Both PANDA DIRC counters have made excellent progress since RICH2016:

- Technical designs have been completed, moving from design to construction stage.
- Installation scheduled for 2023, commissioning for 2024.

- PANDA at FAIR
- DIRC Concept
- PANDA Barrel DIRC
- PANDA Endcap Disc DIRC
- Outlook
THE PANDA EXPERIMENT AT FAIR

Facility for Antiproton and Ion Research at GSI near Darmstadt, Germany

➢ FAIR Accelerator Complex
➢ PANDA Experiment
➢ Barrel DIRC and Endcap Disc DIRC

High Energy Storage Ring
• $5 \times 10^{10}$ stored cooled antiprotons
• 1.5 to 15 GeV/c momentum
• Interaction rate up to 20MHz
• Cluster jet / pellet target
  • High luminosity mode
    $\Delta p/p \approx 10^{-4}$ (stochastic cooling)
    $L = 1.6 \times 10^{32}$ cm$^{-2}$s$^{-1}$
  • High resolution mode
    $\Delta p/p \approx 5 \times 10^{-5}$ (electron cooling)
    $L = 1.6 \times 10^{31}$ cm$^{-2}$s$^{-1}$
FAIR construction making good progress

(snapshots from recent drone video
https://youtu.be/NN_1t2mrgUI)
Antiprotons – Unique Probes for Discoveries and Precision Physics

**PANDA Physics Program**

Examples: charged kaon phase space for 16 benchmark channels (DPM)
- antiproton momentum: 4 GeV/c
- antiproton momentum: 15 GeV/c

**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

*plus* very compact detector design → excellent case for DIRC counters
PANDA: two innovative DIRC detectors for hadronic PID

• **Barrel DIRC**
  First DIRC with lens focusing.
  Goal: 3 s.d. $\pi/K$ separation up to 3.5 GeV/c

• **Endcap Disc DIRC**
  First DIRC for detector endcap region.
  Goal: 3 s.d. $\pi/K$ separation up to 4 GeV/c

Required PID performance great match to DIRC technology
→ BaBar DIRC achieved 3 s.d. $\pi/K$ sep. up to 4 GeV/c
Combination of Barrel and Endcap Disc DIRC: full coverage
DIRC Concept

DIRC counters have been part of every RICH workshop since inaugural meeting in Bari 1993§. Four DIRC talks this year – still, a brief reminder of the DIRC basics never hurts.

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

- 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)

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- 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.

• 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 $\theta_c$, $\phi_c$, $t_{\text{propagation}}$.

• Ultimate deliverable for DIRC: PID likelihoods.

DIRC hit patterns are not your typical Cherenkov rings.

Different DIRCs use different reconstruction approaches to provide likelihood for observed hit pattern (in detector space or in Cherenkov space) to be produced by $e/\mu/\pi/K/p$ plus event/track background.

DIRCs require momentum and position of particle measured by tracking system.
RICH 2007: scaled version of BABAR DIRC
- Radiators: 96 narrow fused silica bars, 2.5m length
- Expansion volume: large water tank
- Sensors: ~7,000 conventional PMTs

Fast simulation: design meets PANDA PID goals.
But: increasingly complex PANDA detector design
required compact imaging region inside magnet yoke

RICH 2013: compact photon camera
- Radiators: 80 narrow fused silica bars, 2.5m length
- Expansion volume: 30 cm-deep tank (mineral oil)
- Sensors: ~15,000 channels of MCP-PMTs
- Focusing: spherical lenses

Detailed simulation: design meets PANDA PID goals.
But: production cost ~50% over budget.

Needed additional cost/performance optimization – cost driver: fabrication of bars and MCP-PMTs.
Main results of a comprehensive cost performance optimization in simulation:
use wider bars (3 per bar box instead of 5) and compact fused silica prisms;
40% fewer bars, 37% fewer MCP-PMTs, lower cost at no performance loss.
Conservative design – similar to proven BABAR DIRC, validated in particle beams in 2015.

Excellent performance, robust, little sensitivity to backgrounds and timing deterioration. Modular design for easy access and optional staged installation of bar boxes.

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
  ~11,000 channels of lifetime-enhanced MCP-PMTs

- **Fast FPGA-based photon detection**.
  ~100ps per photon timing resolution

- **Expected performance (simulation and particle beams)**:
  better than 3 s.d. $\pi/K$ separation for entire acceptance.

For more detail, see PANDA Barrel DIRC TDR, arXiv:1710.00684
Multi-layer spherical lens

Standard fused silica lens with air gap would create large hole in DIRC acceptance for track polar angles for 75-105° (photon captured in lens by internal reflection).

Innovative design: refraction between higher-refractive index material and fused silica.

Solution for PANDA Barrel DIRC:
- lanthanum crown glass (LaK33B) as middle layer in 3-layer lens, focusing/defocusing radii inside lens designed to match prism surface.

\( \lambda = 380\text{nm}: \text{fused silica: } n \approx 1.473, \text{LaK33B: } n \approx 1.786 \)

Prototype built by industry, tested with lasers in lab and with PANDA Barrel DIRC prototype using particle beams at CERN.

Photon yield, resolution, and shape of focal plane agree with simulation, hole in acceptance closed.

(Note that NLaK33B is “radiation hard enough” for PANDA [expected 10 year dose <5Gy] but not for EIC DIRC. Currently investigating alternatives: PbF₂, sapphire, ...)

![Simulation of focal plane of 3-layer lens](image)

![Barrel DIRC: Key Technology](image)
Sensor of choice for PANDA DIRCs: MCP-PMTs (due to 1T magnetic field, high rate, low noise, timing precision)

Lifetime of MCP-PMTs was potential showstopper for Belle II and PANDA until a few years ago.

Recent MCP-PMTs with atomic layer deposition technique exceed requirements for the PANDA DIRC counters.
Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Used geometrical reconstruction (BABAR-like) to determine photon yield and single photon Cherenkov angle resolution (SPR).

Latest generation of MCP-PMTs expected to further increase photon yield by up to 50%.

Yield and SPR reach performance goal.

BABAR DIRC FOMs reached or even exceeded, in particular for most demanding high-momentum forward region.
Final design, 3 bar per bar box, 3-layer spherical lens, prism

Log-likelihood difference from time-based imaging (similar to Belle II TOP)

\[ N_{\text{sep}} = \frac{|\mu_1 - \mu_2|}{0.5(\sigma_1 + \sigma_2)} \]

kaon phase space for 7 GeV/c
3 s.d. PID goal

Design meets PID requirements
- for geometric reconstruction
- for time-based imaging (even better performance)

Log-likelihood difference from time-based imaging (similar to Belle II TOP)

Geant simulation, time-based imaging, \( \sigma_t = 100\text{ps} \)
J. Schwiening, GSI  |  The PANDA DIRC Detectors  |  RICH 2018  |  Moscow, Jul/Aug 2018

BARREL DIRC BEAM TESTS

2008, 2009: GSI

2011: GSI, CERN

2012: CERN


2012: CERN


2012: CERN


2012: CERN

Beam test at CERN PS/T9

- Fused silica prism as expansion volume.
- 4 x 3 array of PHOTONIS Planacon XP85012 MCP-PMTs.
- Narrow bar or wide plate as radiator.
- 3-layer spherical or cylindrical lenses.
- Momentum and angle scans similar to PANDA phase space.
- Goal: PID validation of near-final design (also: test of EIC DIRC lens)
T9 beamline: mixed hadrons (mostly $\pi$ and p), available momentum range 1.5-10 GeV/c

Most measurements at 7 GeV/c – $\pi$/p Cherenkov angle difference (8.1 mrad) approx. same as $\pi$/K at 3.5 GeV/c (8.5 mrad).

Scintillators for trigger (T1-3) and beam spot selection in combination with fiber hodoscope.

Time-of-flight system

Two TOF stations, ~28m distance

Clean tag for pions and protons up to 10 GeV/c.
PHOTONIS Planacon MCP-PMT array

Fused silica prism (33° opening angle)

Spherical 3-layer lens

Narrow bar (35mm width)

Diffuser for PiLas laser pulser
Examples of the Hit Pattern

- 20 degree polar angle
- pions and protons @ 7 GeV/c
- bar + 3 layer spherical lens

- beam data with proton tag
- beam data with pion tag
- geant simulation for pions
Photon yield and single photon Cherenkov angle resolution (SPR) at 7 GeV/c (equivalent to 3.5 GeV/c π/K).

Geometric (“BaBar-like”) reconstruction method.

Very good agreement with detailed prototype Geant simulation.

Calibration of data still ongoing
All results still preliminary
Separation power ($N_{\text{sep}}$) for TOF-tagged pions and protons at 7 GeV/c (equivalent to 3.5 GeV/c $\pi/K$).

Time-based imaging reconstruction method, PDFs from beam data (250ps average timing precision).

PID performance exceeds PANDA requirements, validates narrow bar/spherical lens design.

Result extrapolates to 6.6 s.d. $\pi/K$ at 3.5 GeV/c, 22 deg for fully equipped PANDA Barrel DIRC (simulation with 100 ps timing).
Cost-optimized design completed, performance validated in particle beams

TDR available at arXiv:1710.00684, accepted for publication by Journal of Physics G

Optimizing simulation and reconstruction code with experimental data at GlueX DIRC (‘‘FAIR Phase 0’’) → see talk by M. Patsyuk today.

Starting construction phase, first round of call for tenders this summer.

2018-2023: Component Fabrication, Assembly, Installation

• 2018/2019: Finalize specifications, MoUs, call for tenders and contracts
• 2019-2021: Industrial fabrication of main components (sensors, bars, lenses, prisms)
• 2019-2020: Production and QA of readout electronics
• 2019-2022: Industrial fabrication of bar boxes and mechanical support frame; QA of all components; gluing of long bars, assembly of complete sectors
2023/2024: Installation in PANDA, commissioning
RICH 2007: two design options

- Time-of-Propagation design
  linear array of pixels, very fast photon timing
dichroic mirrors for dispersion mitigation

- Focusing Lightguide design
  2D pixels plus fast photon timing and focusing
  LiF block for dispersion mitigation

- Radiator: single large plate

Both designs showed potential to reach required performance.

RICH 2013: merged into compact 3D design

- Radiator: four optically isolated quadrants
- Imaging: 2D spatial plus fast timing
- Sensors: (d)SiPMs or MCP-PMTs
- Focusing: cylindrical focusing elements
- Fits into tight available space in PANDA endcap

Detailed simulation: design meets PANDA PID goals.
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)

Optical band pass filter for chromatic dispersion mitigation

TOFPET ASIC readout ~30k channels

Beam tests at CERN in 2015 and at DESY in 2016 validated basic performance parameters.
TDR recently completed
\[ \theta_c = \arccos \left( \sin \theta_p \cos \phi_{rel} \cos \varphi + \cos \theta_p \sin \varphi \right) \]
• Thin design for very tight forward endcap space in PANDA
• Large plate surfaces parallel with excellent polish (<1.5nm \( rms \))
• Tight tolerances on dimensions
• Lightguide bars of different lengths needed to place spherical focusing elements into available locations

• Custom 2” MCP-PMTs, asymmetric pixels
• Optical filter to limit photon wavelength range \( \rightarrow n(\lambda) \)
• Optical contact bonding for best possible transmission
• Position resolution better than 150 \( \mu m \)
EDD: Key Technology

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

Single photon sensitivity in high magnetic field (~1T) with long lifetime (~7C/cm²), fast timing (<100ps)

(d)SiPM initially a promising candidate but rejected due to concerns about radiation hardness.

Obtained prototype 2” MCP-PMTs from Hamamatsu and PHOTONIS

Options with custom photocathode available.

Excellent gain and timing performance.

Charge sharing suppressed in magnetic field.

Tubes meet position resolution requirement.

Both good candidates for the PANDA EDD.
• simulation expects about 20 detected photons per charged particle
• the target of 3 s.d. separation power will be achieved for almost the entire active area
Common features:
- fused silica optics
- 50x50x2 cm³ radiator
- MCP-PMTs with high anode granularity

- mixed hadron beam up to 10 GeV/c
- TRBv3 readout
- 3 GeV/c electron beam
- TOFPET ASIC readout
- fully equipped ROM
• single photon resolution of 5.7 mrad was measured
• $5\sigma$ $\pi/p$-separation at 3 GeV/c with single photons

• Cherenkov pattern observed
• resolution of both testbeam campaigns limited by tracking and chromatic dispersion
- photon yield for single MCP-PMT column in agreement with MC data
- increase at 12° due to overlapping Cherenkov patterns (side reflection)
- good agreement for single photon resolution for all angles and positions
- fluctuations are caused by different paths inside the FEL
Photon yield and single photon resolution in good agreement with MC predictions.

- "Combined event" data set is constructed by combining events from different vertical positions to overcome limitation of single sensor/FEL.

- Photon yield and single photon resolution in good agreement with MC predictions.

- Cherenkov angle resolution “per particle” obtained: 2.5 mrad for data (2.2 mrad Geant).

- Performance meets PANDA PID requirements.
• The main technical challenges have been solved (optics, photon sensors, readout)
• Final detector design has been described in a Technical Design Report
• Readout very compact to meet spatial requirements in PANDA

• Goal is to build a full size prototype quadrant until 2021
• Installation of full detector for phase 2 of PANDA in 2025
Both PANDA DIRC prototypes currently in T9 beamline at CERN PS until Aug 15, 2018.

→ direct measurement of PID performance across PANDA phase space
→ test cost-saving design options
CONCLUSION

The PANDA DIRC counters are key components for the PANDA physics program. The designs have matured and both detectors are now moving on to the construction phase. Looking forward to reporting on the component fabrication progress at the next RICH.

On behalf of the PANDA Cherenkov group, especially the team currently taking exciting DIRC data at the CERN PS:

Thank you all for your attention.
THE PANDA EXPERIMENT AT FAIR

Phase-0


Phase-1

start setup

design

construction

PANDA Hall available

installation

commissioning with protons

physics as soon as antiprotons become available

Phase-2

full setup

design

construction

installation

physics

Phase-3

RESR included
OPTICAL COMPONENTS

- Radiator prototype program with industry partners in Europe, USA, Japan;
  ~30 bars/plates produced by 8 companies using different materials and techniques
  (pitch polishing, abrasive polishing, even new idea: extrusion and flame polishing).
  → AOS/Okamoto, InSync, Nikon, Zeiss, Zygo; Heraeus, Lytkarino LZOS, Schott Lithotec.

- 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,
  several prototypes built by industry.
SENSOR CANDIDATES

• Multi-anode Photomultipliers (MaPMTs)
  used successfully in DIRC prototypes,
  sensors of choice for SuperB FDIRC, GlueX DIRC
  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
  used to have issues with rate capability and aging, now solved;
  sensors of choice for Belle II TOP and PANDA DIRCs.
Readout Electronics

~100ps timing per photon for small MCP-PMT pulses – amplification and bandwidth optimization

20MHz average interaction, trigger-less DAQ

Current approach: HADES TRBv3 board with PADIWA amplifier/discriminator.

Near future: DiRICH, integrated backplane, joint development with HADES/CBM RICH.

Mechanical Design

Light-weight and modular, allows staged bar box installation, access to inner detectors.

Mechanical support elements made from aluminum alloy or carbon fiber (CFRP).

Boil-off nitrogen flush for optical surfaces.
## Barrel DIRC Counters

<table>
<thead>
<tr>
<th></th>
<th>BABAR DIRC</th>
<th>BELLE II TOP</th>
<th>PANDA BARREL DIRC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiator geometry</strong></td>
<td>Narrow bars (35mm)</td>
<td>Wide plates (450mm)</td>
<td>Narrow bars (53mm)</td>
</tr>
<tr>
<td><strong>Barrel radius</strong></td>
<td>85cm</td>
<td>115cm</td>
<td>48cm</td>
</tr>
<tr>
<td><strong>Bar length</strong></td>
<td>490cm (4×122.5cm)</td>
<td>250cm (2×125cm)</td>
<td>240cm (2×120cm)</td>
</tr>
<tr>
<td><strong>Number of long bars</strong></td>
<td>144 (12×12 bars)</td>
<td>16 (16×1 plates)</td>
<td>48 (16×3 bars)</td>
</tr>
<tr>
<td><strong>Expansion volume</strong></td>
<td>110cm, ultrapure water</td>
<td>10cm, fused silica</td>
<td>30cm, fused silica</td>
</tr>
<tr>
<td><strong>Focusing</strong></td>
<td>None (pinhole)</td>
<td>Mirror (for some photons)</td>
<td>Spherical lens system</td>
</tr>
<tr>
<td><strong>Photodetector</strong></td>
<td>~11k PMTs</td>
<td>~8k MCP-PMT pixels</td>
<td>~11k MCP-PMT pixels</td>
</tr>
<tr>
<td><strong>Timing resolution</strong></td>
<td>~1.5ns</td>
<td>&lt;0.1ns</td>
<td>~0.1ns</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>25mm diameter</td>
<td>5.6mm×5.6mm</td>
<td>6.5mm×6.5mm</td>
</tr>
<tr>
<td><strong>PID goal</strong></td>
<td>3 s.d. π/K to 4 GeV/c</td>
<td>3 s.d. π/K to 4 GeV/c</td>
<td>3 s.d. π/K to 3.5 GeV/c</td>
</tr>
<tr>
<td><strong>Timeline</strong></td>
<td>1999 - 2008</td>
<td>Installed 2016</td>
<td>Installation 2022/23</td>
</tr>
</tbody>
</table>
DIRC LIMITS

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

(For momenta well above threshold.)

**π/K separation**

**Refractive Indices**

- solid RICH - DIRC: n=1.473 (Fused Silica)
- liquid RICH: n=1.27 (C₆F₁₄ CRID)
- aerogel RICH: n=1.02 (Typical Silica Aerogel)
- gas RICH: n=1.001665 (C₃F₁₂/N₂ CRID Mix)

**σ[θₑ(tot)]**

- 2 mrad
- 1 mrad
- 0.5 mrad

DIRC provides good π/K separation potential significantly beyond 4 GeV/c. Large refractive index limits effective momentum range to below 10 GeV/c.
After BaBar, next-generation DIRC R&D directions could roughly be divided into three imaging approaches using different focusing optics

- **moderate timing, (very) good spatial resolution**
  examples: fDIRC, GlueX DIRC, early PANDA Barrel DIRC
  100-200 ps photon timing, array of (~6mm) 2D pixels → PID primarily based on spatial imaging

- **very fast timing, moderate/poor spatial resolution**
  examples: early Belle II TOP design, early PANDA Disc DIRC design
  ~50 ps photon timing, (~5mm) 1D pixels → PID primarily based on time imaging

- **very fast timing, very good spatial resolution**
  examples: “ultimate fDIRC”, EIC High-Performance DIRC
  <100 ps photon timing, large array of (~3mm) 2D pixels → PID uses full 3D imaging

**Final designs for PANDA DIRCs (and Belle II TOP) are hybrids derived from these initial approaches.**
Chromatic correction using 3D tracks and real bar box in CRT.

Backward photons, long paths

\[
\text{dTOP}/L_{\text{path}} = (\text{TOP}_{\text{measured}} - \text{TOP}_{\text{expected}})/L_{\text{path}}
\]

Data

MC

No chromatic correction

\(\sigma \sim 10.9\text{ mrad}\)

With chromatic correction

\(\sigma \sim 10.0\text{ mrad}\)

Clear improvement of single photon Cherenkov angle resolution, \(~0.8\text{ mrad}\), even with very modest timing precision.

Used three methods to evaluate PID performance of geometry with the narrow bar

- **track-by-track fit** of single photon Cherenkov angle distribution to extract track Cherenkov angle (geometric reconstruction)

- **track-by-track unbinned likelihood hypothesis test** to extract log-likelihood differences (geometric reconstruction)

- **time-based imaging** to extract log-likelihood differences (PDFs were generated from beam data directly using time-of-flight tag, statistically independent data sets)