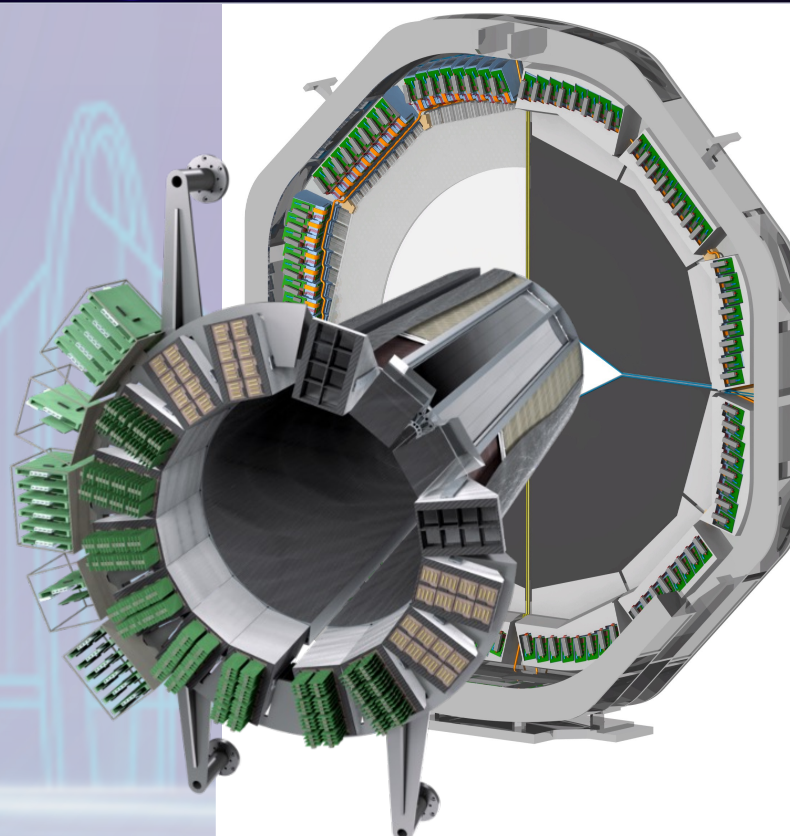
The PANDA DIRC Detectors



The 6th International Workshop on Future Tau Charm Facilities

FTCF, 2024, Guangzhou

November 17th to 21st, 2024

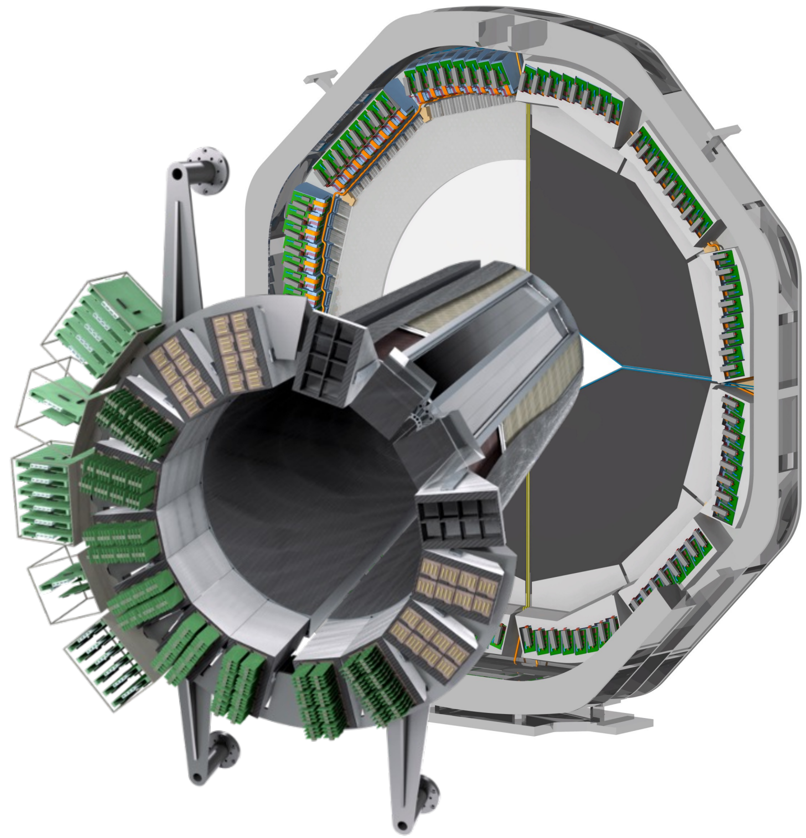
Georg Schepers (GSI)

for the PANDA Cherenkov Group

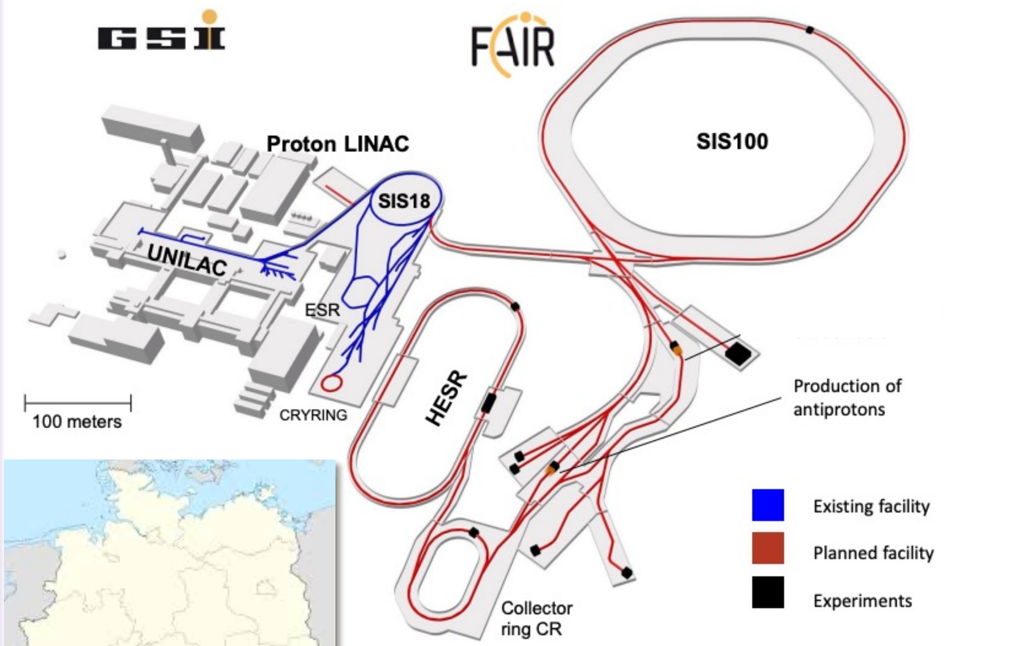
FAU Friedrich-Alexander Universität Erlangen-Nürnberg · Justus-Liebig-Universität Giessen · Goethe Universität Frankfurt am Main · GSI · HIM Helmholtz Helmholtz-Institut Mainz · JGU Johannes Gutenberg Universität Mainz · FAIR

OUTLINE

- PANDA experiment at FAIR
- DIRC concept
- Barrel DIRC Design
- Endcap Disc DIRC Design
- Expected performance
- Validation in beam tests
- Component production and assembly



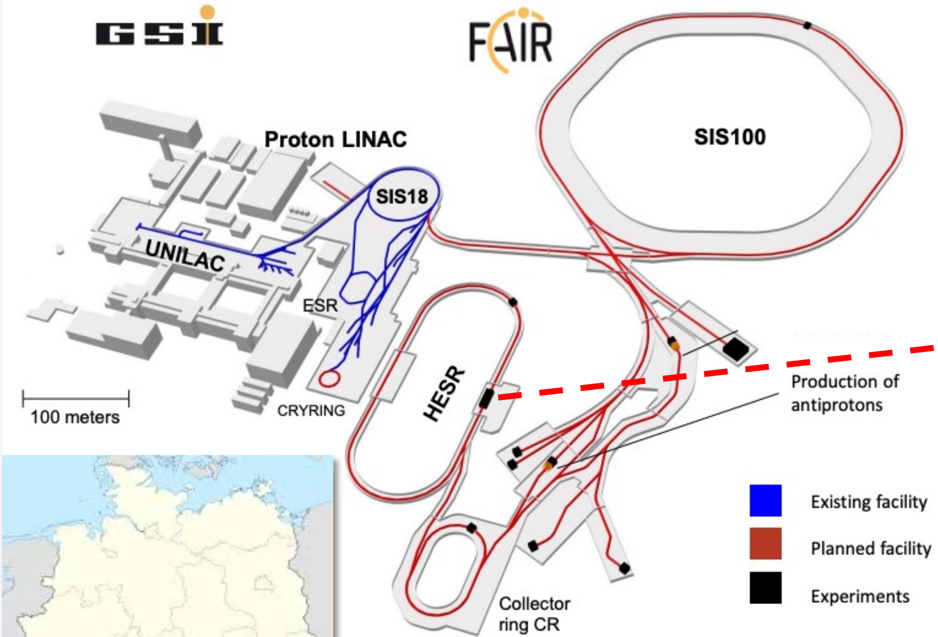
PANDA at FAIR (Facility for Antiproton and Ion Research)



Darmstadt, Germany

- New international lab near GSI
- Particle beams from
  (anti-)protons up to uranium ions
- Unique beam intensity & quality

PANDA at FAIR (Facility for Antiproton and Ion Research)



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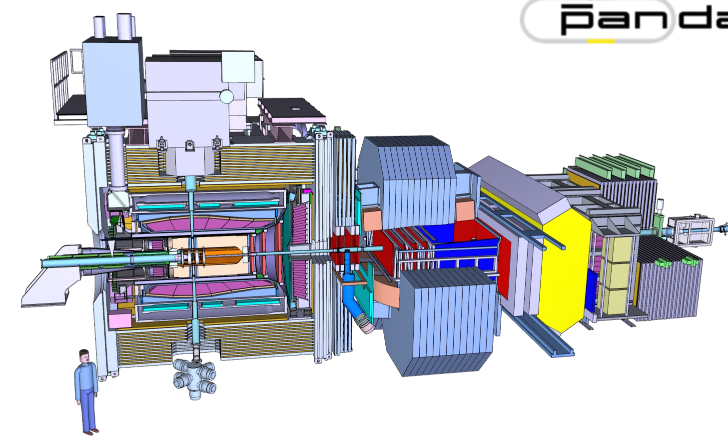
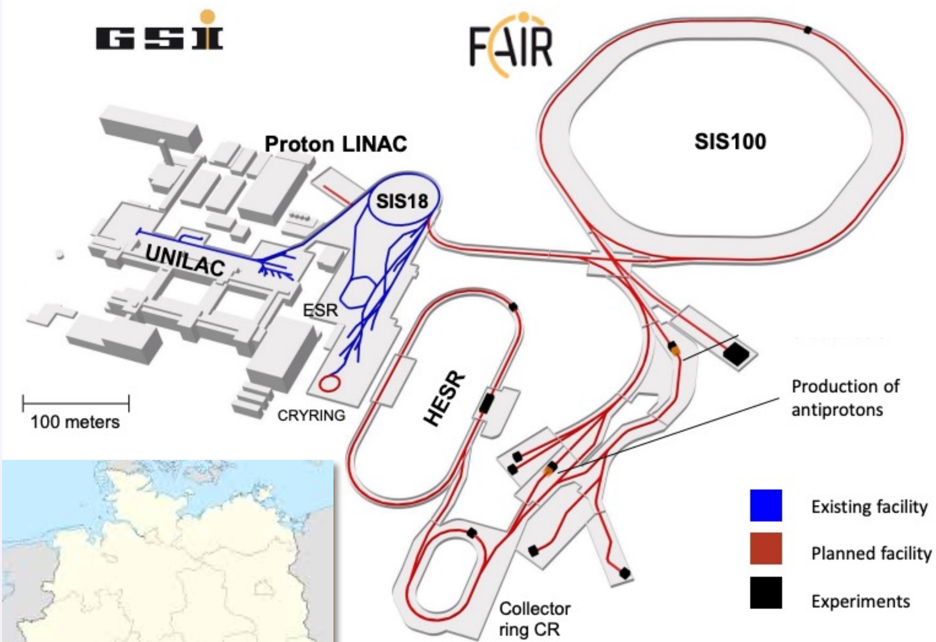


- $\bar{p}$ - Collection in CR, fast cooling
- Accumulation in HESR (High Energy Storage Ring)
- PANDA luminosity ≤ $2x10^{31}cm^{-2}s^{-1}$
- $\bar{p}$ momentum: 1.5 – 15 GeV/c
- Fixed target: cluster jet/pellet

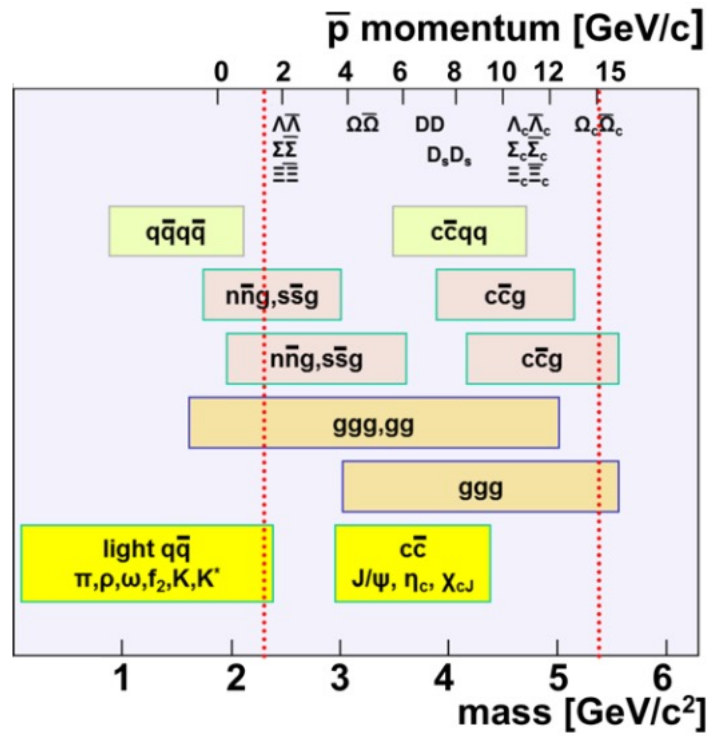
PANDA at FAIR (Facility for Antiproton and Ion Research)



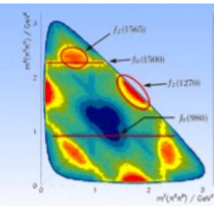
Darmstadt, Germany

- New international lab near GSI
- Particle beams from (anti-)protons up to uranium ions
- Unique beam intensity & quality

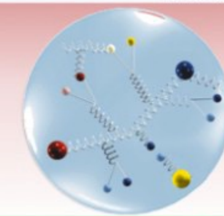
- Work in progress
- Construction of buildings and tunnels
- Introduction of magnets into the tunnel of the SIS100



Hadron Spectroscopy
- Charmonium / Charmed hadrons
- Exotic QCD states
- Spectroscopy



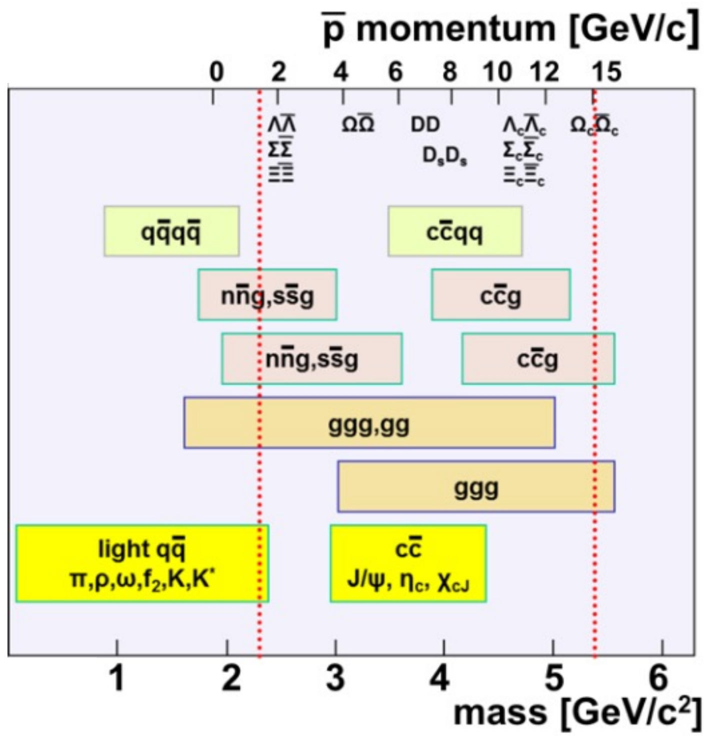
Hadron Structure
- Time-like Nucleon Form Factors
- Generalized Parton Distributions
- Drell-Yan Process

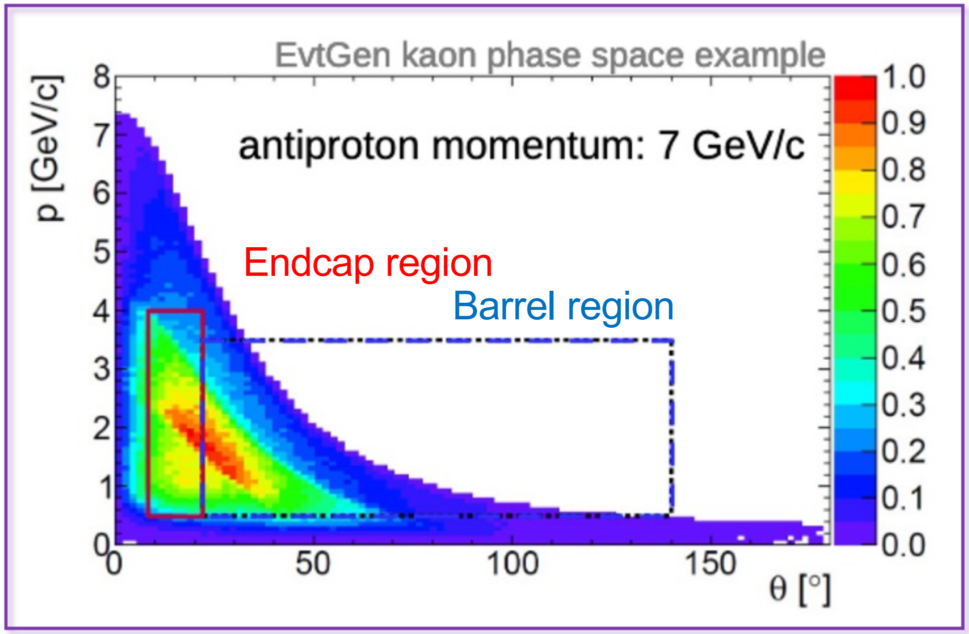


Nuclear Physics
- Production of Λ-Hypernuclei
- Hadrons in Nuclear Medium

- Excellent particle identification required for PANDA physics program
- High interaction rate plus π/K separation for momenta up to 3-4 GeV/c
- Very compact detector design → excellent case for DIRC counters

PANDA: Antiproton annihilation @ HESR





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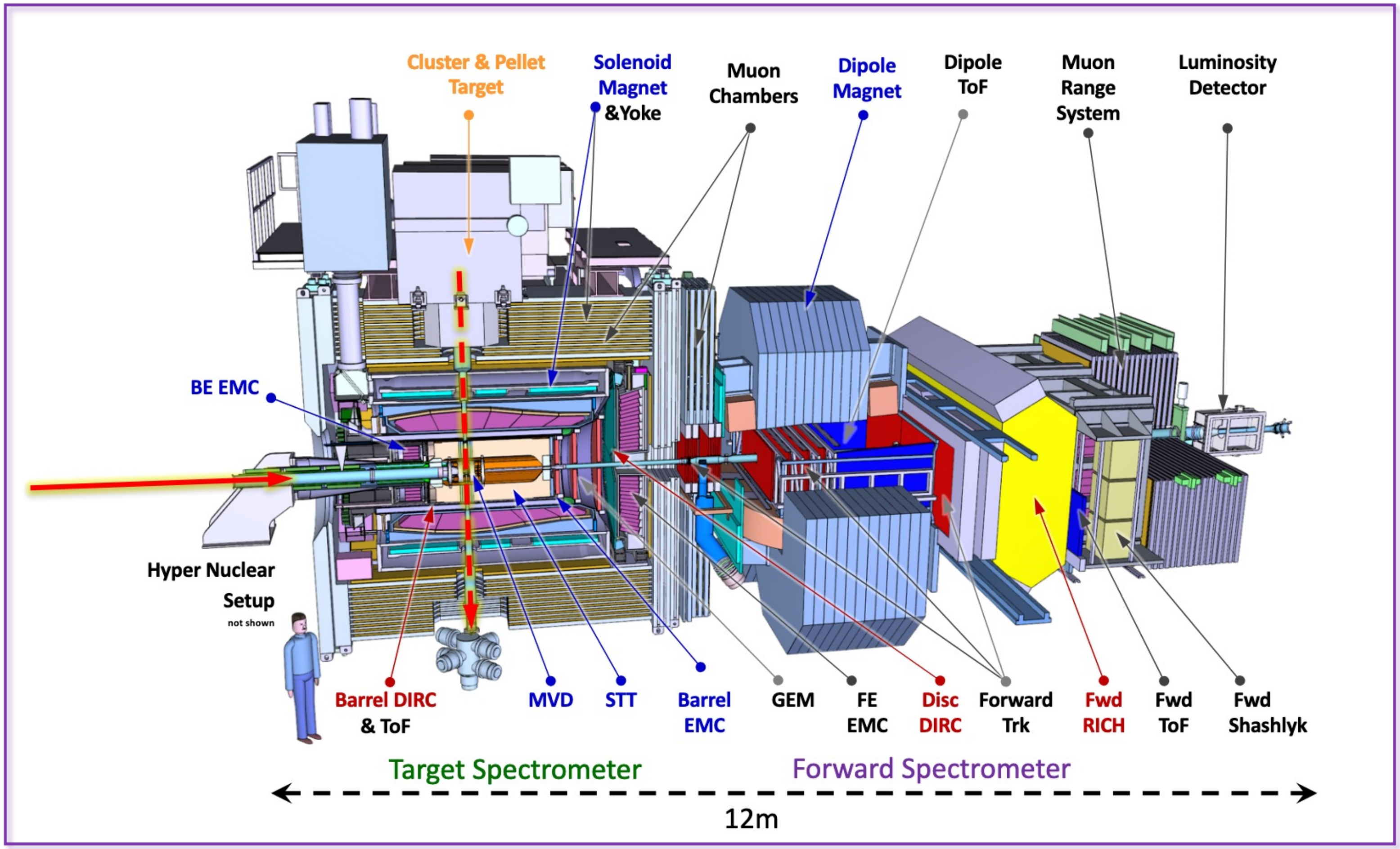
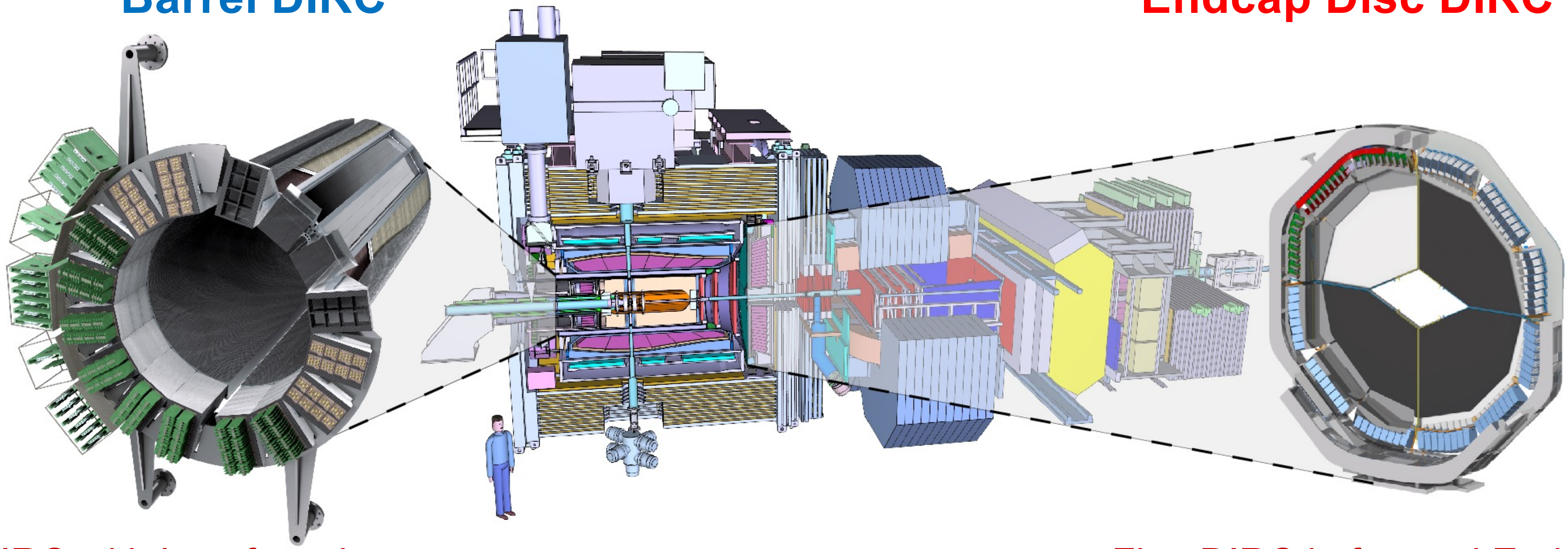
PANDA Detector Layout



Particle ID: PANDA DIRCs

Barrel DIRC

Endcap Disc DIRC



First DIRC with lens focusing

Innovative 3-layer spherical lens

Goal:

3σ π/K separation up to 3.5 GeV/c

for polar angle range 22º-140º

- High interaction rates, up to 20 MHz
- High magnetic field, up to 1 Tesla

Lifetime-enhanced MCP-PMTs

First DIRC in forward Endcap

Small pixels in one direction

Goal:

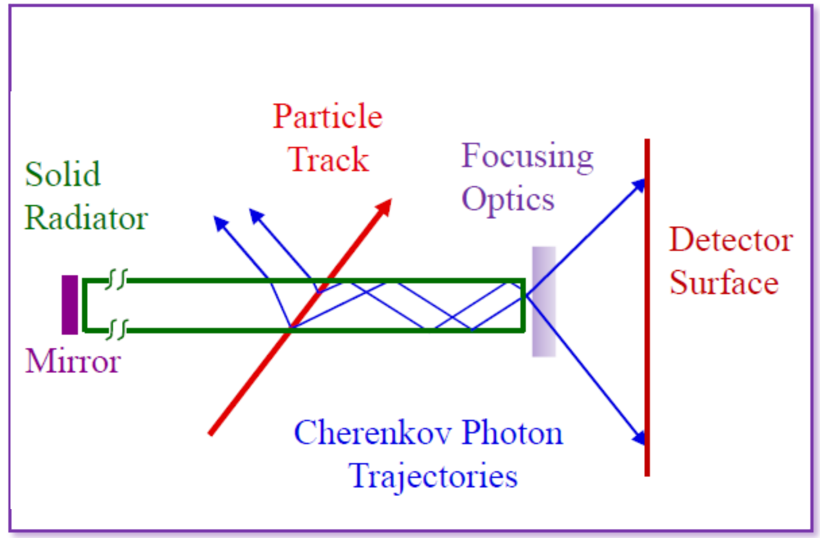
3σ π/K separation up to 4 GeV/c

for polar angle range 5º-22º

Detection of Internally Reflected Cherenkov light

B.N. Ratcliff, SLAC-PUB-6047 (Jan. 1993)

- 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 typically made from Synthetic Fused Silica ("Quartz")

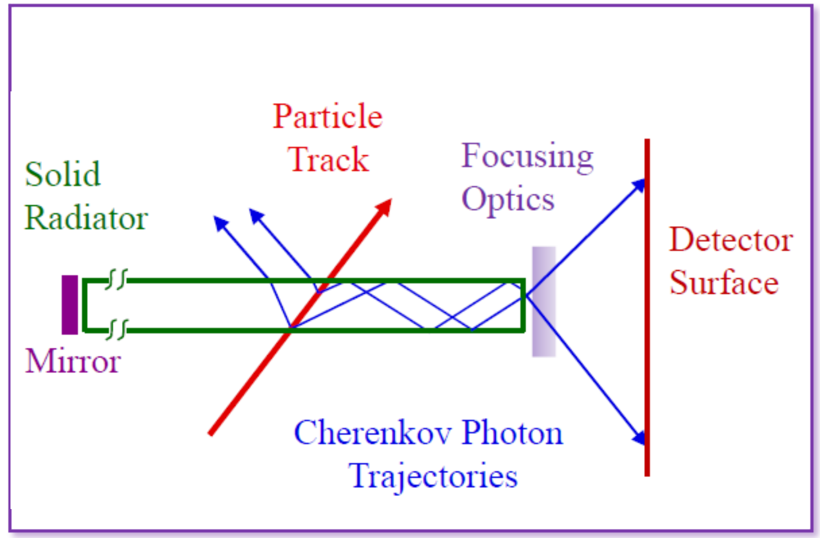


- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

Detection of Internally Reflected Cherenkov light

B.N. Ratcliff, SLAC-PUB-6047 (Jan. 1993)

- Mirror attached to one bar end, reflects photon back to readout end.
- Photons exit radiator via optional focusing optics into expansion region, detected on photon detector array.
- DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, φ_c, $t_{propagation}$.
- Ultimate deliverable for DIRC: PID likelihoods.

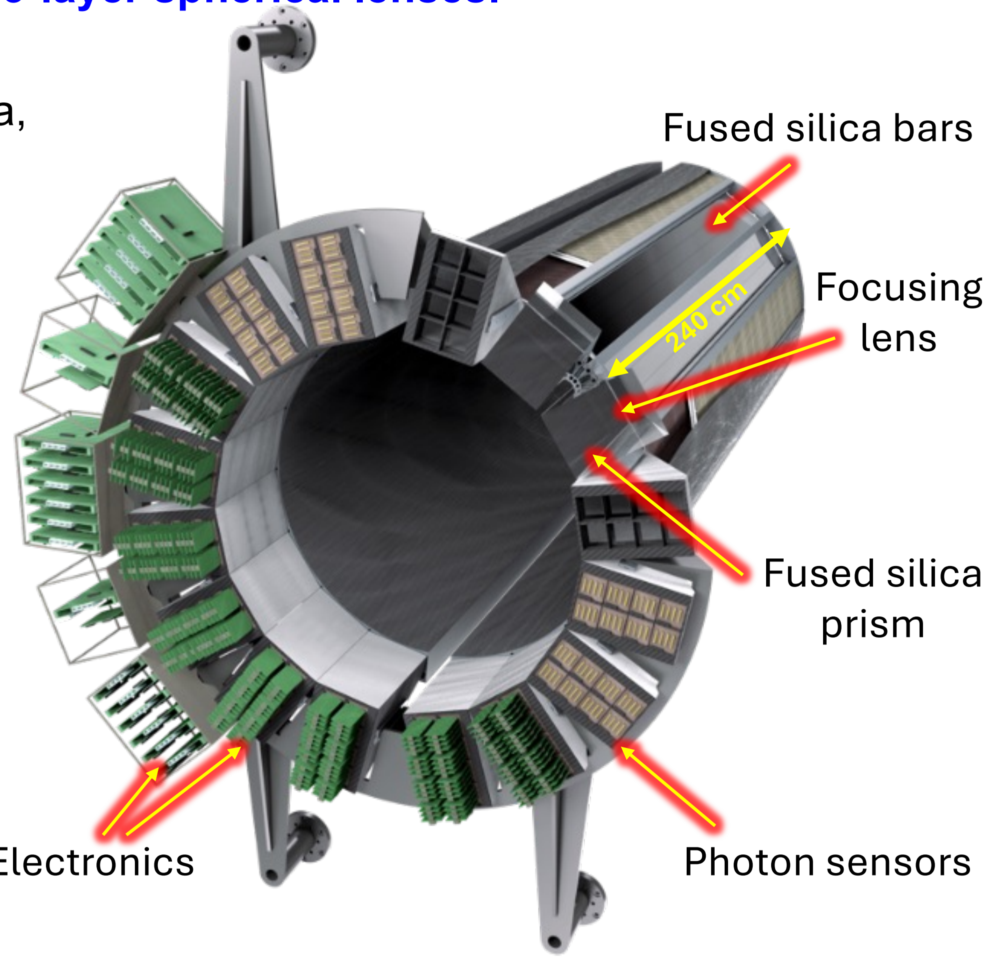


Compact fused silica prisms, 3 bars per bar box, 3-layer spherical lenses.

- 48 radiator bars (16 sectors), synthetic fused silica,
  17mm (T), 53mm (W), 2400mm (L).
- Focusing optics: 3-layer spherical lens
- Compact expansion volume:
  30cm-deep solid fused silica prisms
  ~8,000 channels of
  lifetime-enhanced MCP-PMTs
- Fast FPGA-based readout.
  ~100ps per photon timing resolution (DiRICH)

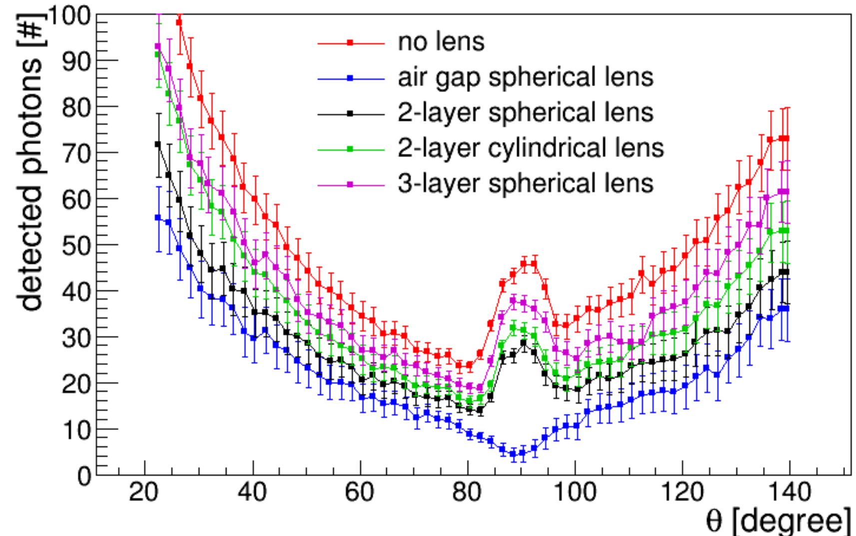
TDR published:

J. Phys. G: Nucl. Part. Phys. 46 045001, arXiv:1710.00684



Barrel DIRC – Technical challenge: Lens focusing

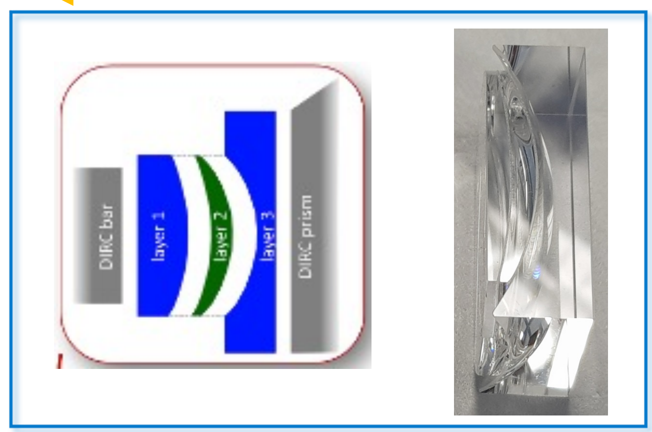
Barrel DIRC counters require focusing for wide range of photon angles



Conventional plano-convex lens with air gap:

limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°, gap in DIRC PID
- Distortion of image plane, PID performance deterioration



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

high-refractive index material (focusing/defocusing)

- Avoids photon loss and barrel PID gap
- Creates flat focal plane – matched to fused silica prism shape

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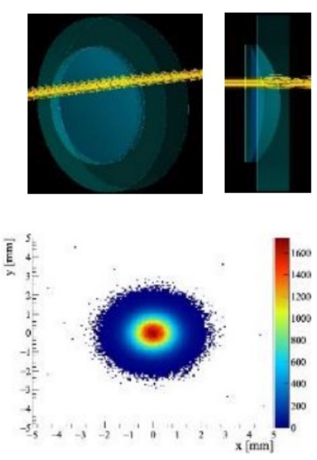

Geant4 simulation of laser beam focus

G. Kalicy, RICH2022

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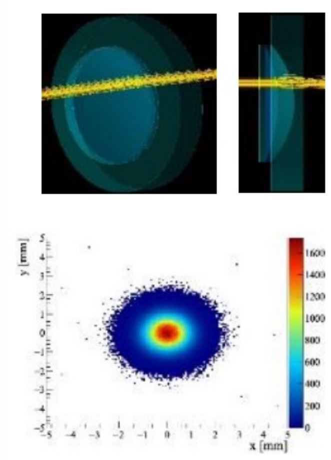


Geant4 simulation of laser beam focus

G. Kalicy, RICH2022

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

R&D activities for PANDA and EIC/ePIC (eRD program):

- Identified radiation-hard material for middle layer: Lanthanum crown glass (LaK33B) for PANDA, sapphire (Al_2O_3) for ePIC tests)
- Validated focusing properties/flat focal plane with laser scan system

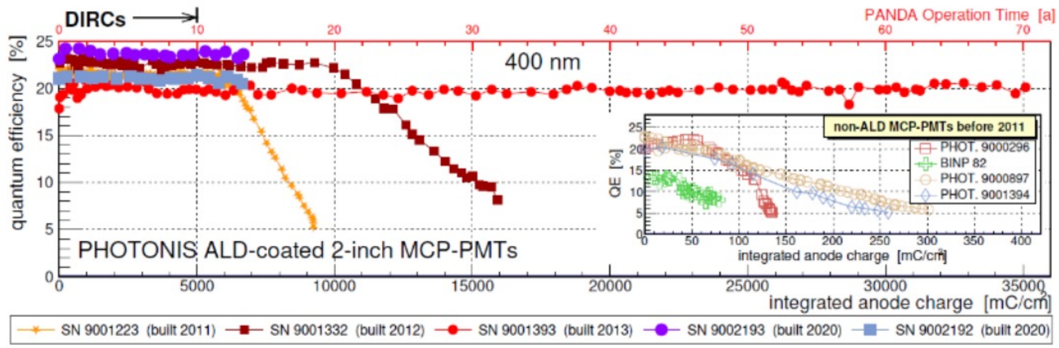
Photon Sensors have to work

- In 1 Tesla magnetic field
- Under high rates

  ~5 C/cm^2 integrated anode charge
- With single photon detection

  Excellent rms-timing
- With high photon yield

  up to 100 photos per particle



A. Lehmann et al., GSI scientific report 2022
DOI:10.15120/GSI-2023-00462

PANDA solution : Life-time enhanced MCP-PMTs

Small pixels and fast single photon timing

- Low sensitivity to backgrounds
- High Cherenkov angle resolution per photon
- Allows chromatic dispersion mitigation
- Asymmetric pitch for the Endcap Disc DIRC

Endcap Disc DIRC

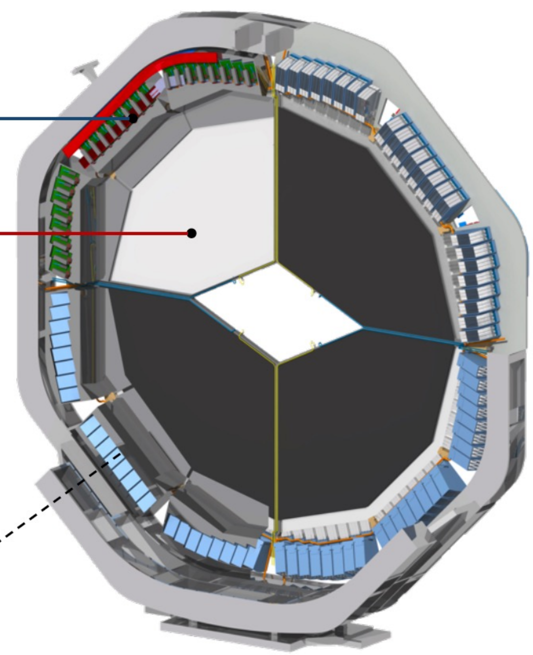
Optics made of synthetic fused silica

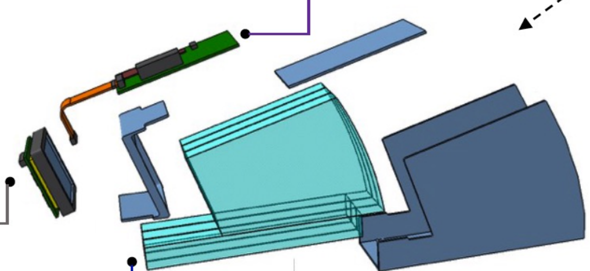
4 independent quadrants

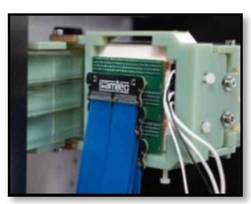
Focusing elements convert angle to position information

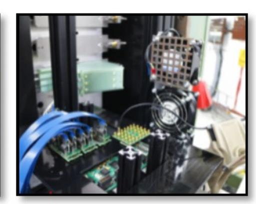
2-inch MCP-PMT with a pitch of 0.5 mm

ASIC-based readout









Quadrant plate dimension:

20mm thickness

1056mm outer radius

Sensors:

96 MCP-PMTs

lifetime-enhanced,~3x100 pixels

Optional:

Optical band pass filter

for chromatic dispersion mitigation

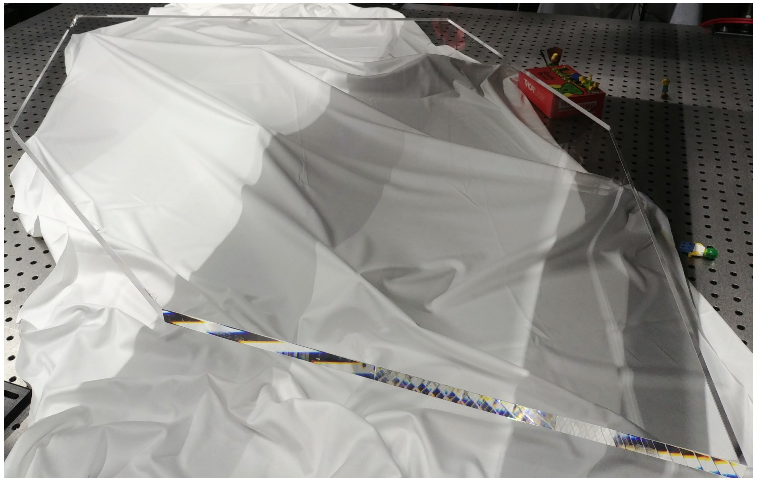
TOFPET ASIC readout

~29k channels

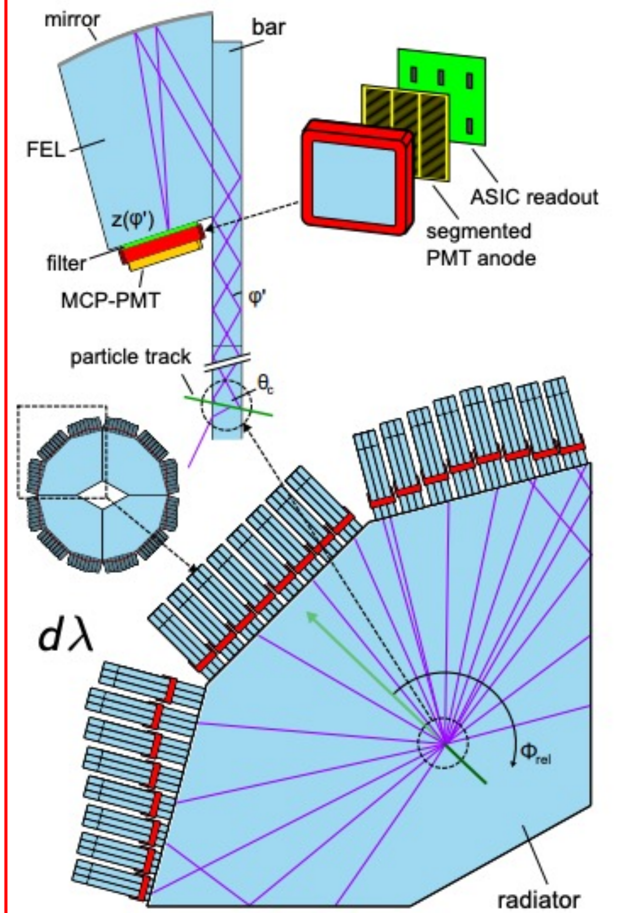
Design validated with particle beams since 2016.

TDR published

TDR: F Davì et al 2022 J. Phys. G: Nucl. Part. Phys. 49 120501, DOI 10.1088/1361-6471/abb6c1



Full-size radiator plate from Nikon Corp, Japan
1nm surface roughness



Focusing elements

- Conversion of angle to position information

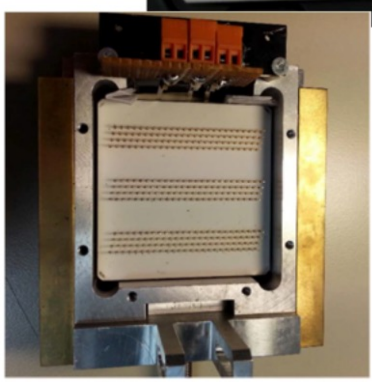
Optical band pass filter

- Mitigation of chromatic dispersion

TDR: F Davì et al 2022 J. Phys. G: Nucl. Part. Phys. 49 120501, DOI 10.1088/1361-6471/abb6c1

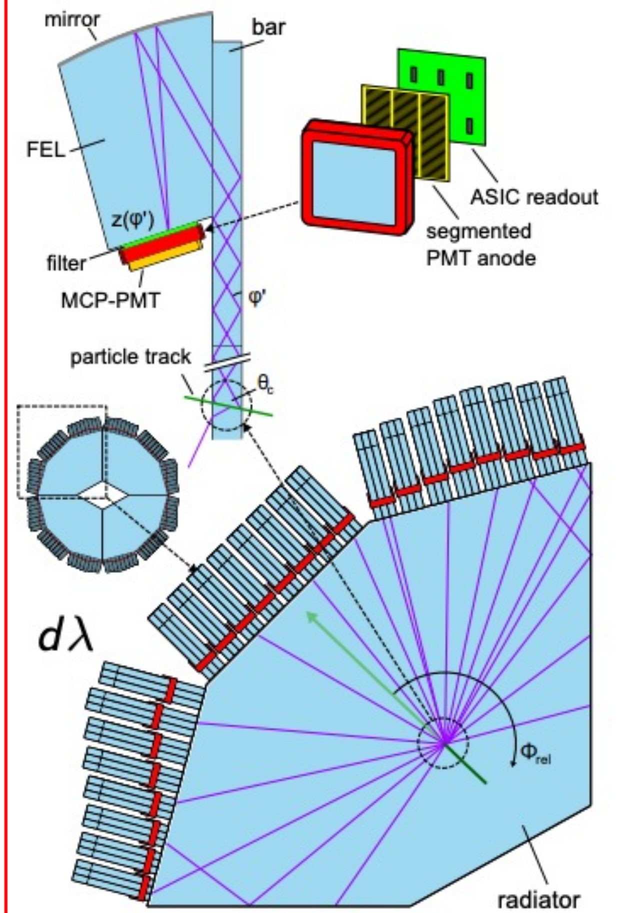
PHOTONIS (3x100)

anode strips



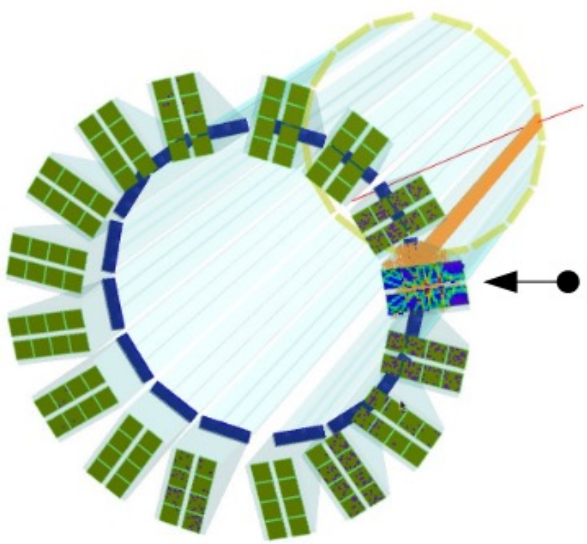
anode pin array

Due to the reconstruction the EDD needs sensor with
- very small pixels (0.5mm pitch) in one direction
- coarse pixels (1-2cm pitch) in the other

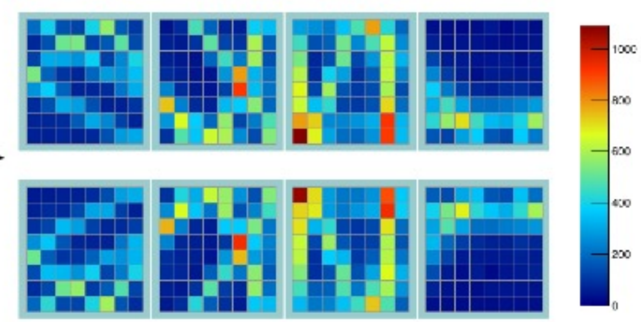


TDR: F Davì et al 2022 J. Phys. G: Nucl. Part. Phys. 49 120501, DOI 10.1088/1361-6471/abb6c1

- Realistic materials properties
- Photon transport efficiency
- Single photon time resolution
- Quantum and collection efficiency
- Dark counts



Accumulated hit pattern from 1000 K^+ at 3.5 GeV/c and 25° polar angle



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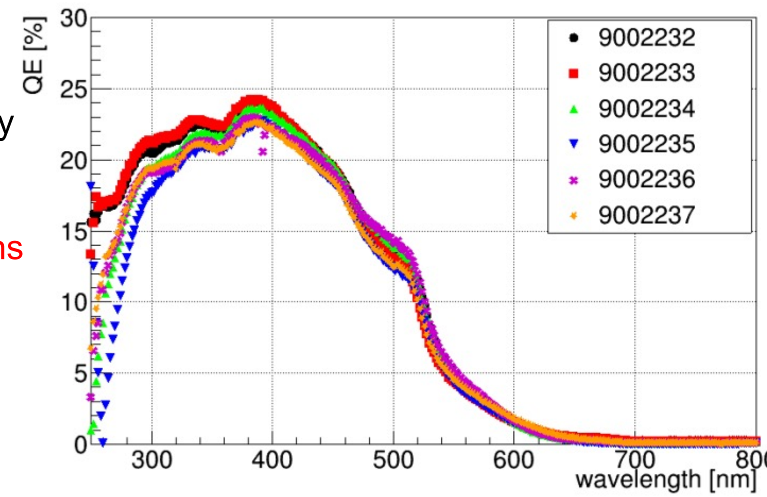
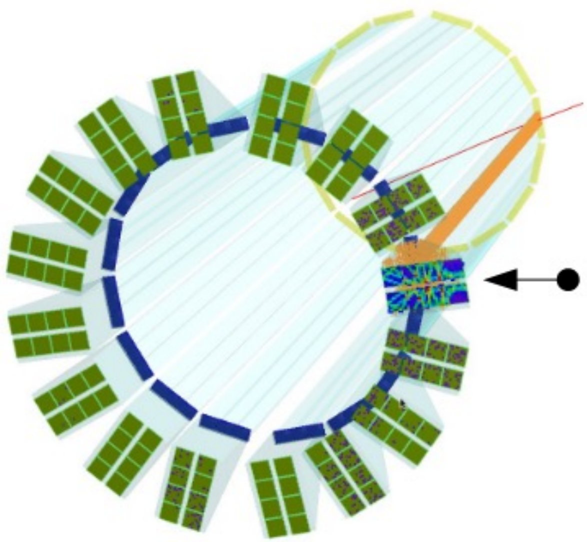
- Single photon time resolution
- Quantum and collection efficiency
- Dark counts

Quantum efficiency of the Photonis Planacons from PANDA series production





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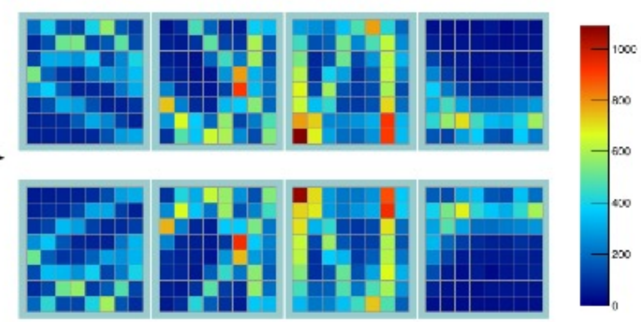
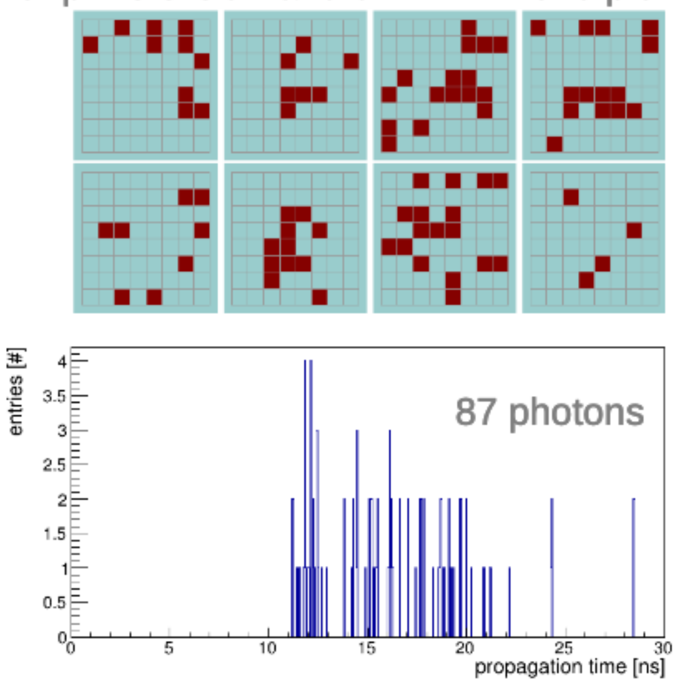
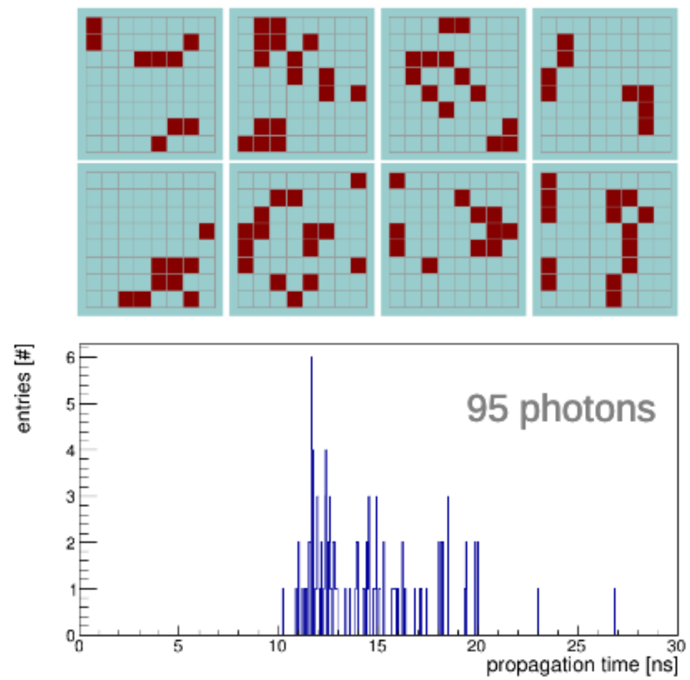


- Number of detected photons
- Photon hit position (6x6 mm^2 pixels)
- Photon propagation time (~100 ps precision)

Examples for p = 3.5 GeV and θ = 22°: one pion



one kaon



simulation

Expected Performance: PID

Detailed Geant4 simulation

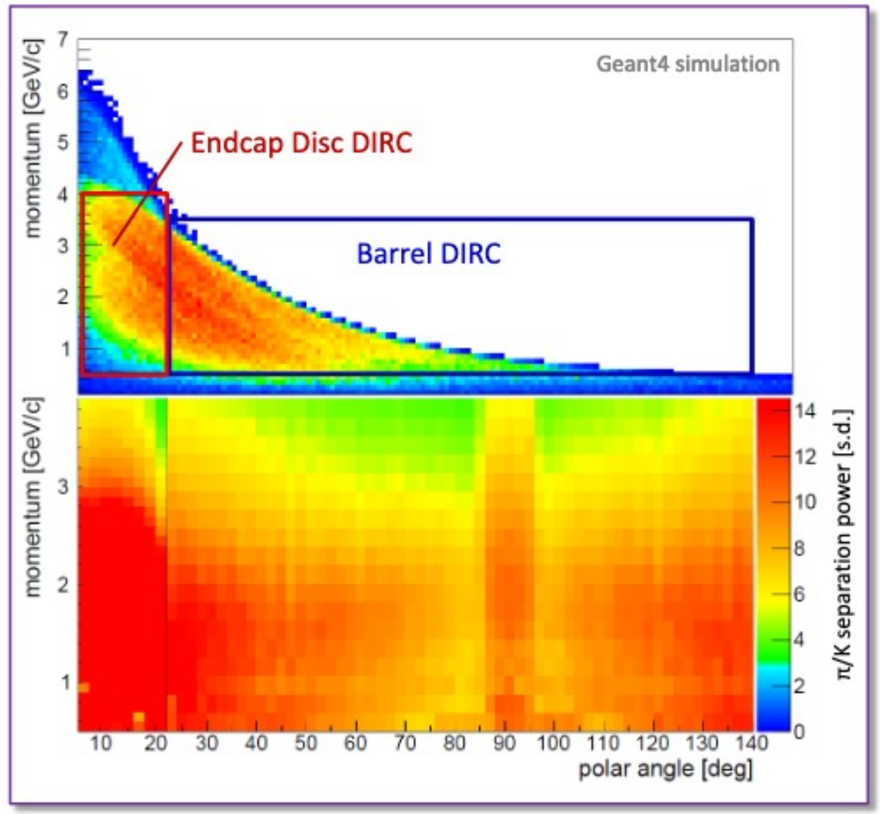
- Wavelength-dependent properties of all optical materials, matched to experimental data
- Realistic photo detection efficiency and timing precision for MCP-PMTs and readout electronics

Barrel DIRC:

- 15-80 detected Cherenkov photons per particle
- Cherenkov angle resolution per photon: 7-10 mrad

Endcap Disc DIRC:

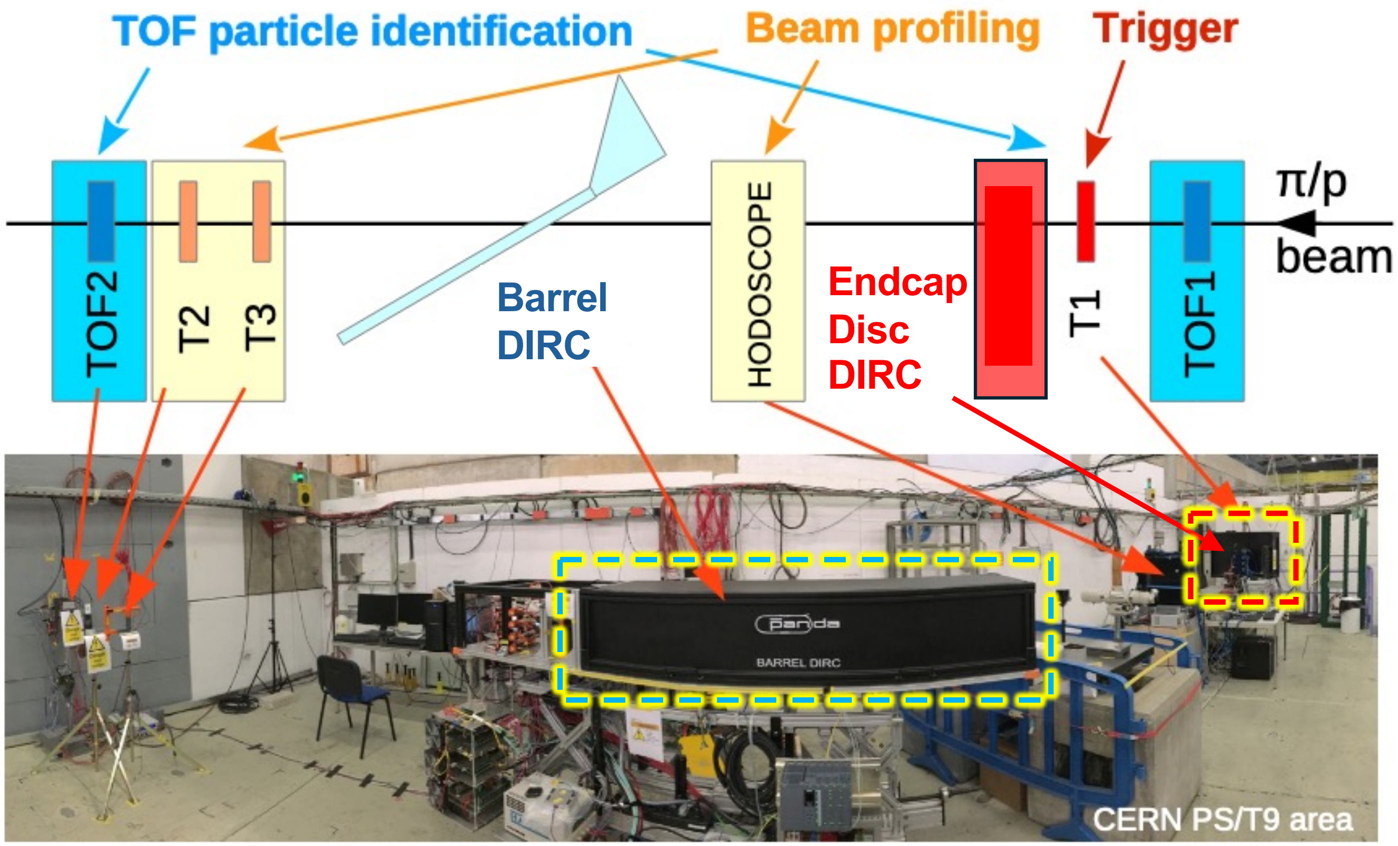
- 20-30 detected Cherenkov photons per particle
- Cherenkov angle resolution per photon: 5-7 mrad

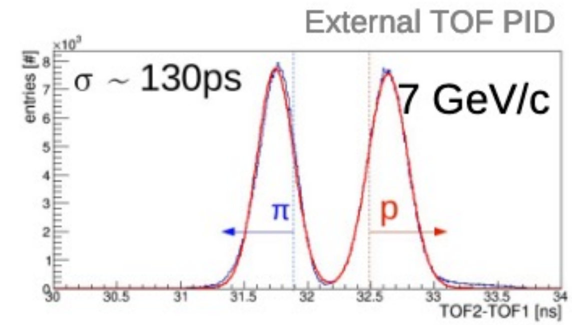


Expected PID performance:

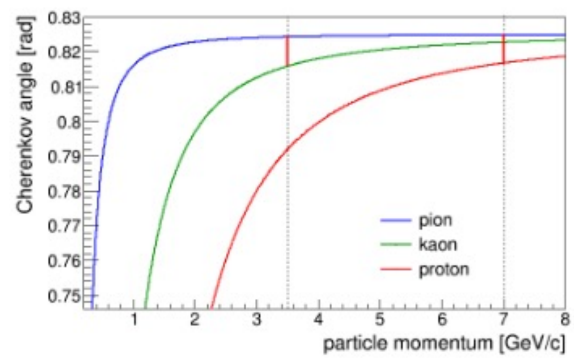
at least 3 s.d. π/K separation power for full acceptance

Validation in Beam Tests

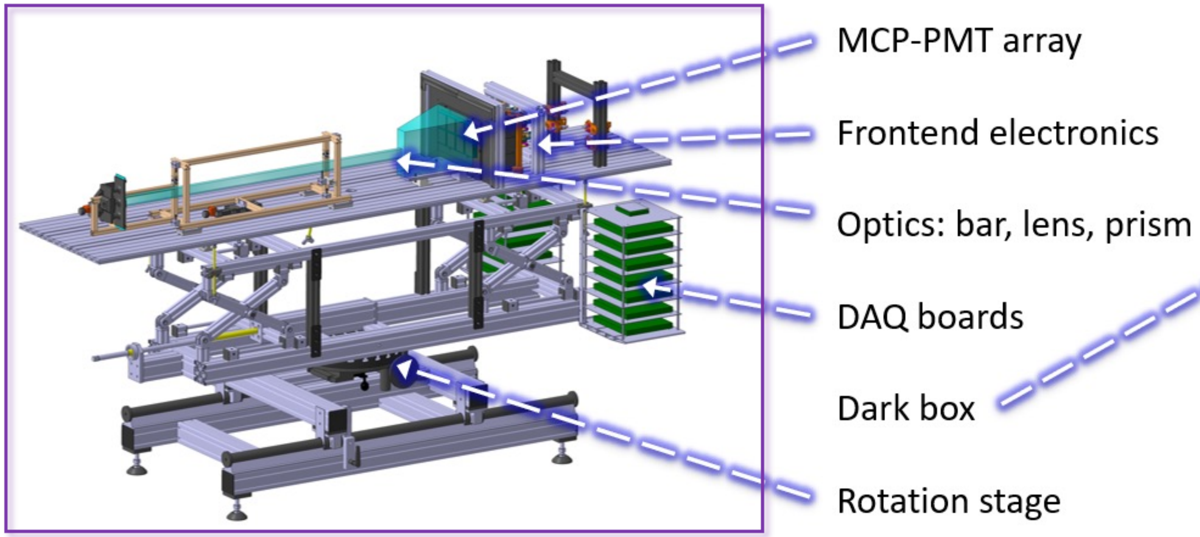


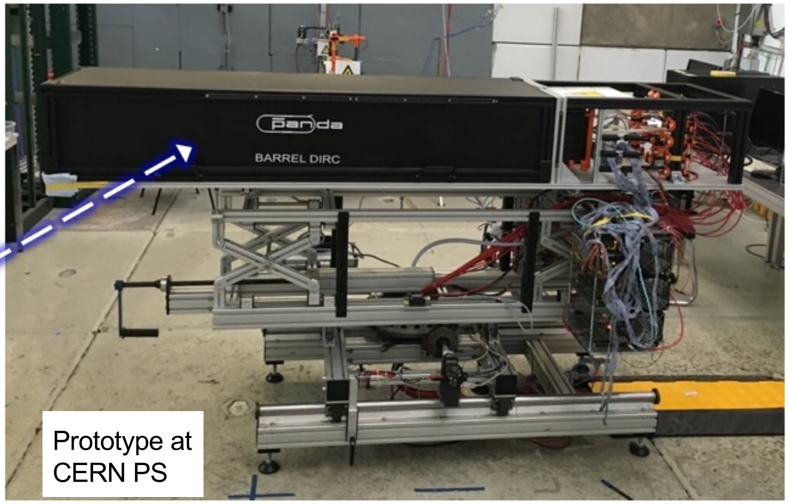


Most of the data taken at 7 GeV/c
(7 GeV/c π/p sep. ≈ 3.5 GeV/c π/K)

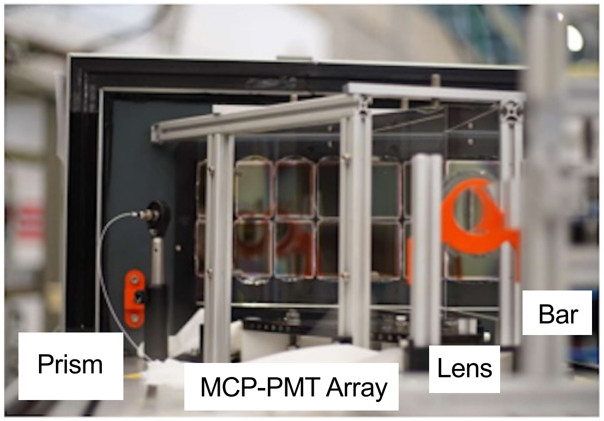


Validation in Beam Tests: Barrel DIRC

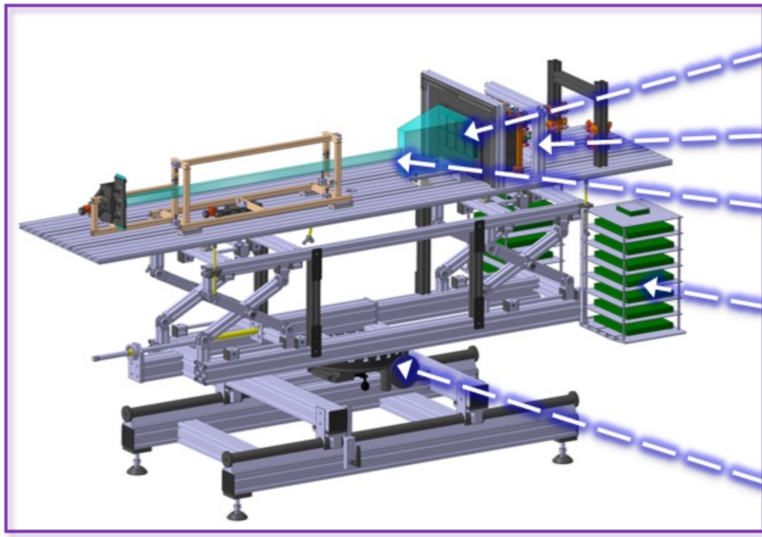


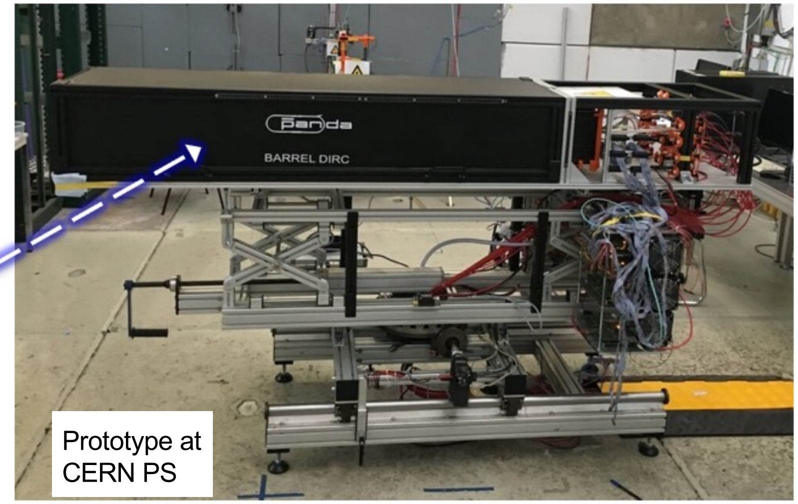


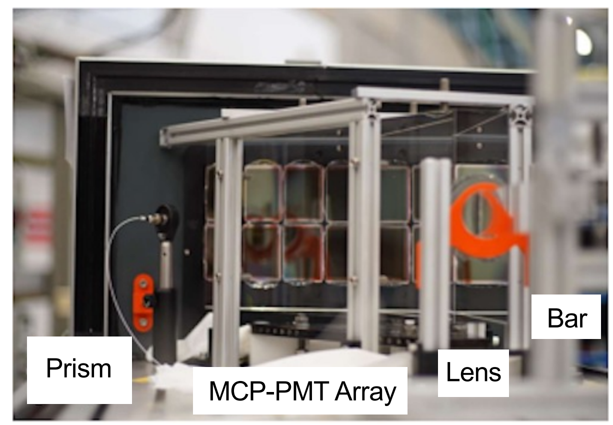
- Narrow fused silica bar (produced for BaBar DIRC)
- 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array
- PADIWA/TRB3 readout (~200 ps time precision)
- PiLas picosecond laser calibration system



Validation in Beam Tests: Barrel DIRC







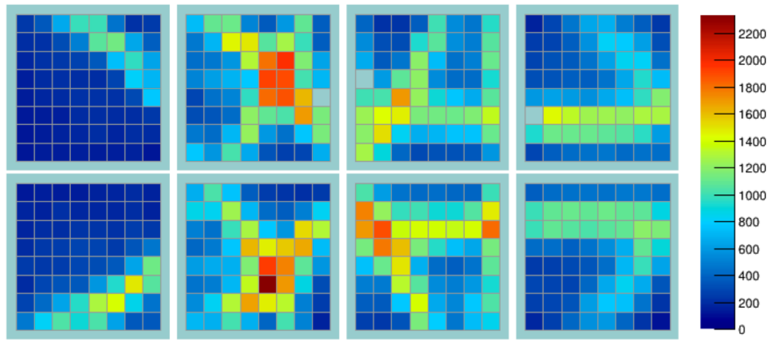
- Direct measurement of PID performance across PANDA phase space
- Measure photon yield, timing precision and Cherenkov angle resolution per particle/per photon, π/p separation power

Validation in Beam Tests: Barrel DIRC

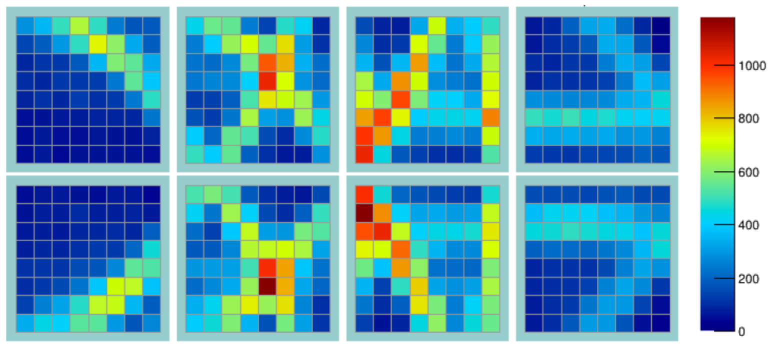
Hit pattern for

- 5k pions
- 20° polar angle
- Three layer compound lens
- 4x2 MCP-PMTs
- Narrow bar
- 33° prism

Very good agreement with simulations

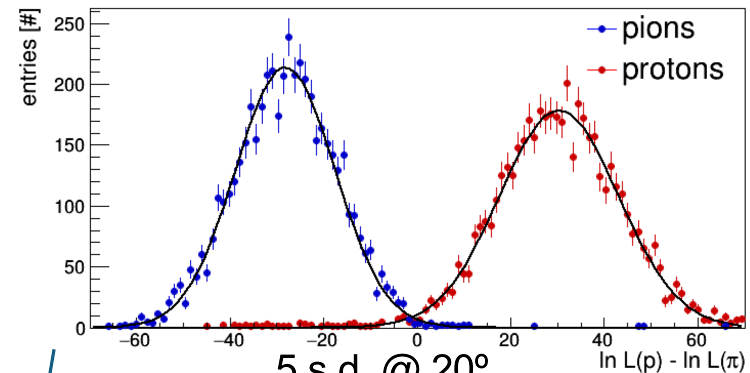


Beam data



Simulation

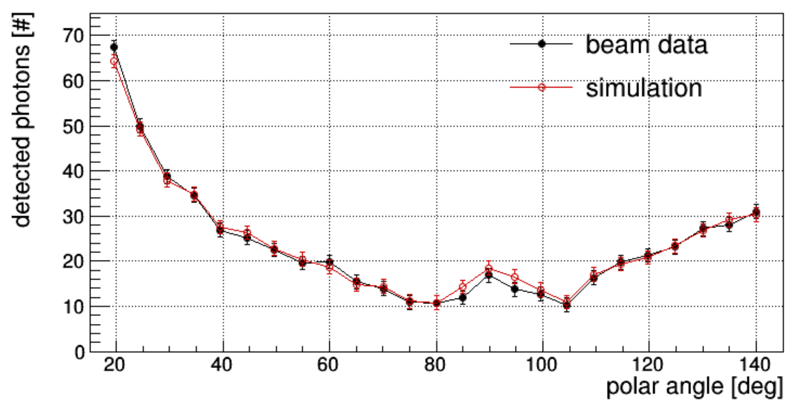
Pion/proton separation power @ 7 GeV/c

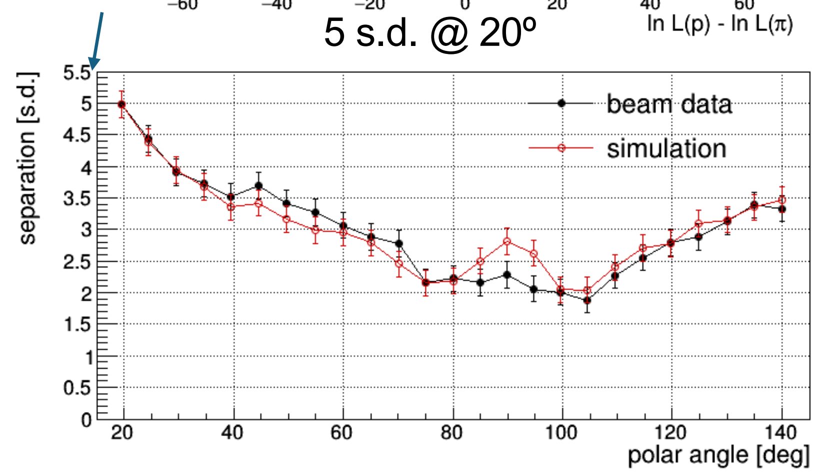


5 s.d. @ 20°

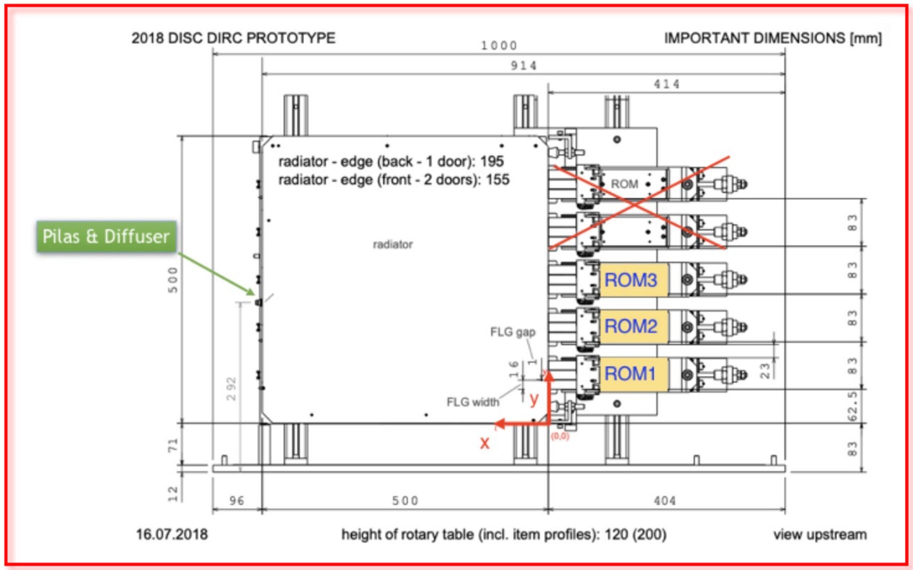
Excellent agreement between data and simulation

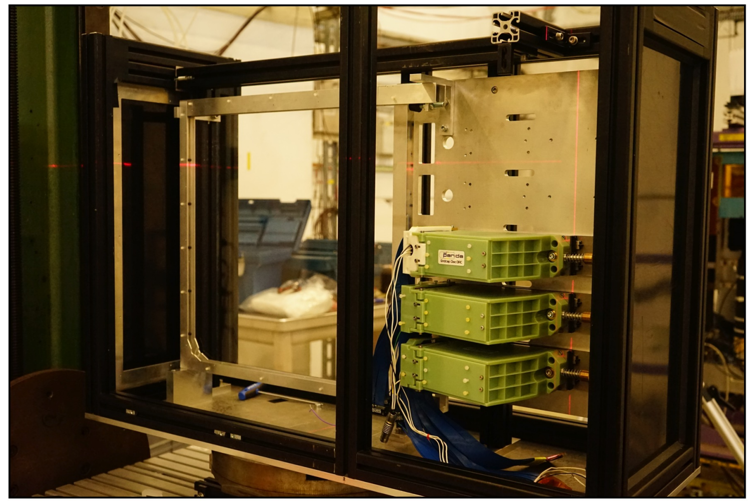
- 10 – 65 photons per particle
- 6-9 mrad Cherenkov angular resolution per photon
- 5 s.d. pion/proton separation at 20°

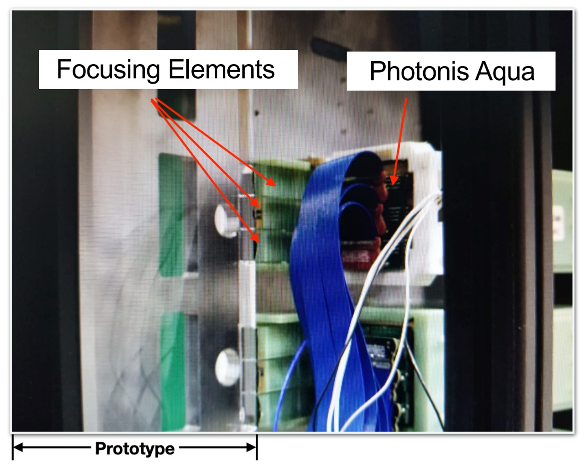




PID performance meets or exceeds PANDA PID requirements





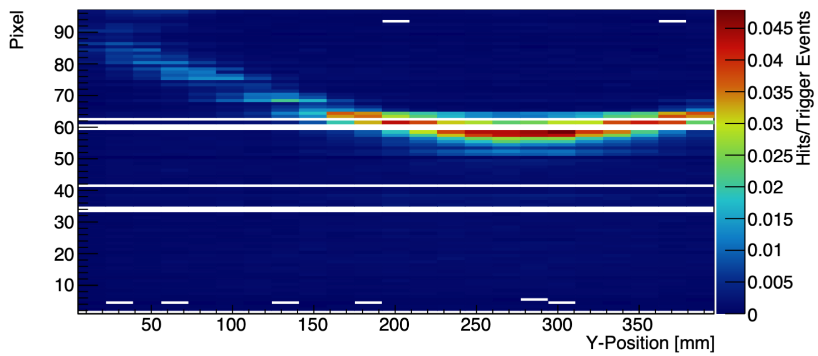


- 9 Focusing Elements (FEL)

  3 Read-out Modules (ROM) • 3 MCP-PMTs
- Photonis Aqua photocathode • 3 Rows, 288 pixels
- In total 960 connected channels
- Clean external PID from MCP-PMT time-of-flight

Example: Prototype at CERN PS, 2018

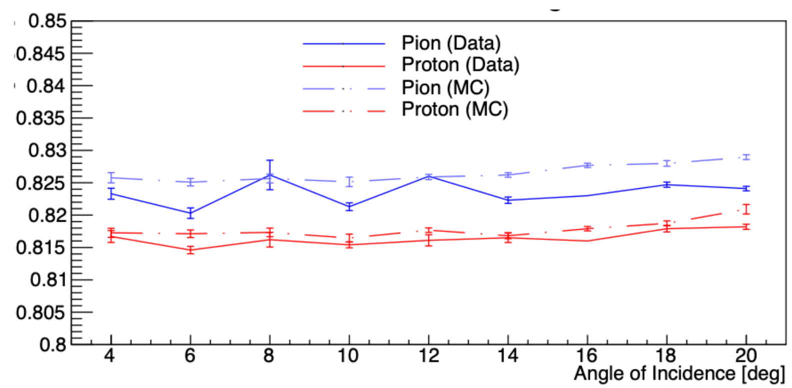
Endcap Disc DIRC hit pattern for 10 GeV/c protons



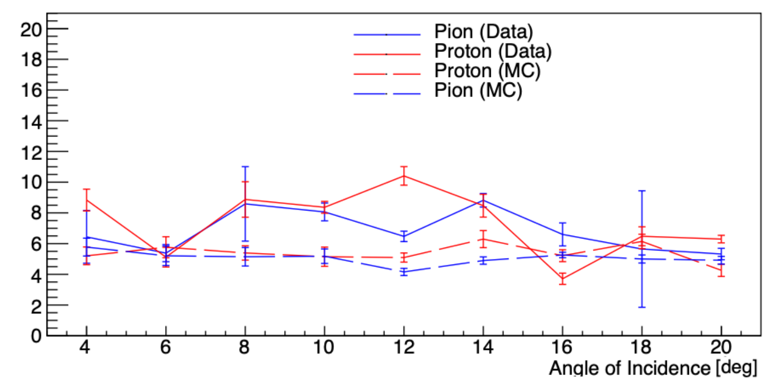
- Scans of beam incident angle and position for different momenta
- Measured Cherenkov angle and resolution per photon
- Simulation describing data features well; tuning, calibration, and analysis still ongoing

Performance in 7GeV/c proton/pion beam

Cherenkov angle per particle [rad]



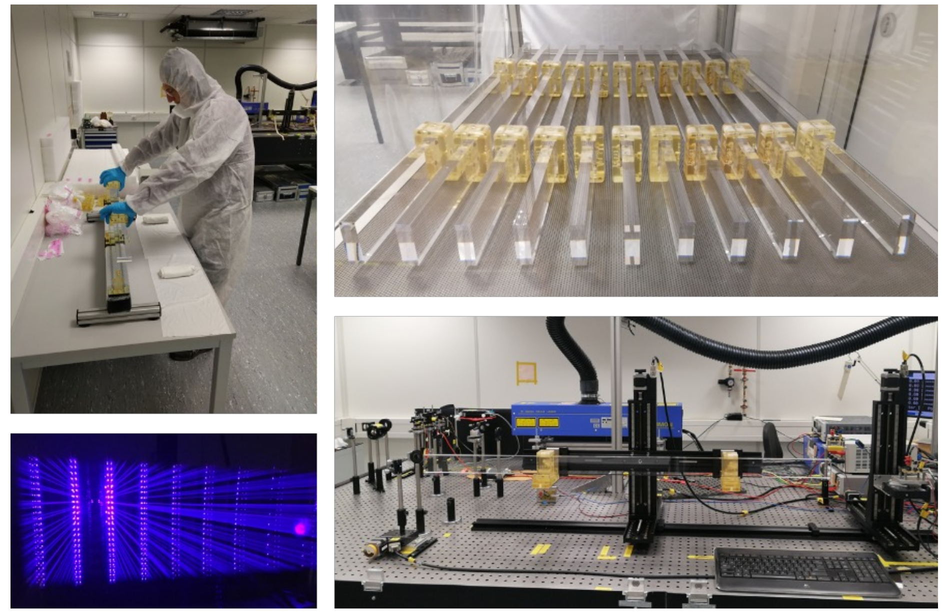
Cherenkov angle resolution per photon [mrad]

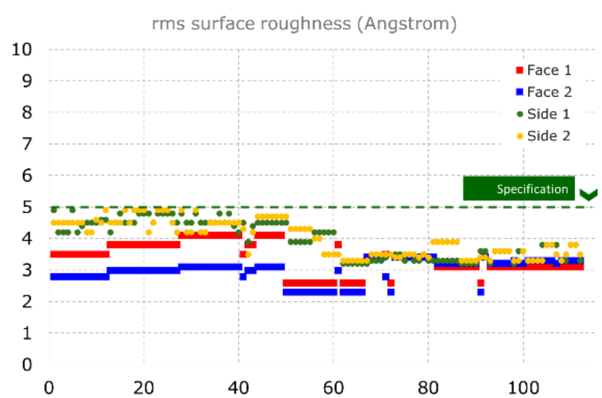


Component Production: Barrel DIRC Bars

QA of DIRC bar production

- Series production of components started in 2019
- Contract for fused silica bars awarded to Nikon Corp, Japan in Sep 2019
- Smooth production, excellent communication
- 112 DIRC bars delivered by Feb 2021, ahead of schedule
- All bars meet or exceed specifications





High photon transport efficiency crucial for DIRC performance.

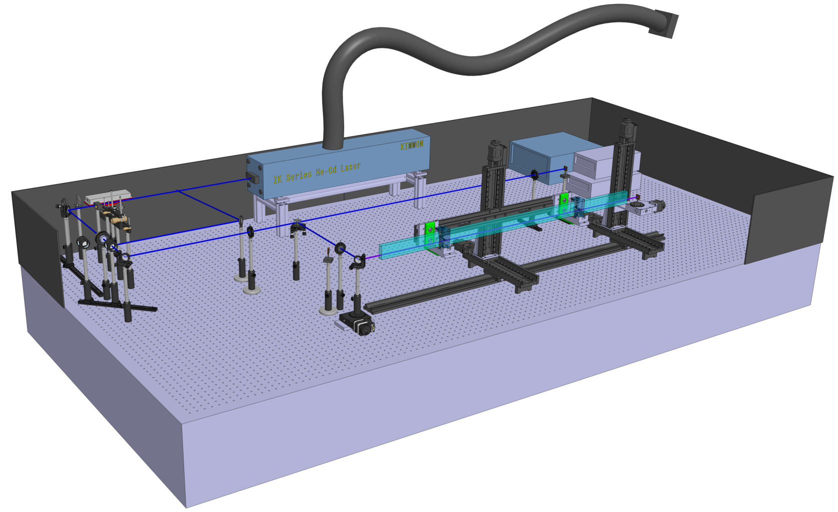
Relevant fabrication specification: rms surface roughness (measured on witness sample pieces)

Goal: measure internal reflection probability for DIRC bar

Important for DIRC radiator:

Internal surface roughness

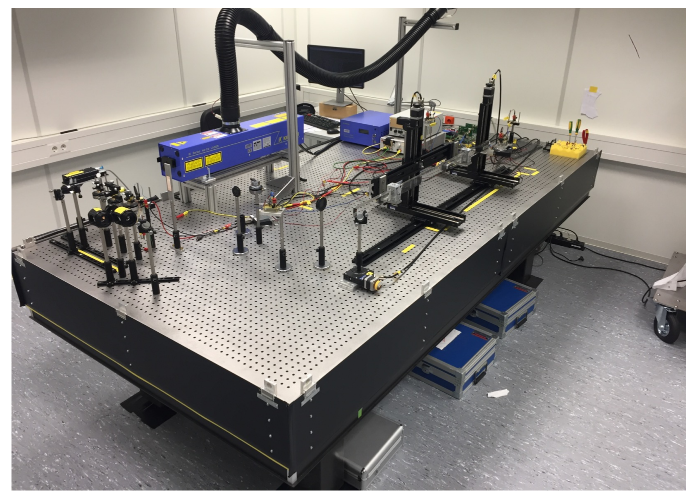
- Could be harmed by the polishing method
- Transport probability reduced



Internal reflection measurements

- 6 laser wavelengths
- Polarized laser beams
  Brewster angle
- 2 photo diodes

Determination of the surface roughness $\mathcal{H}$
with help of the internal reflectivity $\mathcal{R}$ of
6 laser wave lengths via Scalar Scattering Theory



Component Production: Barrel DIRC Bars

Important for DIRC radiator:

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- Could be harmed by the polishing method
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Internal reflection measurements

- 6 laser wave lengths
- Polarized laser beams

  Brewster angle
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Determination of the surface roughness $\mathcal{H}$
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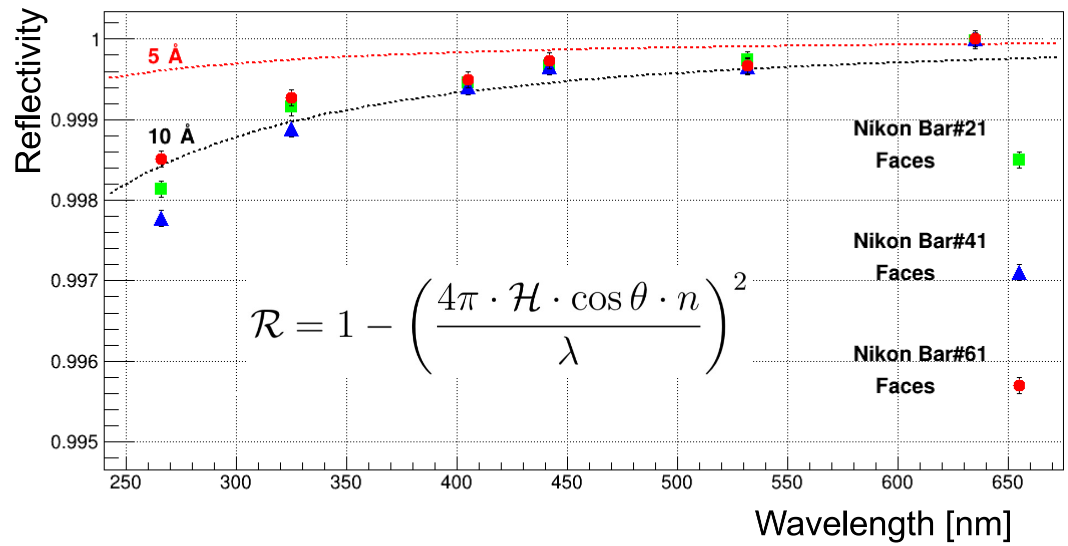
Measured reflectivity of three example Nikon bars



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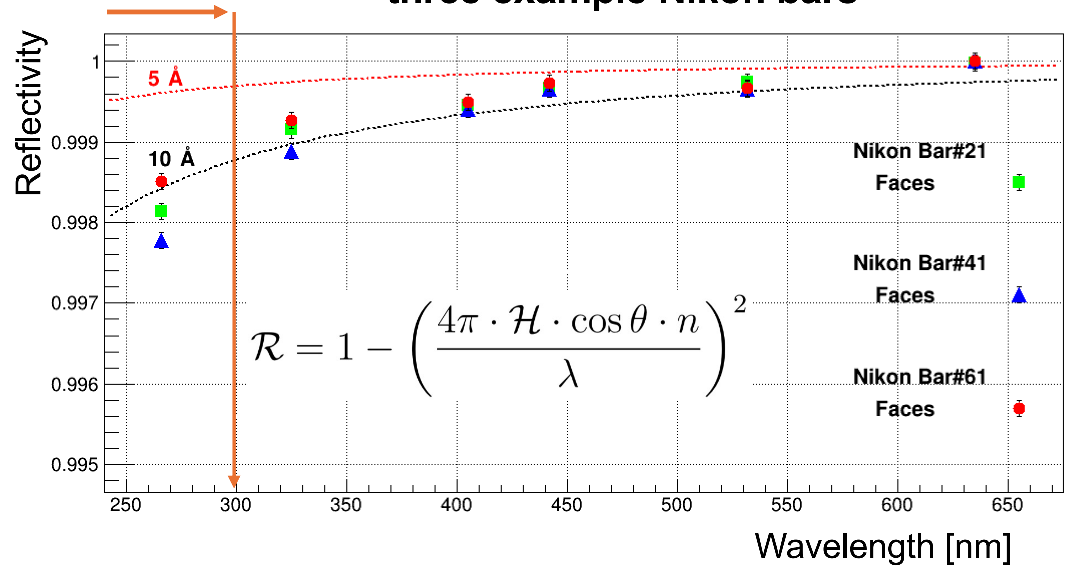
with help of the internal reflectivity $\mathcal{R}$ of
6 laser wave lengths via Scalar Scattering Theory

Epotec 301-2 cut off

Measured reflectivity of three example Nikon bars



$$\mathcal{R} = 1 - \left(\frac{4\pi \cdot \mathcal{H} \cdot \cos\theta \cdot n}{\lambda} \right)^2$$

Over the relevant laser wavelength the internal surface roughness is 5 to 10 Å

Component Production: Barrel DIRC Bars

Important for DIRC radiator:

Internal surface roughness

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- Transport probability reduced

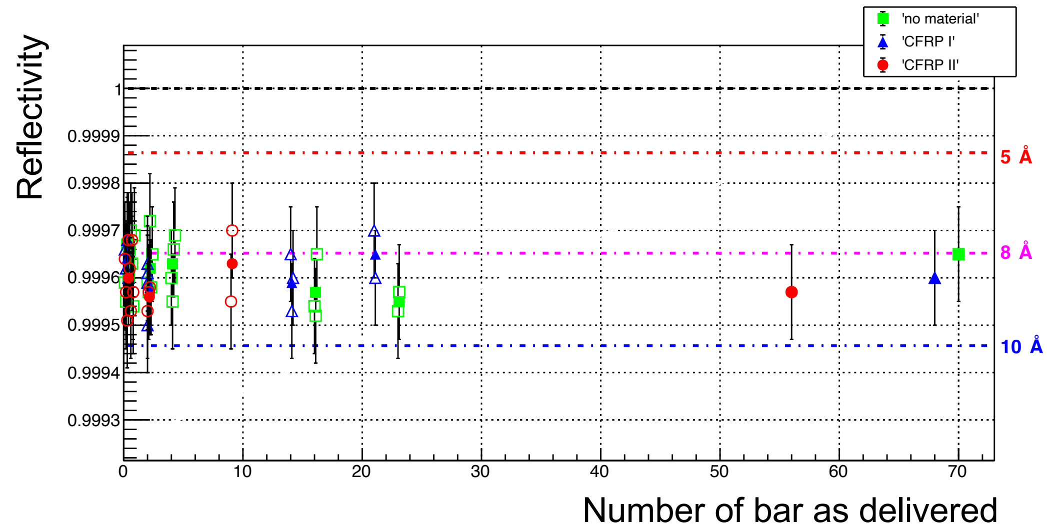
Internal reflection measurements

- 6 laser wavelengths
- Polarized laser beams

  Brewster angle
- 2 photo diodes

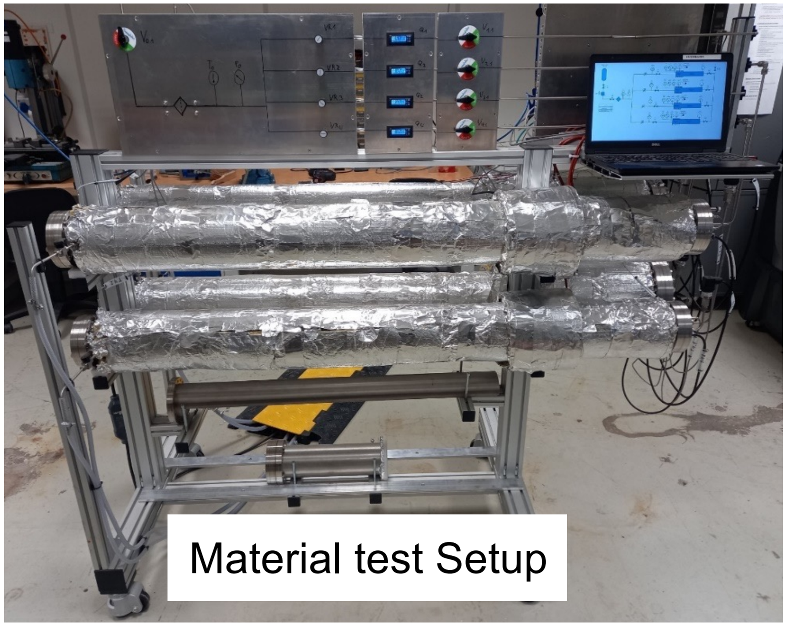
Determination of the surface roughness $\mathcal{H}$ with help of the internal reflectivity $\mathcal{R}$ of 6 laser wave lengths via Scalar Scattering Theory

112 Nikon bars delivered in lots of 10/month



Over the delivery the internal surface quality of the bars remains good or becomes better

Bar Boxes Material: Carbon fiber reinforced polymer (CFRP)



Material test Setup

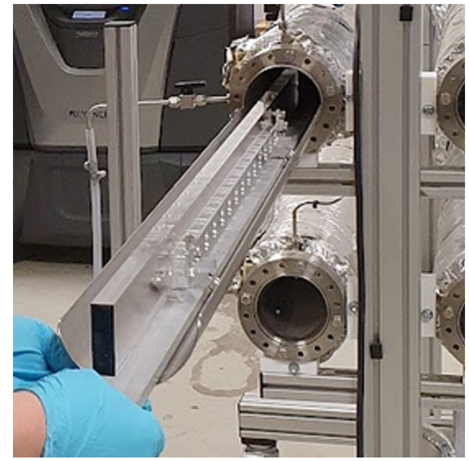
Controlled environment in the four tubes:

- temperature
- nitrogen flow
- pressure
- humidity

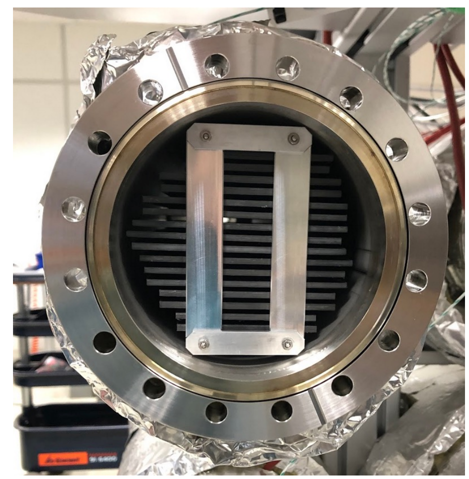
First bar box from CFRP
to house DIRC radiators
with their delicate surfaces

- Two bars exposed to large amount of different CFRP samples
- One reference bar

Bar inserted in the tube



CFRP II (Prototype)
in the vessel

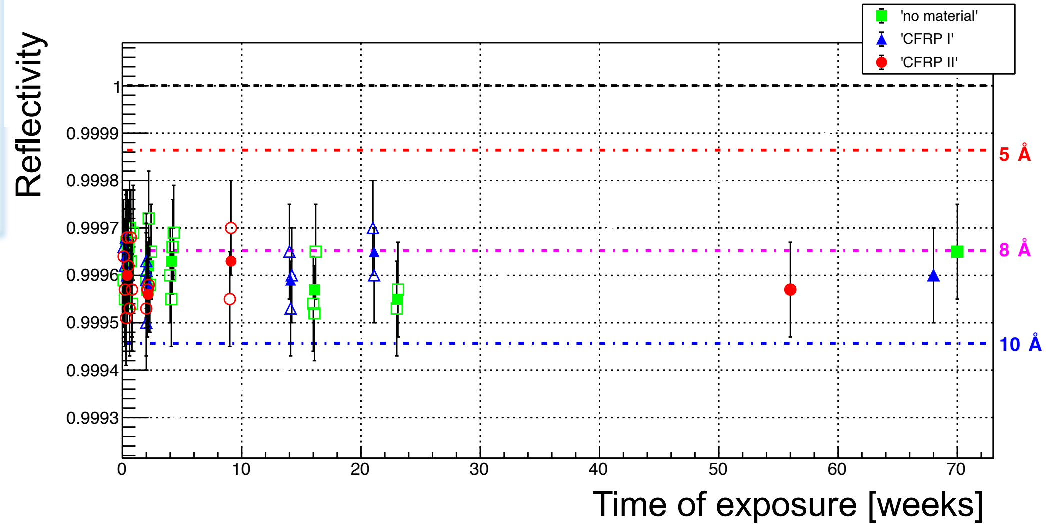


Important for DIRC radiator:

Internal surface roughness

- Could be harmed from the polishing method
- Transport probability reduced

Measured reflectivity of three Nikon bars, two exposed to CFRP and one reference bar.



Internal reflection measurements

- 6 laser wave lengths
- Polarized laser beams
  Brewster angle
- 2 photo diodes

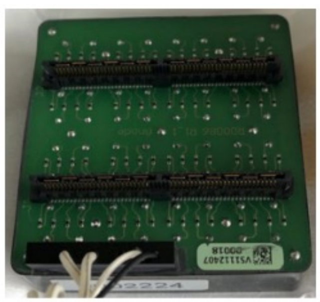
Determination of the surface roughness $\mathcal{H}$ with help of the internal reflectivity $\mathcal{R}$ of 6 laser wave lengths via Scalar Scattering Theory

No obvious hint of surface pollution by the CFRP material probes after 70 weeks of exposure

Component Production: Photon Sensors

- Order for 165 MCP-PMTs placed with Photonis, Netherlands on Dec 2020
- 1 year of delay due to pandemic situation
- Series production of MCP-PMTs at Photonis started and is ramping up

79 MCP-PMTs delivered so far



Photonis XP85112-S-BA

- Order for 165 MCP-PMTs placed with Photonis, Netherlands on Dec 2020
- 1 year of delay due to pandemic situation
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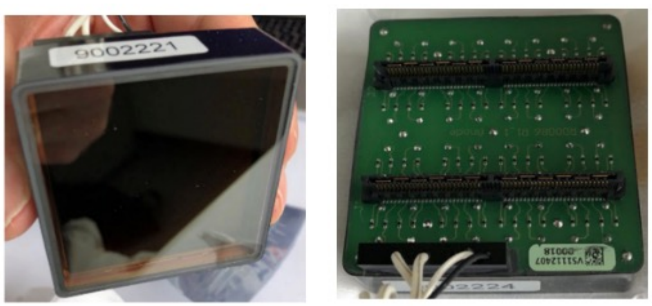
79 MCP-PMTs delivered so far



Photonis XP85112-S-BA

QA measurements in FAU Erlangen

- Quantum efficiency (QE)
- QE homogeneity across the photo cathode surface
- Dark count rate
- Rate stability
- Gain, uniformity, magnetic field
- Afterpulsing fraction
- Time resolution measurements

For a subset of sensors

- the lifetime (quantum efficiency as function of the integrated anode charge)

Component Production: Photon Sensors

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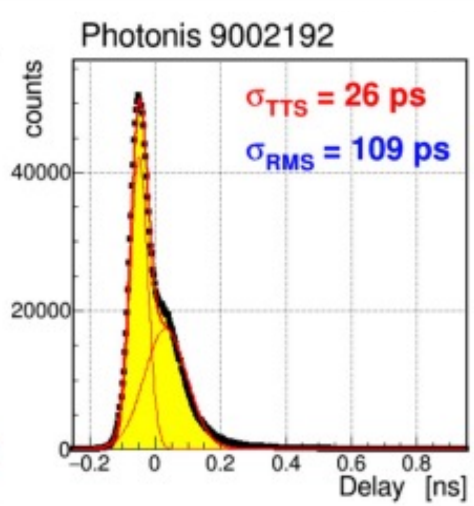


QA measurements in FAU Erlangen

- Quantum efficiency (QE)
- QE homogeneity across the photo cathode surface
- Dark count rate
- Rate stability
- Gain, uniformity, magnetic field
- Afterpulsing fraction

Time resolution measurements

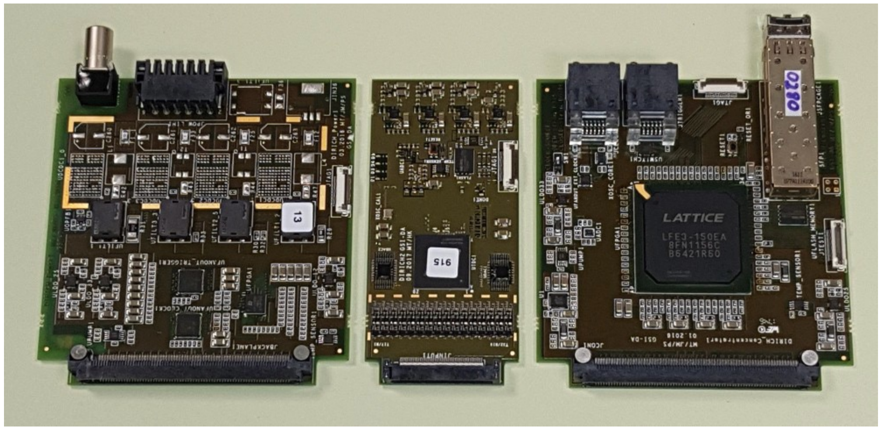
Photon intensity measurement at single photon level and low rate

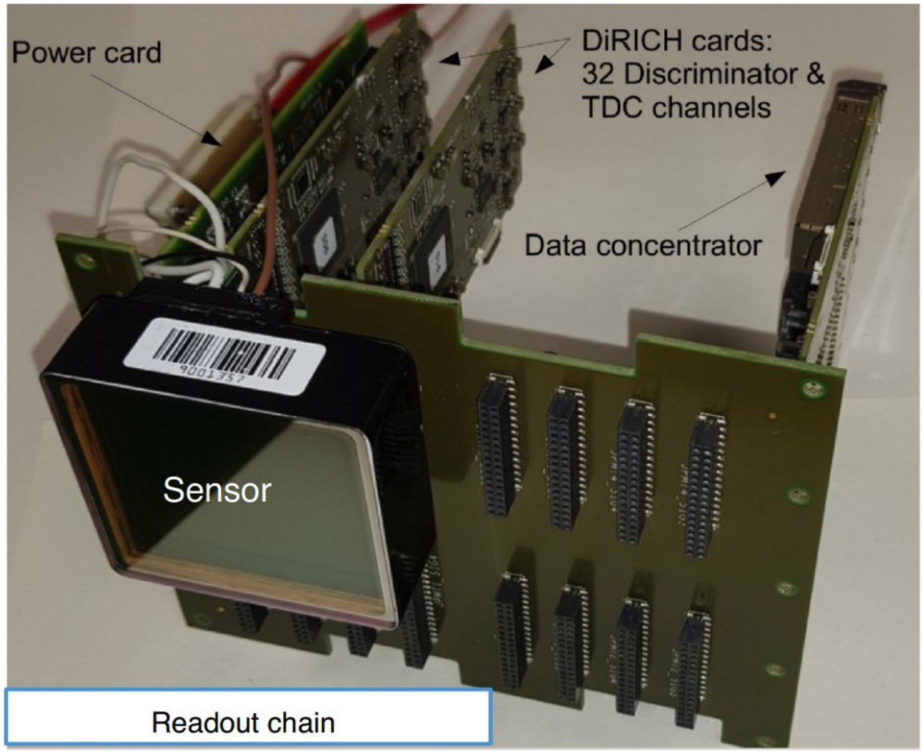
DiRICH readout backplane

(Collaboration with PANDA, CBM, HADES)

- Highly integrated
- Minimal cabling
- ~10 ps internal time precision (disc. +TDC)
- ~50 mW /channel power consumption

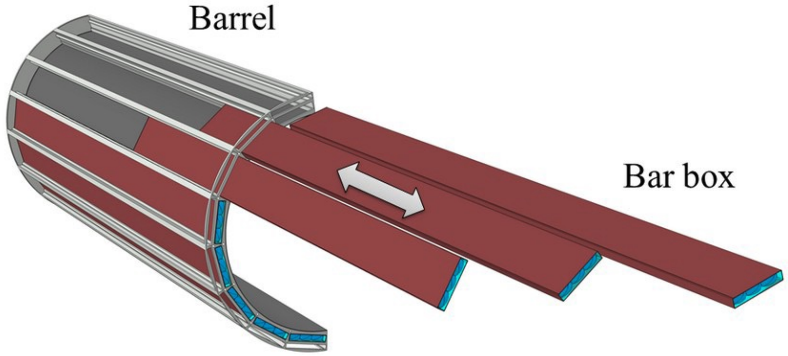
power card DiRICH Data concentrator

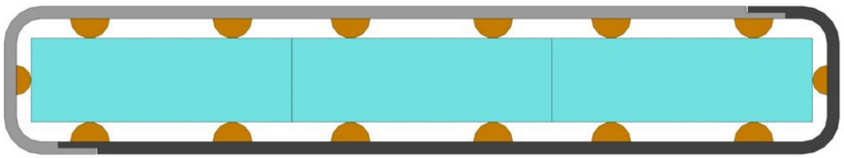




Several test led to this highly integrated solution

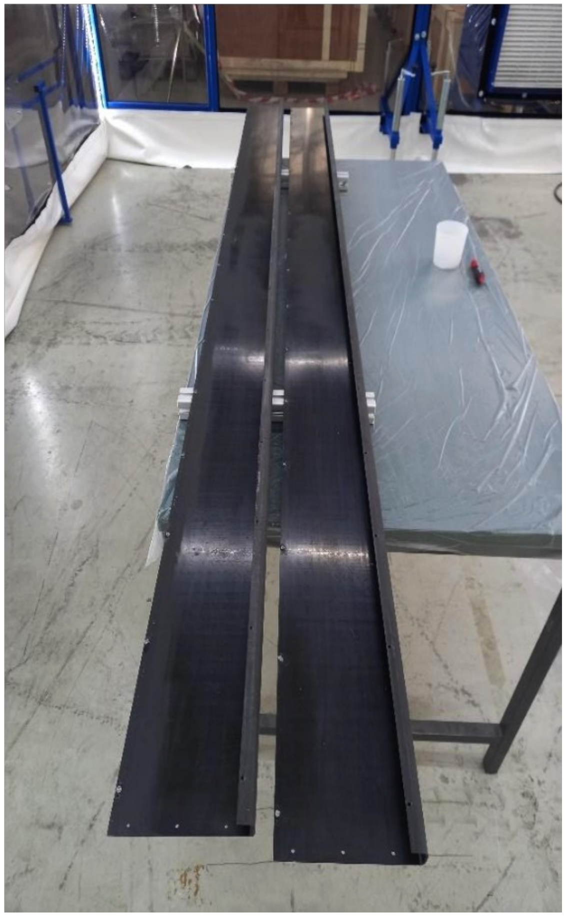
- Carbon fiber reinforced polymer (CFRP)
- Low material budget, Low Z-material
- Stiffness tests
  to be compared with finite element analysis calculations
- Study of long-term outgassing behavior





Three bars in a bar box

Prototype of L-elements



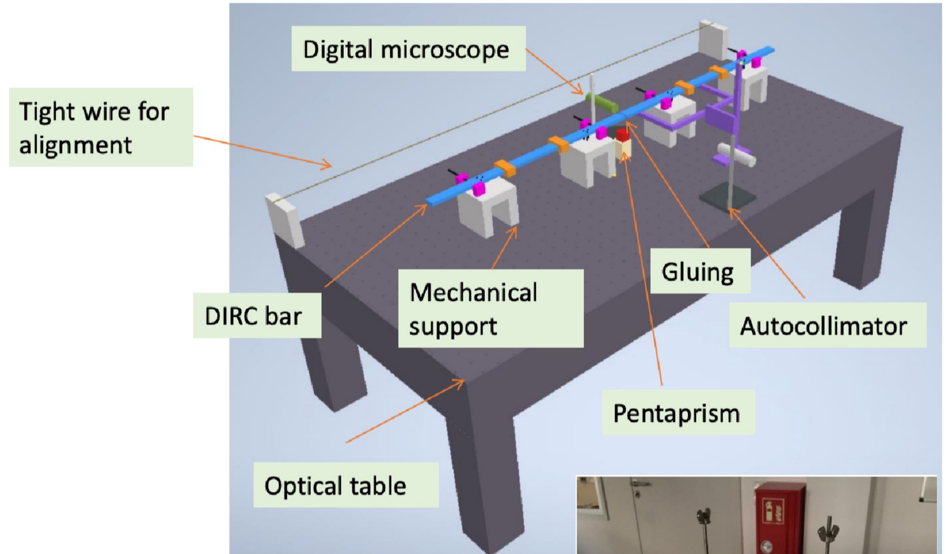
R&D of bar gluing in DIRC lab at HI Mainz, Germany

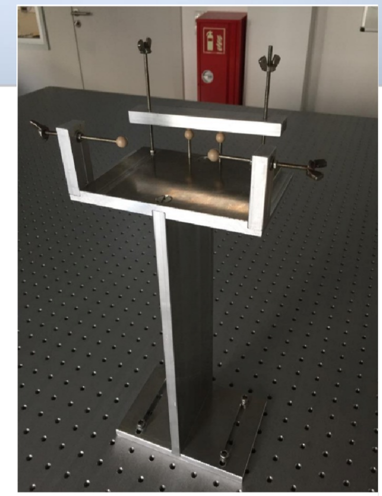
- Procedure is inspired by TOP counter at Belle II and BaBar DIRC
- Excellent alignment accuracy is required to preserve the Cherenkov angle
- Gluing tests with pieces from laser-cut Nikon bar
- Controlled environment for the use of Epotek 301-2 temperature and humidity

Goal:

To glue two bars 17mm x 53mm x 1200mm

back-to-back with less than 30 microns misalignment

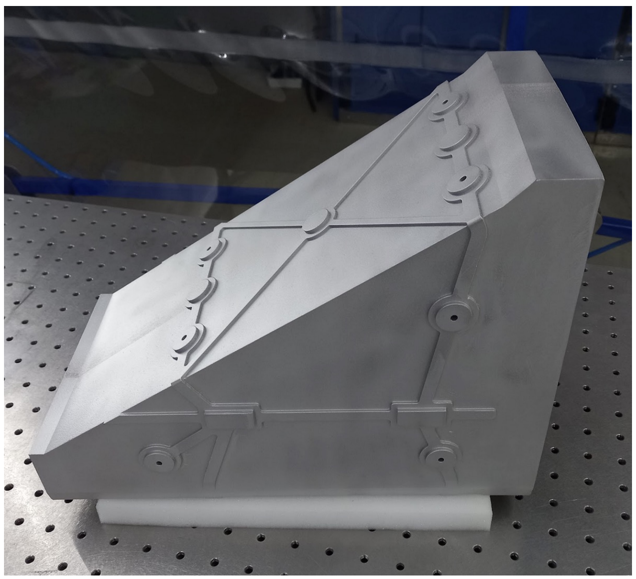


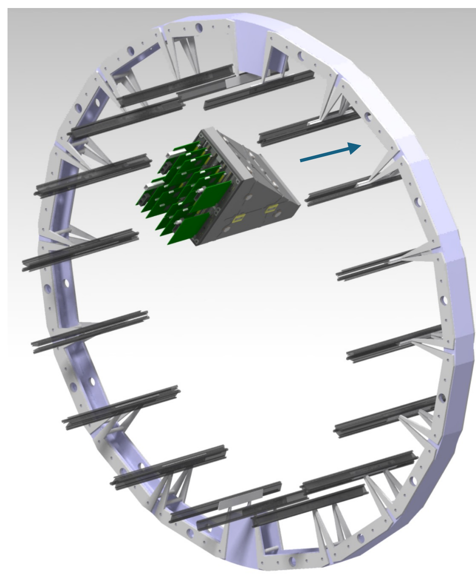


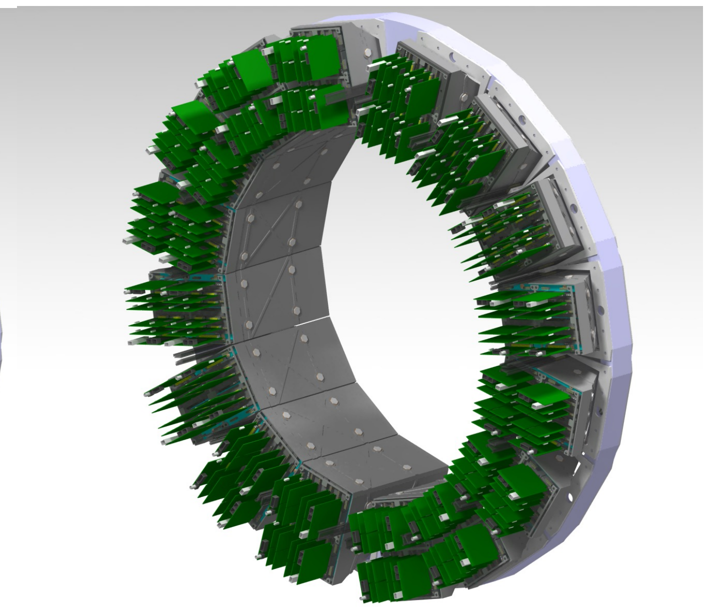
Mechanical support prototype

Readout Box prototype
from 3D-printed aluminum alloy

U-shaped support ring





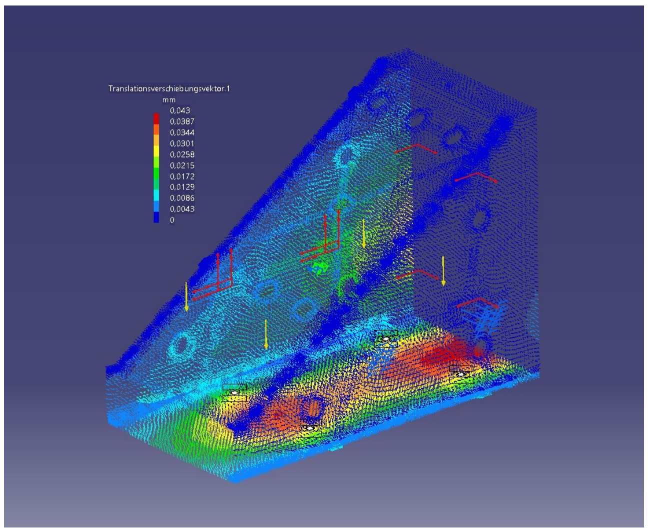


- Prototypes produced from industry
- Assembly procedure to be developed
- Results to be compared with
  finite element analysis calculations

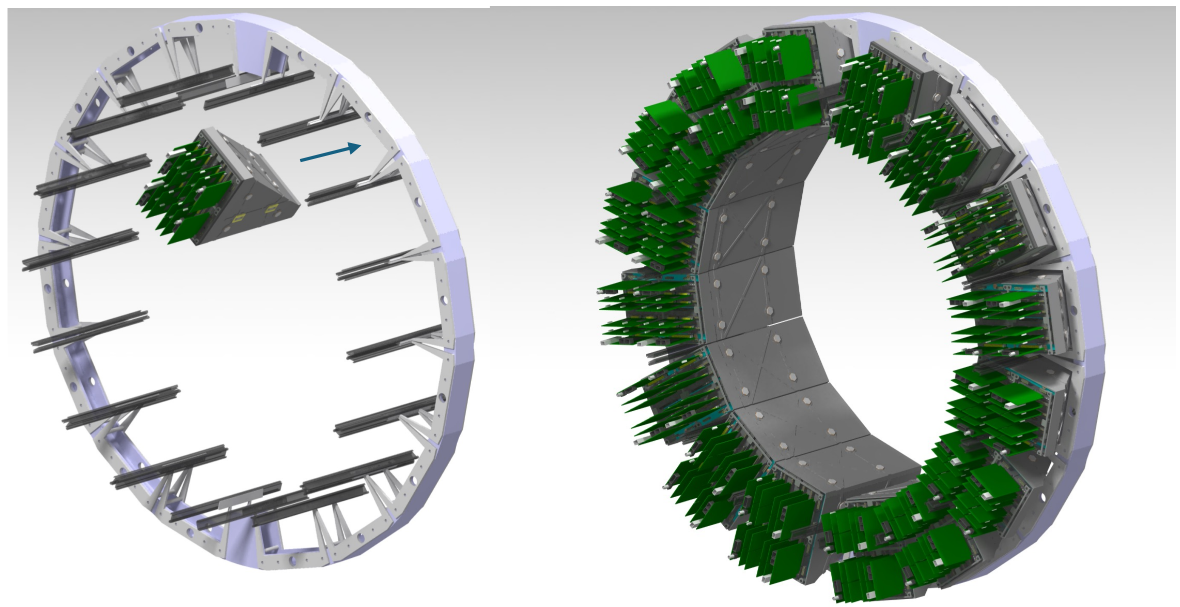
Barrel DIRC: Assembly Procedure

Readout Box prototype
from 3D printed aluminum alloy

U-shaped support ring

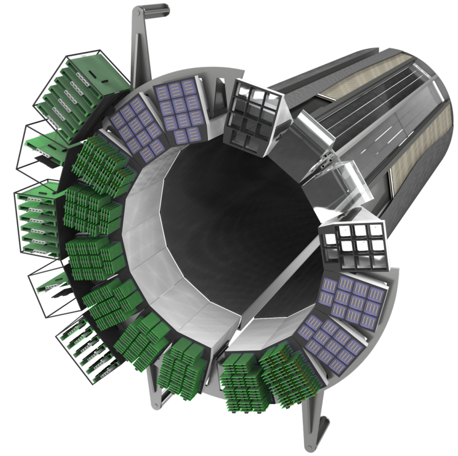


max. deformation (< 0.1mm)
caused by the load of the prism



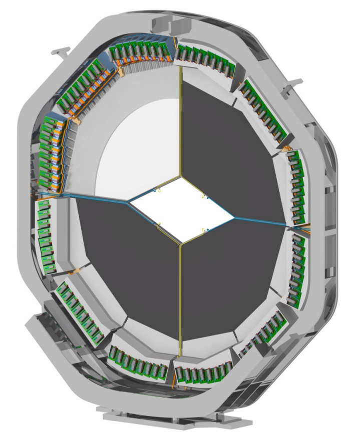
- Prototypes produced from industry
- Assembly procedure to be developed
- Results to be compared with
  finite element analysis calculations

The PANDA DIRCs are key components for the PANDA physics program



Barrel DIRC TDR: J. Phys. G: Nucl. Part. Phys. 46 045001, arXiv:1710.00684

- First DIRC with lens focusing
- Performance proved in beam tests
- All radiator bars delivered by Nikon, Japan
- Delivery of MCP-PMTs by Photonis, Netherlands is ongoing
- Assembly procedure to be tested with prototype components



Endcap Disc DIRC TDR: F Davì et al 2022 J. Phys. G: Nucl. Part. Phys. 49 120501

- First DIRC in the Endcap
- Promising beam tests with MCP-PMTs with asymmetric pitch

Thank you very much for your attention

View into a DIRC bar with 442nm Laser light

PANDA Cherenkov Group