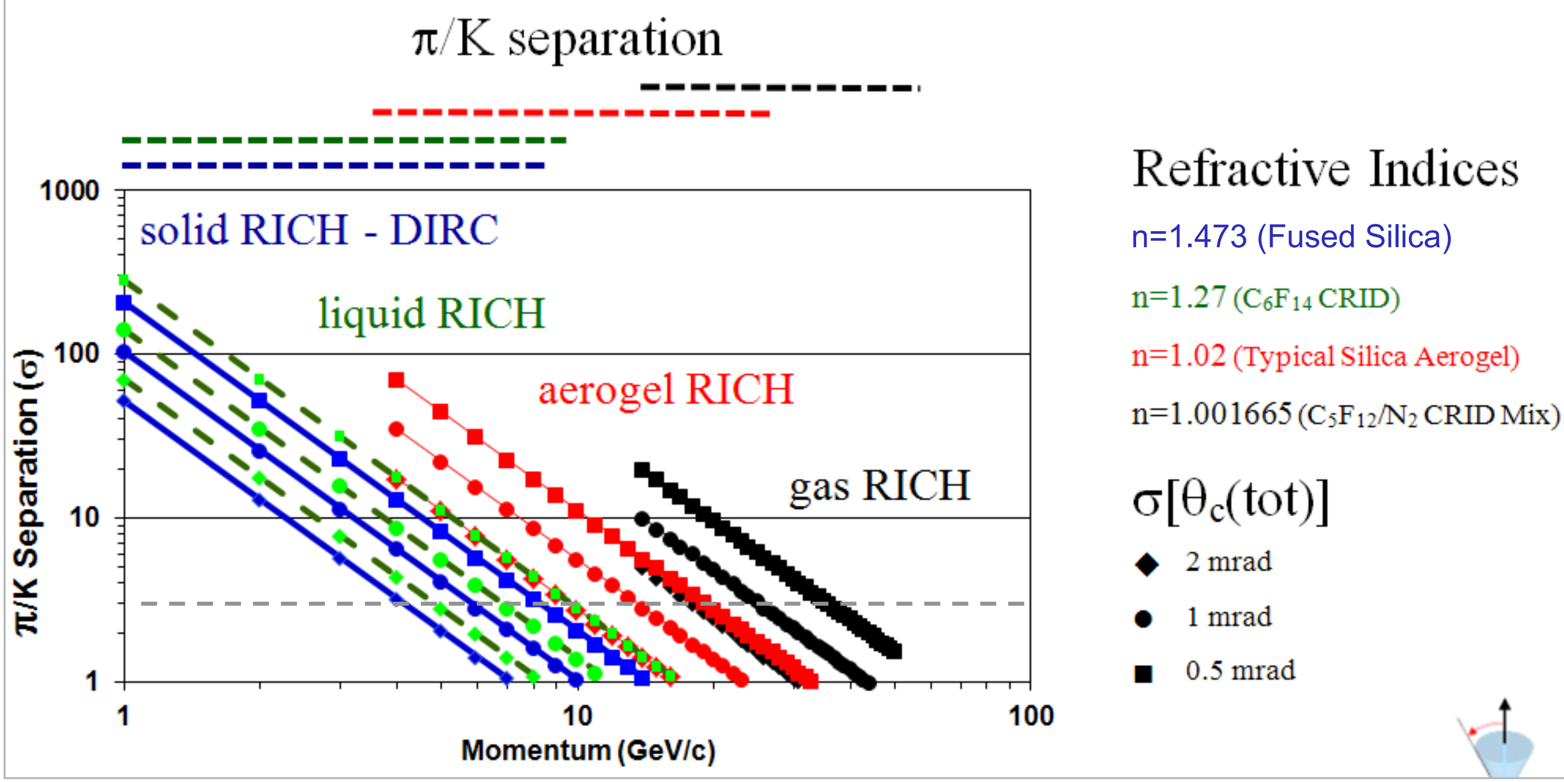


Compact expansion volume of fuzed silica (quartz)

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*

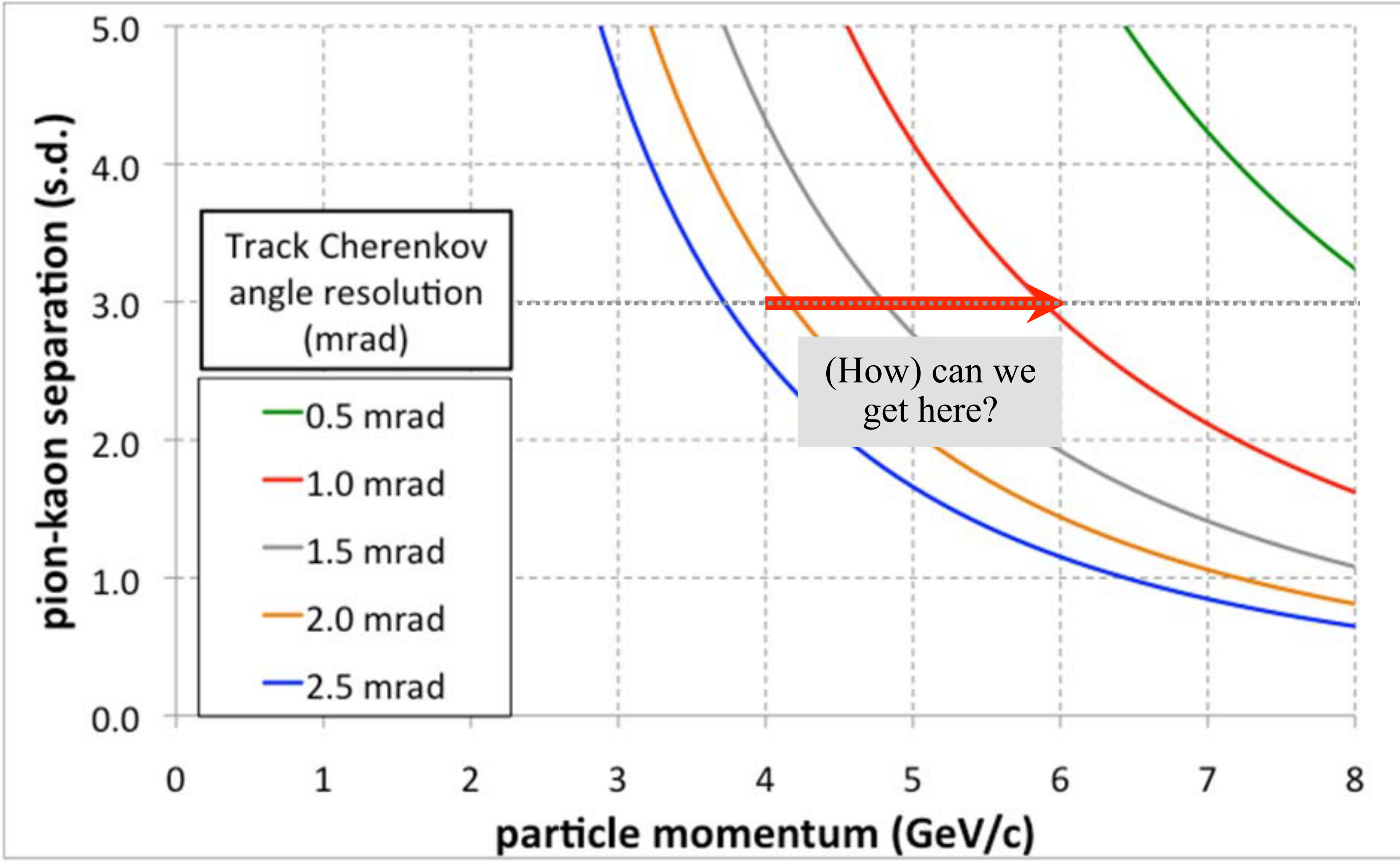
⇦ *angular error per track*

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

Tentative performance goal for DIRC@EIC

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



- Proof-of-concept simulations suggest possible to reach 6 GeV/c at forward angles

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

- 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

Specific R&D steps for simulations and prototyping

1. Develop new focusing lens-based optics

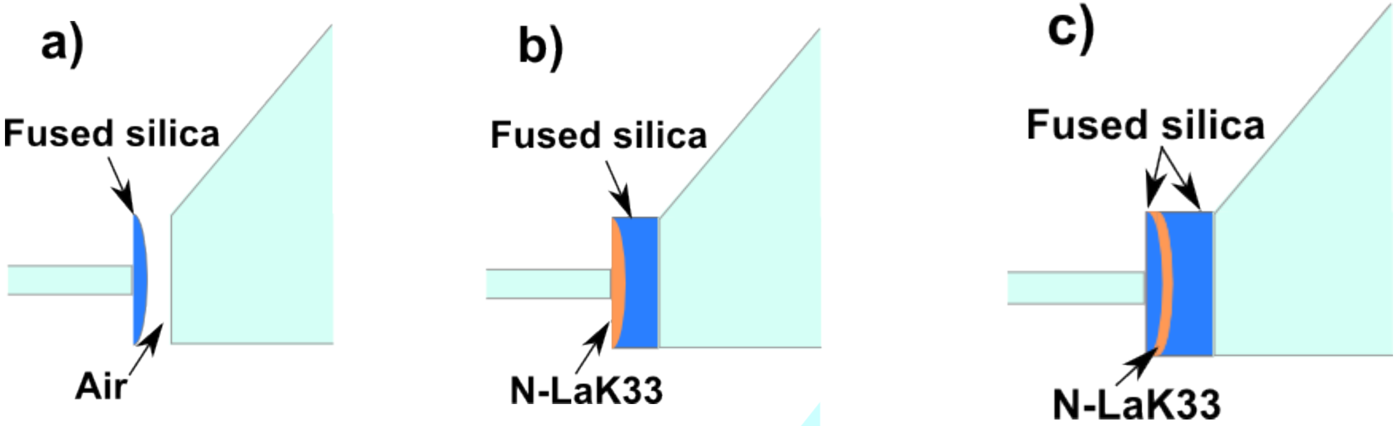
- Allows high performance and compact "camera" size
- Advanced lenses with high index of refraction counteract photon loss at 90°
- Design, procurement, and beam test of first three-layer lens has been **completed**
- Simulations and analysis of test beam data will provide a **final lens design**
  - This lens will also focus on radiation hardness, replacing NLAK with, e.g., PbF_2
  - The latter is important even if no further optical improvements can be made
- The goal is to test a final lens in beam at CERN
- Alternative configurations (mirror-based optics) can be investigate through simulations

2. Optimize the expansion volume (EV) geometry

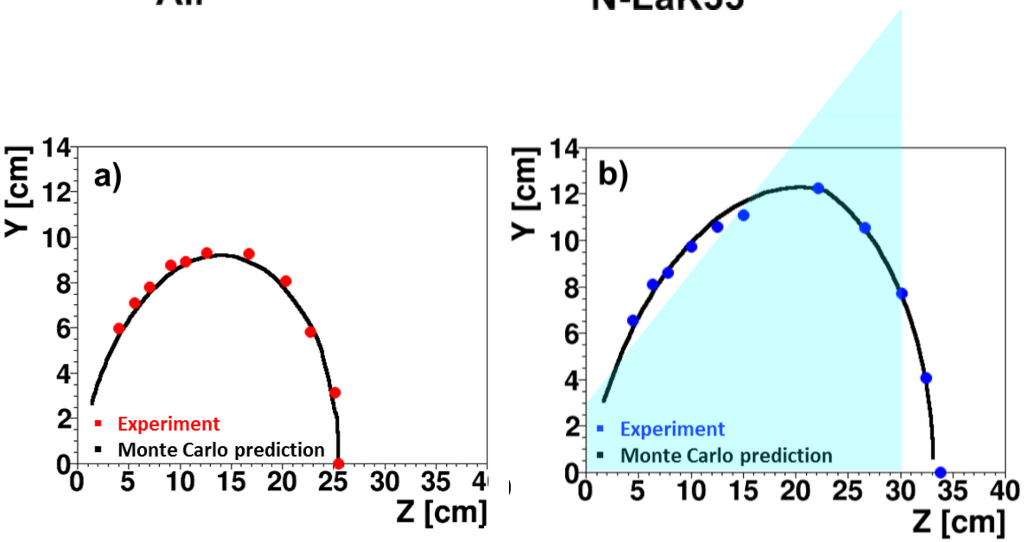
- Fused-silica prism EVs are available through synergies with PANDA R&D
- Advanced lenses have a complicated focal planes
- Can one improve performance by adapting the EV to the focal plane of the final lens?
- If yes, then tests to be made in the final year with a simple EV prototype

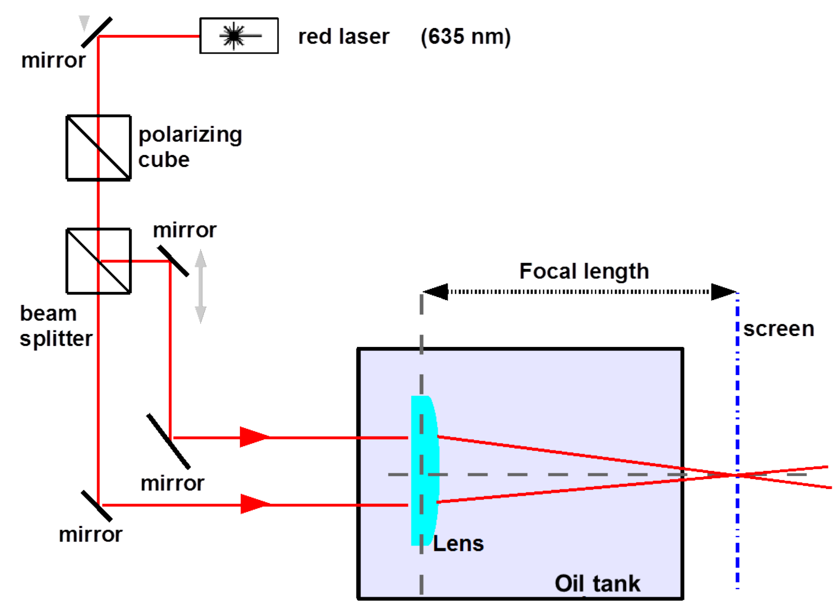
3. Implement findings in the simulation of a DIRC for an EIC detector

Lens evolution aimed to catch photons around 90°



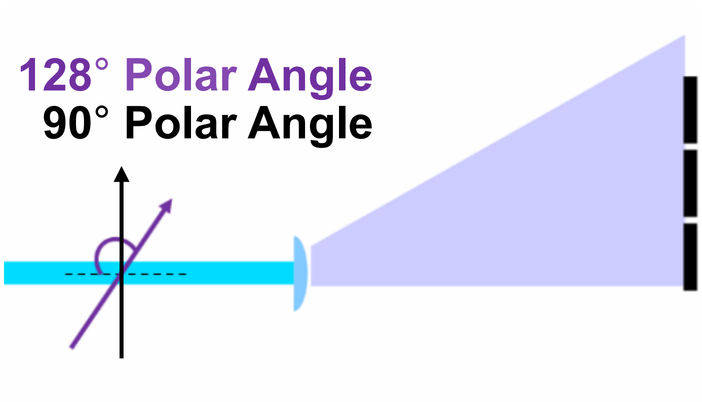
- c) is the 3rd generation lens
- Developed for the EIC R&D
- It resolves photon yield issues and improves single-photon resolution



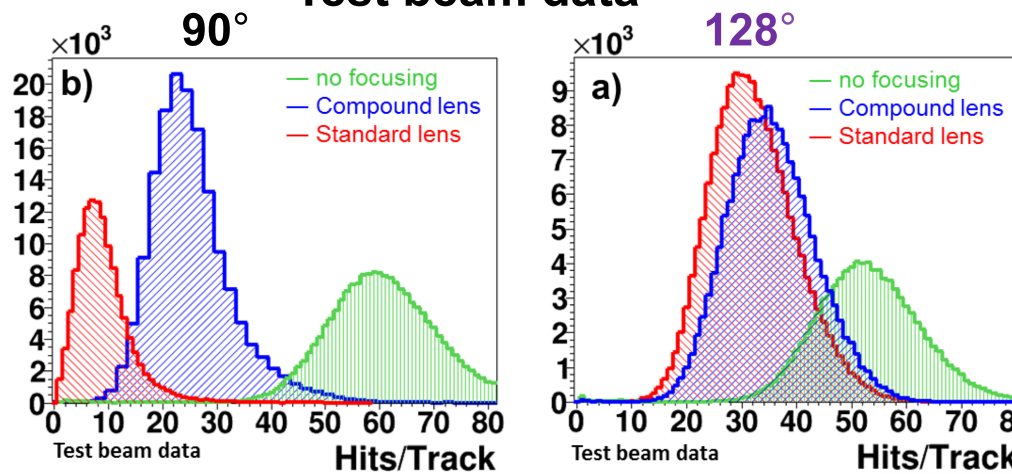


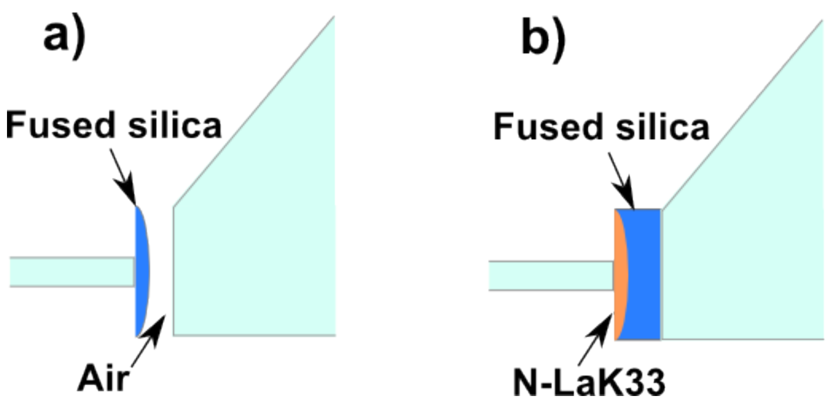
- Lenses have complicated focal planes
- Can resolution be further improved by matching lens and EV?
- Can elliptical lenses with stronger focusing in one plane be developed?

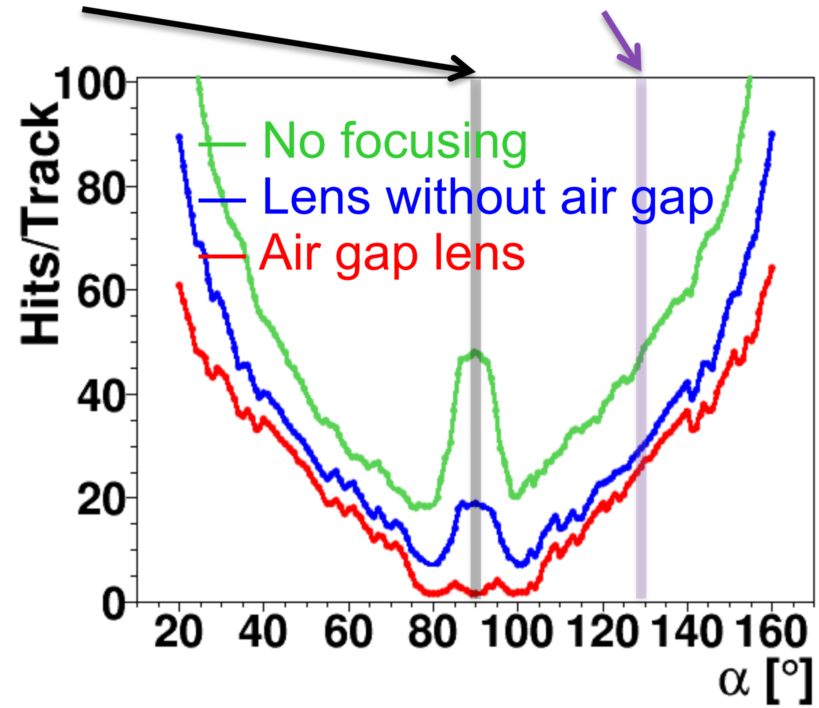
Early lenses without air gap



Test beam data







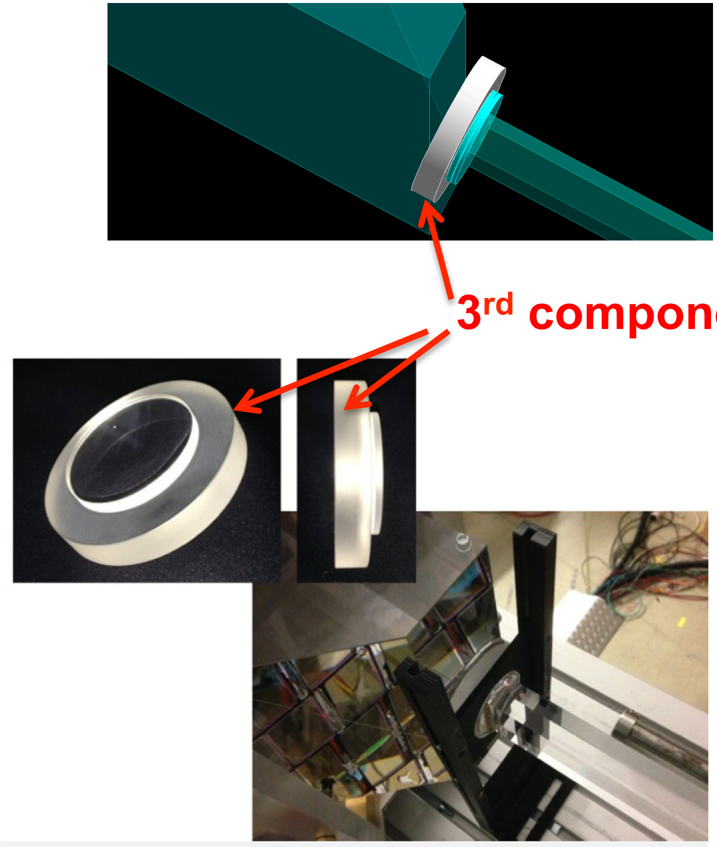
Monte Carlo data

- The 2-layer lens addressed the photon yield at 90°, but resolution (incl. kaleidoscopic effect) was not satisfactory for steeper angles
  - A 3-layer lens is needed for the EIC DIRC

Evolution of the 3-component lens simulations

1. Lens design and implementation

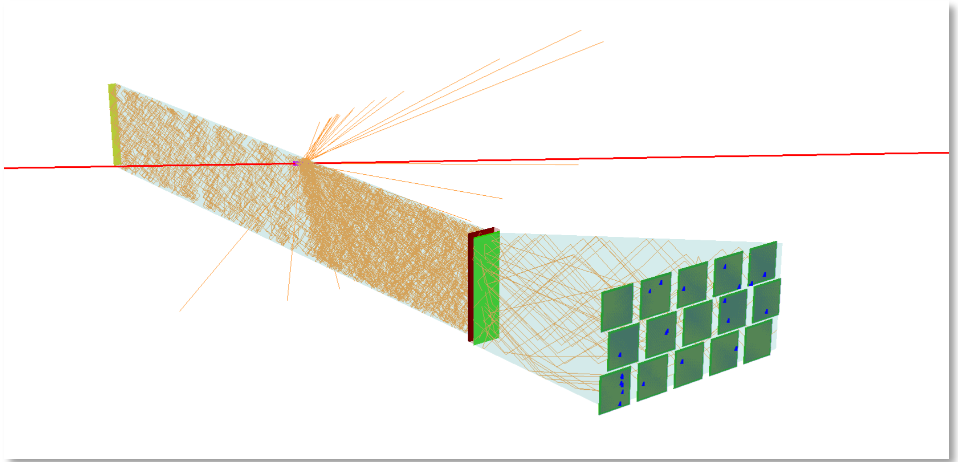
- Initial approach
  - Rectangular shapes
  - 3rd lens component had the same diameter as 1st and 2nd
- Modified lens
  - Circular shapes
  - Dimensions as shown



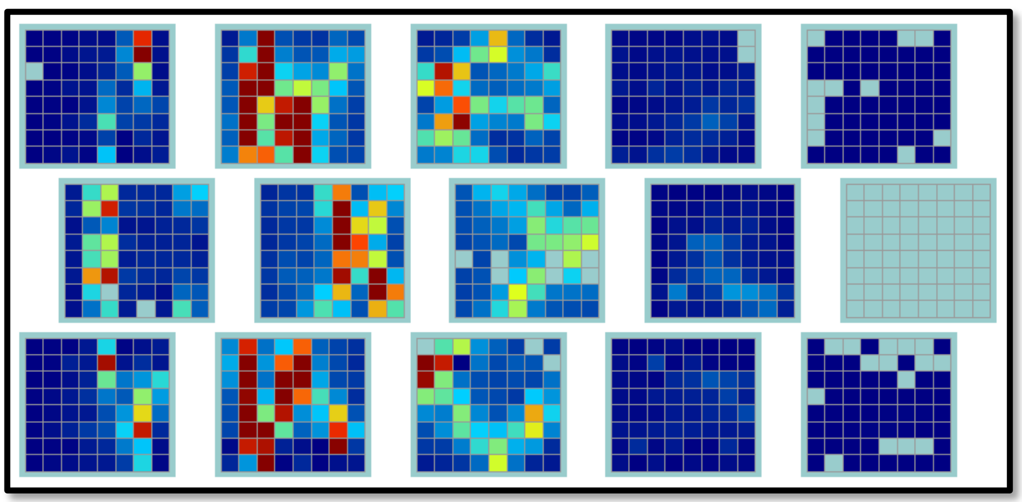
2. Sensors

- Initially generic 3x3 mm pixels with no gaps were assumed.
- Currently two cases explicitly simulated
  - Planacon MCP-PMTs with 6.5 mm pixels and 1.5 mm frame for benchmarking against test beam data
  - Future 2x2 mm pixel sensor (with the same quantum efficiency as the Planacon MCP-PMT)

Beam tests at GSI in the summer of 2014

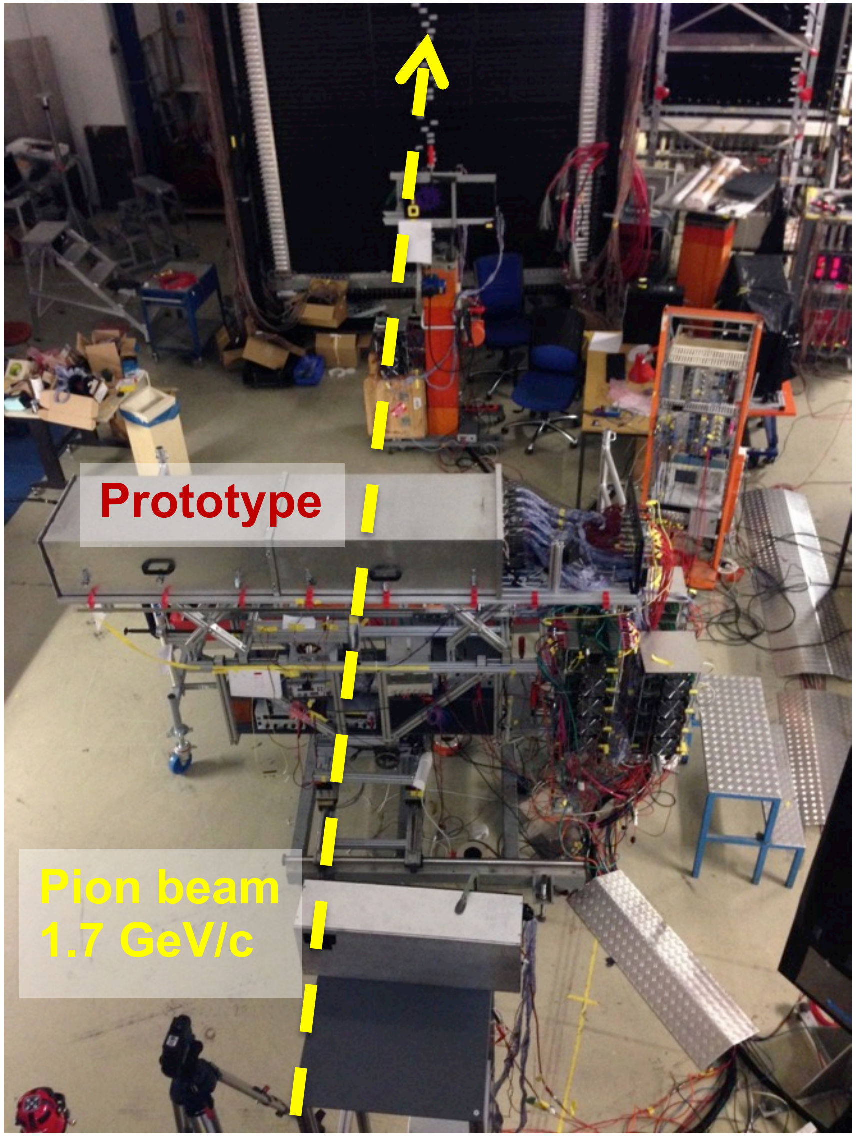


- Data with new 3-layer lens (36 mm wide bars)



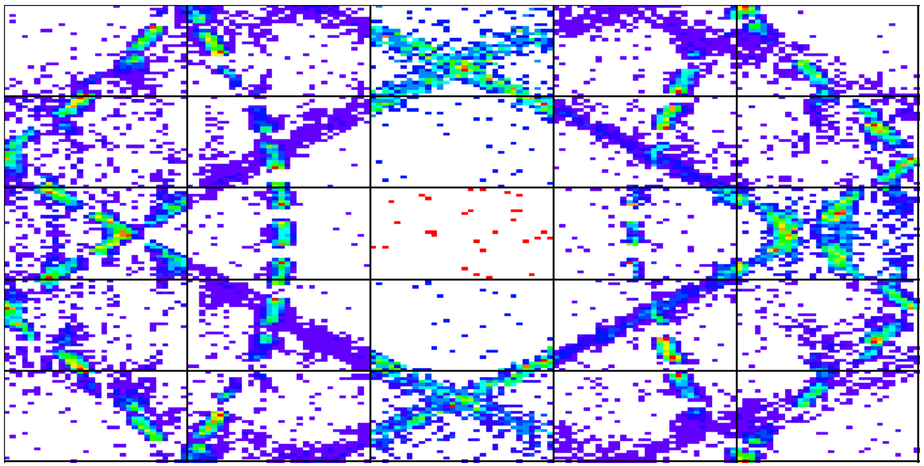
Photonis Planacon MCP-PMTs

Beam data, 125 deg:

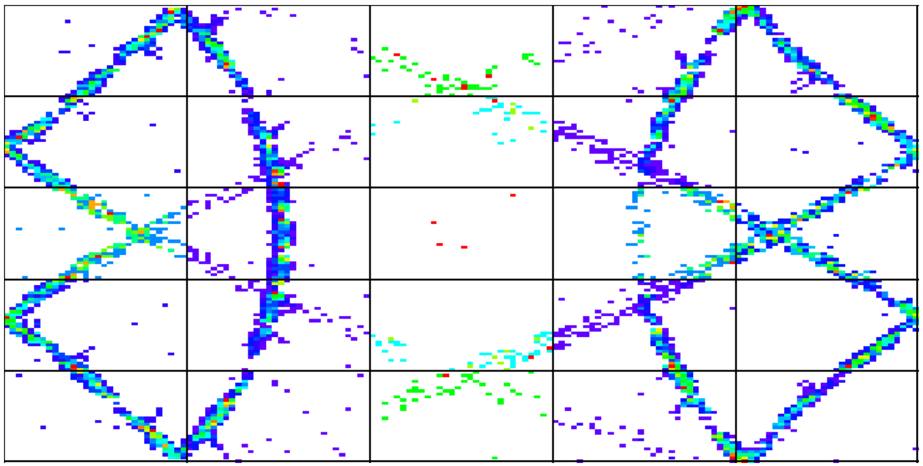


3-component lens: simulated rings for a 122° track

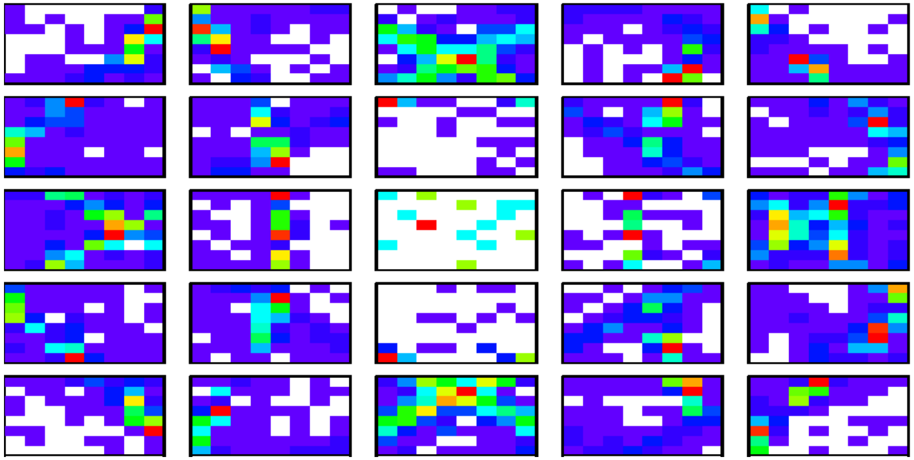
Procured, 2x2 mm pixel MCP



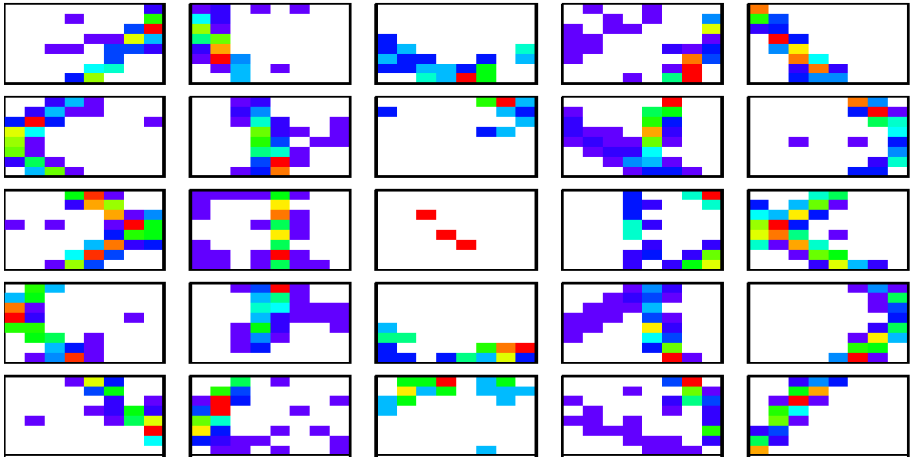
Initial, 2x2 mm pixel MCP



Procured, Planacon (6.5x6.5 mm) MCP

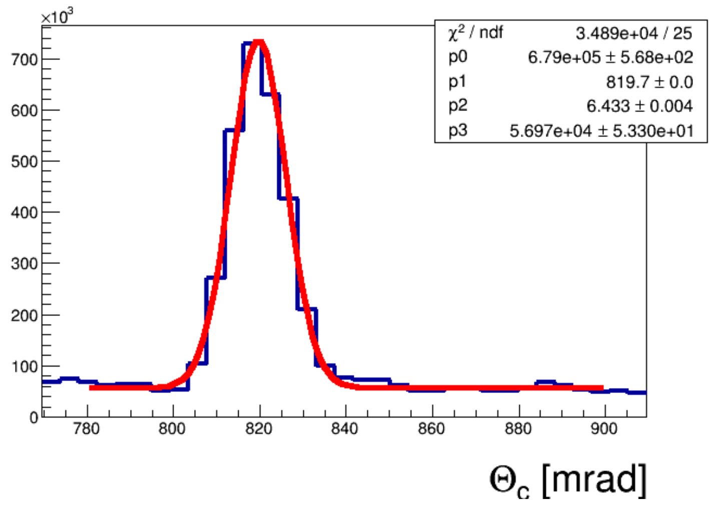


Initial, Planacon (6.5x6.5 mm) MCP

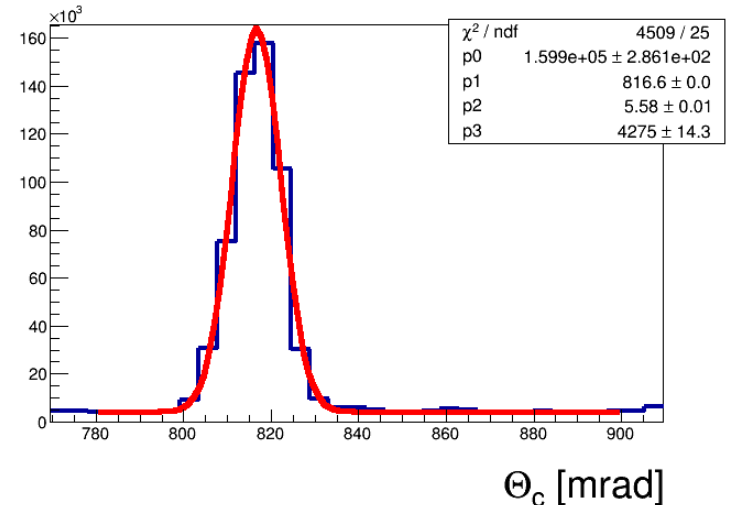


3-component lens: θ_c for a 122° track

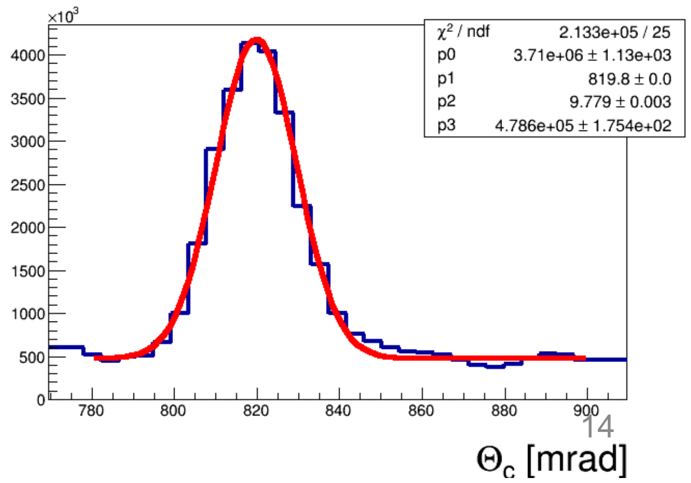
Procured, 2x2 mm pixel MCP



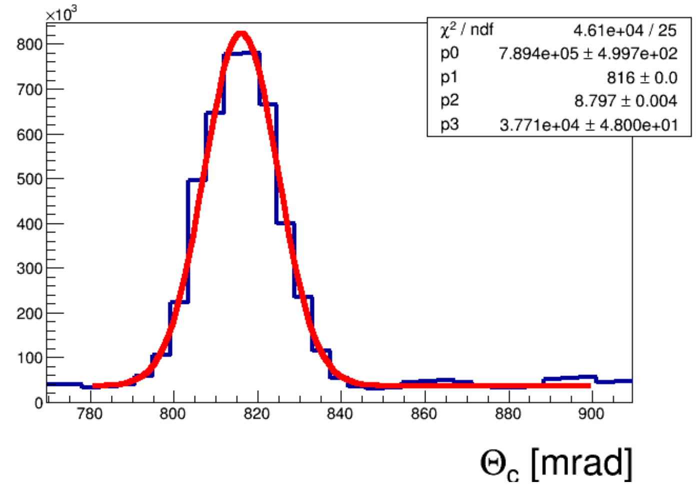
Initial, 2x2 mm pixel MCP



Procured, Planacon (6.5x6.5 mm) MCP



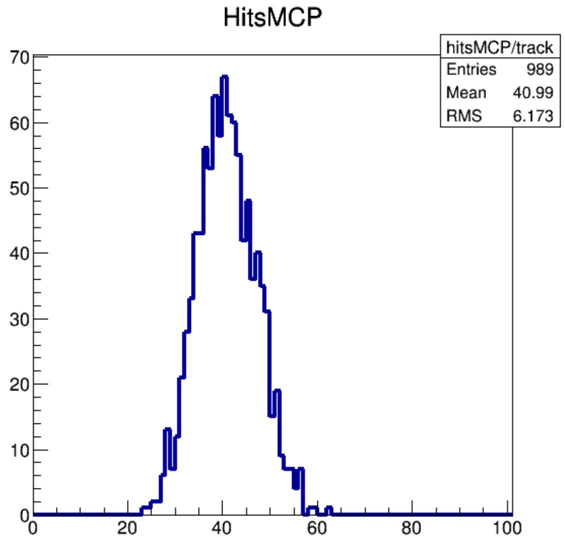
Initial, Planacon (6.5x6.5 mm) MCP



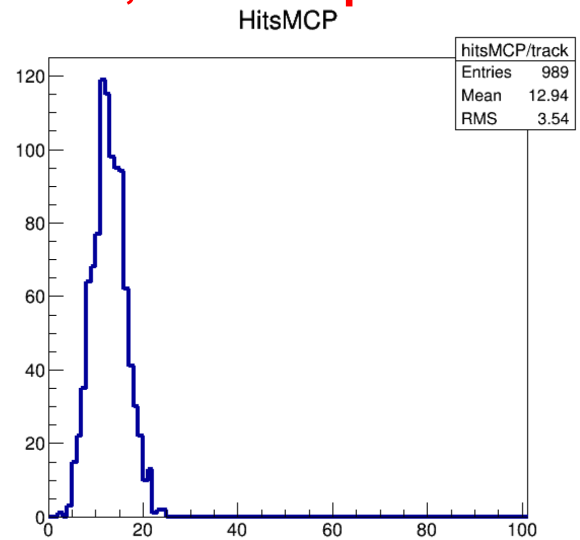
- For optimal performance, photosensors should have pixels no larger than 2-3 mm

3-component lens: photons for a 122° track

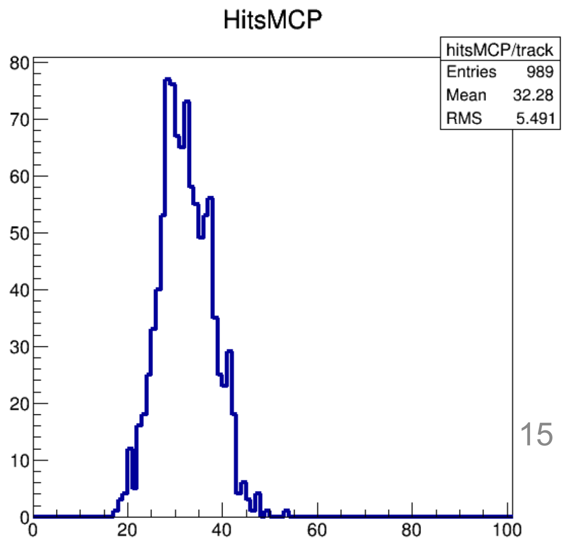
Procured, 2x2 mm pixel MCP



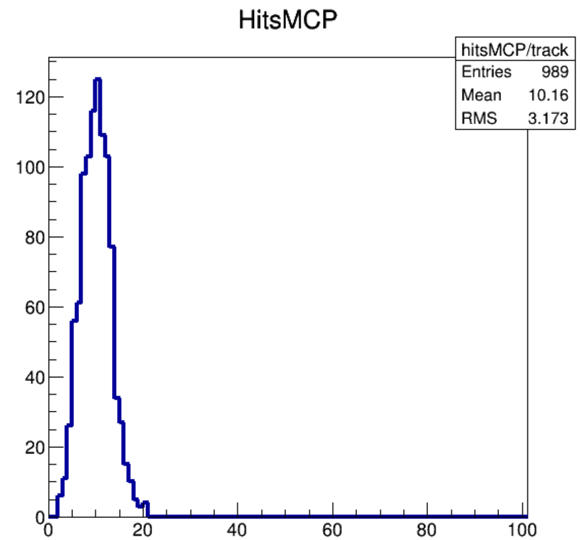
Initial, 2x2 mm pixel MCP



Procured, Planacon (6.5x6.5 mm) MCP

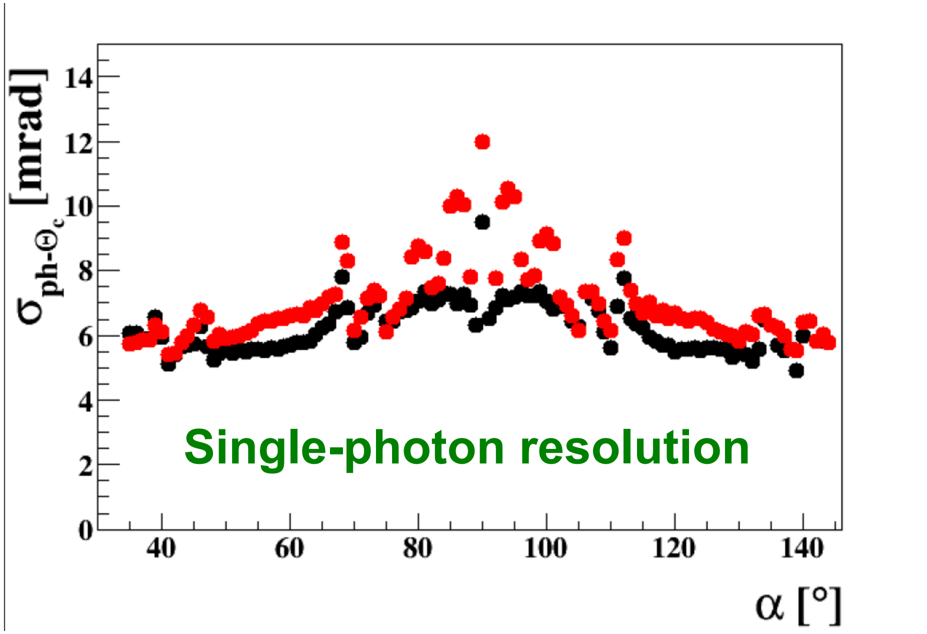


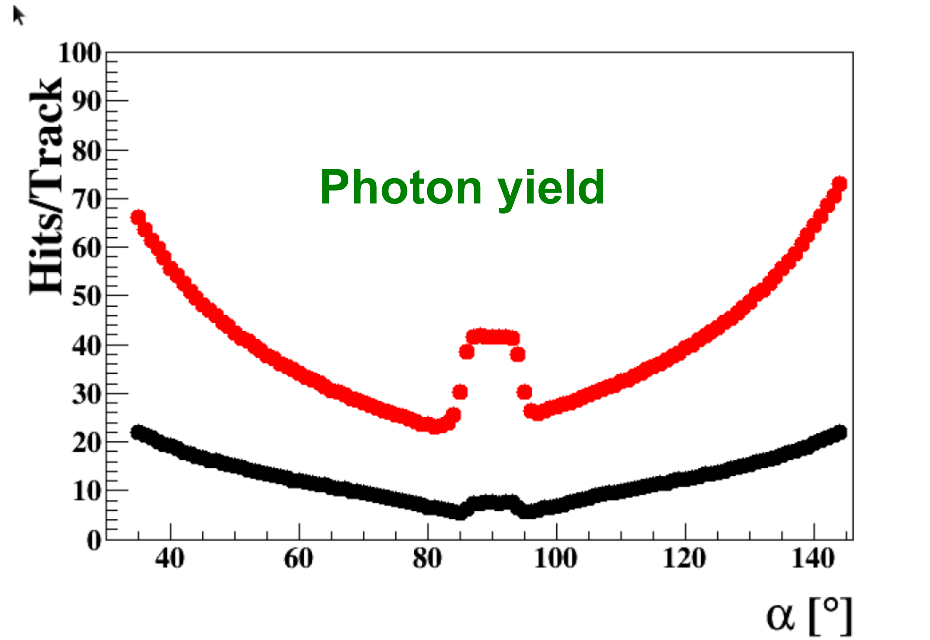
Initial, Planacon (6.5x6.5 mm) MCP

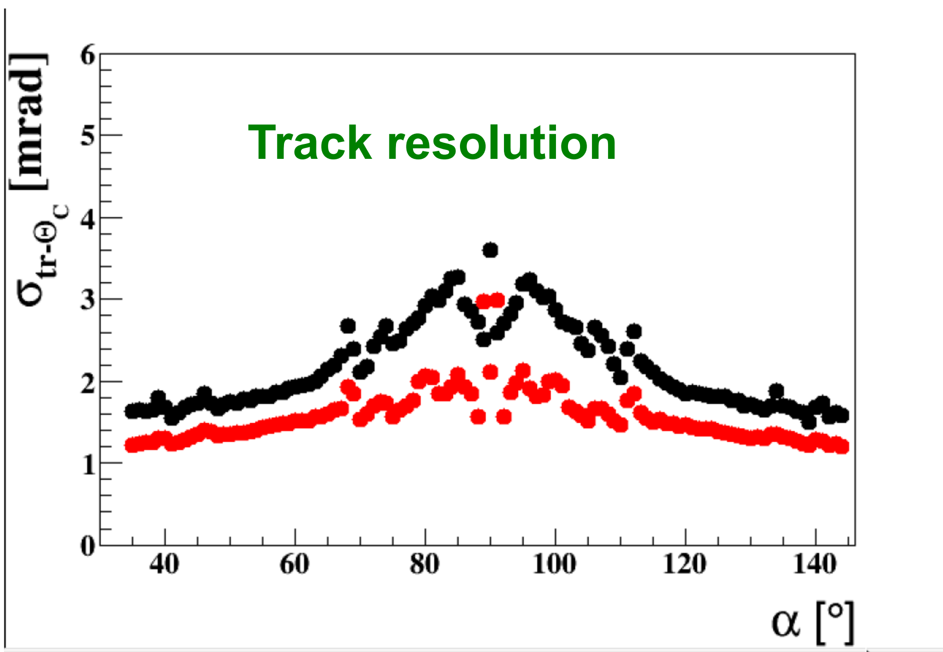


- The improved lens design (which was procured) significantly improved photon yields

Improvements in the 3-component lens design



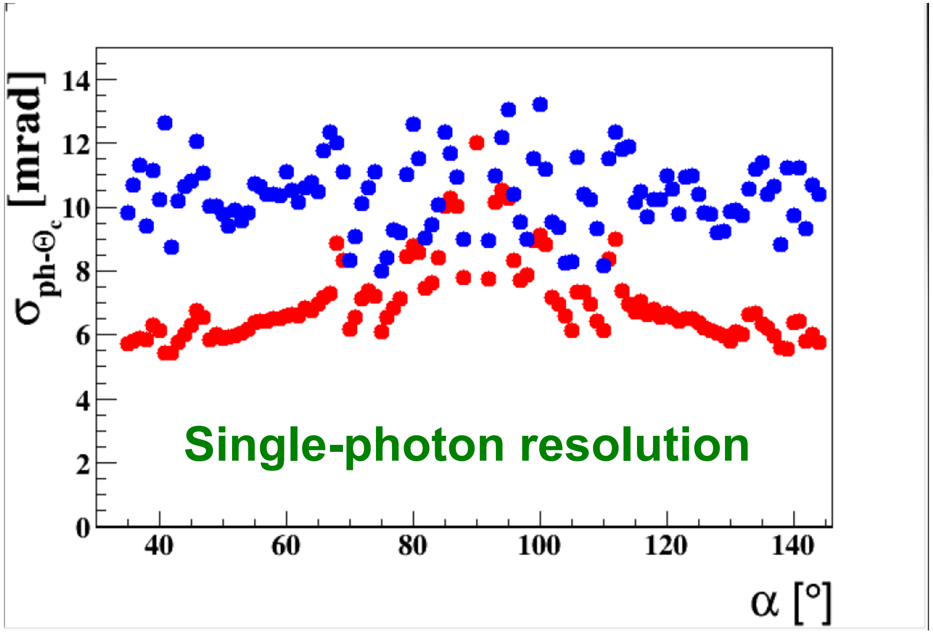


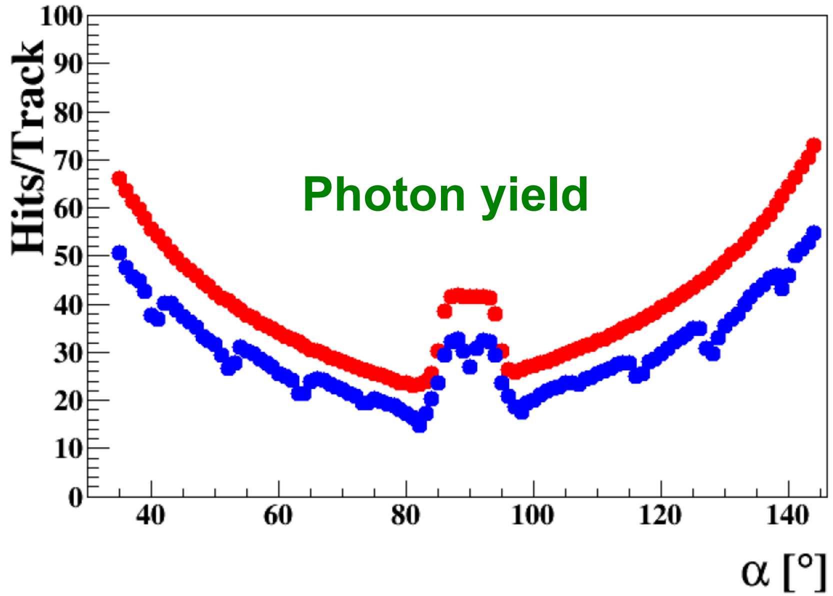


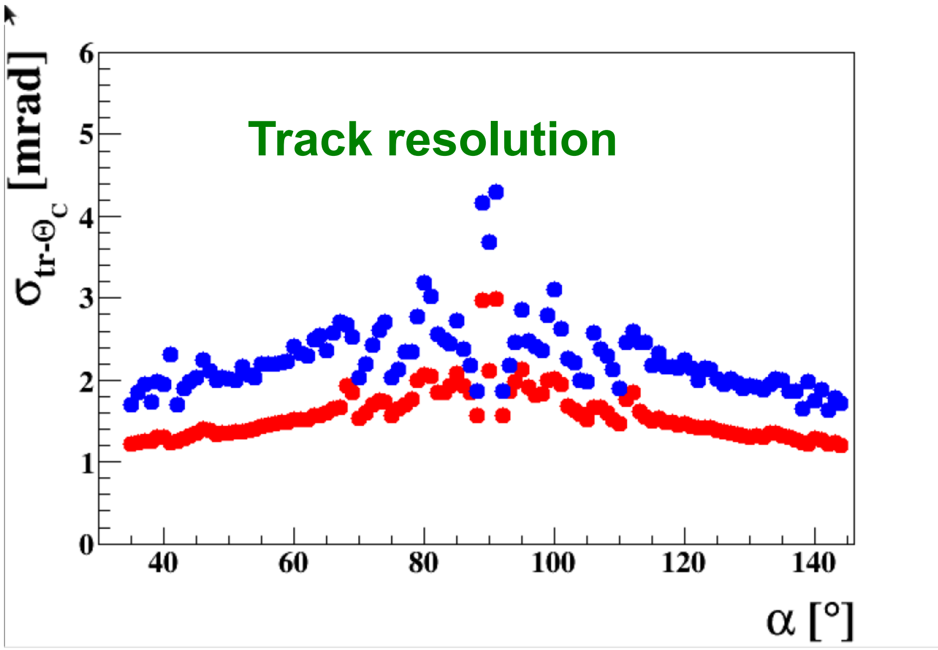
Initial 3-component lens, 2x2 mm MCP
Procured 3-component lens, 2x2 mm MCP

- The optimization of the 3-component lens from initial simulation to procurement greatly improved the photon yield for all polar angles.

Performance of the procured 3-component lens



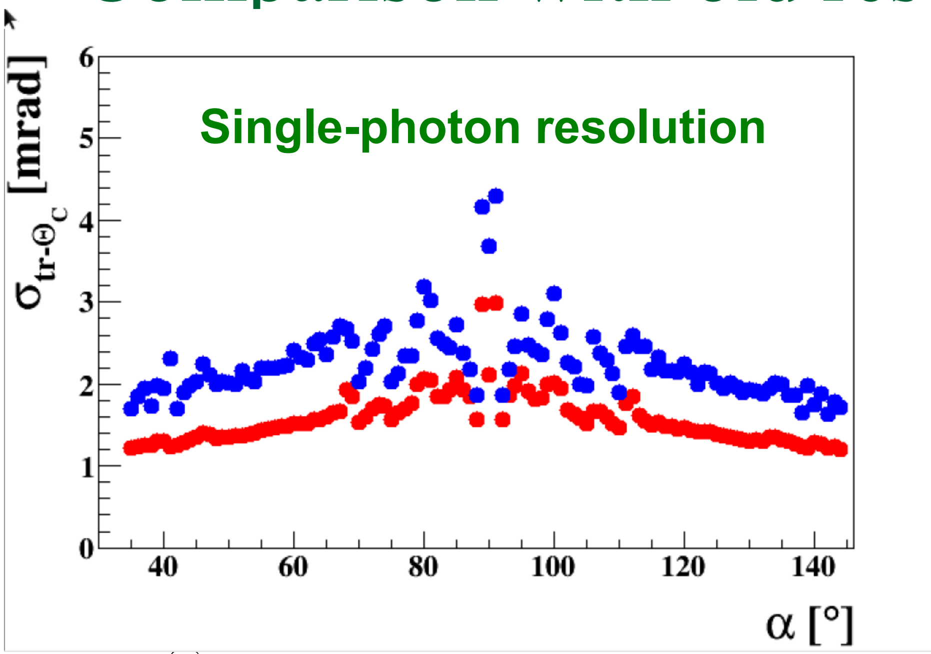


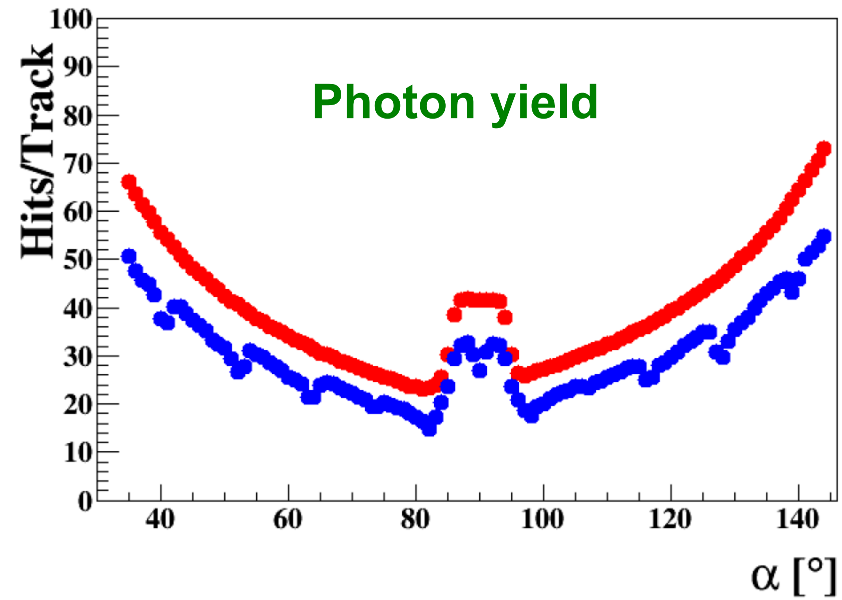


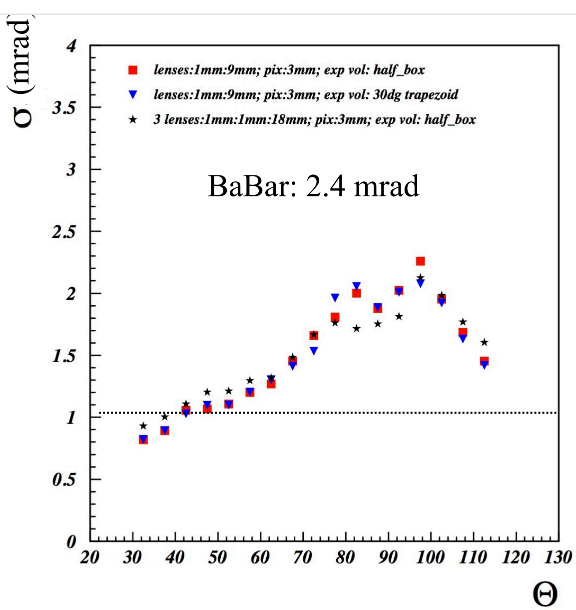
Procured 3-component lens, Planacon MCP
Procured 3-component lens, 2x2 mm MCP

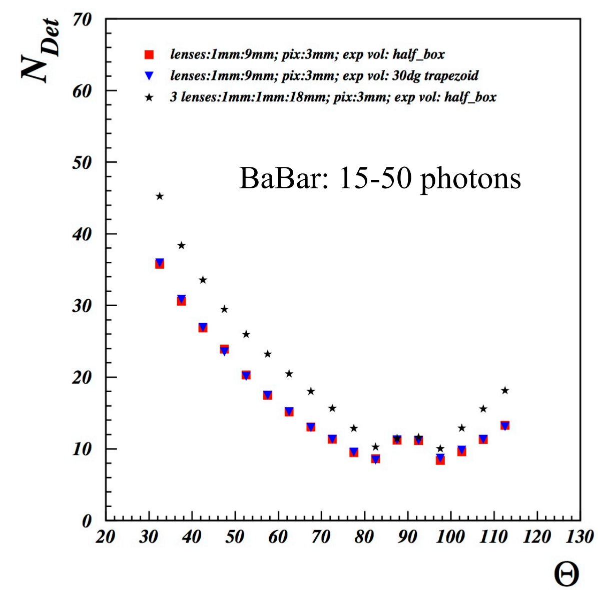
- A high-performance DIRC will require small-pixel photosensors.
- The simulation confirms that a resolution close to 1 mrad (6 GeV/c) can be reached at forward (and backward) angles.

Comparison with old results



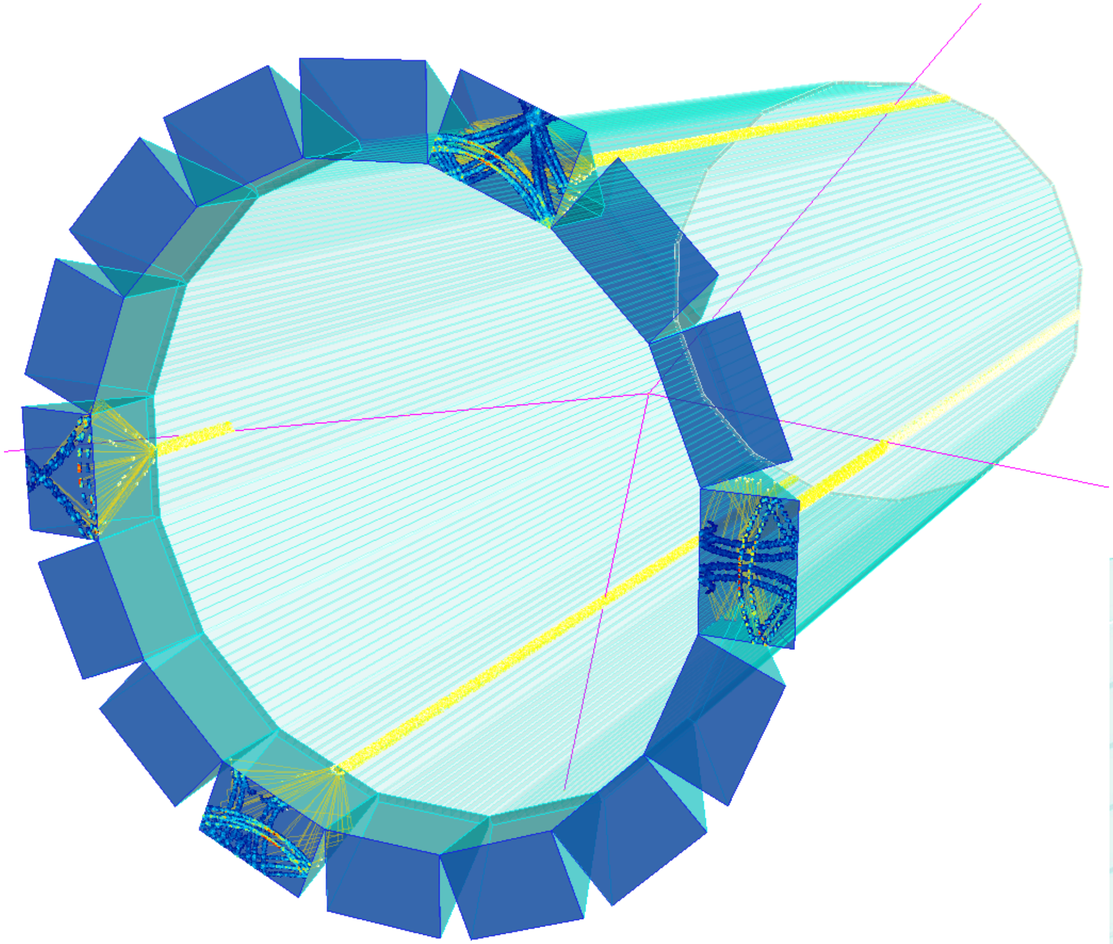






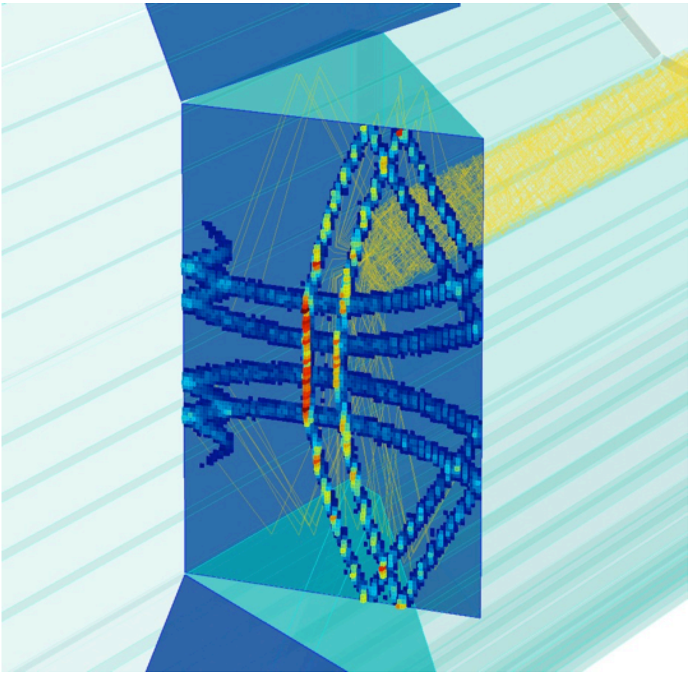
- Note that the scales differ, but that the (blue) resolution at any given angle is similar

GEANT4 simulation with narrow bars



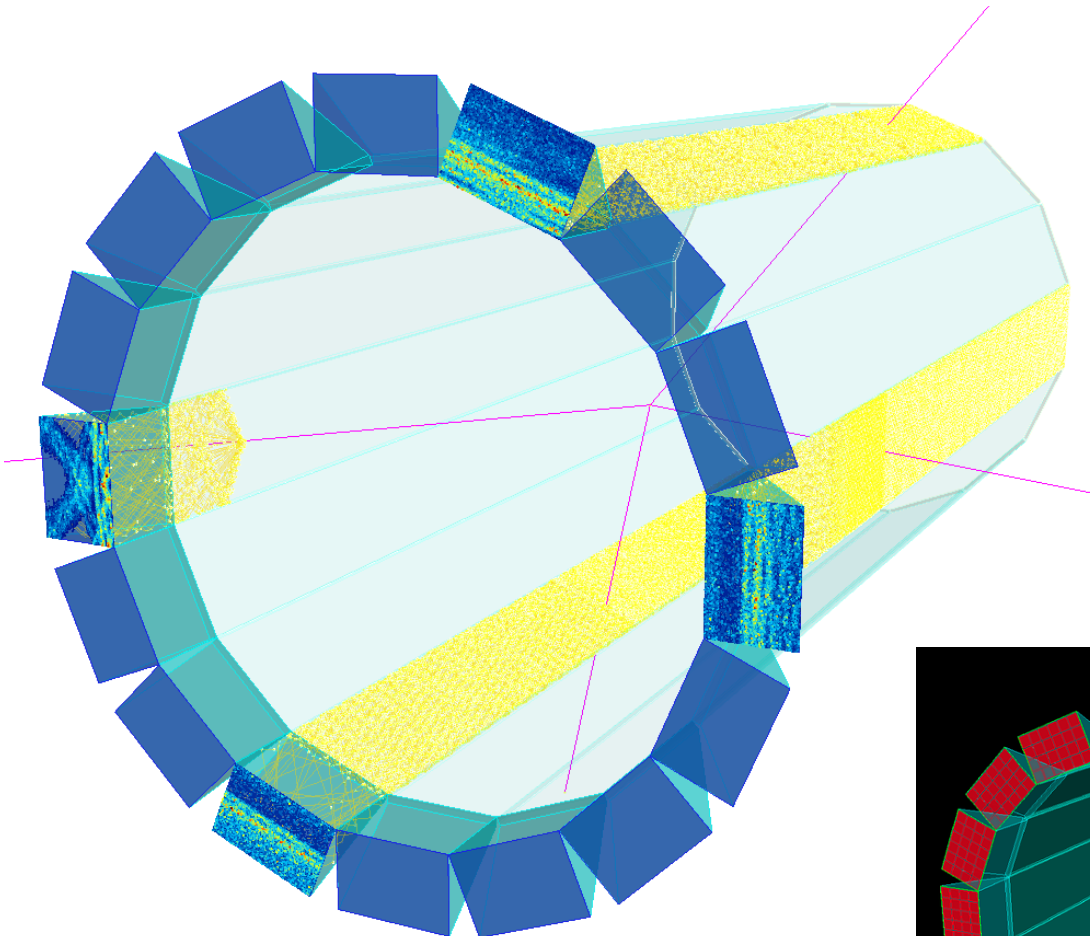
- Standalone GEANT4 simulation developed at GSI
  - Can be integrated with various frameworks (GEMC, eicROOT)

- Closeup of the spherical 3-layer lens without air gap

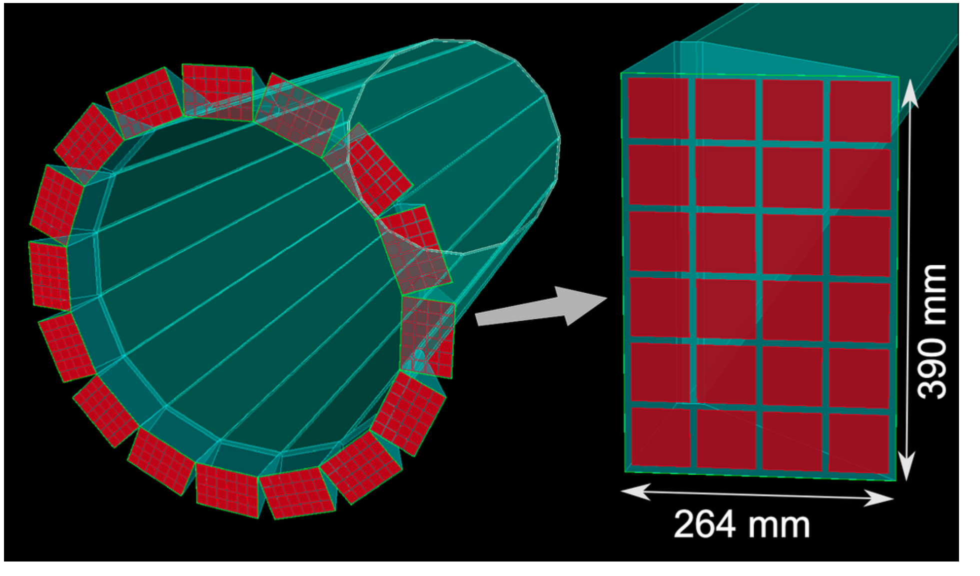


- 16 bar boxes assumed, but this can be adjusted to the specific EIC detectors

GEANT4 simulation with wide plates



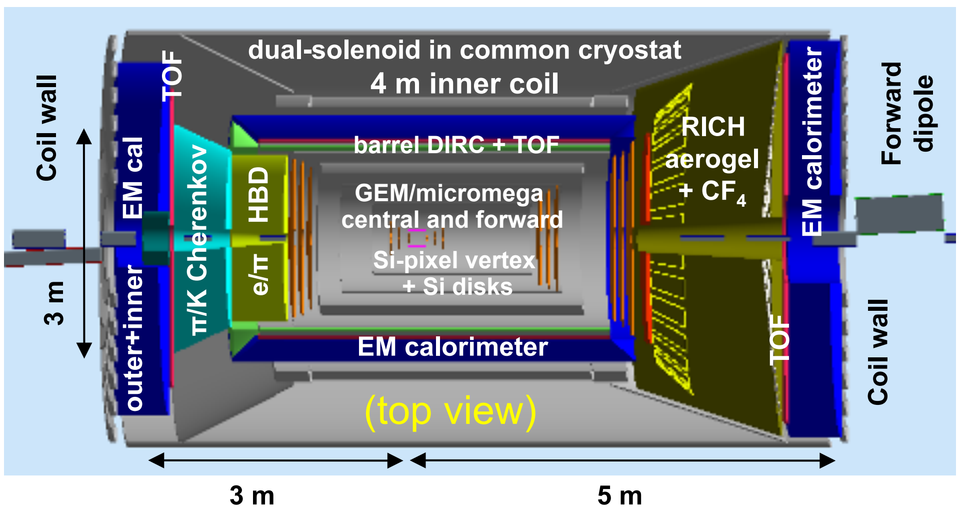
- A combination of precision timing (as in Belle II) and full spatial imaging could provide an interesting alternative to bar boxes.
- New reconstruction algorithms are needed!



- 16 wider bars (plates), each with a width comparable to that used in Belle II

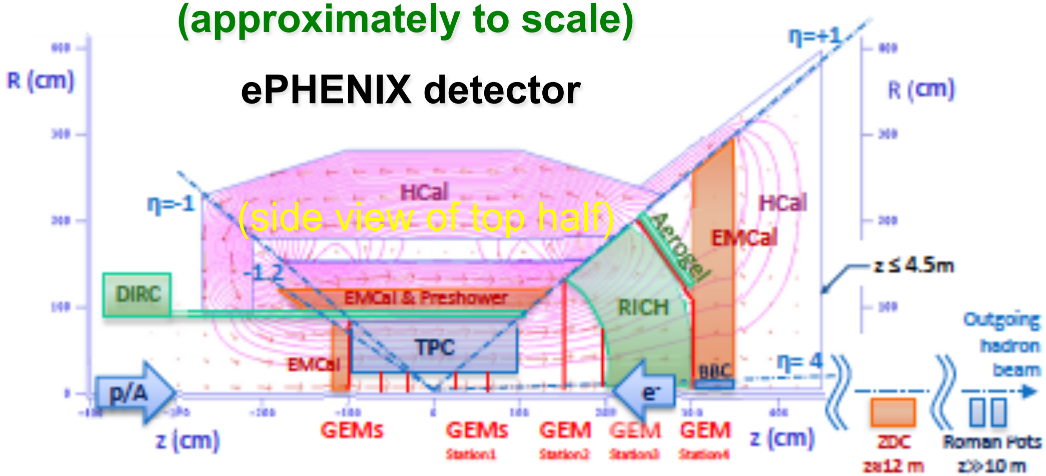
Integration with EIC detector concepts

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.

Summary of ongoing simulations

1. Proof-of-concept 1 mrad resolution verified

- New drcprop simulations, using a more robust reconstruction algorithm, show a resolution comparable to the one originally obtained.
  - The old reconstruction indicated erroneously showed too many photons, but this was offset by improvements in the design of the 3-layer lens

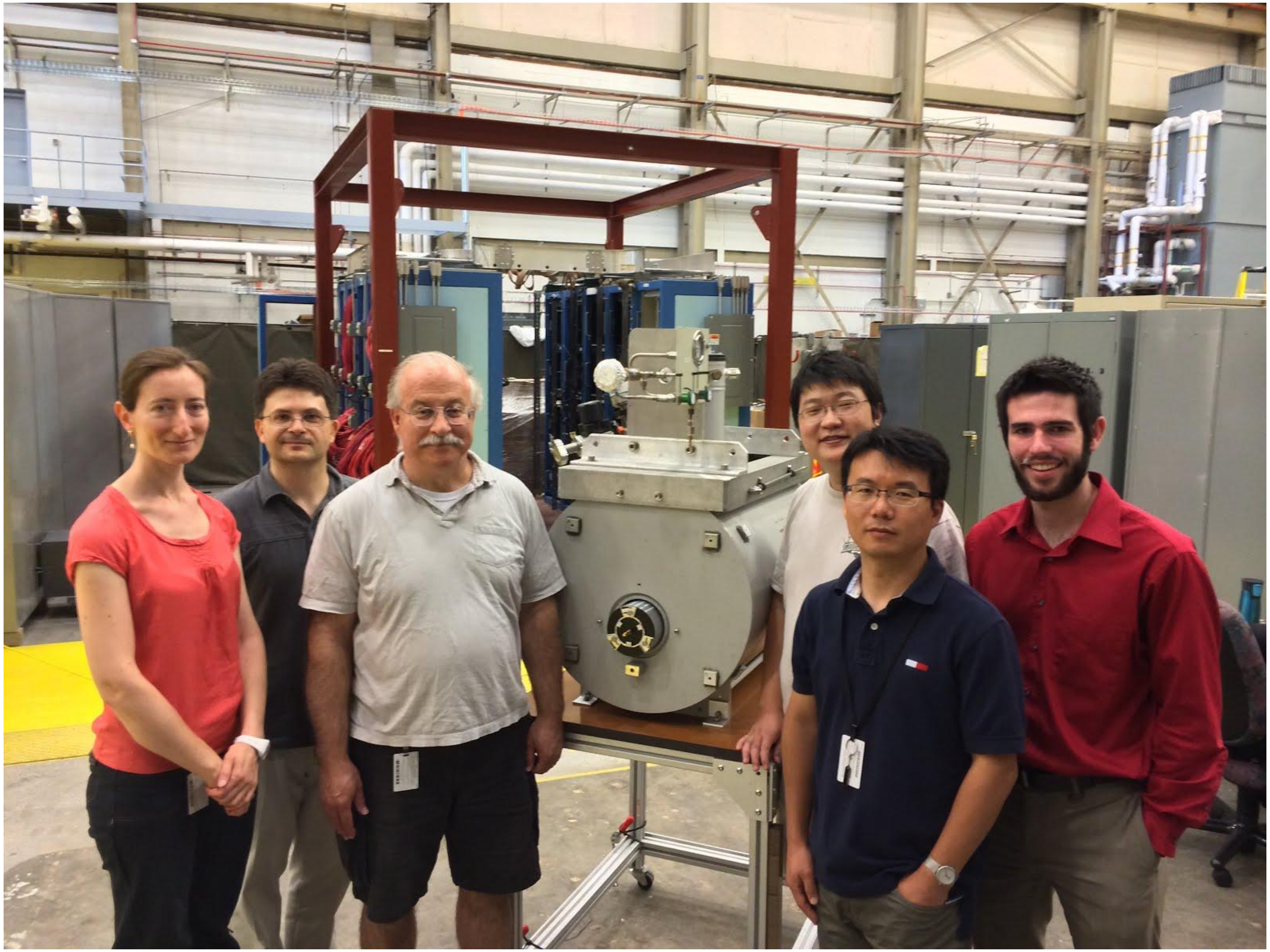
2. Simulations for test beam and EIC detector under way

- Benchmark against the results of the test beam data of the 3-layer lens.
  - Reproduced conditions from the 2014 test beam at GSI
- Further improvements in lens design?
- Optimization of the DIRC for the EIC detector

3. GEANT4 simulations getting started

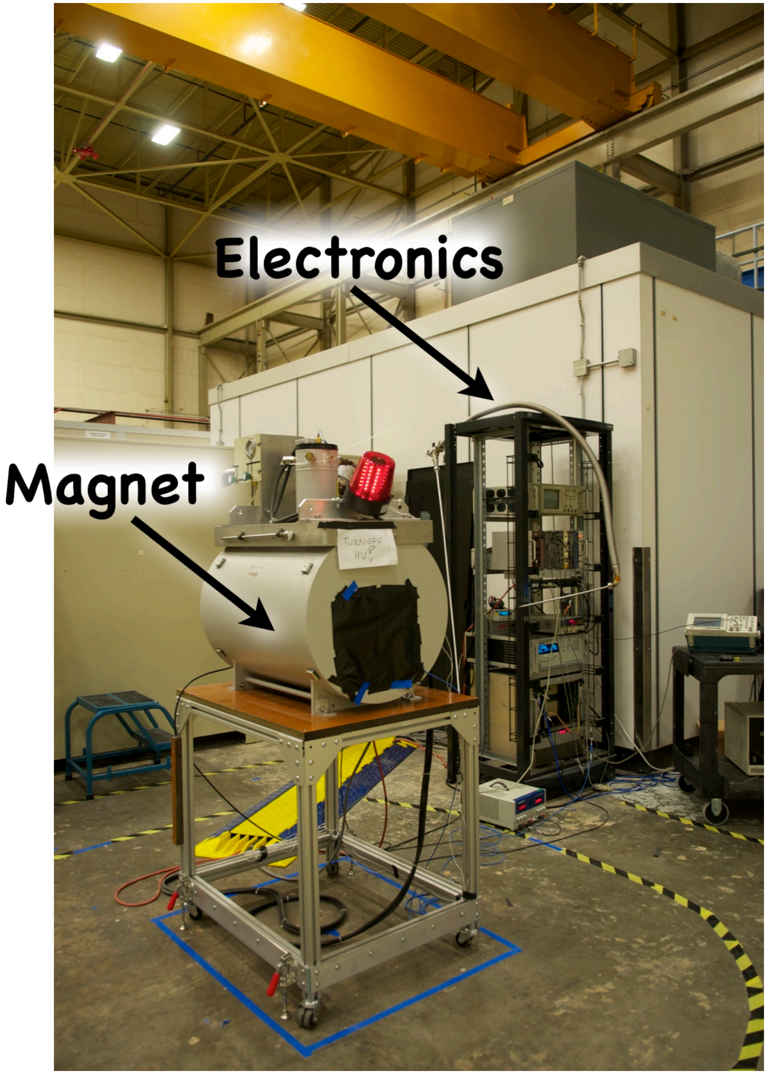
- Will eventually merge into the general EIC detector simulation

Tests of 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 is now in operation!

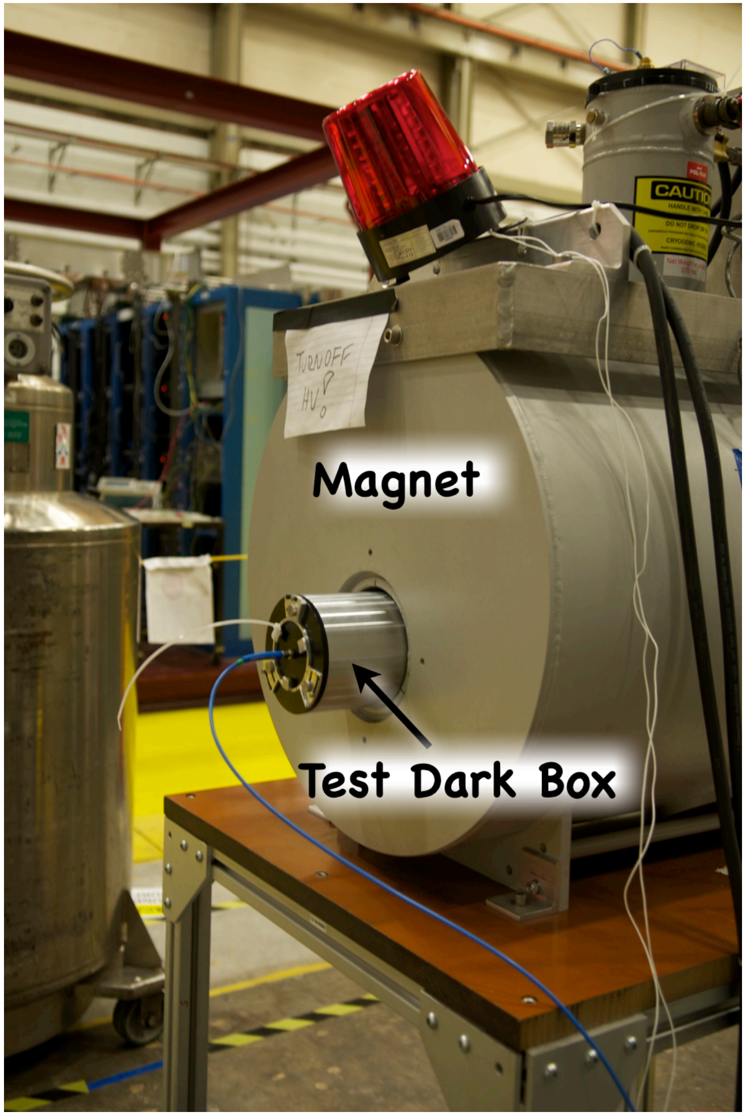


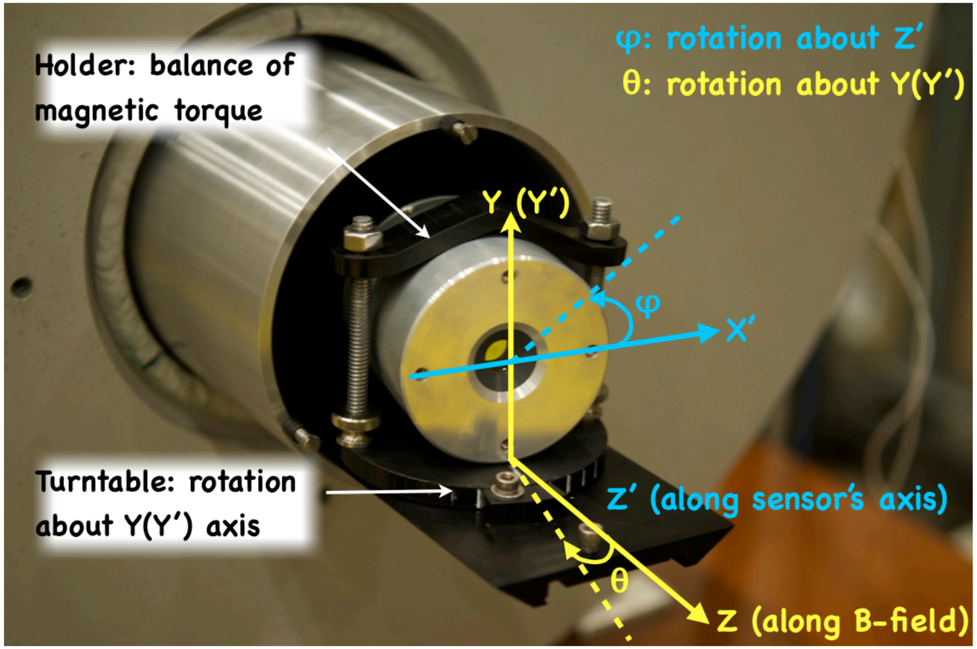
T. Cao and G. Kalicy during cooldown (LHe dewar is visible)

Commissioning carried out late summer and production data were taken before Thanksgiving 2014.

One run per semester is planned during years 4 and 5

First sensors tested in B field up to 5 T

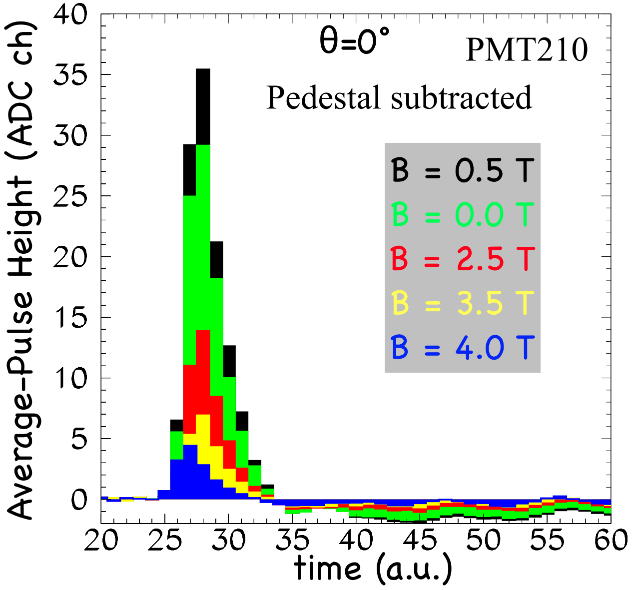


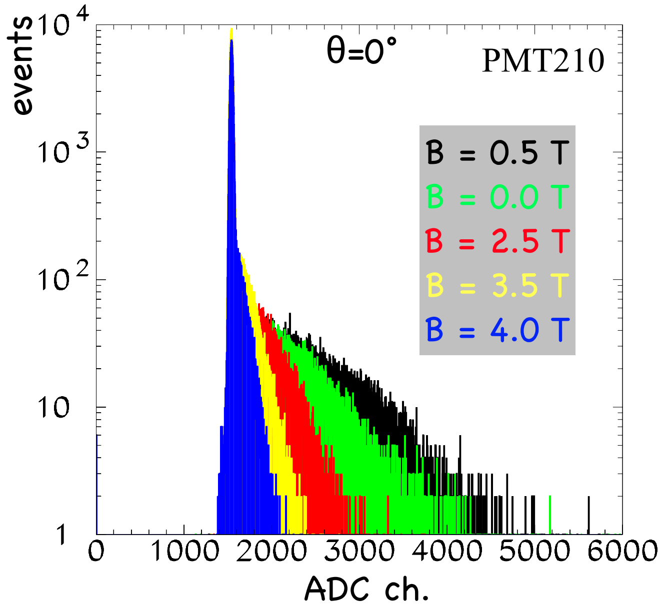


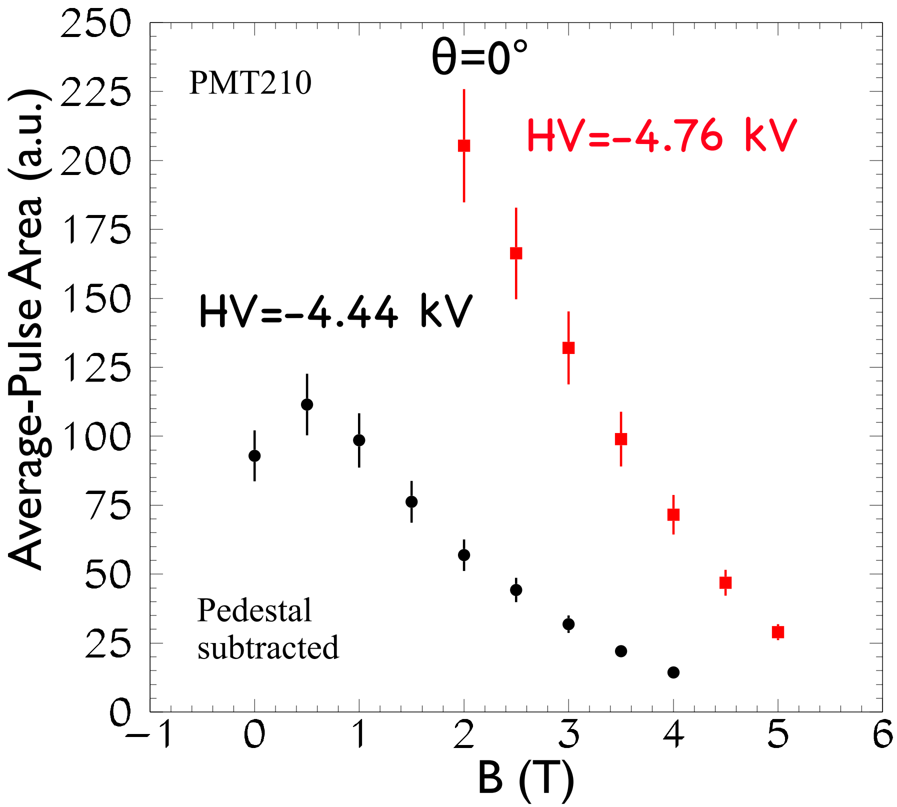
- The pictures show the dark tube which is inserted into the FROST 5 T solenoid and the Photek PMT210 mounted in the rotatable holder

- In addition to the PMT210, the Photek PMT240 and Photonis PP0365G MCP-PMTs were also tested during the November run.

Sample high-B field data from the November run





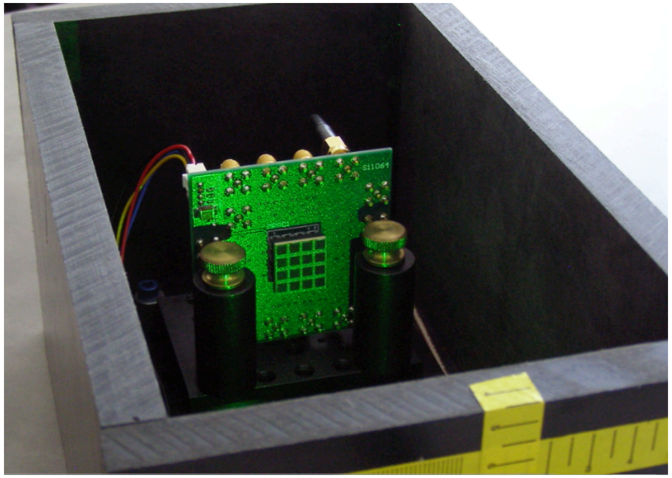


- Very preliminary data in arbitrary units for the Photek PMT210 for one specific azimuthal orientation with respect to the B-field

High-B field – planned sensor tests

Photonis Planacon multi-pixel MCP-PMTs at JLab

Katod single-anode MCP-PMTs. Two have been ordered, with 3 and 5 µm pore size, respectively



Non-magnetic dark box with pulsed LED for the DVCS solenoid – note the GlueX SiPM (Hamamatsu S11064-050P(X))

- The next round(s) of tests will include the Photonis Planacons on loan to JLab, the finally delivered Katod MCP-PMTs, and a MCP-PMT donated by Hamamatsu

- In the future, additional sensors can be tested in either the FROST or DVCS magnets, including SiPMs or LAPPDs

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!

Budget summary

Budget	Year 1	Year 2	Year 3	Year 4	Year 5	*Total*
Postdoc (50%)	$53,290	$54,000	$55,200	$52,305	$55,147	*$269,942*
Students	$8,300	$13,764	$13,764	$13,784	$13,764	*$63,356*
Hardware	$41,970	$58,630	$24,000	$30,000	$36,000	*$190,600*
Travel	$11,440	$13,606	$22,036	$18,931	$10,089	*$76,102*
Total	*$115,000*	*$140,000*	*$115,000*	*$115,000*	*$115,000*	*$600,000*

Budget	Year 1	Year 2	Year 3	Year 4	Year 5	*Total*
Old Dominion University (ODU)	$53,290	$54,000	$55,200	$52,305	$55,147	*$269,942*
Catholic University of America (CUA)	$9,800	$8,300	$8,300	$8,300	$8,300	*$43,000*
University of South Carolina (USC)		$7,606	$12,646	$12,646	$7,606	*$40,504*
JLab and GSI (through MoU)	$51,910	$70,094	$38,854	$41,749	43,947	*$246,554*
Total	*$115,000*	*$140,000*	*$115,000*	*$115,000*	*$115,000*	*$600,000*

- 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)*

Summary

New simulations indicate that 1 mrad resolution is indeed possible

New, advanced lens performed well in test beam and simulation

High-B field sensor testing facility has taken its first data

Backup

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

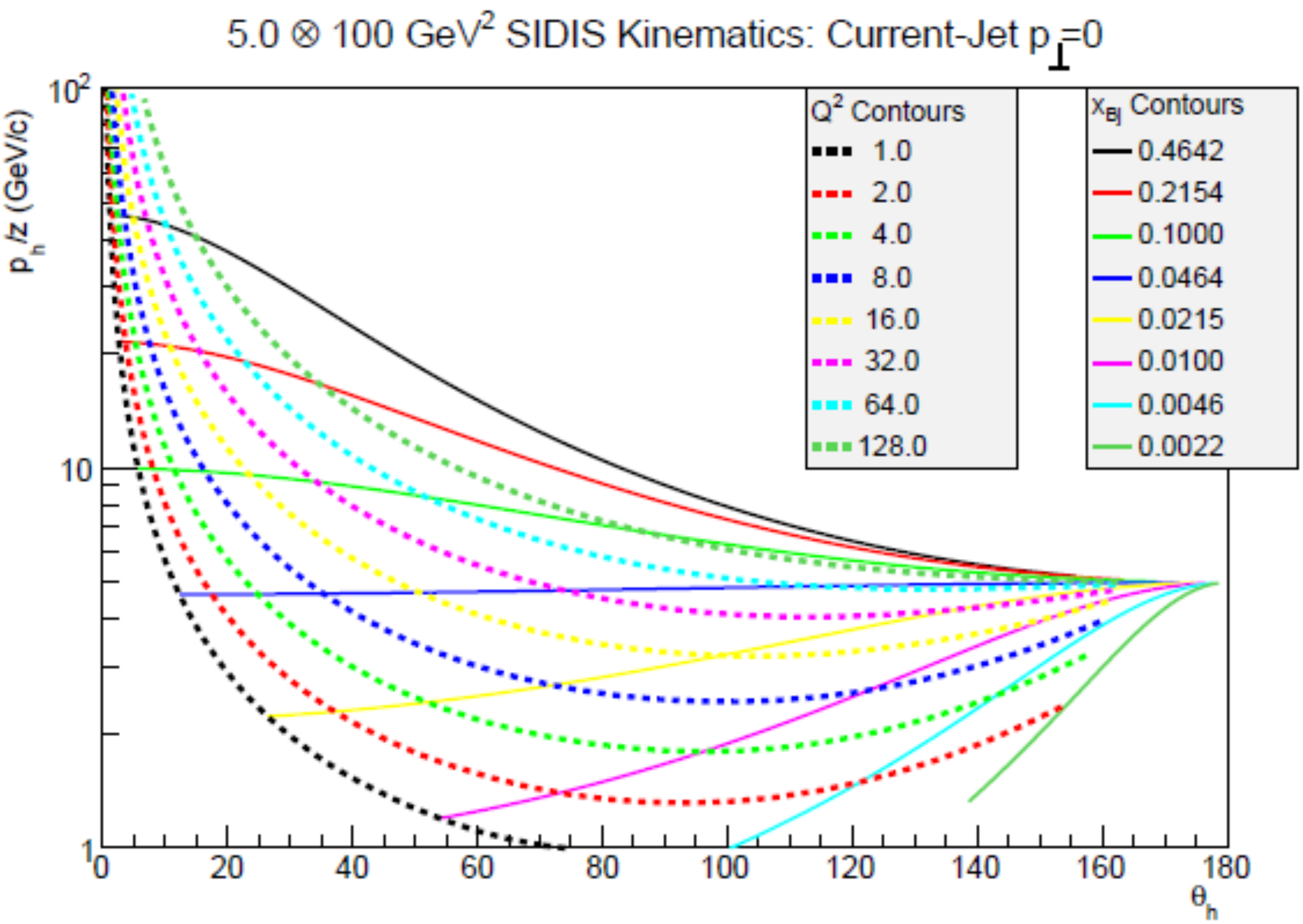
- University of South Carolina and Jefferson Lab

4. Detector integration

- Catholic University of America

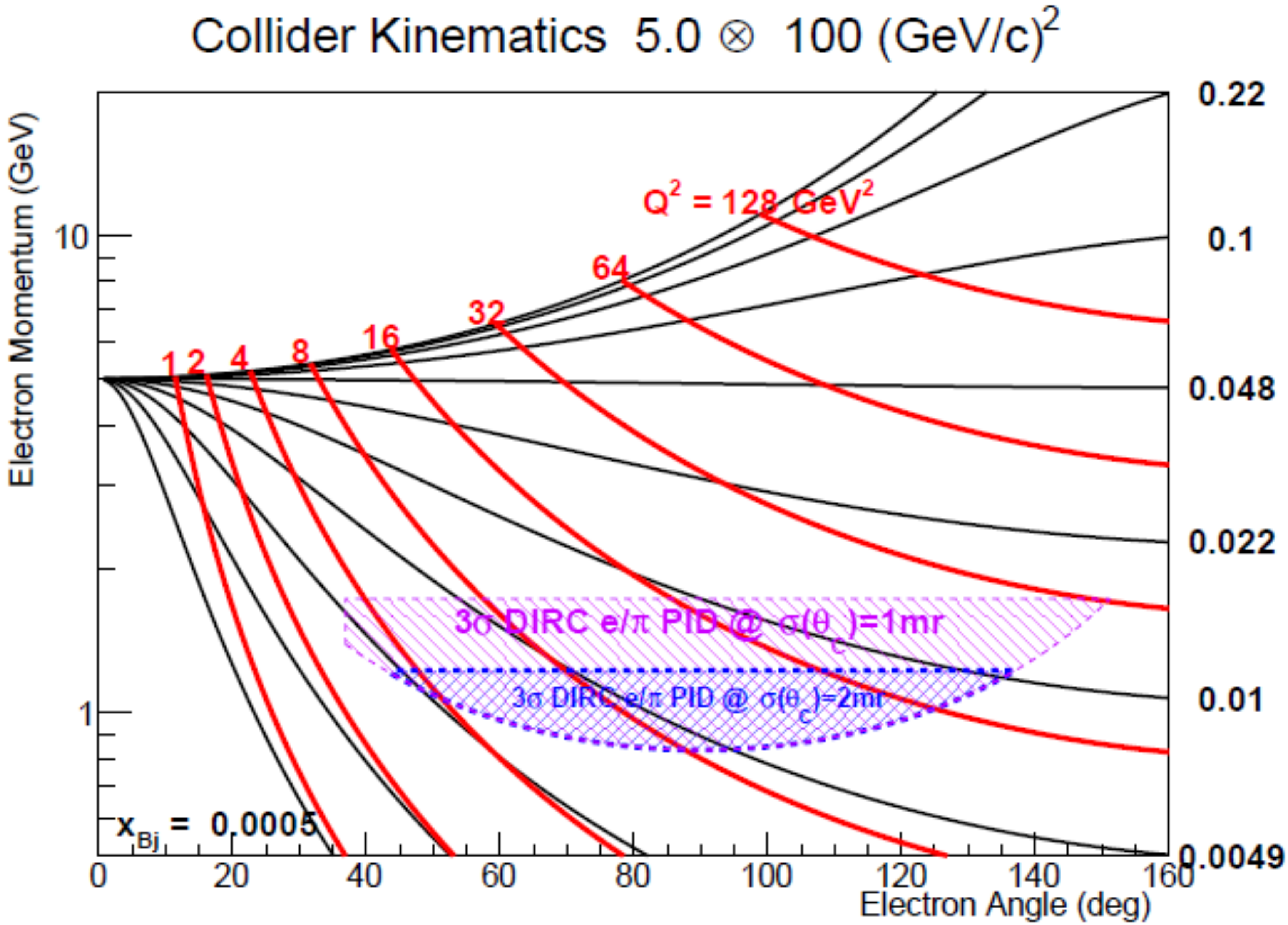
Note: **The proposal is a collaborative effort and most institutions will contribute to more than one of the areas above regardless of their primary responsibility**

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

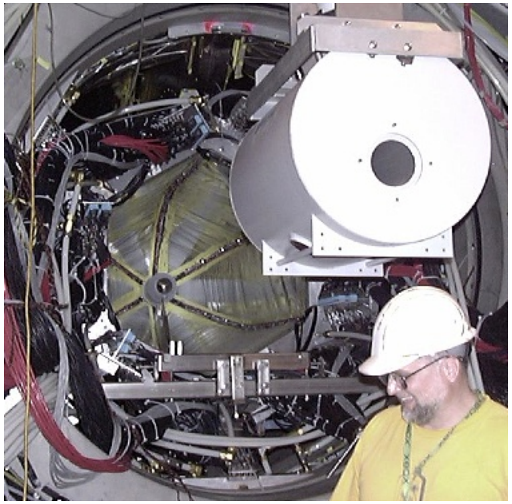


- High-Q^2, low-x electrons have low momenta and require good pion suppression

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)



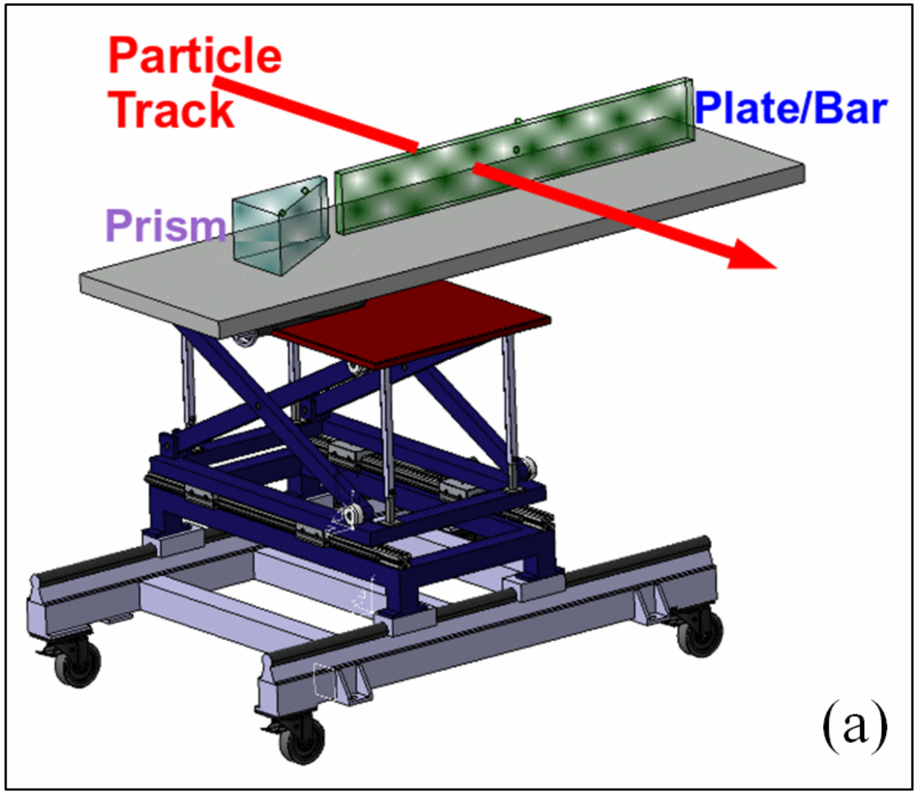
CLAS FROST solenoid
with 5 inch bore

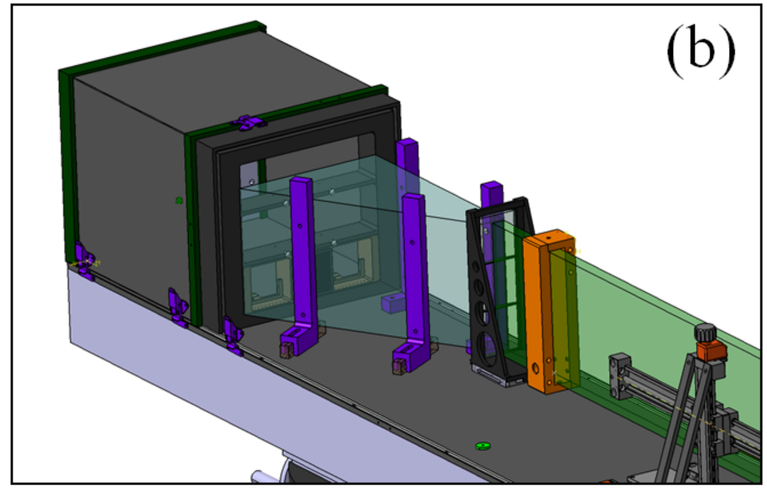
Long-term strategy for facility

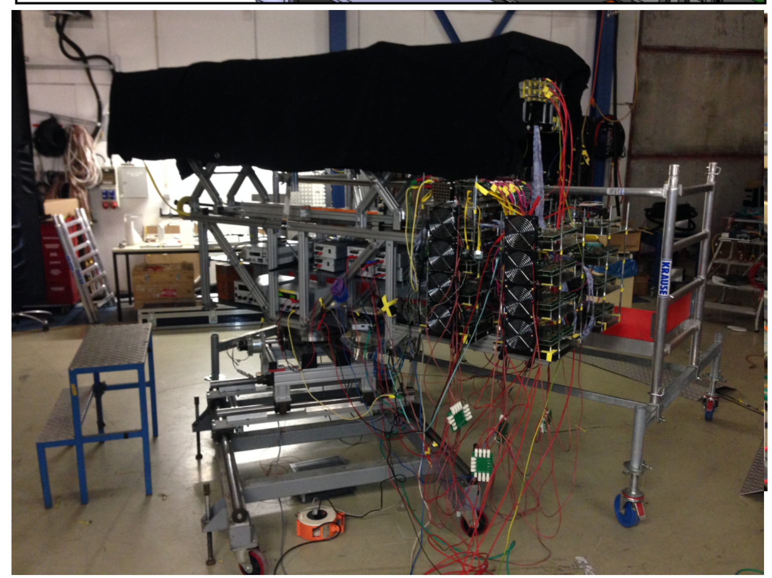
- Perform first series of tests using smaller magnet.
- In the future, a larger bore can be needed to accommodate larger sensors (LAPPDs) or provide more space for rotations
- Test boxes have been built for both magnets (C. Zorn)
- Both magnets will be part of the facility and can be used for future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

CLAS DVCS solenoid with 9 inch bore

Test beam setup



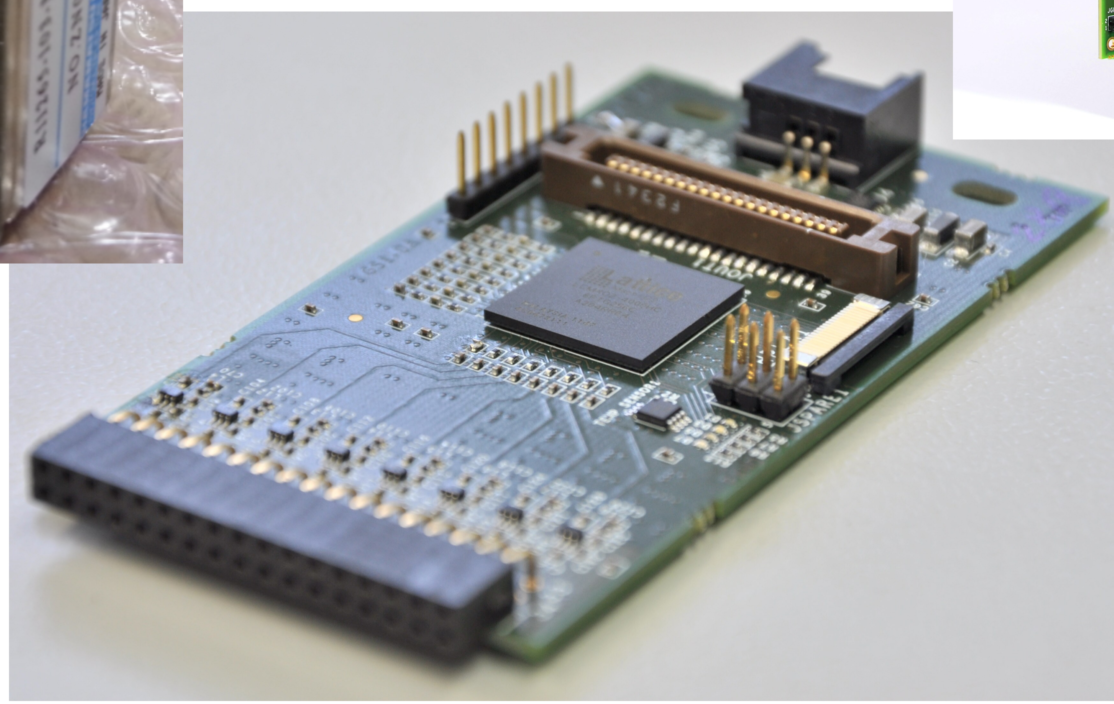




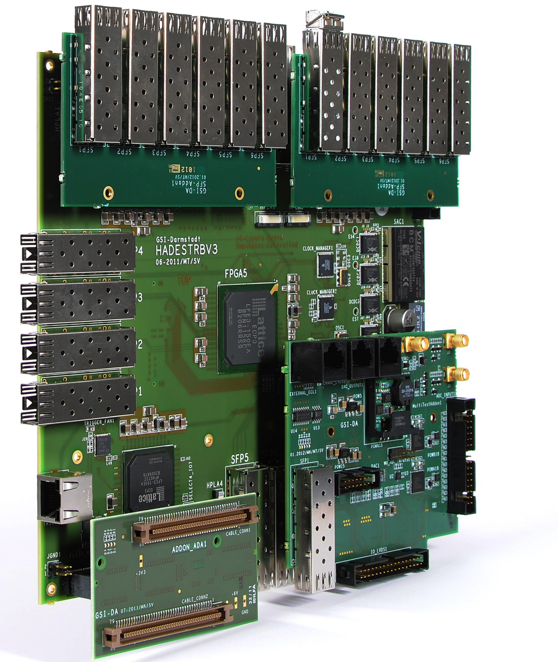
- The EIC DIRC prototype will take full advantage of synergies with PANDA DIRC R&D.
- The goal is to test the new lenses and small-pixel sensors, initially using existing GSI expansion volumes, and later with an EV geometry optimized for the lens focal plane.

Procurements for test at GSI

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



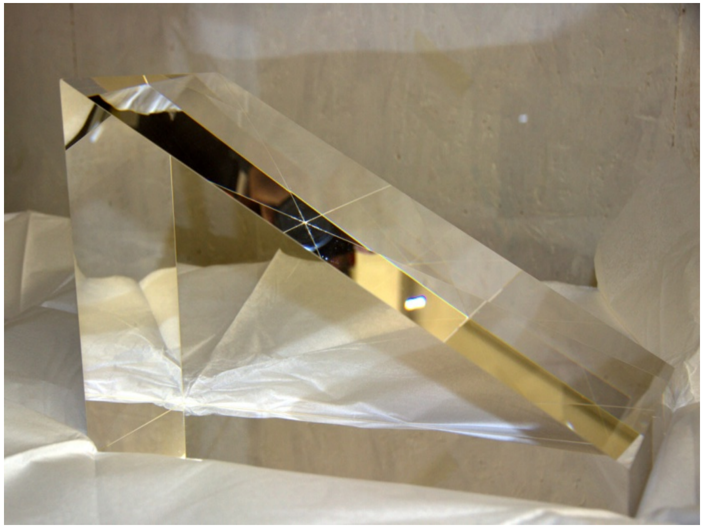
PaDiWa interface card for connecting the procured MaPMTs (via Hamamatsu E11906 sockets) to the TRBv3 DAQ card (right).



TRBv3 DAQ card with AddOns

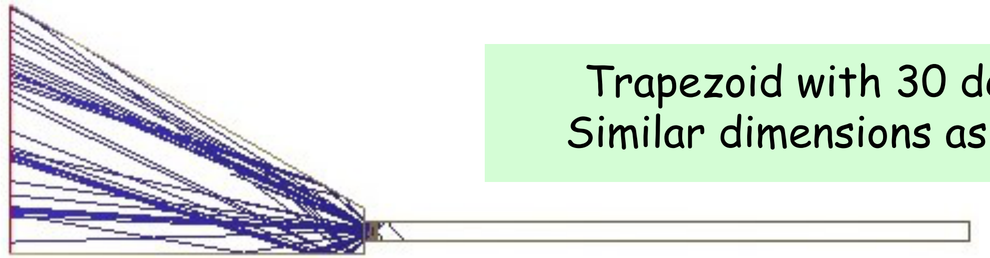
The new three-layer lens was delivered for the August/September test beam!

Expansion volume geometries

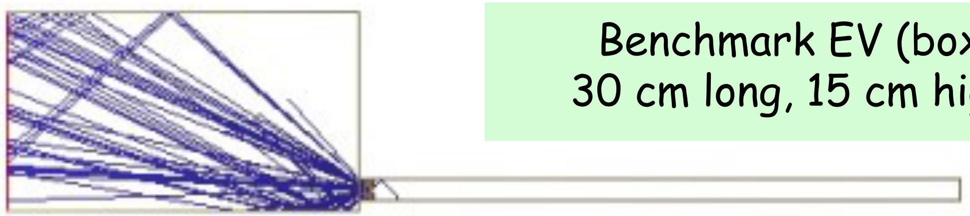


One of two fused silica EVs now available at GSI

- Initial simulations were performed for two benchmark geometries: box and trapezoid
- Trapezoid matches 30 cm long EVs available through synergies with GSI R&D.
  - Excellent opportunity for developing optics
- Once optics development is complete, an expansion volume matching the focal plane will be developed
  - Interplay between pixel size and sensor placement close to focal plane?

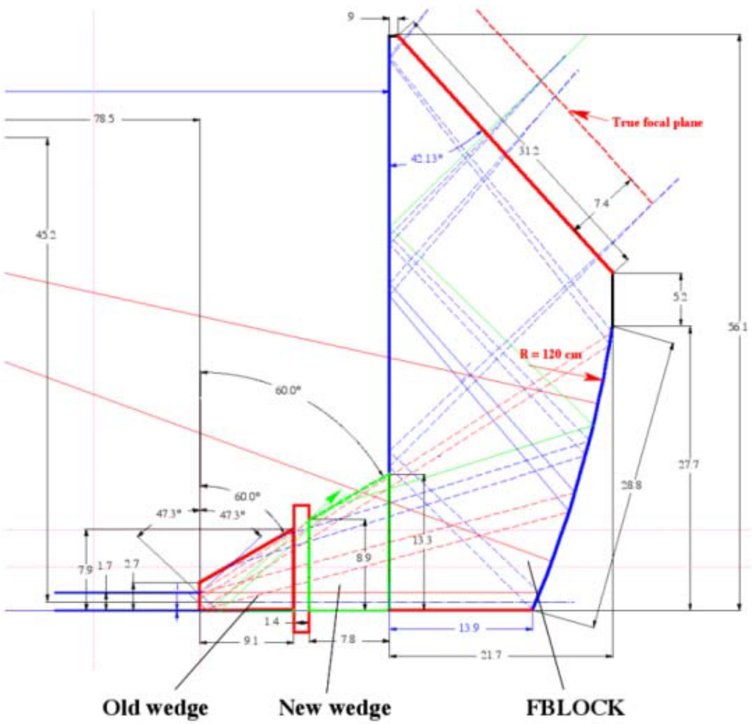


Trapezoid with 30 degree angle
Similar dimensions as for the box

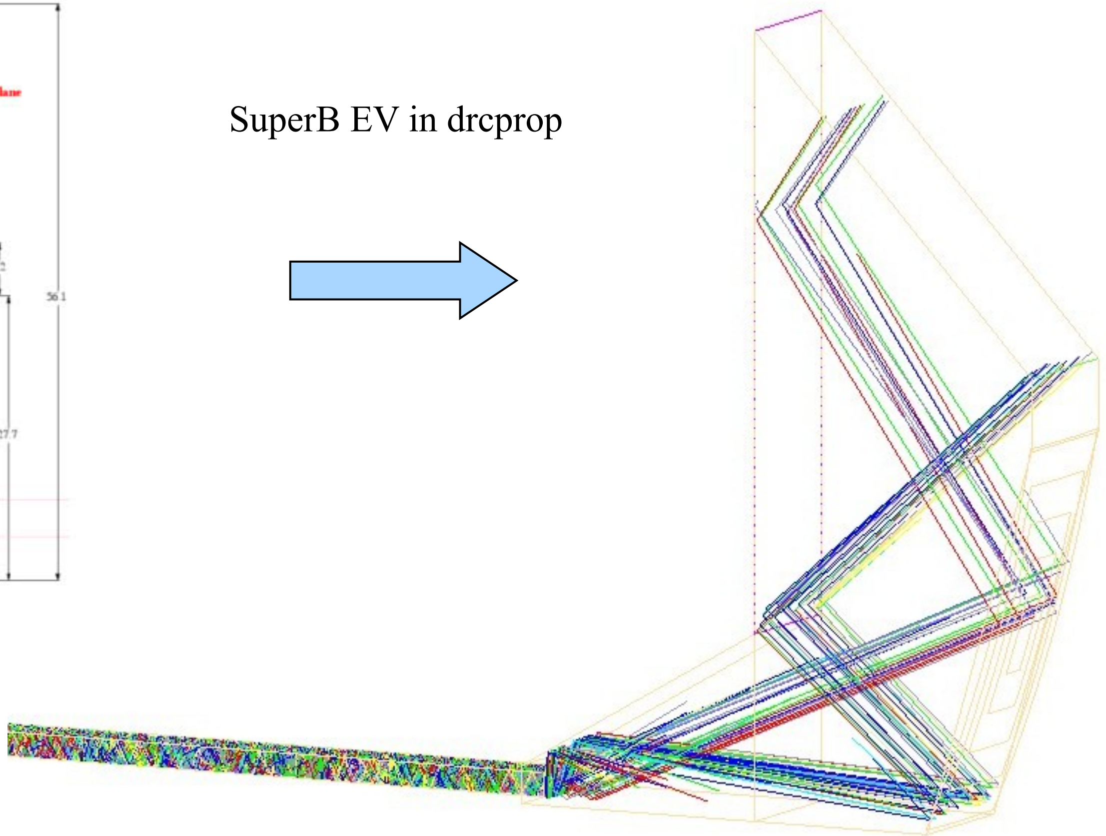


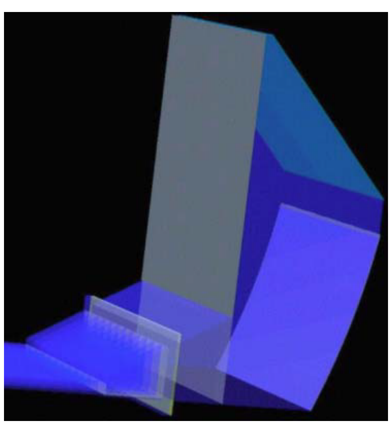
Benchmark EV (box) geometry
30 cm long, 15 cm high, 1 cm step

Focusing-mirror optics implemented in drcprop



SuperB EV in drcprop





- SuperB mirror optics have been implemented in drcprop
- Will be modified to fit EIC requirements