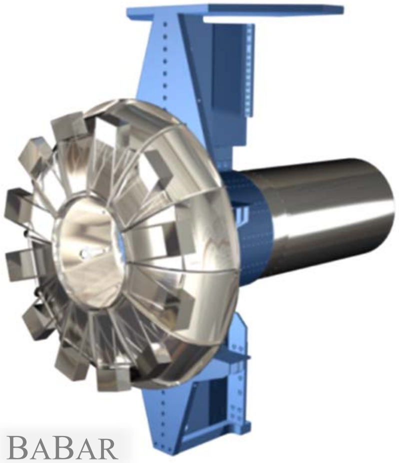
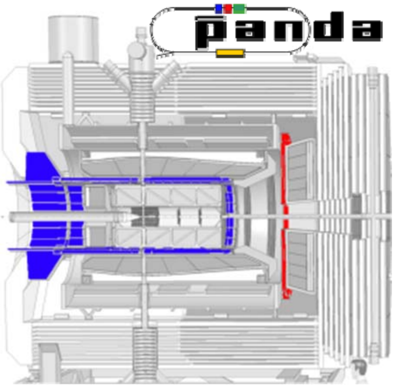
DIRC DETECTORS FOR PANDA AND BEYOND

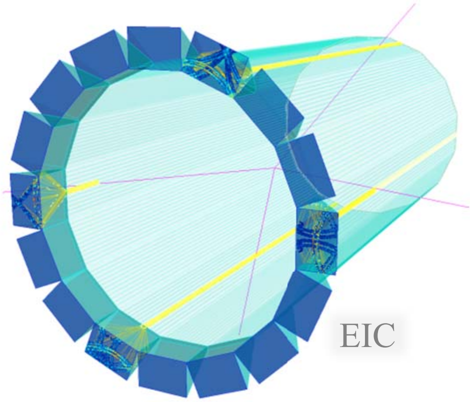
Jochen Schwiening

GSI



BABAR





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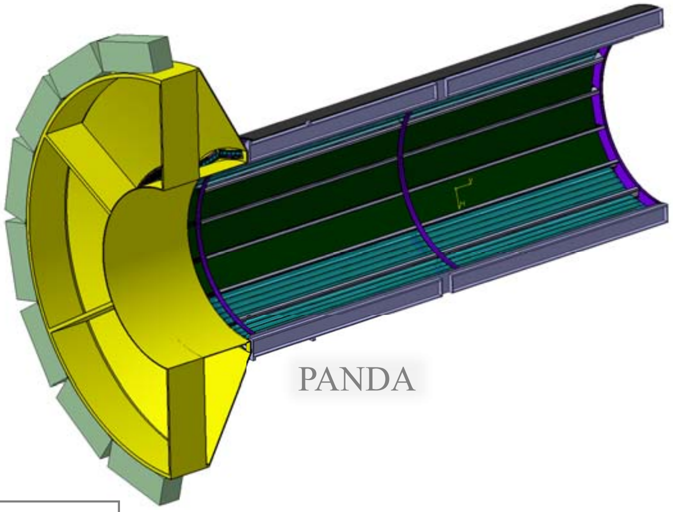
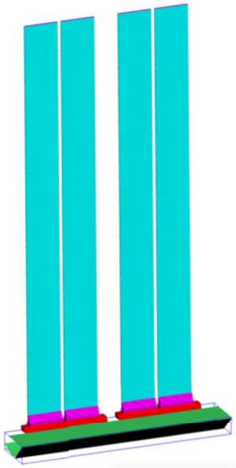


PANDA



GLUEX

Thanks to my colleagues in the GSI DIRC group (HAD1 and SBPD) for providing material for this seminar.

DIRC DETECTORS?

Why do you hear a talk about DIRC counters in the Storage Rings seminar today?

One reason is that I hope to introduce SBPD to you: what we do in the
Stored Beams PANDA Detectors project department on that campus far, far away…

Heck offices
Home of the GSI PANDA groups since 2013

We're charged with coordinating the
GSI in-kind contributions to PANDA:
PANDA Barrel DIRC counter (100% GSI PMA funded), Calorimeter readout electronics, and liaison to FZ Juelich PANDA PMA packages (Straw Tube Tracker and Microvertex Detector).

DIRC DETECTORS?

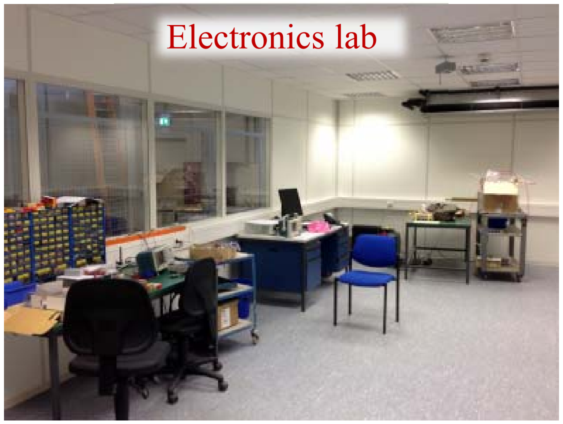
The DIRC group:

4 physicists and 2 engineers in SBPD
plus 3 PhD students and additional physicists from HAD1 group.

New DIRC lab containers in the Heckhalle (since Nov 2014).


DIRC lab containers


Optical lab (bar measurements)

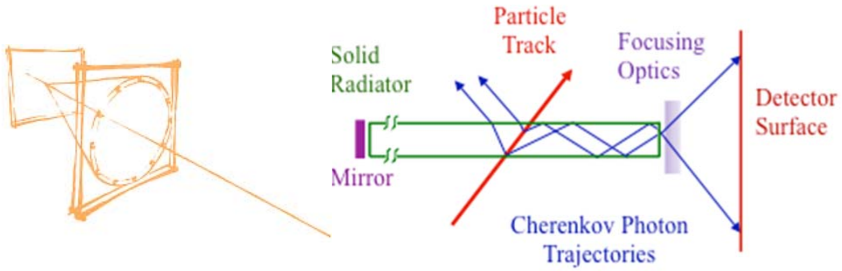

Electronics lab

Our core expertise and main focus are DIRC detectors – thus, this talk.

The other reason for this talk: DIRC detectors are new, challenging, of interest to future experiments, and (we think) quite a bit of fun.

OUTLINE

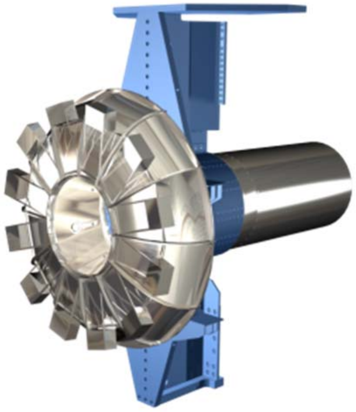
BRIEF INTRODUCTION



CHERENKOV EFFECT

RING IMAGING CHERENKOV COUNTERS

DIRC CONCEPT

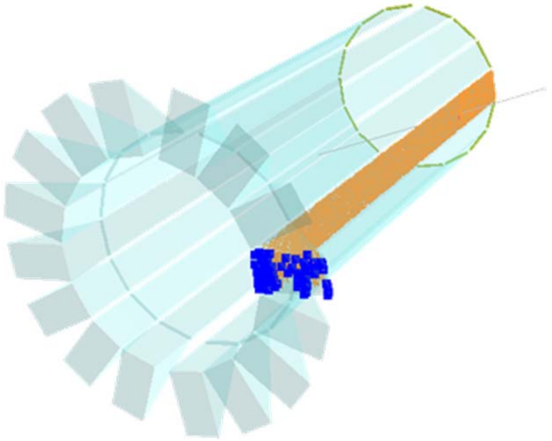


EXPERIENCE WITH DIRCS: BABAR

FUTURE DIRCS

PANDA BARREL DIRC

STATUS, CHALLENGES, PLANS

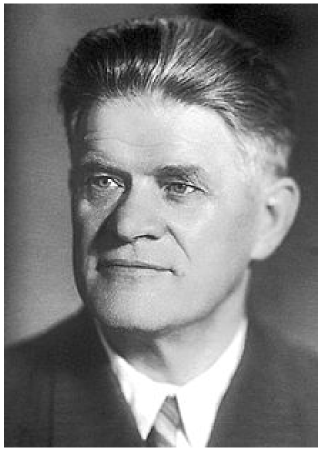


DIRC R&D FOR THE EIC CENTRAL DETECTOR

DIRC FOR THE GLUEX DETECTOR UPGRADE

CHERENKOV EFFECT

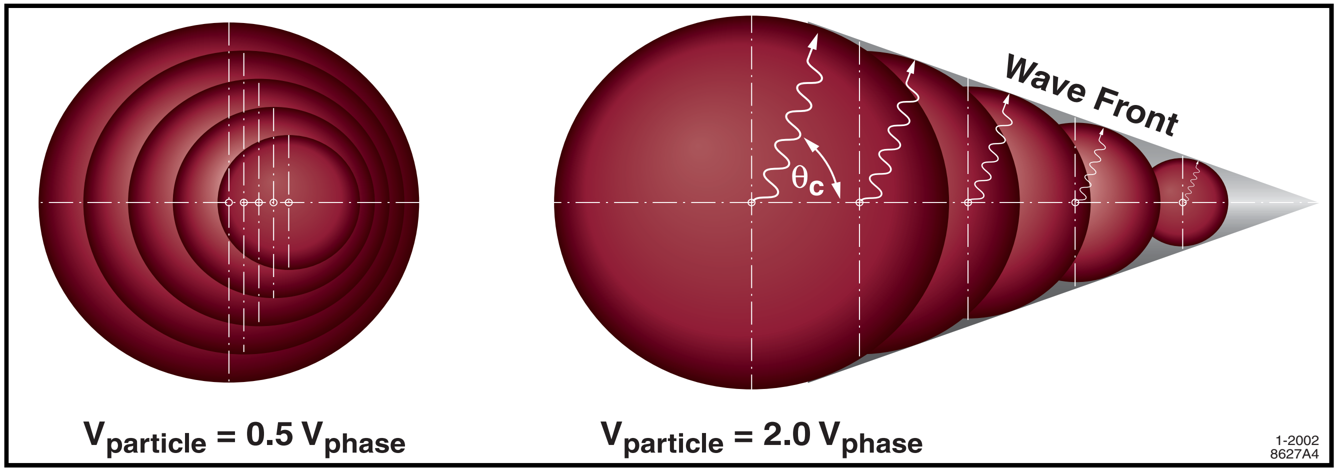
- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (he won the Nobel Prize for it in 1958).
- Theory of Relativity: nothing can go faster than the speed of light *c* (in vacuum).
- However, due to the refractive index *n* of a material, a particle *can* go faster than the *local* speed of light in the medium $c_p = c/n$.
- This is analogous to the bow wave of a boat travelling over water or the sonic boom of an airplane travelling faster than the speed of sound.



Павел Алексеевич
Черенков

This and some of the following slides thanks to Roger Forty's lectures at 2010 ICFA Instrumentation School, Bariloche
http://particulas.cnea.gov.ar/workshops/icfa/wiki/index.php/Particle_Identification

CHERENKOV RADIATION



Threshold: $$\beta_{thresh} = \frac{v_{thresh}}{c} = \frac{1}{n(\lambda)}$$

Production angle: $$\cos\theta_c = \frac{1}{\beta\, n(\lambda)}$$

Number of photons: $$N_{photons} = L\frac{\alpha^2 z^2}{r_e m_e c^2}\int \sin^2\theta_c(E)\,dE$$

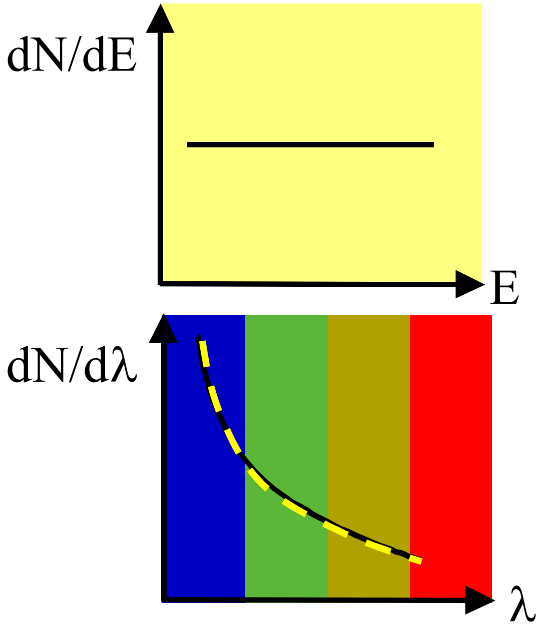
Commercial break… Looking for a nice review of Cherenkov Detectors?

"Handbook of Particle Detection and Imaging" Claus Grupen, Irene Buvat (eds.), Springer-Verlag Berlin Heidelberg 2011

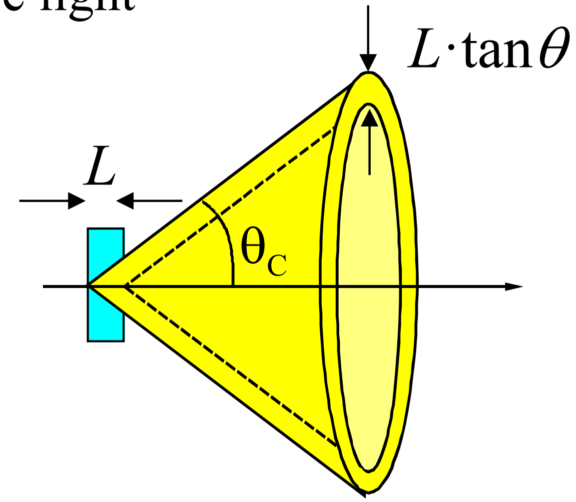
→ Chapter 12: "Cherenkov Counters", *Blair Ratcliff & Jochen Schwiening*

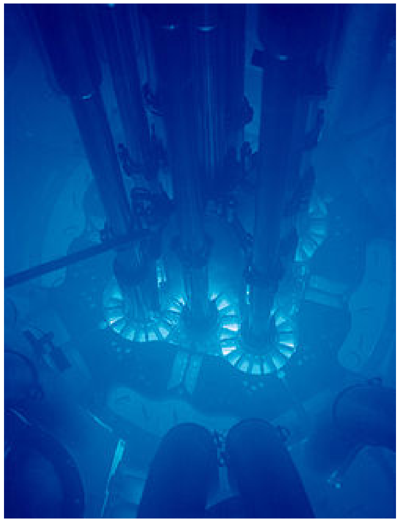
CHERENKOV RADIATION

- Cherenkov light produced equally distributed
  over photon energies, proportional $1/\lambda^2$
  → eery blue light seen in nuclear reactors



- For a given medium, refractive index n,
  there is a threshold for light production at $\beta = 1/n$
  - Tracks with $\beta < 1/n$ give no light
  - Tracks with $\beta > 1/n$ give light

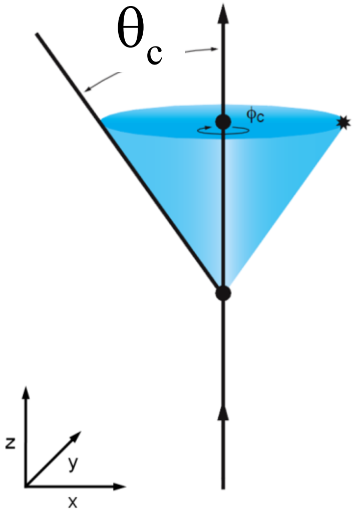




CHERENKOV DETECTORS

Cherenkov radiation: attractive properties for particle detectors

- Existence of a threshold velocity;
- Number of photons related to particle velocity;
- Emission angle related to particle velocity;
- Angle and photon yield depend on particle charge Z.

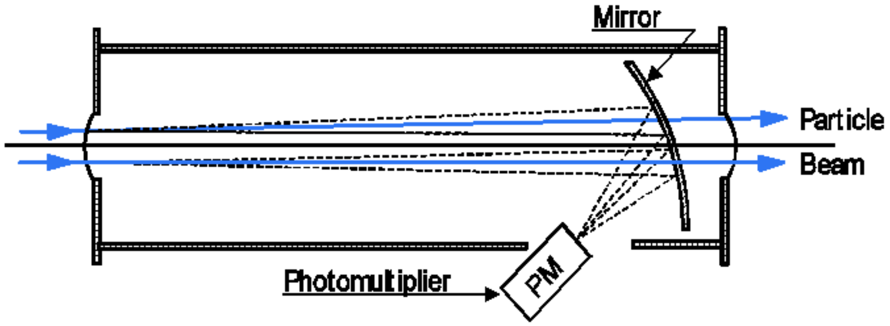


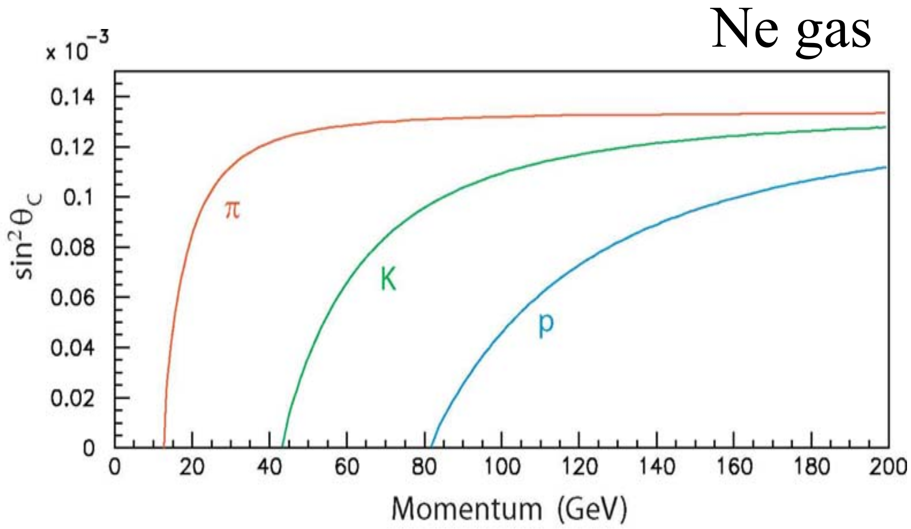
Main Cherenkov detector concepts in particle physics:

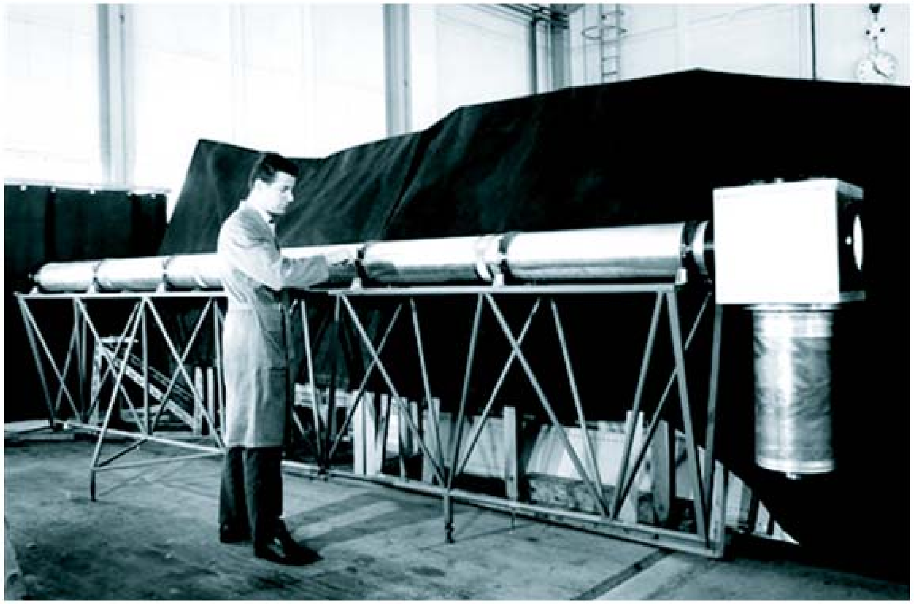
- Select material with refractive index n where particle type A produces Cherenkov light, particle type B does not → threshold counter
- Select material with refractive index n where multiple Cherenkov photons are detected for most particle species, image Cherenkov ring, precisely measure Cherenkov angle → Ring Imaging Cherenkov counter (RICH)
- Compare ring image with expected image for e/μ/π/K/p (likelihood test) or calculate mass from track β using independent momentum measurement (B field, tracking).

THRESHOLD CHERENKOV DETECTORS

- Well-defined, tunable value of $\beta_{thr} = 1/n$ in threshold Cherenkov detectors.
- Select n based on application.
  Example: identify particles in a beam line with a 50 GeV π^+ beam with some proton contamination.
- By choosing a medium with a suitable refractive index (in this case Neon), it can be arranged that the π will produce light, but the protons will not.



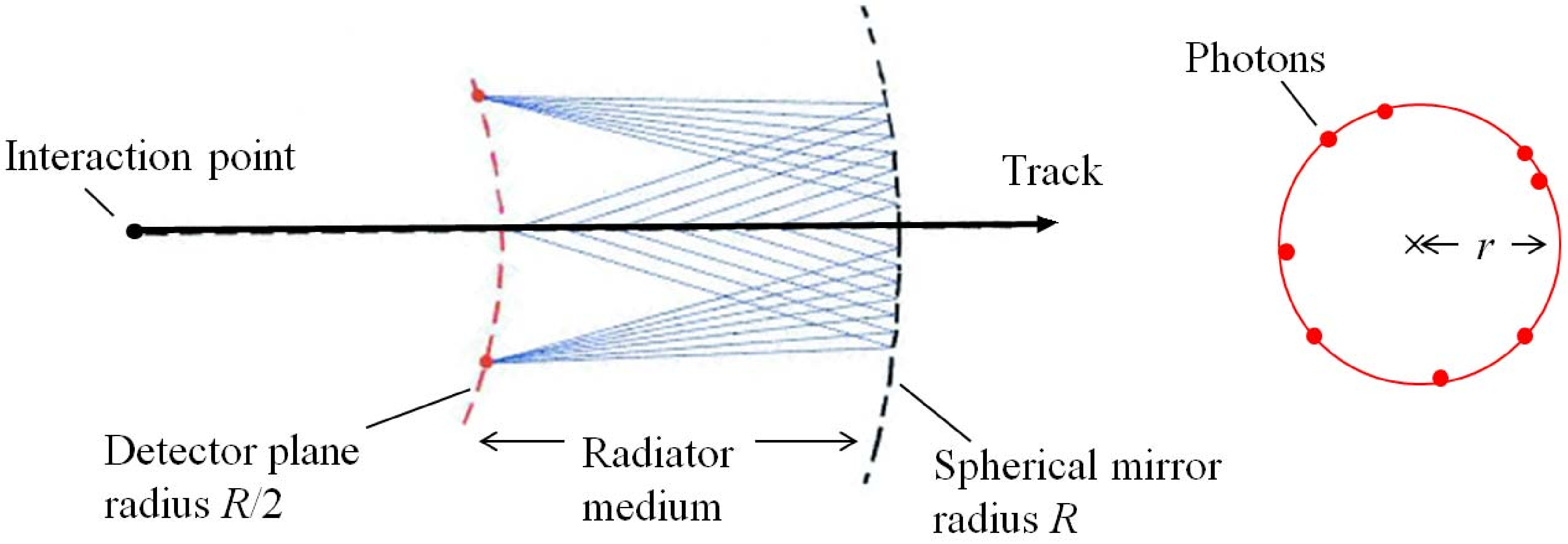




RING IMAGING CHERENKOV DETECTORS

- Threshold counters mostly give a yes/no answer,
  less useful when the tracks have a wide momentum range
  even though some are used in modern experiments (for example Belle ACC).

- However, more information can be extracted from the Cherenkov angle
  → the Cherenkov cone can be imaged into a ring with multiple photons.



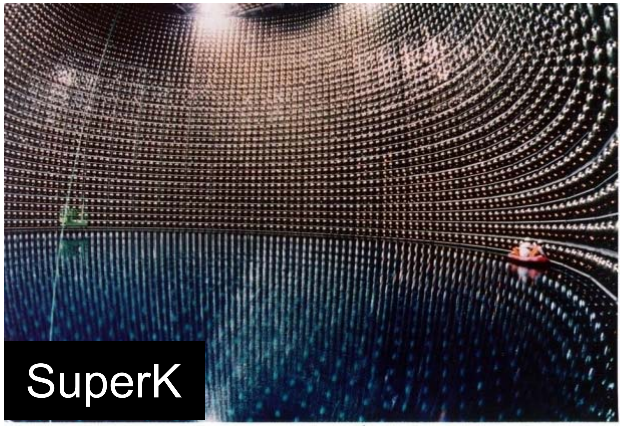
- Measuring the ring radius r allows the Cherenkov angle θ_c to be determined
  each photon provides measurement of θ_c, combining N photons → error $\sigma(\theta_c)/\sqrt{N}$.

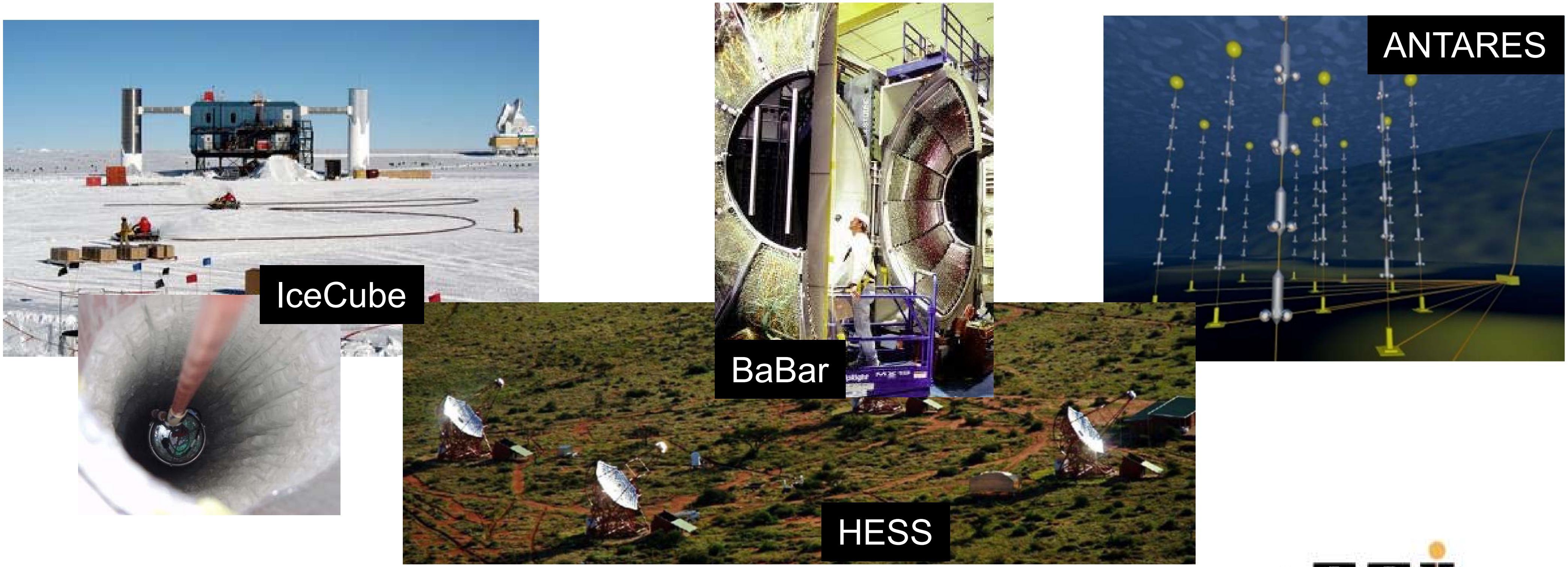
  → powerful principle behind Ring Imaging Cherenkov (RICH) detectors

RING IMAGING CHERENKOV DETECTORS

RICH detectors come in many shapes and sizes in particle physics, nuclear physics, and particle astrophysics.

- Large neutrino observatories underground or in ice/deep sea (SuperK, KM3net, IceCube, etc)
- Imaging Air Cherenkov Telescopes (HESS, etc)
- Space experiments (AMS, CREAM, etc)
- High-energy physics (BaBar, LHCb, PANDA, etc)





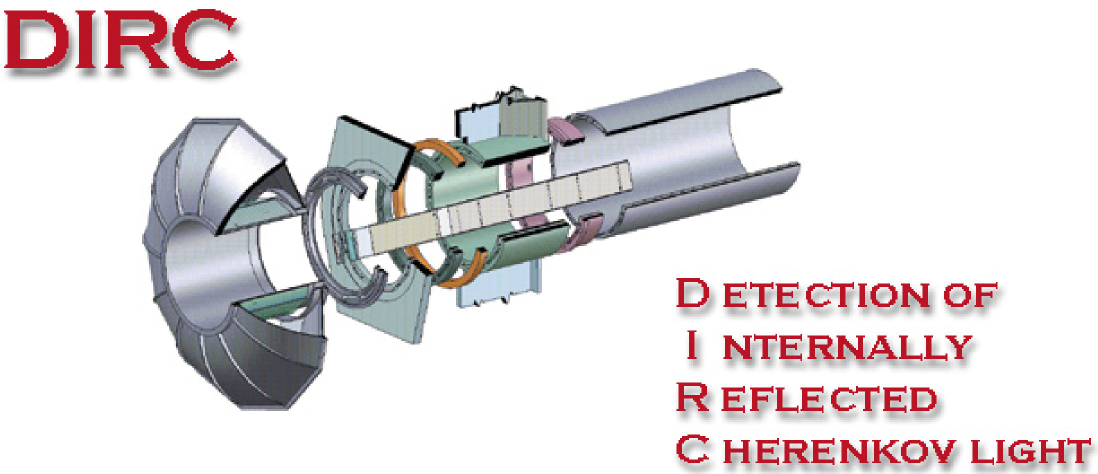
DIRC CONCEPT

Detection of Internally Reflected Cherenkov Light

Novel type of Ring Imaging CHerenkov detector *(first proposed in 1992[§])* based on total internal reflection of Cherenkov light.

Used for the first time in BABAR (SLAC) for hadronic particle ID (8+ years in factory mode).

Improvements in photon detectors have motivated R&D efforts to improve the successful BABAR-DIRC and make DIRCs interesting for other experiments.

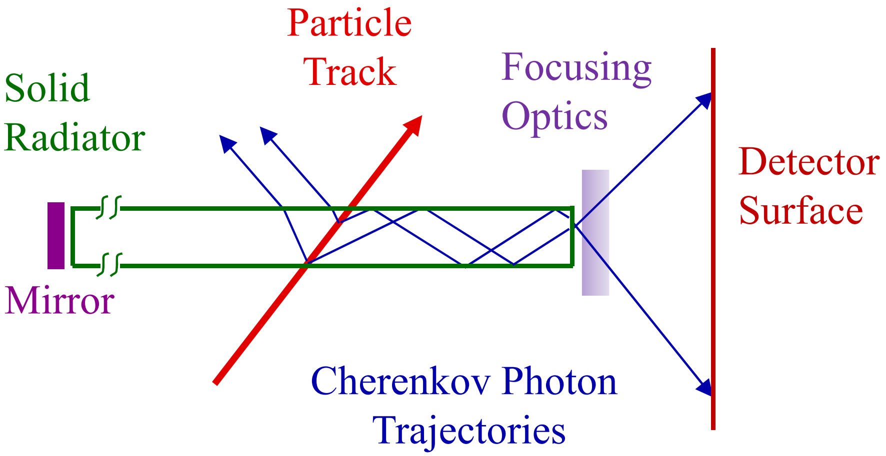


[§] *B.N. Ratcliff, SLAC-PUB-6047 (Jan. 1993)*

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 $\cos\theta_c = 1/\beta n(\lambda)$.

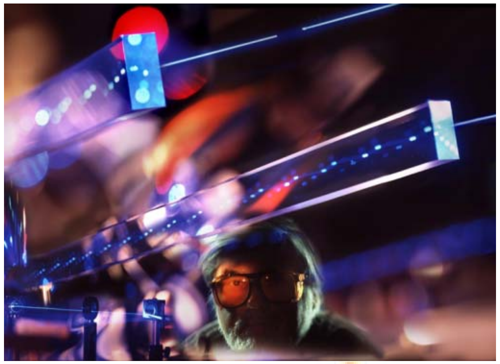
- For $n > \sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.



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

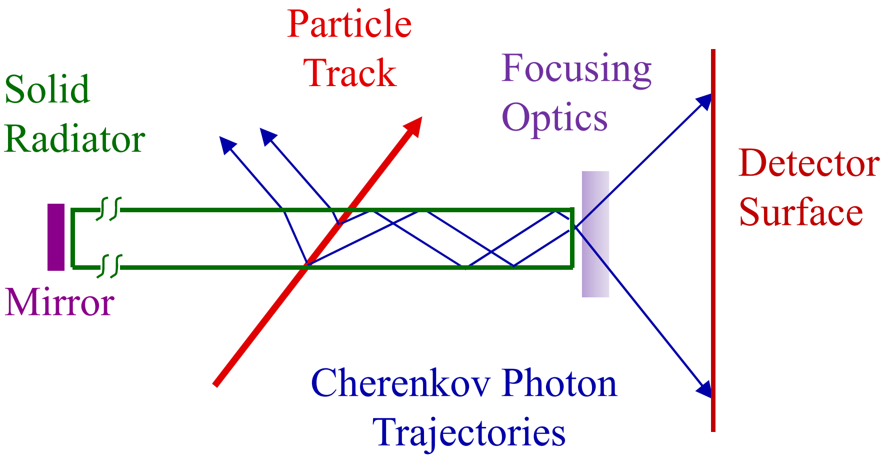
- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

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



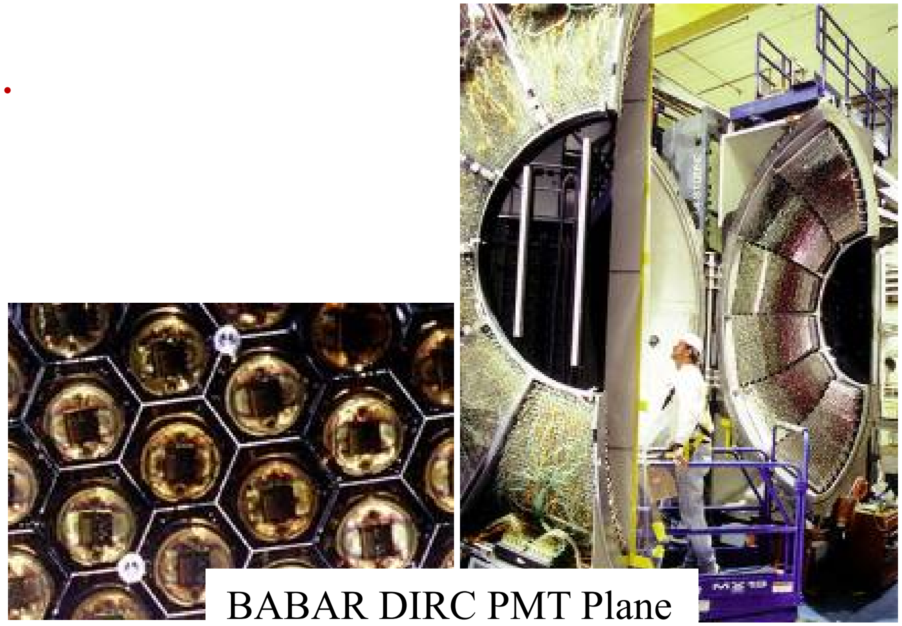
DIRC CONCEPT

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



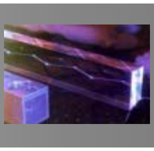
- DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$.

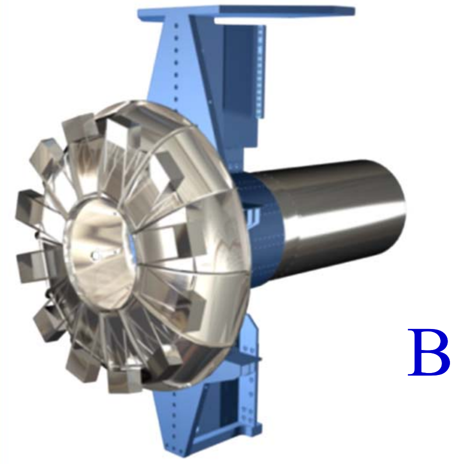
- Ultimate deliverable for DIRC: PID likelihoods.
  Calculate likelihood for observed hit pattern
  (in detector space or in Cherenkov space)
  to be produced by e/μ/π/K/p
  plus event/track background.



BABAR DIRC PMT Plane

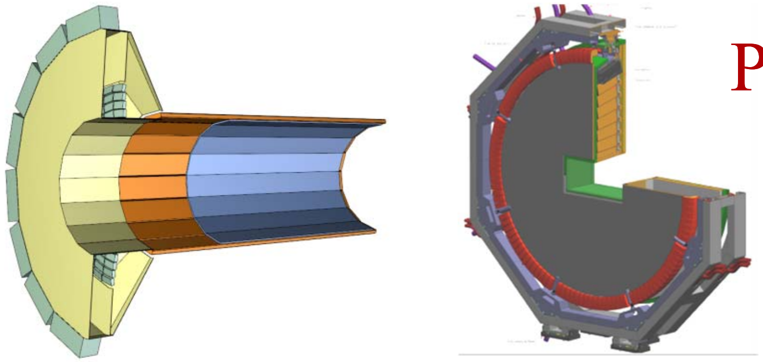
DIRC COUNTERS





First of its kind – excellent performance, easy to operate, essential ingredient in most BABAR publications.

BABAR
DIRC



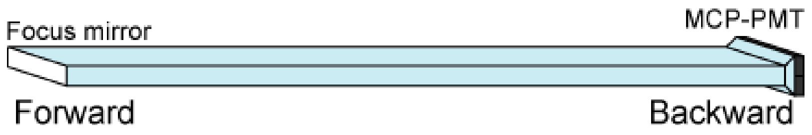
PANDA DIRCs

Barrel DIRC: focusing, compact version of BABAR DIRC.

Disk DIRC: first endcap DIRC.

… plus fDIRC (Cabbibo Lab), GlueX (JLab), DIRC@EIC, ...

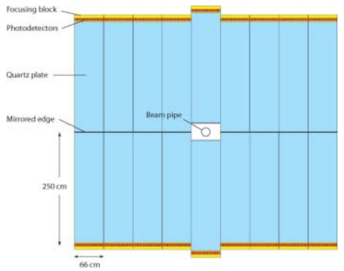
Belle II TOP (KEK)



First DIRC with plate geometry.

PID from excellent timing (TOF+TOP) plus fine X and coarse Y info.

LHCb TORCH (CERN)



Considered for LHCb upgrade

Measure particle time-of-flight via Cherenkov photon timing

BABAR DIRC TIME LINE

- 1992: first publication of DIRC concept (Blair Ratcliff).
- 1993-1996: progression of prototypes and DIRC R&D.
- Nov 1994: decision in favor of DIRC for hadronic PID for BABAR.
- Nov 1998: installed part of DIRC; start of cosmic ray run, commissioning run.
- April 1999: BABAR moves into beam line, added 4 more bar boxes.
- Nov 1999: all 12 bar boxes installed, start of first physics run.
- April 2008: last event recorded with BABAR.

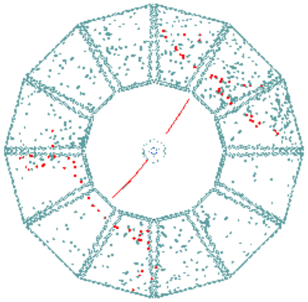
PEP-II peak luminosity: 12.07×10^{33} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ (4 × design)

BABAR total recorded: ~ 467M $B\bar{B}$ pairs.

BABAR DIRC ran in factory mode for 8+ years.

Detailed review of the BABAR DIRC:
Nucl. Instr. Methods ***A*** *538 (2005) 281-357*

BABAR DIRC EXPERIENCE

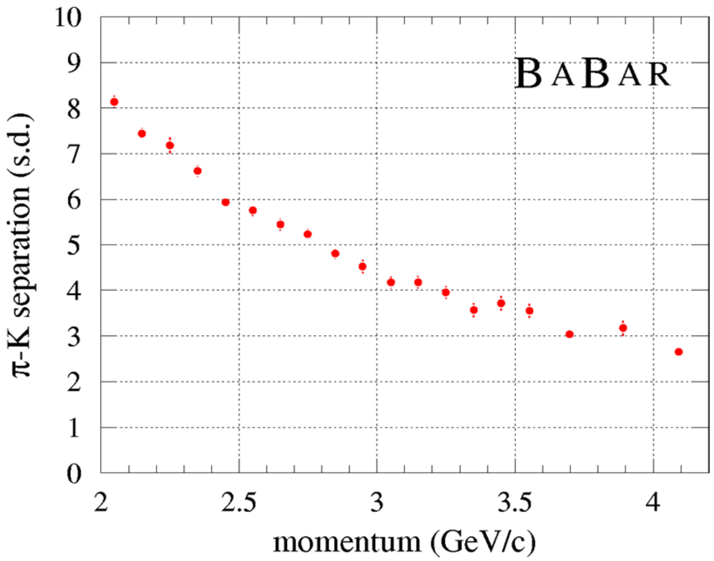


DIRC operations were stable and robust

- Calibration constants stable to typically *rms* < 0.1ns per year.
- No problems with water or gas systems.
- No evidence for deterioration of bar surfaces or glue boundaries.
  BABAR DIRC bars will be reused for DIRCs in GlueX (JLab) and LHCb (CERN).

DIRC provided excellent PID performance

- Quickly reached design performance for photon yield and Cherenkov angle resolution.
- Clean separation of pions and kaons up to kinematic limit (4.2 GeV/c).
- Essential ingredient in most BABAR physics analyses.



THE DIRC IN BABAR

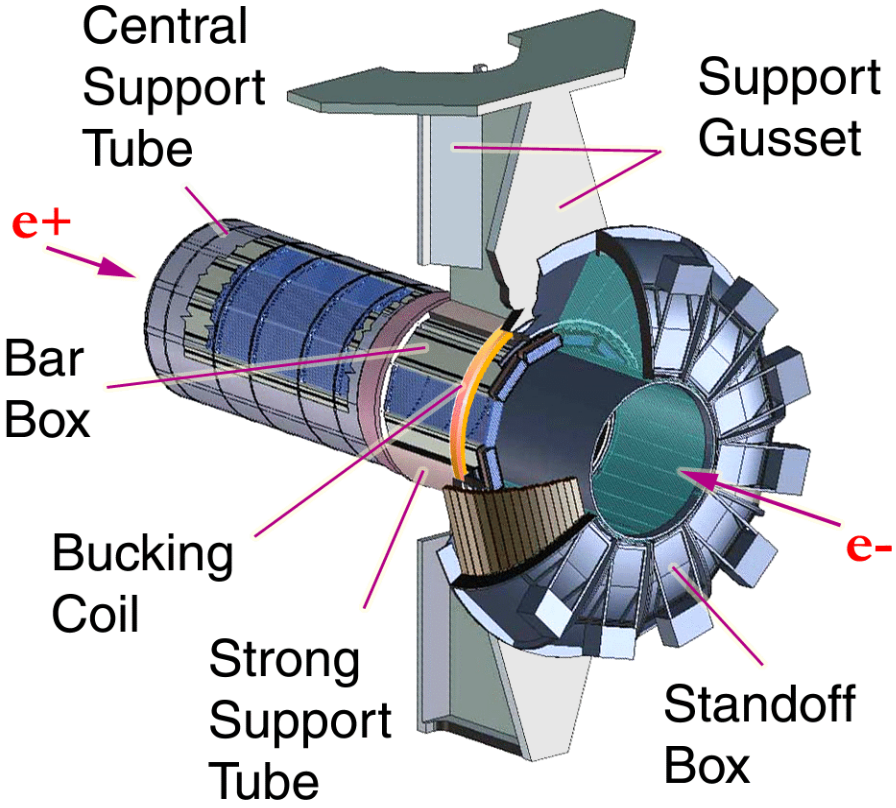
Size:

~170cm diameter, ~600cm length

~8 cm radial thickness (incl. supports)

Photon detector array:

10,752 PMTs ETL 9125



Expansion volume:

large tank with ~6000 liters of ultra-pure water

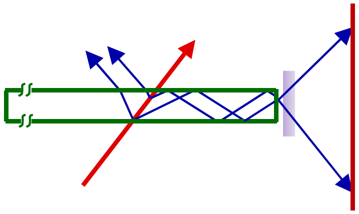
Radiators:

144 long narrow bars (synthetic fused silica)

17mm x 35mm x 4900mm

largest technical challenge (and source of delays)

DIRC RECONSTRUCTION



DIRC “Ring” images:

- limited acceptance for total internal reflection,
- reflection ambiguities (initial reflection up/down, left/right, reflection off mirror (and wedge)

→ up to 16 (θ_c, ϕ_c) ambiguities per PMT hit),

- toroidal detection surface,

→ Cherenkov ring images are distorted:

complex, disjoint images

Low energy photons from accelerator hit Standoff Box.

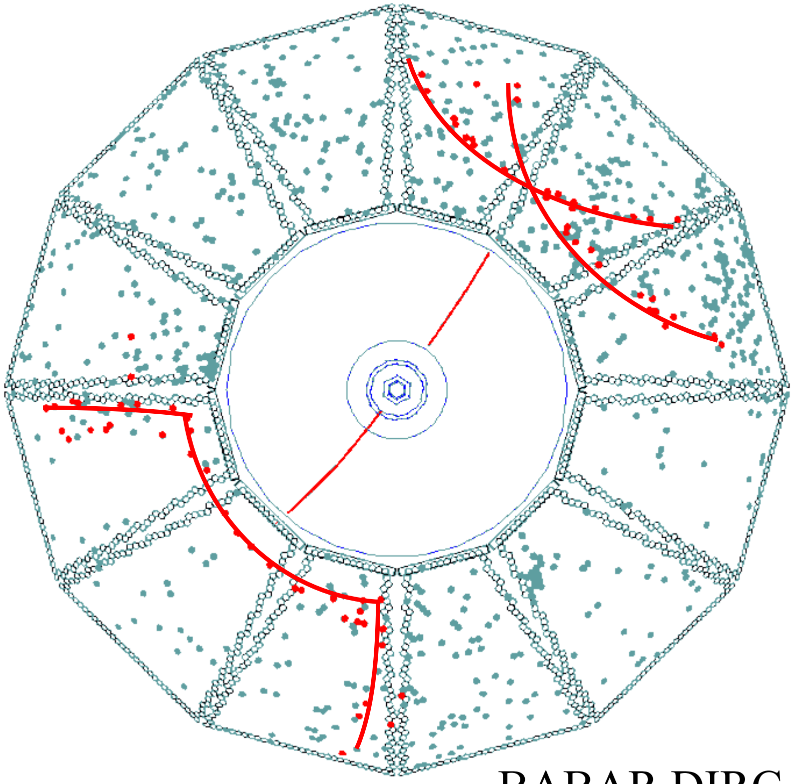
At typical luminosity that caused rates of 80-200 kHz/tube.
(100× the rate expected during experiment design phase.)

80-200 kHz ⊗ 10,752 PMTs ⊗ ± 300 nsec trigger window

→ 500-1300 background hits (~10% occupancy)

compared to

50-300 Cherenkov photons



BABAR DIRC

Note that accelerator induced background currently expected to be no issue at PANDA.

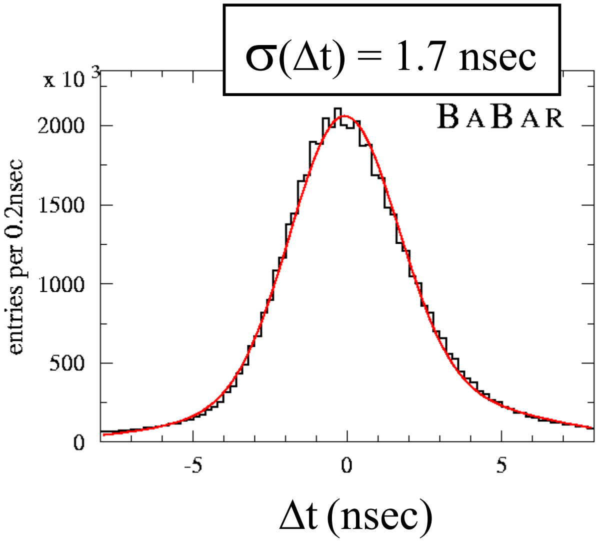
BABAR DIRC RECONSTRUCTION

For BABAR DIRC time information provided powerful tool to reject accelerator and event related background.

Calculate expected arrival time of Cherenkov photon based on

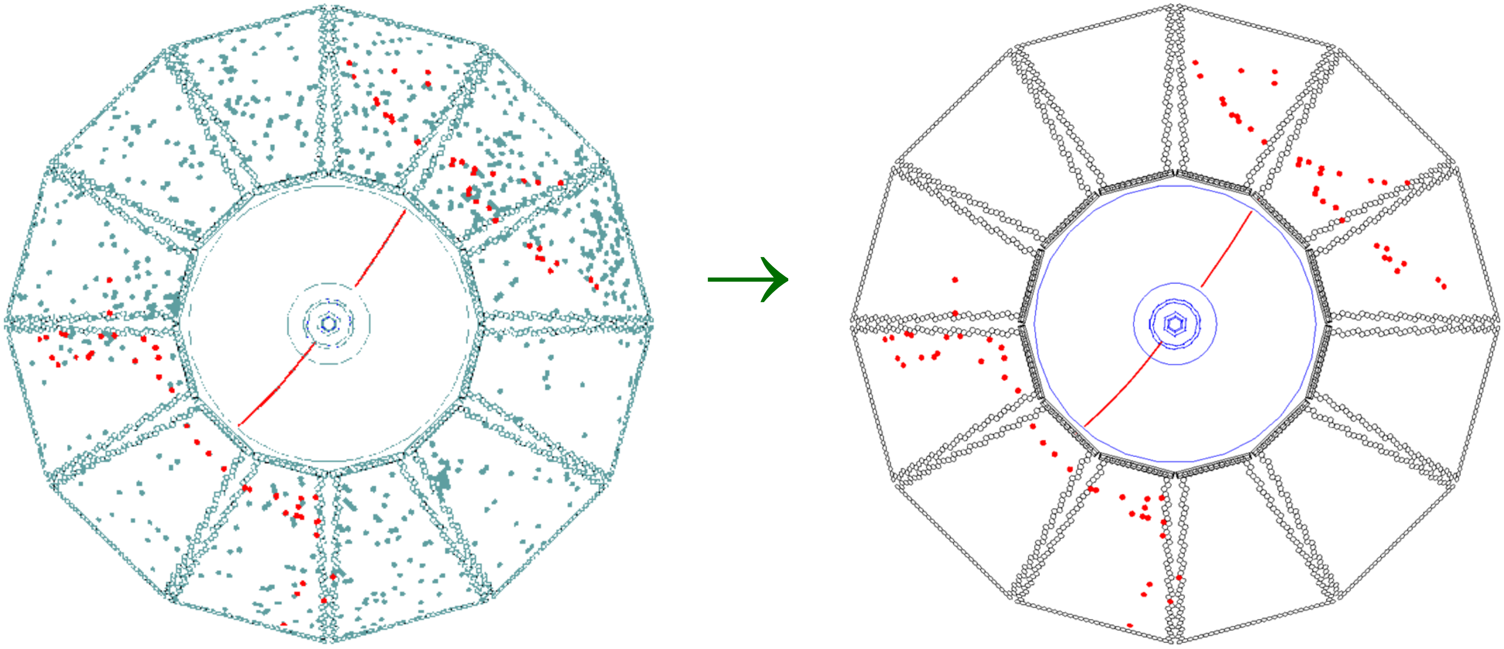
- track TOF
- photon propagation in radiator bar and in water

Δt: difference between measured and expected arrival time



± 300 nsec trigger window → ± 8 nsec Δt window

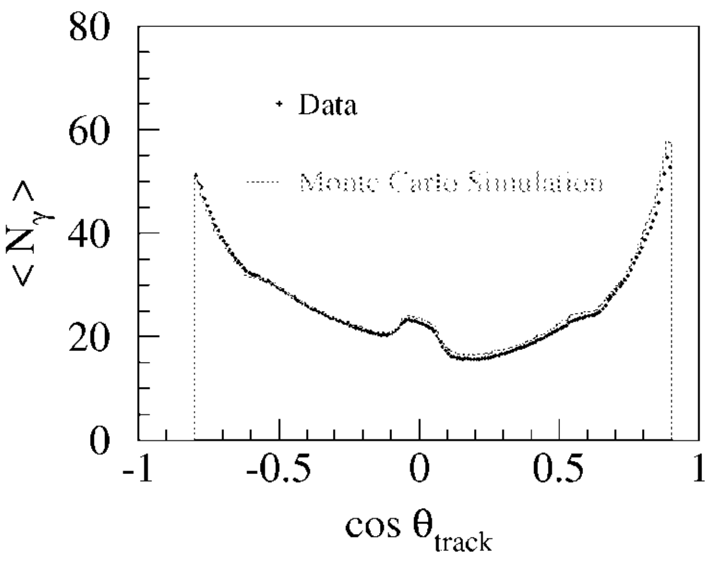
(~500-1300 background hits/event) (1-2 background hits/sector/event)

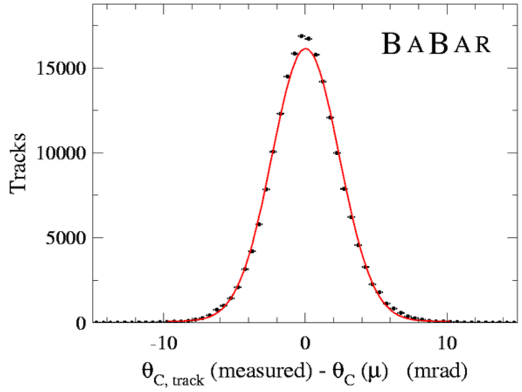


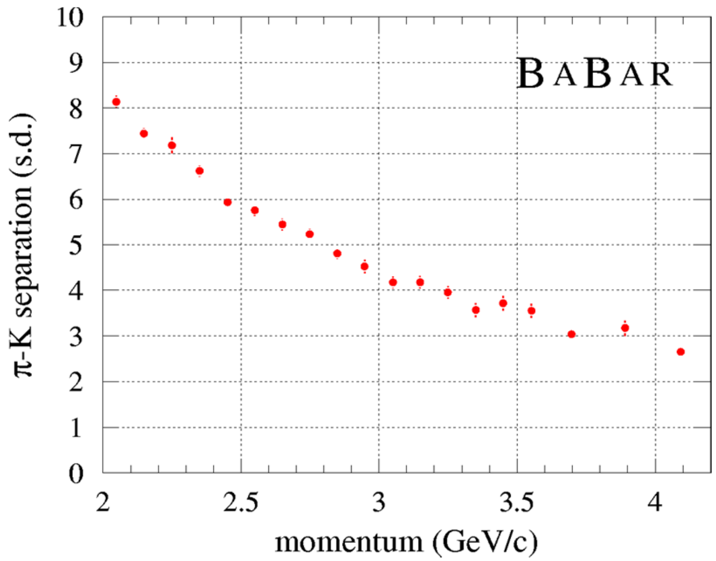
Δt also used to determine event time for “self-triggering” of DIRC.

BABAR DIRC PERFORMANCE

Single photon timing resolution	1.7ns
Single photon Cherenkov angle resolution	~10mrad
Photon yield	20-60 photons per track
Track Cherenkov angle resolution	2.4mrad (di-muons)
π/K separation power	4.3σ @ 3GeV/c, ~3σ @ 4GeV/c







Excellent performance: reliable, robust, easy to operate,

significant impact on almost all BABAR physics results.

Fused silica bars in great shape after 15+ years (GlueX, TORCH).

IMPROVING ON BABAR DIRC

The DIRC approach was very successful in BABAR.

As early as 2000 R&D efforts underway to improve future DIRCs.

- Make DIRC less sensitive to background
  - decrease size of expansion volume;
  - use photon detectors with smaller pixels and faster timing;
  - place photon detector inside magnetic field.
- Investigate alternative radiator shapes (plates, disks)
- Push DIRC π/K separation by improving single-photon θ_C resolution
  - focusing optics to reduce bar size contribution;
  - smaller pixels to reduce pixel size contribution;
  - mitigate effect of dispersion using fast timing, filters, etc.

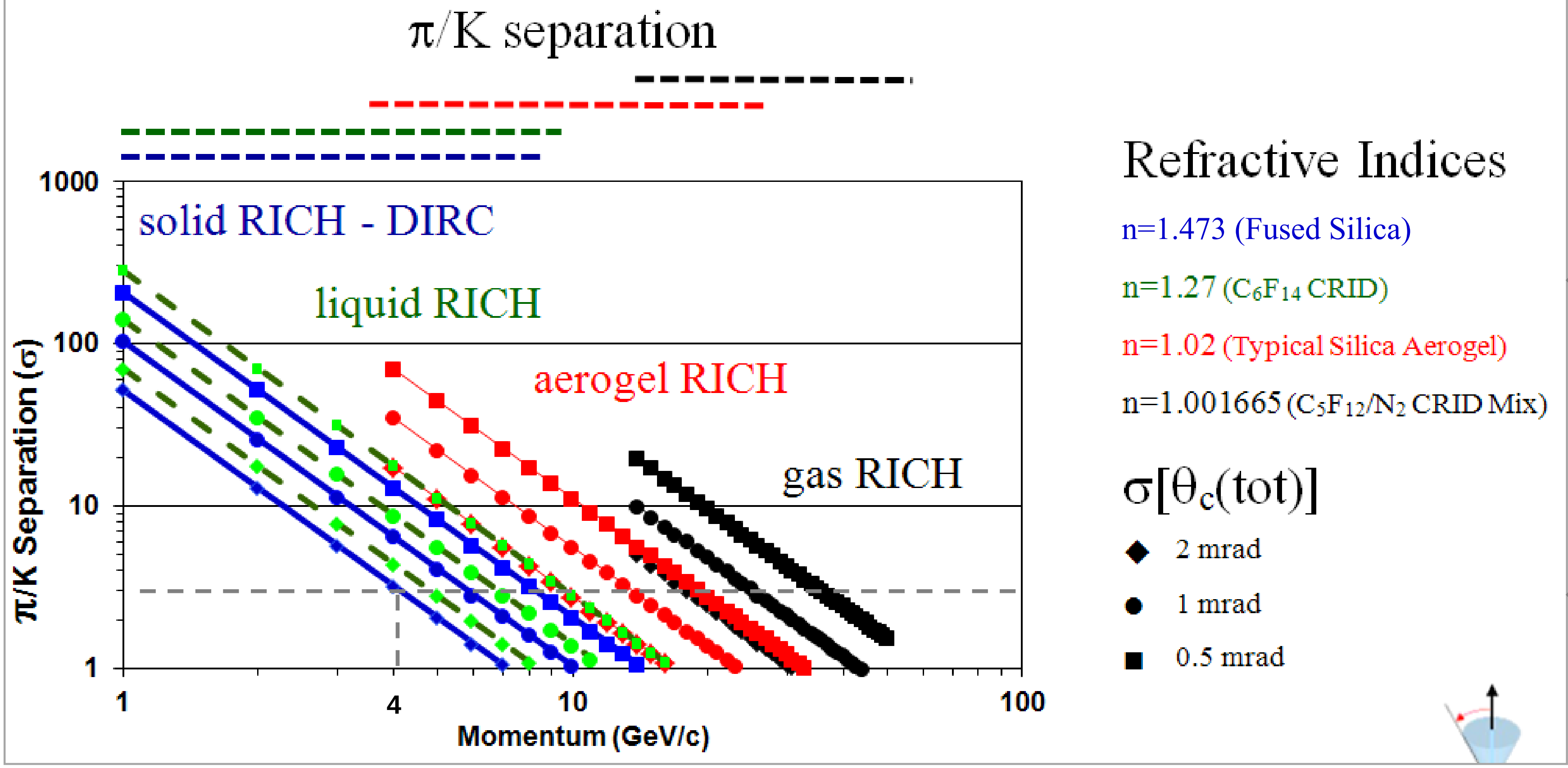
→ R&D for SuperB fDIRC – Belle II TOP – PANDA DIRCs (and beyond…)

☹ ☺ ☺

DIRC 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*

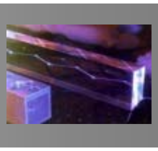
⇦ *angular error per track*

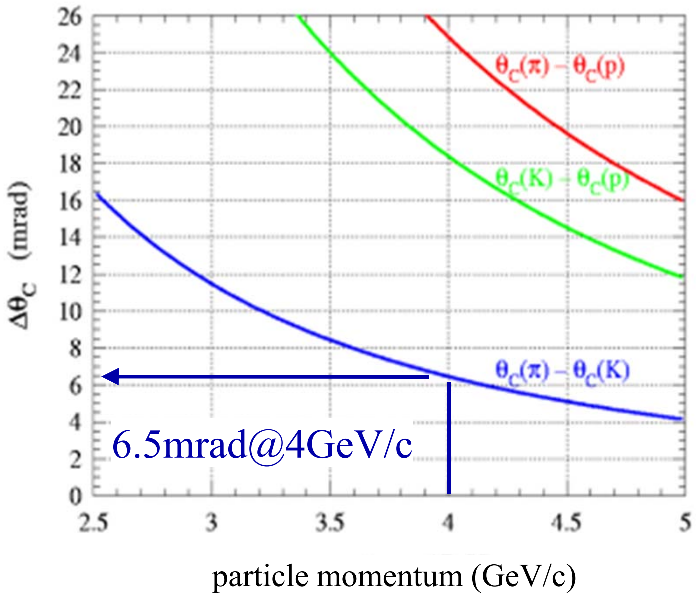
DIRC provides good π/K separation potential significantly beyond 4 GeV/c.

Large refractive index limits effective momentum range to below 10 GeV/c.

based on B. Ratcliff RICH2002

IMPROVING DIRC RESOLUTION





PID performance driven by Cherenkov angle (θ_C) resolution.
Required resolution defined by refractive index of radiator.

Example: π/K separation in synthetic fused silica <n>≈1.473
→ 6.5 mrad π/K difference in θ_C at 4 GeV/c;
→ need ~ 2.2 mrad resolution for 3 s.d. separation.

Cherenkov angle resolution determined by single photon resolution (scales with $1/\sqrt{N_\gamma}$) and correlated terms (mult. scattering, etc).

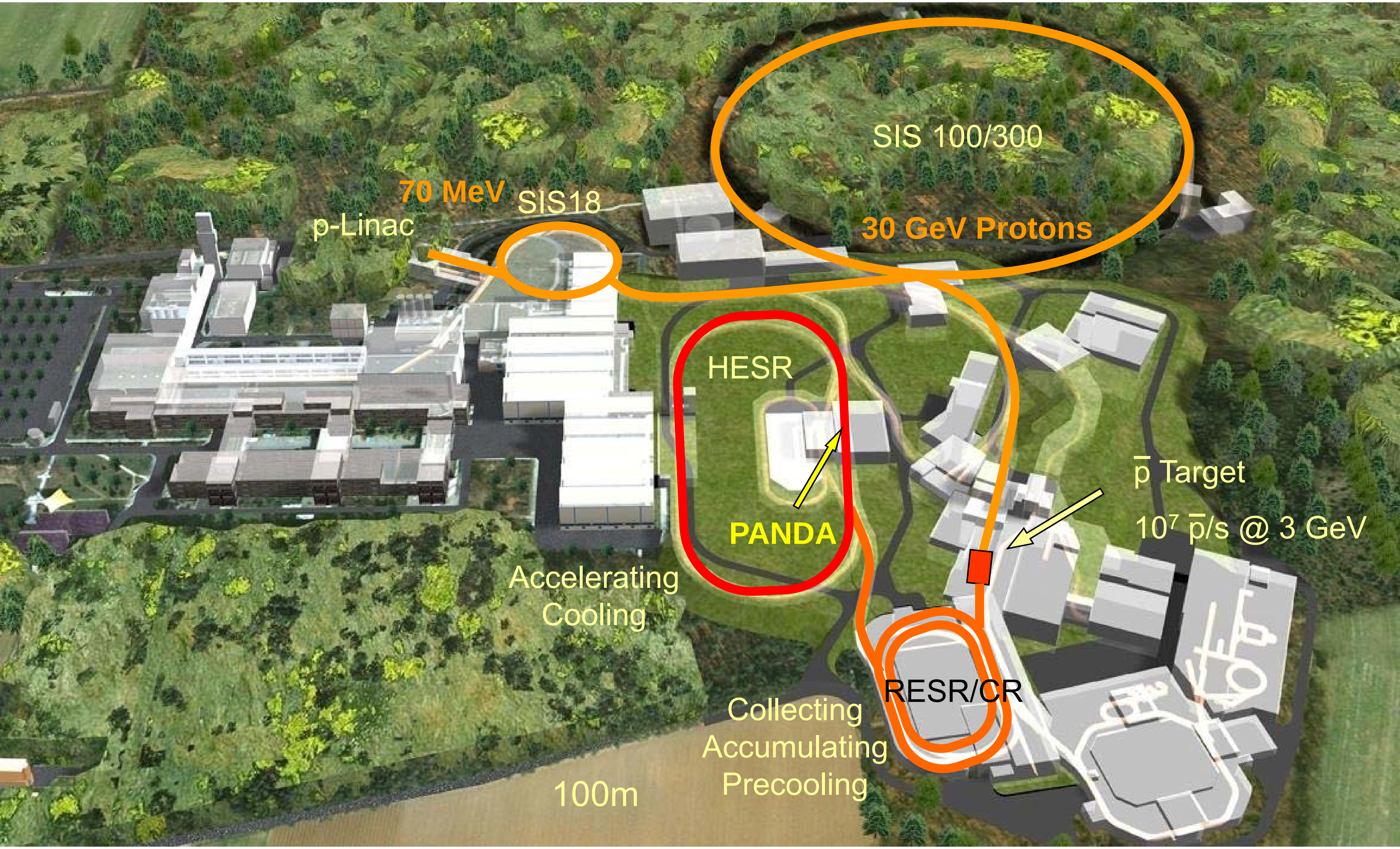
R&D ideas to push DIRC 3 s.d. π/K separation limit to higher momenta than BABAR.

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

Limited in BABAR by:			Could be improved 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	→	4-5 mrad per photon → < 1.5–2 mrad per track

BELLE II,
PANDA & EIC
DIRC Designs

PANDA AT FAIR



PANDA AT FAIR

Google Maps view

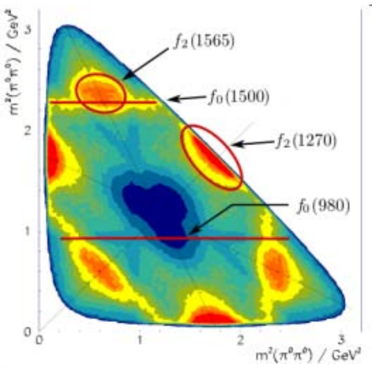
(aerial photo taken Dec 2013)

Site webcam

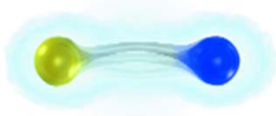
PANDA PHYSICS PROGRAM

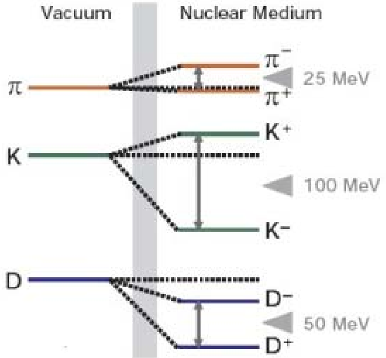
Study of QCD with Antiprotons

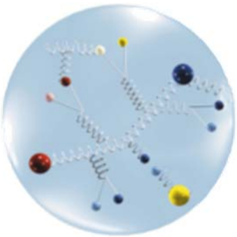
- Charmonium Spectroscopy
  - Precision Spectroscopy
  - Study of Confinement Potential
  - Access to all these puzzling X, Y and Z
- Search for Exotics
  - Look for Glueballs and Hybrids
  - Gluon rich environment → high discovery potential
  - Disentangle Mixing via PWA
- Hadrons in Medium
  - Study in-medium modification of Hadrons
- Nucleon Structure
  - Generalized Parton Distribution
  - Timelike Form Factor of the Proton
  - Drell-Yan Process
- Hypernuclear Physics ... *and more*

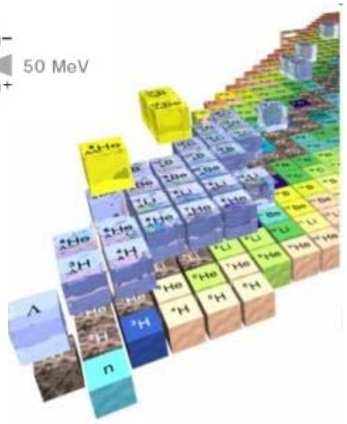


K. Götzen
TROIA'09



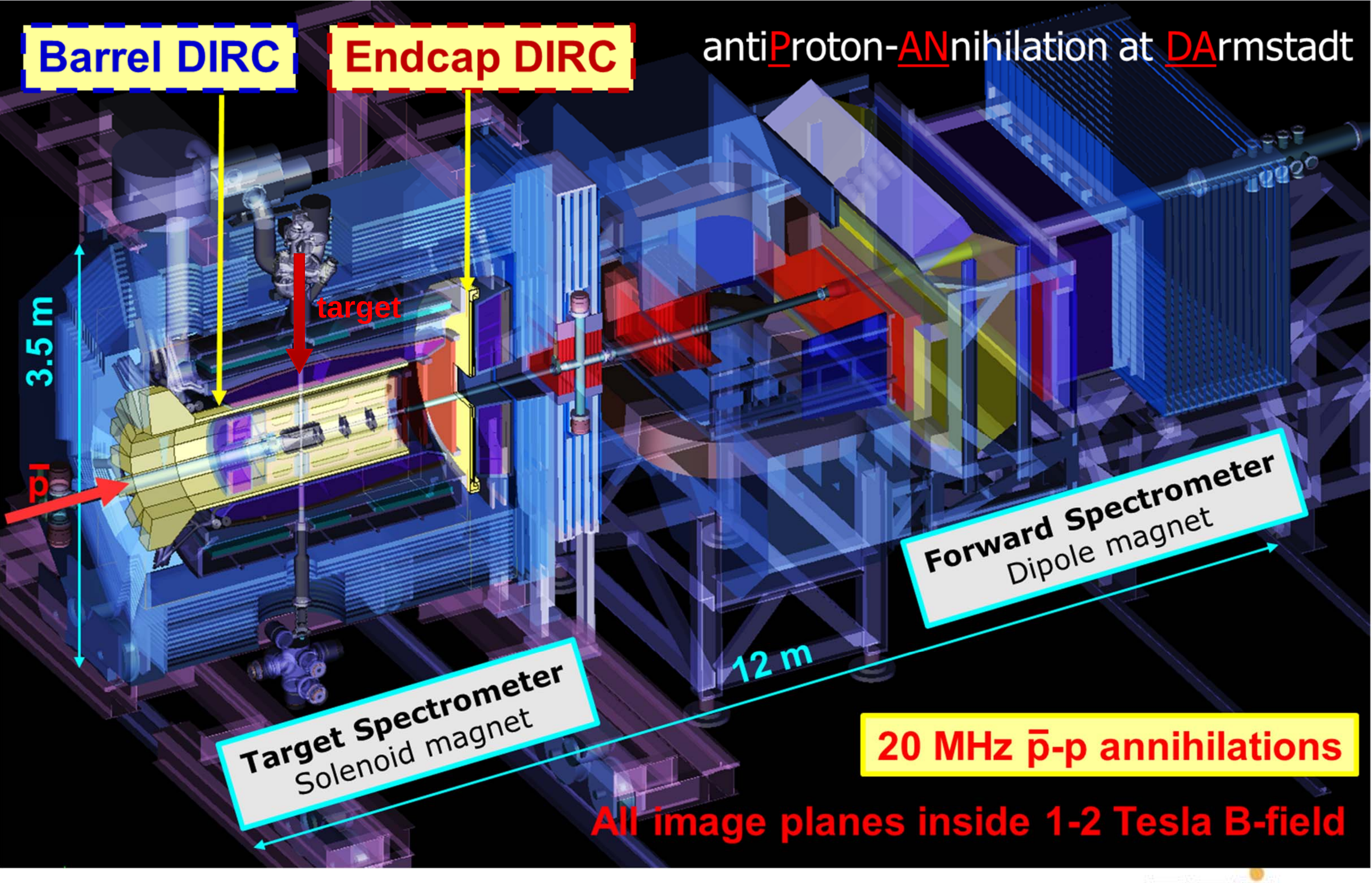






Excellent particle identification required.

THE PANDA DETECTOR



antiProton-ANnihilation at DArmstadt

20 MHz p̄-p annihilations

All image planes inside 1-2 Tesla B-field

DIRCs IN PANDA

PANDA: two DIRC detectors

- Barrel DIRC

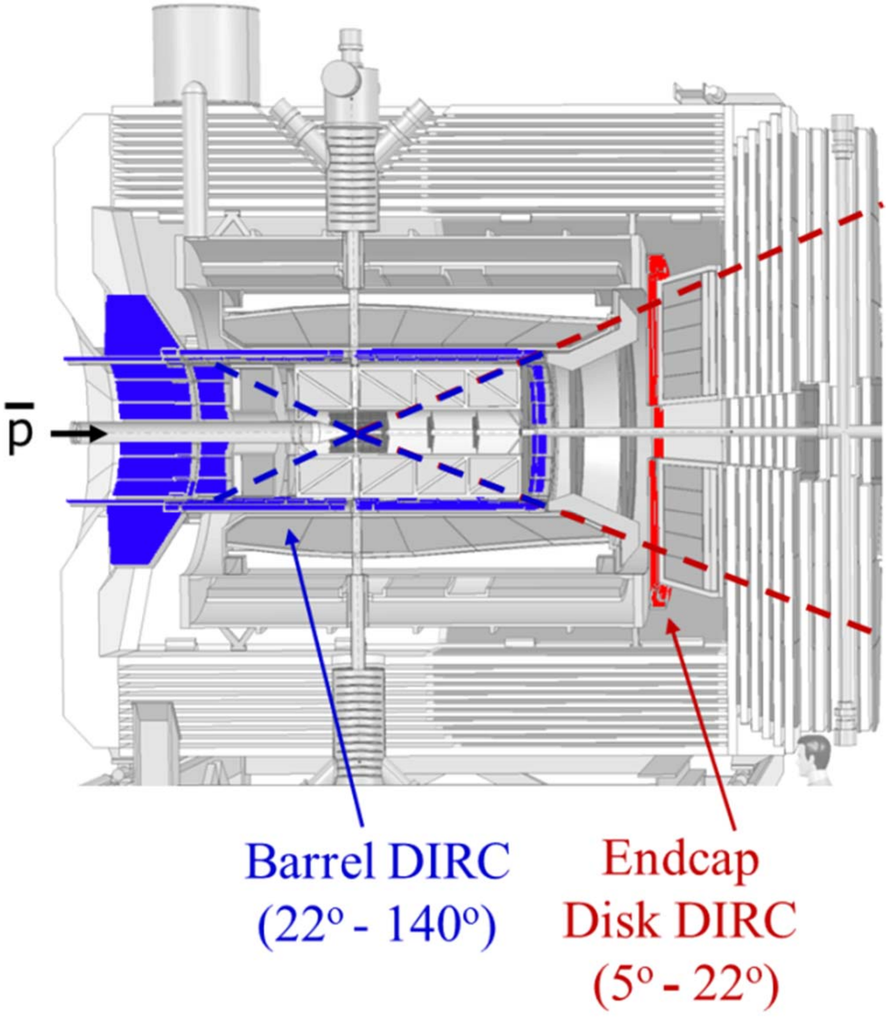
German in-kind contribution to PANDA

Lead and coordination: GSI (HAD1 and SBPD).

- Endcap Disc DIRC

Lead and coordination: Giessen Univ.

Close cooperation with Mainz (electronics) and Erlangen (sensors).



PANDA Cherenkov Group:

JINR Dubna, FAU Erlangen-Nürnberg, JLU Gießen, U. Glasgow, GSI Darmstadt, HIM and JGU Mainz, SMI OeAW Vienna.

Thanks for the material provided for this talk.

DIRCs IN PANDA

PANDA: two DIRC detectors

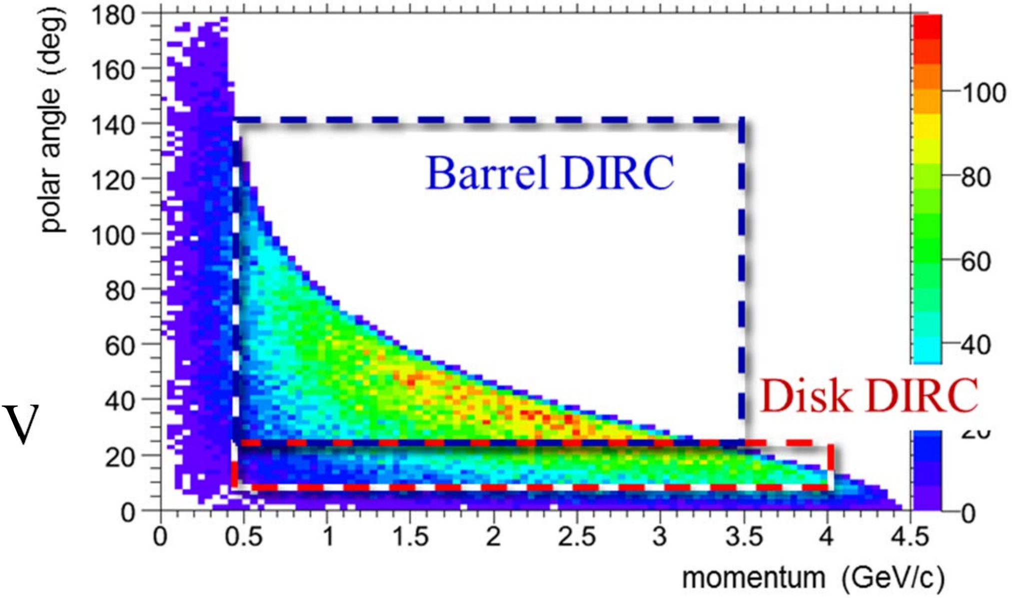
- **Barrel DIRC**

  German in-kind contribution to PANDA

  PID goal: 3σ π/K separation for p<3.5 GeV

- **Endcap Disc DIRC**

  PID goal: 3σ π/K separation for p<4 GeV/c.



Kaon distribution of the radiative decay

$J/\psi \rightarrow K^+K^-\gamma$

(search of glue balls)

Best barrel DIRC performance required at steep forward angles (highest momenta for most physics channels of interest).

Good match to DIRC technology: larger photon yield at steep angles (longer path in fused silica).

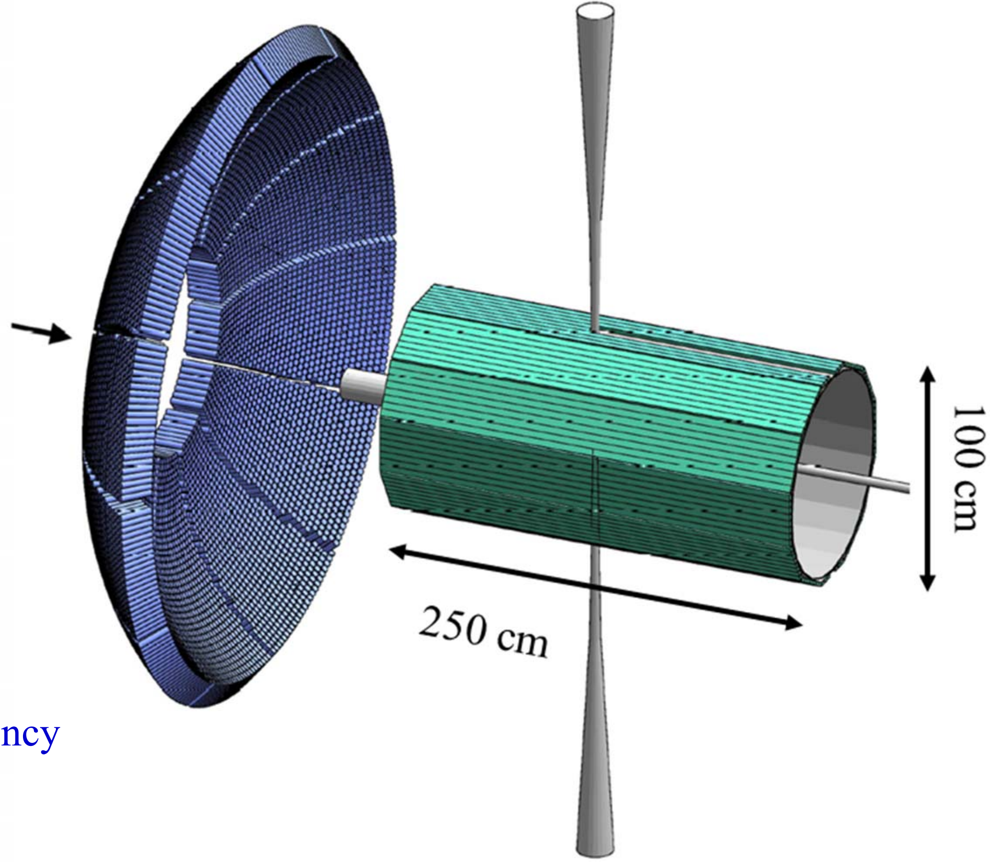
Highest momentum particles and about half the tracks per event seen by Disc DIRC.

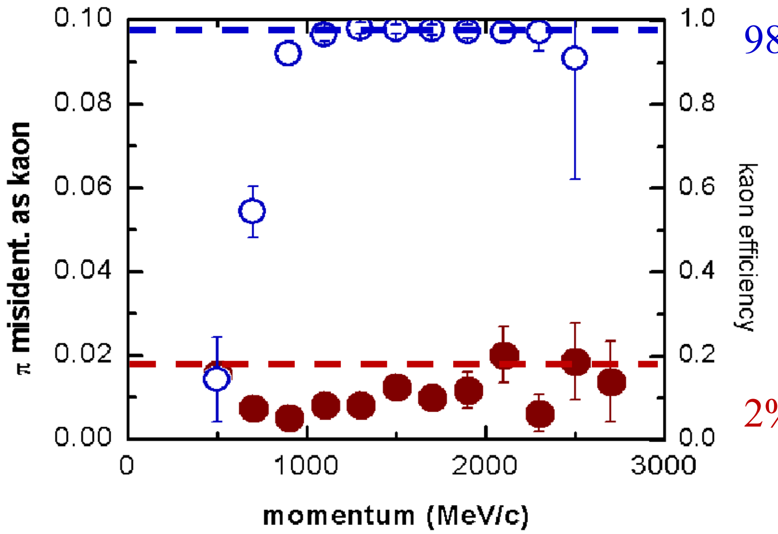
PANDA BARREL DIRC DESIGN

Initial approach (before 2007): scaled version of BABAR DIRC

- 96 narrow fused silica bars, 2.5m length
- Expansion volume: water tank
- ~ 7,000 conventional PMTs

Fast simulation:
performance good match to PANDA





98% kaon ID efficiency

Fast simulation

2% pion mis-ID rate

... but: impossible to integrate into
very crowded PANDA space
(especially that water tank)

→ new, more compact design needed

PANDA BARREL DIRC

Baseline design: based on BABAR DIRC with key improvements

- Barrel radius ~48 cm; expansion volume depth: 30 cm.
- 80 narrow radiator bars, synthetic fused silica

  17mm (T) × 32mm (W) × 2400mm (L).
- Focusing optics: lens system.
- Compact photon detector:

  30 cm oil-filled expansion volume

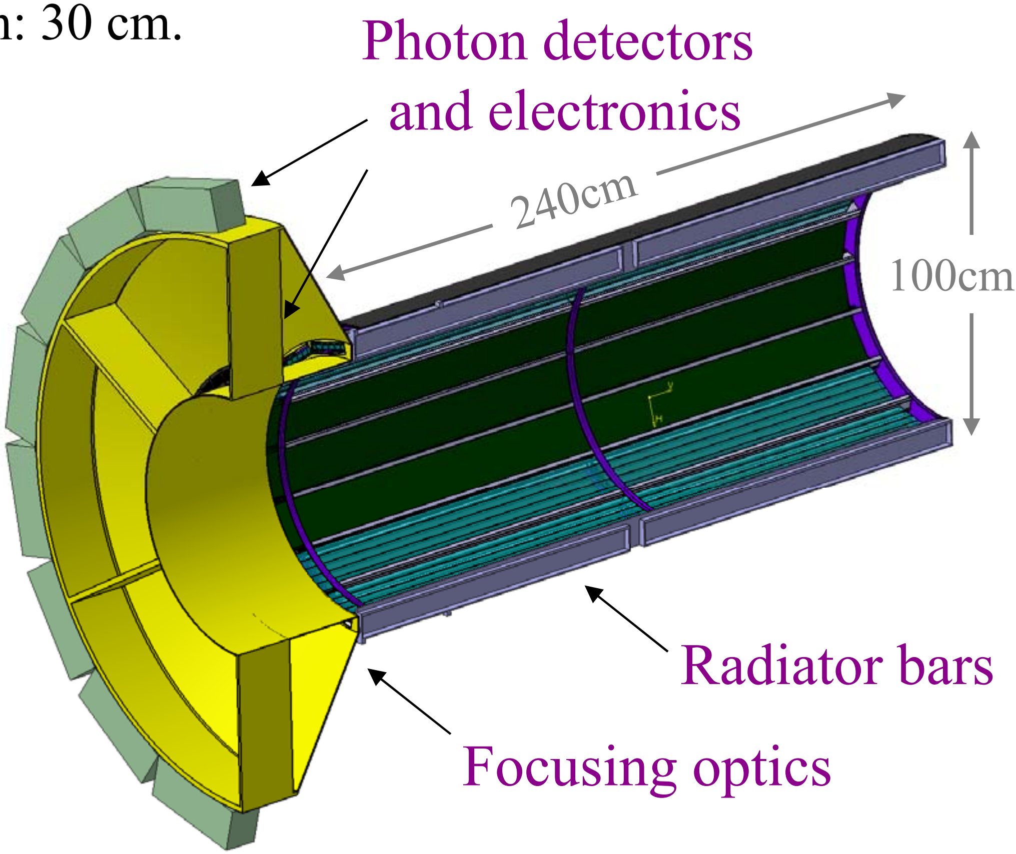
  ~15,000 channels of MCP-PMTs

  in ~1T B field.
- Fast photon detection:

  fast TDC plus ADC (or ToT) electronics.
- Expected performance:

  Single photon Cherenkov angle resolution: 8-10 mrad.

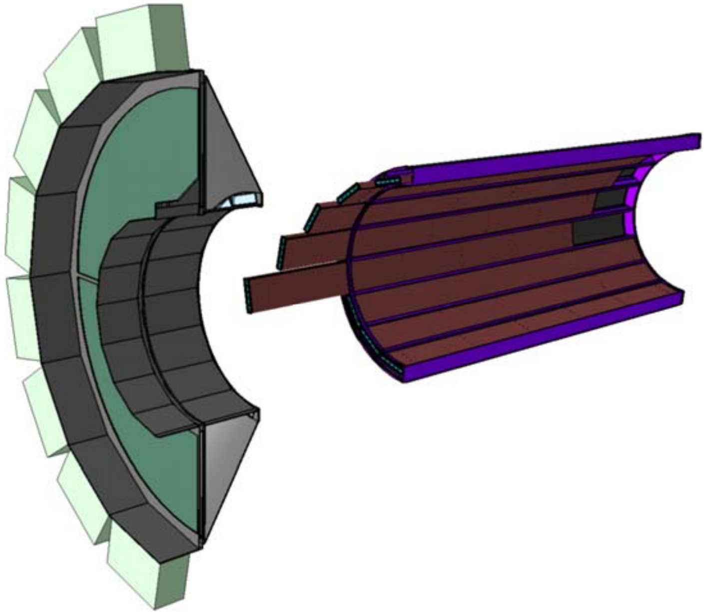
  Number of photoelectrons for β≈1 track: at least 20.



Validate design/options in 2015,
TDR by mid-2016.

PANDA BARREL DIRC

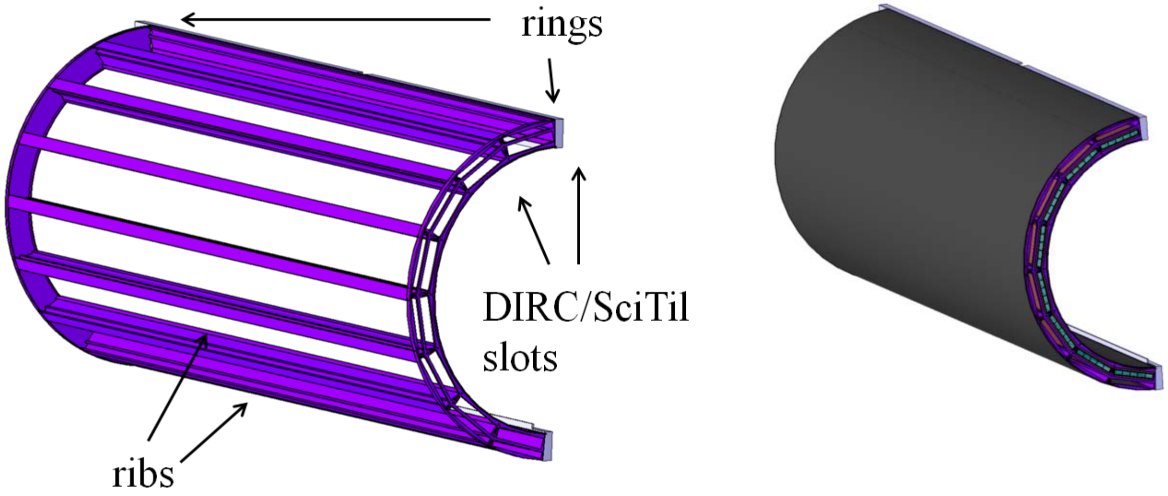
Mechanical Design



Modular mechanical design.

Bar boxes slide into slots, can be installed/removed as required (in case of delays or for repairs).

Expansion volume detaches for access to bar boxes and tracking detectors.



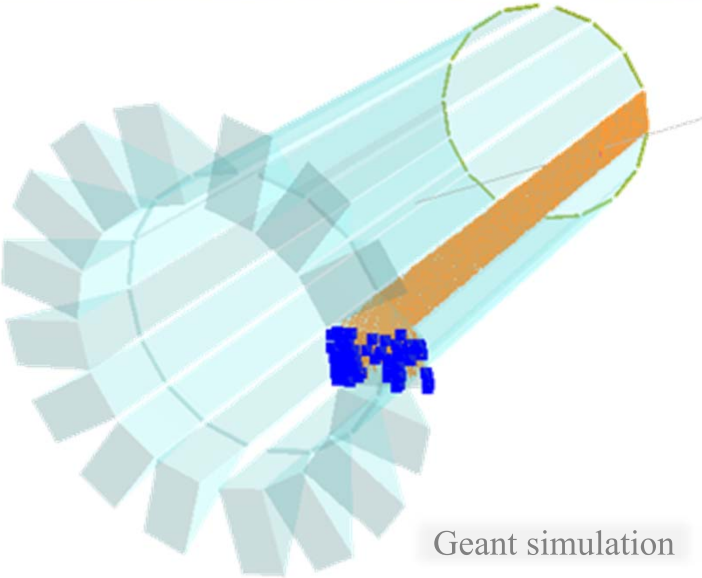
Bar boxes provide much of the required stability

- bars placed side-by-side in carbon fiber bar box, N_2 flow
- rings in 2 locations in Z couple DIRC mechanics to central PANDA support beam
- slots in rings for DIRC and SciTil (time of flight) containers
- ribs along the length of the barrel provide required stiffness
- wheels mounted on bar box run on rails attached to the ribs
- carbon fiber sheets provide additional strength

PANDA BARREL DIRC OPTIONS

Investigating several design options:

Use of one wide fused silica plate (16cm) per sector
instead of 5 narrow (3.2cm) bars


Geant simulation

Radiator fabrication dominant cost driver for Barrel DIRC.

Belle II is leading the way with plate fabrication for their DIRC (TOP counter), prototyping, and software development.

Smaller number of pieces could drastically reduce the radiator fabrication cost (1.5M€+ savings possible).

Purchased prototype plate and tested at CERN T9 test beam 2012,
software development and data analysis ongoing,
additional beam test in 2015 required for decision.

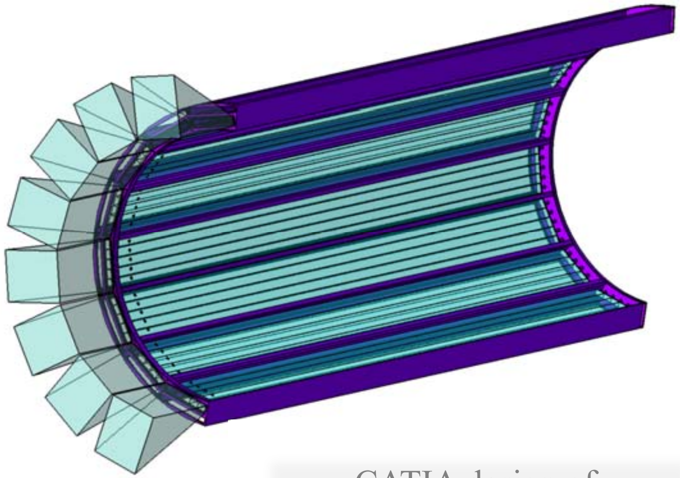

Prototype bar and plate

PANDA BARREL DIRC OPTIONS

Investigating several design options:

Segmented optical expansion volume, "camera"

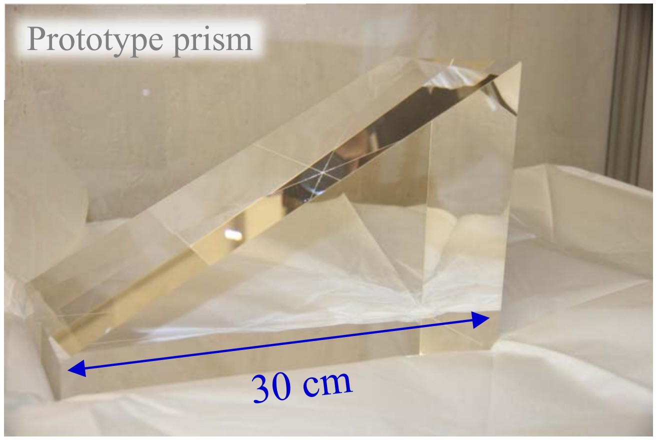
- one solid fused silica prism per sector instead of oil tank
  → better optical and operational properties,
  good match to possible geometry with wide plates.
- but: reflections in prism complicate reconstruction for baseline design with narrow bars, add background.
- Design also reduces the number of required MCP-PMTs.
  (the next largest item in our budget).



CATIA design of
Barrel DIRC geometry with
narrow bars and prisms

Purchased prototype prism in 2012,

- tested combination at CERN T9 test beam,
- software development and data analysis ongoing,
  additional beam test in 2015 required for decision.



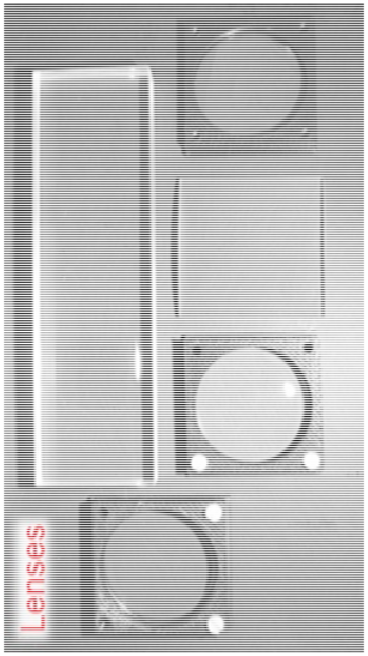
Prototype prism

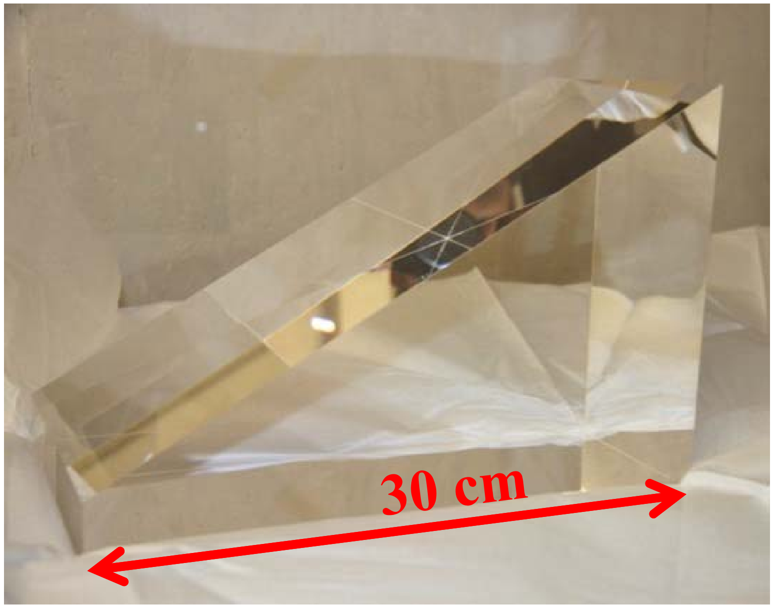
PANDA BARREL DIRC R&D

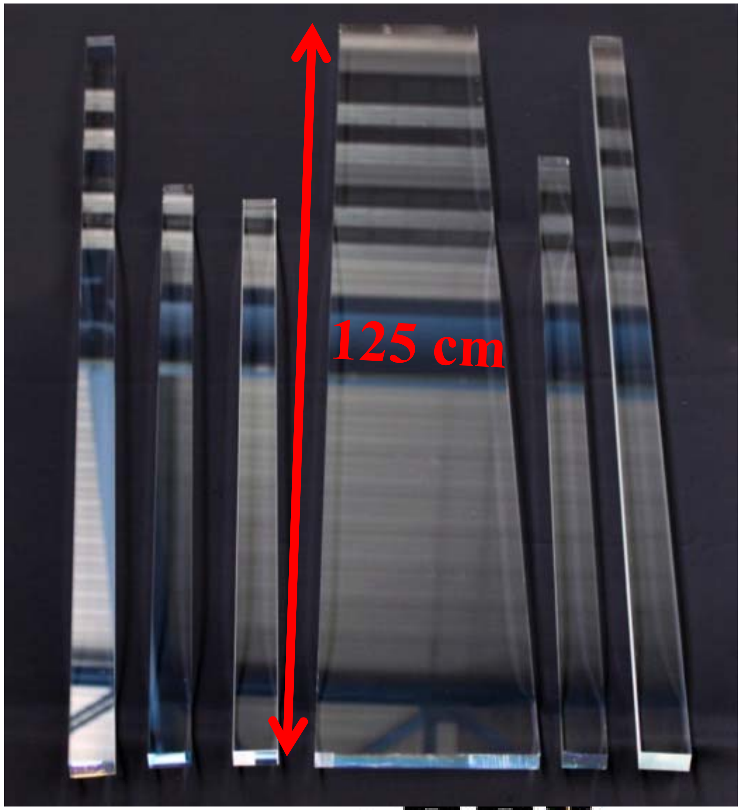
Emphasis on validating sensors and optics

Detailed simulation to define requirements, optimize reconstruction (bars/plates).

- Radiator prototype program with industry partners in Europe, USA, Japan;
  ~30 bars/plates produced by 6 companies using different materials and techniques.
- Two solid fused silica prism prototypes (30° and 45° top angle) built by industry.
- Designed several spherical and cylindrical lenses, with and without air gap, built by industry.
- Optical lab and particle beams to test performance.
- Tested DIRC sensor properties, including lifetime.







DIRC RADIATOR CHALLENGES

Production of large fused silica pieces (bars, plates) is known to be challenging.

DIRCs require mechanical tolerances on flatness, squareness, and parallelism
with optical finish and long sharp edges.
→ difficult, potentially expensive, few qualified vendors worldwide.

BABAR-DIRC used bars polished to 5 Å *rms*, non-squareness < 0.25 mrad;
successfully done for BABAR, needed to qualify/retrain vendors 10+ years later.

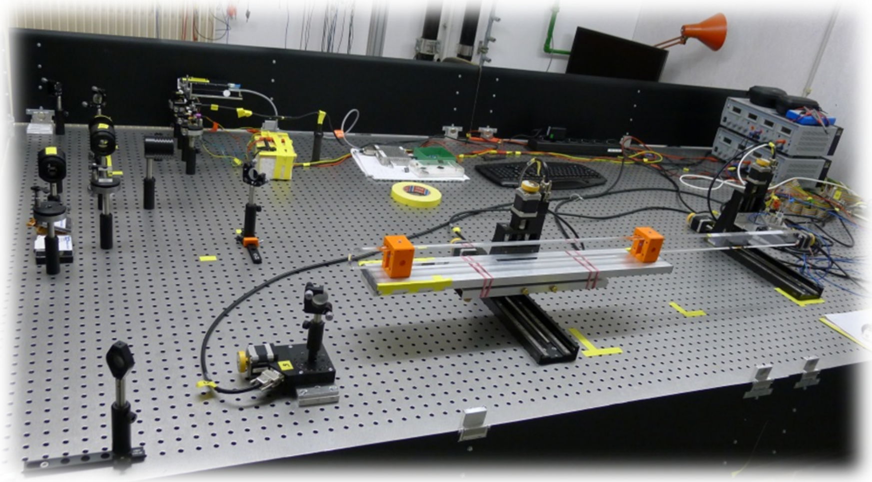
Radiator production has been the source of severe DIRC project delays for BABAR and Belle II.

Trying to stay ahead of the curve, worked with potential vendors in Europe and USA,
obtained prototype bars, plates from several companies, verifying surfaces and angles.

First impression: major players (AOS, InSync, Zeiss, Zygo) all capable of producing
high quality DIRC bars (to be confirmed in our optical lab).

RADIATOR QUALITY TEST

Motion-controlled scanning setup



Scan bar surface for measurement of
  coefficient of total internal reflection (R)
  and bulk attenuation (Λ) of prototype
  radiator bars at multiple laser wavelengths
  → determine quality of surface finish with few Å accuracy.

Testing prototype bars from
  AOS/Okamoto, InSync Inc., Heraeus, Lytkarino LZOS, Schott Lithotec, Zeiss, Zygo.
    (first meeting with Nikon last week, seem quite motivated to get into the DIRC game)

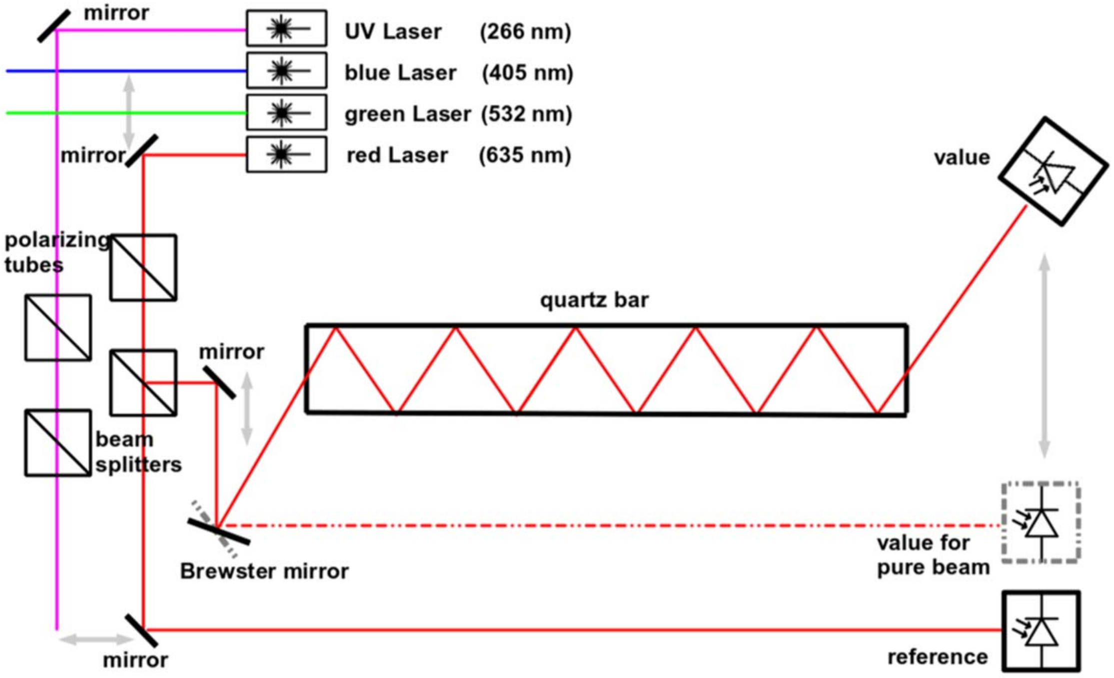
Raw material used: Suprasil 1 & 2, Lithosil Q0, Spectrosil, Corning 7980.

Requirements on bulk attenuation, surface roughness, squareness of bar sides, flatness,
  and edge quality expected to be comparable to BABAR-DIRC.
  (Shorter photon paths in PANDA will allow relaxation of some specs.)

RADIATOR QUALITY TEST

Scan ~100 bar entry positions with laser

- Determine attenuation length Λ by aiming laser down length of bar *(correct for Fresnel loss).*
- Measure coefficient of total internal reflection R by bouncing laser off bar surfaces;
  for 80 cm-long bar: 31 internal reflections
  from bar faces or 15 from bar sides.

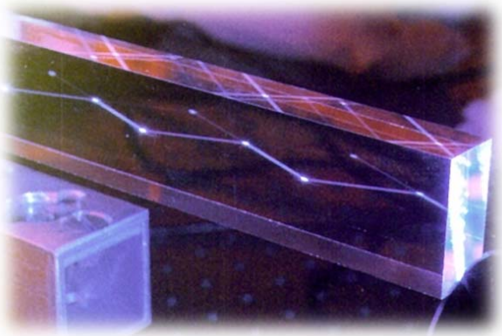


- Diode measures transmitted intensity T *(normalized to reference intensity).*
- Calculate R from mean transmitted intensity T:

$$T = R^N \cdot \exp\left(-\frac{L}{\Lambda}\right)$$

- Calculate surface roughness σ from R using scalar theory of scattering:

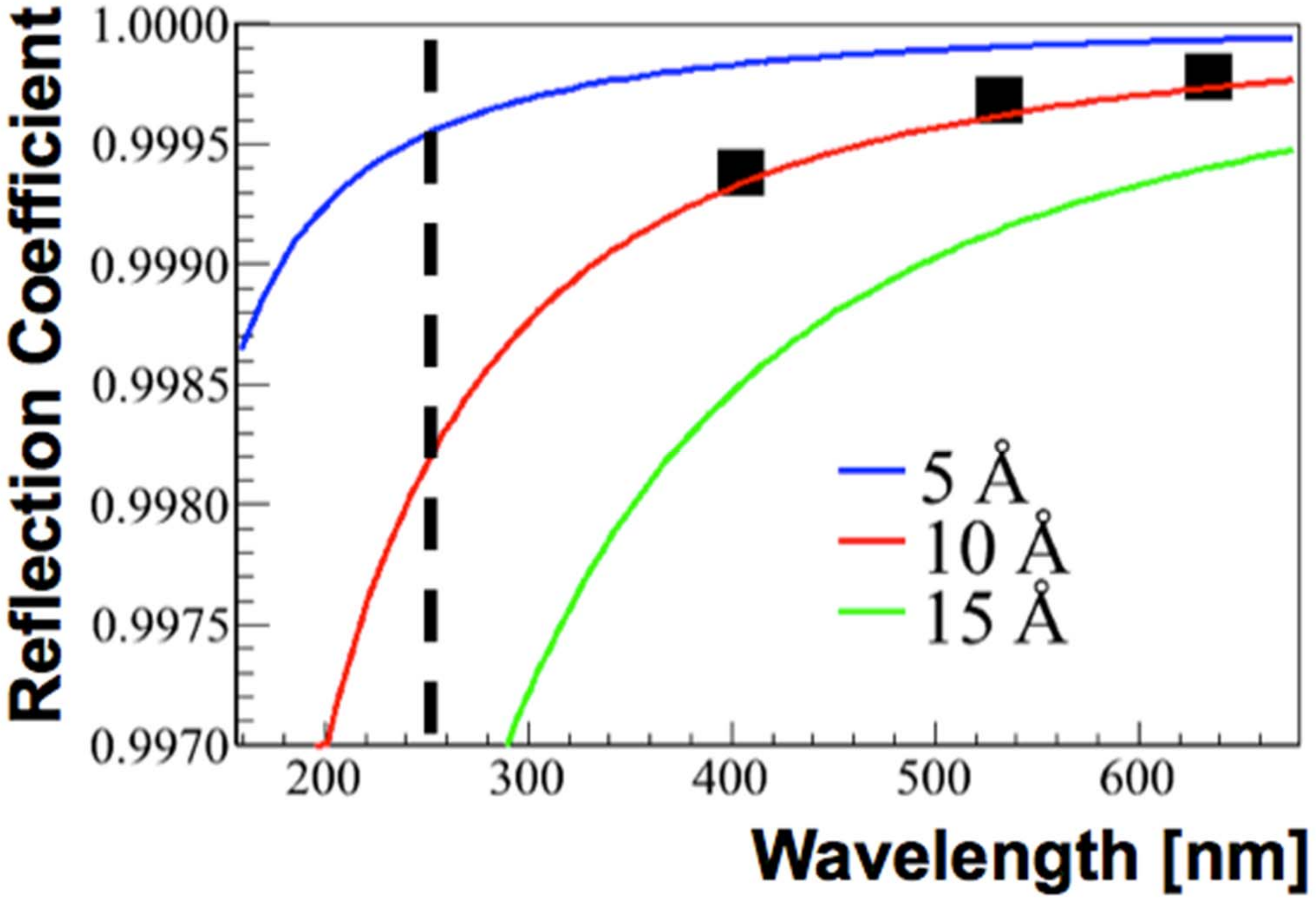
$$R = 1 - \left(\frac{4\pi \cdot \sigma \cdot n \cdot \cos\alpha}{\lambda}\right)^2 \quad \text{for } \sigma << \lambda.$$



RADIATOR QUALITY TEST

Measured coefficient of total internal reflection
for a Schott Lithotec bar for three wavelengths
compared to expectation from scalar theory of scattering.

R. Hohler
DPG 2010



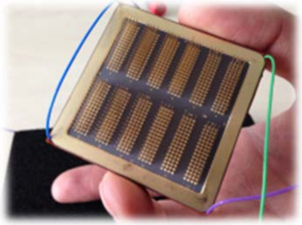
Good agreement with production specs from vendor: 10 – 20Å *rms* roughness.

PANDA DIRC SENSOR CHALLENGES

PANDA DIRCs require compact, fast multi-pixel sensor with single photon sensitivity in strong magnetic field with trigger-less DAQ and 20MHz average interaction rate.

- Good geometrical resolution over a large surface
  - multi-pixel sensors with ~5x5 mm anodes for Barrel DIRC, ~0.5mm anode pitch in radial direction for Disc DIRC.

Hamamatsu 6x128

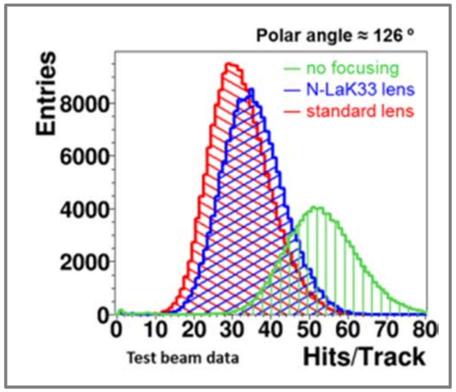


PHOTONIS 3x100

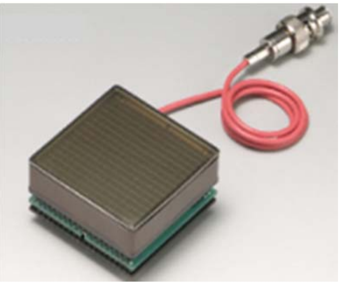
PHOTONIS 8x8

- Single photon detection inside B-field
  - high gain (> 5×10^5) at 1-2 Tesla
- Time resolution for photon time of propagation and/or dispersion correction
  - very good time resolution of <100 ps for single photons
- Few photons per track
  - high detection efficiency PDE = QE * CE * GE
  - low dark count rate
- Photon rates in the MHz regime
  - high rate capability with rates up to MHz/cm^2
  - long lifetime with integrated anode charge of 0.5 to 2 C/cm^2/y
  - multi-hit capability with 10-15 photons per 60x60mm unit

PANDA Barrel DIRC Prototype



DIRC SENSOR CANDIDATES

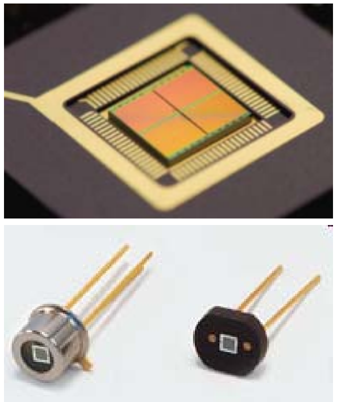


- Multi-anode Photomultipliers (MaPMTs)

  used successfully in DIRC prototypes,

  was sensor of choice for SuperB FDIRC

  ruled out by 1T magnetic field



- Geiger-mode Avalanche Photo Diodes (SiPMs)

  high dark count rate problematic for reconstruction (trigger-less DAQ)

  radiation hardness an issue in PANDA environment

- Micro-channel Plate Photomultipliers (MCP-PMTs)

  good PDE, excellent timing and magnetic field performance

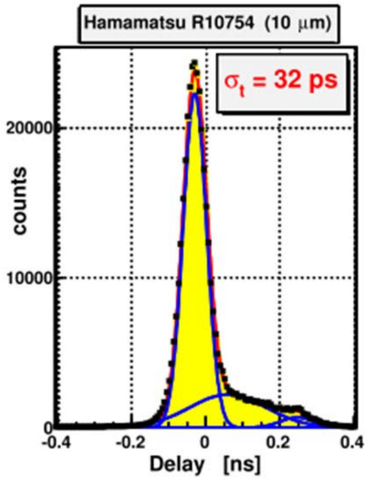
  issues with rate capability and aging

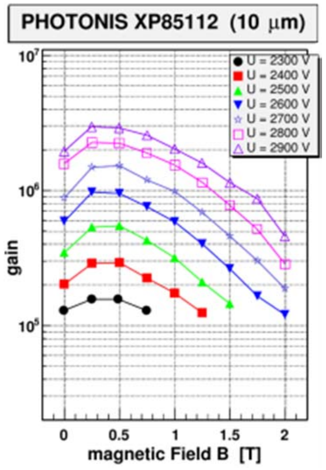
MCP-PMT PERFORMANCE EXAMPLES

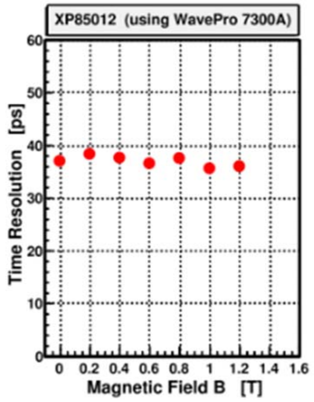
Detailed study of MCP-PMT performance:

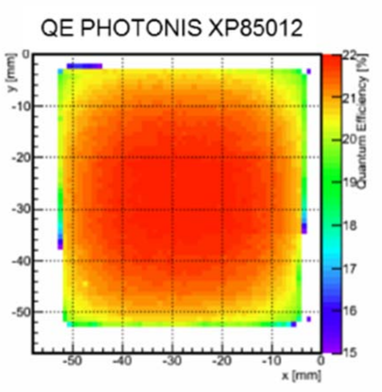
- prototypes from BINP, PHOTONIS, Hamamatsu
- single photon time resolution
- gain and quantum efficiency scans
- charge sharing/cross-talk
- rate capability
- tests with and without magnetic field

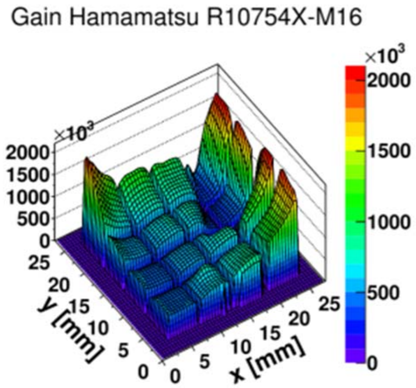
MCP-PMTs meet *most* PANDA DIRC goals.

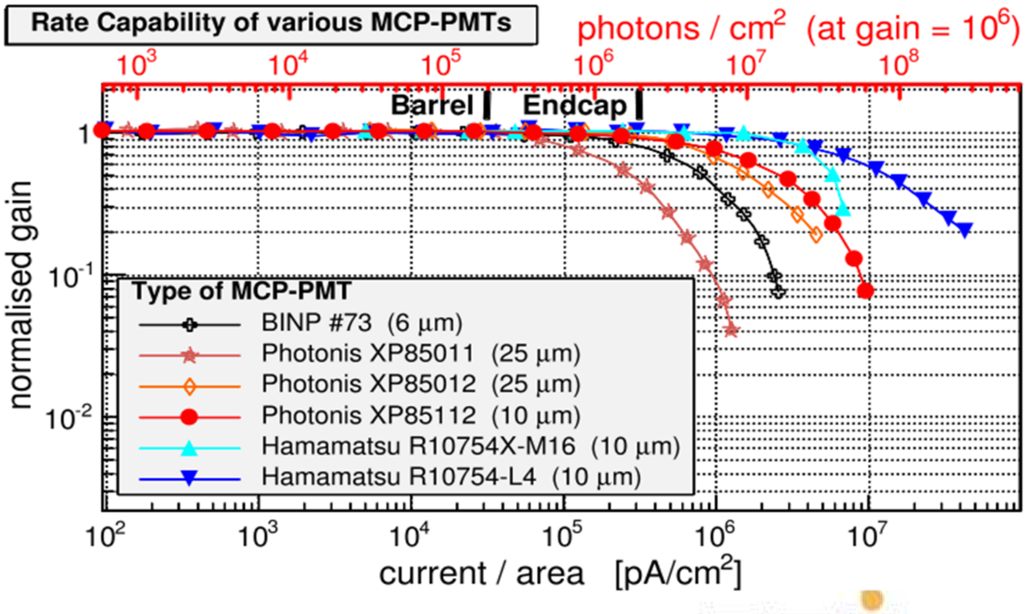












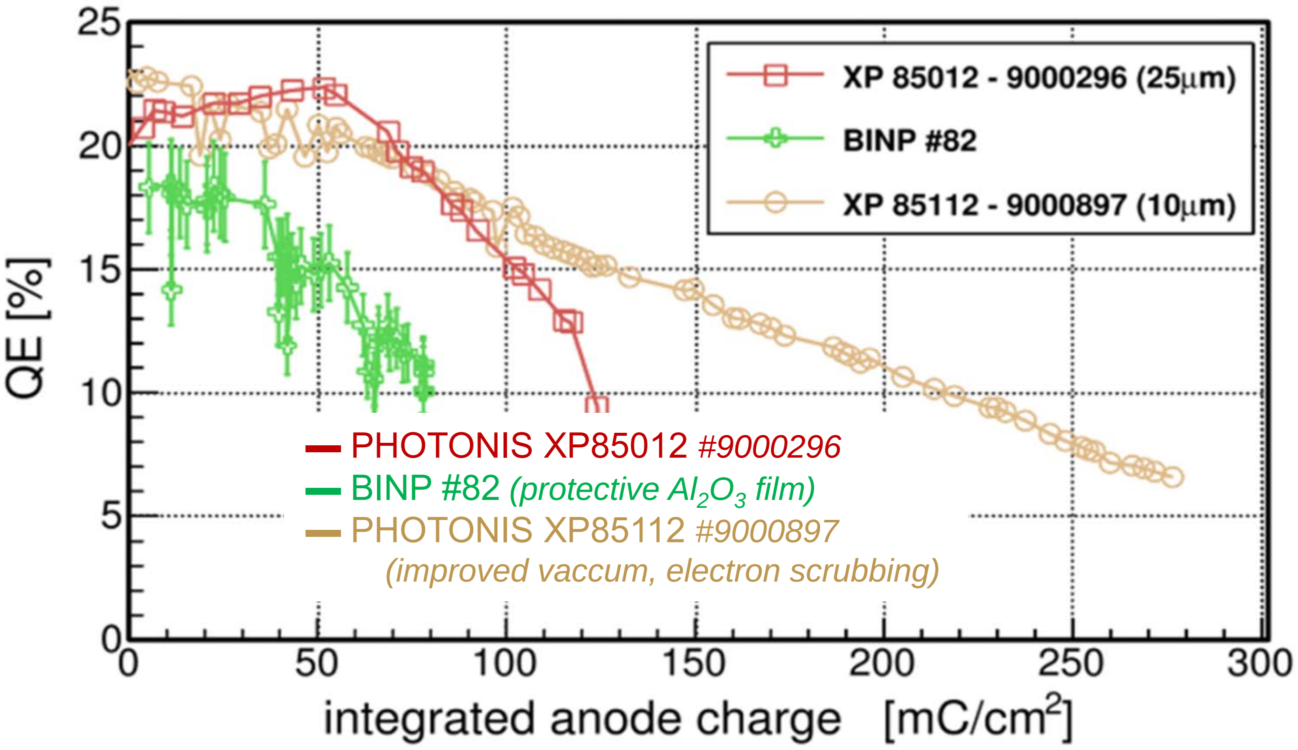
All results from Erlangen group.
For a more complete review:
A. Lehmann's talks at
RICH 2013 and at LIGHT14

MCP-PMT LIFETIME IN 2011

The main issue with using MCP-PMTs for PANDA DIRCs:

aging of photocathode

Status of our MCP-PMT lifetime measurements in 2011



Quantum efficiency reduced by 50% or more at only <200 mC/cm^2

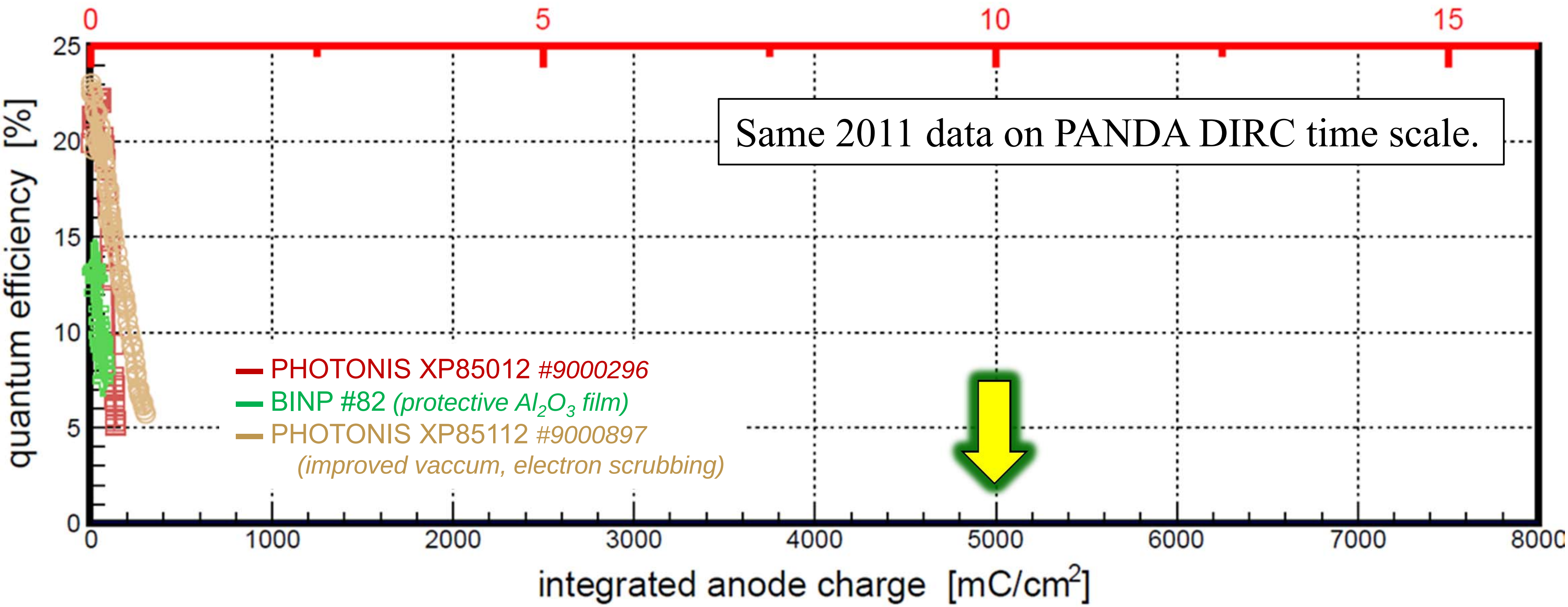
But: PANDA DIRCs require lifetime of 5-10 C/cm^2

MCP-PMT LIFETIME IN 2011

The main issue with using MCP-PMTs for PANDA DIRCs:

aging of photocathode

Status of our MCP-PMT lifetime measurements in 2011



Same 2011 data on PANDA DIRC time scale.

None of the MCP-PMTs in 2011 would have survived for more than 2 months in PANDA.

→ needed factor ~50 (“breakthrough”) improvement in MCP-PMT lifetime

MCP-PMT AGING

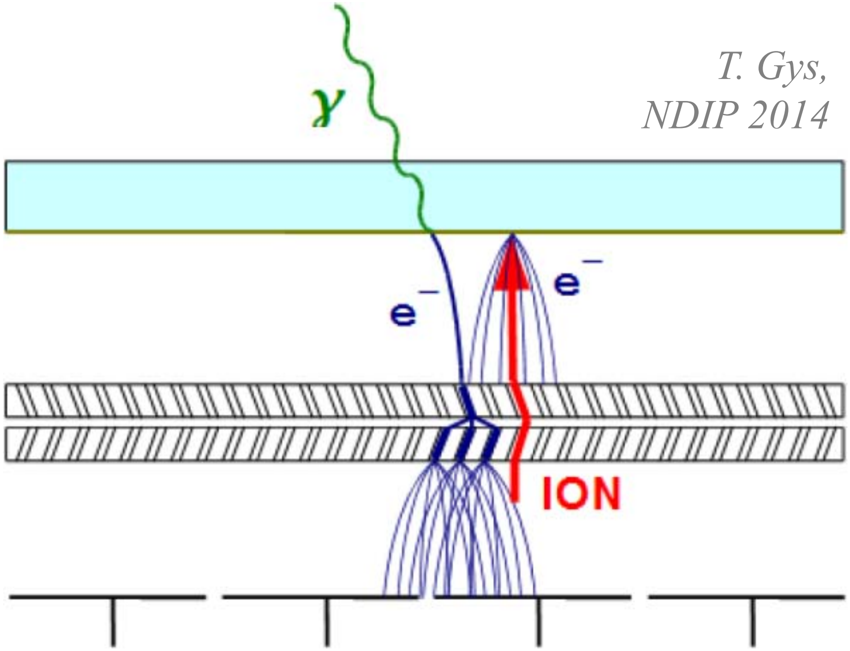
Ion feedback

Amplification process causes

- Ionization of residual gas atoms
- Desorption of atoms from MCP material (especially H and Pb)
- Damaging of MCP surfaces → gain may change

Ions accelerated towards photo cathode

- Production of secondary pulse
- Ions may react with PC
- PC gets damaged and work function may gradually change
- Degradation of Quantum efficiency (QE)

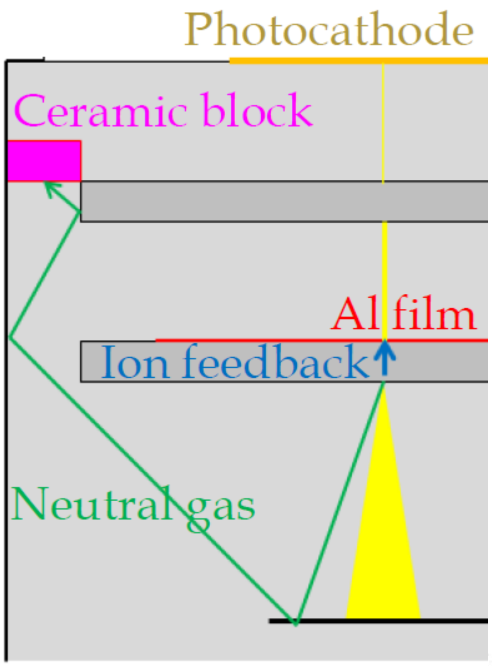


T. Gys, NDIP 2014

Neutral molecules from residual gas

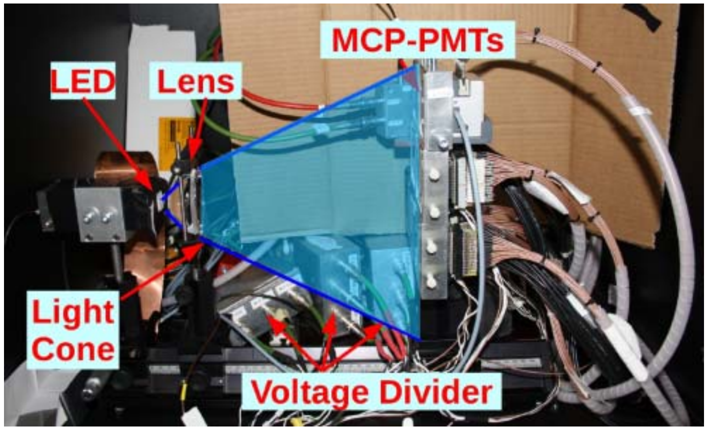
Passing between MCPs and walls

CO_2, O_2 and H_2O react with PC

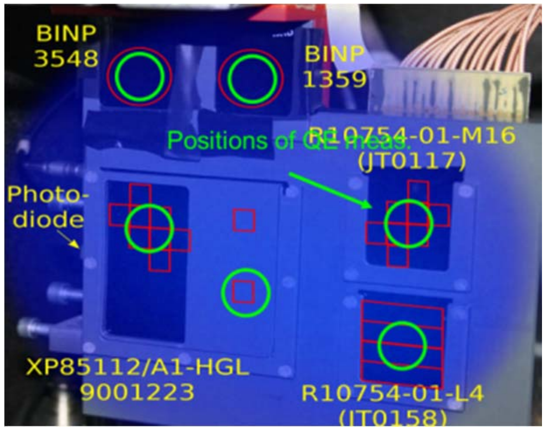


K. Matsuoka, RICH 2013

MCP-PMT AGING MEASUREMENTS



Detailed study of aging (Erlangen U.)
in close collaboration with industry

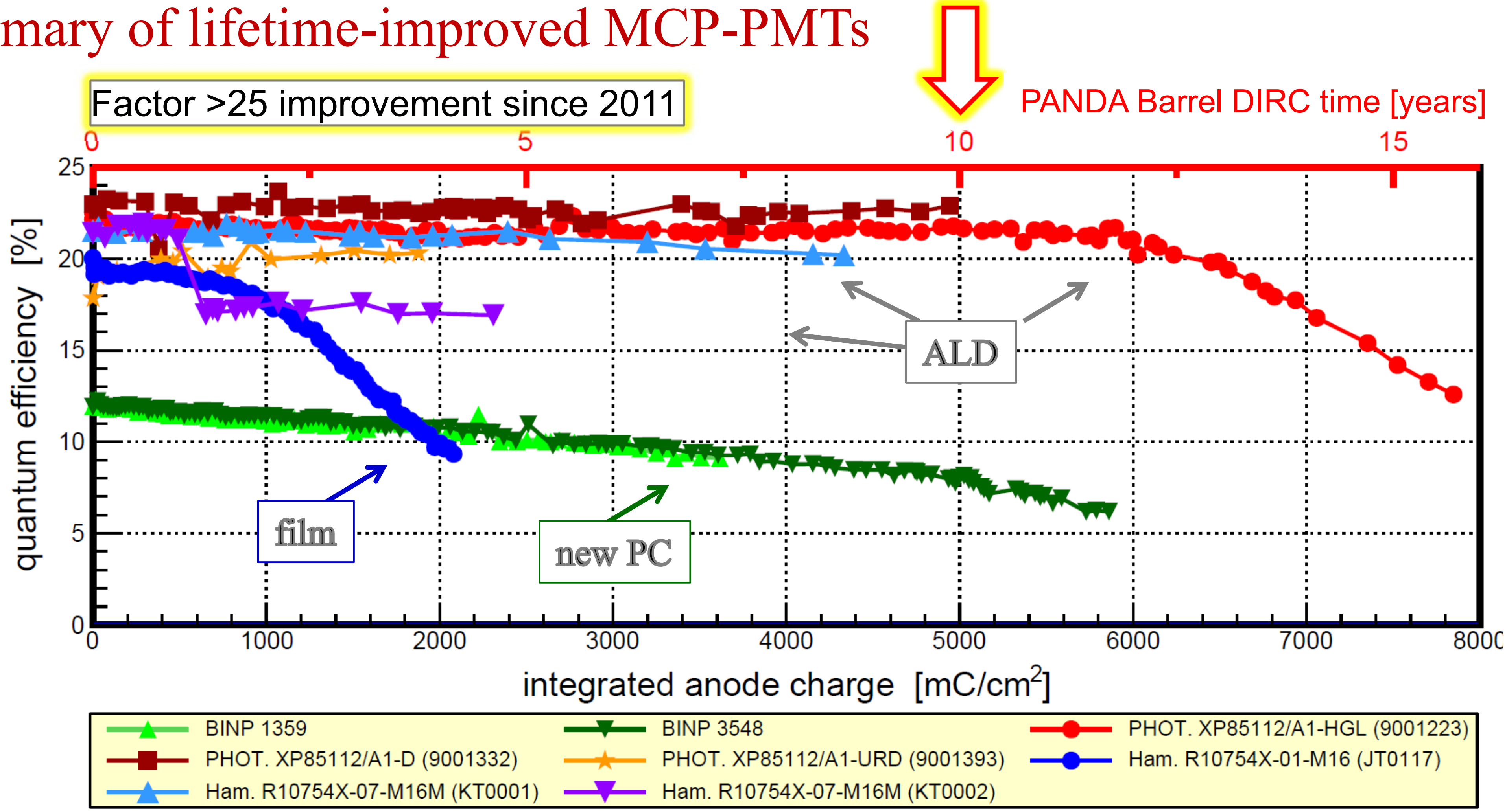


	Sensor ID	Integrated charge (as of Oct. 1, 2014) [mC/cm^2]	Diff. charge (maximum) [mC/cm^2/d]	# of measurements	# of QE scans	Comments
PHOTONIS XP85112	9001223	**7852**	13.5	151	14	Start: 23 Aug. 11 ongoing
	9001332	**4948**	21.8	55	7	Start: 12 Dec. 12 ongoing
	9001393	**1879**	11	19	3	Start: 23 Jan. 14 ongoing
Hamamatsu R10754X	JT0117 (M16)	**2086**	14.1	86	7	Start: 23 Aug. 11 Stop: 24 Jul. 12
	KT0001 (M16M)	**4331**	30.1	31	5	Start: 20 Aug. 13 ongoing
	KT0002 (M16M)	**2312**	20.1	26	6	Start: 21 Oct. 13 ongoing
BINP	1359	**3616**	10.6	90	8	Start: 21 Oct. 11 Stop: 06 May 13
	3548	**5925**	11.8	128	11	Start: 21 Oct. 11 ongoing

MCP-PMT LIFETIME RESULTS

Summary of lifetime-improved MCP-PMTs

Factor >25 improvement since 2011



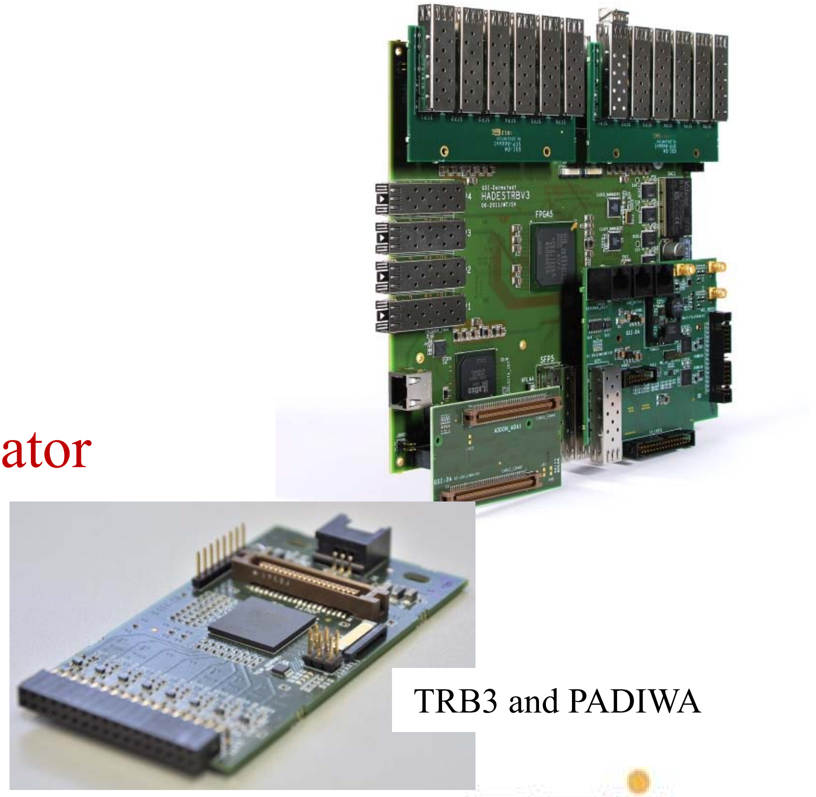
Latest MCP-PMTs with ALD technique meet all requirements for the PANDA Barrel DIRC.

ELECTRONICS CHALLENGES

Close cooperation with CSEE

M. Traxler et al.

- Signal rise time typically few hundred picoseconds.
- 10-100x preamplifier usually needed.
- High bandwidth 500MHz – few GHz (optimum bandwidth not obvious).
- Pulse height/charge information required for < 100 ps timing (time walk correction),
  and desirable for 100-200 ps timing (ADC / time over threshold / waveform sampling / ...)
- PANDA will run trigger-less.
- Radiation hardness may be an issue (FPGA).
- Large data volume (to disk: up to 200 Gb/s).
- Current approach:
  HADES TRBv3 board with amplifier/discriminator
  front-end card mounted on MCP-PMT.
- Verify electronics performance with fast laser pulsers
  and several dedicated beam times.

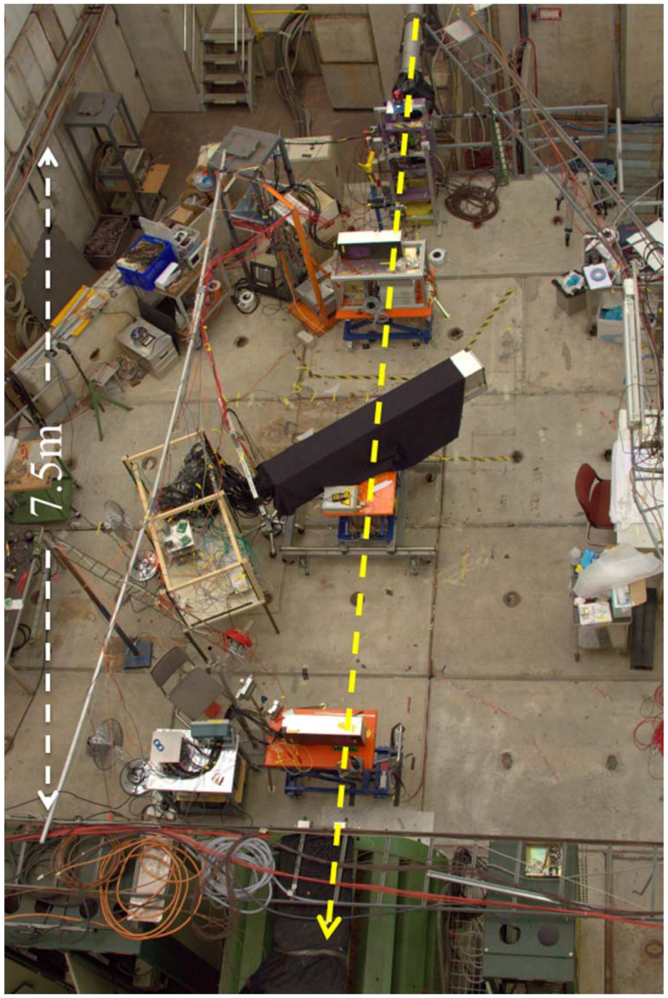


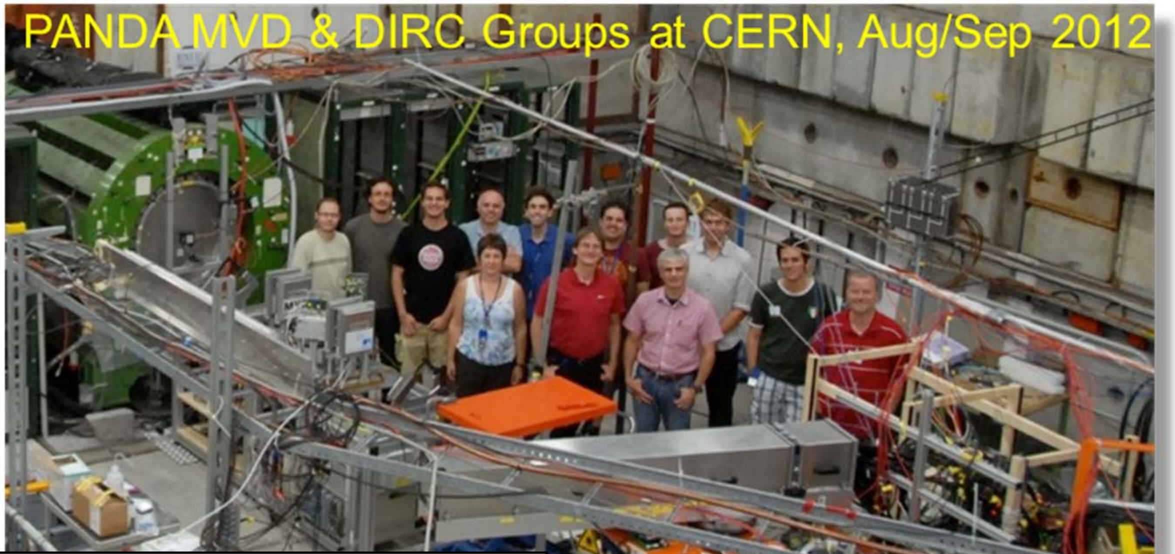
TRB3 and PADIWA

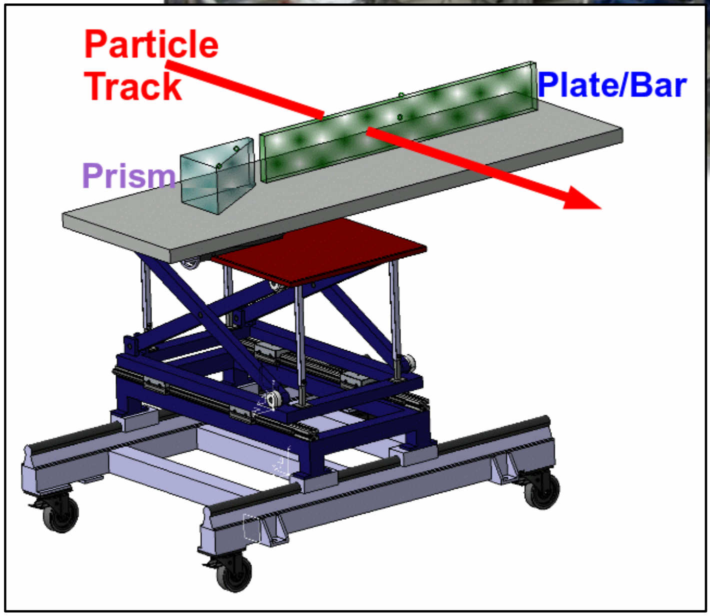
BARREL DIRC BEAM TESTS

Increasingly complex prototypes tested with
particle beams in 2008, 2009, 2011, 2012, 2014

CERN 2012




PANDA MVD & DIRC Groups at CERN, Aug/Sep 2012

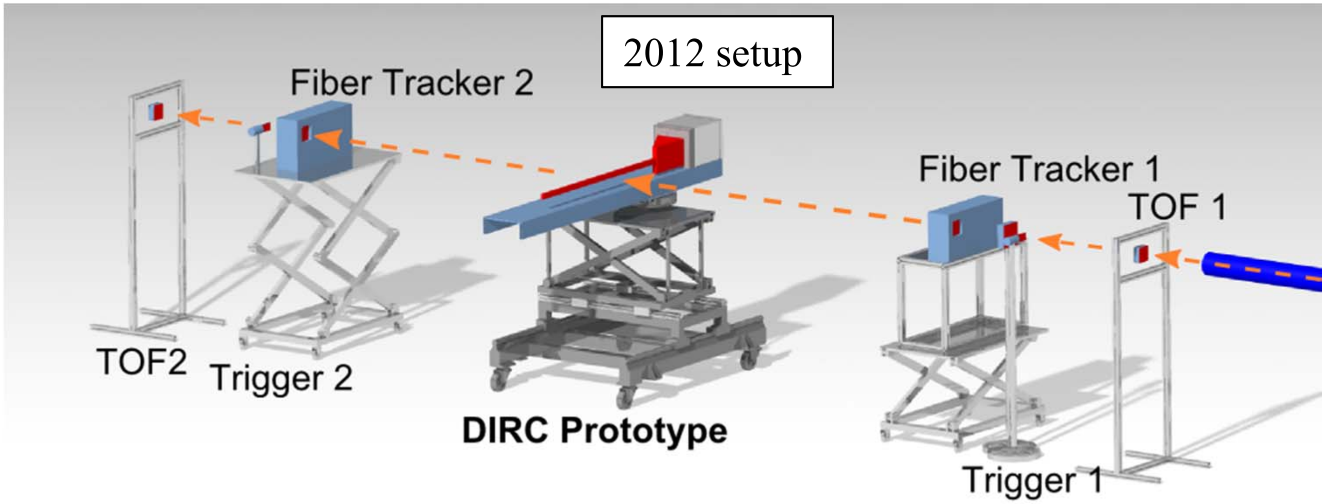


BARREL DIRC BEAM TESTS

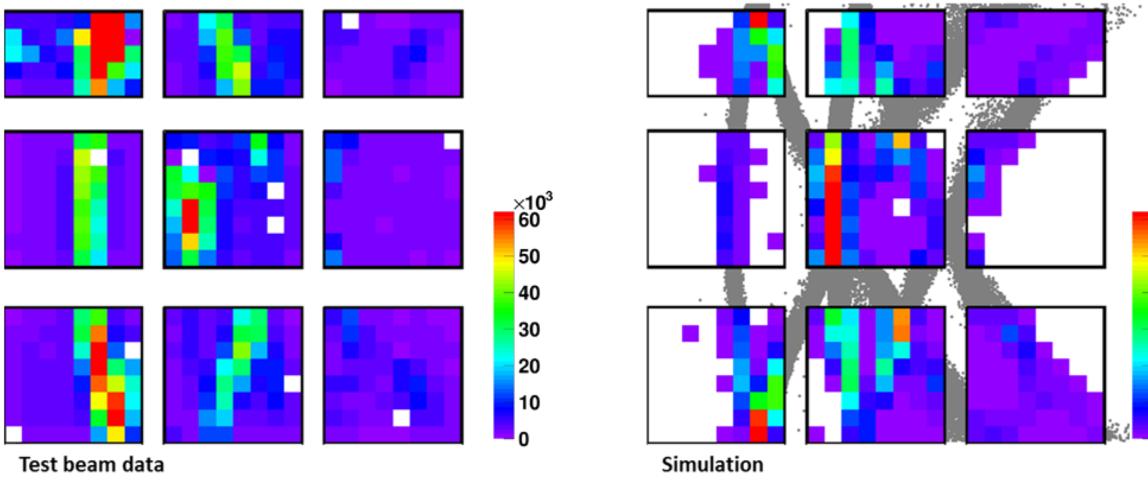
Increasingly complex prototypes tested with
particle beams in 2008, 2009, 2011, 2012, 2014

2012

Prototype with narrow bars
CERN PS
mixed hadron beam 1 – 10 GeV/c

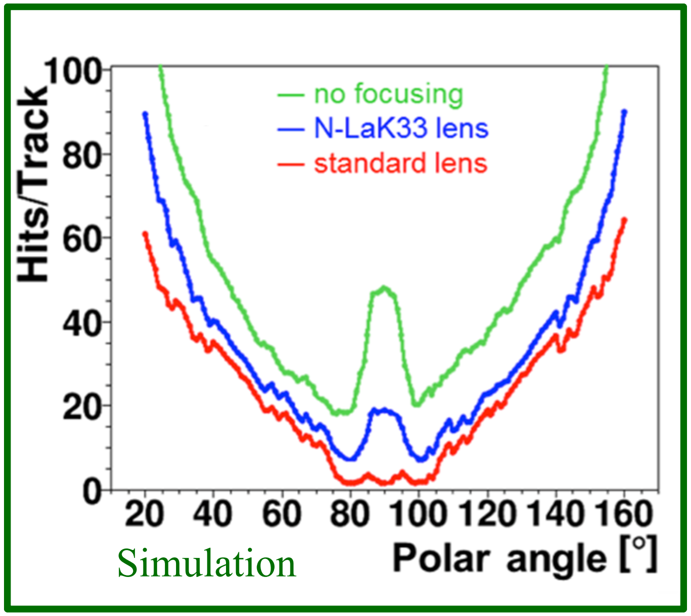


Determined photon yield and single photon Cherenkov angle resolution for different bars and focusing optics over wide angular range.

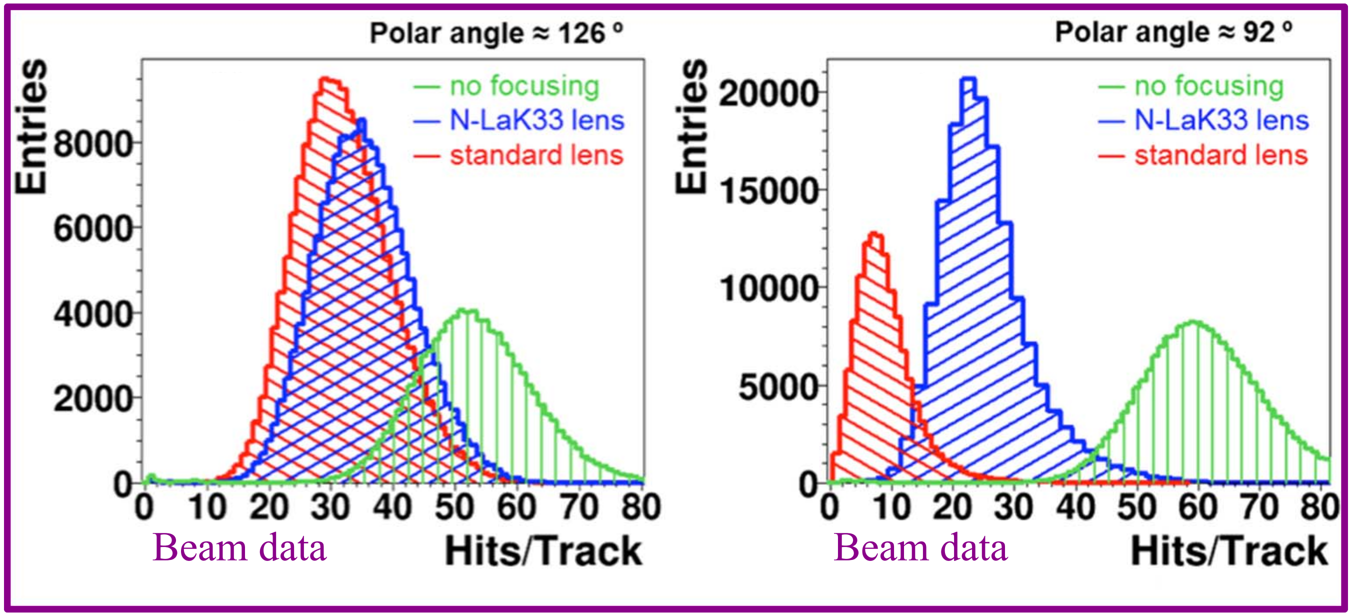


First tests with fused silica prism
and wide plate.

BARREL DIRC BEAM TESTS 2012

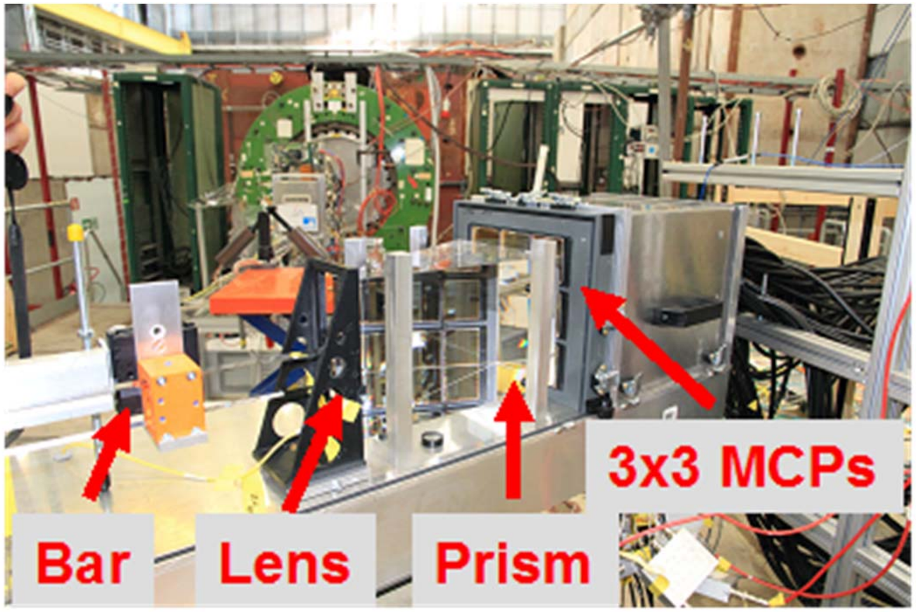


Simulation

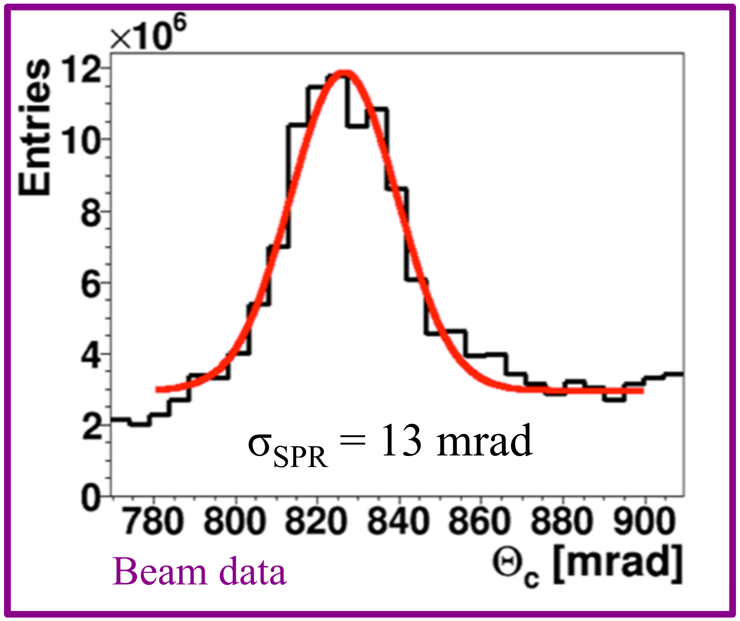


Beam data

Beam data



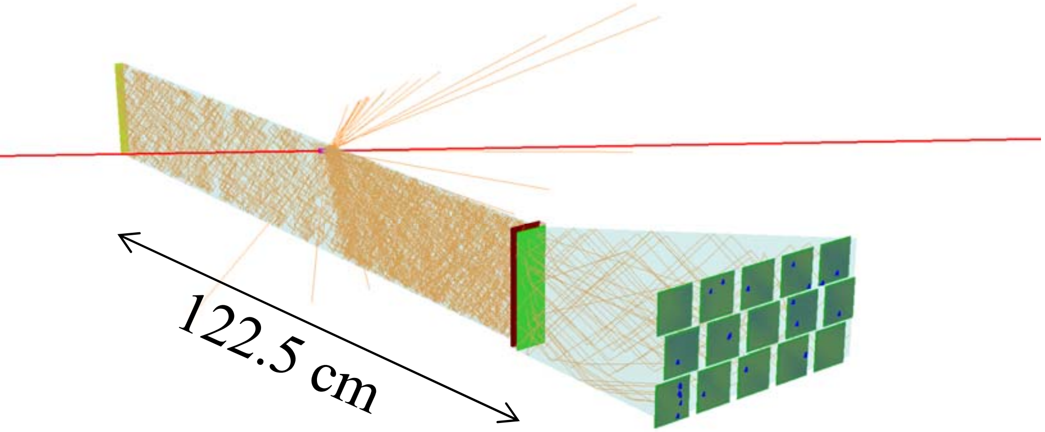
2012

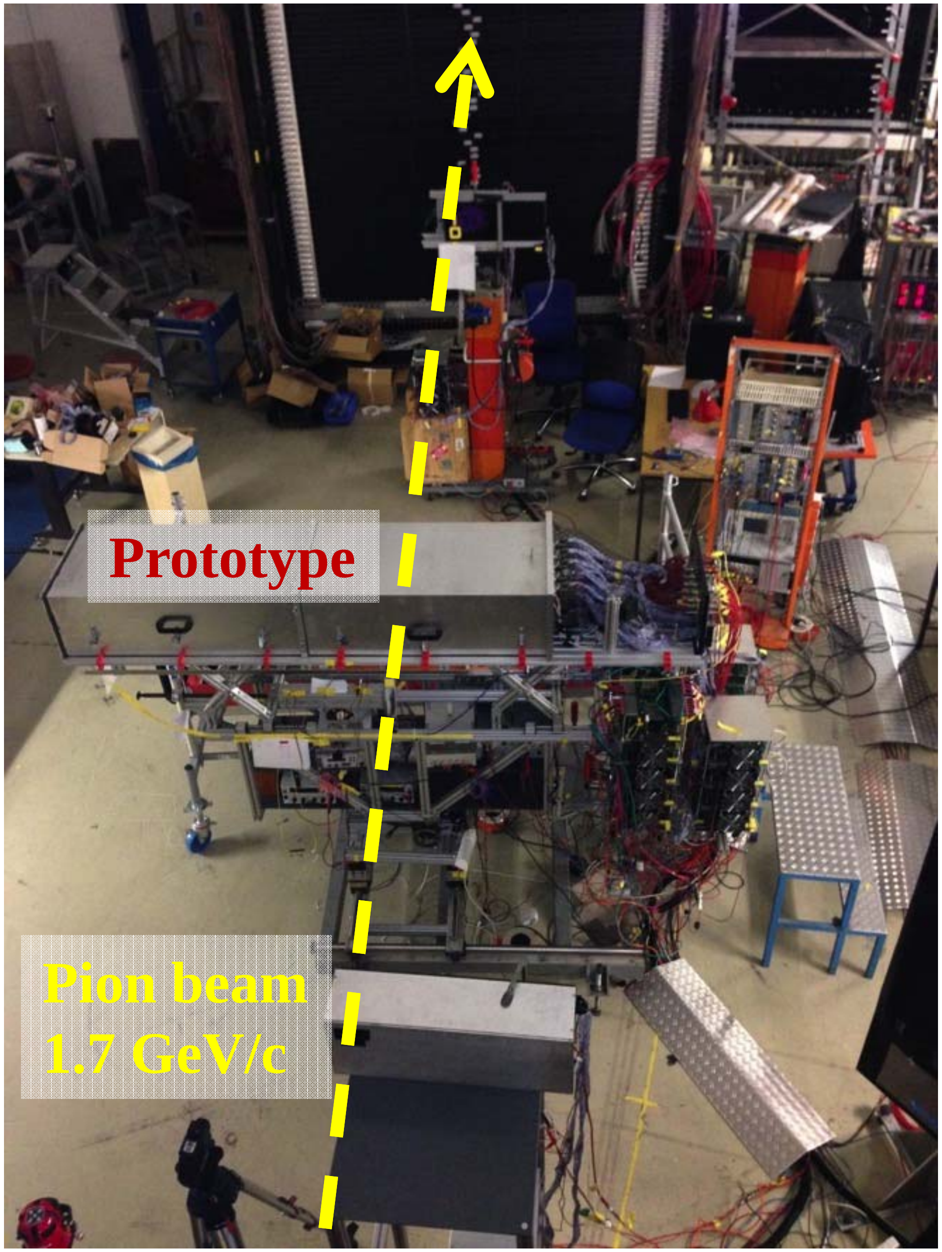


σ_{SPR} = 13 mrad

Beam data

BARREL DIRC BEAM TESTS 2014

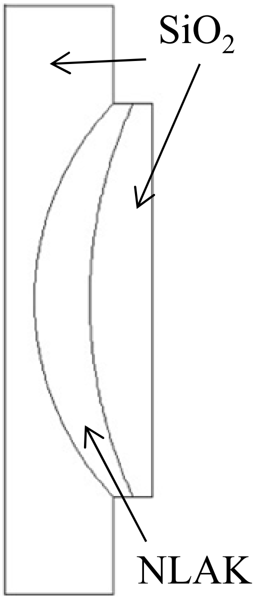


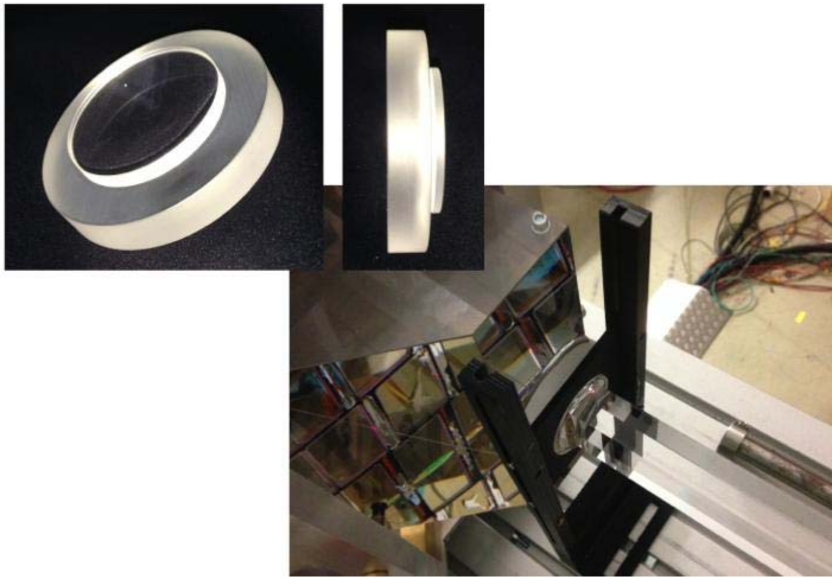


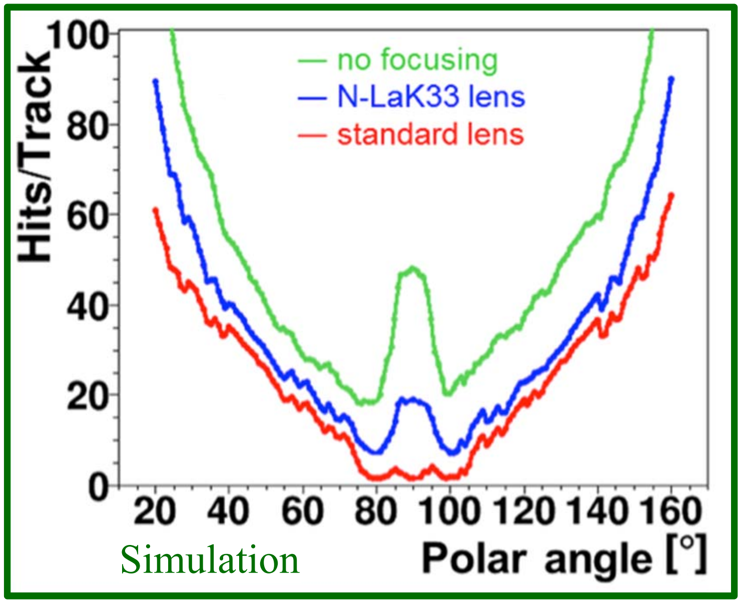
Beam time at GSI; 5 weeks in summer 2014

- 2014 prototype is similar to a module of the final detector
- 5 x 3 array PHOTONIS Planacon MCP-PMT
- 960 pixels (in total >1200 readout channels)
- Wide plate w/ and w/o focusing lens
- Narrow bar with different lenses
- Run ended in September
- Calibration/simulation/analysis ongoing

BARREL DIRC BEAM TESTS 2014







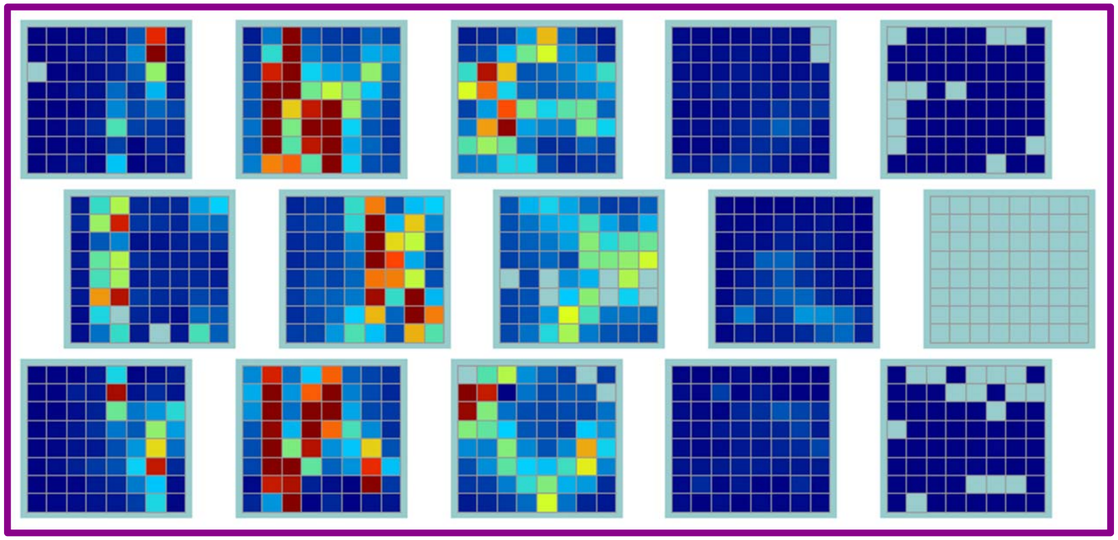
Narrow Bar Data (36mm width)

New 3-component lens with better focusing and no air gap to reduce photon loss (synergy with DIRC@EIC)

No comparison with simulation yet but data show typical folded DIRC “ring” structure.

very preliminary

Beam data, 125 deg:



BARREL DIRC BEAM TESTS 2014

Wide Plate Simulation

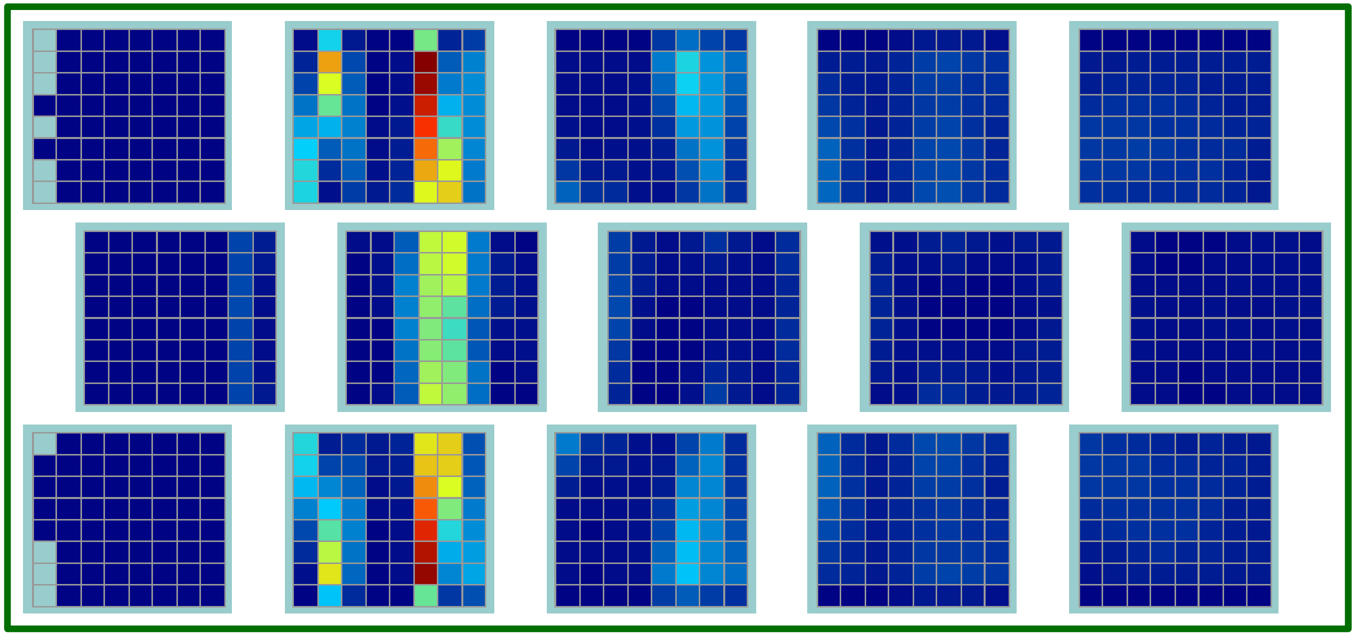
(175mm width)

Geant 4

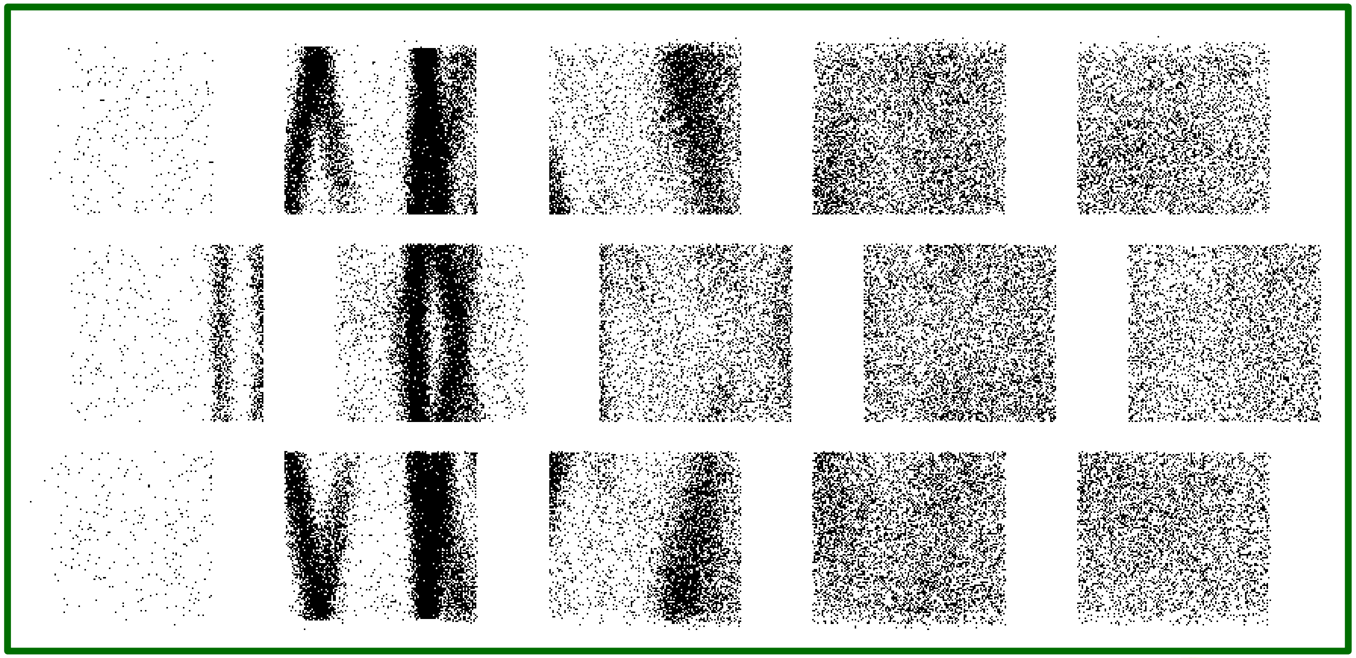
Radiator plate
Cylindrical lens (no air gap)
Prism EV (45° top angle)

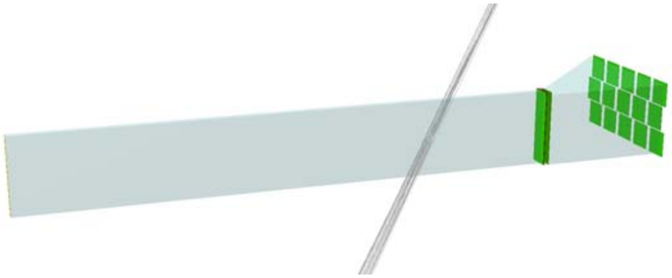
120° polar angle
1.7 GeV/c pions

pixelated:



true locations:





BARREL DIRC BEAM TESTS 2014

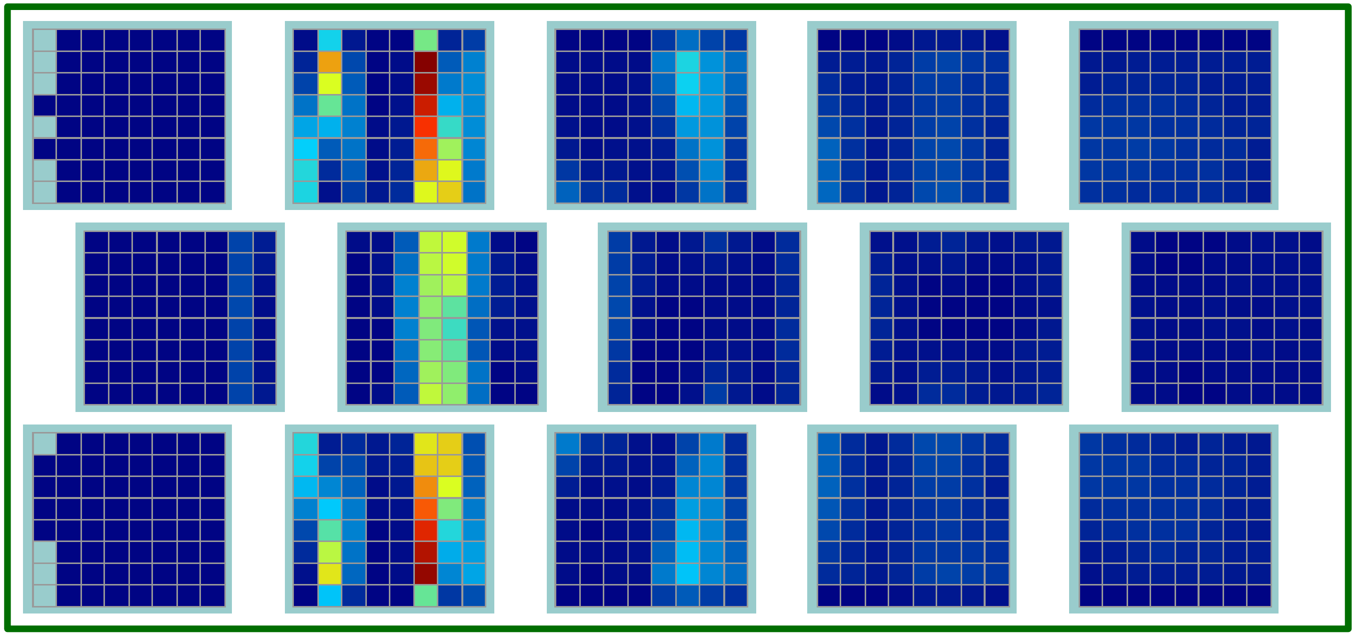
Wide Plate Data:

First glimpse on occupancies with raw cuts on timing and event multiplicity

Simulation predicts ~20 hits/track

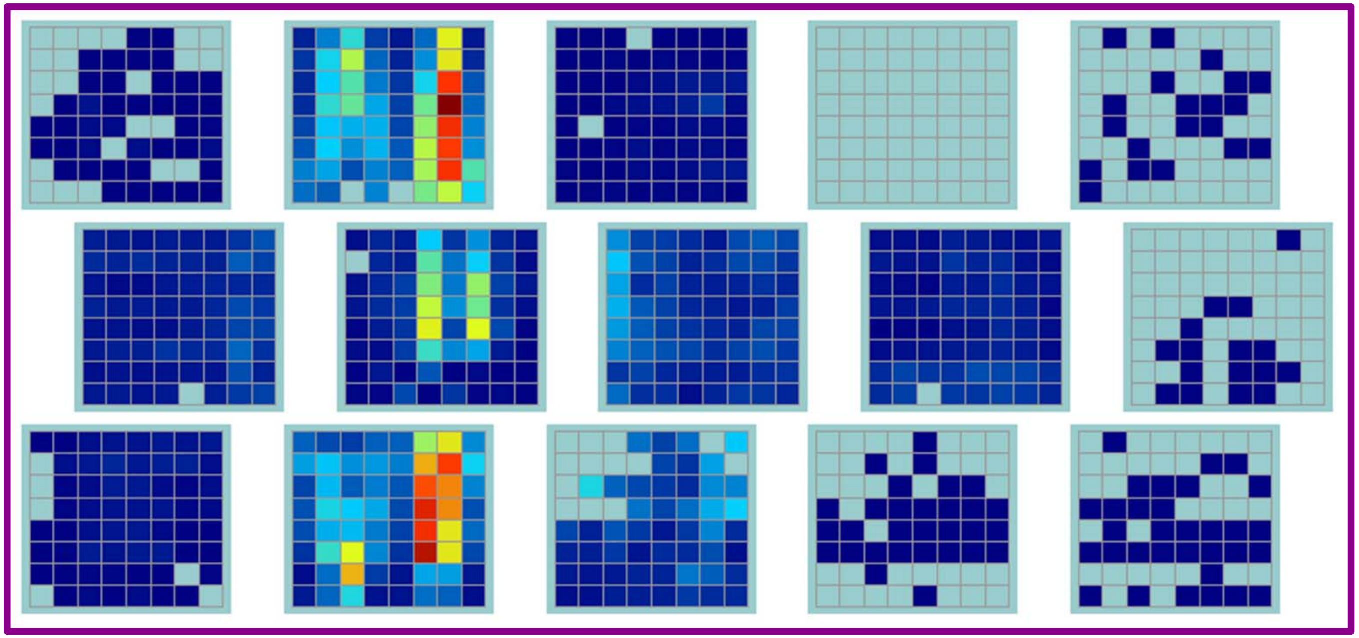
No results yet, stay tuned.

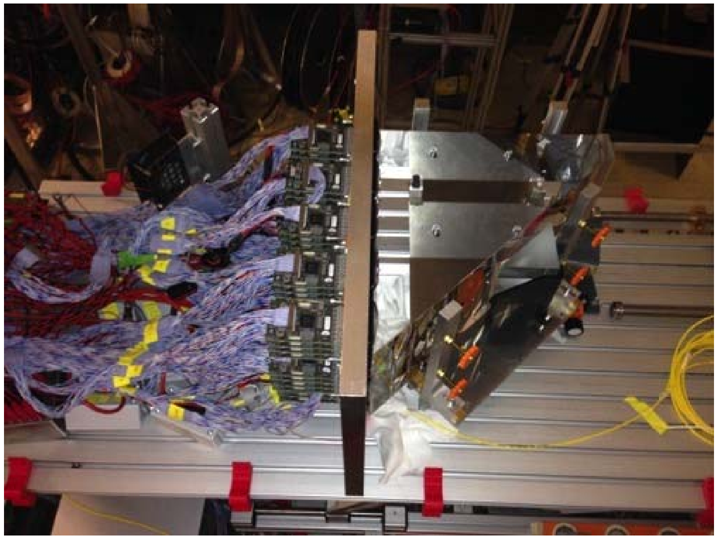
Simulation:



very preliminary

Beam data:





PANDA BARREL DIRC

Our core mission as DIRC group and PANDA detectors department is
the design, construction, and operation of the PANDA Barrel DIRC counter.

We are nearing completion of the R&D phase, need successful test beam campaign at CERN PS/T9 this year (May, June/July) to make final decisions:

- narrow bars or wide plates (cost savings)?
- monolithic "oil tank" or fused silica prisms (improved operations)?

Next milestone after test beam: submit TDR by mid-2016.

PANDA Barrel DIRC is our immediate future – what about the long-term strategy?

Our DIRC expertise is interesting to other labs and experiments, started cooperation with Jefferson Lab in 2011

- Participating in DOE grant for R&D on DIRC counter for Electron Ion Collider detector.
- Now starting to explore possible cooperation on GlueX DIRC.

DIRC-based PID for the EIC

— Progress Report and Renewal Proposal

T. Cao[1], R. Dzhygadlo[2], T. Horn[3], C. Hyde[4], Y. Ilieva[1], G. Kalicy[4],
P. Nadel-Turonski[5,*], K. Park[4], K. Peters[2], C. Schwarz[2], J. Schwiening[2],
W. Xi[5], N. Zachariou[1], C. Zorn[5].

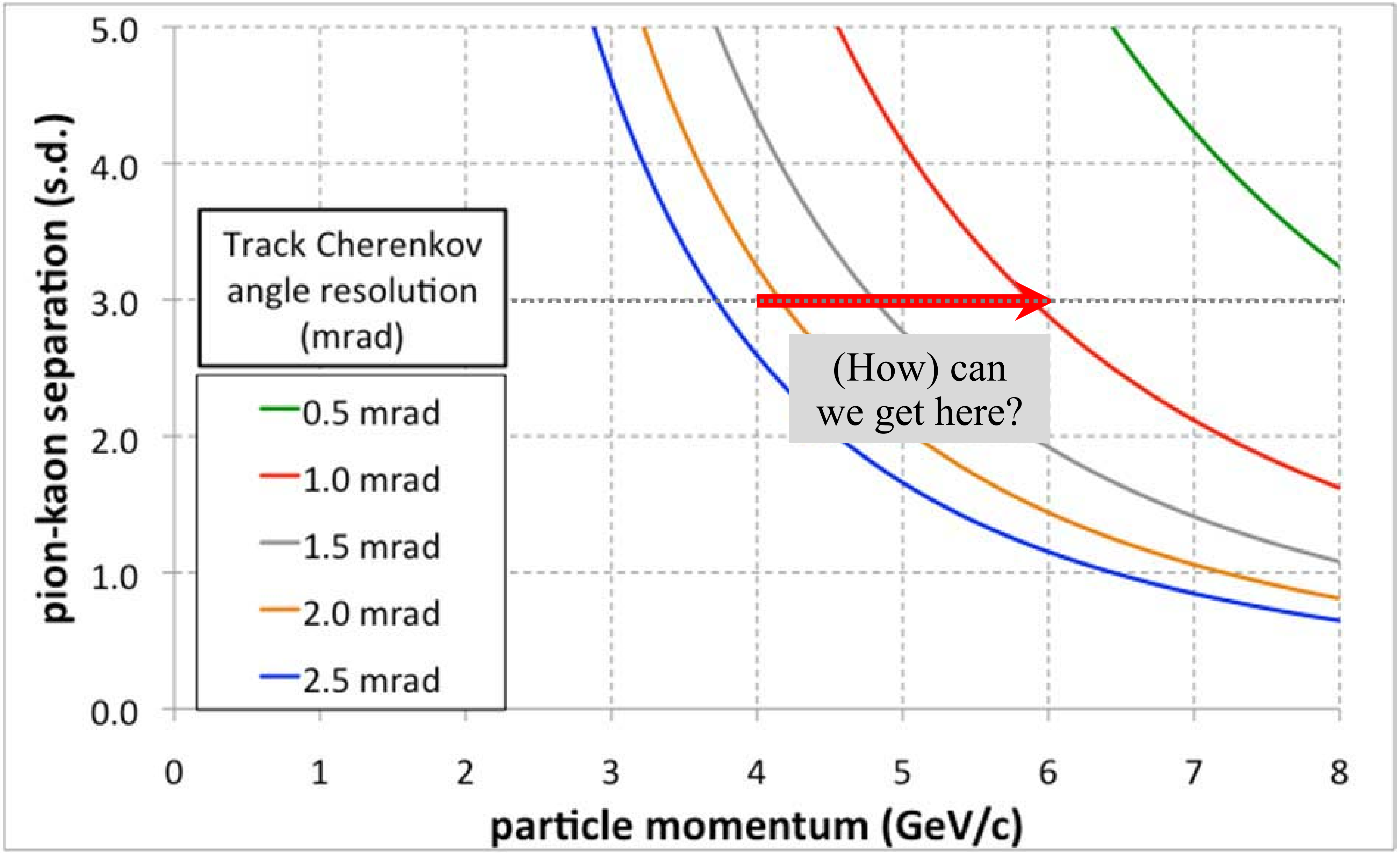
1) University of South Carolina, Columbia, SC 29208
2) GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
3) The Catholic University of America, Washington, DC 20064
4) Old Dominion University, Norfolk, VA 23529
5) Jefferson Lab, Newport News, VA 23606

Generic Detector R&D for an Electron Ion Collider.

DOE Funding since 2011.

Thanks for the material provided for this talk.

DIRC@EIC R&D GOAL



(How) can we get here?

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

DIRC@EIC R&D ROADMAP

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

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

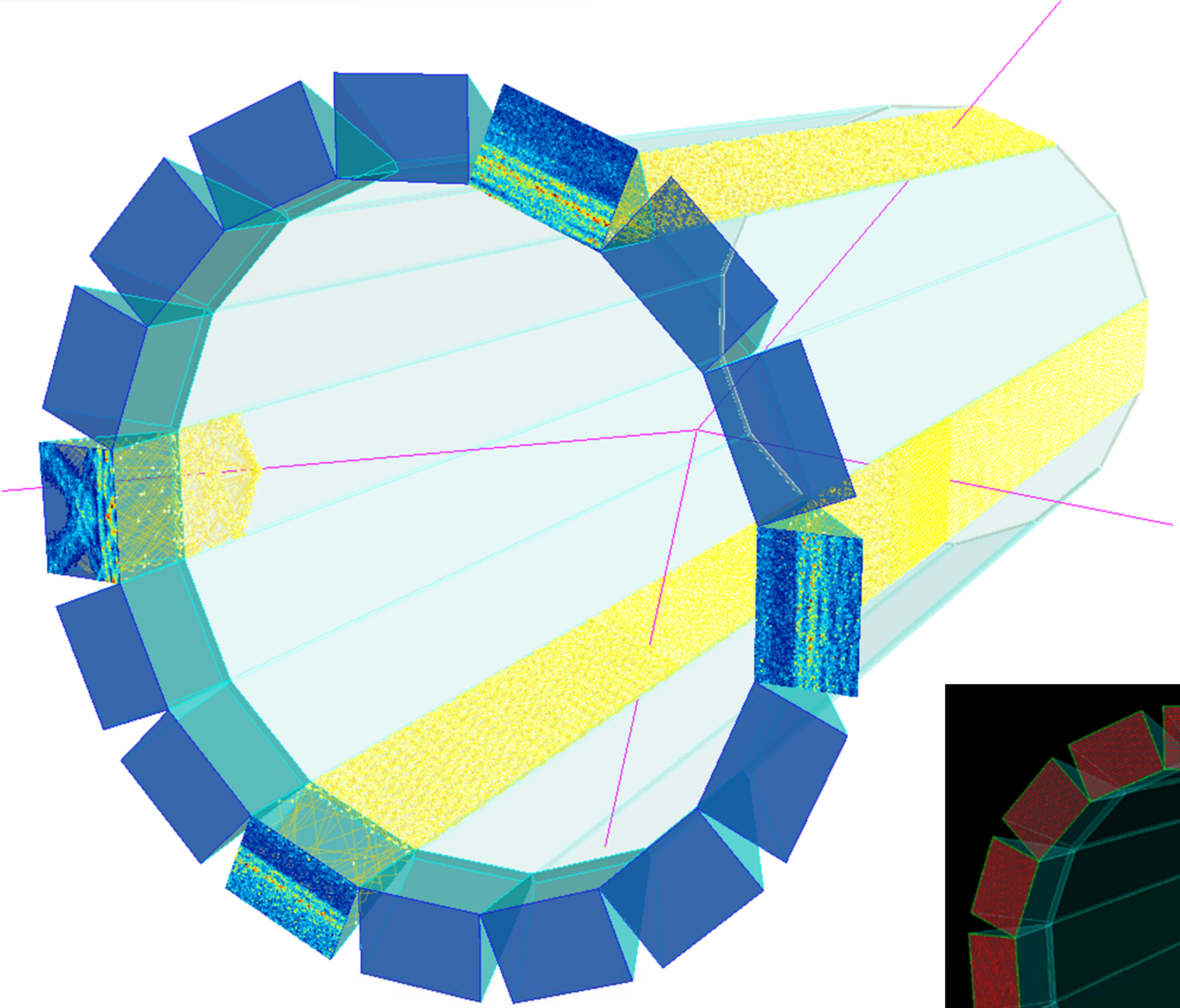
- Compact readout “camera” (focusing + expansion volume (EV) + sensors)
  - simulations, lens and EV design, prototyping, test beams
- Operation in high magnetic fields (up to 3 T)
  - sensor tests up to 5T

Our current R&D focus.

3. Study integration of the DIRC with other detector systems

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

DIRC@EIC R&D ROADMAP

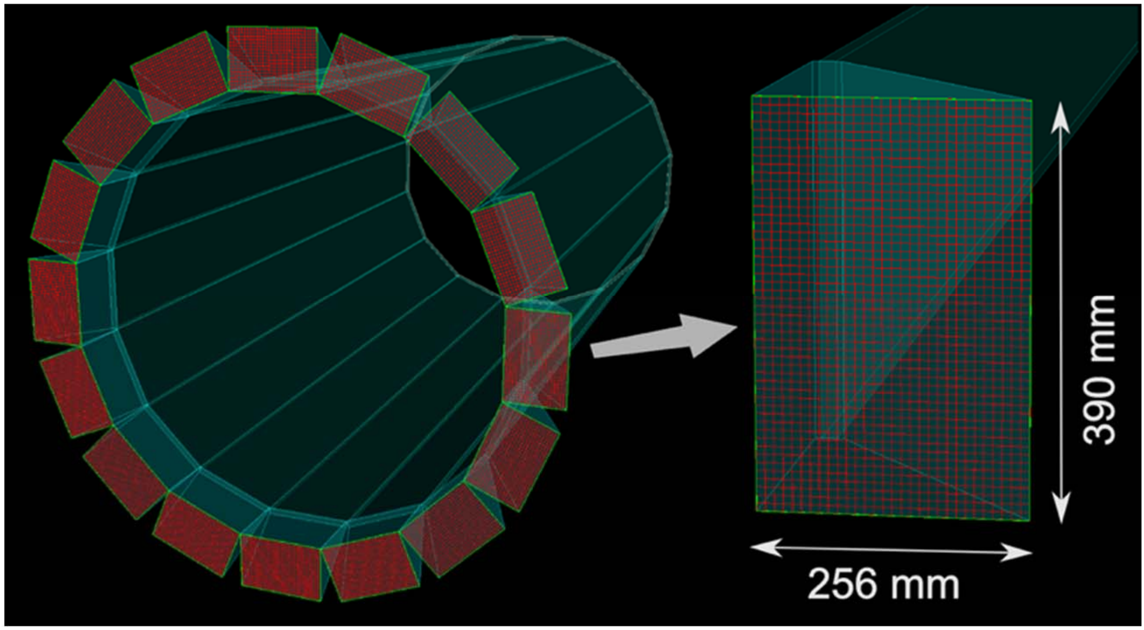


Geant4

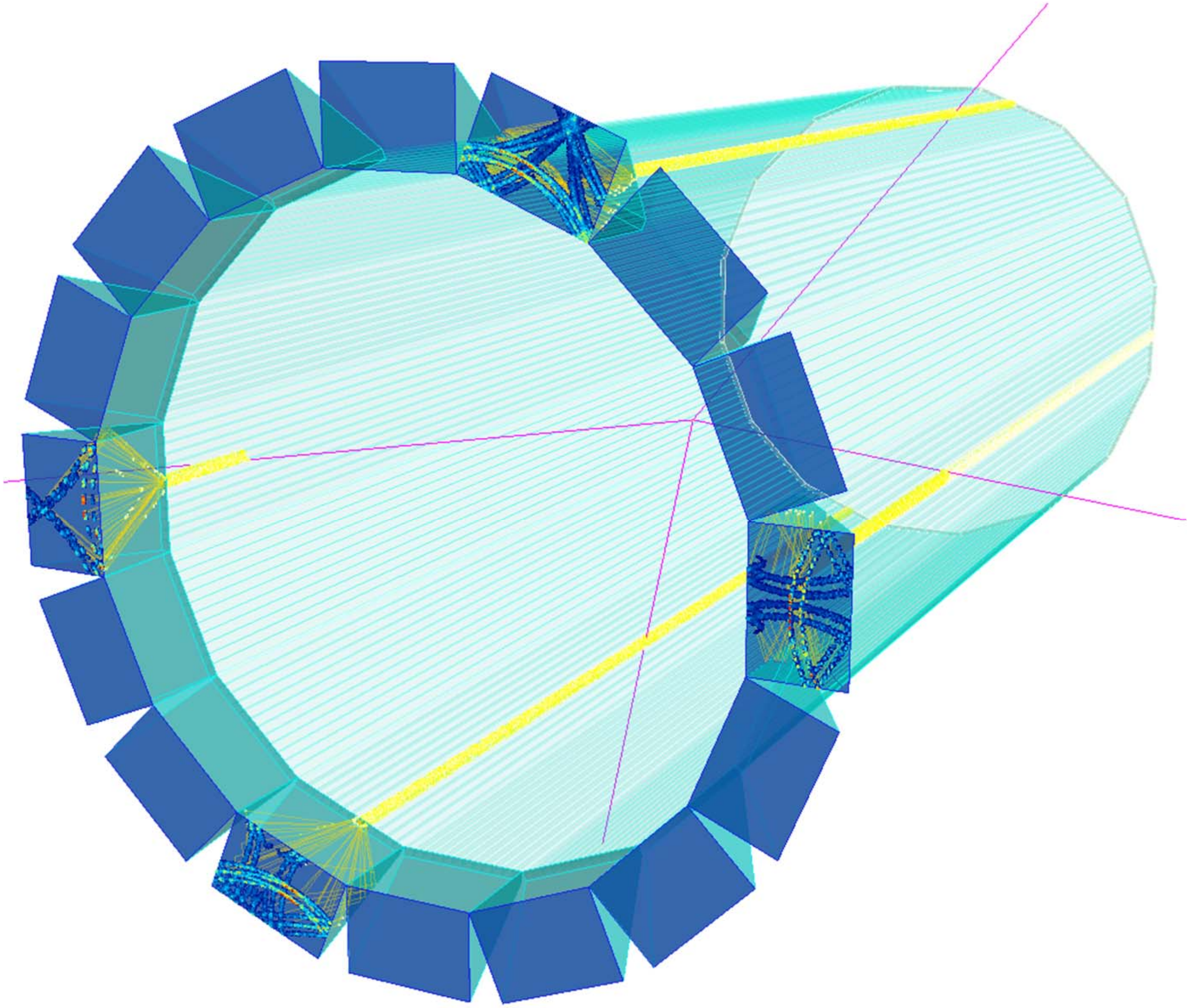
Wide plate geometry

Size of EV/prism readout end:
256mm x 390mm

Simulation w/o B field: straight tracks, symmetric patterns.



DIRC@EIC R&D ROADMAP

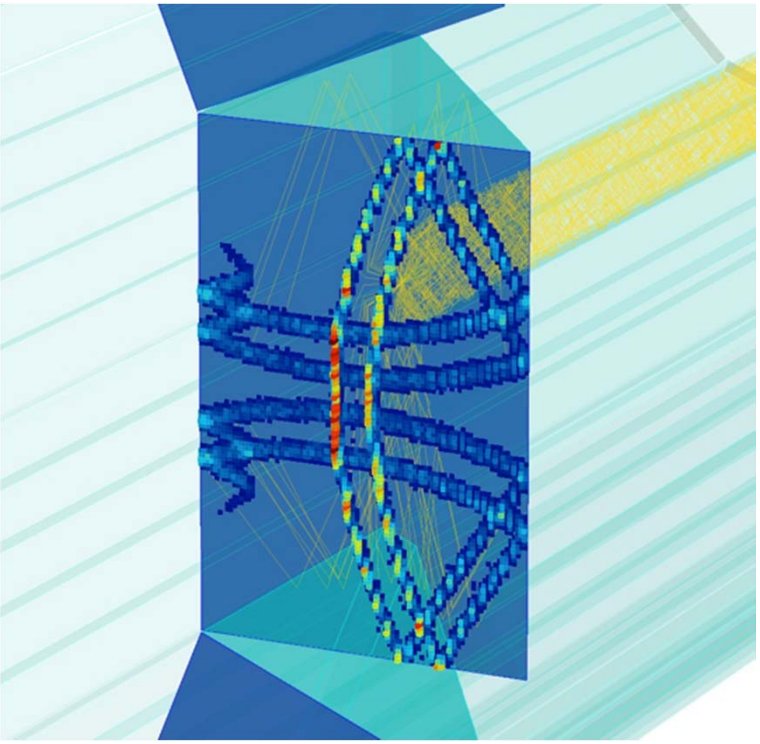


Geant4

Narrow bar geometry

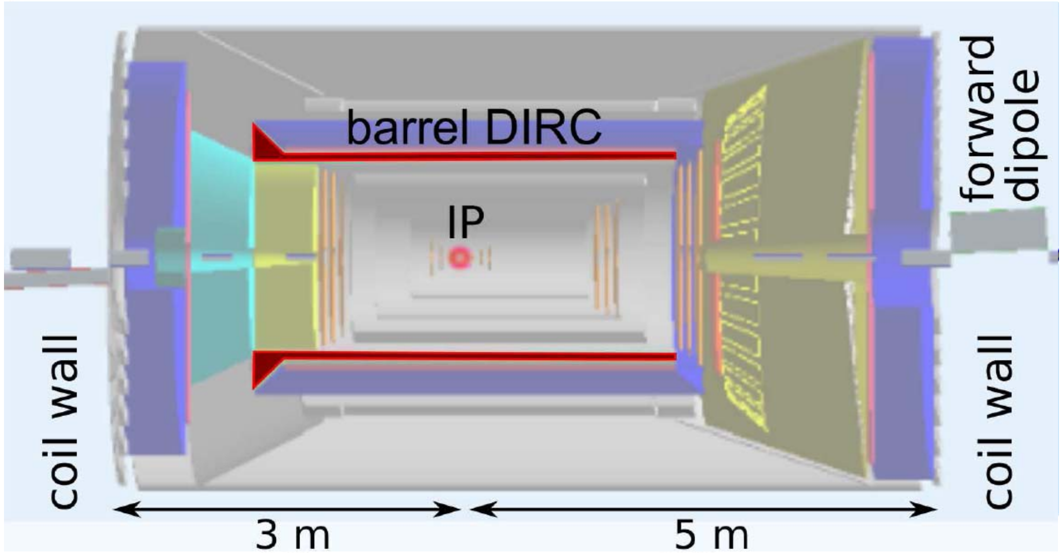
Spherical lens w/o air gap.

(Remember: synergy with
PANDA Barrel DIRC R&D)



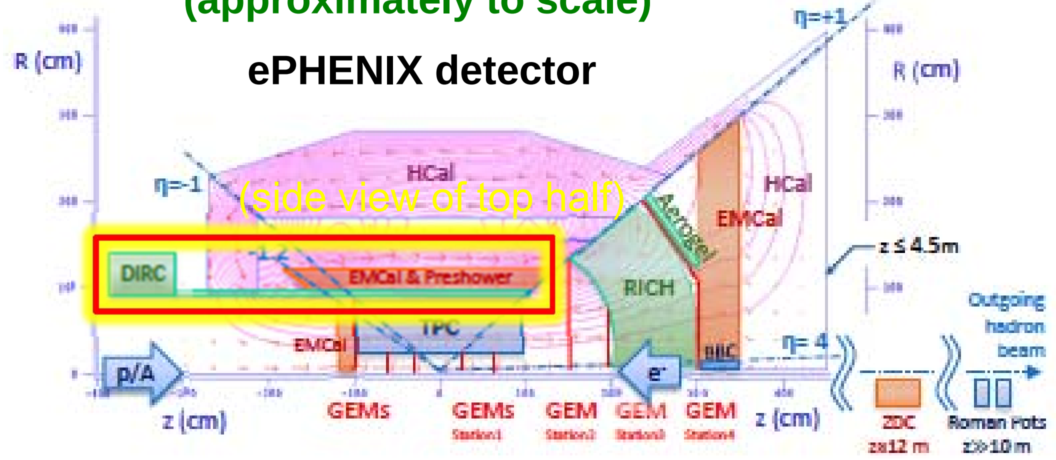
Integration with EIC detector concepts

MEIC IP1 detector



(approximately to scale)

ePHENIX detector

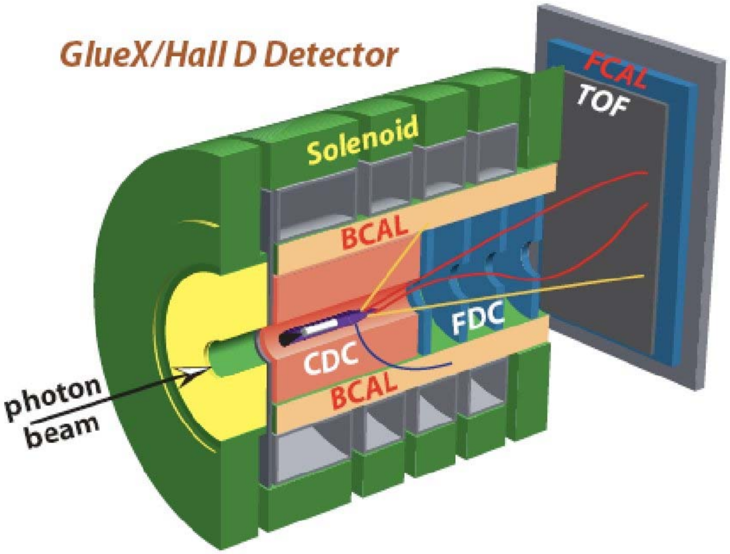


- The central detector concepts developed at JLab and BNL, exemplified by MEIC IP1 and ePHENIX, both offer plenty of space for the DIRC readout.
  - **Sensors easily accessible!**
- Internal vs external "camera"
  - Placement of sensors outside of the field is possible, but requires long bars (plates)
  - 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.

GLUEX DIRC

Hall D experiment at Jefferson Lab (new hall for 12 GeV upgrade), first data recorded in 2014.

Goal: upgrade to improve hadronic particle identification for forward angles (pion vs. kaons)

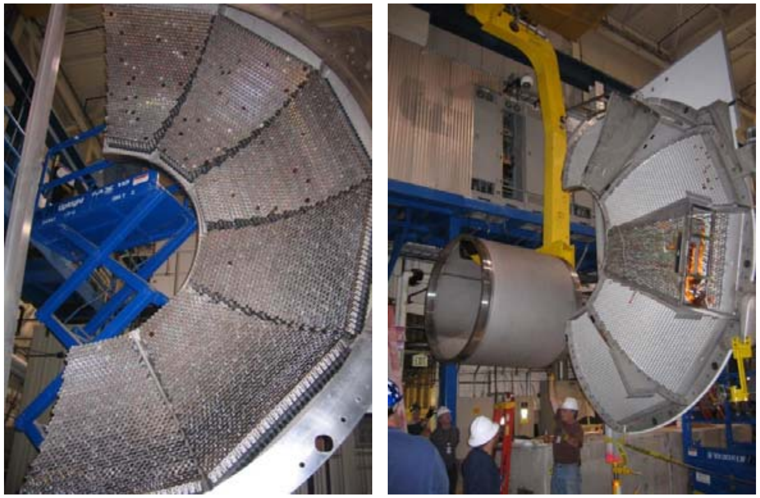


GLUEX DIRC

Similar momentum region as BABAR, which ended data taking in 2008 and removed the DIRC components in 2011.

BABAR DIRC bar boxes in storage, available *(PANDA applied to call for proposals, no luck...)*

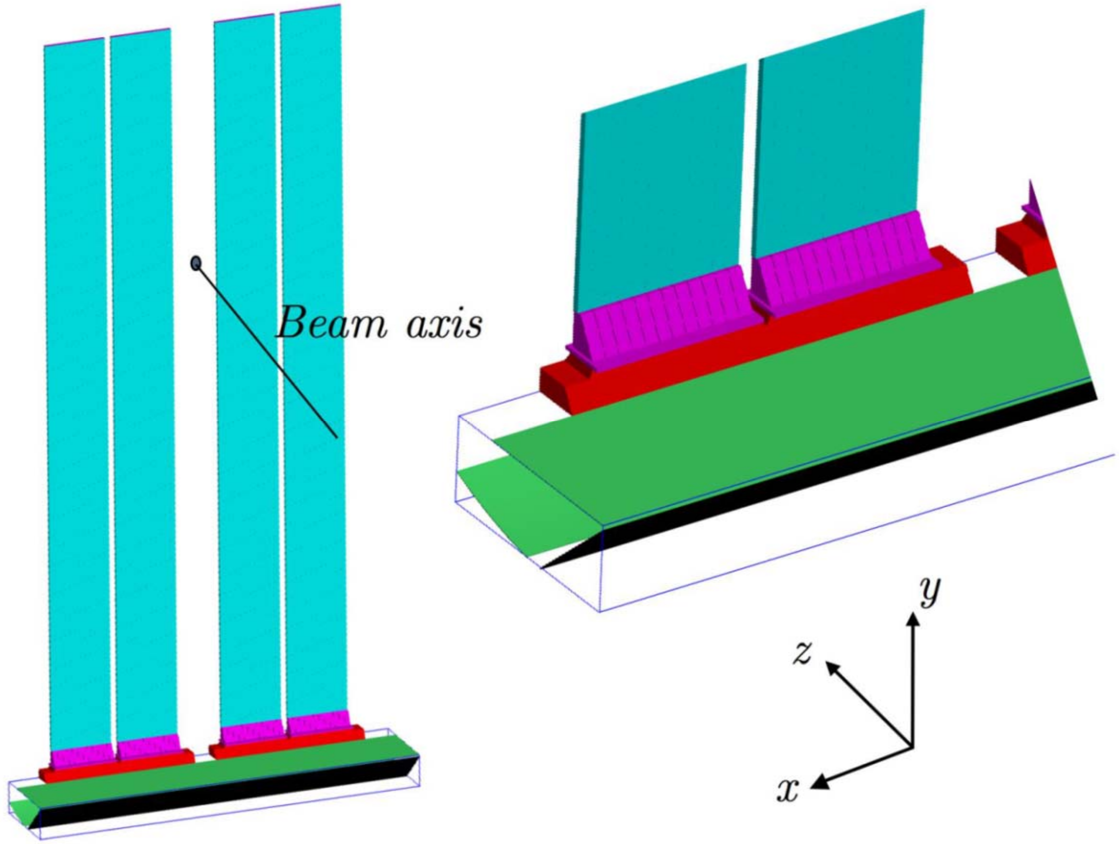

All 12 BABAR DIRC bar boxes in storage at SLAC

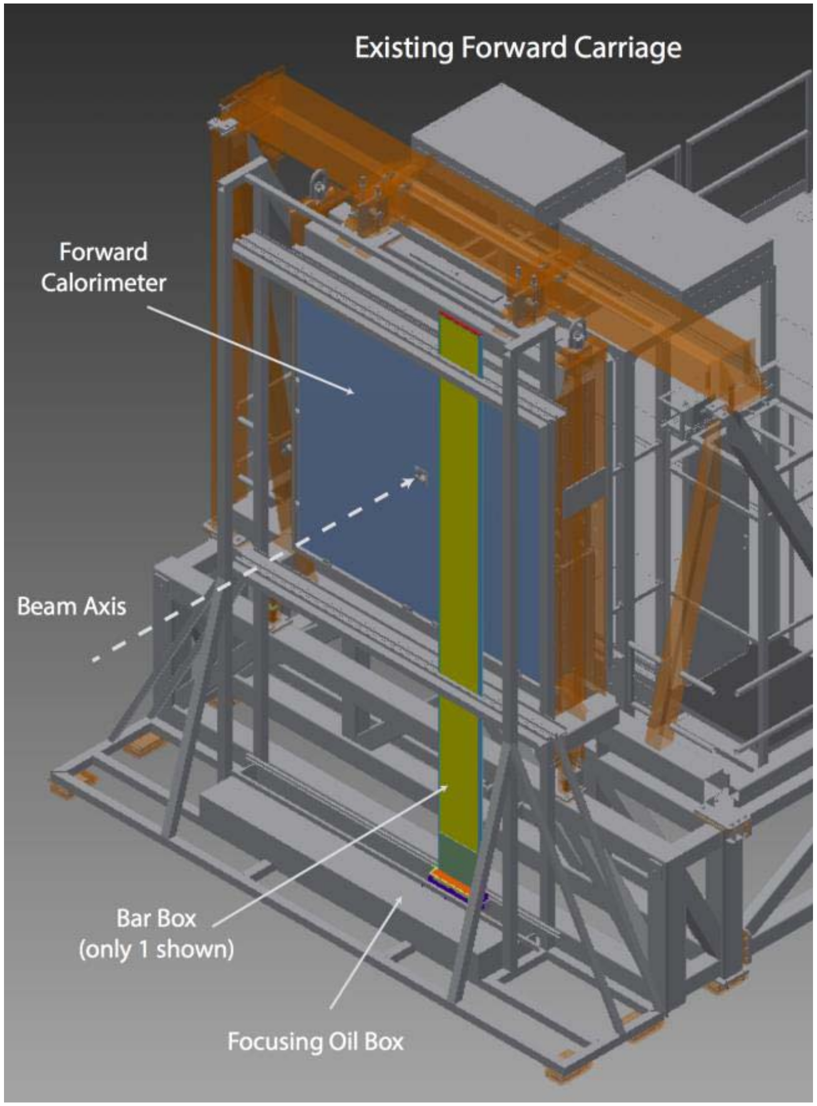

Disassembly of BABAR DIRC at SLAC

GLUEX DIRC

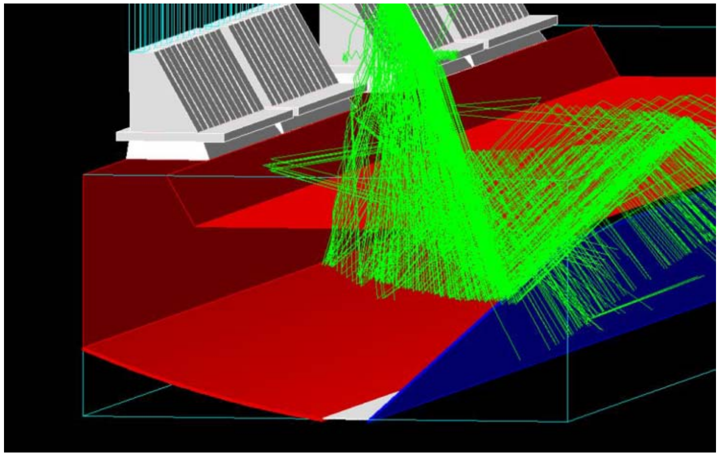
In 2014 GlueX received DOE approval to obtain 4 bar boxes from BABAR DIRC.

Plan: place BABAR DIRC bar boxes
in front of forward calorimeter.
Also considering horizontal placement option
to reduce stress on old glue joints.





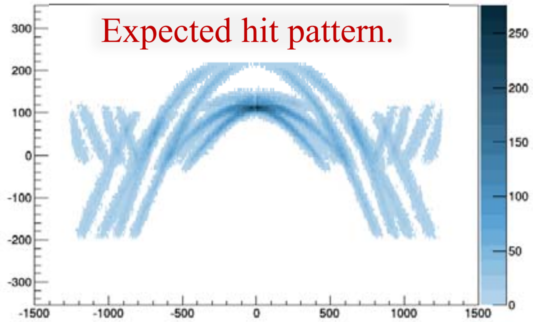
GLUEX DIRC



Keep bar boxes unchanged but build new
expansion volume and optics (based on fDIRC).

Interesting challenge:
- How to transport 4 fragile 15+ year old bar boxes from SLAC to JLab (and one more to CERN)

Developing prototype optics, software,
transport container... short timescale – busy times.


Expected hit pattern.

Why do we care?

Possible future cooperation between GSI and JLab,
PANDA/CLAS12/GlueX, MoU in preparation.

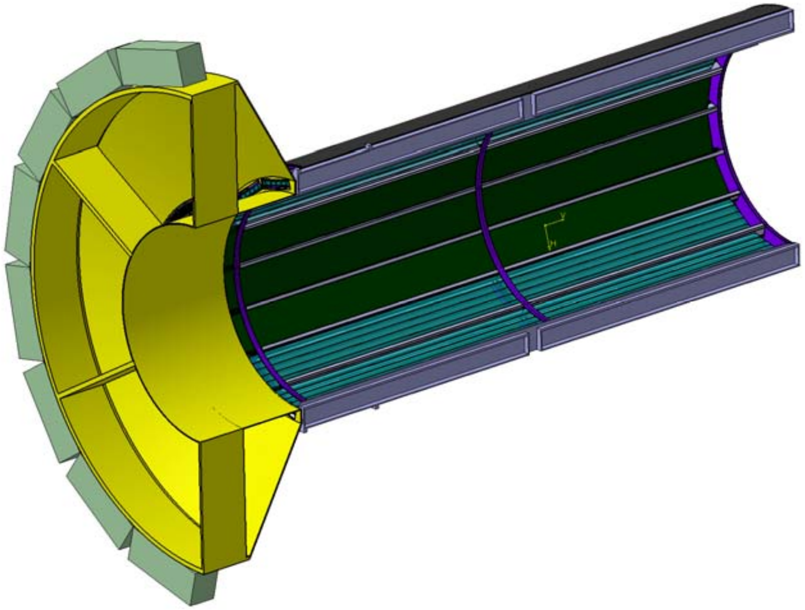
Will explore potential synergies and possible future contributions from GSI group
to GlueX DIRC (simulation, reconstruction) at JLab meeting later this month.

SUMMARY

DIRC counters have emerged as a prime candidate for hadronic PID for Belle II, PANDA, GlueX, TORCH.

The PANDA Barrel DIRC design evolved from scaled-down BABAR DIRC to a compact fast focusing DIRC.

Baseline design with narrow bars and high-n lens system appears to meet PANDA PID goals.



Recent lifetime advances make MCP-PMTs an excellent sensor choice.

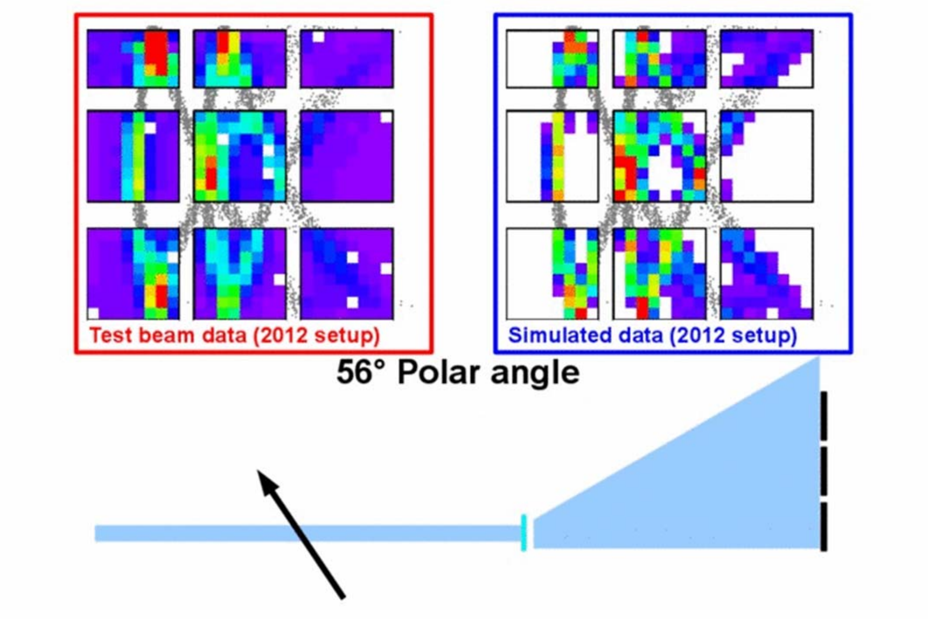
Ongoing prototype program to identify multiple potential vendors for radiator fabrication.

Decision on wide radiator plates and on solid fused silica prisms as Cherenkov cameras due 2015.

Leading edge technologies, benefit from delayed technology decision
→ system still in R&D phase, Technical Design Report planned for mid-2016.

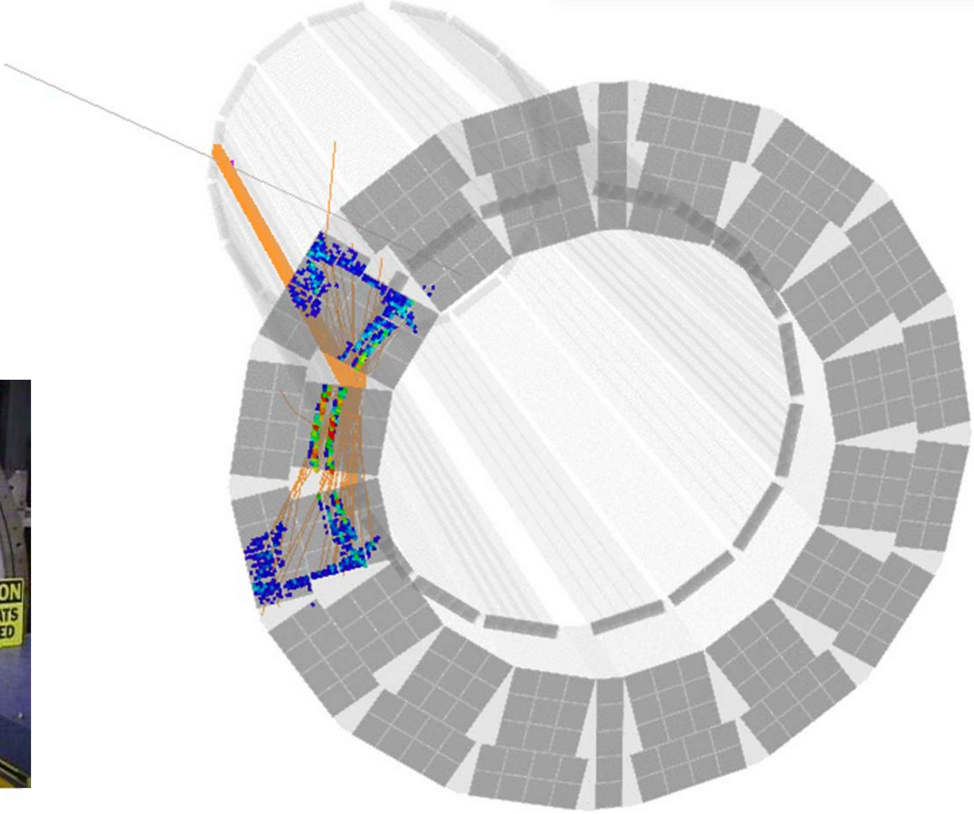
GSI DIRC group expertise in demand for future DIRC R&D projects and detectors.

THANK YOU



Hit patterns for 2012 prototype with narrow bars and fused silica prism for different polar angles.

Geant simulation of hit pattern for narrow bars and oil tank geometry for different polar angles.



Blair Ratcliff, BABAR DIRC.