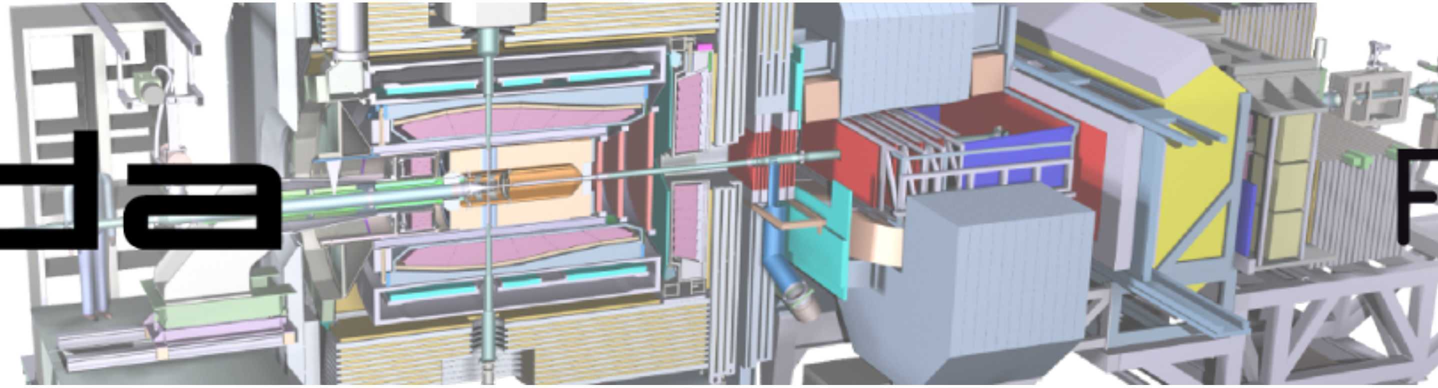


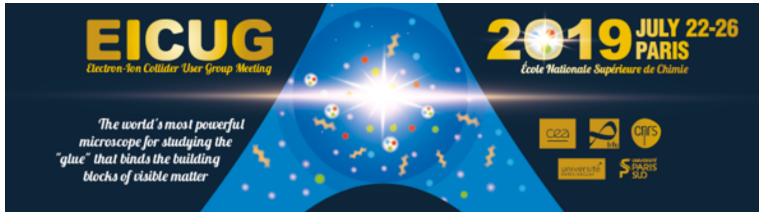
panda.gsi.de

PANDA: Detector Design and R&D

Jochen Schwiening

GSI Helmholtzzentrum für Schwerionenforschung GmbH

for the PANDA Collaboration

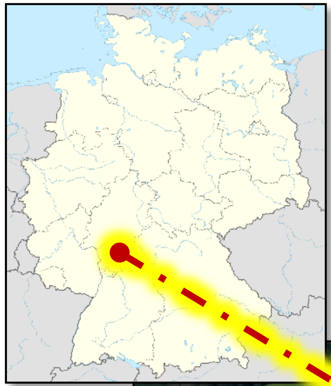


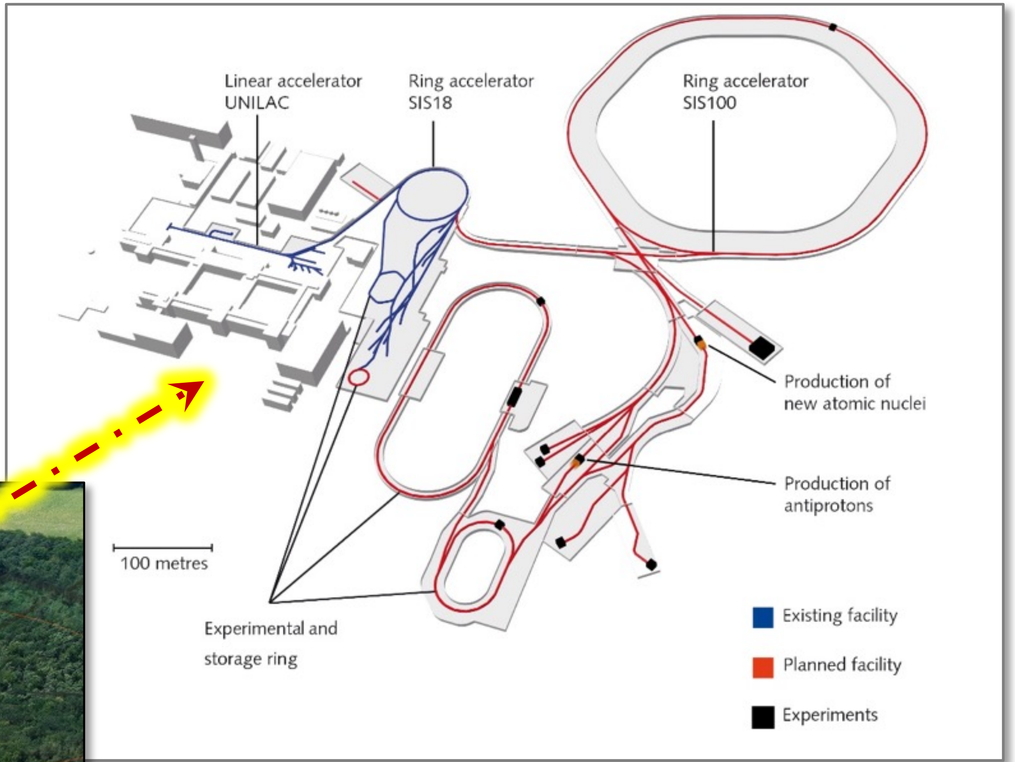
EIC UG, Paris, Jul 22 – 26, 2019

- Antiprotons at FAIR
- The PANDA Experiment
- Detector Overview
- Highlights of Ongoing R&D

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
- Four research pillars



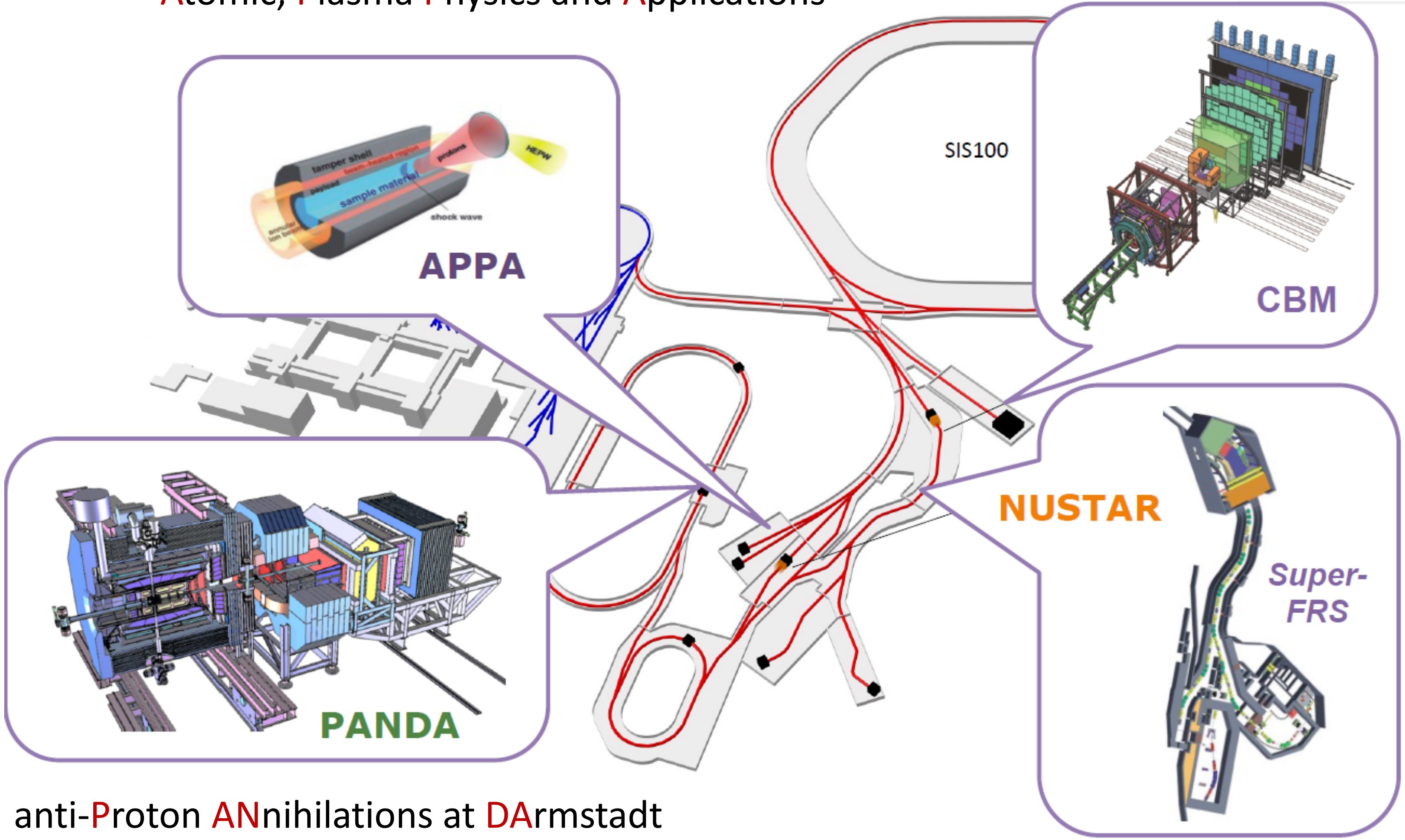


FAIR – The Four Research Pillars

- materials research
- particle physics
- nuclear physics
- anti-matter physics
- astrophysics
- bio-medial sciences
- hadron physics
- plasma physics
- atomic physics
- biophysics
- extreme matter

Condensed Baryonic Matter

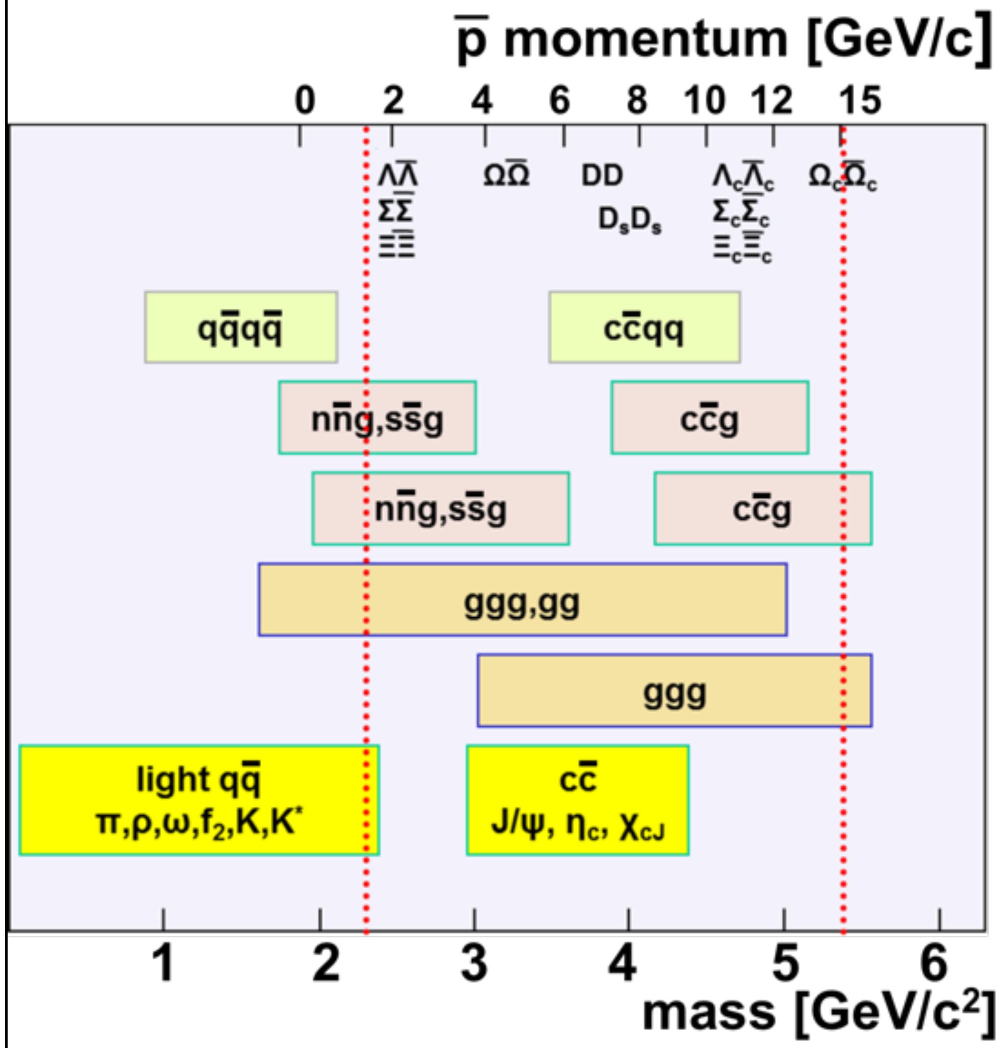
Atomic, Plasma Physics and Applications



anti-Proton ANnihilations at DArmstadt

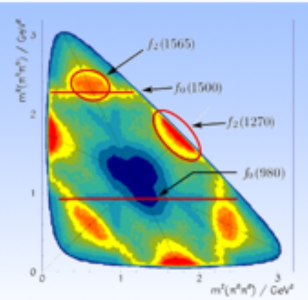
NUclear STructure, Astrophysics, and nuclear Reactions

Antiprotons – Unique Probes for Discoveries and Precision Physics



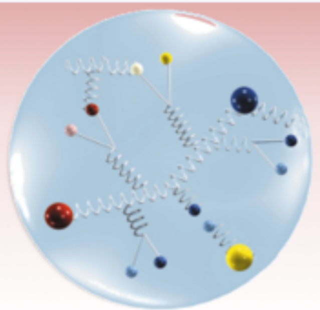
Hadron Spectroscopy

- Charmonium / Charmed hadrons
- Exotic QCD states
- Spectroscopy



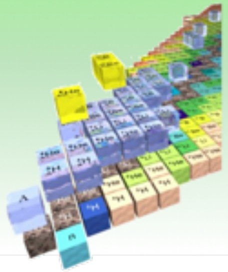
Hadron Structure

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



Nuclear Physics

- Production of Λ-Hypernuclei
- Hadrons in Nuclear Medium



ANTIPROTONS AT FAIR

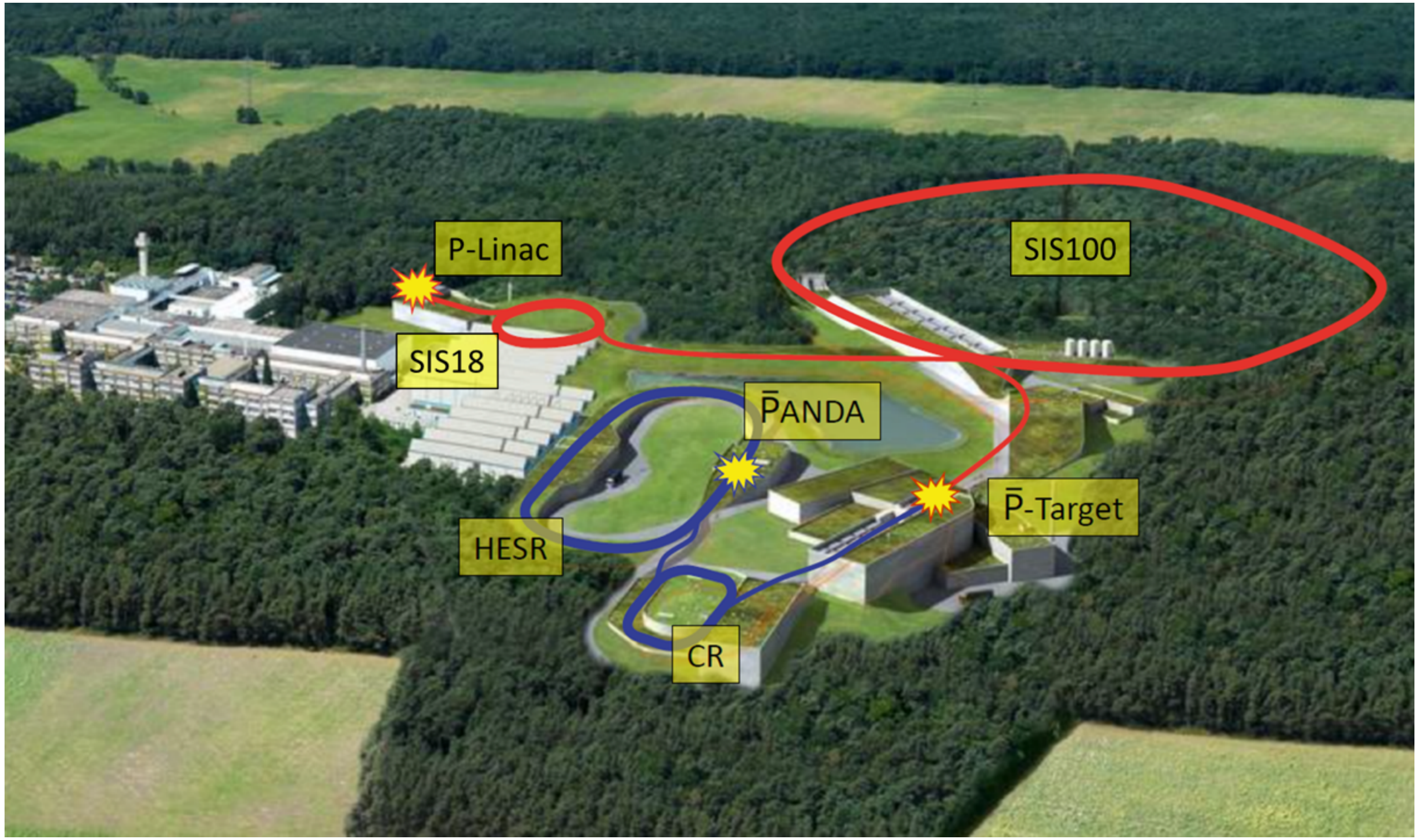
- Proton Linac *(70 MeV)*
- Accelerate p in SIS18/100 *(4/29 GeV)*
- Produce $\bar{p}$ on Ni/Cu target *(3 GeV)*
- Collection in CR, fast cooling
- Accumulation in HESR
- PANDA luminosity $\leq 2 \times 10^{31} cm^{-2} s^{-1}$
- $\bar{p}$ momentum: 1.5 – 15 GeV/c
- Fixed target: cluster jet/pellet

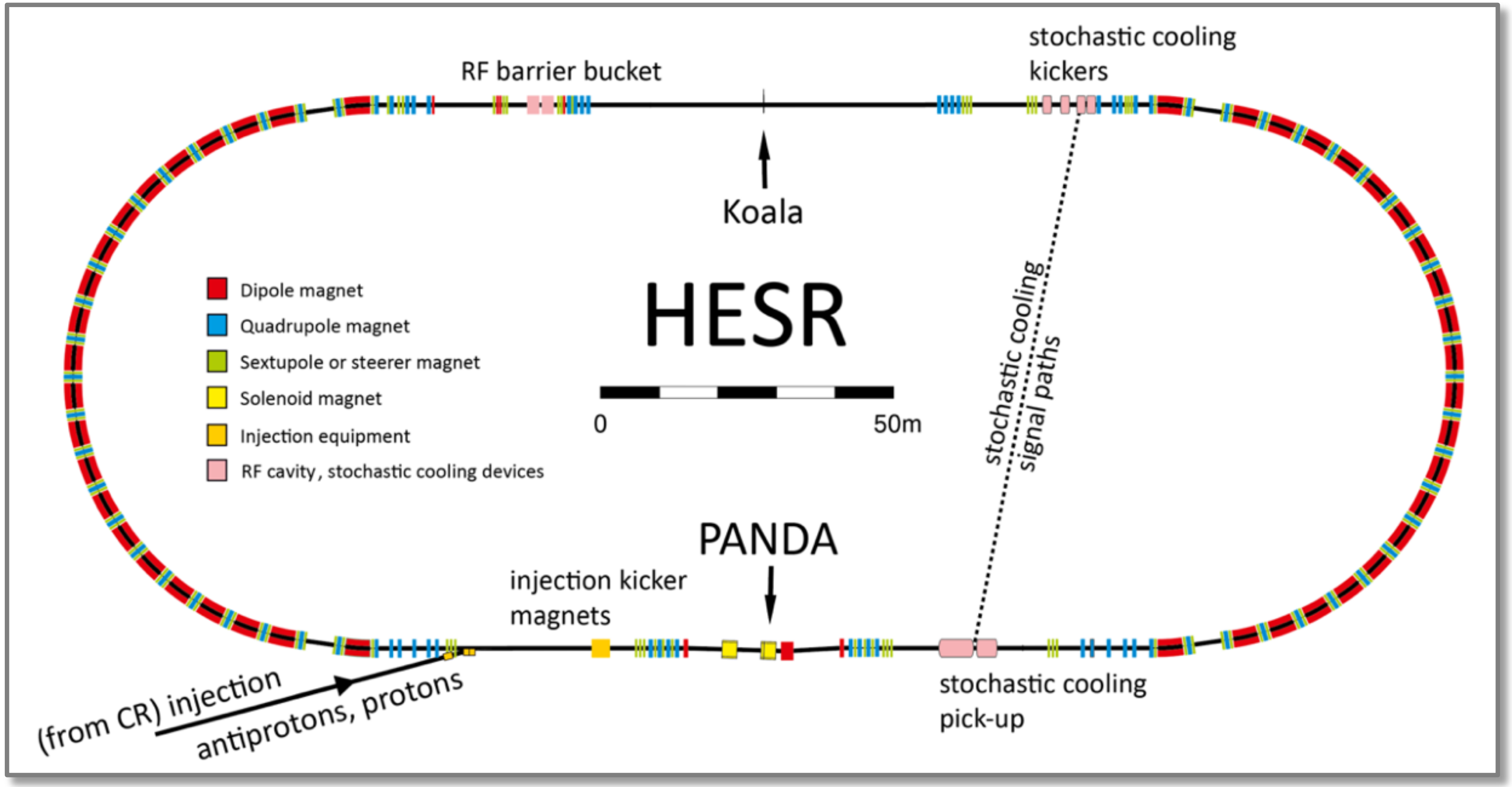
- Full FAIR version (Phase 3, after 2026)

  Accumulation in RESR, slow cooling

  Storage in HESR

  PANDA luminosity $\leq 2 \times 10^{32} cm^{-2} s^{-1}$

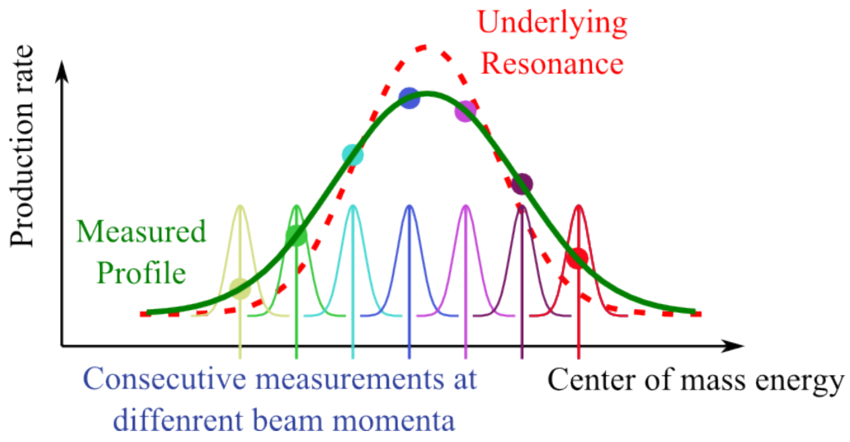




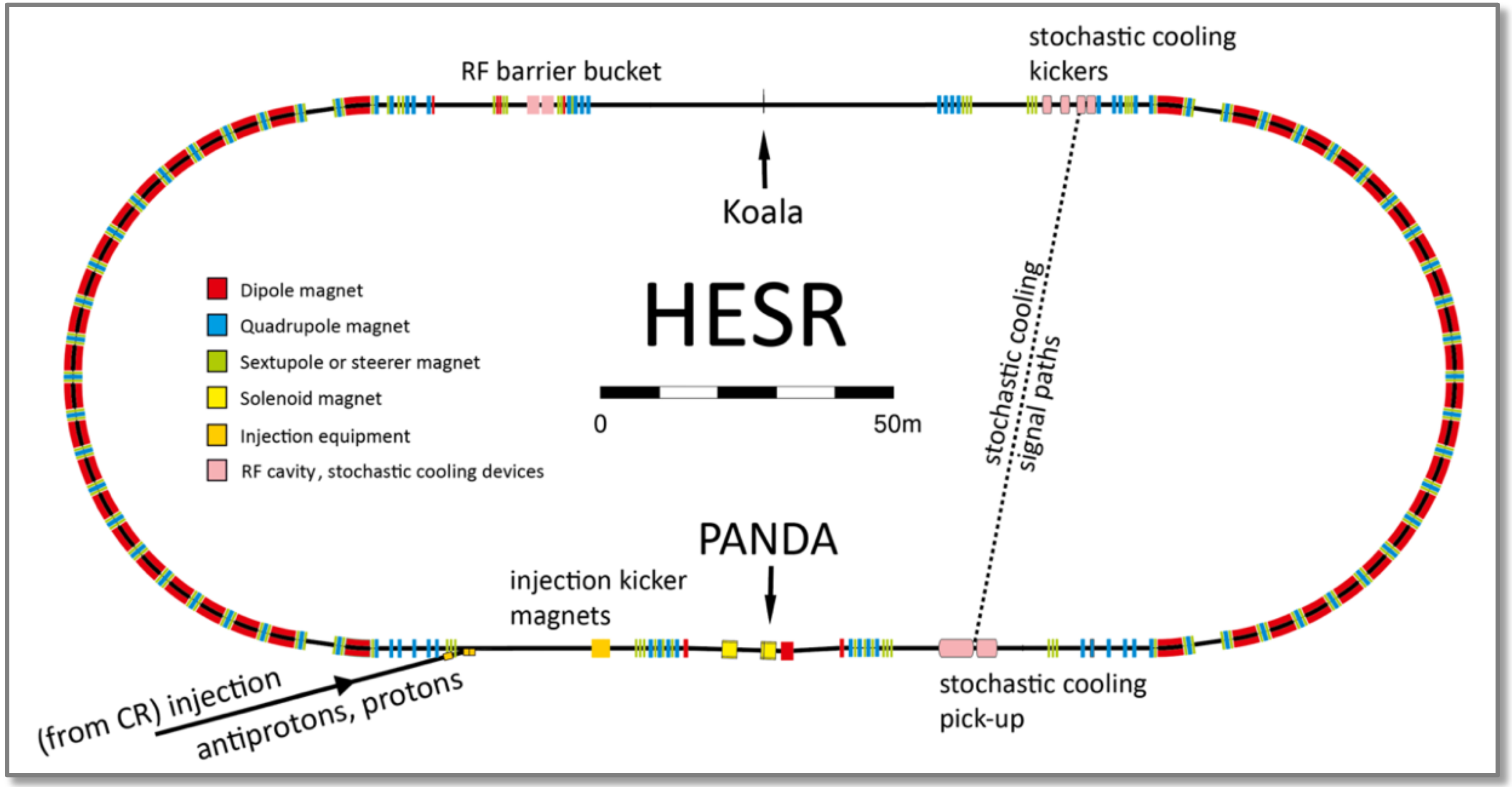
Circumference	575 m
Momentum	1.5 – 15 GeV/c

Stochastic cooling
over full momentum range
⟶ $\Delta E \approx 50$ keV

Production experiments
with high-precision beam energy



Mode	High luminosity (HL)	High resolution (HR)
$\Delta p/p$	$\sim 10^{-4}$	$\sim 4\times10^{-5}$
L ($cm^{-2}s^{-1}$)	2×10^{32}	2×10^{31}
Stored $\bar{p}$	10^{11}	10^{10}



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Stored p̄	10^{11}	10^{10}

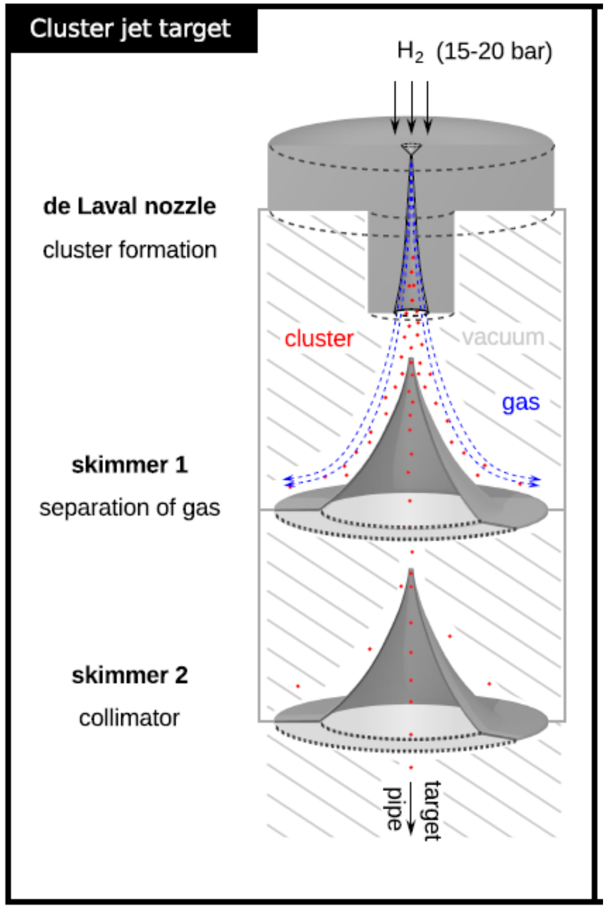
Cluster Jet Target

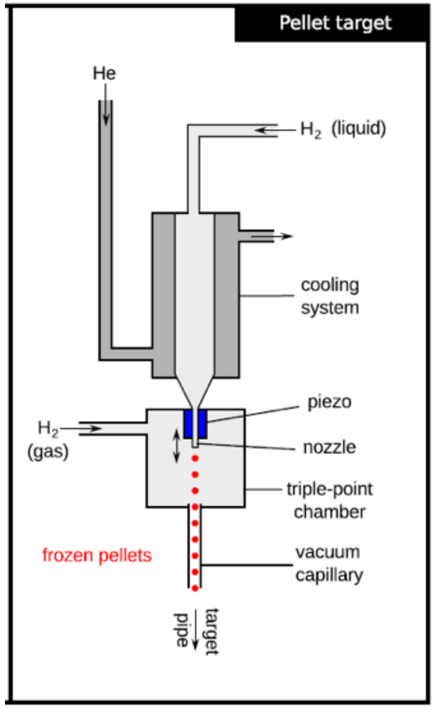
- Expansion of pre-cooled and compressed hydrogen gas into beam pipe
- Cluster jets move with supersonic speed during condensation
- Cluster size: $10^3 – 10^5$ atoms/cluster

Pellet Target

- Small droplets of frozen hydrogen created in triple point chamber
- Pellet diameter: 10 – 30 µm
- Vertical injection into target tube
- Falling speed: 60 m/s
- Flow rate: 100,000 pellets/s
- Potential for higher density, additional targets possible

Goal: 4 x 10^{15}cm^{-2} target density





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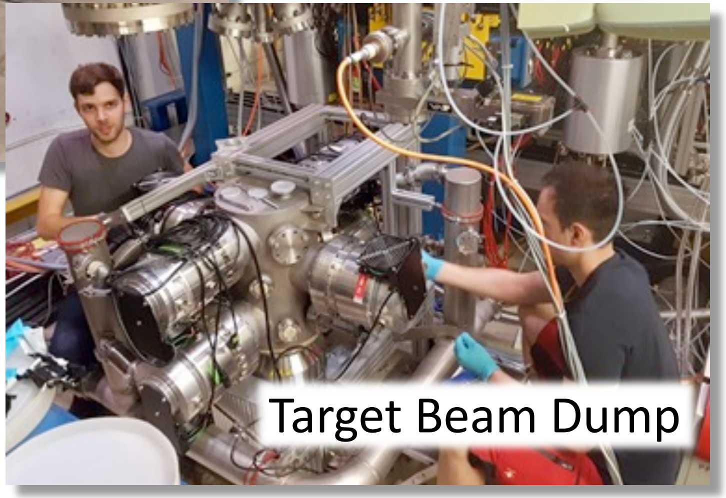
- Potential for higher density, additional targets possible

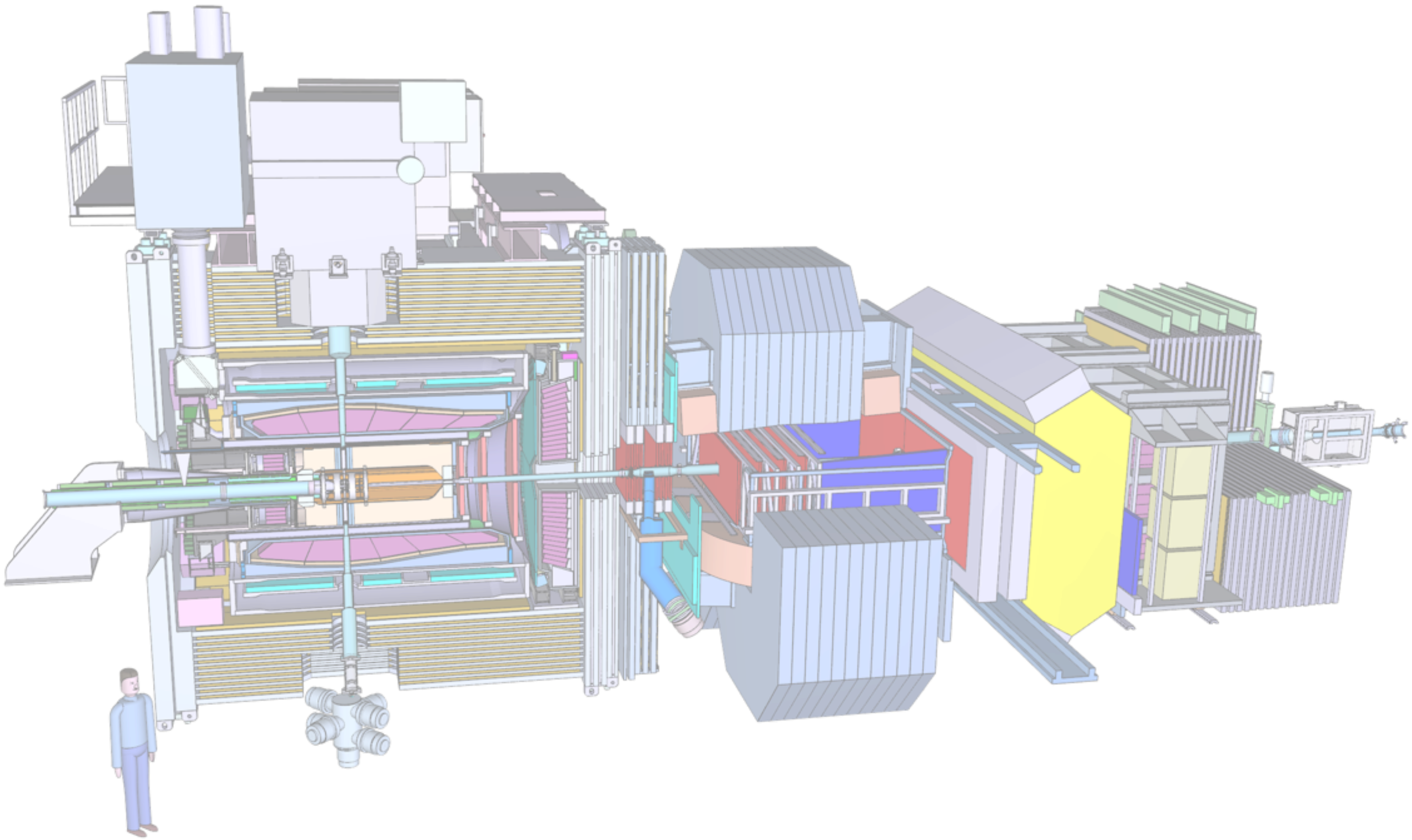
Record of 2 x 10^{15}cm^{-2} target density already achieved
Continuous development (nozzle/alignment)


Cluster Jet Target

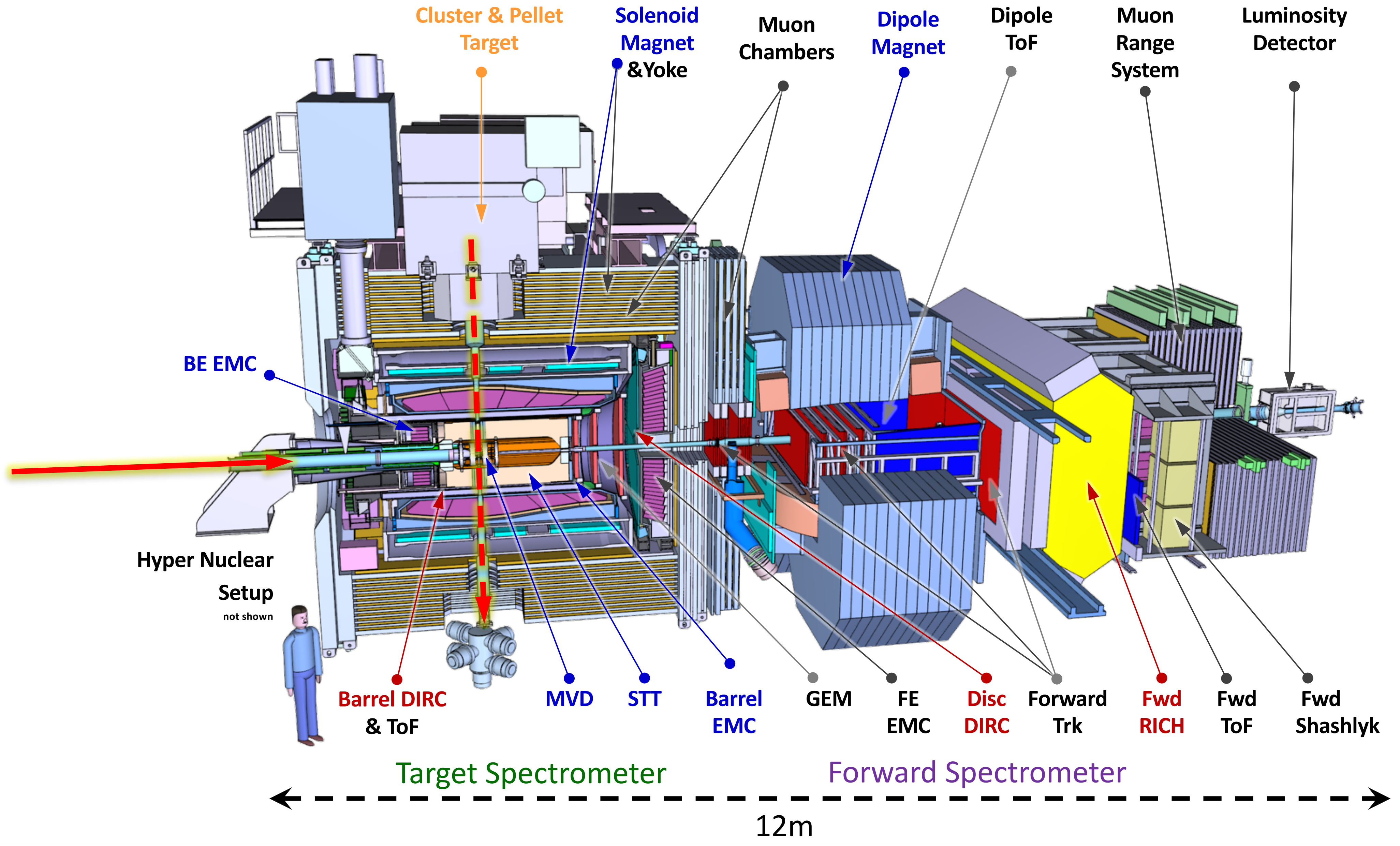

Target Beam Dump

DETECTOR REQUIREMENTS

- 1.5 – 15 GeV/c antiprotons on fixed target
  → asymmetric layout
- 4π acceptance
- High rate capability: up to
  20MHz average interaction rate
- Efficient event selection for data reduction
- Continuous data acquisition
- Momentum resolution: ~1%
- Precision vertex information for D, K^0_s, Y
- γ detection for 1 MeV – 10 GeV
  → crystal calorimeter
- Good Particle ID (e, μ, π, K, p)
  → dE/dx, ToF, RICH/DIRC, muon chambers



Detector Layout



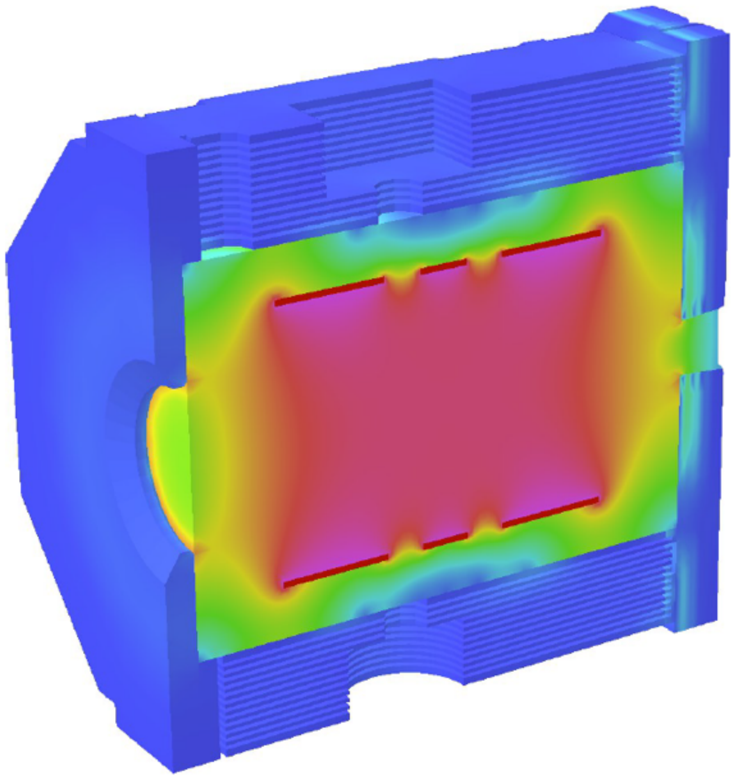
MAGNETS

Solenoid Magnet

- Super conducting coil, 2 T central field (B_z)
- Segmented coil for target
- Instrumented iron yoke – muon chambers
- Doors laminated, instrumented, retractable

Status

- Design and production contract with BINP started
- Cooperation with CERN for cold mass
- Conductor production development
- Joint venture, BINP and Russian Institutes
- Yoke production started



Inner bore: ∅ 1.9 m /L: 2.7 m

Outer yoke: ∅ 2.3 m /L: 4.9 m

Total weight: 300 t

Dipole Magnet

- Normal conducting racetrack design, 2 Tm
- Forward tracking detectors partly integrated
- Dipole also bends the beam
- HESR component

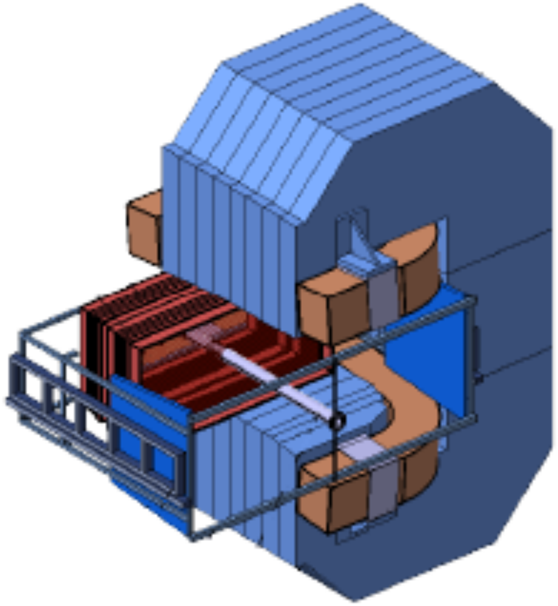
Status

- Design contract with BINP started

Vertical acceptance: ± 5°

Horizontal acceptance: ± 10°

Total weight: 200 t



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Dipole Magnet

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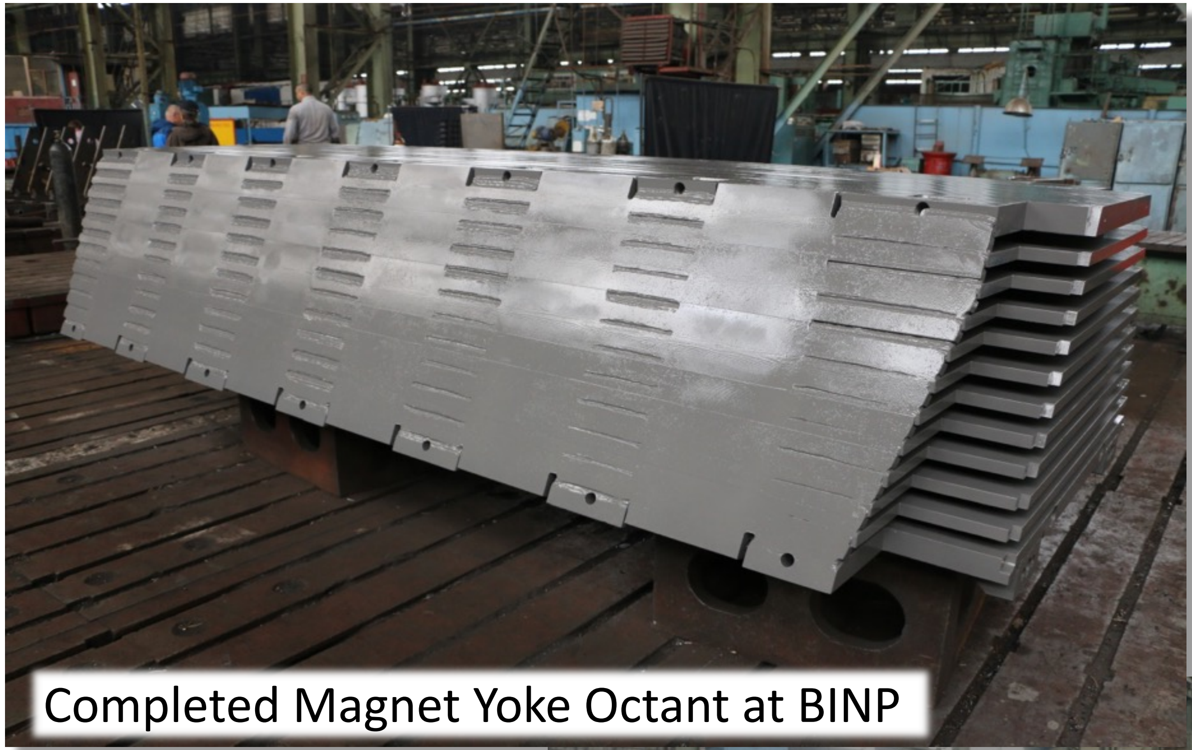
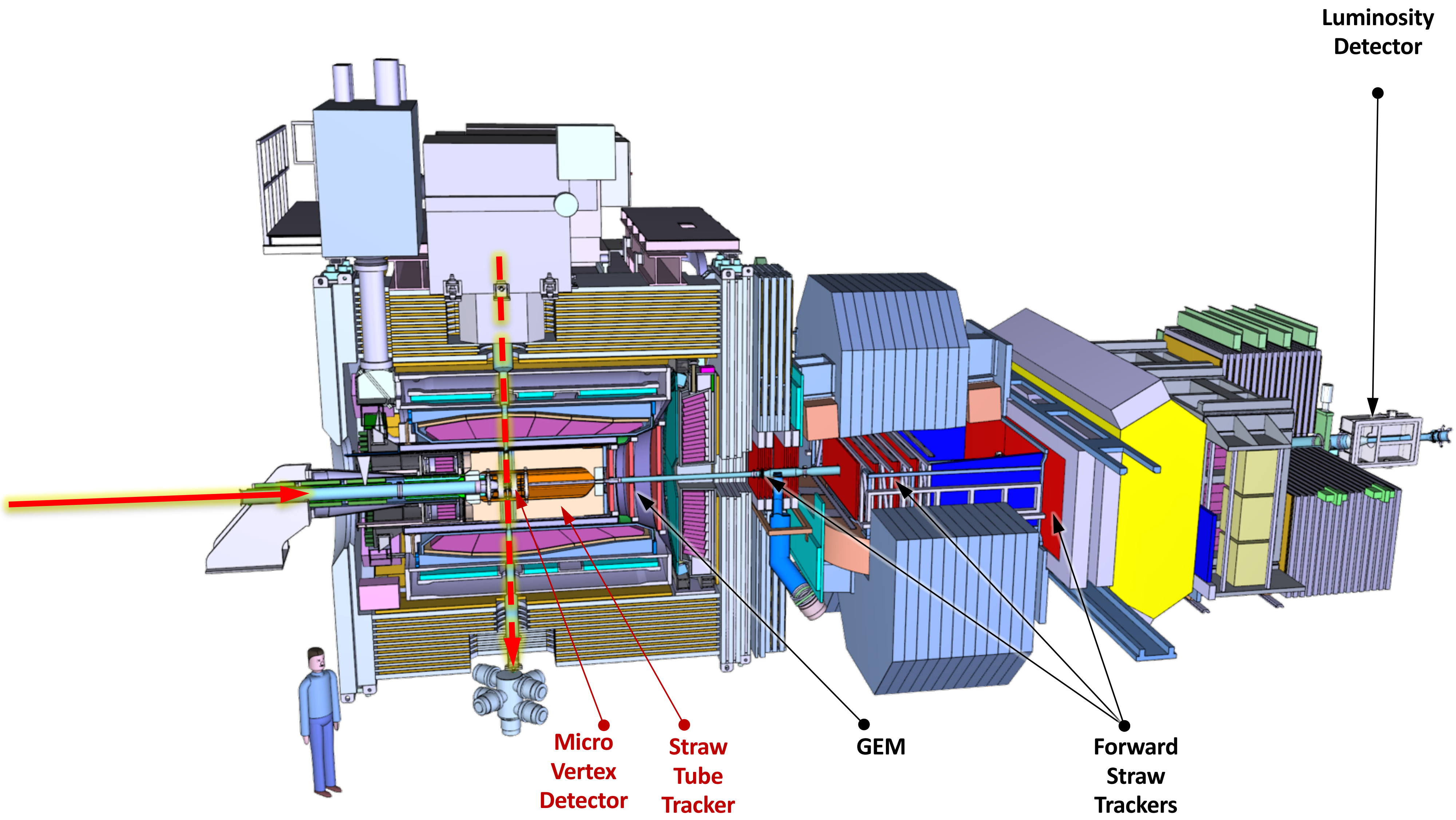
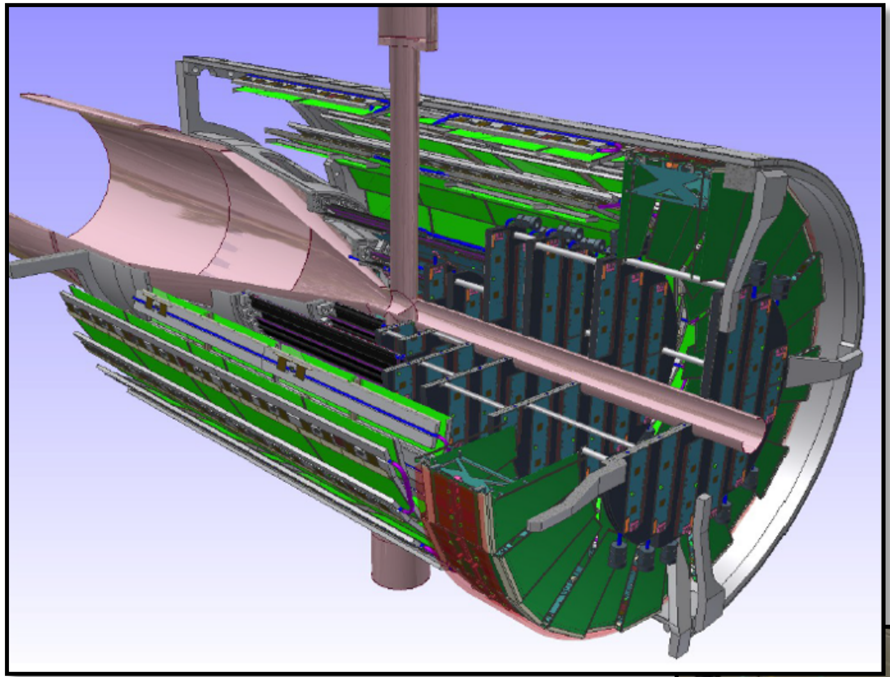


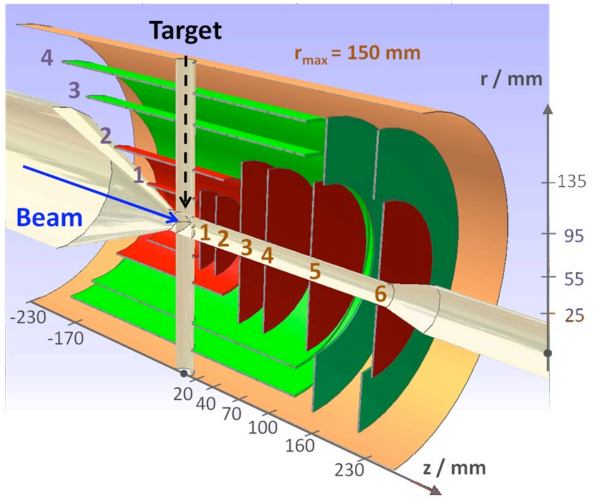
Completed Magnet Yoke Octant at BINP


Luminosity
Detector
Micro
Vertex
Detector
Straw
Tube
Tracker
GEM
Forward
Straw
Trackers

Detector Design

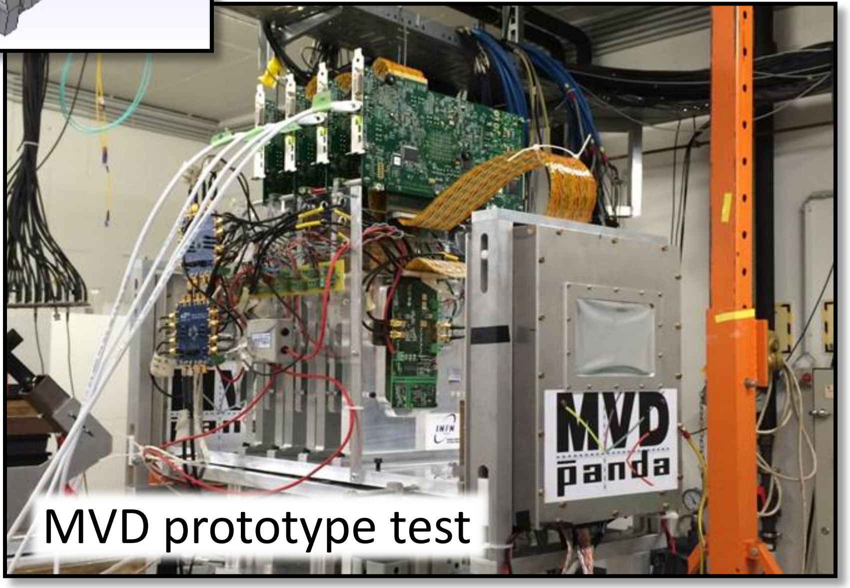
- Silicon Pixels and Strip detector
- 4 barrels and 6 forward disks
- Inner layers: hybrid pixels ($100\times100\ \mu m^2$)
  - Readout ASIC ToPiX
  - Thinned sensor wafers
- Outer layers: double-sided strips
  - Rectangles and trapezoids
  - Readout ASIC PASTA
- Mixed forward disks (pixels/strips)
- 50 µm vertex resolution, $\delta p/p \sim 2\%$
  Important for D meson vertexing
- Design challenges
  - Low mass supports
  - Cooling in small volume
  - Radiation tolerance $\sim 10^{14} n_{1 MeV\ eq} cm^{-2}$





Status

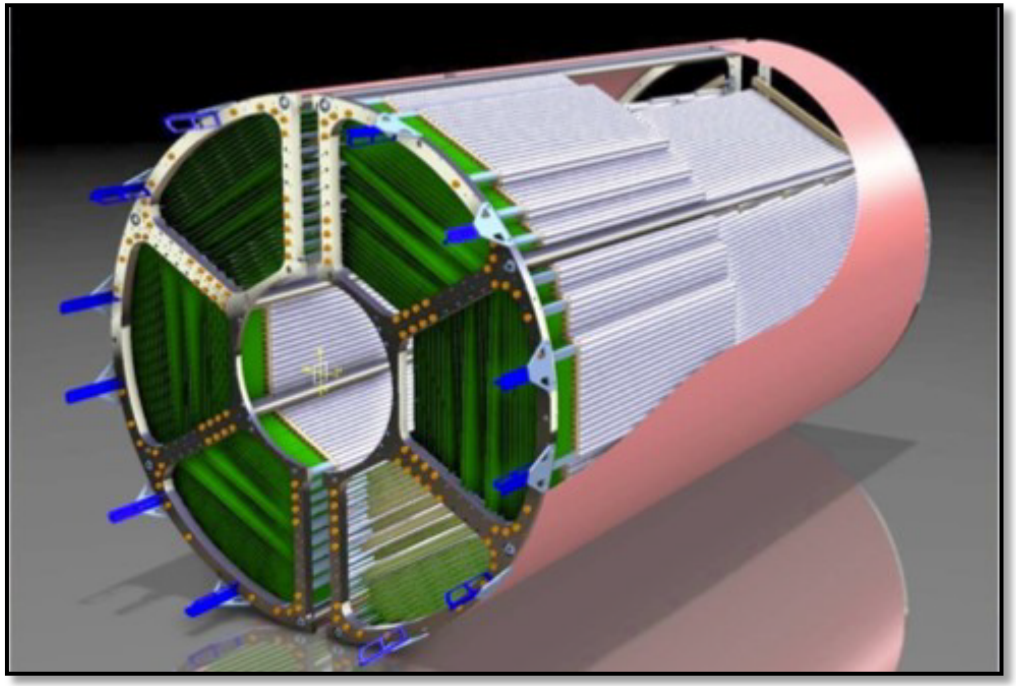
- TDR completed 11/2011
- ASIC prototypes tests & adaptation
- Detailed service planning



MVD prototype test

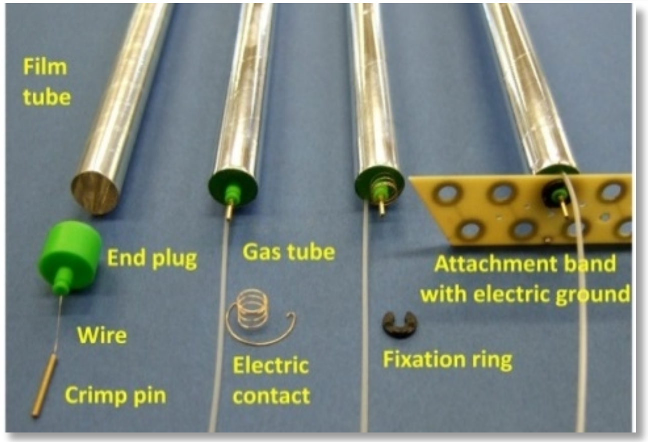
Detector Design

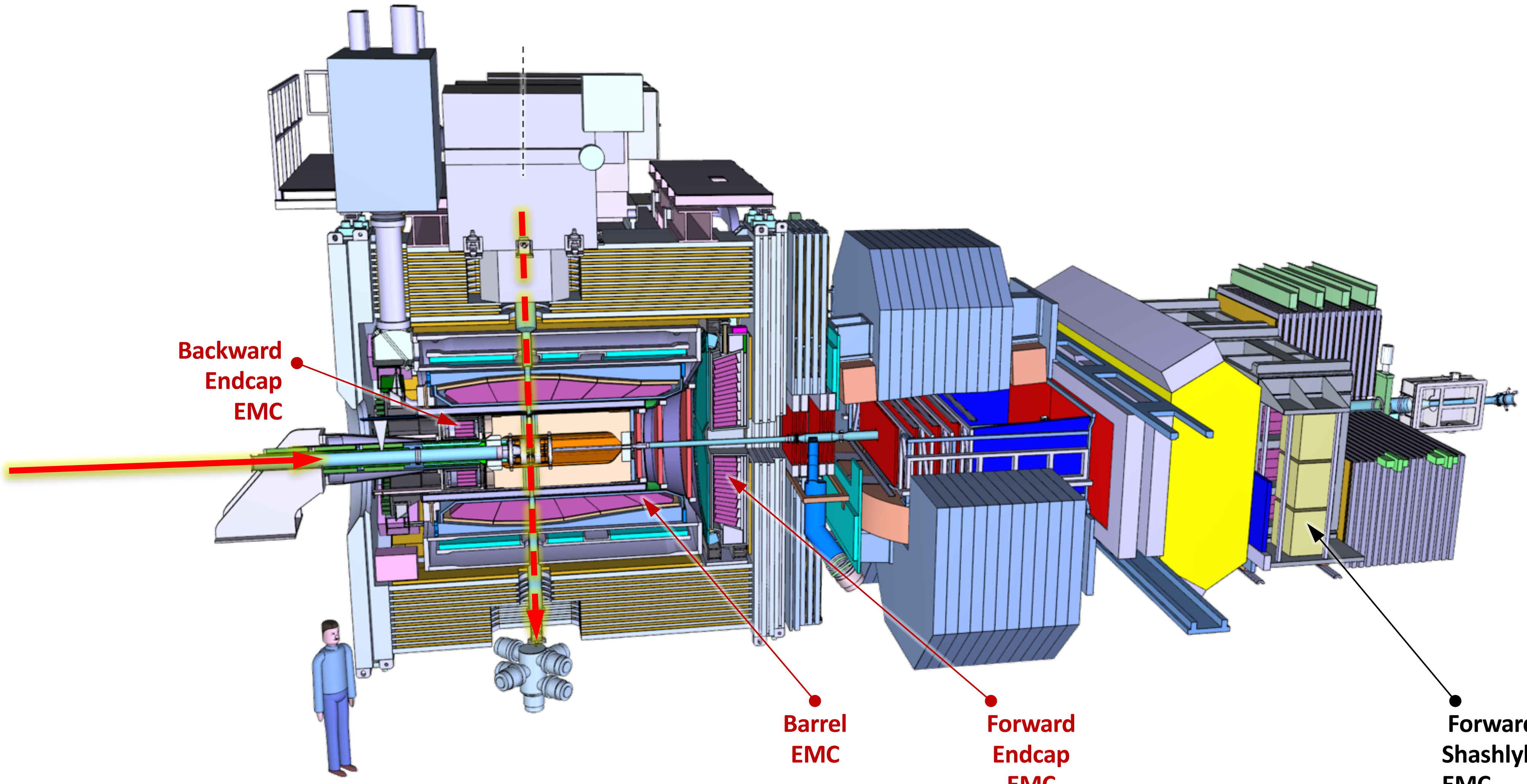
- Layers of drift tubes
- R_{in}= 150 mm, R_{out}= 420 mm, l=1500 mm
- Tube made of 27 µm thin Al-mylar, ∅=1cm
- Self-supporting straw double layers at ~ 1 bar overpressure (Ar/CO_2) developed at FZ Jülich
- 4600 straws in 21-27 layers, of which 8 layers skewed at 3°
- Resolution: r,ϕ ~150µm, z ~1mm
- Material Budget
  - 0.05% X/X0 per layer
  - Total 1.3% X/X_0



Status

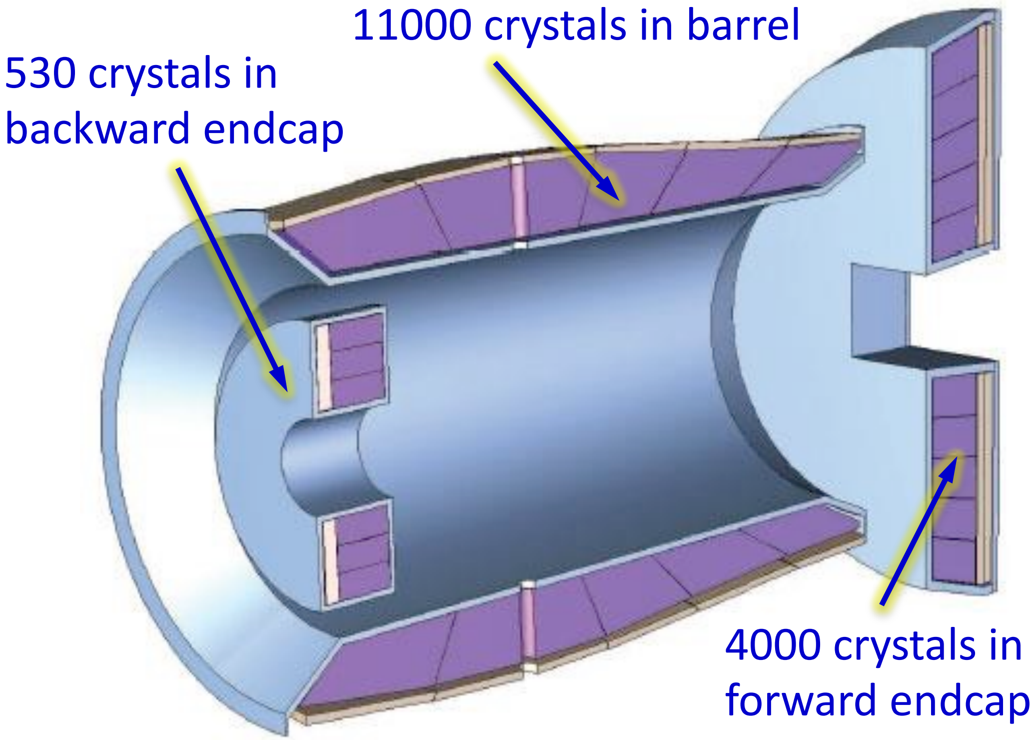
- TDR published in 02/2013
- Readout prototypes & beam tests
- Ageing tests: up to 1.2 C/cm^2
- Straw series production almost completed

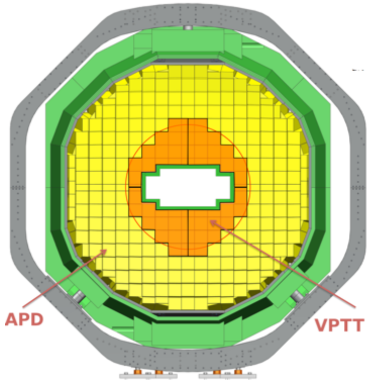


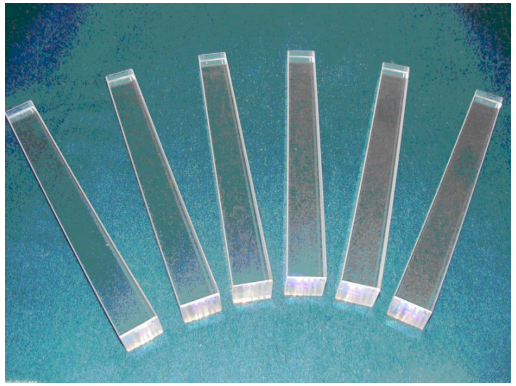

Backward
Endcap
EMC
Barrel
EMC
Forward
Endcap
EMC
Forward
Shashlyk
EMC

Target Calorimeter

- Crystal Calorimeter based on ~15,500 high quality second-generation PWO II ($PbWO_4$) crystals
  - Small radiation length X_0 = 0.89 cm (20cm ≈ 22 X_0)
  - Short decay time τ=6.5 ns
  - Increased light yield, operated at -25°C
  - Time resolution <2ns
  - Coverage: 99.8% of 4π
  - Barrel design: σ(E)/E ≈ 1.5%/√E + const.
- Main part produced at BTCP, Russia
- Mass production of remaining ~40% of the crystals at Crytur (Czech Republic), high-quality crystals received
- Crystals are tested for scintillation yield, optical transmission, radiation hardness
- Sensor: Photo Tetrodes (VPTT, 20% of FW endcap) or Large Area APDs (all others)







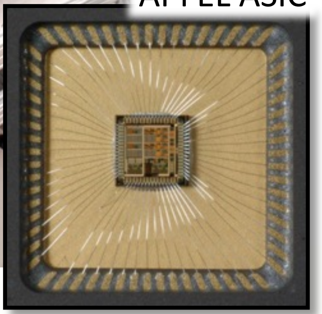
Barrel EMC

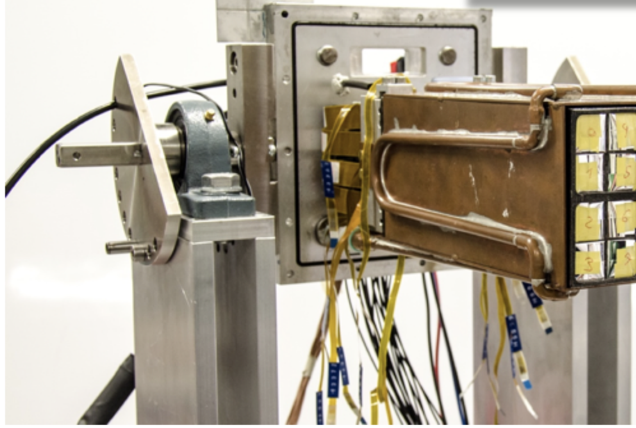
- PWO crystal production ongoing
- EoI to fund remaining crystals
- APD Screening
  - Screening of 30000 APDs
  - Process highly automated
- All alveoles produced
- APD readout APFEL ASIC produced
- First slice (of 16) assembled

Backward Endcap EMC

- Submodule design ready
- Prepare series production
- Readout: new ASIC tests successful

Activities at MAMI - BWE EMC data taking with A1 spectrometer for high-resolution electron scattering in coincidence with hadrons (FAIR Phase 0)





Forward Endcap EMC Status

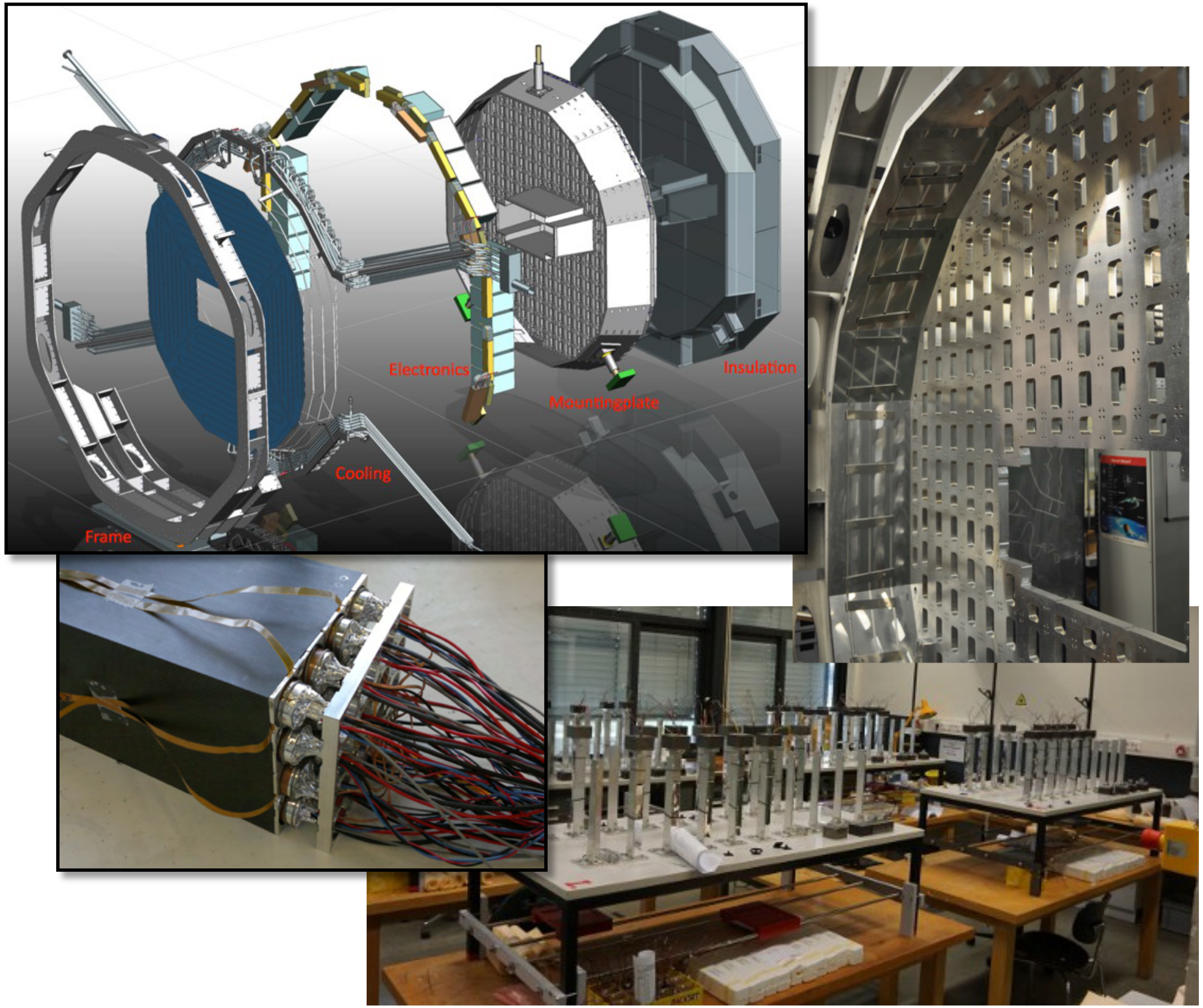
- Production & assembly well advanced
- All crystals have been produced

- VPTT all characterized
  - Modules production done
- APD screening progress
  - Modules assembly started

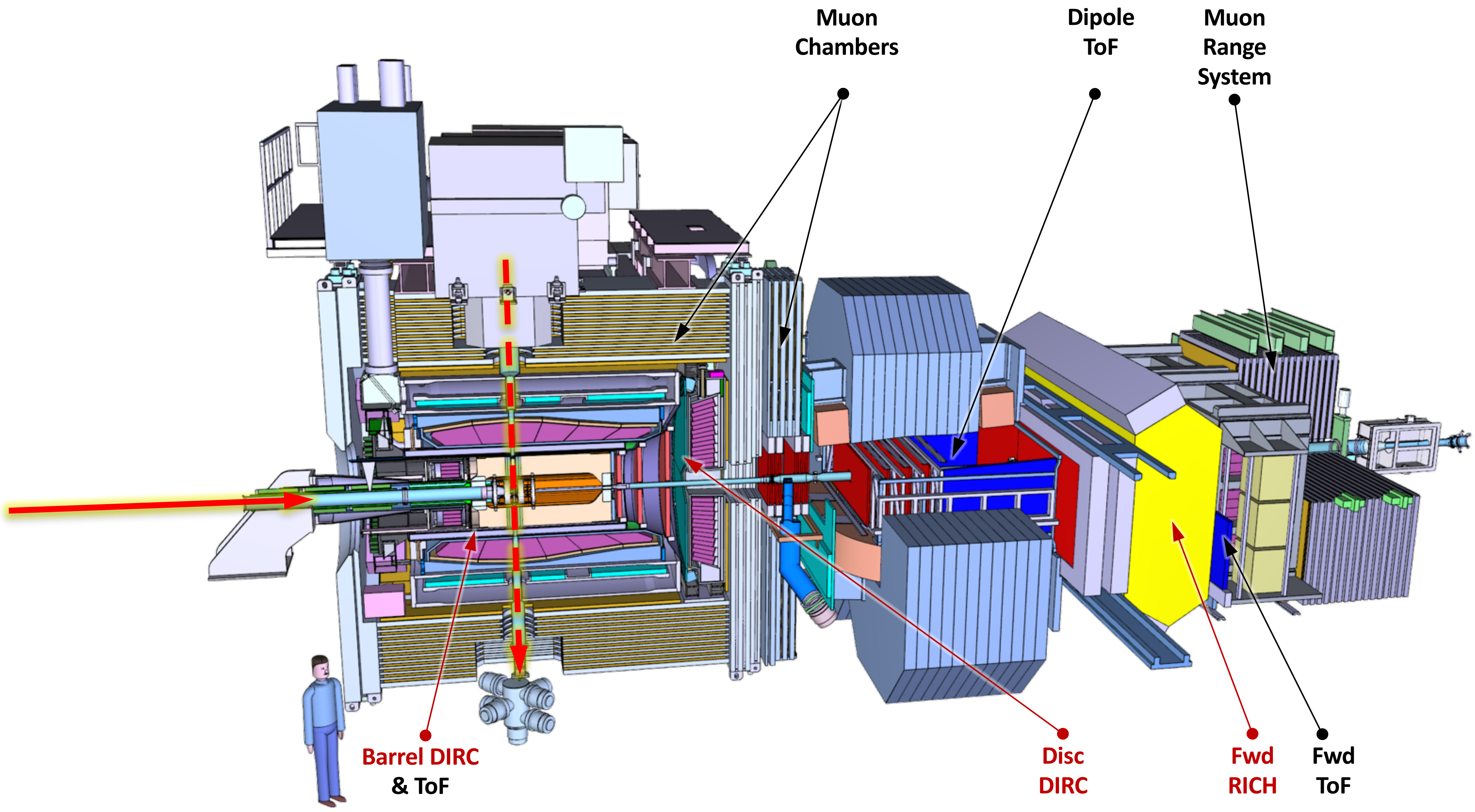
- FADCs for digitization
  - SADC board in production (w/ Versatile Link/VL+)

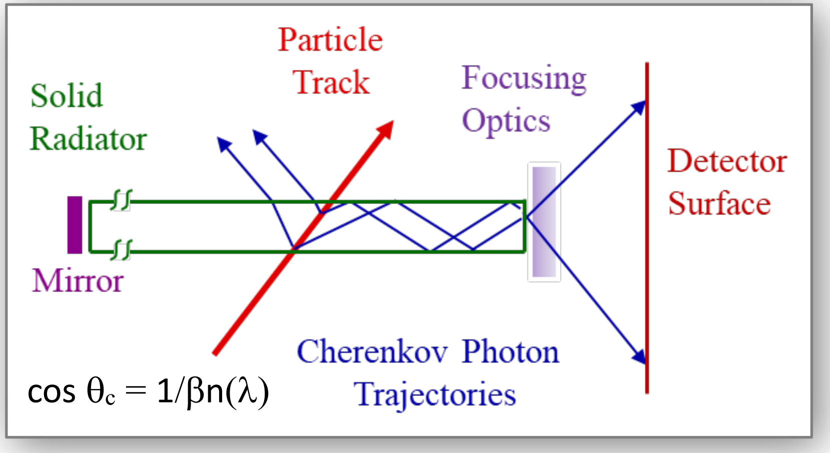
- Test stand for module calibration with cosmics
- Cooling system available, controls tests
- Pre-assembly support prepared

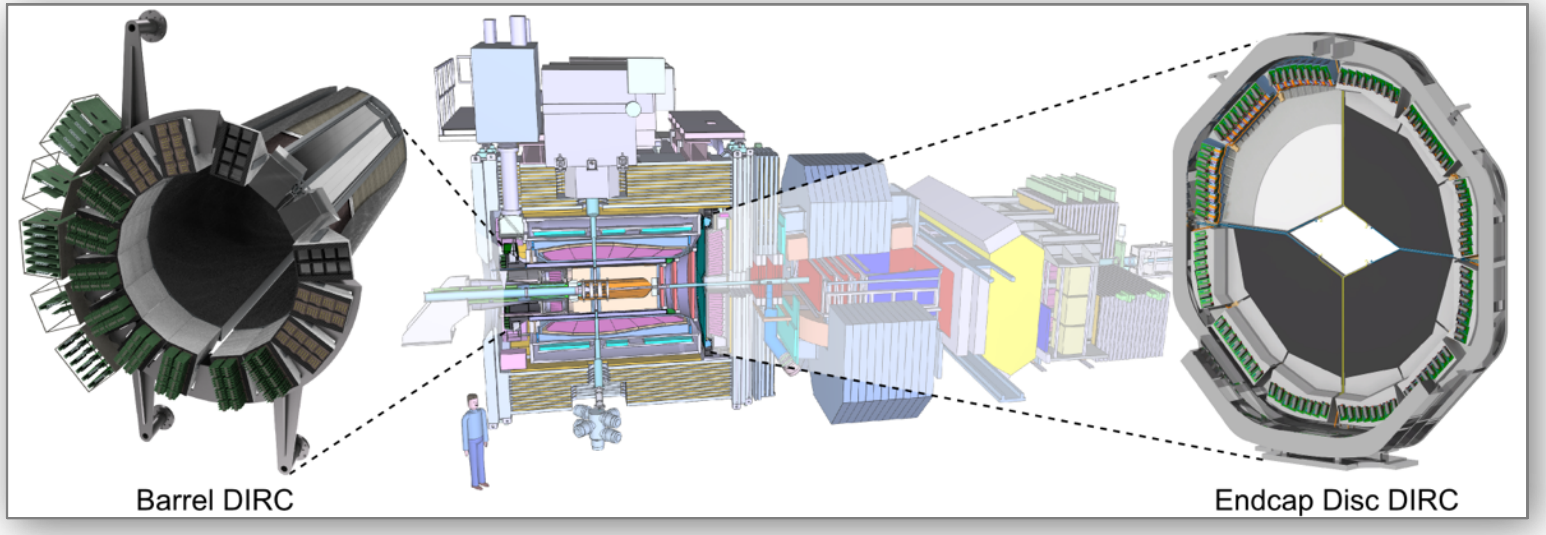
- First detector system to be fully assembled

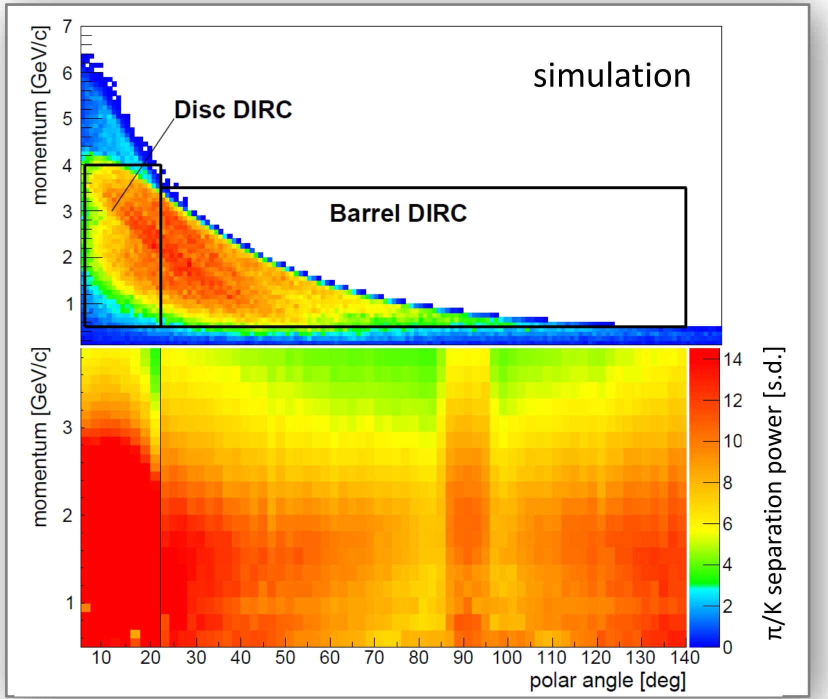


PANDA Detector: Particle ID









- **Barrel DIRC**

  First DIRC with lens focusing

  Goal: 3 s.d. π/K separation up to 3.5 GeV/c, 22°-140°

- **Endcap Disc DIRC**

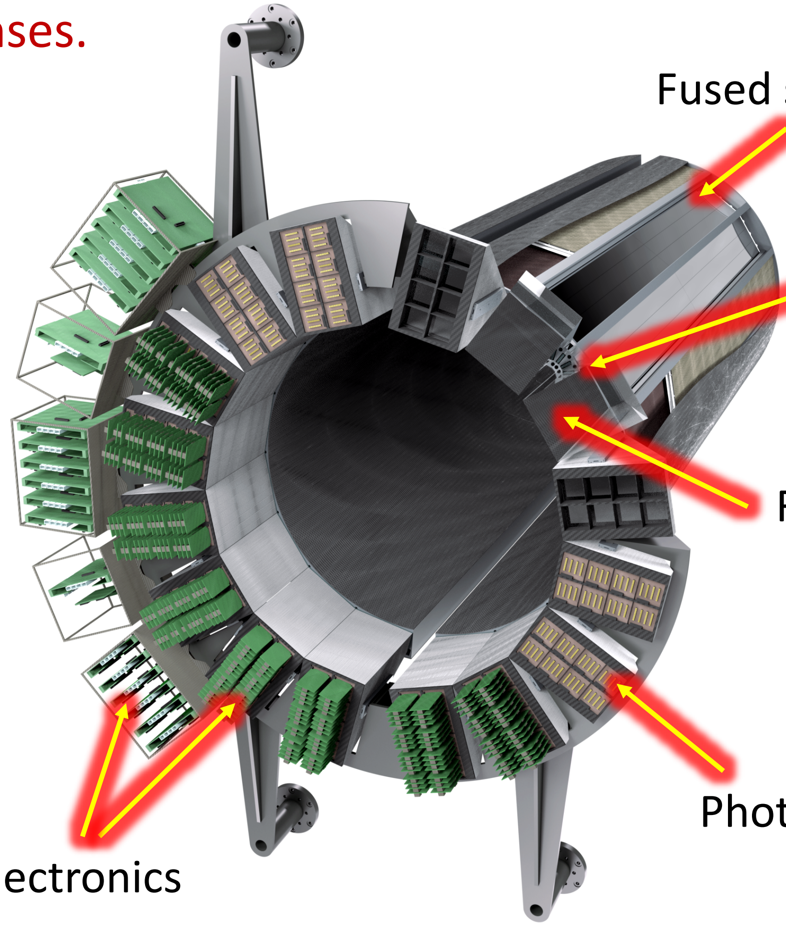
  First DIRC designed for detector endcap region

  Goal: 3 s.d. π/K separation up to 4 GeV/c, 5°-22°

Key technologies: fast single photon timing in high B-fields with small pixels and long lifetime; high-quality fused silica radiators

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: innovative 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 electronics
  ~100ps per photon timing resolution (DiRICH)
- Expected performance (simulation and particle beams):
  25-110 detected photons per particle,
  ≥ 3 s.d. π/K separation at 3.5 GeV/c



Conservative design – similar to proven BABAR DIRC, validated with particle beams since 2015.

TDR published, call for tenders for most costly long-lead items (bars, sensors) underway

Optimizing simulation and reconstruction code with experimental data from GlueX DIRC

PANDA-EIC synergy: ***eRD14***
see G. Kalicy poster on the High-Performance DIRC

PARTICLE ID: ENDCAP DISC DIRC (EDD)

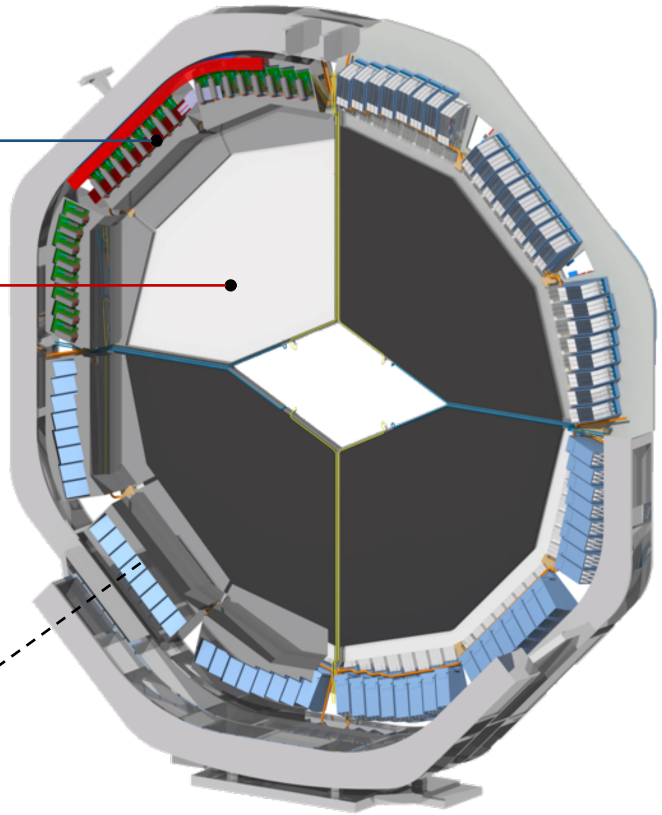
Optics made of synthetic fused silica

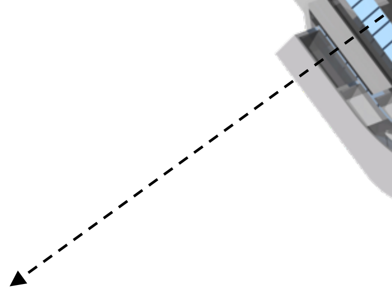
4 independent quadrants

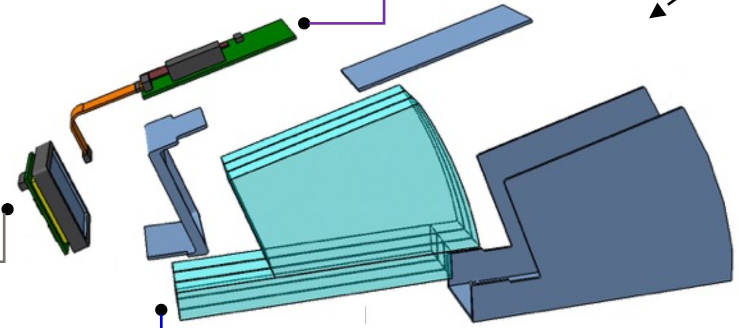
Focusing elements convert angle to position information

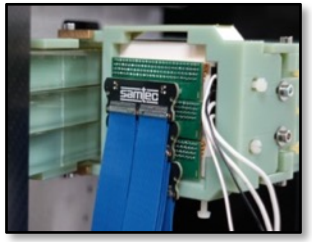
2-inch MCP-PMT with a pitch of 0.5 mm

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

~29k channels

Expected performance

~25 detected photons per particle,

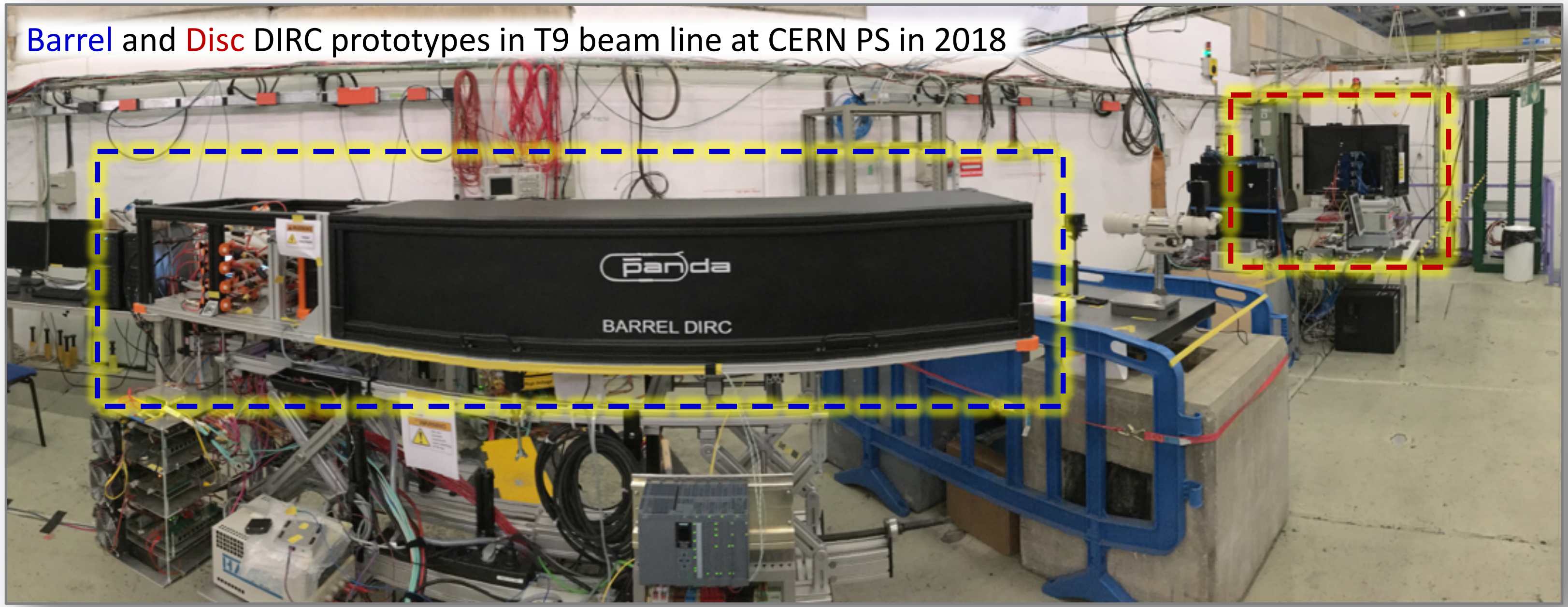
≥ 3 s.d. π/K separation at 4 GeV/c

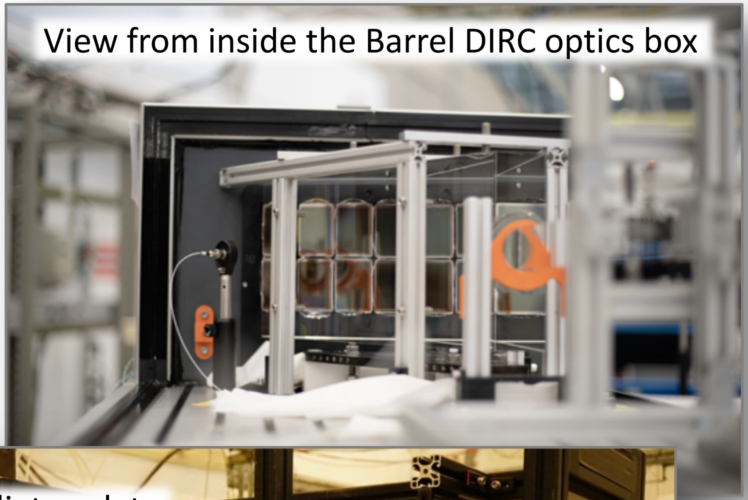
Novel design, validated with particle beams since 2016.

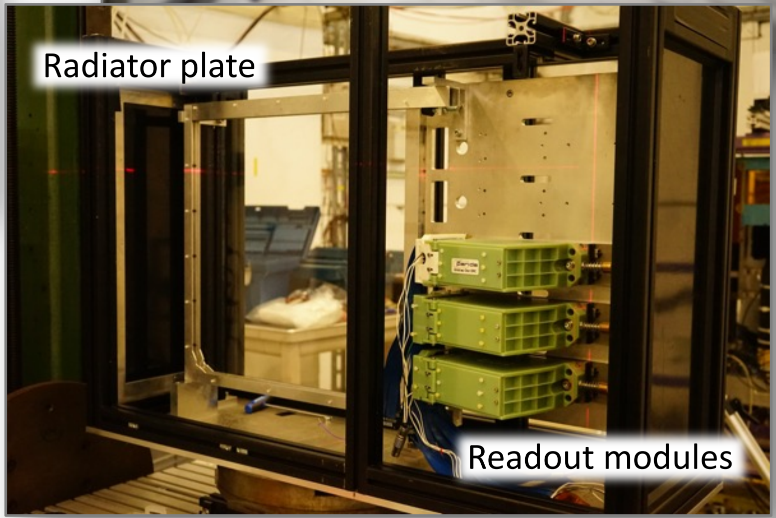
TDR recently completed

first-of-series quadrant in 2026

Increasingly complex prototypes in particle beams at GSI, DESY, and CERN PS



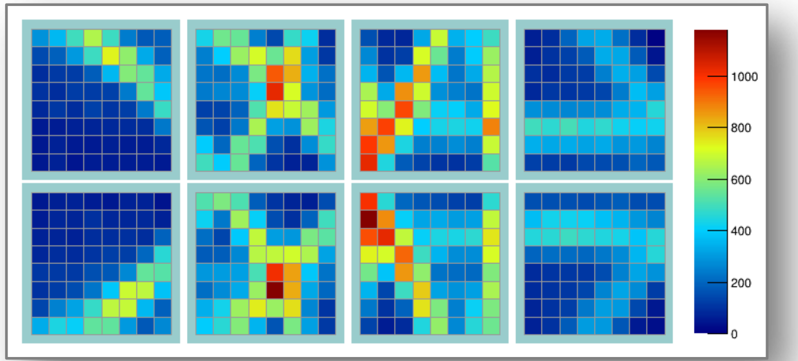




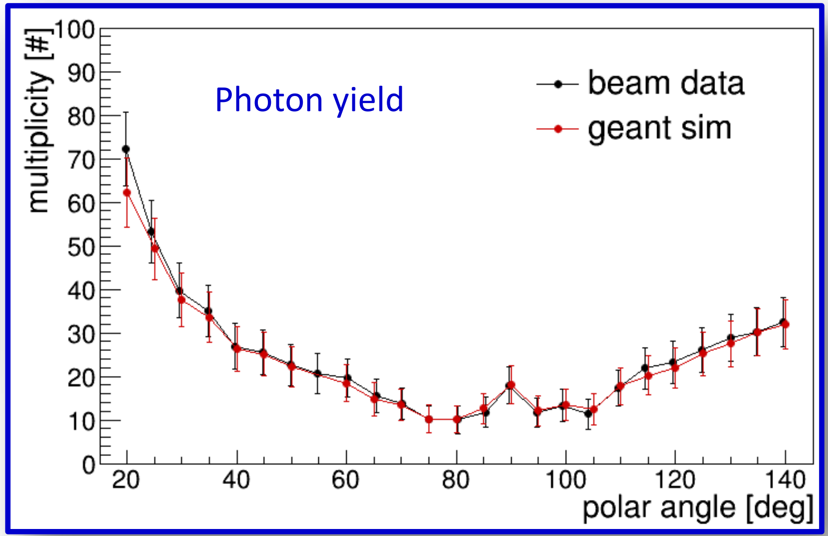
- direct measurement of PID performance across PANDA phase space
- external PID from MCP-PMT time-of-flight stations
- measure photon yield, timing precision (picosecond laser calibration) and Cherenkov angle resolution per particle/per photon, π/p and π/K separation power
- validation of cost-saving design options

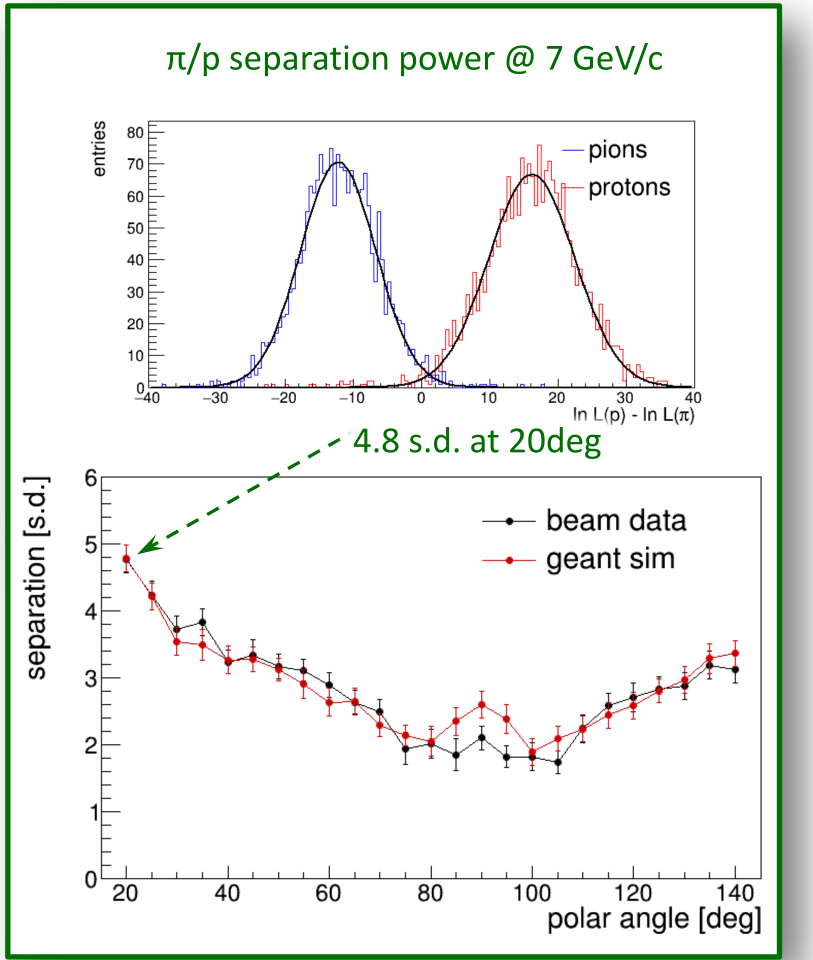
Barrel DIRC Beam Test

Example: 2018 prototype at CERN PS: π/p beam at 7 GeV/c, equivalent to π/K at 3.5 GeV/c



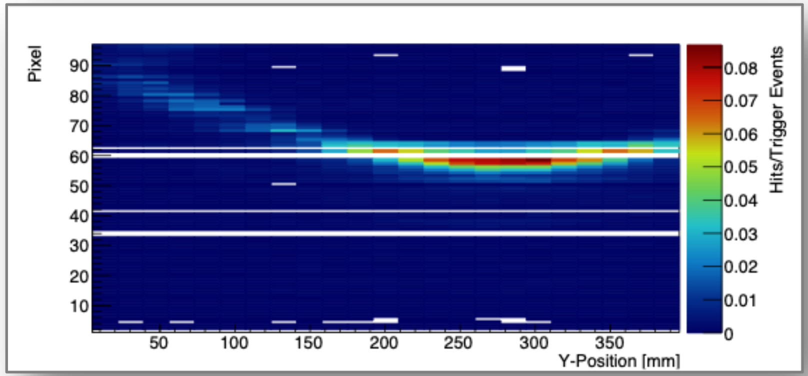
Barrel DIRC hit pattern at polar angle 20°



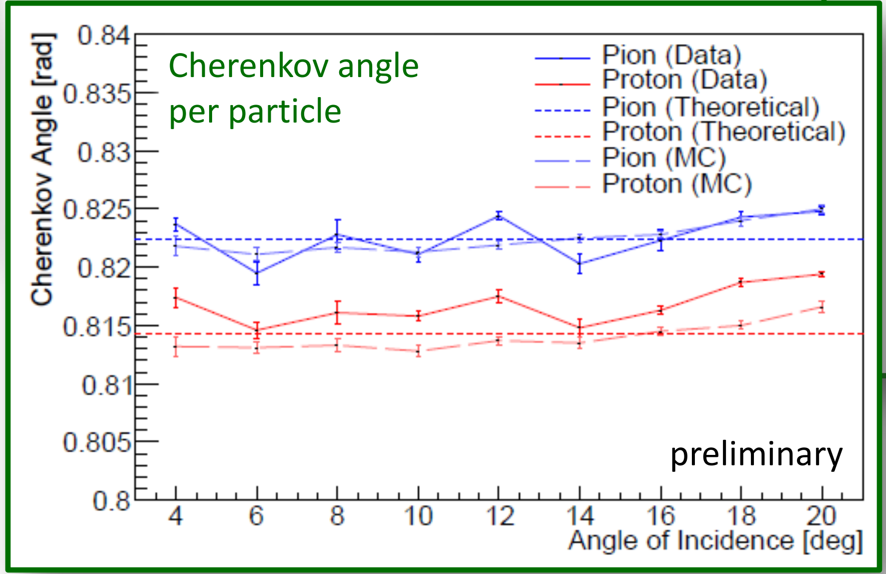


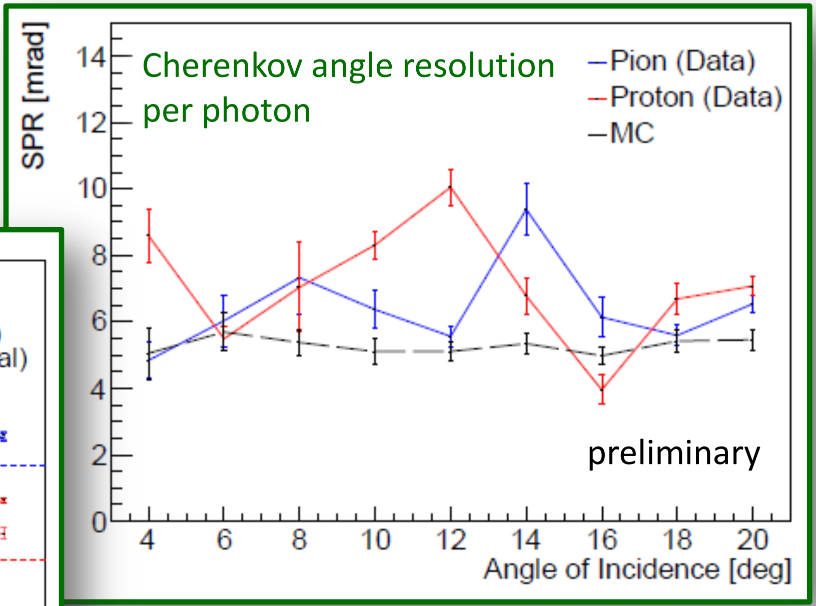
- narrow fused silica bar, 3-layer spherical lens, 30 cm-deep fused silica prism expansion volume, 2x4 Planacon MCP-PMT array, PADIWA/TRB3 readout
- measured photon yield and Cherenkov angle resolution in excellent agreement with expectation and Geant4 simulation
- achieved π/K separation power of N_{sep}=4.8 s.d. with time imaging reconstruction for most challenging phase space region (expect better photon timing in PANDA)
- PID performance meets or exceeds PANDA PID requirements

Example: 2018 prototype at CERN PS



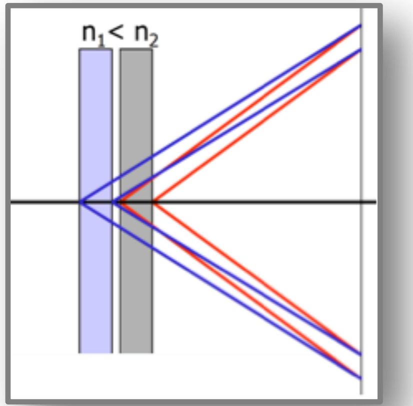
Disc DIRC hit pattern for 10 GeV/c protons





- fused silica radiator plate, 9 focusing elements, 3 fine-segmentation anode MCP-PMTs
- TOFPET 2 ASIC readout, still to be optimized for MCP-PMT signals
- measured Cherenkov angle and resolution per photon
- simulation describing data features well; tuning, calibration, and analysis still ongoing

Particle ID: Forward RICH

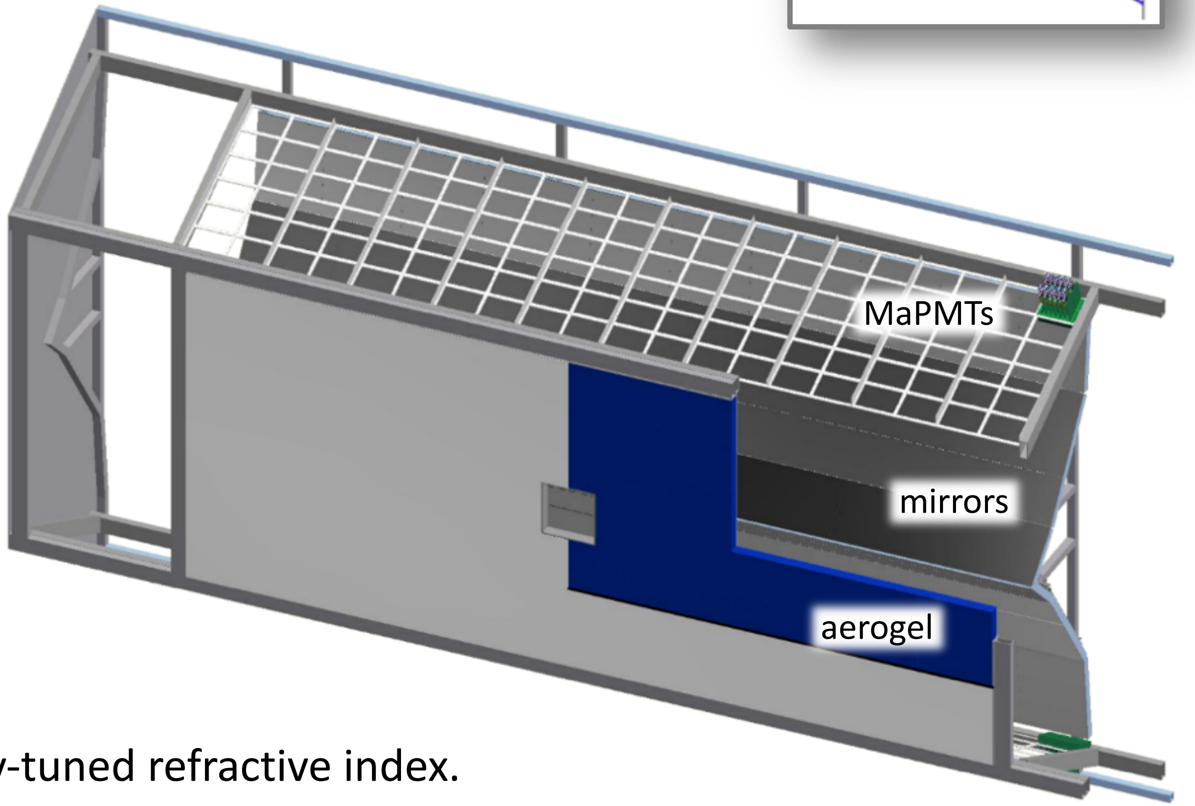


Design based on "Focusing Aerogel"

Increase light yield without deterioration of photon resolution

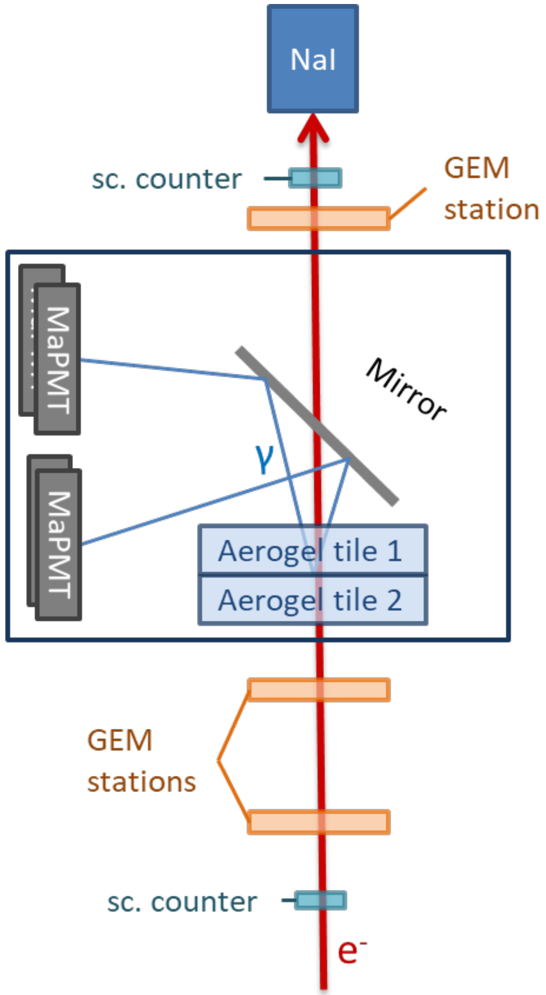
by combining multiple tiles with different refractive index

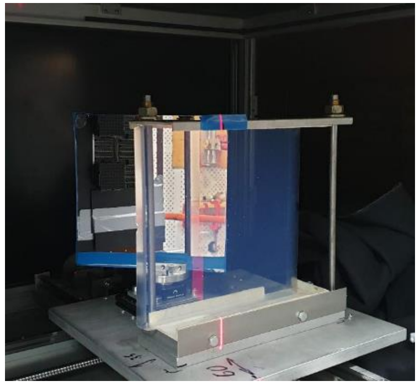
- Coverage: θ_x<10°, θ_y<5°
- 40mm thickness focusing aerogel tiles (2 or 3 layers), n≈1.05
- Focusing mirrors direct Cherenkov photons to sensor array above/below beam
- Mirrors: 2mm float glass, Al+SiO_2 coating
- Sensors: ~240 Hamamatsu H12700 MaPMTs
- Fast FPGA-based readout electronics: DiRICH (same as PANDA Barrel DIRC, HADES/CBM RICH)
- Expected performance: ≥ 3 s.d. π/K separation for 2 – 10 GeV/c

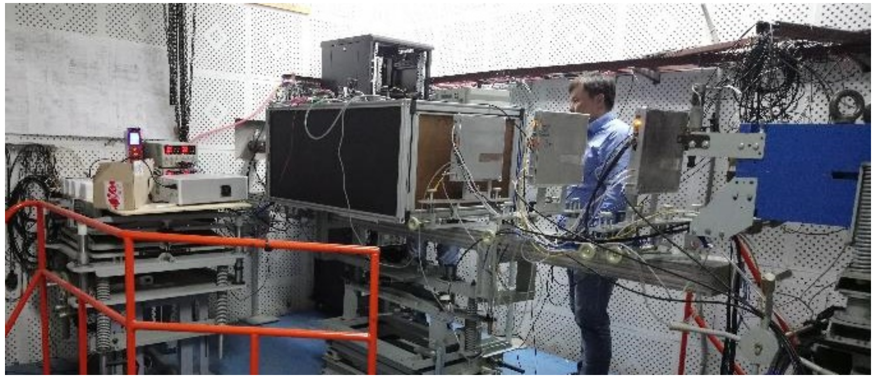


Key technology: high-quality transparent aerogel tiles with finely-tuned refractive index.

Prototype test at with electrons at BINP in 2019 with DiRICH&PADIWA&TRB3 readout







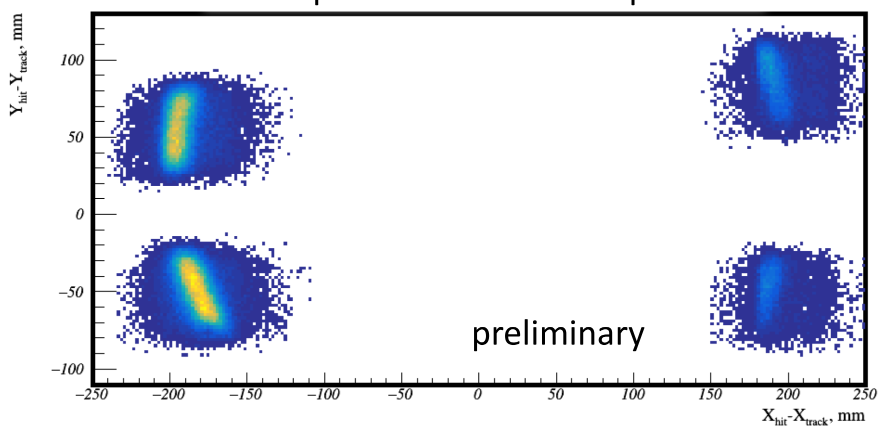
4 MaPMTs, 2 read by PADIWA, 2 by DiRICH

256 channels total

Aerogel: n=1.0526, t=2cm & n=1.0500, t=2cm

Flat mirror at 45° w.r.t. the sensors and aerogel

Hit map corrected for track position



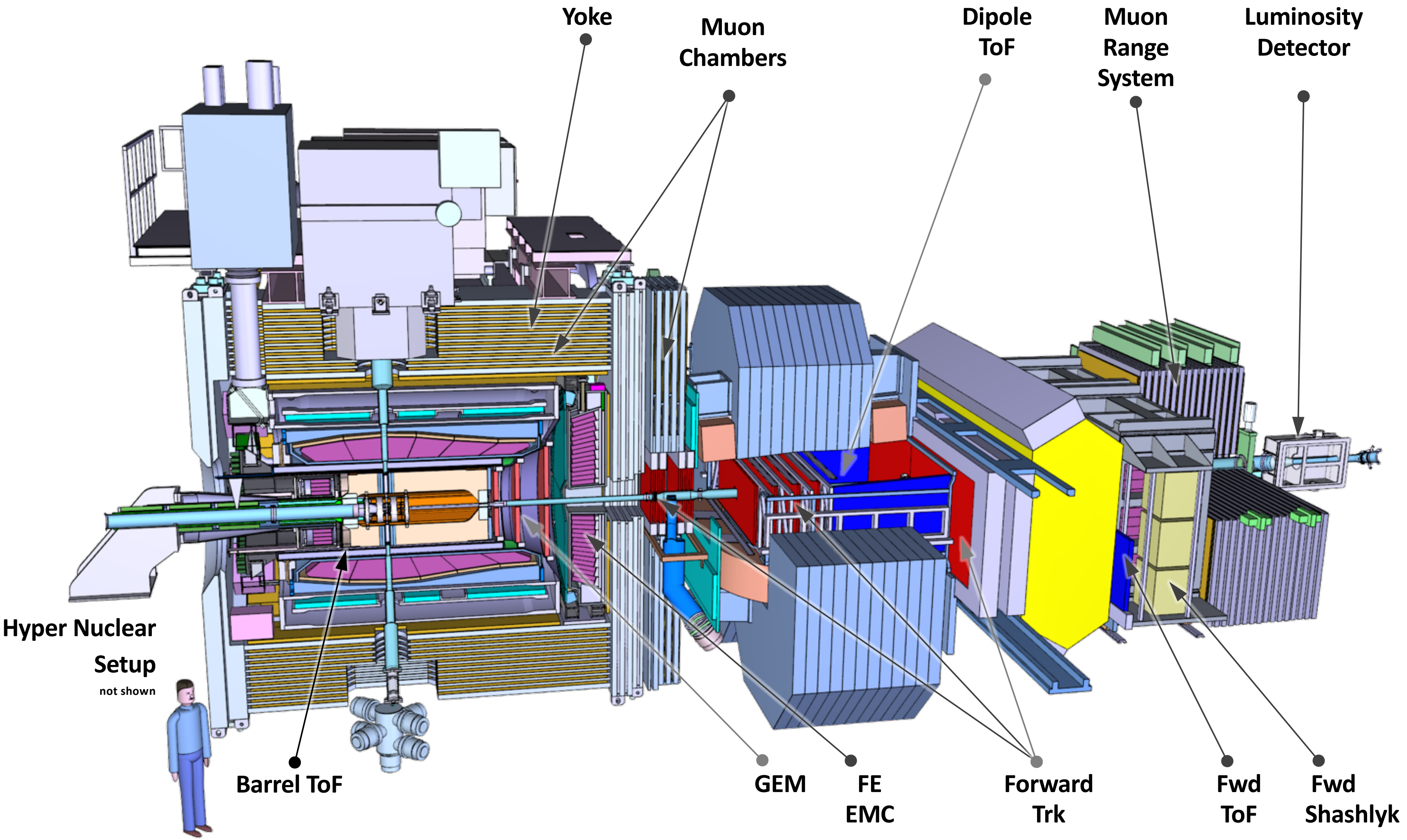
Parameter	Test beam	Calculation
N_{pe}	16	39
R, mm	201	199
$\sigma_{R,\,1pe}$, mm	3.3	3.1

preliminary

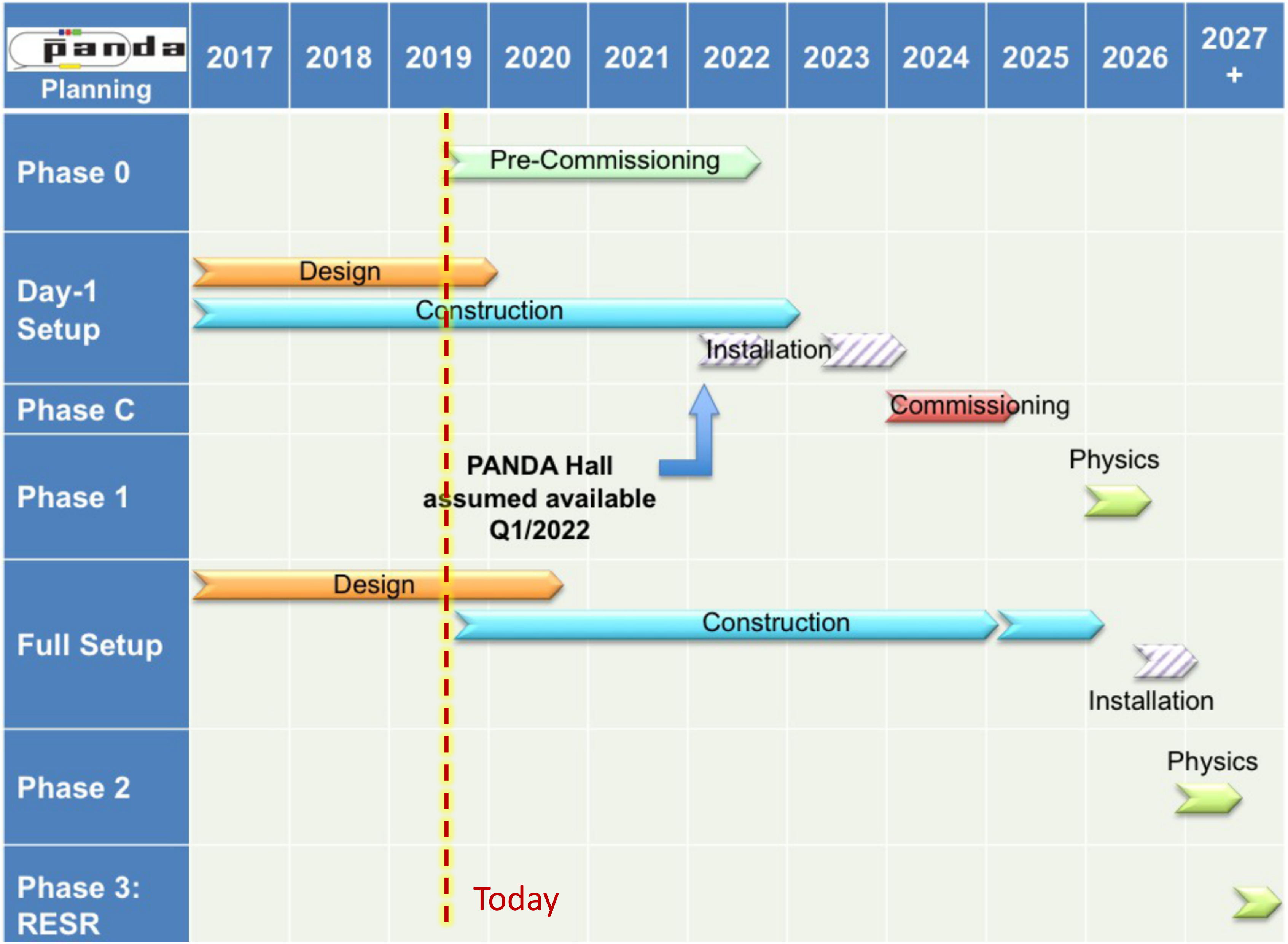
- analysis ongoing
- promising preliminary results

Detector Layout

Apologies to the many PANDA systems I did not have time to mention (see extra material)



PANDA SCHEDULE



Experiments with PANDA detectors and software at HADES, MAMI, and GlueX

Construction of Phase 1 systems

Two Phase 1 installation periods
1. Solenoid, dipole, supports
2. All Phase 1 detectors

Commissioning with cosmics and beam (protons / antiprotons)

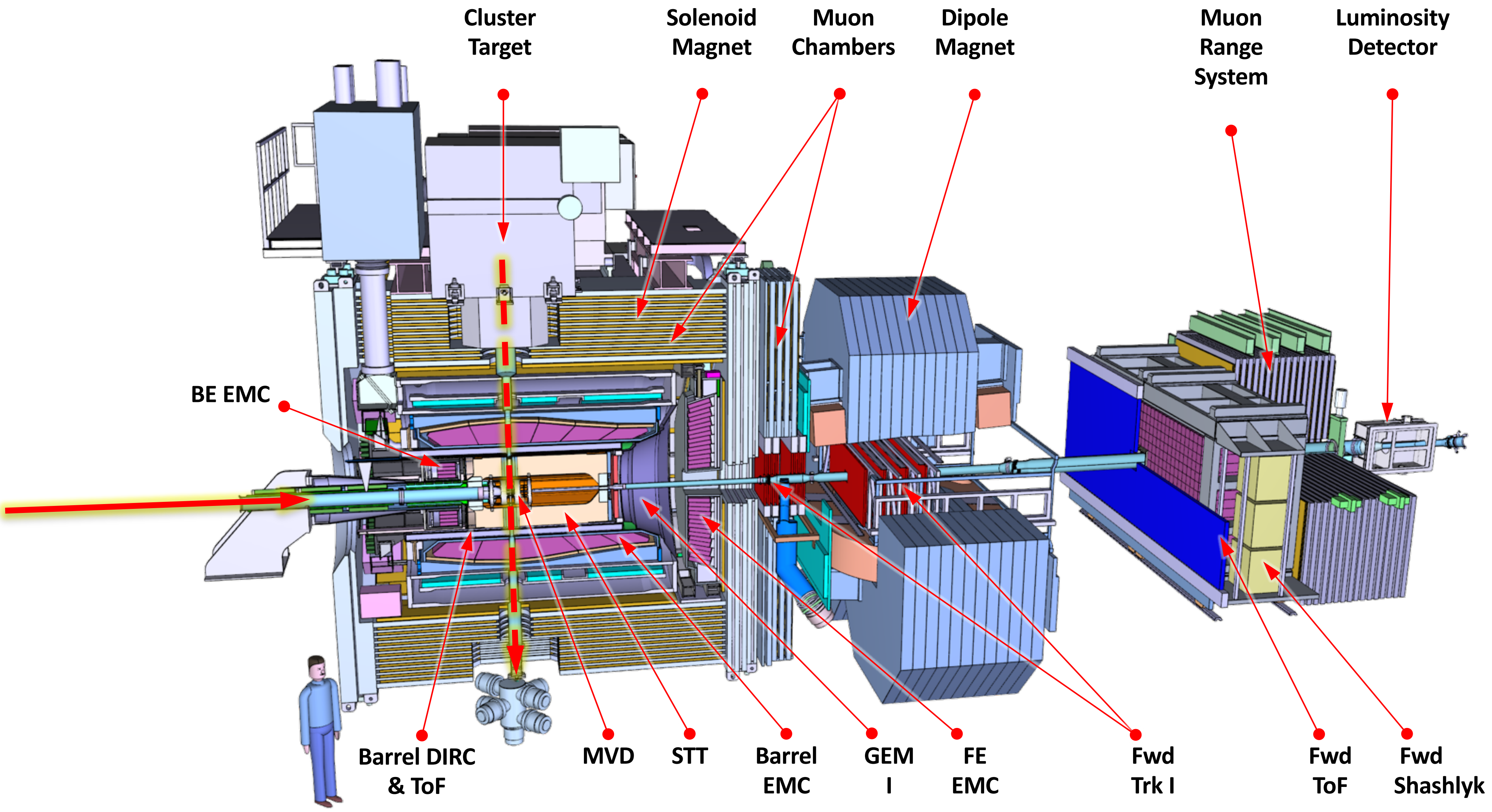
Physics with antiprotons

Construction of Phase 2 systems

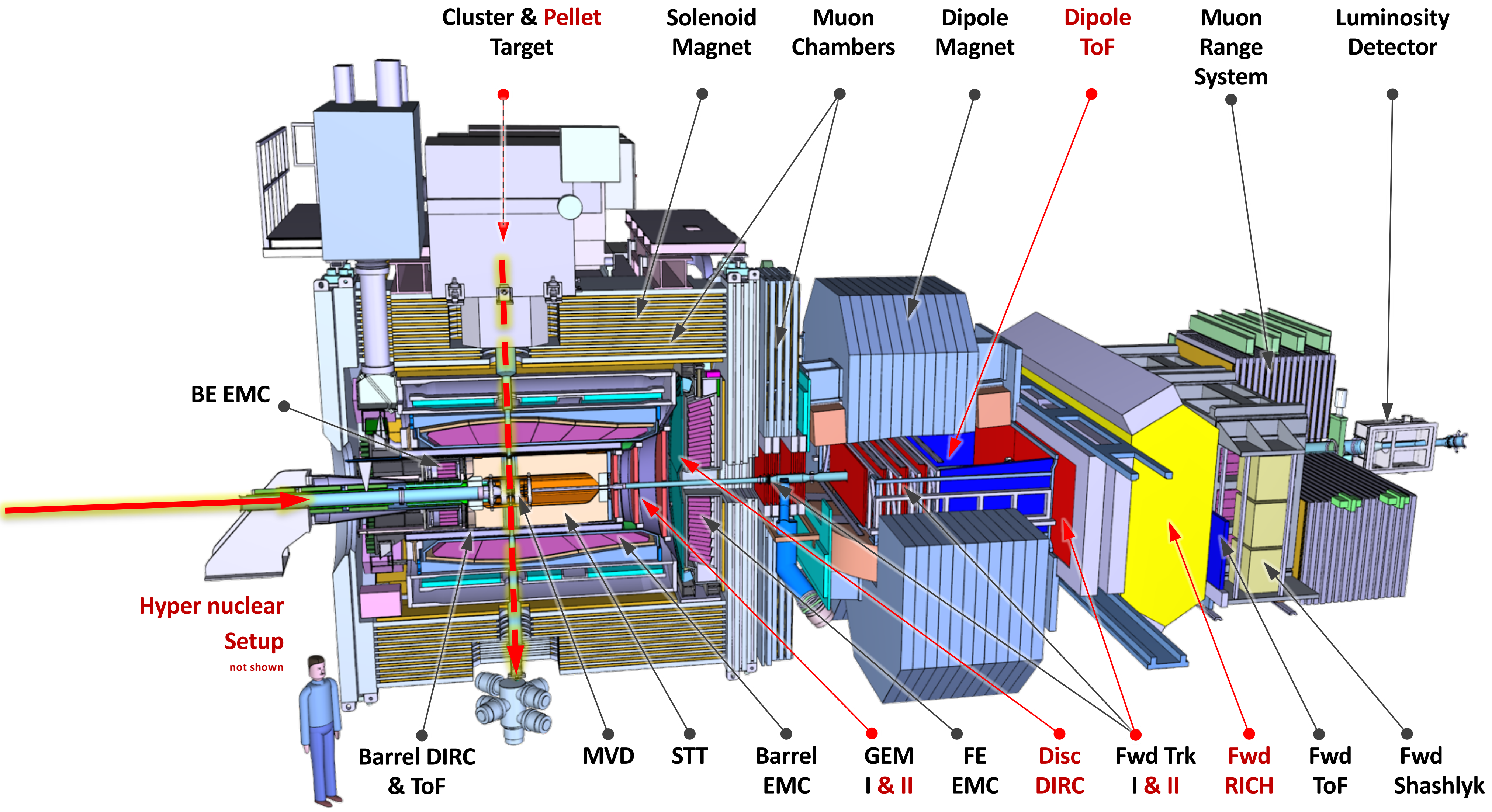
Installation period for remaining Phase 2 detectors

Physics with antiprotons

START SETUP (PHASE 1)



Full Setup (Phase 2)



FAIR construction making good progress

(snapshots from recent drone video
www.gsi.de/en/researchaccelerators/fair/fair_civil_construction/photos_and_videos.htm)

#UniverseInTheLab

Summary & Outlook

Present Status of PANDA

- PANDA project making excellent progress
- Most Phase 1 detector TDRs complete
- Preparation for construction MoUs ongoing
- Sharpened physics focus and detector start configuration

Timeline for PANDA Construction

- Construction of detector systems has started
- Pre-assembly of first components has started
- Installation at FAIR planned for 2022 - 2023
- Commissioning with cosmics and beam 2024 - 2025

PANDA physics with antiproton beam starting in 2026

- Versatile physics machine with full detection capabilities
- PANDA will shed light on many of today's QCD puzzles

https://fair-center.de/index.php?id=329&L=0

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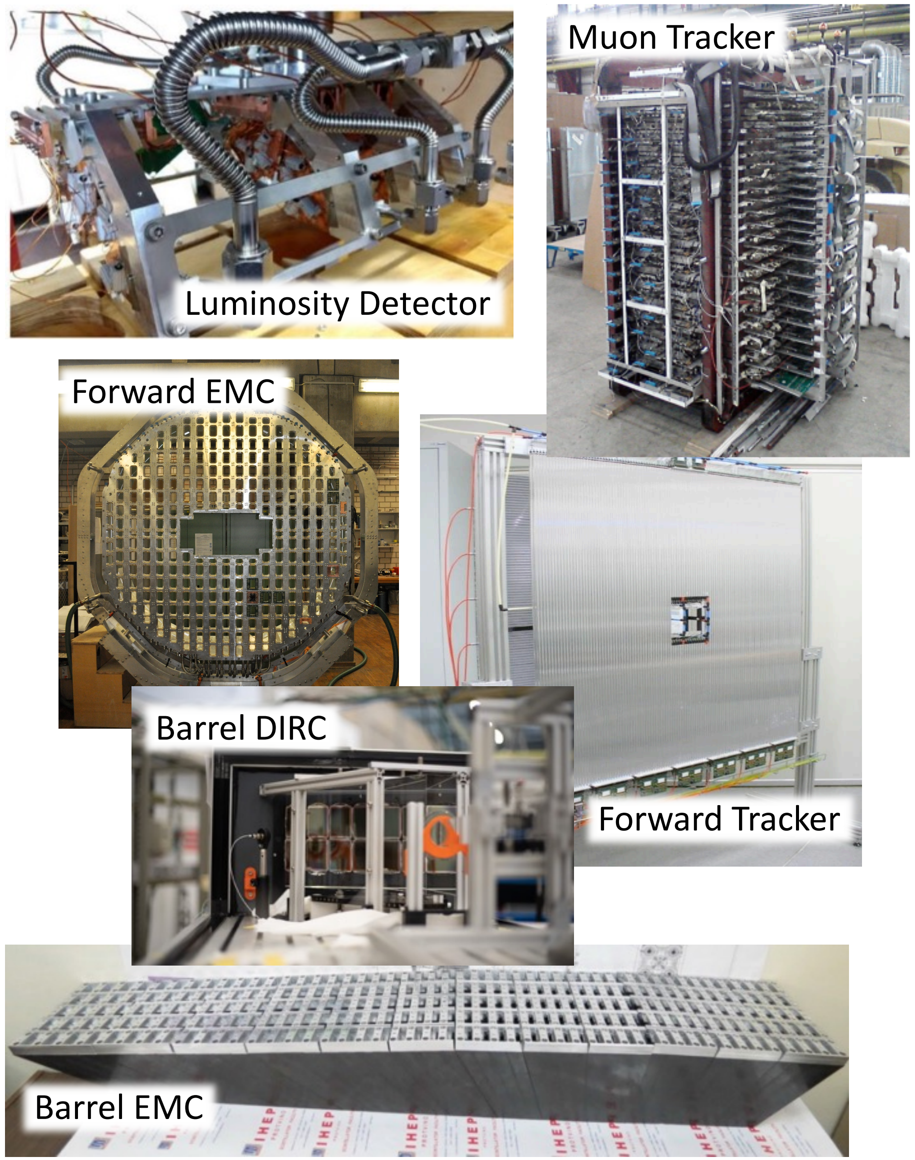

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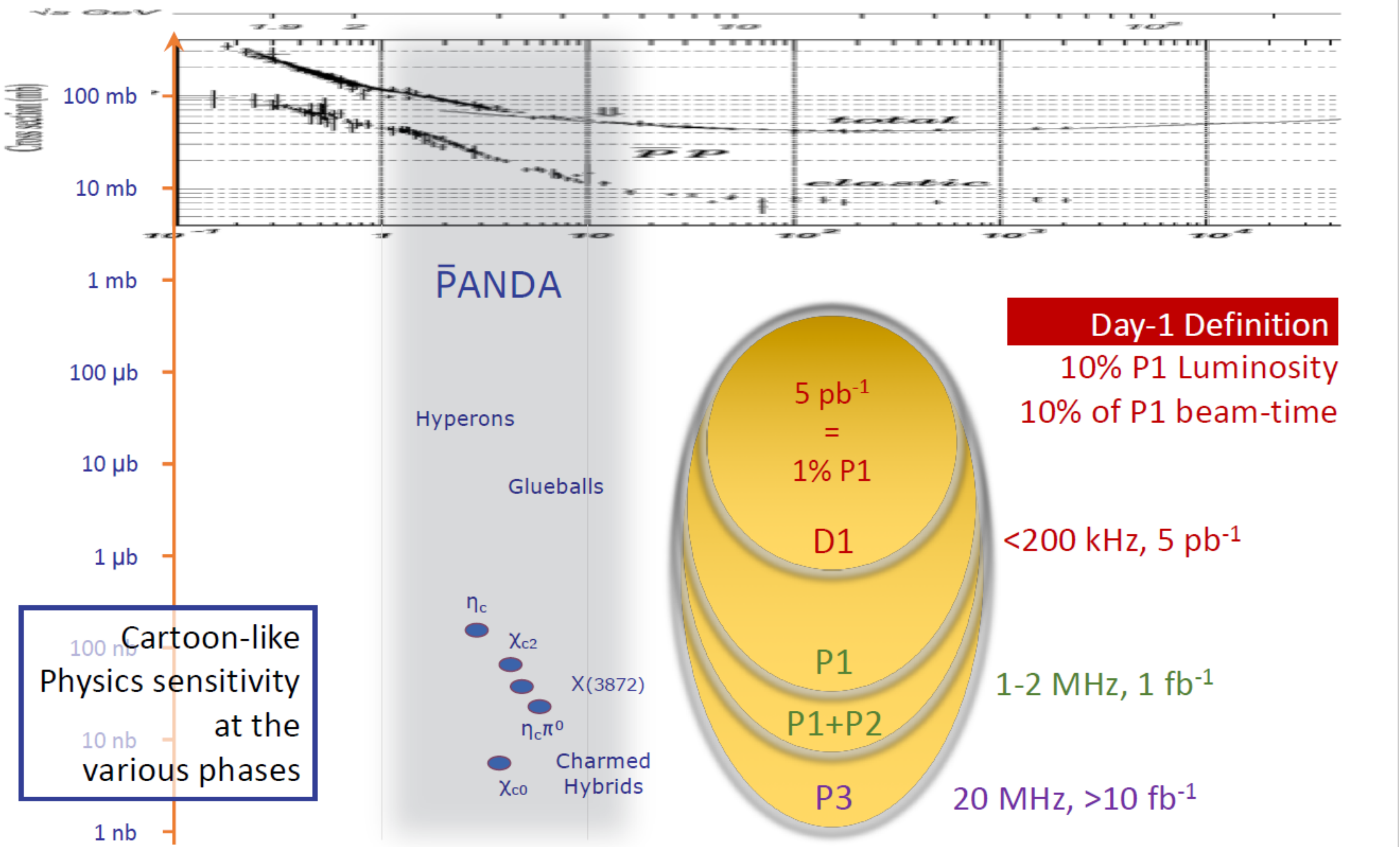
On behalf of

Thank you all for your attention.

And thanks to my PANDA colleagues, especially A. Belias, for help with the slides

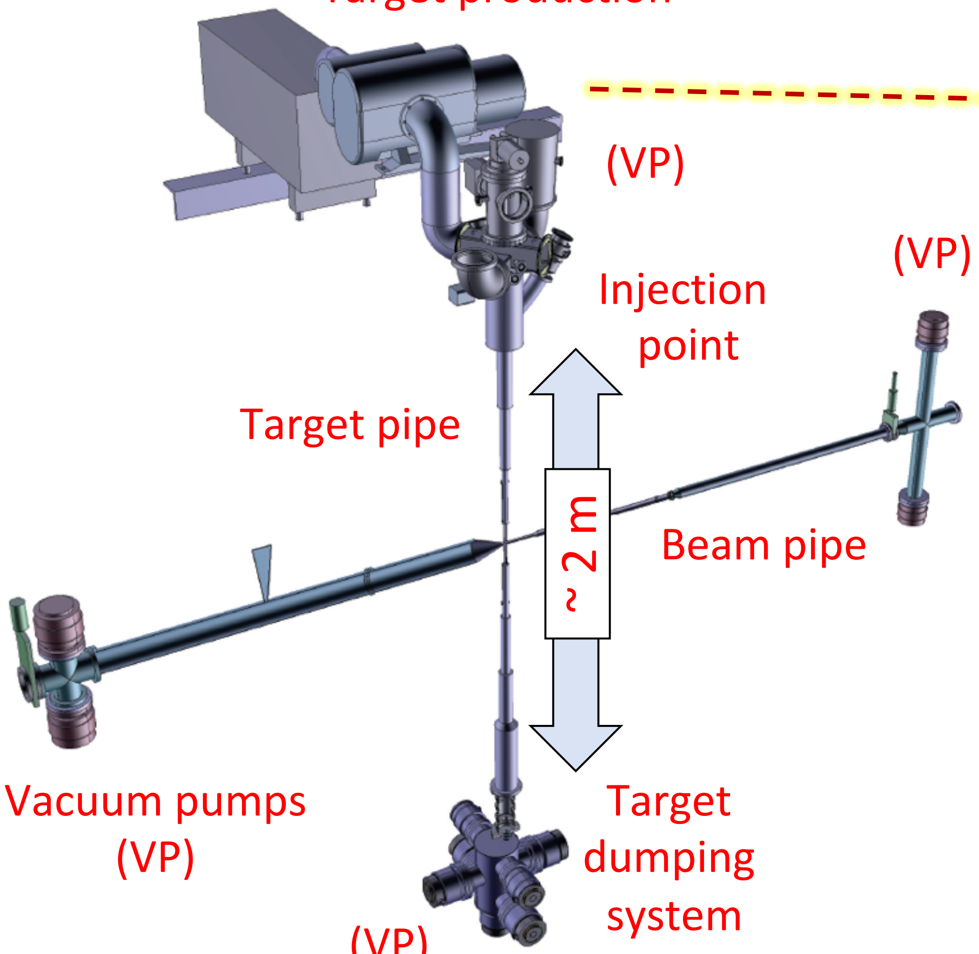
Extra Material

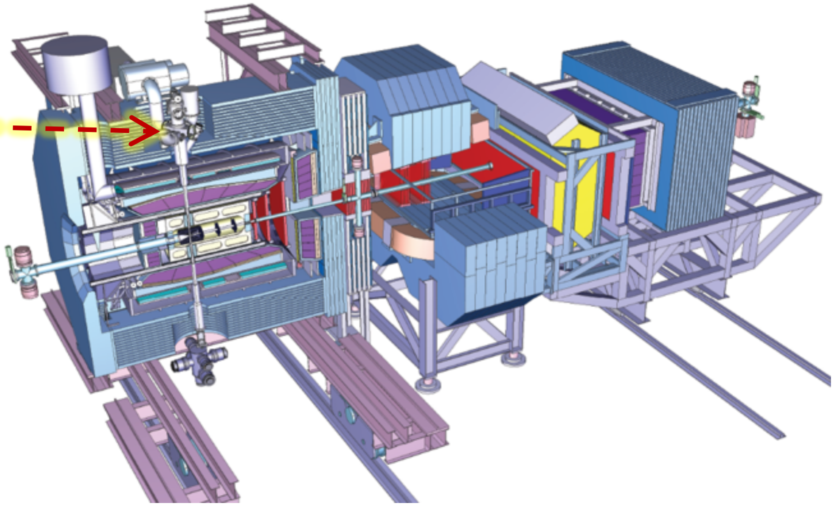
Phases of PANDA – Sensitivities in a nutshell



K. Peters | PANDA Overview | EuPPS Workshop

INTERACTION REGION





- Vacuum system, pumps, shutters
- Beam pipe, target cross, flanges
- Interfaces with detectors, target
- Support for pipe, MVD services
- Mounted on central space frame

Forward Tracking inside Solenoid

- Tracking in high occupancy region
- Important for large parts of physics

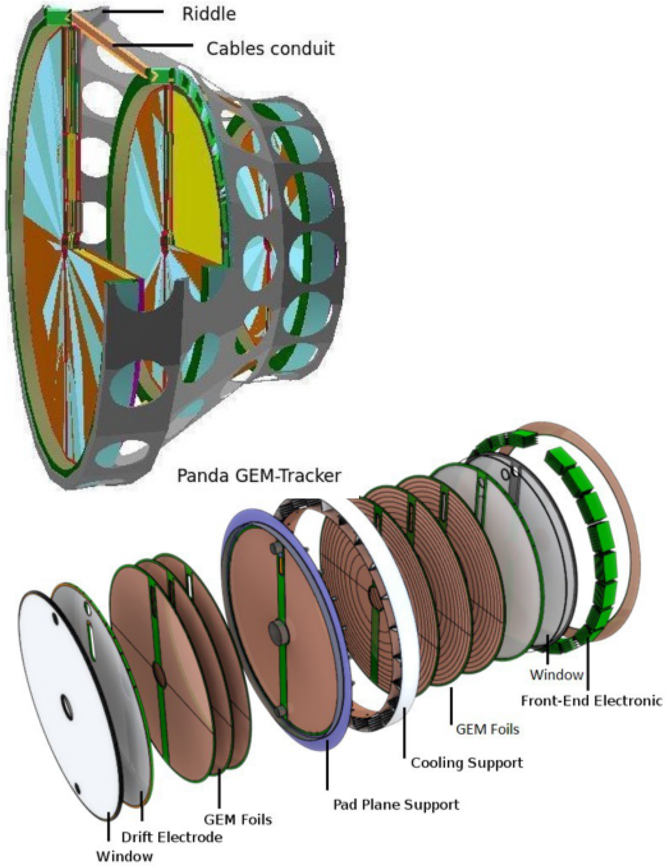
Detector design

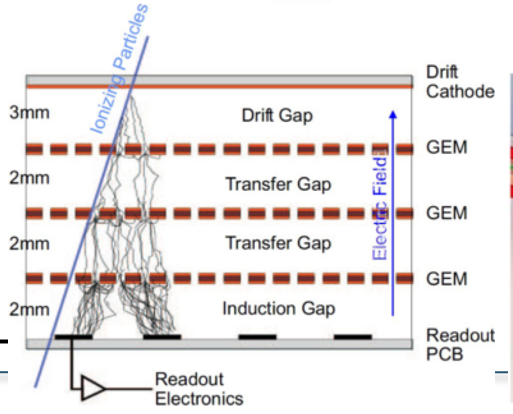
- 3 stations with 4 projections each
  - ➔ Radial, concentric, x, y
- Central readout plane for 2 GEM stacks
- Large area GEM foils developed at CERN
  (50µm Kapton, 2-5µm copper coating)
- ADC readout for cluster centroids
  - ➔ Approx. 35000 channels total
- Challenge to minimize material

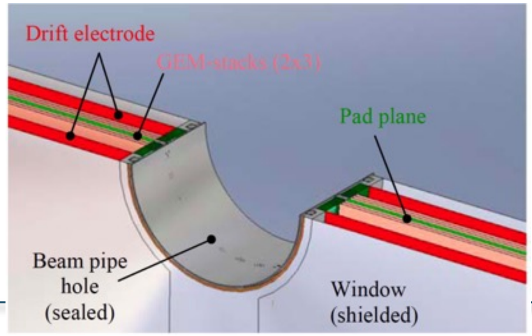
Status

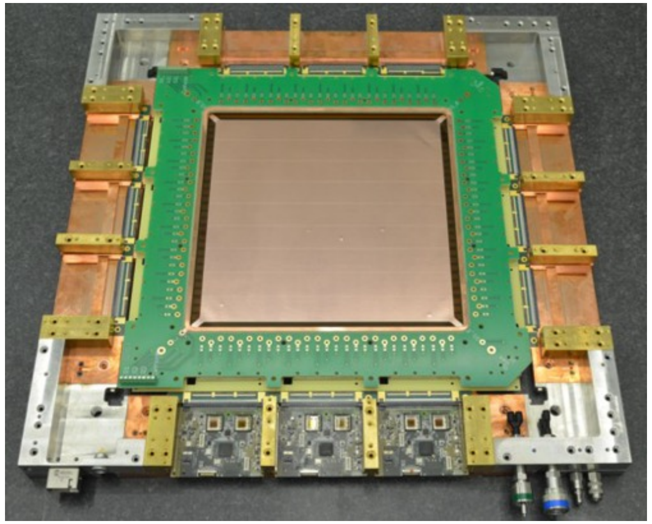
- Advanced mechanical concept
- Demonstrator construction ongoing,
  - GEM foils from TECTRA delays
- Available electronics unstable

➔ Other readout electronics required









2D Demonstrator

Challenges - Opportunities:

- Completion of demonstrator
- Characterization of GEM foils
- **Readout electronics**
- Full size prototype design
- Lack of manpower
  - → need expert groups

A. Belias,
GlueX-PANDA workshop,
May 2019

FORWARD TRACKER

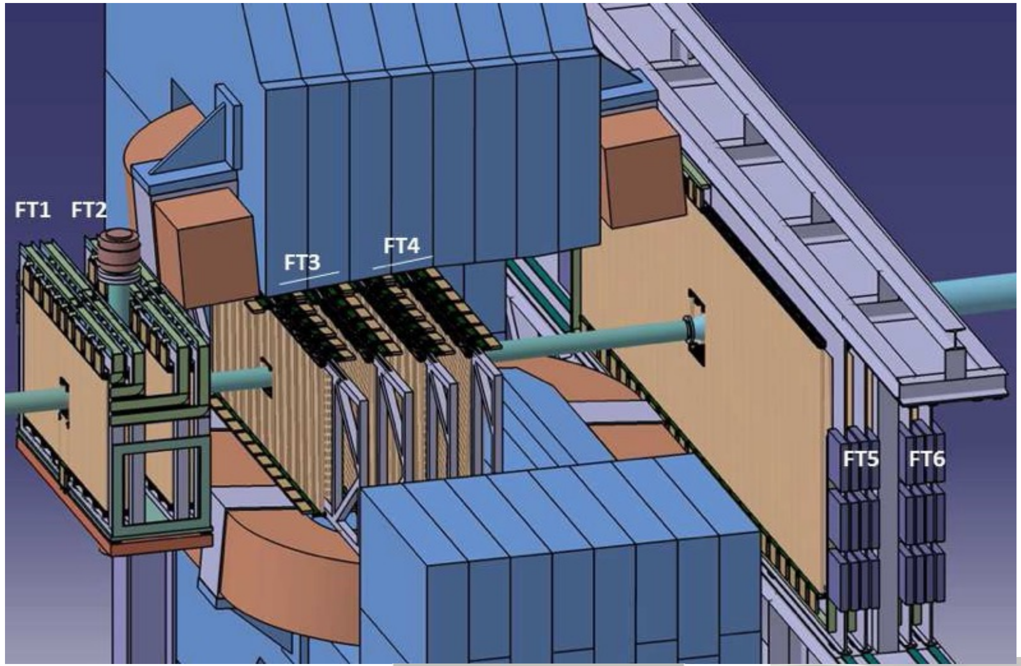
Tracking in Forward Spectrometer

- Straw tubes, same as in STT (Barrel), vertically arranged in double layers
- 3 stations with 2 chambers each
  - FT1&2 : between solenoid and dipole
  - FT3&4 : in the dipole gap
  - FT5&6 : large chambers behind dipole
- 4 projections 0°/ ± 5°/0° per chamber
- Readout ASIC PASTTREC and TDC-FPGA
  - later upgrades for High Luminosity runs

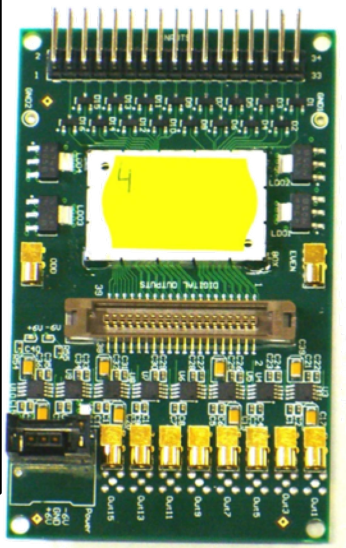
Status

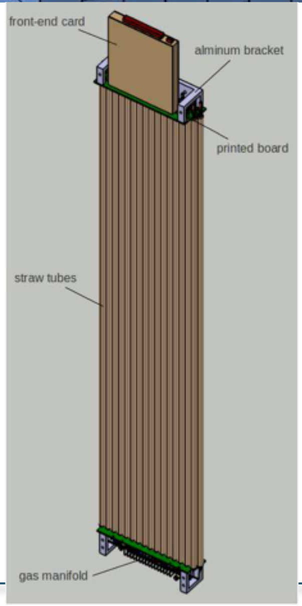
- TDR approved by FAIR ECE
- Testbeam campaigns 2018/2019
- Ongoing stereoscopic scans
- Aging tests: up to 1 C/cm^2

Full Straw Tube Prototypes in HADES at GSI
2019: Installation – 2020: Data Taking



A. Belias, GlueX-PANDA workshop, May 2019





The proposed idea:

- LHCb replaces its outer tracker with scintillating fibres for high intensity
- Short modules 2.4m, 20% of all

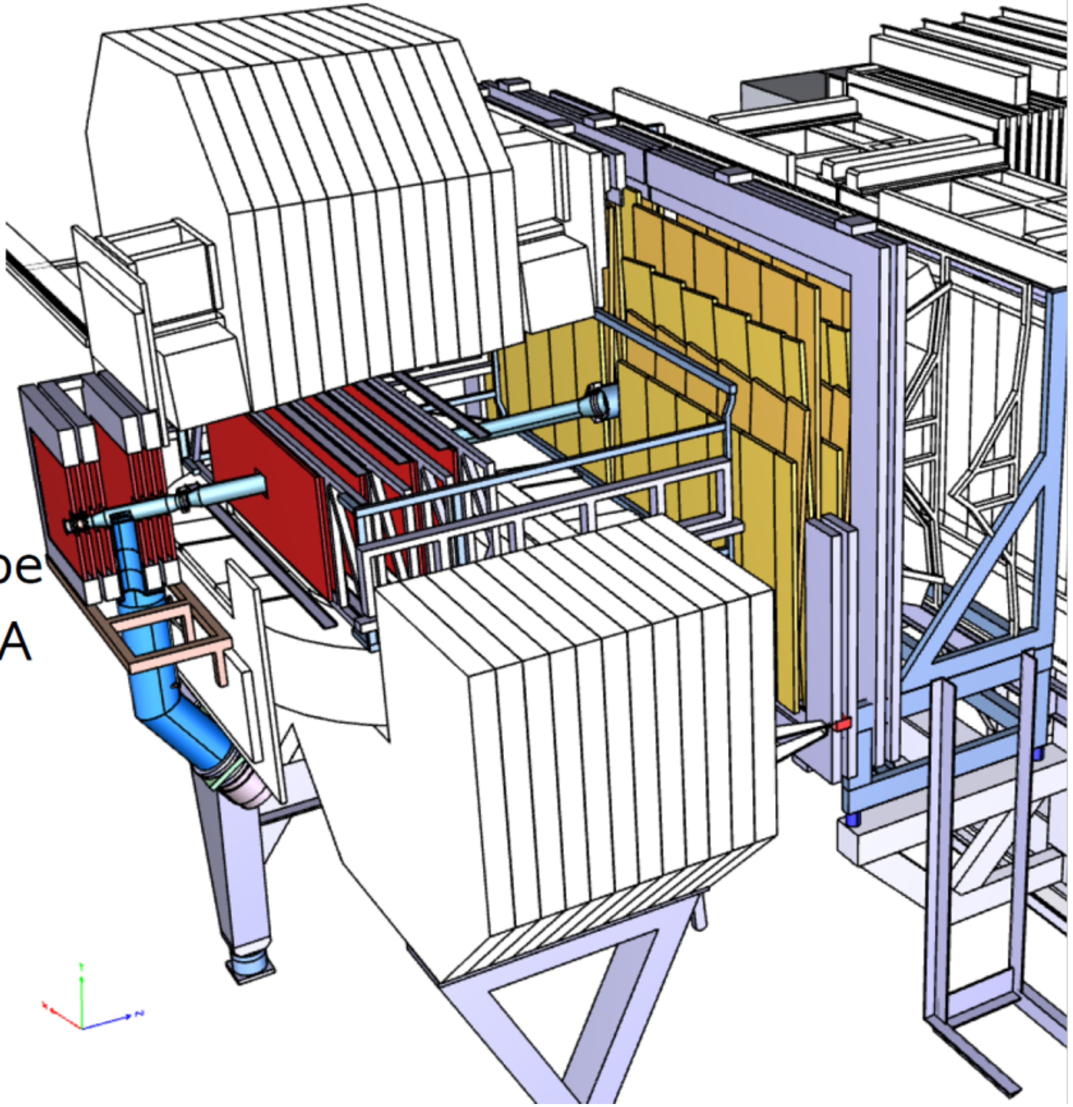
  PANDA could use these modules

Conceptual layout:

- Using all short modules inc. spares:
  → cover 4m with 2x4 planes
- Somewhat larger hole around beampipe
- Radiation length 2x higher than PANDA

Project assessment status:

- Spares can be delivered to GSI
- Active planes need to cool down
- Electronics: interface to TRB needed
- Mechanics: proposal for Thailand

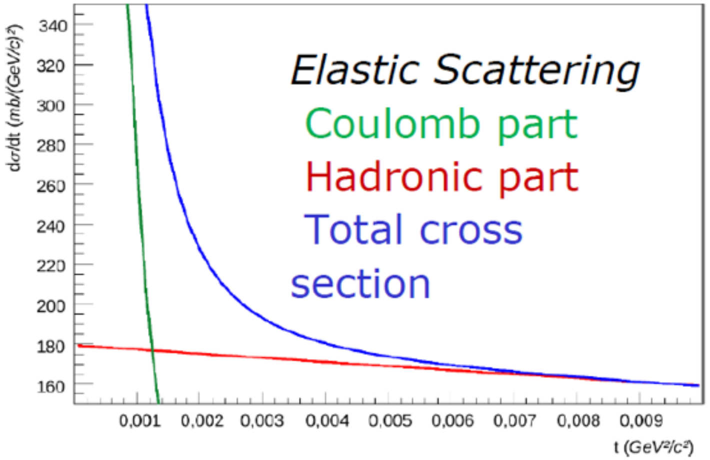


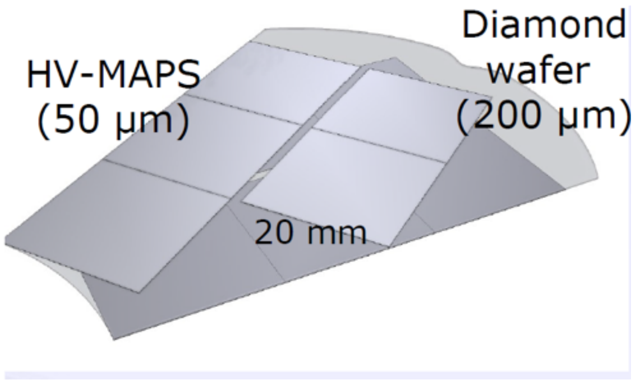
Elastic scattering:
- Coulomb part calculable
- Scattering of p̄ at low t
- Precision tracking of scattered p̄
- Acceptance 3-8 mrad

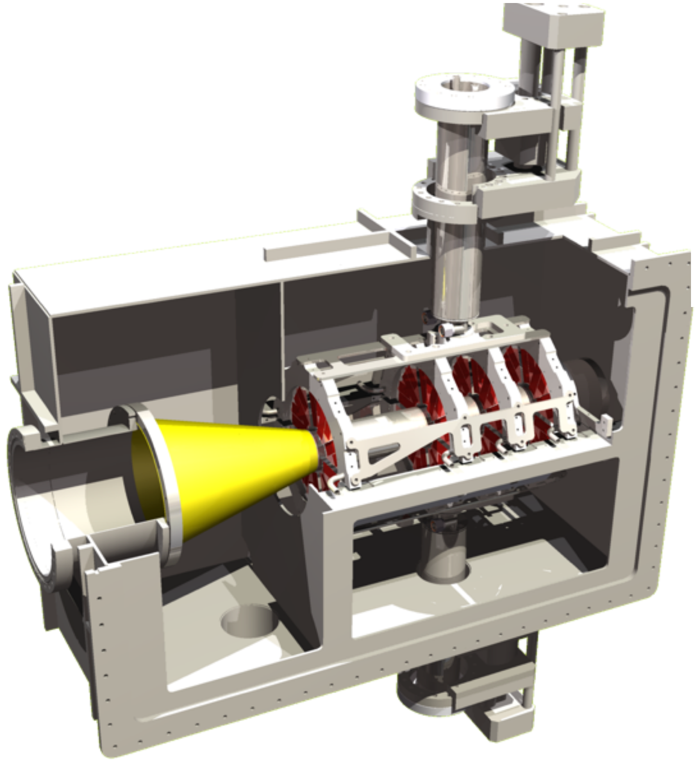
Detector layout:
- Roman pot system at z=11 m
- Silicon pixels (80x80 µm2):
  4 layers of HV MAPS (50 µm thick)
- CVD diamond supports (200 µm)
- Retractable half planes in sec. vacuum

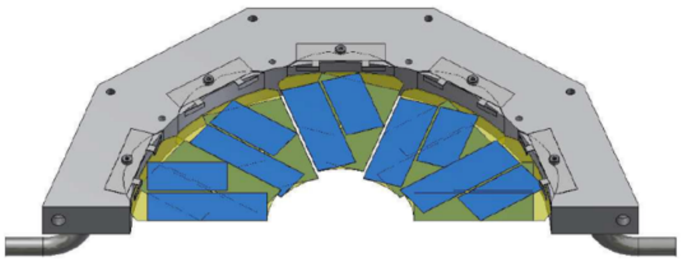
HV MAPS:
- Development for Mu3e Experiment at PSI
- Active pixel sensor in HV CMOS
  - faster and more rad. hard
- Digital processing on chip

Status:
- TDR submitted to FAIR ECE
- Mechanical vessel, cooling, vacuum, design ready
- New MuPix prototype 1x2 cm^2 in test
- FPGA readout tests









Forward electromagnetic calorimeter

- Interleaved scintillator and absorber layers
  - 0.3 mm lead and 1.5 mm scintillator
  - total depth 680 mm (380 layers)
  - transverse size 55x55 mm^2
- WLS fibers for light collection
- PMTs for photon readout
- FADCs for digitization
- Active area size 297x154 cm^2

Status

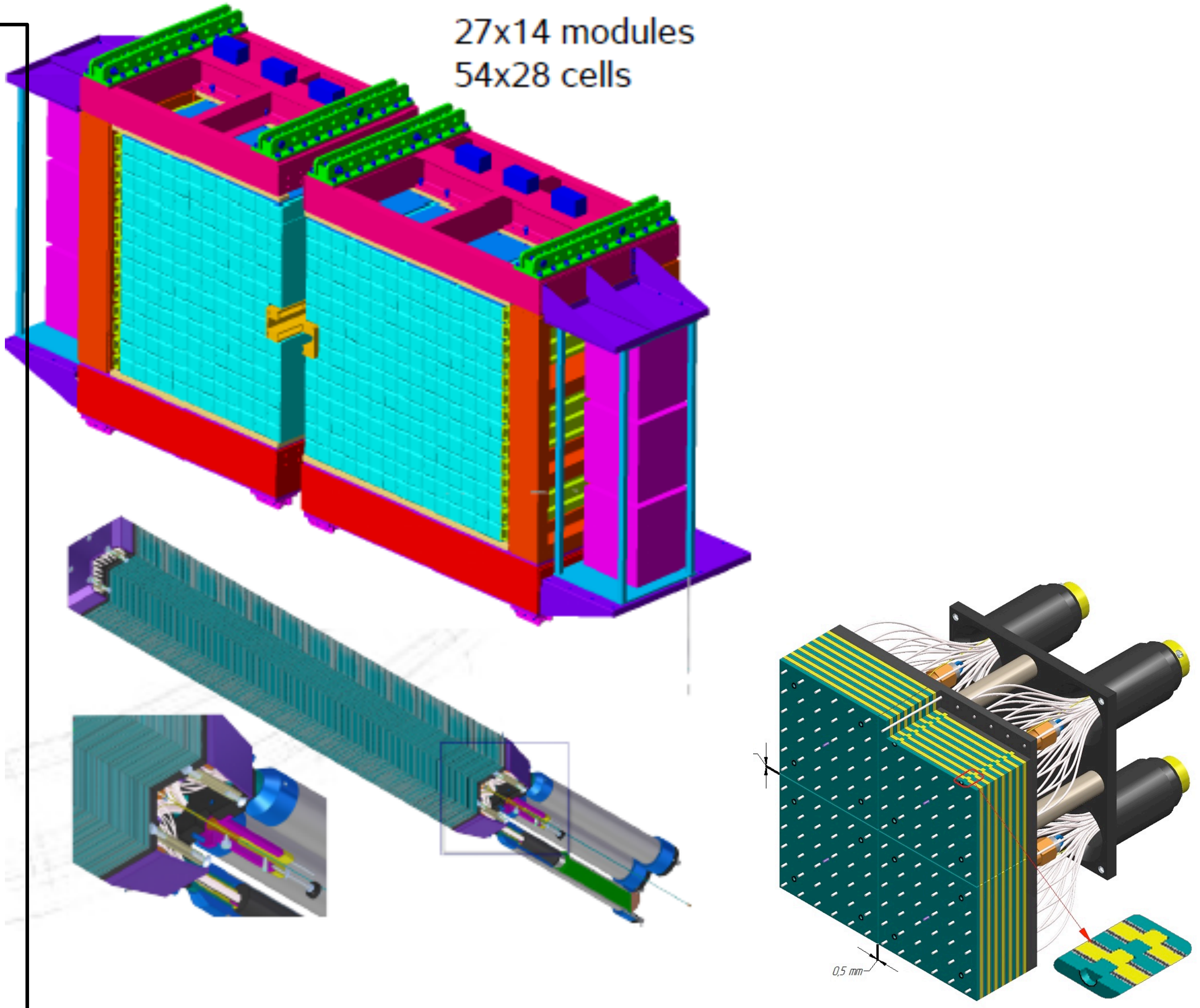
- TDR approved by FAIR ECE
- SADC readout board in production
- Module design 2 x 2 cells of 5.5 x 5.5 cm^2 verified
- Tests with electrons and tagged photons:

→ **Energy resolution**

- $\frac{\sigma_E}{E} = 5.6/E \oplus 2.4/\sqrt{E[\text{GeV}]} \oplus 1.3$ [%] (1-19 GeV e$^-$)
- $\frac{\sigma_E}{E} = 3.7/\sqrt{E[\text{GeV}]} \oplus 4.3$ [%] (50-400 MeV γ)

→ **Time resolution** 100 ps/$\sqrt{E[\text{GeV}]}$

27x14 modules
54x28 cells



Barrel Time of Flight

Target Spectrometer

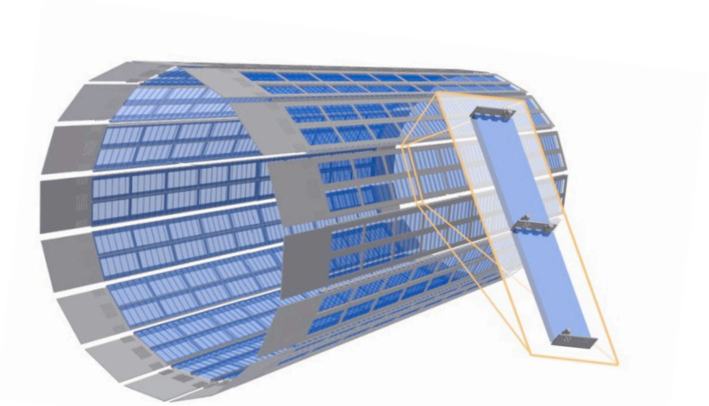
ToF in-between Barrel DIRC and Barrel EMC

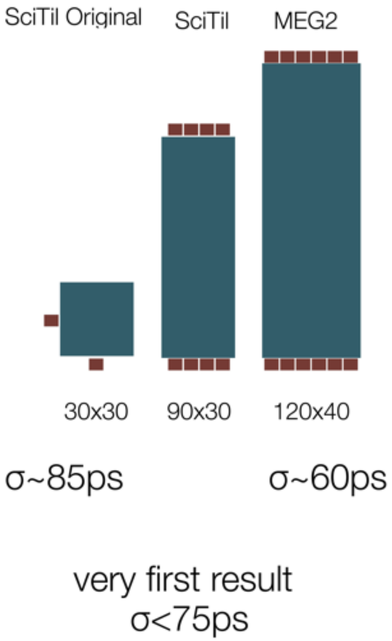
Scintillator Tile Hodoscope

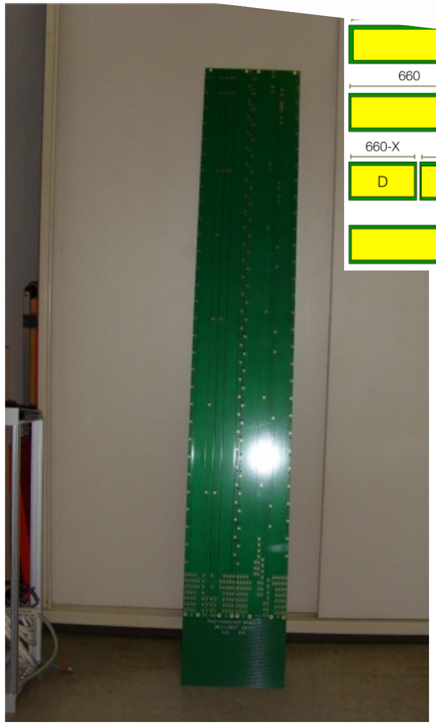
- Scintillator tiles 5 mm thick
- Photon readout with SiPMs (3x3 mm2)
  - High PDE, time resolution, rate capability
  - Work in B-fields, small, robust, low bias
- System time resolution: <100 ps achieved
- ASIC ToFPET for SiPM readout – Co-development
- Layout: long multilayer PCB for transmission (“railboard”)

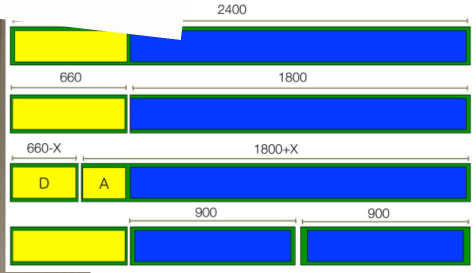
Status

- TDR approved by FAIR ECE
- Study of scintillator thickness (3-6 mm):
  - 5mm thickness confirmed as optimal
- SiPM radiation hardness studies planned
- Full Prototype readout “railboard” required
- QA of SiPM required









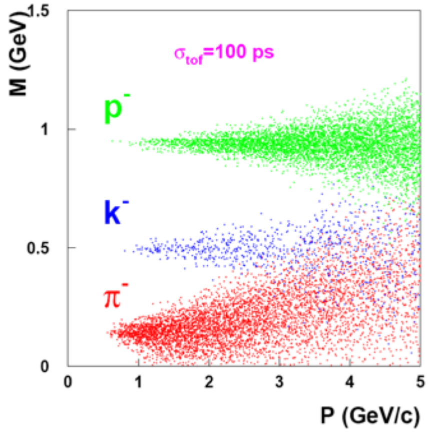
Prototype readout “railboard” 1m long!

Forward Time of Flight

Forward Spectrometer PID
- Time of Flight essential
- No start detector
- Relative timing to Barrel ToF

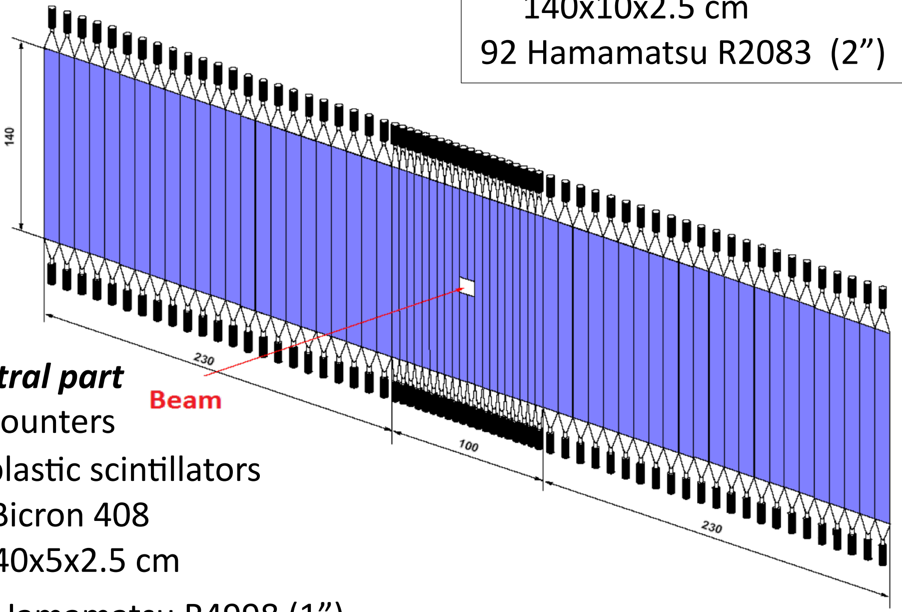
Detector layout
- Scintillator wall at z=7.5m made of 140 cm long slabs
- Bicron 408 scintillator
- PMT readout on both ends
- 10 cm slabs on the sides, 5 cm slabs in the center
- Readout FPGA

Status
- TDR approved by FAIR ECE
- Readout optimization ongoing
- Design laser calibration system



Goal: Time-of-flight with σ(t) better than 100 ps

Side parts
2x23 counters
46 plastic scintillators
Bicron 408
140x10x2.5 cm
92 Hamamatsu R2083 (2")

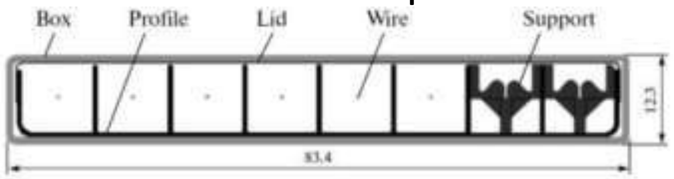


Central part
20 counters
20 plastic scintillators
Bicron 408
140x5x2.5 cm
40 Hamamatsu R4998 (1")

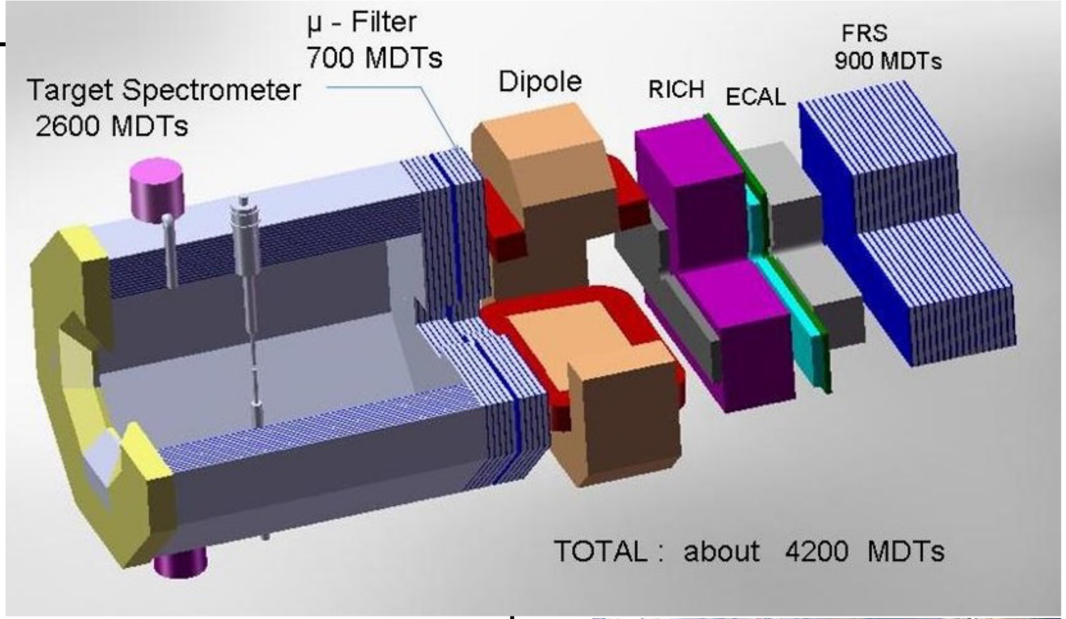
Muon Detector System

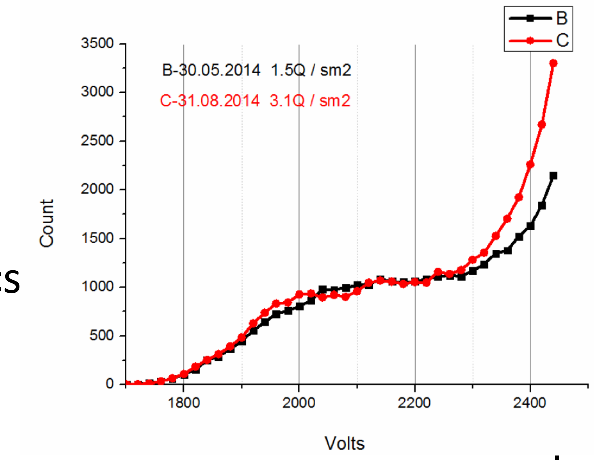
Muon system rationale
- Low momenta, high BG of pions
➔ Multi-layer range system

Muon system layout
- *Barrel*: 12+2 layers in yoke
- *Endcap*: 5+2 layers
- *Muon Filter*: 4 layers
- *Fw Range System*: 16+2 layers
- *Detectors:* Drift tubes with wire & cathode strip readout

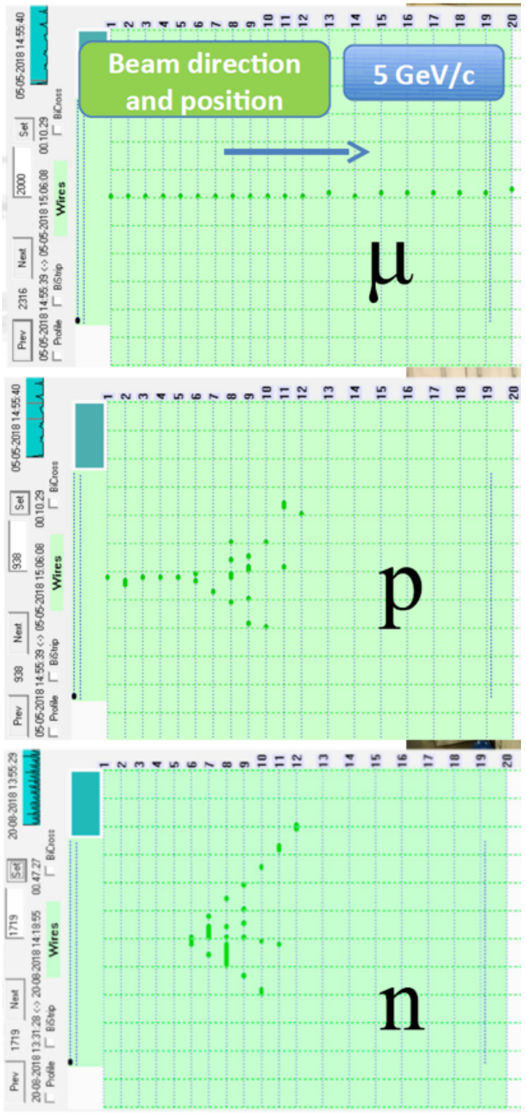


Status
- TDR approved by FAIR ECE
- Testbeams at CERN, aging, cosmics
- Aging tests up to 3C/cm2
- Digital FEE (Artix-7) development
- Production designs starting



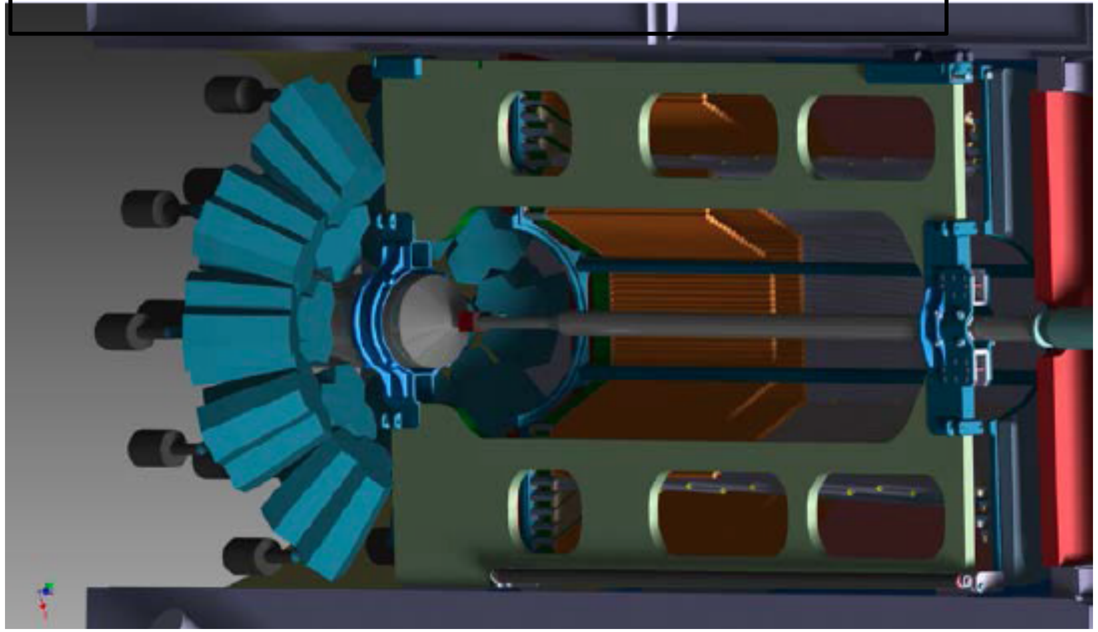


Testbeam results:
- μ, p and n easily resolved

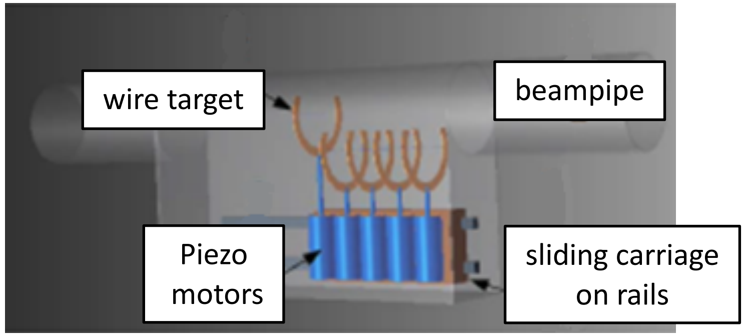


Principle:
- Produce hypernuclei from captured Ξ

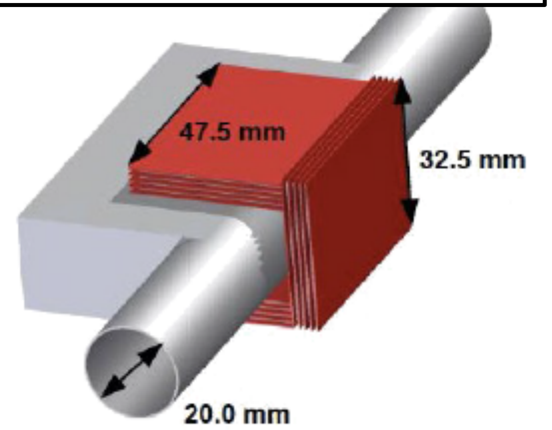
Modified Setup:
- Primary retractable wire/foil target
- Secondary active target to capture Ξ and track
  products with Si strips
- HP Ge detector for γ-spectroscopy



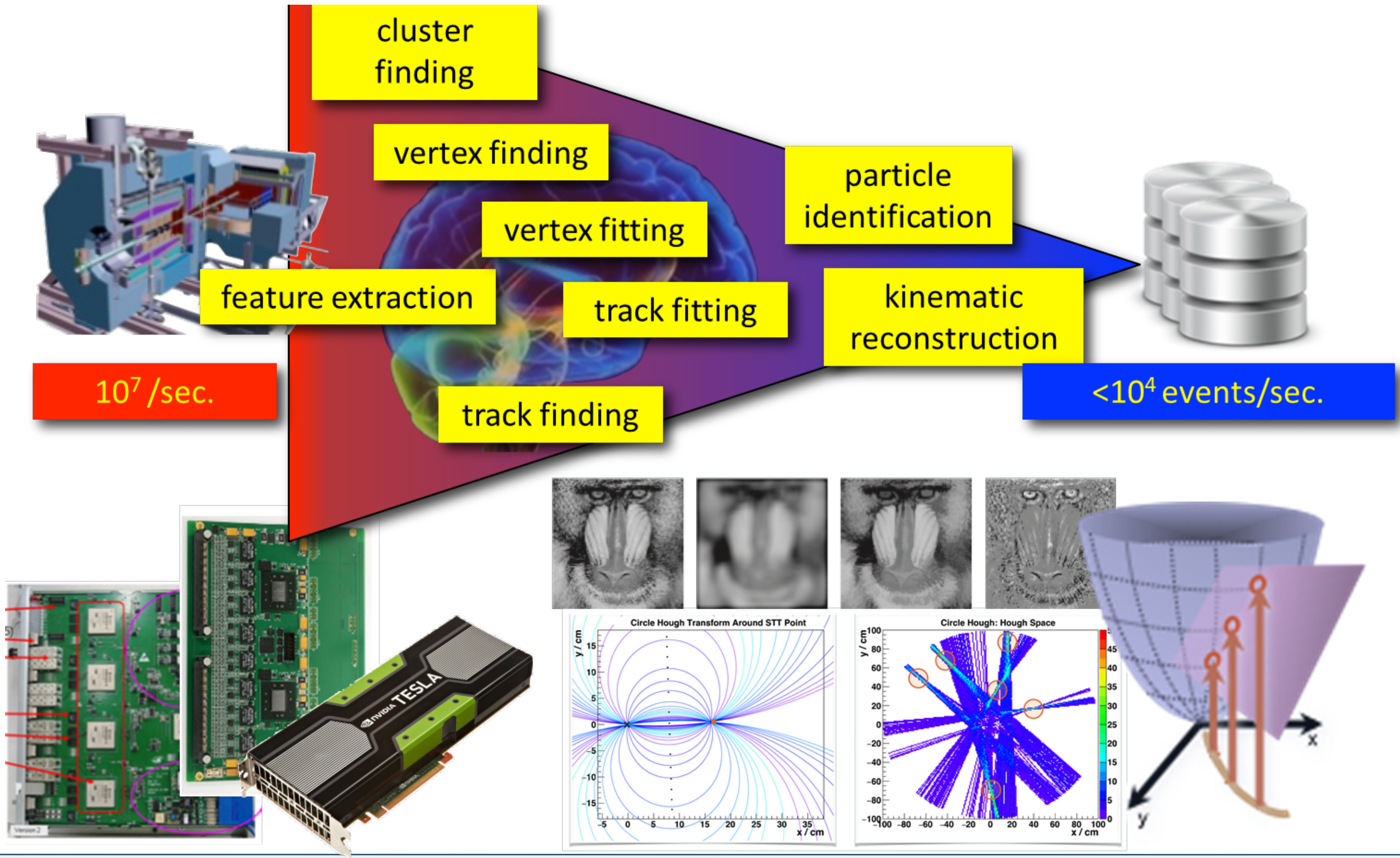
Primary target:
- Diamond wire
- Piezo motored wire holder



Active secondary target:
- Silicon microstrips
- Absorbers



Intelligent *in-situ* data processing



Multi-layer spherical lens

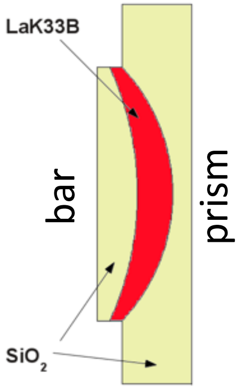
G. Kalicy, DIRC2013
X. He, RICH2018

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).

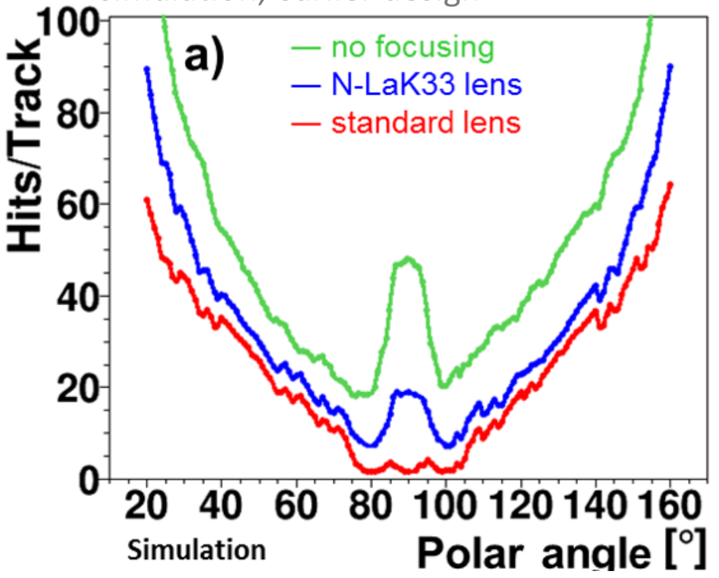
Innovative design: refraction between higher-refractive index material and fused silica.

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.
- *(λ=380nm: fused silica: n≈1.473, LaK33B: n≈1.786)*



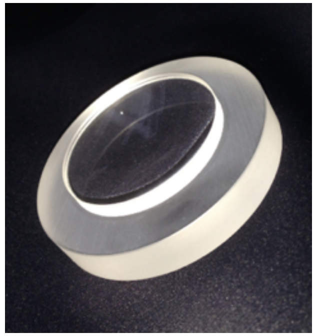
simulation, earlier design



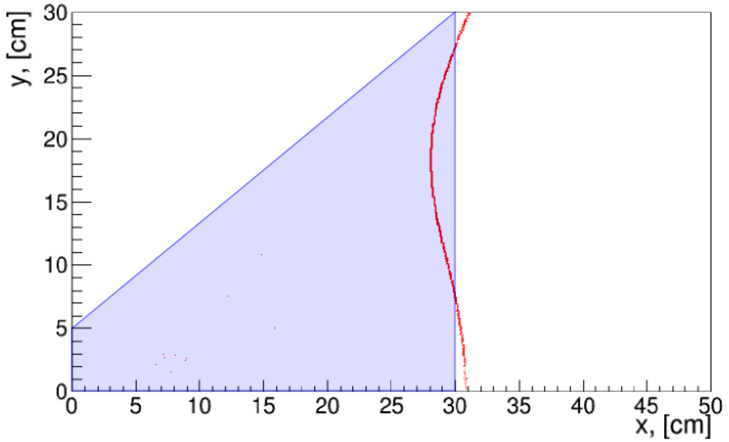
Prototype built by industry, tested with lasers in lab and with PANDA Barrel DIRC prototype using particle beams at CERN.

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 hpDIRC. Currently investigating alternatives: PbF_2, sapphire, see Greg's poster...)



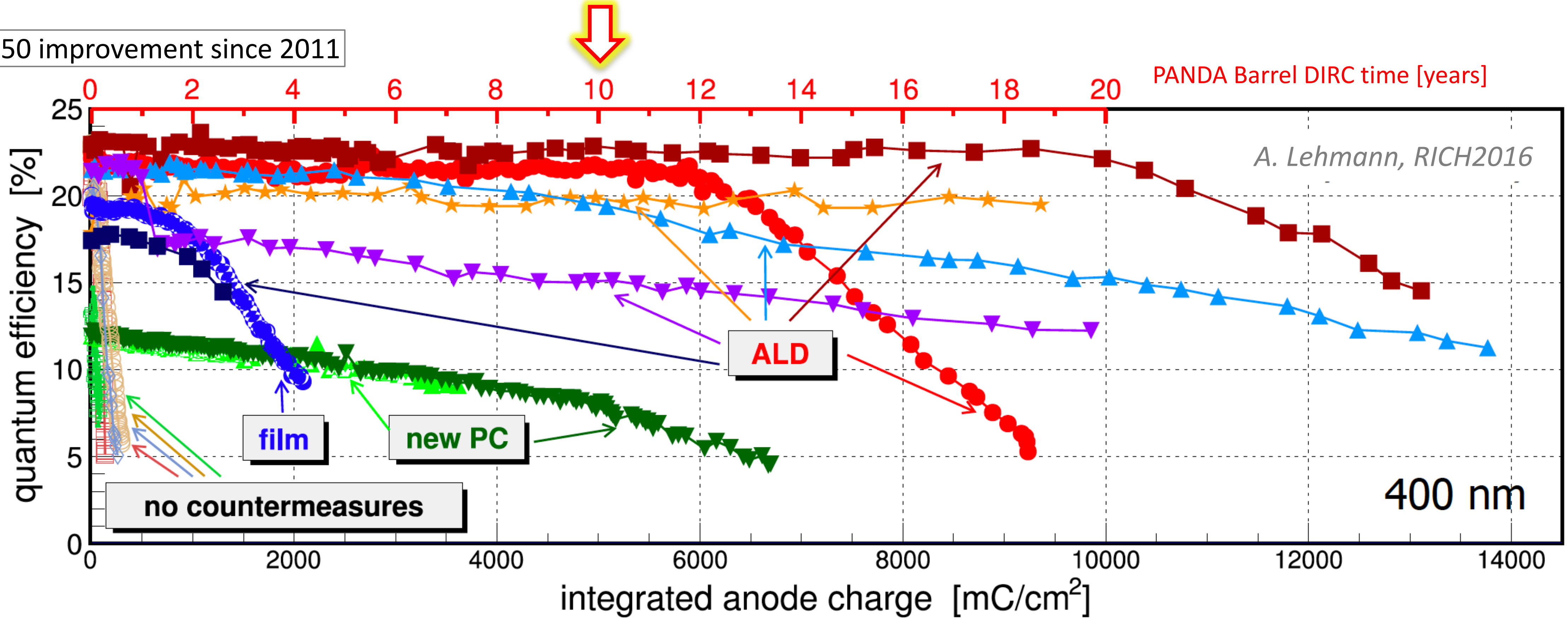
simulation: focal plane of 3-layer lens



Sensor of choice for PANDA DIRCs: MCP-PMTs (due to 1T magnetic field, high rate, low noise, timing precision)

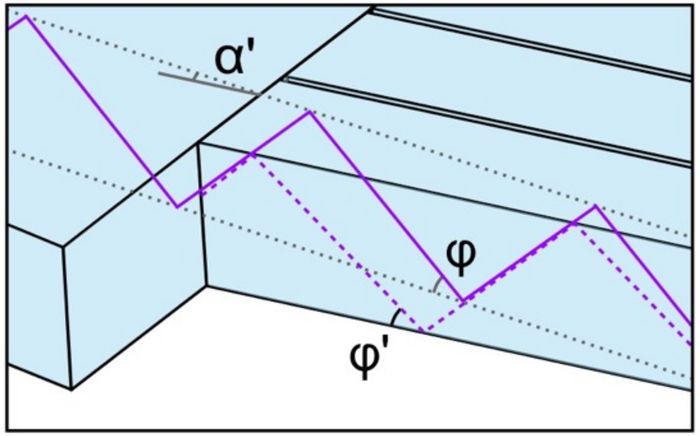
Lifetime of MCP-PMTs was potential showstopper for Belle II and PANDA until a few years ago.

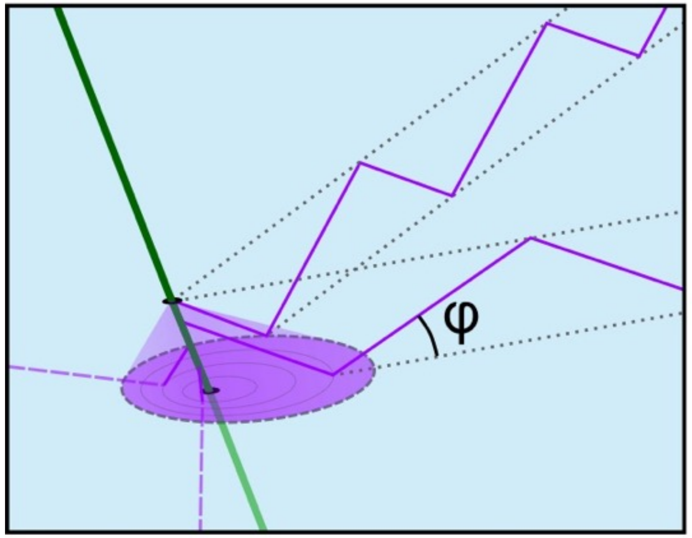
Factor >50 improvement since 2011

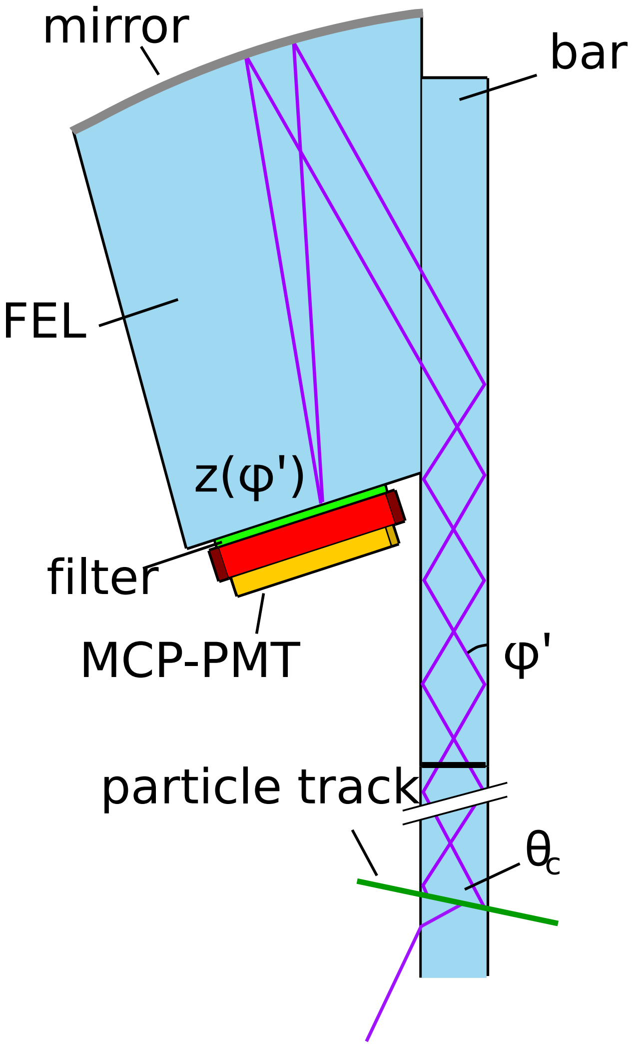


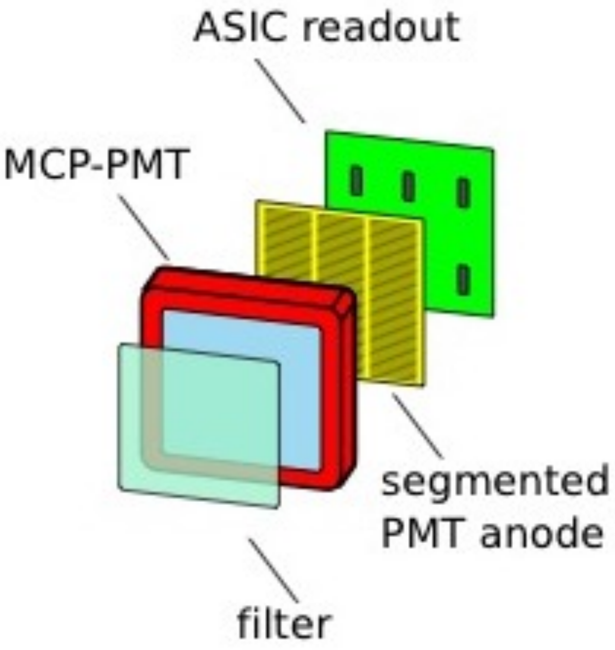
Recent MCP-PMTs with atomic layer deposition technique exceed requirements for the PANDA DIRC counters.

ENDCAP DISC DIRC PRINCIPLE









$$\theta_c = \arccos\left(\sin\theta_p \cos\phi_{\mathrm{rel}} \cos\varphi + \cos\theta_p \sin\varphi\right)$$

EDD: Key Technology

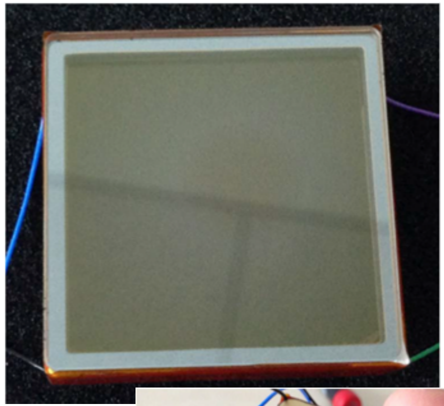
J. Rieke, IEEE 2014,

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

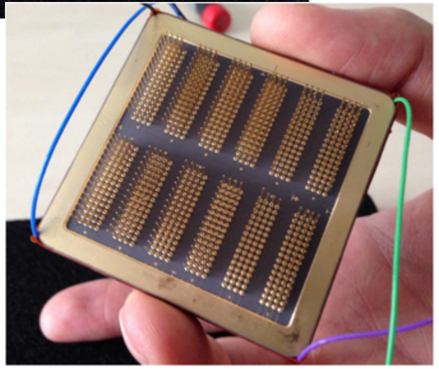
Single photon sensitivity in high magnetic field (~1T) with long lifetime (~7C/cm^2), fast timing (<100ps)

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

Hamamatsu (6x128)



front view



anode pin array

Obtained prototype 2'' MCP-PMTs from Hamamatsu and PHOTONIS

Options with custom photocathode available.

Excellent gain and timing performance.

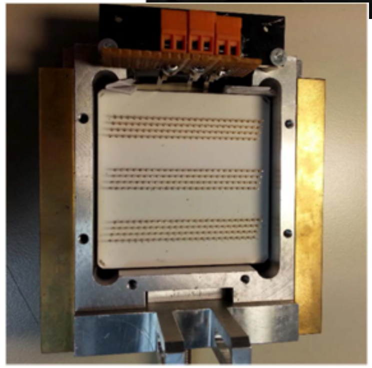
Charge sharing suppressed in magnetic field.

Tubes meet position resolution requirement.

Both good candidates for the PANDA EDD.

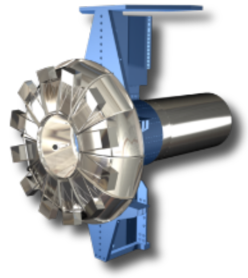
PHOTONIS (3x100)

anode strips

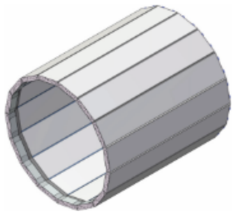


anode pin array

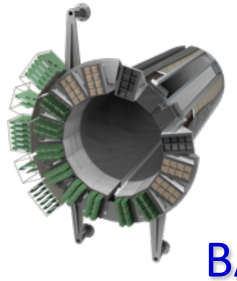
Barrel DIRC Counters



BABAR DIRC



BELLE II TOP



PANDA BARREL DIRC

Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*
Barrel radius	85cm	115cm	48cm
Bar length	490cm *(4×122.5cm)*	250cm *(2×125cm)*	240cm *(2×120cm)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*
Expansion volume	110cm, ultrapure water	10cm, fused silica	30cm, fused silica
Focusing	None (pinhole)	Mirror (for some photons)	Spherical lens system
Photodetector	~11k PMTs	~8k MCP-PMT pixels	~8k MCP-PMT pixels
Timing resolution	~1.5ns	<0.1ns	~0.1ns
Pixel size	25mm diameter	5.6mm×5.6mm	6.5mm×6.5mm
PID goal	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 3.5 GeV/c
Timeline	1999 - 2008	Installed 2016	Installation 2023/24