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for the PANDA Cherenkov Group

- PANDA at FAIR
- Barrel DIRC Technical Design
- PID Performance Validation
- Outlook

The PANDA Cherenkov Group:
THE PANDA EXPERIMENT AT FAIR

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

- FAIR Accelerator Complex
- PANDA Experiment
- Barrel DIRC Detector

High Energy Storage Ring
- \(5 \times 10^{10}\) stored cooled antiprotons
- 1.5 to 15 GeV/c momentum
- Cluster jet / pellet target
- High luminosity mode
  \(\Delta p/p \approx 10^{-4}\) (stochastic cooling)
  \(L = 1.6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
- High resolution mode
  \(\Delta p/p \approx 5 \times 10^{-5}\) (electron cooling)
  \(L = 1.6 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}\)
Study of QCD with Antiprotons

Non-perturbative QCD

Hypernuclei

Precision Hadron Spectroscopy

Exotic States (Glueballs, Hybrids)

In-Medium Modifications

Nucleon Structure

Excellent PID required
PANDA: two DIRC detectors for hadronic PID

- **Barrel DIRC**
  German in-kind contribution to PANDA
  Goal: 3 s.d. $\pi/K$ separation up to 3.5 GeV/c

- **Endcap Disc DIRC**

  Goal: 3 s.d. $\pi/K$ separation up to 4 GeV/c

PANDA is back on track; installation to start in 2021.
Initial approach: 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

Improved design: 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 cost/performance optimization – cost driver: fabrication of bars and MCP-PMTs.
Baseline Design

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.
BASELINE DESIGN

Baseline design – compact fused silica prisms, 3 bars per bar box, spherical lenses.

- 48 radiator bars (16 sectors), synthetic fused silica, *(instead of 80 bars in DIRC2015 design)*
  - 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 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.

Conservative design – similar to proven B\(\text{A}\)B\(\text{A}\)R DIRC, baseline design for TDR.

Excellent performance, robust, little sensitivity to backgrounds and timing deterioration.
Caveat: still ~20% over budget. *(USD/€ exchange rate recently not our friend...)*
EXPECTED PERFORMANCE: BASELINE

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)

Yield and SPR reach performance goal.

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

Expected Performance: Baseline

Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Barrel DIRC PID 3 s.d. goal
(from kaon phase space)

Design meets PID requirements
• for geometric reconstruction

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

Geant simulation, geometric reconstruction

(green color: ~ 3 s.d. separation)
EXPECTED PERFORMANCE: BASELINE

Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

from earlier: kaon phase space for 7 GeV/c

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Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Expected Performance: Baseline

Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Barrel DIRC PID 3 s.d. goal
(from kaon phase space)

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

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

Geant simulation, time-based imaging, \( \sigma_t = 100\text{ps} \)
Second cost optimization result: geometry based on wide plates.

Replacing 3 bars/bar box with 1 wide plate saves significant fabrication costs.

- 16 radiator plates (16 sectors), synthetic fused silica \((\text{instead of 48 narrow bars})\)
  \(17\text{mm} \times 160\text{mm} \times 2400\text{mm}\).

- **Focusing optics**: triplet cylindrical lens system
  (or no lens – to be determined)

- **Expansion volume and readout same as baseline.**

- **Expected performance (according to simulation):**
  better than 3 s.d. \(\pi/K\) separation for entire acceptance.

- Included in TDR as design option.

Wide plate design would fit our budget – but it is no longer a “BABAR-like” DIRC.

- Geometric reconstruction approach unavailable, have to rely on time-based imaging PDFs.
- Design is more sensitive to timing precision and backgrounds than narrow bars.
- Needed to be validated with particle beams.
EXPECTED PERFORMANCE: PLATE OPTION

Cost-saving option, 1 plate per bar box, cylindrical lens

\( \pi/K \) separation power from time-based imaging (Belle II-like algorithm, PDFs from simulation).

Wide plate with focusing exceeds PID requirements for entire acceptance range.

(Performance somewhat worse than narrow bar design.)

![Geant simulation](green color: ~ 3 s.d. separation)
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.

• Three solid fused silica prism prototypes (30°, 33°, 45° top angle) built by industry (AGI).

• Designed several spherical and cylindrical lenses, with and without air gap,
  2-layer and 3-layer prototypes built by industry.
FOCUSING LENSES

2-layer and 3-layer lenses → minimize photon loss at bar/lens/expansion volume transition.

Prototypes built by industry and tested in lab and with particle beams.

Good imaging properties – but radiation hardness of lanthanum crown glass (LaK33B)?

Irradiation test with X-rays ongoing (DIRC@EIC R&D, eRD14 PID consortium);

Initial result: LaK33 is sufficiently radiation hard for PANDA (10 year dose @ lens: <5Gy).

shape of focal plane in Geant simulation for 3-layer spherical lens

G. Kalicy, talk this afternoon
FOCUSING LENSES

2-layer and 3-layer lenses → minimize photon loss at bar/lens/expansion volume transition.

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Accumulated dose for PANDA Barrel DIRC (10 years nominal operation, simulation) [Gy]

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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 both 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.

For PANDA: 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.

➢ M. Traxler, talk tomorrow morning
BARREL DIRC BEAM TESTS

2008, 2009: GSI

2011: GSI, CERN

2012: CERN

2014, 2015, 2016: GSI, CERN
2015 CERN Beam Test

Beam test at CERN PS/T9 (May/June, July 2015)

- Fused silica prism as expansion volume.
- 5 x 3 array of Planacon MCP-PMTs.
- Narrow bar and wide plate as radiator.
- Many different imaging/lens configurations.
- Momentum and angle scans.
- ~500M triggers during 34 days of data taking.

M. Hoek, FLASH Poster
2015 CERN Beam Test

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Prototype layout 2015

Readout electronics

Narrow bar, spherical lens, prism

Wide plate, no lens, prism

2015 CERN BEAM TEST
PID performance evaluated for $\pi/p$ at 7 GeV/c.

(Close match to $\pi/K$ at 3.5 GeV/c.)

Cherenkov angle difference:

$\Delta\theta_C (\pi-p) = 8.1\text{mrad} @ 7\text{GeV/c}$

$\Delta\theta_C (\pi-K) = 8.5\text{mrad} @ 3.5\text{GeV/c}$
Hit pattern for data and simulation

36 mm-wide bar with 3-layer spherical lens, 5 GeV/c beam momentum.

Observe sharp image with expected structures, described well by simulation.

Proton image shifted by one column compared to pion image (Cherenkov angle difference).

Event selection uses fiber hodoscope, scintillator triggers and time-of-flight.

Data calibrated using picosecond laser pulser.

Specific prototype simulation, tuned to beam parameters, includes quantum efficiencies from 2D scan data for each MCP-PMT.
PERFORMANCE OF NARROW BAR

Simulation describes data quite well.

narrow bar with 3-layer spherical lens
7 GeV/c proton tag
Single photon Cherenkov angle resolution (SPR)

\(\theta_{\text{track}} = 25^\circ\)
SPR=11mrad

\(\theta_{\text{track}} = 125^\circ\)
SPR=8mrad

geometric reconstruction
Performance of Narrow Bar

narrow bar, 3-layer spherical lens

7 GeV/c proton tag

Figures of merit meet PANDA requirements

Simulation describes data reasonably well.

Some differences due to group of older, less efficient MCP-PMTs, issues with thresholds and noise in data (see hit pattern).
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 (geom. reco)

- track-by-track unbinned likelihood hypothesis test to extract log-likelihood differences (geom. reco)

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

narrow bar, 3-layer spherical lens

7 GeV/c proton tag

track-by-track Cherenkov angle fit

general reconstruction

Calculate separation power with

$\Delta \theta_C (\pi-K)=8.5\text{mrad}$

$\Delta \theta_C (\pi-K)/\sigma = 3.5\text{ s.d.} @ 25^\circ$

$\rightarrow$ meets PANDA requirement
narrow bar, 3-layer spherical lens

7 GeV/c proton tag, 25° polar angle

time-based imaging method (PDFs from beam data, timing precision ~150-300 ps)

\[ \frac{\pi}{p} \text{ separation power} = 3.6 \text{ s.d.} \]

\[(\text{equivalent to } 3.8 \text{ s.d. } \frac{\pi}{K} @ 3.5 \text{ GeV/c})\]

\[\rightarrow \text{meets PANDA requirement}\]

*Time-based imaging provides best performance for narrow bar.*

Corresponds to 5+ s.d. \(\frac{\pi}{K} @ 3.5 \text{ GeV/c}\) for the fully equipped PANDA Barrel DIRC.
Barrel DIRC beam test at CERN PS/T9
Goal: validate PID performance of cost-saving design option (wide plates)
Improved prototype layout and electronics
Three weeks of beam (Oct 14-Nov 2), 500M triggers
Prototype layout 2016

T9 beamline in 2016

Readout electronics

Wide plate/lens/prism

Barrel DIRC

TOF1 (20m upstream)

Fiber hodoscope

Trigger1

Trigger2

Trigger3

TOF2
Results for data and simulation

175mm-wide plate with 2-layer cylindrical lens, 7 GeV/c beam momentum.

Plate image looks different from bar, less structure.

Pattern and photon yield agree with simulation.

(lens/prism size mismatch caused some photon loss and performance degradation)
PERFORMANCE OF WIDE PLATE

wide plate, 2-layer cylindrical lens

7 GeV/c proton tag, 25° polar angle

time-based imaging method (PDFs from beam data, timing precision ~150-200 ps)

π/p separation power = 3.1 s.d.
(equivalent to 3.2 s.d. π/K @ 3.5 GeV/c)
→ meets PANDA requirement

Wide plate without 2-layer cylindrical lens
does not quite meet PID goal (2.8 s.d. π/p separation).
Design with narrow bars, 3-layer spherical lens, and compact prisms meets or exceeds the PANDA PID requirements. Performance robust in terms of background and timing resolution. Simulation and PID performance validated with particle beams in 2015.

Wide plate with 2-layer cylindrical lens also meets PANDA PID requirements. Performance validated with particle beam in 2016.

• **PID performance** of narrow bars slightly better than for wide plates.
• **System cost** of narrow bar design ~15% higher than for wide plates.
• Wide plate more sensitive to background, multiple tracks per sector, pile-up effects, and timing precision degradation.
• **Geometric reconstruction** algorithm only possible for narrow bar geometry.

Decision in favor of narrow bars, baseline design in TDR.
The PANDA Barrel DIRC design has been completed, the performance validated.

Important milestone: Technical Design Report submitted in Sep. 2016, received positive FAIR review, approval expected this month.

But: we know that we’re not done yet, exciting times are ahead.

A lot of technical issues still need to be resolved (discussions at this DIRC workshop are very helpful):

• gluing of bars, bar box assembly
• detailed design of mechanical support (CFRP bar boxes?)
• mechanical and optical coupling of bar boxes and MCP-PMTs to prism
• readout electronics (DiRICH) validation (HADES RICH) and optimization for MCP-PMTs
• ...and we all know how much fun the mass production and QA of bars and MCP-PMTs can be...
New prism, 33° opening angle
→ hit patterns closer to PANDA reality, better MCP-PMT coverage.

Will test different MCP-PMT layouts:
possible cost-reduction for PANDA.

Primary goals for Barrel DIRC prototype:

- study hit patterns for near-final prism size, compare MCP-PMT layouts
- study quality of optical coupling using silicone sheets/cookies
- new MCP-PMT/readout electronics assembly
- study time-based imaging PDFs
- study impact of azimuthal track angle
- study performance of new 3-layer cylindrical lens (with bar or plate)
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One more (final?) beam test opportunity: Aug 23 – Sep 13, 2017 at the CERN PS/T9.
New 3-layer cylindrical lens (*eRD14 funding*), important for future DIRC@EIC design.

→ improved flatness of focal plane

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One more (final?) beam test opportunity: Aug 23 – Sep 13, 2017 at the CERN PS/T9.
2017-2023: Component Fabrication, Assembly, Installation.

- 2018-2022: Industrial fabrication of bar containers and mechanical support frame; QA of bars, gluing of long bars, assembly of complete bar boxes. Detailed QA (scans, aging study) of MCP-PMTs. Assembly of readout units.
- 2022/2023: Installation of mechanical support frame in PANDA, insert bar boxes, mount readout modules. Ready as “Start Setup / Day One” detector in PANDA.

Thank you for your attention.