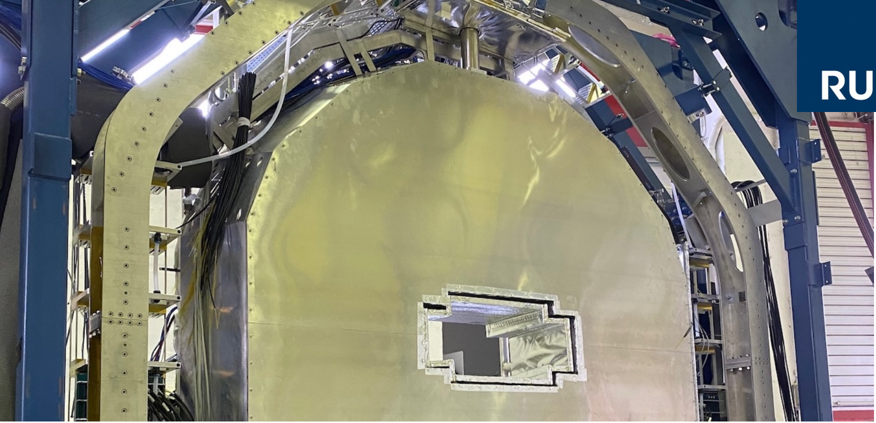


RUB

Setup and COSY Proton Beam Tests of the PANDA Forward Endcap Calorimeter at FAIR

CALOR 2024, Tsukuba, Japan, 21 May 2024

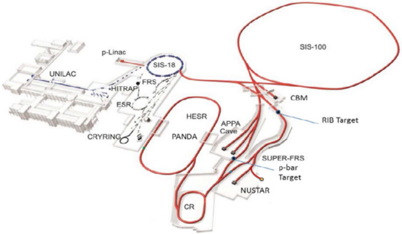
Thomas Held Institut für Experimentalphysik I, Ruhr-Universität Bochum

RUHR UNIVERSITÄT BOCHUM RUB STRONG 2020 bmb+f Großgeräte der physikalischen Grundlagenforschung panda FAIR JÜLICH FORSCHUNGSZENTRUM

$\overline{\text{P}}$ANDA at FAIR - Facility for Antiproton and Ion Research

- Accelerator facility at Darmstadt (GSI) under construction
- Primary beams: Protons up to 30 GeV/c, heavy ion beams up to 35 GeV/c (U^{92+})
- Secondary beams: Radioactive beams, antiprotons up to 15 GeV/c
- $\overline{\text{P}}$ANDA at FAIR:
  - Located at slow ramping synchrotron storage ring for internal target (HESR)
  - Stochastic and electron cooling of $\overline{\text{p}}$ beam

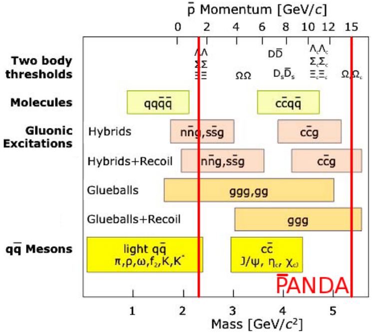
Mode:	High Luminosity	High Resolution
$\Delta p/p$	$\approx 10^{-4}$	$4 \cdot 10^{-5}$
$\mathcal{L}$ [cm^{-2}s^{-1}]	10^{32}	10^{31}
Stored $\overline{\text{p}}$	10^{11}	10^{10}



The $\overline{\text{P}}$ANDA Experiment

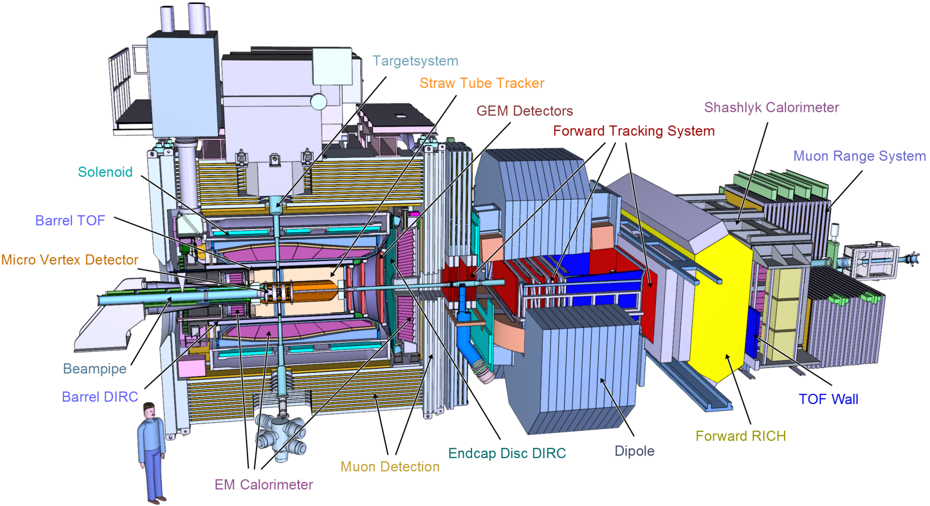
- $\bar{p}p$ annihilations, fixed hydrogen target (nuclear target)
- $\bar{p}$ momenta: 1.5 GeV/c - 15 GeV/c
- $\sqrt{s} \leq 5.5$ GeV
  - Associated production of singly charmed baryons (up to Ω_c)
  - Covering upper mass range predicted for charmonium hybrid states

- Hadron spectroscopy
  - Light mesons
  - Charmonium
  - Open charm
  - Search for exotics
  - Baryons (double strange, charmed)
- Proton structure
- Mesons in nuclei
- Hypernuclei



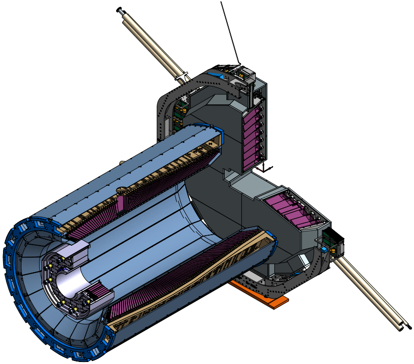
- Exclusive studies require full reconstruction of final states

The $\overline{\text{P}}$ANDA Detector



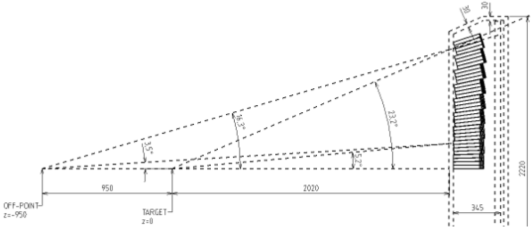
The $\overline{\text{P}}$ANDA Target Calorimeter

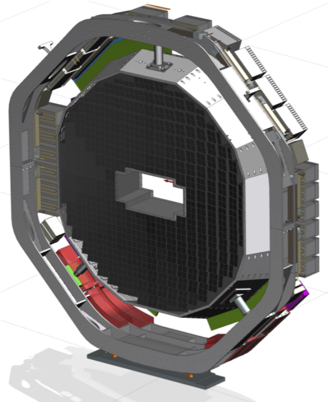
- $\overline{\text{P}}$ANDA physics:
  Full reconstruction of multi-photon and lepton-pair channels
- Good energy and spatial resolution for photons up to 15 GeV
- Low energy threshold (10 MeV)
- Full angular coverage (Incl. forward calorimeter)
- High yield
- High background rejection
- Barrel part plus two endcaps
- Homogeneous
- 16000+ lead tungstate crystals



The Forward Endcap of the $\overline{\text{P}}$ANDA Target Spectrometer

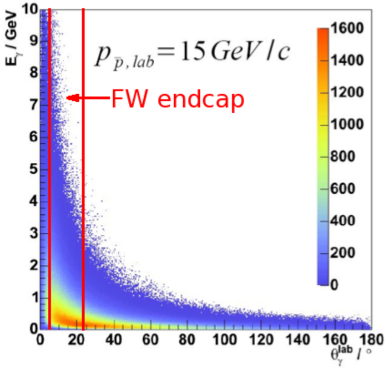
- 3856 $PbWO_4$ crystals
- Crystals read out by Vacuum Photo Tetrodes (VPTTs) and Avalanche Photo Diodes (APDs)
- Angular coverage: $5^\circ < \theta < 23.6^\circ$
- Magnetic field of up to 1.2 T
- Off-pointing geometry

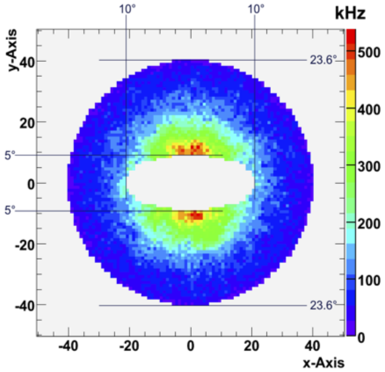




The Forward Endcap of the $\overline{\text{P}}$ANDA Target Spectrometer

- High dynamic range: 3 MeV – 12 GeV
- Single crystal hit rates up to $10^6\,s^{-1}$
- Radiation dose rate: 125 Gy/a (at full luminosity)





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Scintillation Crystals

- Crystals: $\approx 25 \times 25 \times 200$ mm^3, slightly tapered
- PWO-II type lead tungstate

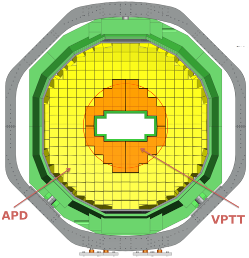
THE CHARACTERISTICS OF PWO-I AND PWO-II CRYSTALS

Characteristics	PWO-I (CMS)	PWO-II (PANDA)
Luminescence maximum, nm	420	420
La, Y concentration level, ppm	100	40
Light yield of full-size (20 cm) crystal with PMT readout (bialkali-cathode)(at room temperature, phe/MeV	8-12	17-22
Limit of the radiation induced absorption coefficient at 420 nm, m^{-1}	1.5	1.0
Light yield temperature coefficient at T= +20° C, %/ °C	-2.0	-3.0
Scintillation decay time at room temperature, ns	10 - 30	10 - 30
EMC working temperature, °C	+18	-25
Statistical term of EMC energy resolution, %	2.7	2.0
Expected energy range of EMC	150MeV - 1TeV	10MeV - 10GeV

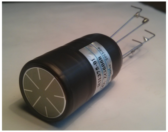
From: Nuclear Science Symposium Conference Record, 2008. NSS '08. IEEE,

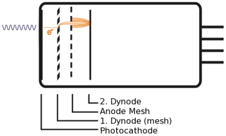
http://dx.doi.org/10.1109/NSSMIC.2008.4774932

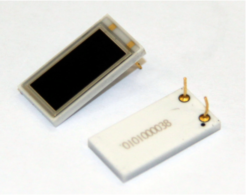
The Photo Sensors



	VPTT (Hamamatsu)	APD (Hamamatsu)







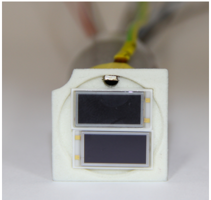
	VPTT (Hamamatsu)	APD (Hamamatsu)
Quantum efficiency	$\approx 20\%$	$\approx 80\%$
Active area	$\approx 200\,\mathrm{mm}^2$	$100\,\mathrm{mm}^2$
Gain	typ. 50	200
Dark current	$\leq 1\,\mathrm{nA}$	max. $20\,\mathrm{nA}$
Capacitance	$\approx 22\,\mathrm{pF}$	$\approx 270\,\mathrm{pF}$

The Readout Units: Sensor(s) Plus Preamp(s)

- One photo tube / two APDs per crystal
- Encapsulation of preamps:
  Casting compound

  $\rightarrow$ Moisture resistant operation (kV)
- Shielding: Aluminum tube/tape
- Blue LED: Stimulated crystal LY recovery

  (IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 60, NO. 6, DECEMBER 2013)

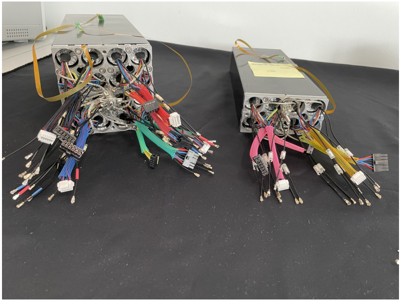


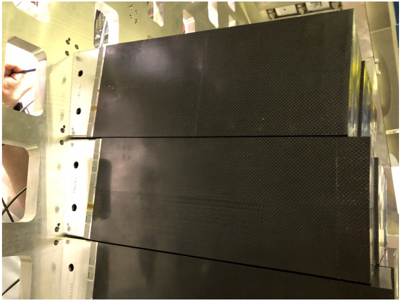
The Crystal Units: Crystals plus Readout Units

- Gluing of readout units to crystals
- Extreme requirements to adhesive:
  - Δ T = 50 K
  - Substancial differing thermal expansion coefficients ($PbWO_4$, quartz glass, epoxy)
  - Extreme smooth (polished) crystal surface
  - Radiation hard optical transparancy
- Adhesive: Dowsil RTV 3145 (plus Dowsil primer!)
- Crystals wrapped in 3M DF2000MA mirror foil

The Crystal Submodules

- Submodules comprising 16 (8) crystals
- Mechanical support structure: Carbon fibre alveoles
- Individual interface pieces: Orientation on back plate



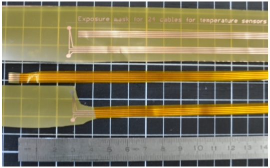


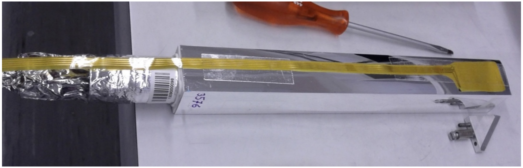
The Crystal Submodules

- All submodules precalibrated using cosmics (at -25℃, in upright position)
- Precise determination of external dimensions
- Final step: Fixing carbon fibre alveole to aluminum inserts by injected glue

Temperature Monitoring

- Crystal light yield and APD gain temperature dependent
- High precison monitoring (and regulation) of temperature mandatory
- Dense crystal packing:
  Need for very thin temperature sensors
  (Pt wire on Kapton foil, $d < 160\,\mu m$)
- 500+ sensors in total (2 per submodule)

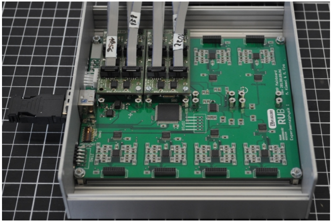


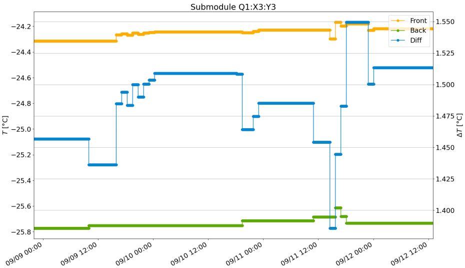


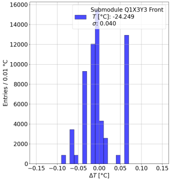
Temperature Monitoring

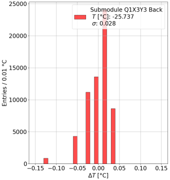
Readout boards

- 64 input channels
- 8 piggyback boards on 1 mainboard
- 14-bit ADCs
- Calibration of sensors and boards!



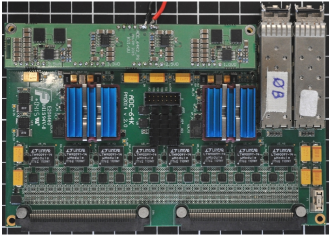






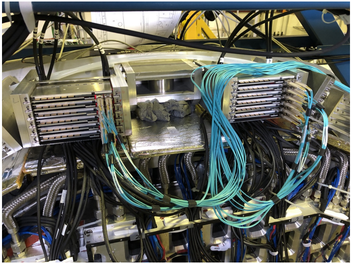
- TDR: $\Delta T < 0.1\,°C$
- Resolution: $< 0.05\,°C$

Digitization

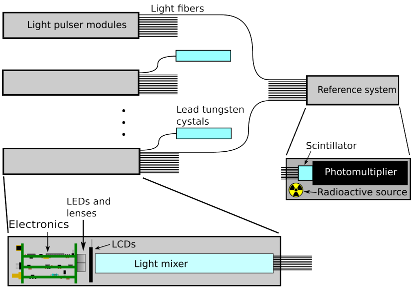


- 64 channel Sampling ADC boards
- 80 MS/s, 14 bit resolution
- 32 single ended 50 Ω signal inputs
- Analog shaping stages
- High/low gain splitting

- 2 Kintex-7 FPGAs, online feature extraction
- 2 optical interfaces (SFP, 2 Gbit/s)
- Dedicated cooling crates located in support frame
- Total of about 220 boards

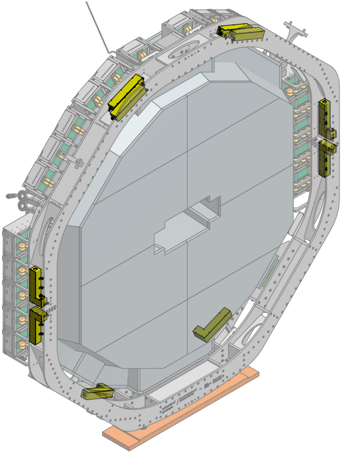


Monitoring System



- Monitoring LY loss, linearity checks
- Modeling scintillation light
- Full dynamic range
- $LaBr_3(Ce)$ based reference system

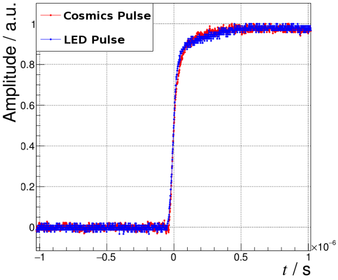
- 10 light pulser modules sitting inside support frame

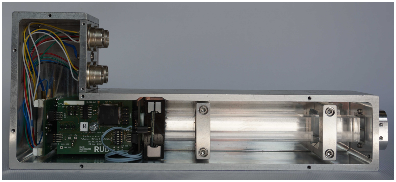


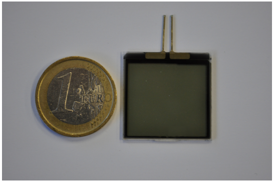
Monitoring System

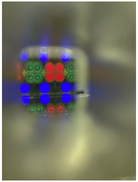
LED pulser:

- Blue, green, and red light pulses
- Blue: MOSFET based HV discharge circuit
- Green and red: Kapustinsky pulser
- Compact design: LCD attenuators



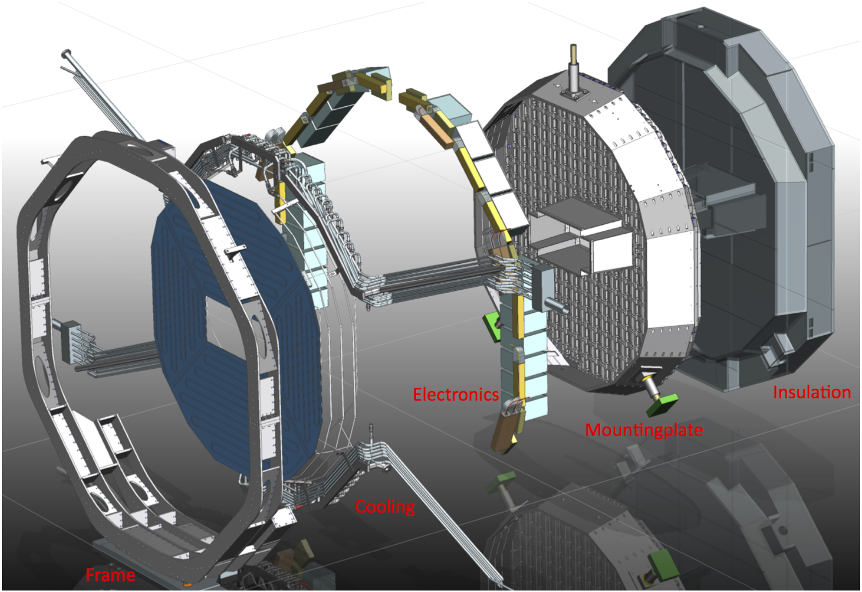




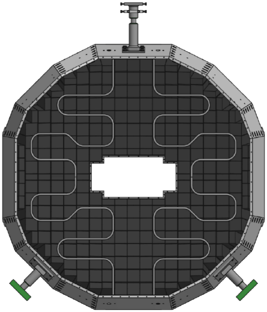


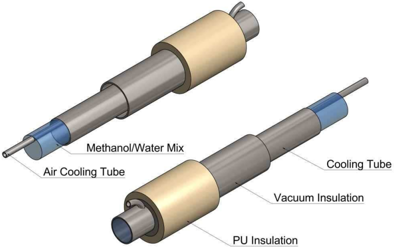
(NUCLEAR INST. AND METHODS IN PHYSICS RESEARCH, A 997 (2021) 165167)

Mechanics And Cooling



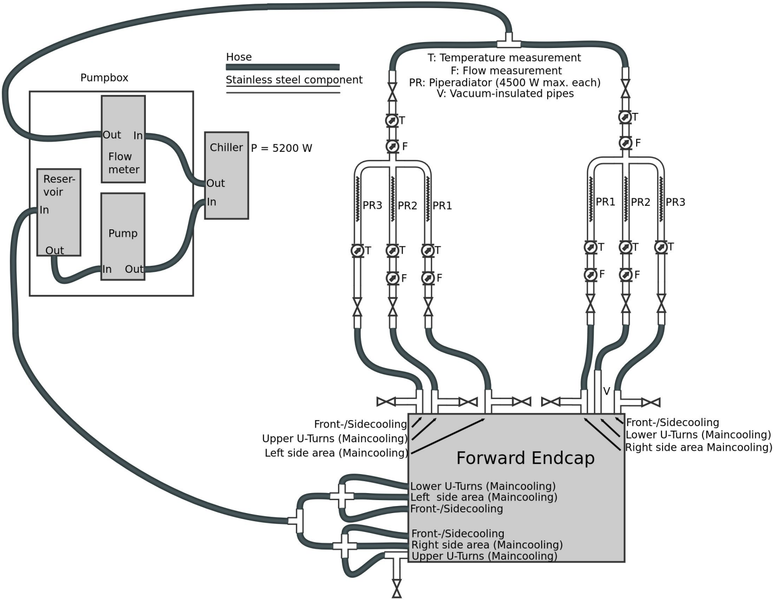
Cooling: Front/Air



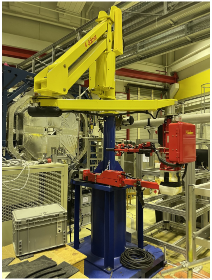
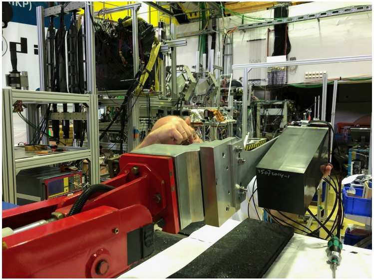


- Front cooling:
  Plastic tube glued to 0.8 mm aluminum front plate
- Air/nitrogen cooling:
  Gas pipes running inside coolant supply lines

Cooling Circuit

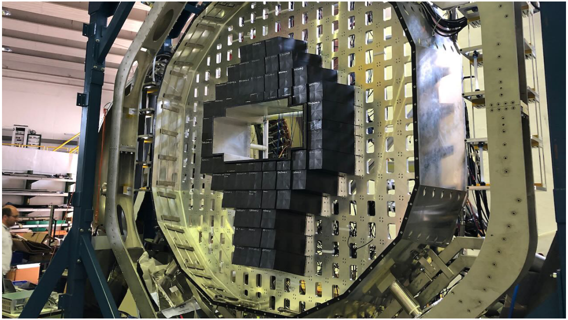


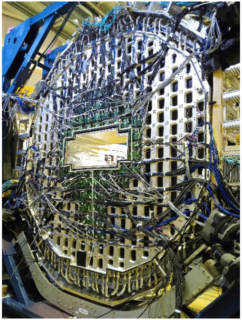
Build-up at FZ Jülich (COSY)

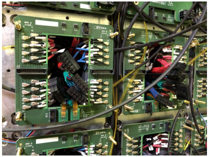
- Frame errection
  $\rightarrow$ Submodule mounting
  $\rightarrow$ Cabling
  $\rightarrow$ Thermal insulation
- Manipulator arm for submodule mounting borrowed from CMS

COSY Beam Time Setup



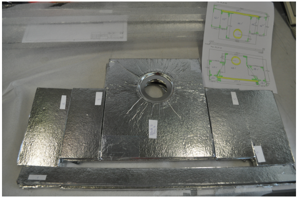


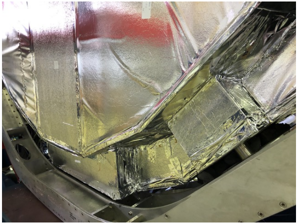
- Beam time setup:
  - All VPTT equipped crystals mounted
  - Plus six 16-crystal submodules read out by APDs
  - 864/3856 crystals mounted

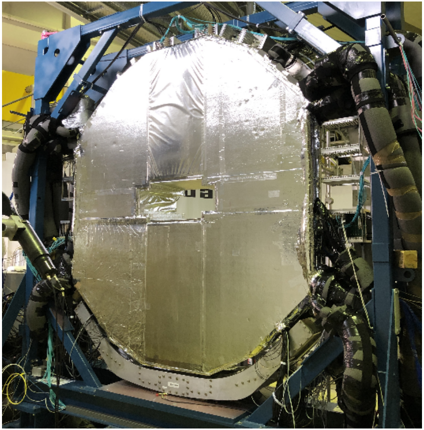


Thermal Insulation

- Thermal insulation by vacuum insulation panels
- Two layers with overlapping edges
- Low thermal conductivity, expensive, susceptible



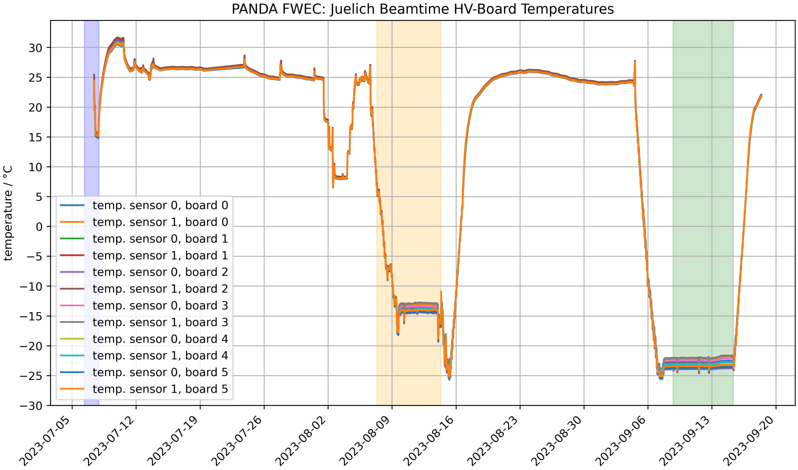




Experimental Setup at COSY Accelerator, Jülich

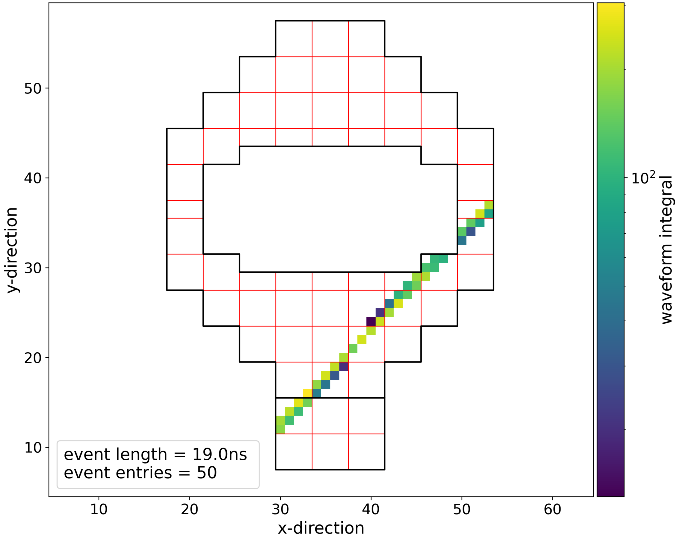
- 2.5 GeV/c proton beam on plastic target in 2 m distance from detector

Beamtime Overview by Means of Temperature

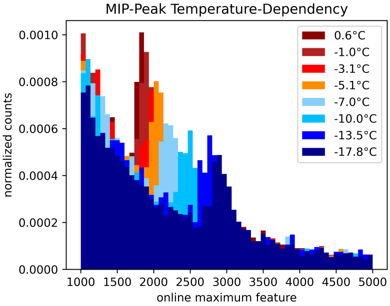


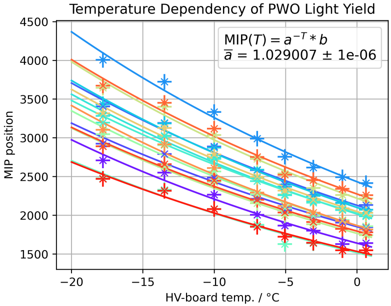
- 2 days of DAQ and hardware tests in July 2023
- 2 weeks of test beam in August and September 2023

- $\overline{\text{P}}$ANDA triggerless DAQ not available yet
- No central trigger: Constrained free-running system
- Synchronizïation of clocks and events (external time marks across all SADCs)



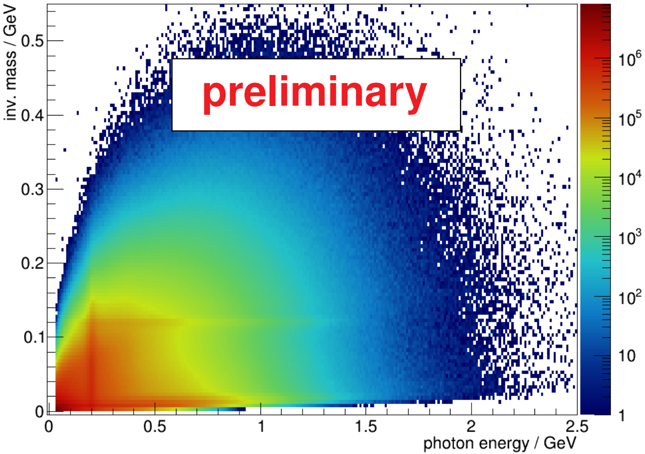
$PbWO_4$ Light Yield vs. Temperature



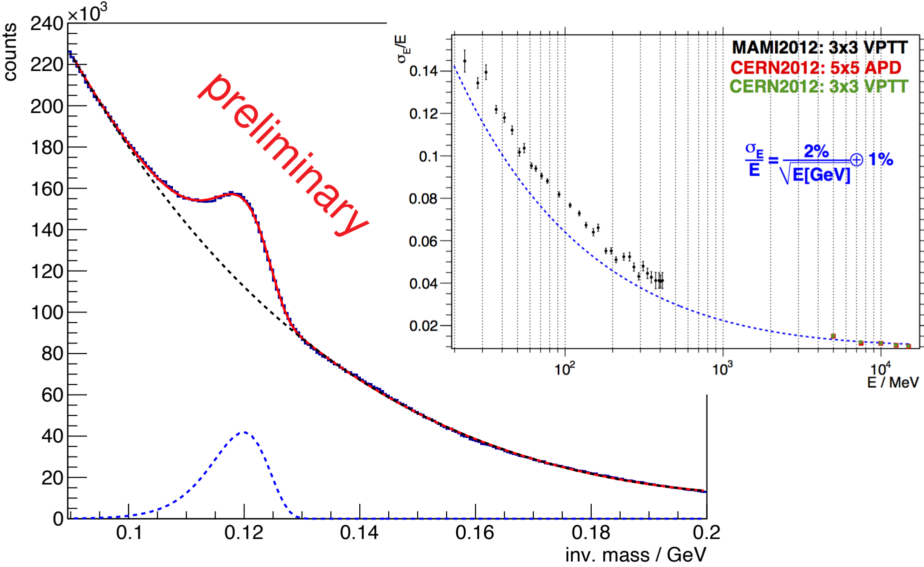


- MIP peaks nicely shift with temperature
- Light yield dependency about 3 %/℃, as expected
- Measured with VPTT-equipped channels
  (no temperature dependant APD gain involved)

Two-Cluster Events Invariant mass



- Clear MIP peak at $\approx 200\,\mathrm{MeV/c^2}$ photon energy (π^+/π^-)
- Band structure at $120\,\mathrm{MeV/c^2}$ invariant mass (π^0)



- Energy correction functions still to be derived/applied
- About 5 MeV/c^2 resolution ($\approx 3.5\,\%$)

Summary

- $\overline{\text{P}}$ANDA forward endcap calorimeter set up (VPTTs) and beam tested in 2023
- First operation of whole system at -25 °C
- 220 TB of compressed waveforms recorded
- Analyses still ongoing (π^0 calibration)
- Cooling lines and cabling dismounted, preparation for move
- Transport to ELSA, Bonn soon
- Completion (mounting all submodules) and first physics usage at Crystal Barrel experiment

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research and innovation programme under grant agreement No 824093