Status of the PANDA DIRC Detectors

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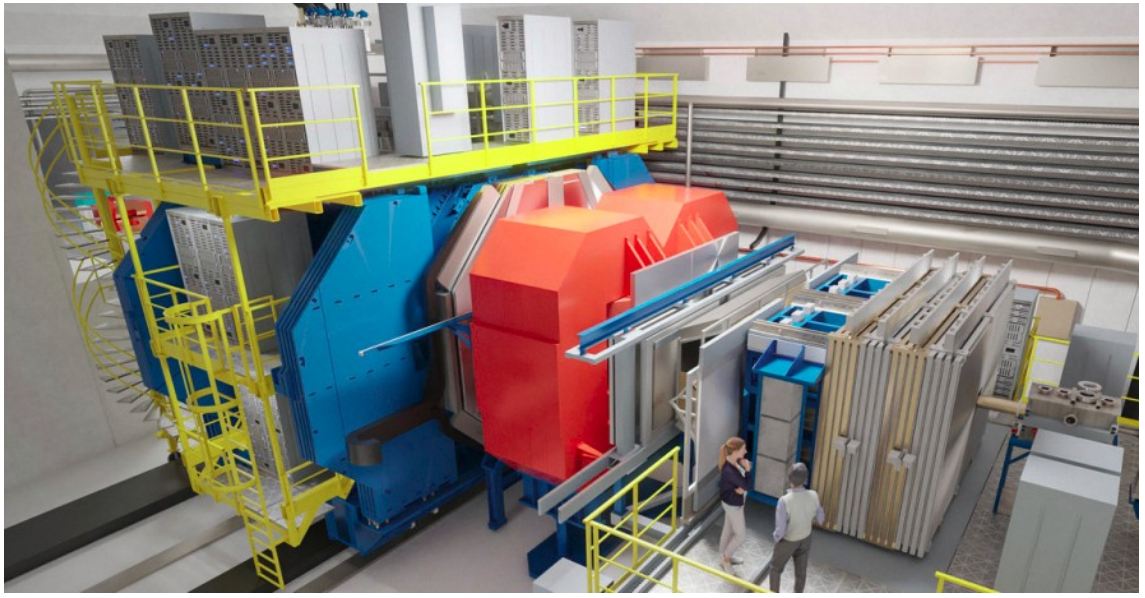
- Introduction
- Status of Endcap Disc DIRC
- Status of Barrel DIRC
  - Design and prototype tests
  - Current activities with various components
  - Status of bar and sensor series production
- Summary and outlook



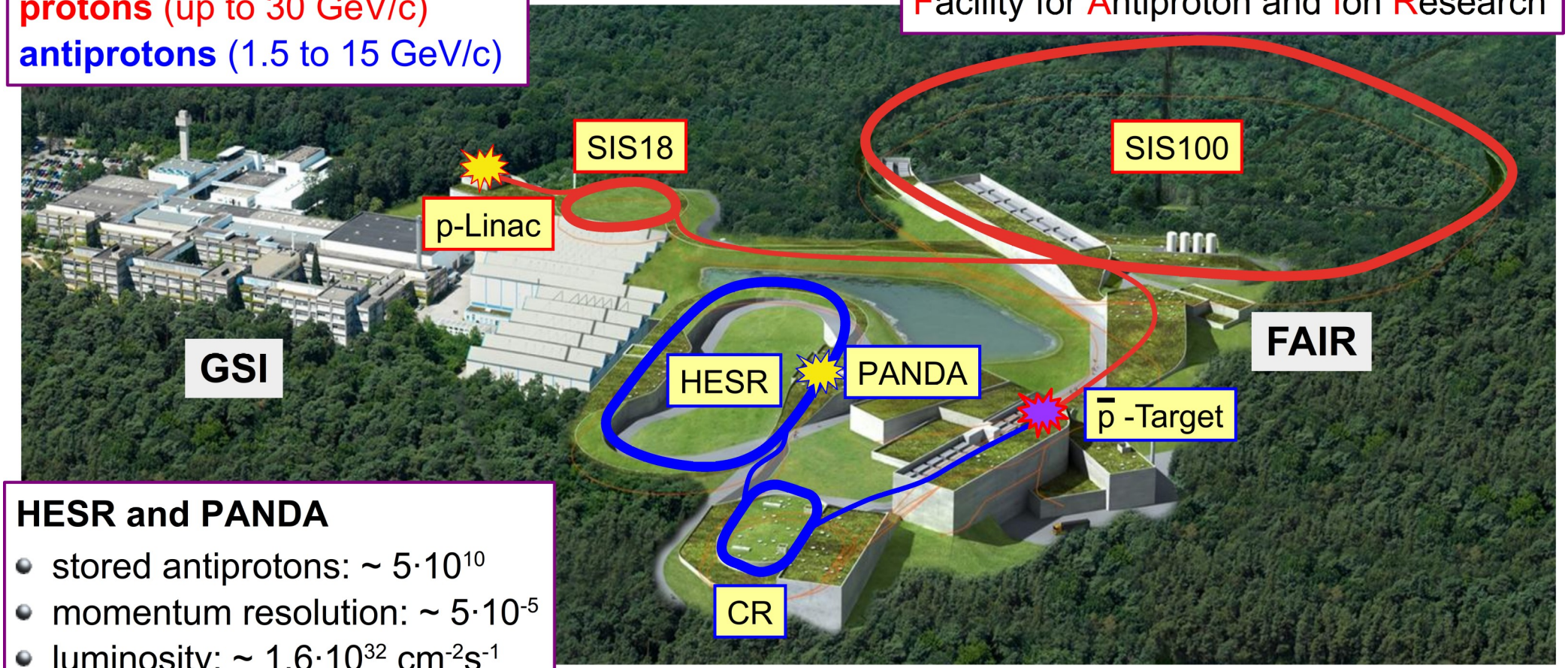
FAIR

panda

FAIR and HESR/PANDA at GSI

protons (up to 30 GeV/c)
antiprotons (1.5 to 15 GeV/c)

Facility for Antiproton and Ion Research

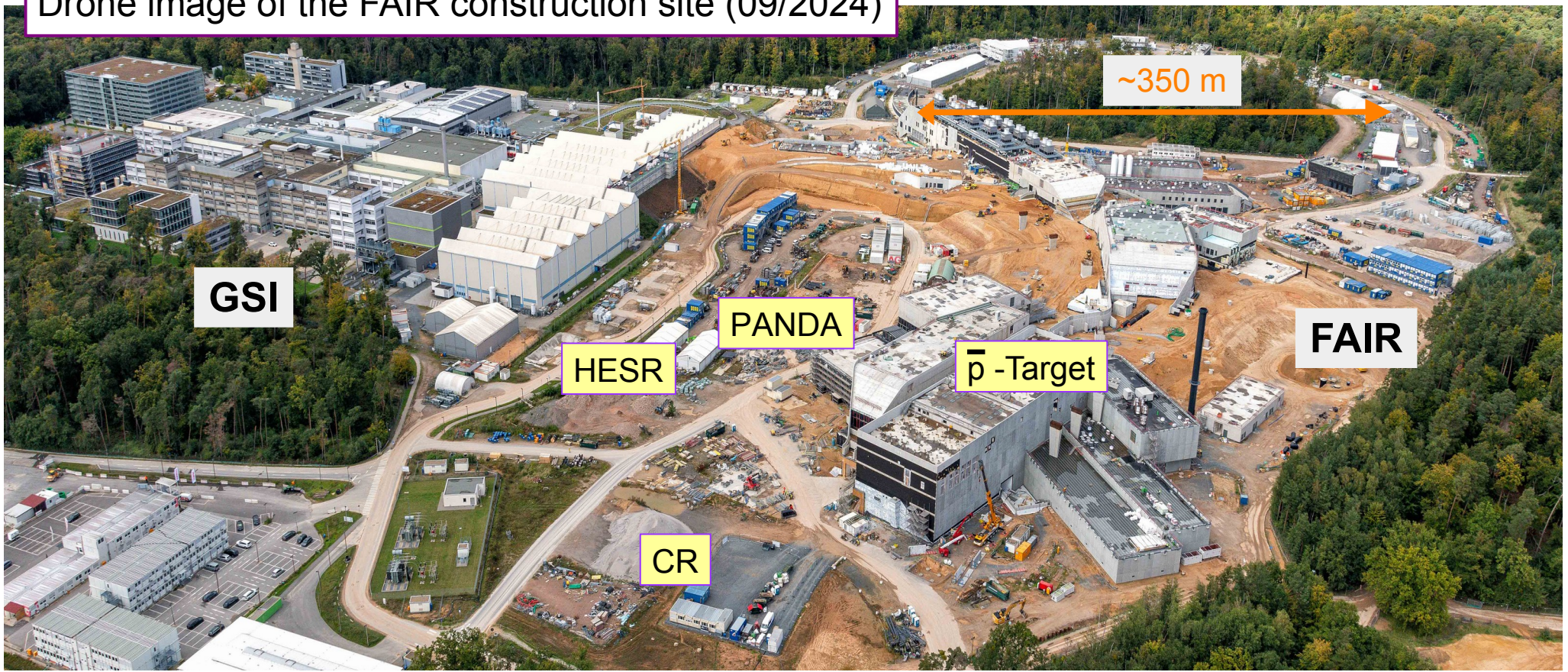


HESR and PANDA

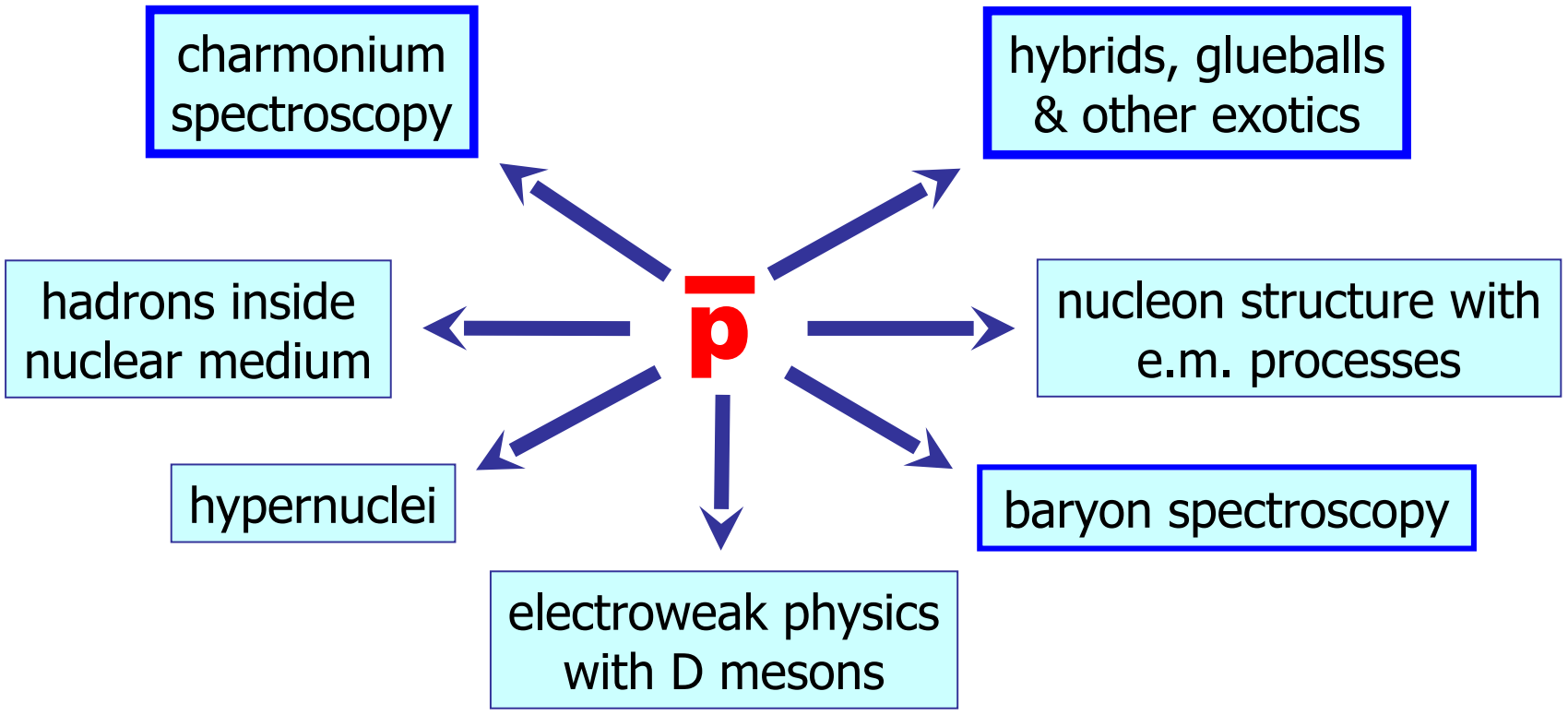
- stored antiprotons: ~ $5 \cdot 10^{10}$
- momentum resolution: ~ $5 \cdot 10^{-5}$
- luminosity: ~ $1.6 \cdot 10^{32}$ $cm^{-2}s^{-1}$

FAIR and HESR/PANDA at GSI

Drone image of the FAIR construction site (09/2024)

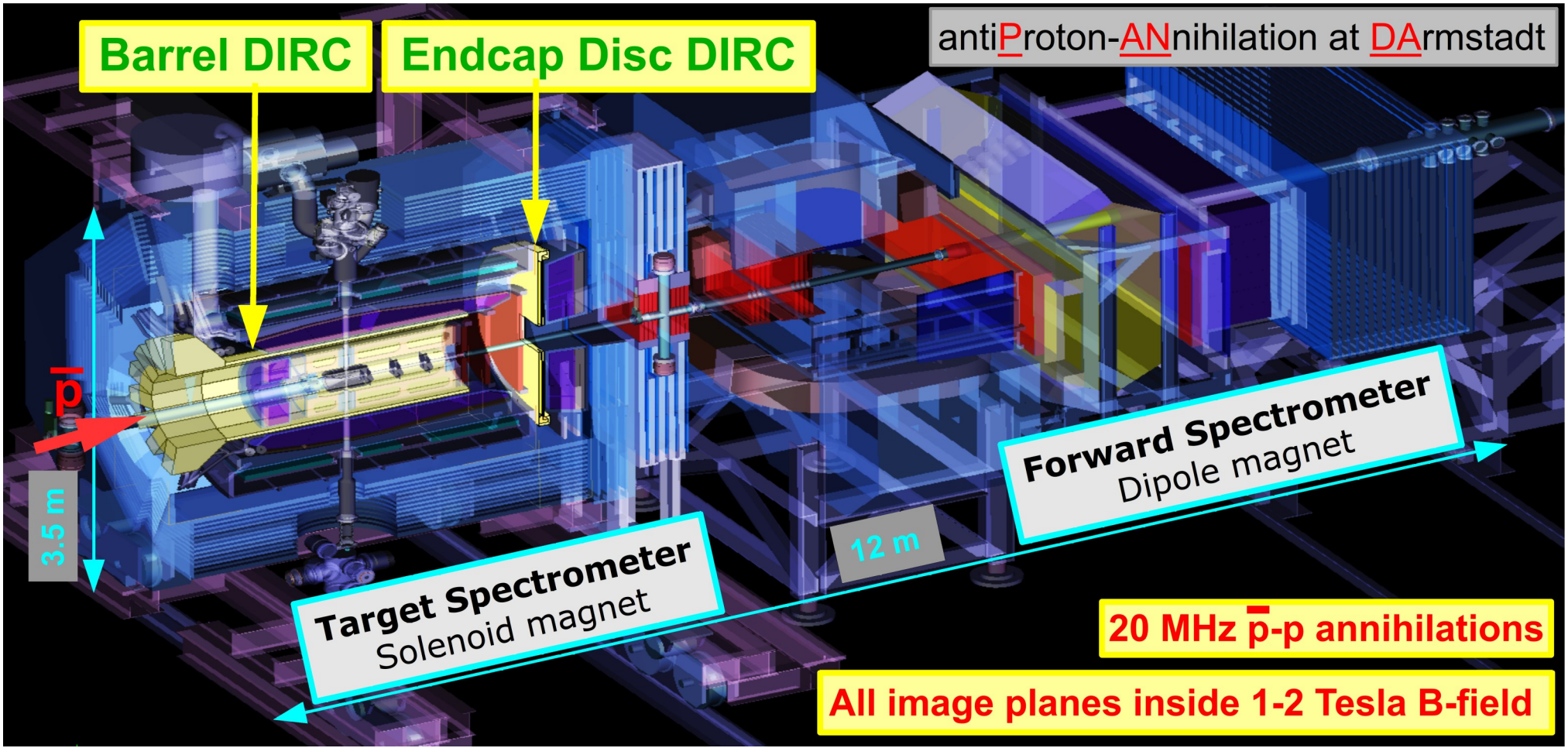


PANDA Physics Program

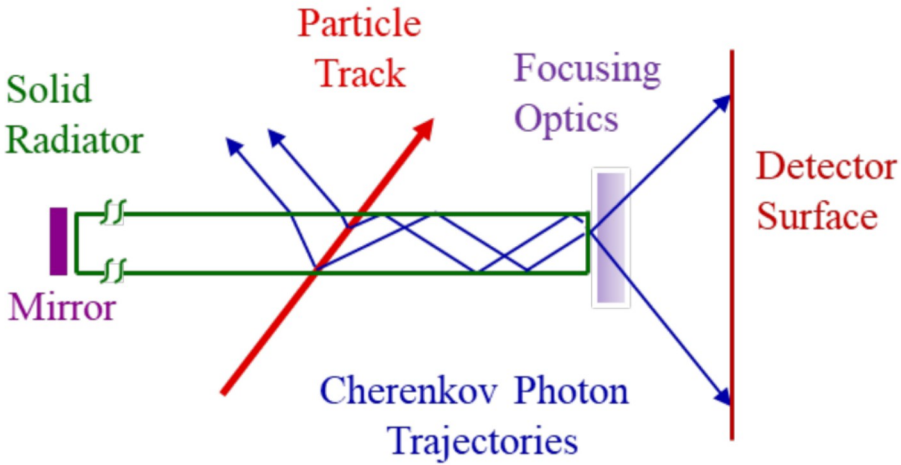


Excellent PID required, in particular π/K separation

PANDA Detector at FAIR

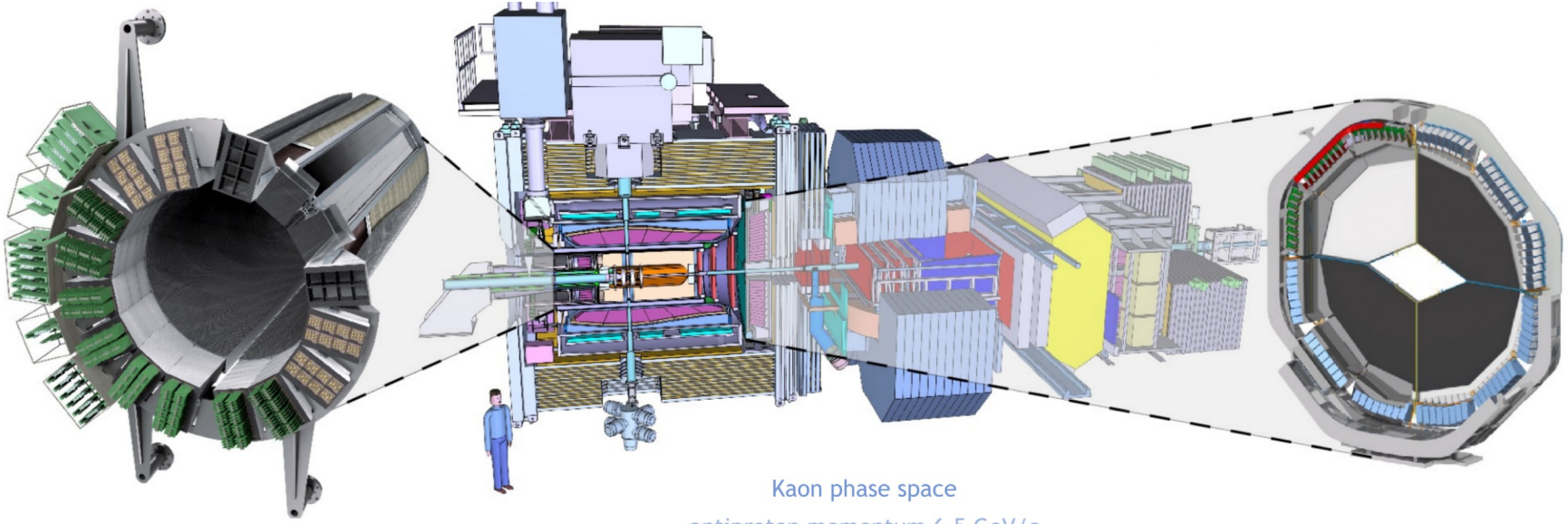


DIRC Principle

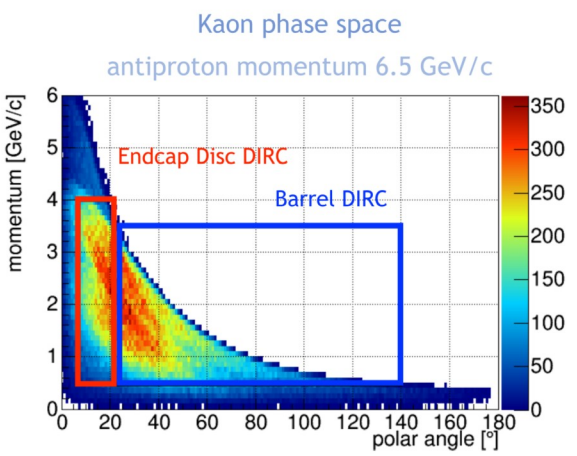


- **Radiator = light guide**
  - $\beta \approx 1$ tracks and refractive index $n > \sqrt{2}$
    → some photons are always reflected internally
  - Fulfilled by synthetic fused silica (Quartz)
  - **Bar, plate or disc**
- Cherenkov photons
  - Generated by charged particles with $\beta > 1/n$ on a cone with a half opening angle $\cos \theta_C = 1/n\beta$
  - **Cherenkov angle must be maintained after many total reflections along radiator**
    → requires highly polished optical surfaces that are exactly perpendicular and parallel
  - Reach image plane directly or via mirror reflection using focusing optics and expansion volume
- Image plane = detector surface
  - Multi-pixel array of photon detectors
  - **3D-measurement of x, y, and time of Cherenkov photons** corresponding to θ_C, φ_C and t_{top}
  - Used to calculate PID likelihoods

PANDA DIRC Detectors



- **Barrel DIRC**
  - Optimized design compared to BaBar DIRC
  - Lens focusing + prism expansion volume
  - 16 independent sectors
  - Multi-anode microchannel-plate PMTs
  - PID goal: 3σ π/K separation up to 3.5 GeV/c for a polar angle range from **22° to 140°**

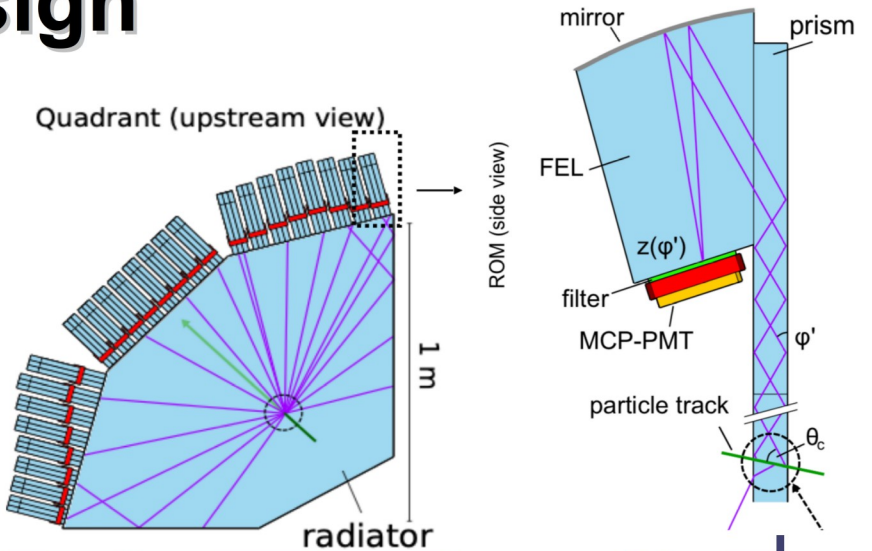


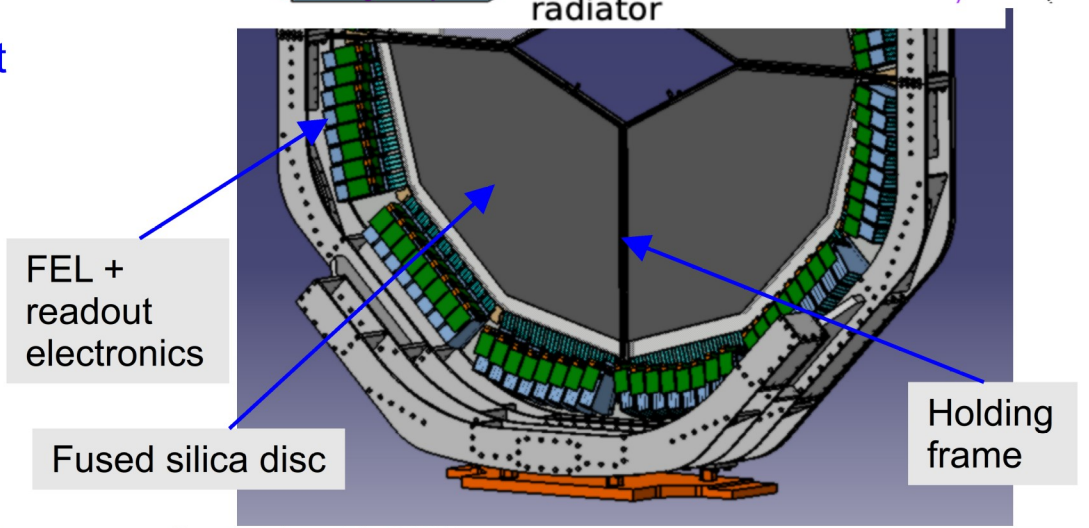
- **Endcap Disc DIRC**
  - Novel disc-shaped DIRC design
  - Special focusing elements (FEL)
  - MCP-PMTs with high pixel density
  - PID goal: 3σ π/K separation up to 4 GeV/c for a polar angle range from **5° to 22°**

Endcap Disc DIRC -- Design

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

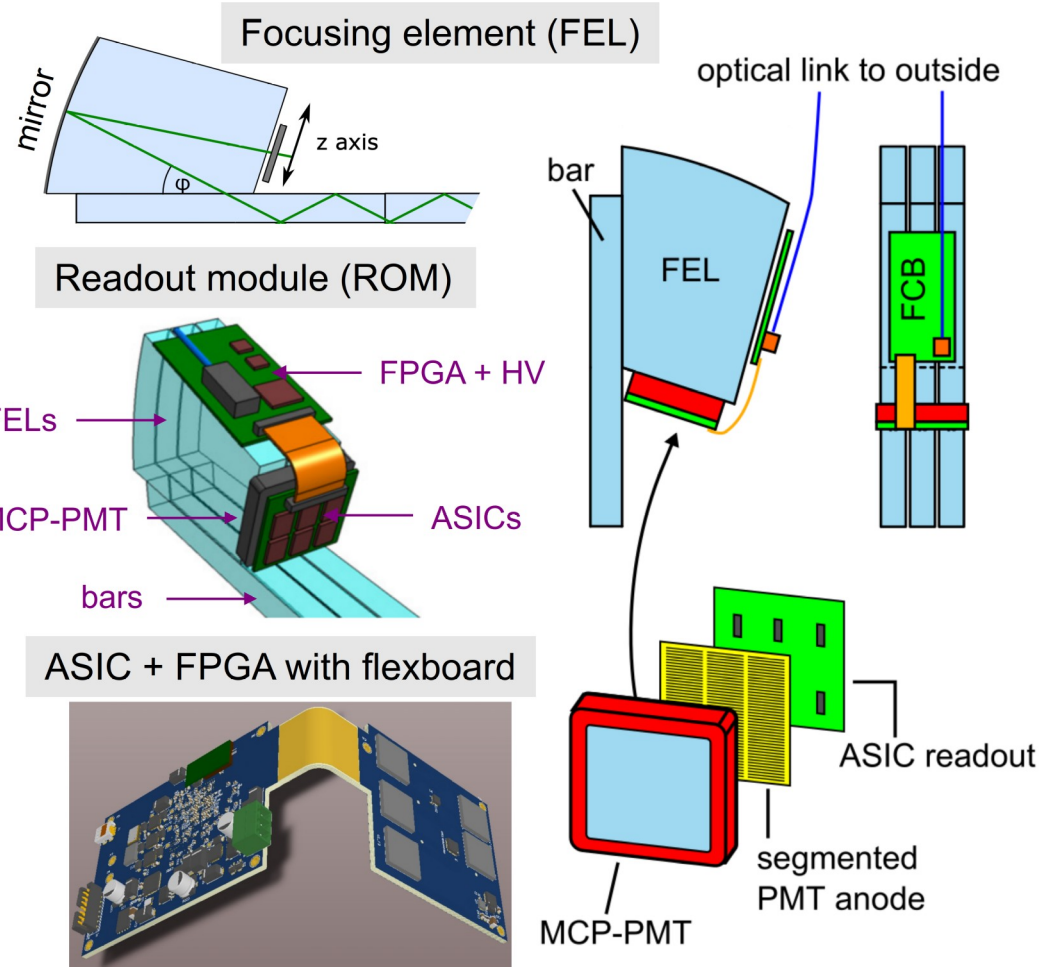
- Radiator disc (dodecagon)
  - 4 independent quadrants
  - Synthetic fused silica
  - 20 mm thickness, 1056 mm outer radius
- Frame to hold quadrants in place
  - Stabilizing cross for all 4 independent quadrants
- Optics (FEL + Quartz bar)
  - Focusing elements (FEL, 16 mm wide) convert Cherenkov angle to position information
  - Mirror focuses photons onto sensor plane
  - Quartz bars connect disc and FEL
- Readout
  - 3 FELs read out by 1 MCP-PMT
  - 2-inch MCP-PMT with 0.5x16 mm pitch
  - TOFPET2 ASIC + FPGA-based FEE





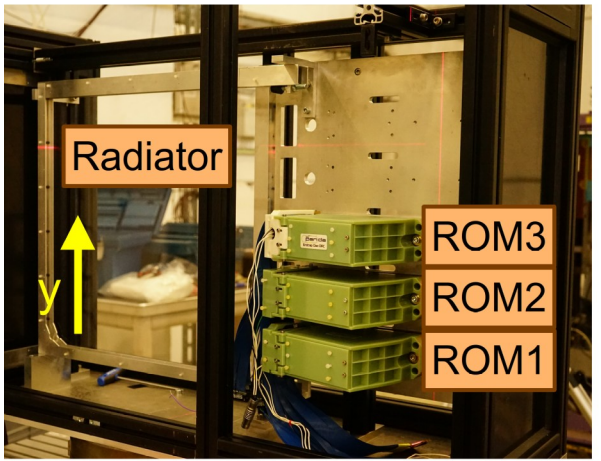
Endcap Disc DIRC -- Optics and Readout

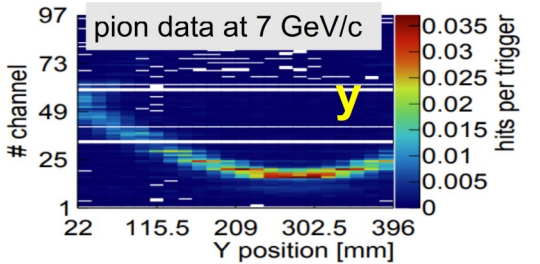
- Optics
  - 3 bars and 3 FELs build **one readout module**
  - 16 mm thickness of each bar and FEL
  - Polished mirror surface of FEL
- Readout module (ROM)
  - 1 microchannel-plate PMT (2") with highly segmented anode (3x100 pixels)
  - MCP-PMT with blue-enhanced photo cathode to reduce chromaticity and enhance lifetime
  - 24 ROMs per quadrant
- Readout electronics
  - MCP-PMT read out by TOFPET2 ASICs
  - Flexboard connects to FPGA based FEE (FCB)
  - Connection to “outside world” by optical link

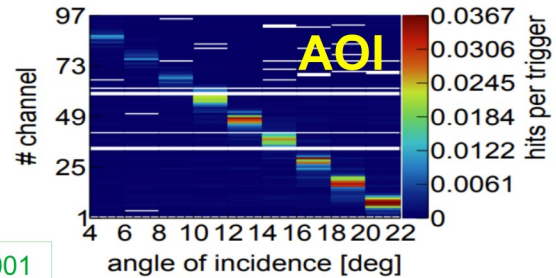


Endcap Disc DIRC -- Beam Tests + Results

- Test beam at CERN T9 area in 2018
  - Pion/proton beam separated by TOF
  - Quadratic radiator disc (50x50 cm^2)
  - Read out by 3 ROMs with TOFPET2
- Measurements
  - Scans along **y** → different pixels hit → **corresponds to Cherenkov angle**
  - Scans at different **beam angles (AOI)**
- Results
  - Single photon angle resolution <10 mrad
  - Reconstr. Cherenkov angle per particle shows fair agreement with simulations
  - **Cherenkov angles separated up to ~8 GeV/c (i.e. ~4 GeV/c for π/K)**

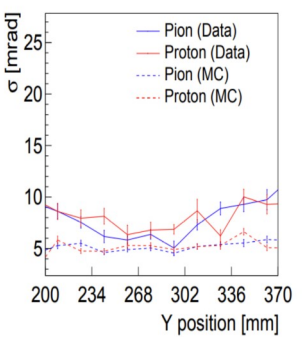


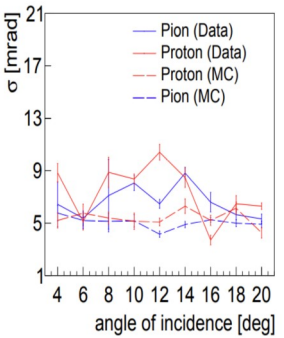




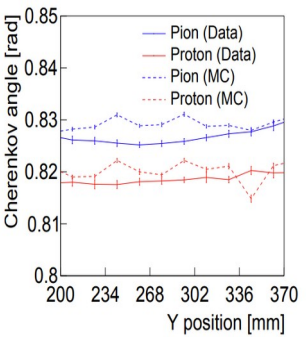
I. Köseoglu et al., JINST **15** (2020) C03001

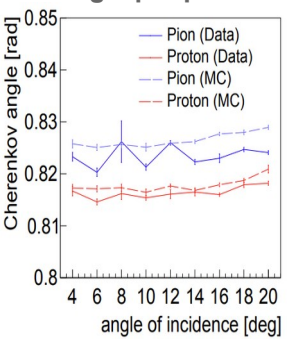
Cherenkov angle resolution per photon





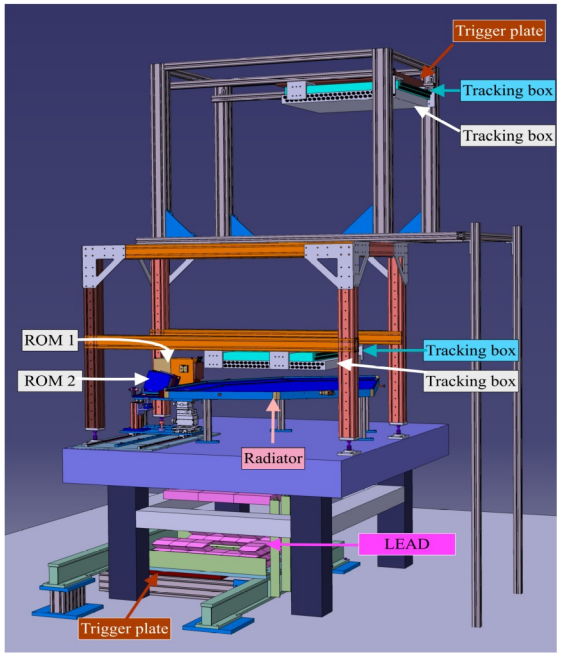
Reconstructed Cherenkov angle per particle

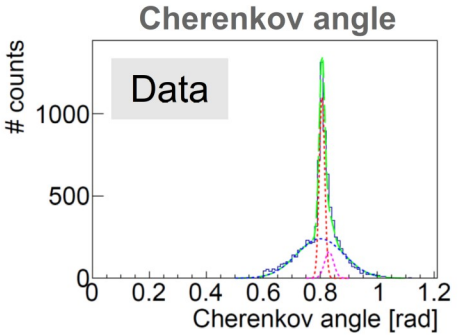


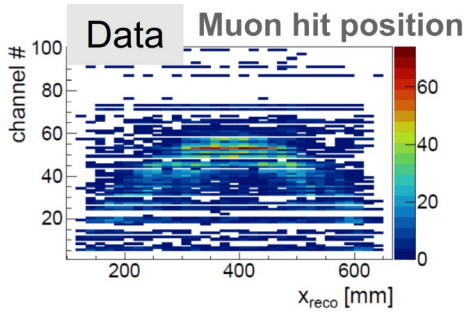


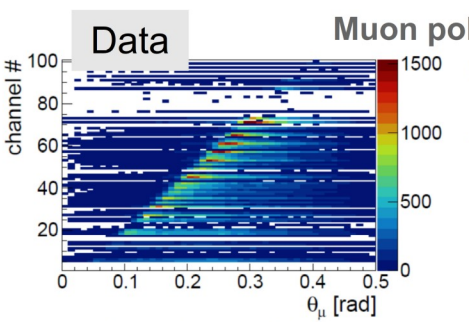
Disc DIRC -- Giessen Cosmics Station (GCS)

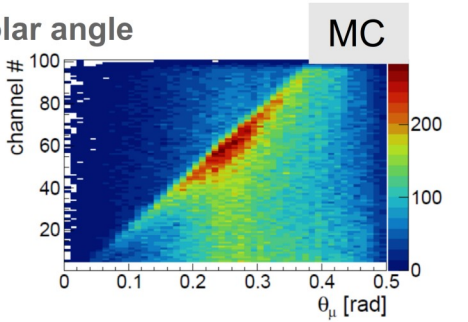
- Cosmics station for DIRC prototype tests
  - 2 tracking boxes for muon track determination
  - Trigger plates + lead absorber suppress electrons
  - Fits full-size Endcap Disc DIRC quadrant
- Available Disk DIRC components
  - Prototype radiator (1 quadrant, ¼ Disc DIRC)
  - Several ROMs and MCP-PMTs for R&D
  - TOFPET2-ASIC (to test readout electronics)
- Very first results
  - Plots show measured patterns of Cherenkov photons which are compared to simulations
  - Muon polar angle (lower) and hit position (center)
  - Cherenkov angle resolution ~10 mrad (upper)
- Disc DIRC development currently on hold











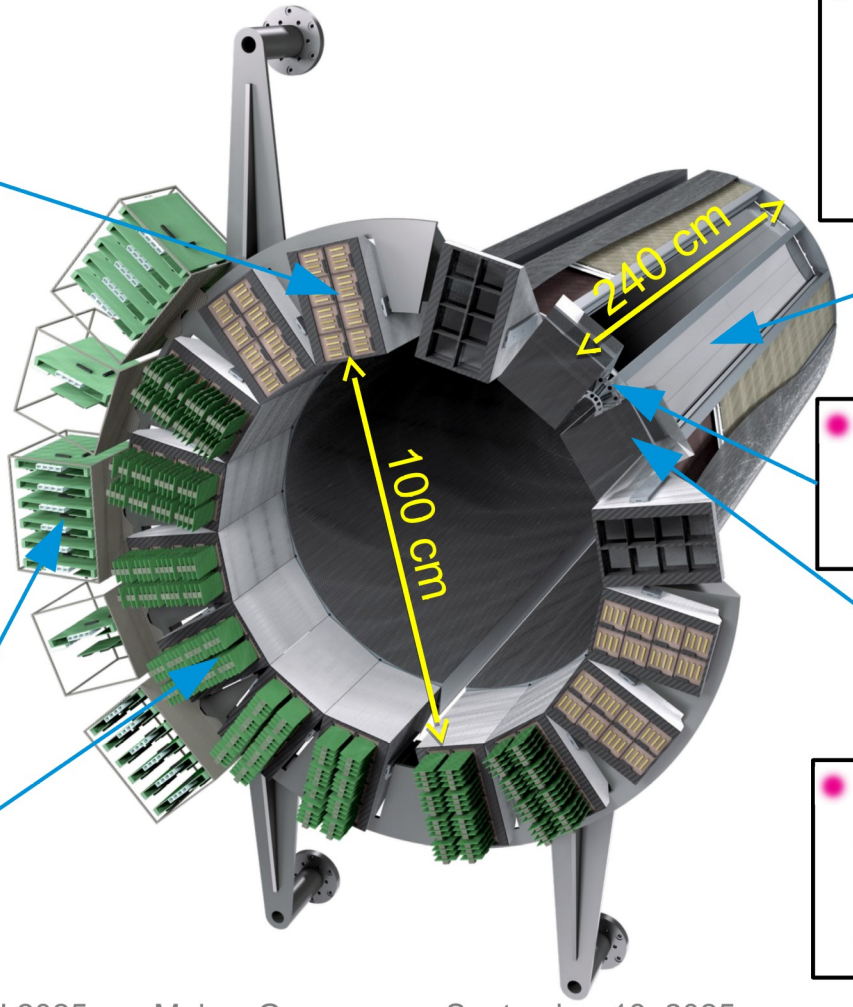
Barrel DIRC -- Final Design

Barrel DIRC TDR, B. Singh et al., 2019,
J. Phys. G: Nucl. Part. Phys. **46** 045001

- Photon detectors
  - 2x2 inch^2 active area
  - 8x8 pixel MCP-PMTs

- Performance goals for >3σ π/K separation
  - **Detected photons/track:** >20 at β ≈ 1
  - **RMS time resolution:** σ_t ~ 100 ps
  - **Position resolution:** σ_{xy} ~ 2 mm

- Readout electronics
  - DiRICH frontend boards
  - TRB3 (trigger and readout)



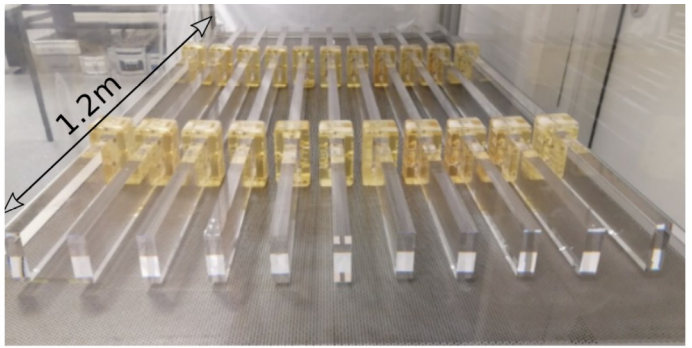
- Radiators
  - Synthetic fused silica
  - 16 sectors
  - 48 bars (17x53x2400 mm^3)
  - Flat mirror at forward end

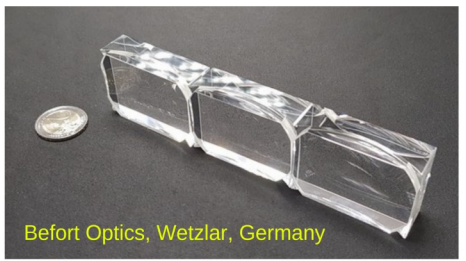
- Focusing optics
  - Multi-layer spherical lenses
  - High refractive index

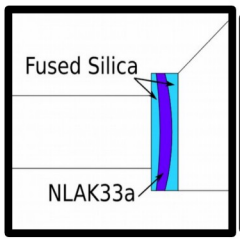
- Expansion volume
  - Prisms
  - Synthetic fused silica
  - 30 cm depth

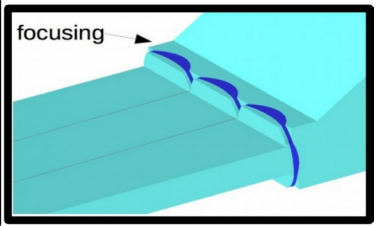
Barrel DIRC -- Optics Layout

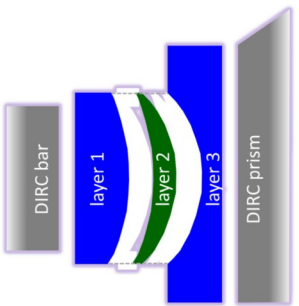
- Radiator bars
  - 3 synthetic fused silica bars (17 x 53 x 2400 mm^3) per sector
  - **2 bars** of 1.2 m length **glued back-to-back** with Epotek 301-2
  - **Surface roughness of 5 Å** and **squareness of <0.25 mrad** maintain the angle and a highly efficient light transport
  - Flat mirror at downstream end
- Novel 3-layer spherical lens
  - 3 layers: lanthanum crown glass sandwiched between two pieces of synthetic fused silica
  - Provides sharp images with low photon loss
  - Reduces number of required DIRC bars
- Fused silica prism as expansion volume
  - Compact! Reduced sensor area!
  - 30 cm base length, 33º opening angle

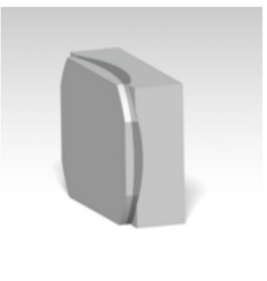


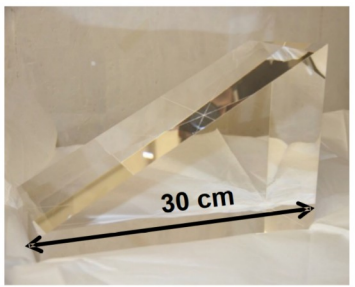






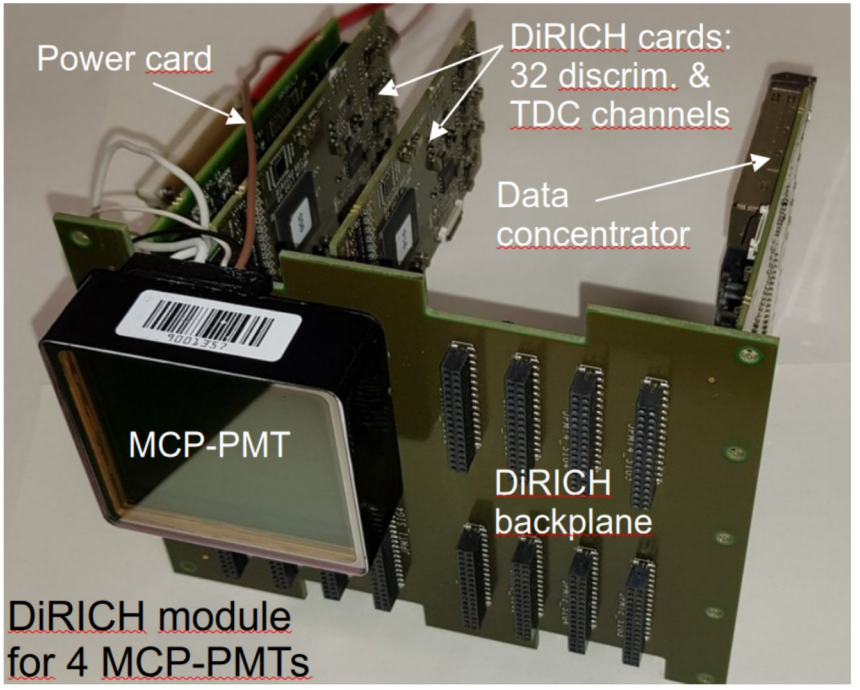


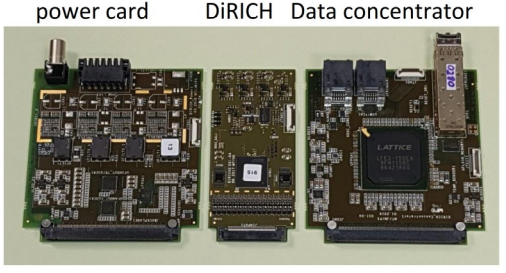




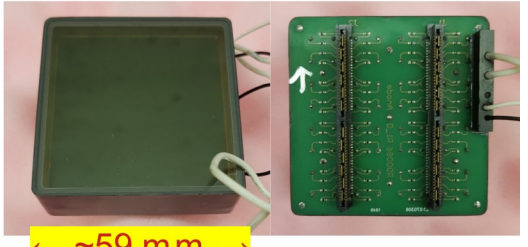
Barrel DIRC -- Readout

- 128 two-inch MCP-PMT photon detectors
  - Fast and efficient detection of single photons in ~1 T magnetic field
  - Lifetime-enhanced (ALD) multi-anode design
    - 8x8 anode pixels with ~2 mm position resolution (σ_{xy})
    - ~100 ps single photon timing precision (RMS)
    - >80% active area ratio
- Electronics to digest fast MCP-PMT signals
  - MCP-PMT and **DiRICH** frontend board connected by highly integrated backplane with minimal cabling
    - 2 DiRICH boards / MCP-PMT
    - 4 MCP-PMTs / backplane
  - Provides time and pulse height (ToT) information
    - ~10 ps internal time precision (discriminator + TDC)
    - ~50 mW / channel power consumption
  - **TRB3** for clocks, (triggers), and communication





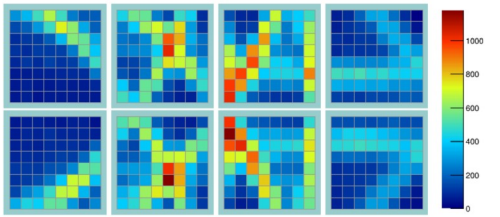
Photonis XP85122-S-BA



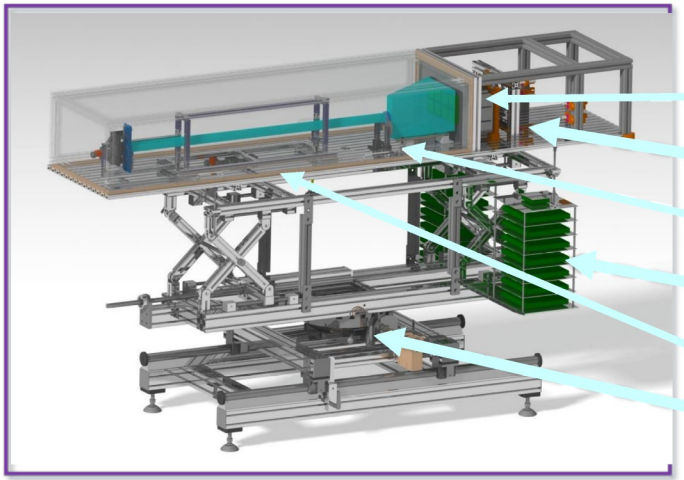
Barrel DIRC -- Prototype Tests

- Several beam tests at CERN and GSI
- Scans of beam incident angle and position for different momenta
  - Measurement of **Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation** in excellent agreement with Geant4 simulation
  - Achieved **π/K separation of 5 s.d.** with time imaging reconstruction for most populated phase space region
- Used for validation and optimization of DIRC design and simulation/reconstruction code

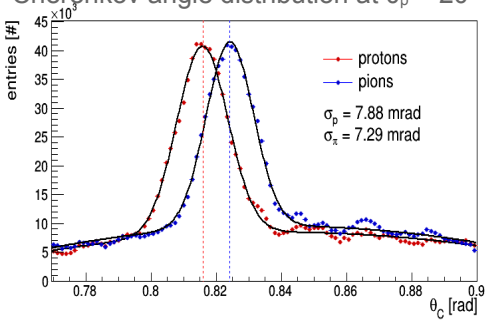
accumulated hit pattern at polar angle of 20°



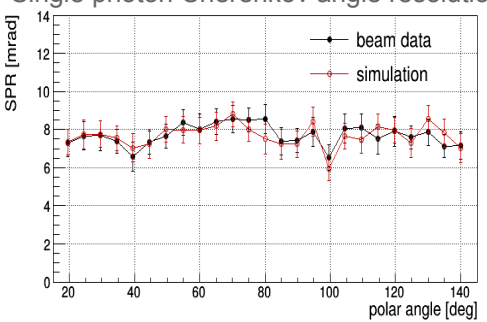
Height adjustable and rotatable test setup



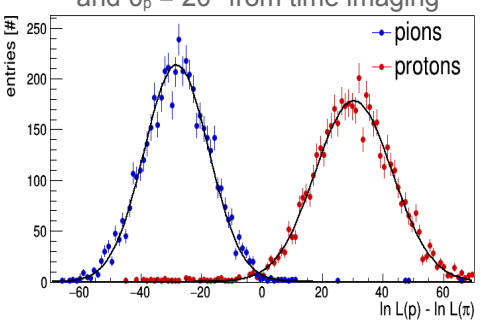
Cherenkov angle distribution at θ_p = 20°



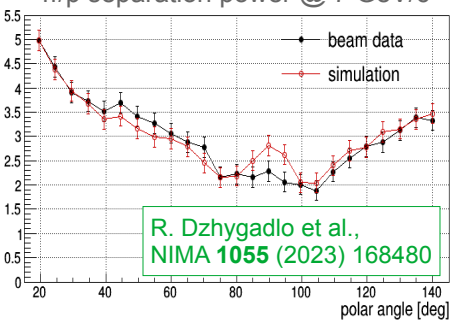
Single photon Cherenkov angle resolution



Likelihood distribution @ 7 GeV/c and θ_p = 20° from time imaging



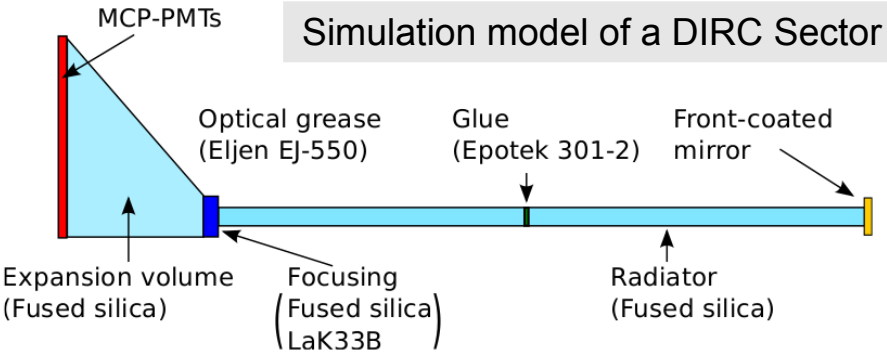
π/p separation power @ 7 GeV/c



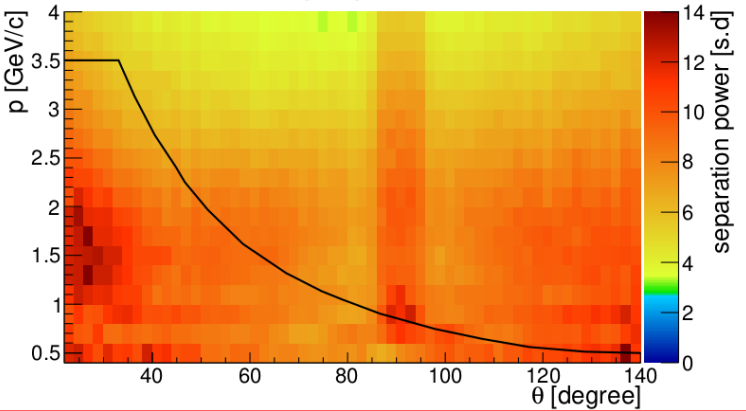
Barrel DIRC -- Software Status

- Simulation
  - Realistic material and photon transport description
    - **Transmittance and refraction** (λ-dependent)
    - **Geometry** with bar/readout boxes and support structures
    - Photon transport efficiency (with angle and bar-roughness)
    - **Collection** and **quantum efficiencies** (λ) of PMTs
    - Realistic **single photon time resolution**
    - **Dark counts and dead time** of electronics
- Reconstruction of Cherenkov angle
  - Geometrical
    - BaBar-like with **Look-Up-Tables (LUT)**
    - Does not depend on precise timing but useful for calibration
  - Time Imaging
    - Belle II TOP-like with **Probability Density Functions (PDF)**
    - Most optimal use of position and time information
  - Neural networks

Simulation model of a DIRC Sector



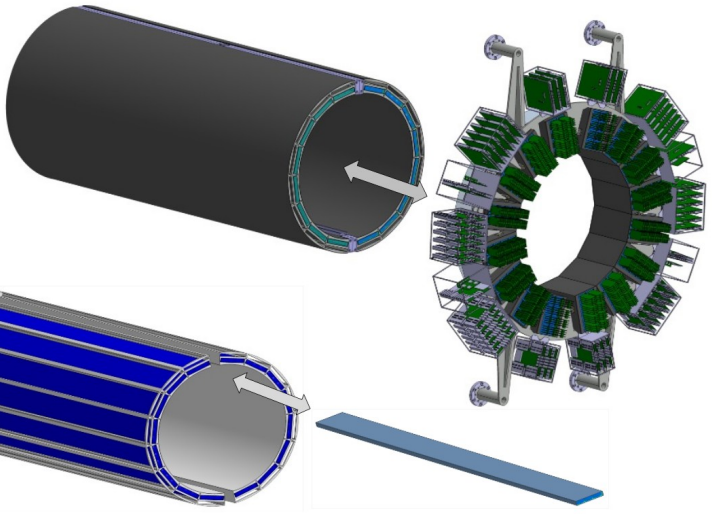
Geant4: Time-imaging with simulated PDFs

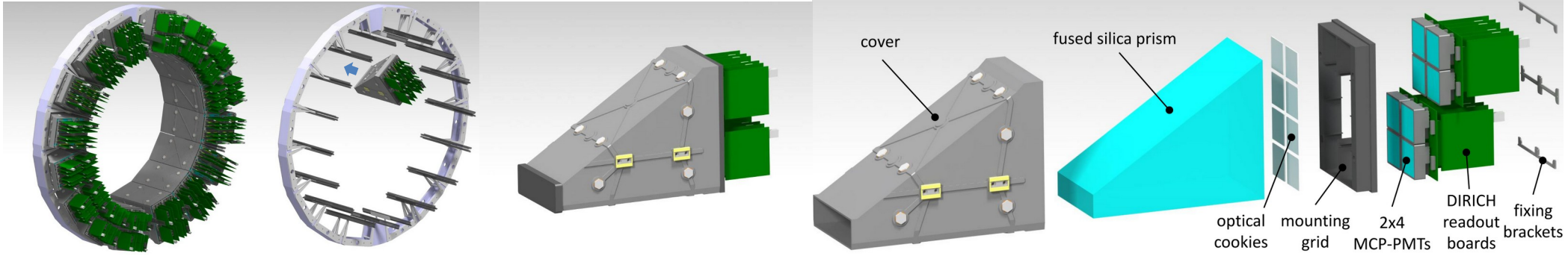


>3σ π/K separation fulfilled in whole Barrel DIRC relevant phase space (underneath the black line)

Barrel DIRC -- Mechanical Design

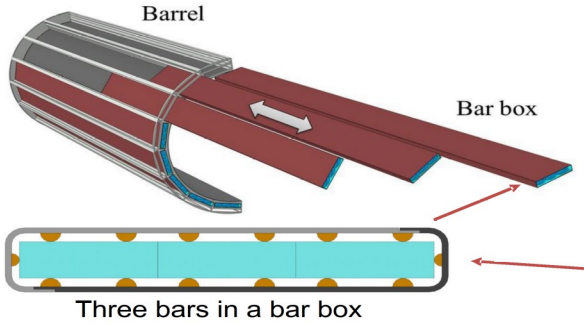
- Mechanical DIRC support based on
  - **Detachable modular structures** for bars and prisms/MCP-PMTs
- 16 bar boxes
  - Containers of carbon fiber reinforced polymer (CFRP)
    - Assembled from two L-shaped elements
    - Slide into mechanical barrel support structure
    - Fused silica bars inside bar boxes supported by PEEK buttons
- 16 readout boxes
  - 3D-printed aluminum alloy (light-weight and high-strength)
  - 2 rails for each box fixed at U-shaped aluminum alloy support ring



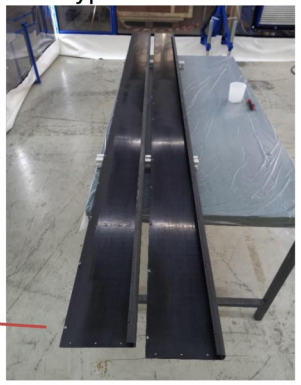


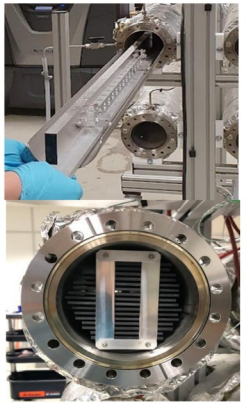
Barrel DIRC -- Radiator Pollution Tests

Bar box
Carbon fiber reinforced polymer (CFRP)

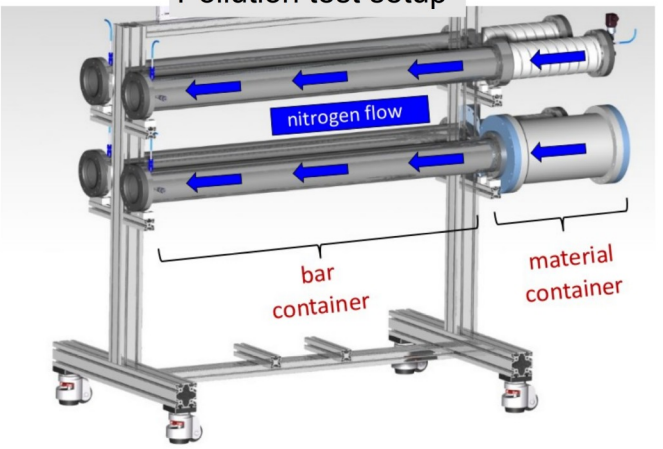


Prototype of L-elements

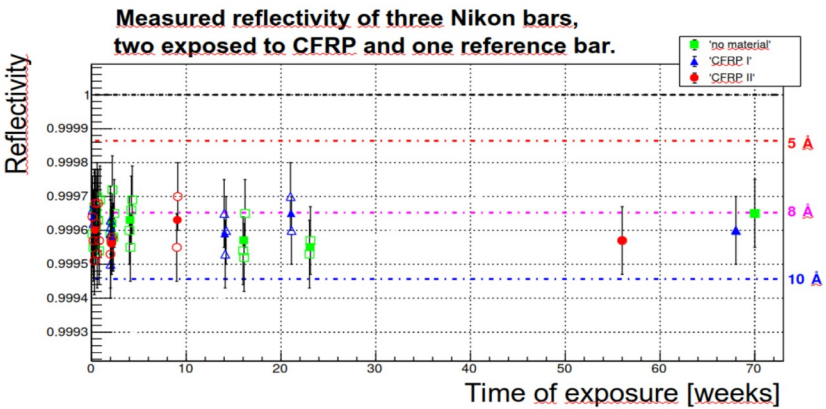




Pollution test setup



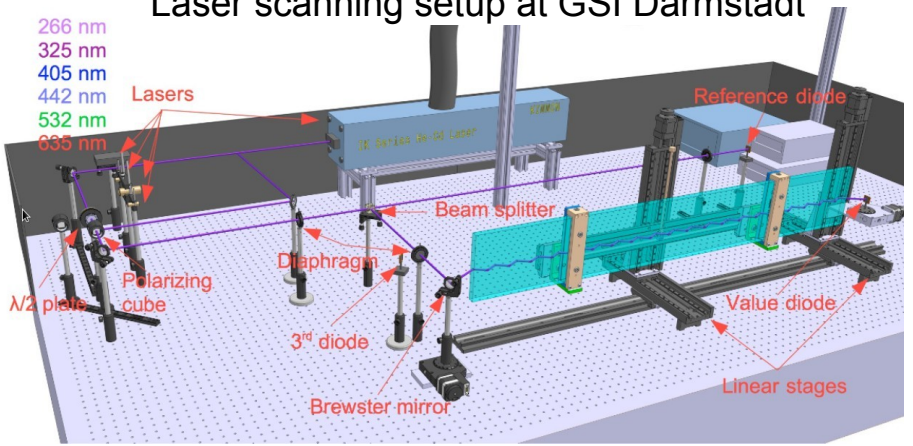
- Confirmation that CFRP and other materials can be used safely – particular concerns regarding possible (resin) outgassing
- **Radiator bar placed in steel tube with nitrogen flowing** over container material and bar surfaces
- Measure effects of material outgassing on bar surfaces
  - **Monitoring sensors**: pressure, flow rate, humidity, temperature
  - Optional heating of the material container to accelerate the tests
  - **Reflection coefficient** of bar gets **regularly measured** in laser lab
- **No effect observed after >2 years**

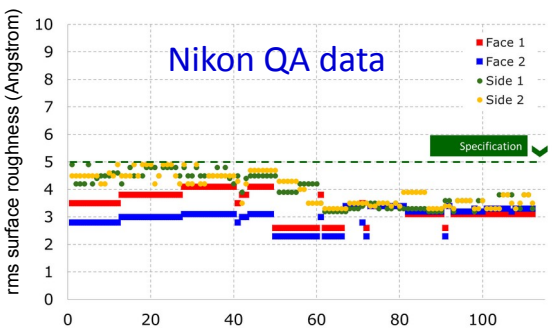


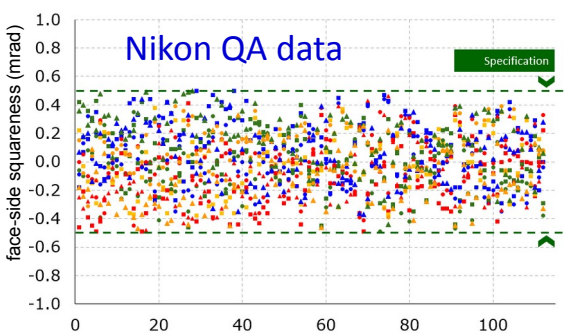
Barrel DIRC -- Radiator Bar Production

- Contract awarded to Nikon Corp, Japan
  - For 112 DIRC bars in 09/2019
  - Production completed in 02/2021 ahead of schedule
- Quality assurance tests at Nikon and at GSI
  - 6 wavelength of polarized laser beams available
  - Measured reflectivity $\mathcal{R}$ using ~50 internal reflections → deduction of surface roughness $\mathcal{H}$
  - Face-side squareness
- **All bars comply with fabrication specifications**

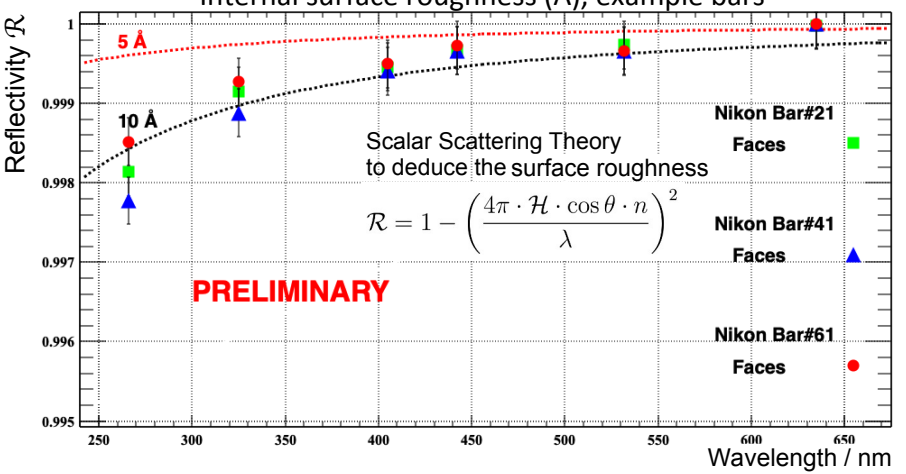
Laser scanning setup at GSI Darmstadt







Internal surface roughness (Å), example bars

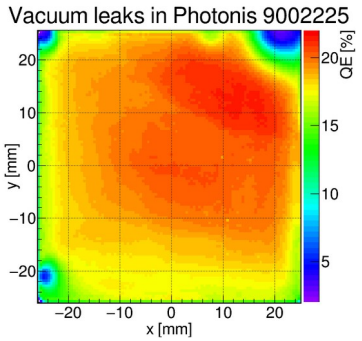


Barrel DIRC -- MCP-PMT Production

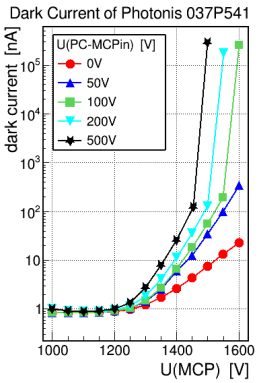
More details in Talk of K. Gumbert on Wednesday

- Contract awarded to PHOTONIS, Netherlands
  - For 165 2-inch ALD-coated MCP-PMTs in 12/2020
  - First MCP-PMTs arrived in 05/2022
- Quality assurance tests at Erlangen
  - Measured for (almost) all MCP-PMTs
    - Gain curve; quantum and collection efficiency
    - 2D(xy) QE and gain scans across full active area
    - 3D-scans (x,y,t) to determine time resolution and quantify dark count rate, afterpulse rate, and crosstalk
    - Rate capability
  - For few selected tubes lifetime and gain in B-field
- Current status
  - Faced many problems during production phase, e.g.
    - Vacuum micro-leaks and escalation on some tubes
    - High DCR and afterpulse rates on several tubes
  - Series production only ~50% completed

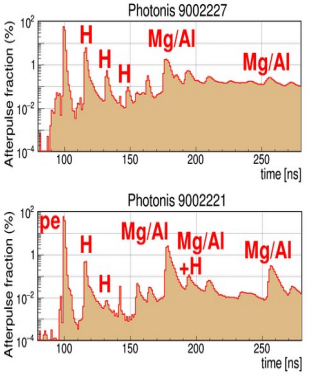
vacuum micro-leaks

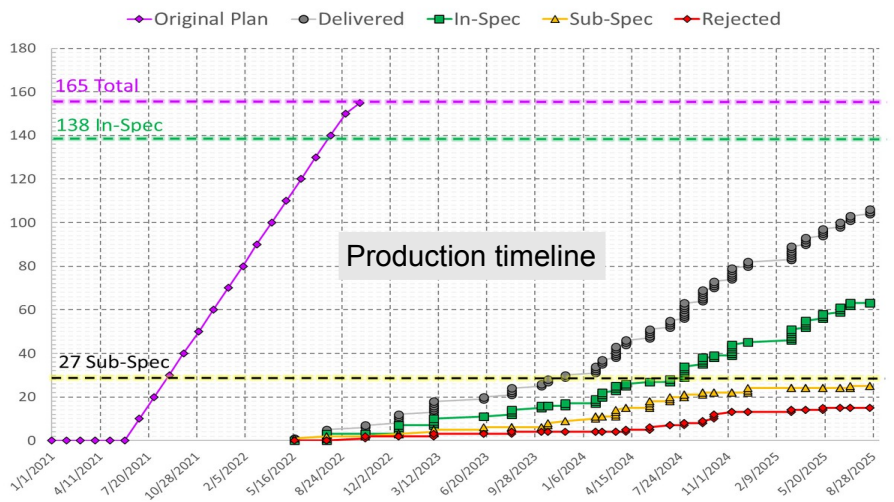


escalation



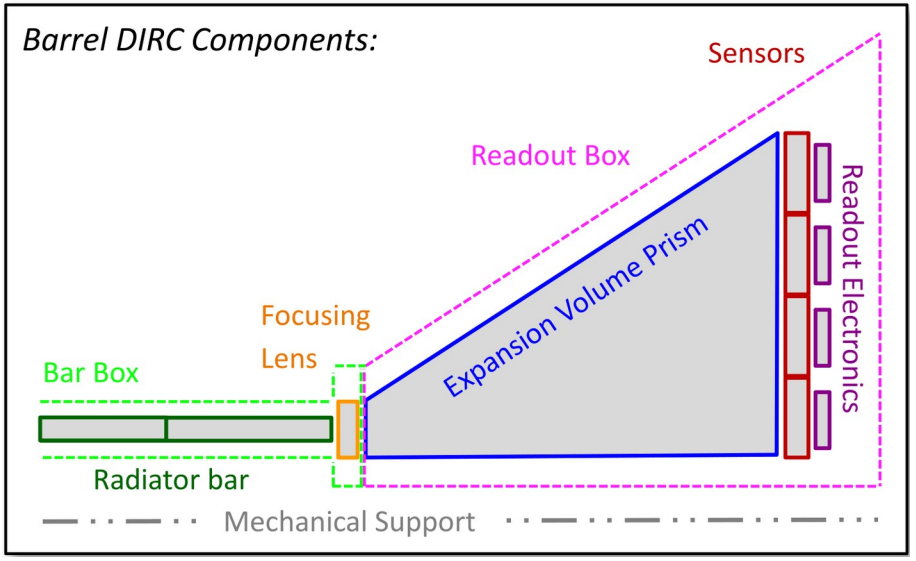
afterpulses





Barrel DIRC -- Current Status and Plans

- MCP-PMT series production and QA
  - ~100 tubes delivered → only two-thirds are good
  - Contract with PHOTONIS canceled in Aug. 2025
- Work close to be finalized
  - R&D on radiator bar gluing
  - Coupling sensor – prism and prism – focusing lens
  - CFRP material tests and calibration system
  - Optimization of readout electronics
- Further optimization of design and specs
  - Focusing lenses and expansion prisms
  - Bar boxes, readout boxes
  - Mechanical support
  - Cooling, cabling, installation
- Continue software optimization



- Pre-production of a full-size prototype sector
  - Assemble and test a complete prototype sector
  - 6 bars, 8 MCP-PMTs, 1 prism, 3 lenses available
  - Procurement of remaining component (electronics, bar boxes, readout boxes)
  - Standalone cosmics and/or beam tests

PANDA DIRCs -- Status and Outlook

- Endcap Disc DIRC
  - All activities have currently come to a standstill
    - Key group (Giessen) has disbanded in 2022
- Barrel DIRC
  - Previous plan: component fabrication, assembly, and installation until end of 2023
  - Significant delays due to Covid19 (2020) and the consequences of Russia/Ukraine war (2022)
    - Sanction against Russia → lack of financial and manpower resources
    - PANDA (DIRC) is starting to lose key personal (e.g., due to retirements, etc.)
- Outlook
  - No PANDA detector before 2032
  - New responsibilities must be defined for Endcap Disc DIRC
    - Need for new groups and funding
  - Prototype production and tests for Barrel DIRC sectors will continue
    - Search for alternatives for the ~50% missing photon detectors (Photek MCP-PMTs, HRPPD, …?)
    - Need for additional financial resources for final assembly