Construction of the Forward Endcap Calorimeter of the $\overline{\text{P}}$ANDA Experiment at FAIR

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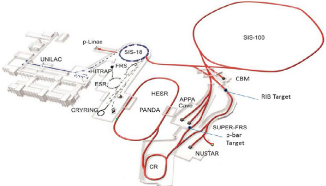
$\overline{\text{P}}$ANDA at FAIR - Facility for Antiproton and Ion Research

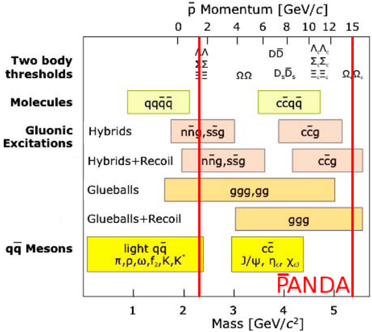
- Accelerator facility at Darmstadt (GSI) under construction
- Primary beams: Protons up to 30 GeV/c, heavy ion beams up to 35 GeV/c (U^{92+})
- Secondary beams: Radioactive beams, antiprotons up to 15 GeV/c
- $\overline{\text{P}}$ANDA at FAIR:
  - Located at slow ramping synchrotron storage ring for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



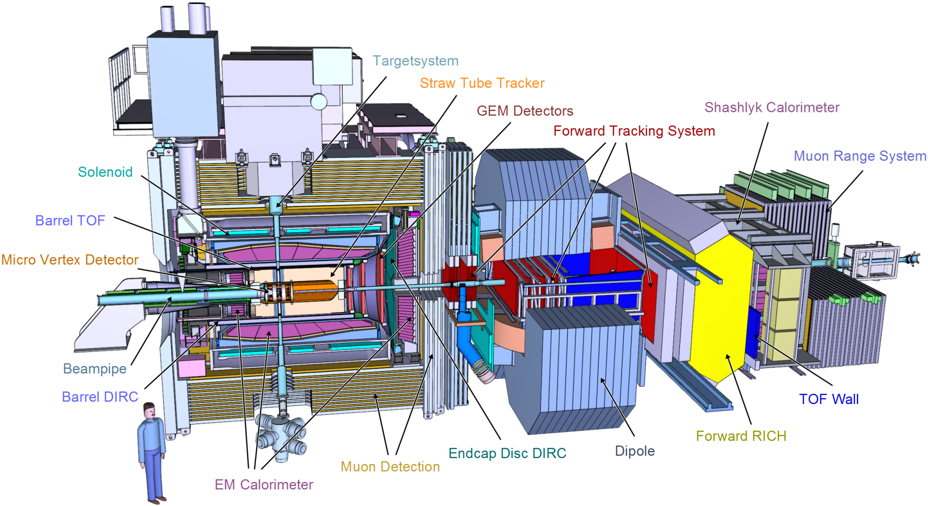
The $\overline{\text{P}}$ANDA Experiment

- $\bar{p}p$ 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



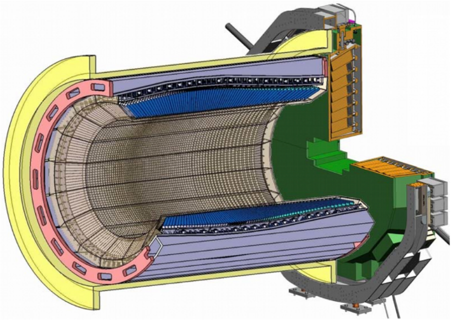
- Exclusive studies require full reconstruction of final states

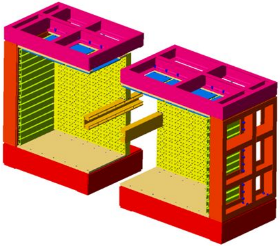
The $\overline{\text{P}}$ANDA Detector



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

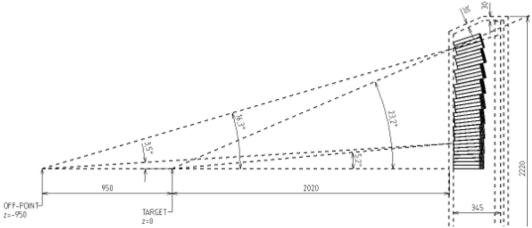
- $\overline{\text{P}}$ANDA physics: Full reconstruction of multi-photon and lepton-pair channels of utmost importance
- Low energy threshold (10 MeV)
- Good energy and spatial resolution for photons up to 15 GeV
- Full angular coverage, high yield and background rejection
- Target spectrometer: Barrel part plus two endcaps (homogeneous, 16000 lead tungstate crystals)
- Forward spectrometer: Shashlyk type sampling calorimeter (lead absorbers, plastic scintillators)

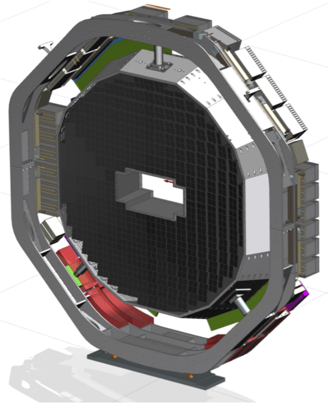




The Forward Endcap of the $\overline{\text{P}}$ANDA Target Spectrometer

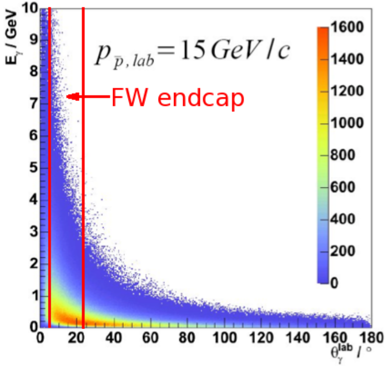
- 3856 $PbWO_4$ crystals
- Crystals read out by Vacuum Photo Tetrodes (VPTTs) and Avalanche Photo Diodes (APDs)
- Angular coverage: $5^\circ < \theta < 23.6^\circ$
- Magnetic field of up to 1.2 T
- Off-pointing geometry

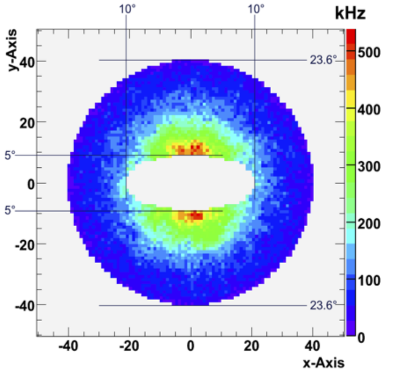




The Forward Endcap of the $\overline{\text{P}}$ANDA Target Spectrometer

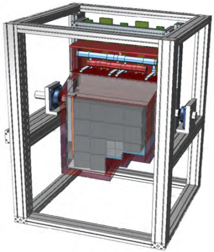
- High dynamic range: 3 MeV – 12 GeV
- Single crystal hit rates up to $10^6\,s^{-1}$
- Radiation dose rate: 125 Gy/a (at full luminosity)

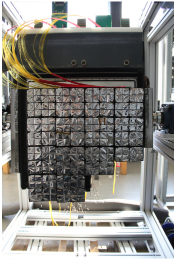


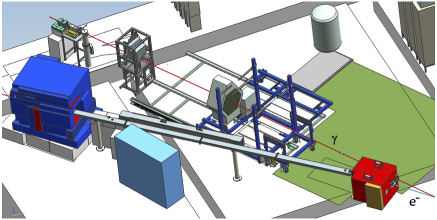


Prototype Beam Measurements

Location	Particles	Momentum	Emphasis
CERN/SPS	e^+ μ^+	10, 15 GeV/c 150 GeV/c	Max. $\overline{\text{P}}$ANDA energy Dep. energy $\approx$ 230 MeV
ELSA/Bonn	Tagged γ	1, 2.1, 3.1 GeV	Rates up to $2 \cdot 10^6\,\text{s}^{-1}$
MAMI/Mainz	Tagged γ	20 – 415 MeV	Excellent beam energy resolution
CERN/SPS	e^- $\pi^+, K^+, \overline{p}$	5 – 15 GeV/c 15, 50 GeV/c	Fibre / Si-strip TrackingStation

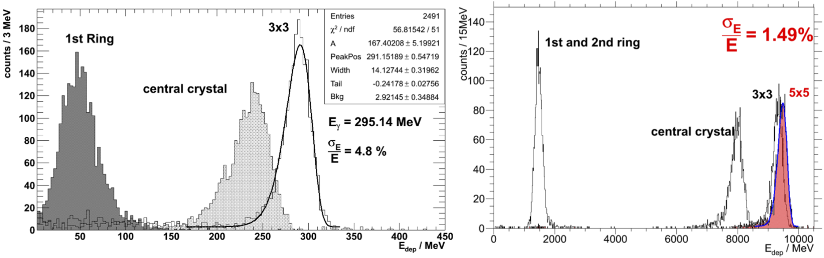






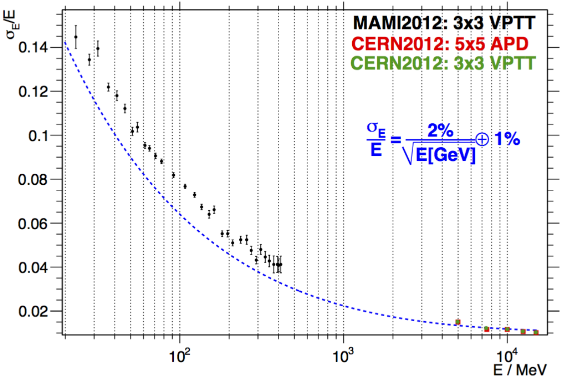
Prototype Beam Measurements

- Tagged photons (Mainz Microtron): E_γ = 295.14 MeV
- 10 GeV positrons (CERN SPS)
- 5 $\times$ 5 (3 $\times$ 3) crystal matrix (VPTT readout)

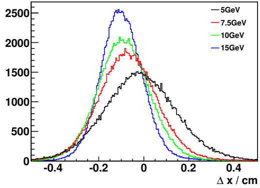


Prototype Beam Measurements

- Energy resolution derived from beam times vs. technical design need:
  - Requirements met at high energies
  - Improvements done to finally meet low energy requirements: Improved optical coupling, signal shaping, feature extraction, optimized preamp gain



Spatial resolution:
0.9 mm (15 GeV e^-)
1.6 mm (5 GeV e^-)



(Crystal dimensions: $25 \times 25 \times 200$ mm^3)

Scintillation Crystals

- Crystals in forward endcap only slightly tapered
- All crystals available and screened

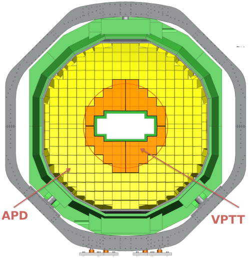
THE CHARACTERISTICS OF PWO-I AND PWO-II CRYSTALS

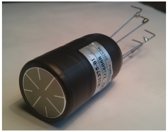
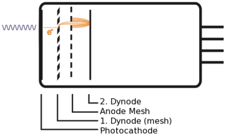
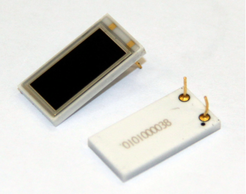
Characteristics	PWO-I (CMS)	PWO-II (PANDA)
Luminescence maximum, nm	420	420
La, Y concentration level, ppm	100	40
Light yield of full-size (20 cm) crystal with PMT readout (bialkali-cathode)(at room temperature, phe/MeV	8-12	17-22
Limit of the radiation induced absorption coefficient at 420 nm, m^{-1}	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)
	 	
Quantum efficiency	$\approx 20\%$	$\approx 80\%$
Active area	$\approx 200\,\text{mm}^2$	$100\,\text{mm}^2$
Gain	typ. 50	200
Dark current	$\leq 1\,\text{nA}$	1 pA – max. 20 nA
Capacitance	$\approx 22\,\text{pF}$	$\approx 270\,\text{pF}$

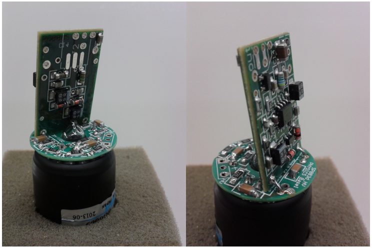
The Readout Units

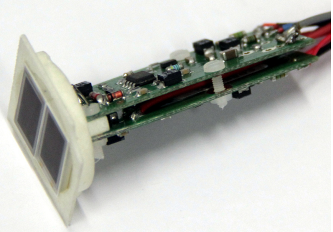
- VPTT Readout Units:

  - One tube per crystal

  - Dynode supply voltage divider PCB directly soldered to tube base

  - One compact preamp PCB





- APD Readout Units:

  - Two APDs per crystal

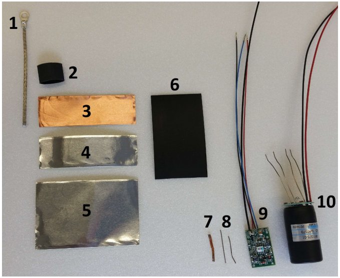
  - Preamps back to back

  - Common LV supply

  - Seperate HV supplies

The VPTT Readout Units

- Encapsulation of electronics:
  Shrinking tube filled with casting compound
- Moisture resistant operation (kV)
- Shielding: Self-adhesive copper and aluminum tapes
- Bar code tag

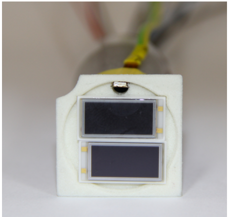


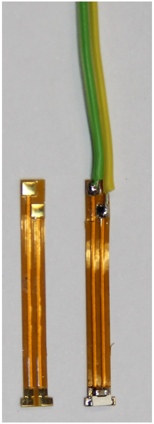
The APD Readout Units

- Encapsulation, shielding: Aluminum tube filled with casting compound
- Blue LED: Stimulated crystal LY recovery

(IEEE TRANSACTIONS ON NUCLEAR SCIENCE,

VOL. 60, NO. 6, DECEMBER 2013)

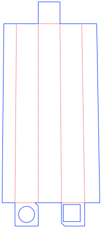


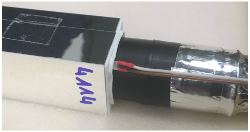


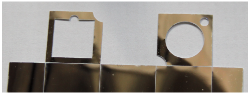
The Crystal Units

- Gluing of readout units to crystals: Crystal units
- Extreme requirements to adhesive:
  - Δ T = 50 K
  - Substancial differing thermal expansion coefficents ($PbWO_4$, quartz glass, epoxy)
  - Extreme smooth (polished) crystal surface
  - Radiation hard optical transparancy
- Adhesive: Dow Corning RTV 3145 (plus DC Primer!)

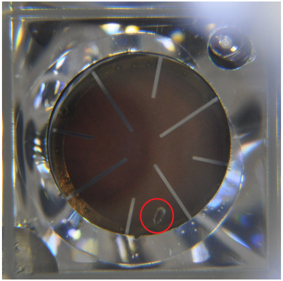
- Crystals wrapped in 3M DF2000MA mirror foil prior to gluing
- Mirror foil laser cut and grooved







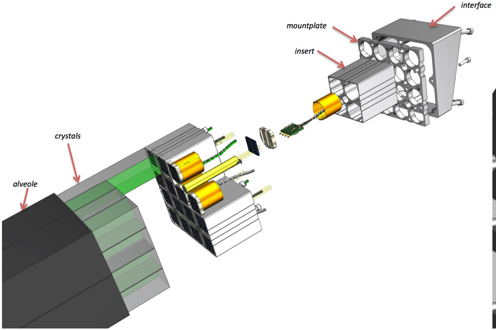
The Crystal Units

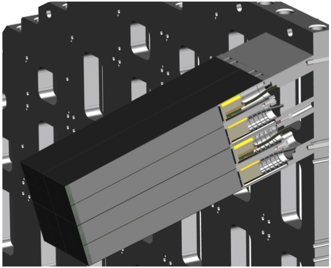


- The gluing process:
  - ▶ Certain amount (VPTT, APDs) by pneumatic applicator
  - ▶ Curing under pressure (1 week)
  - ▶ Aligning suspension in production line
  - ▶ Monitoring of coupling via camera
  - ▶ Several optical checks per unit
  - → 20 h time window for removal

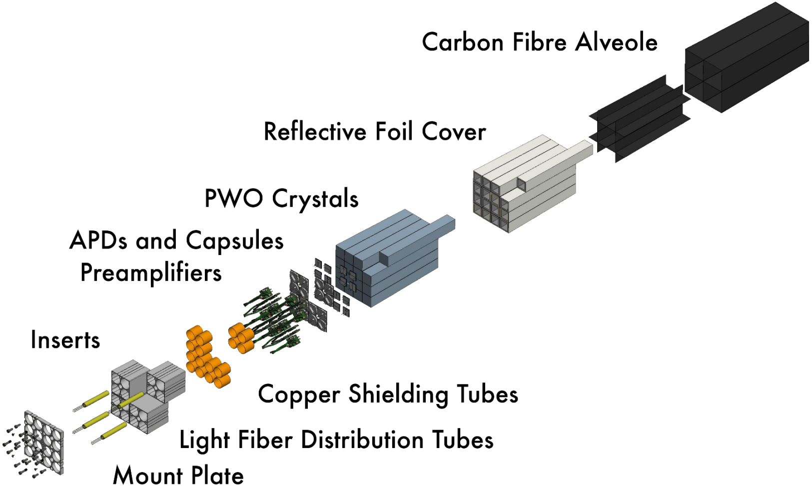
The Crystal Submodules

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

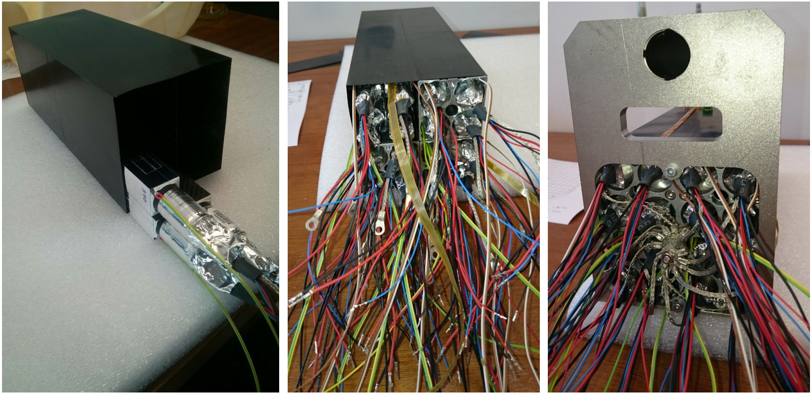




The Crystal Submodules



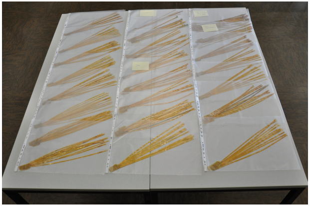
The Crystal Submodules

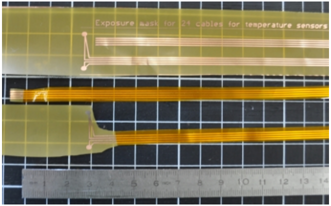


- Proper grounding: combining all readout unit shieldings
- Two temperature sensors per submodule

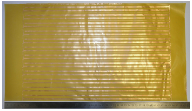
Temperature Monitoring

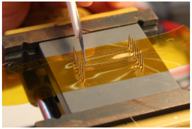
- Crystal light yield temperature dependent
- APD gain temperature dependent
- High precison monitoring (and regulation) of temperature mandatory
- Dense crystal packing: Need for very thin temperature sensors (Pt wire on Kapton foil)
- No commercial supplier

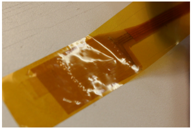


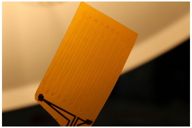


Temperature Monitoring



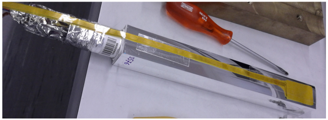






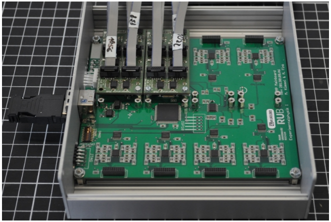
Temperature Sensors:

- TDR: $\Delta T < 0.1\,^{\circ}\mathrm{C}$
- Resolution $< 0.02\,^{\circ}\mathrm{C}$
- Width $< 20\,\mathrm{mm}$
- Thickness $< 160\,\mu\mathrm{m}$
- 500 sensors (2 per submodule)

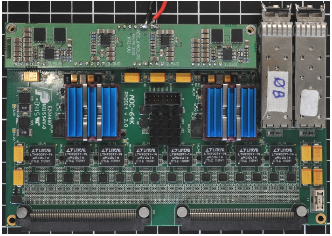


Dedicated readout boards (THM$\overline{\text{P}}$s)

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

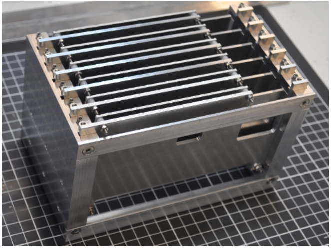


Digitization

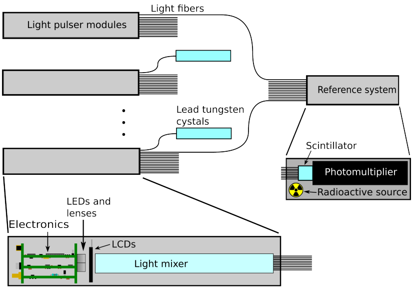


- 64 channel Sampling ADC boards
- 80 MS/s, 14 bit resolution
- 32 single ended 50 Ω signal inputs
- Analog shaping stages
- High/low gain splitting

- 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

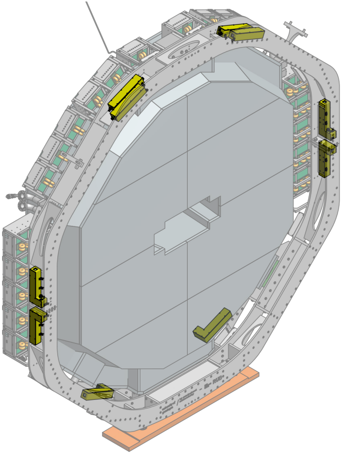


Monitoring System



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

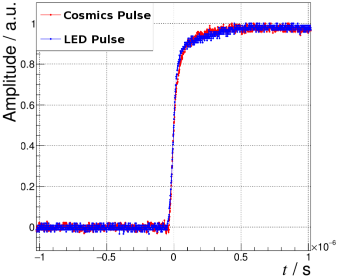
- 10 light pulser modules sitting inside support frame

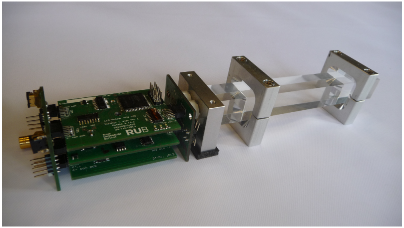


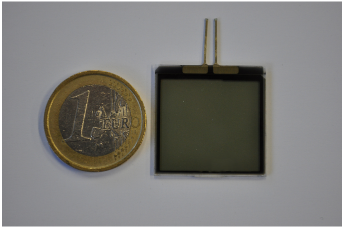
Monitoring System

LED pulser:

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

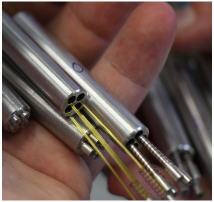


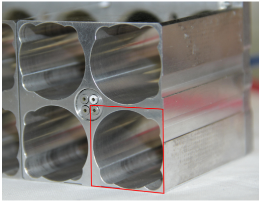


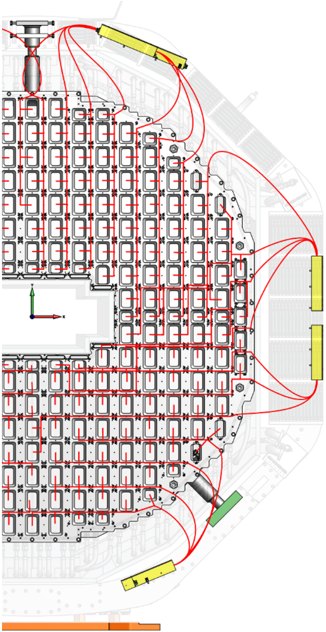


Monitoring System

- 30 km of silica/silica fibres
- Dedicated routing scheme with respect to fibre length
- Spring loaded air coupling to crystals from readout side







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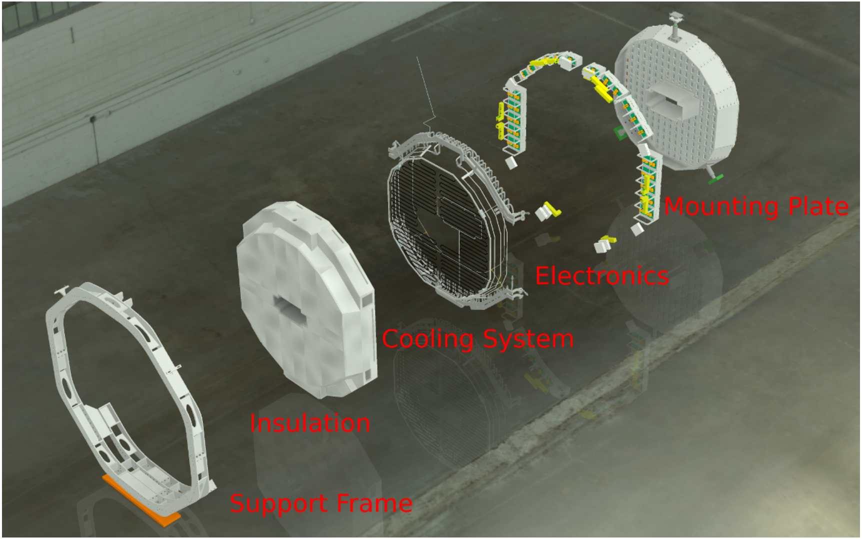
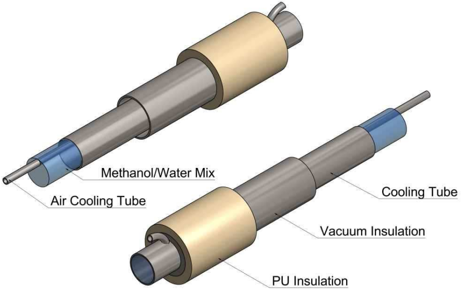
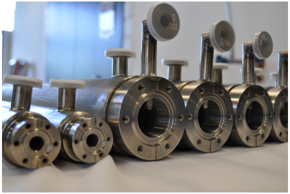
Mechanics And Cooling

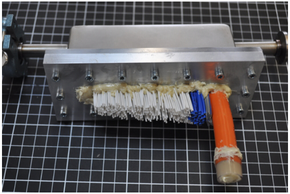


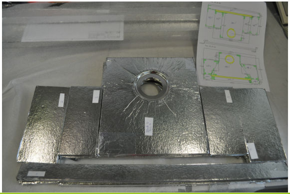
Cooling

- One central cooling machine
- Main cooling: Bores in backplane
- Additional: front, side, air cooling
- Air tight sealing of cold volume
- Thermal insulation by VIPs

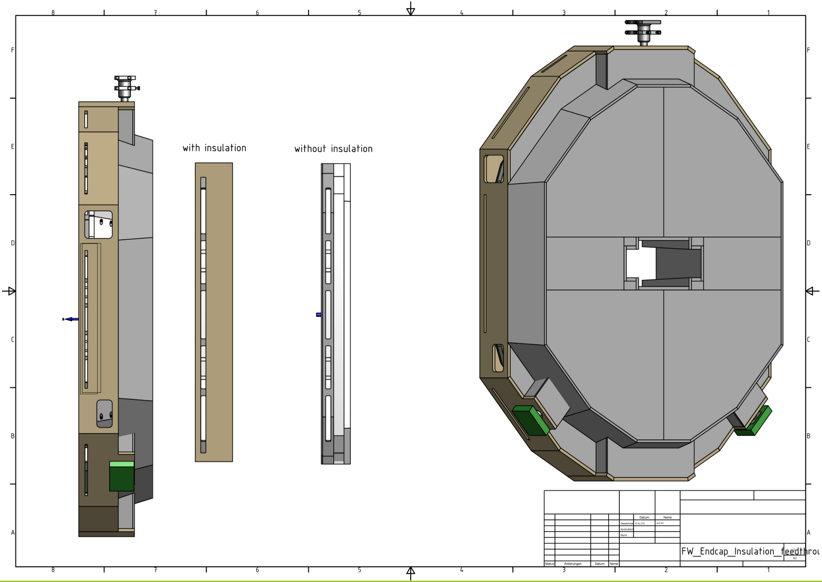






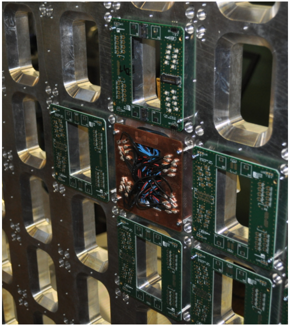


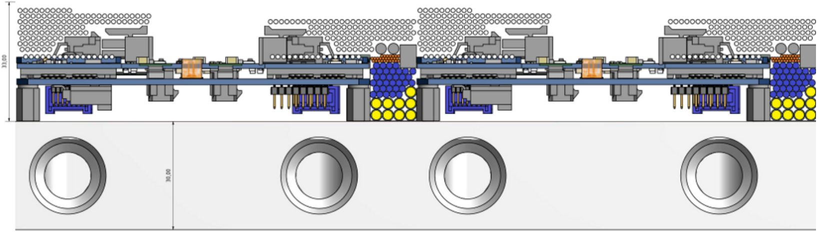
Thermal Insulation



Mechanics and Cooling

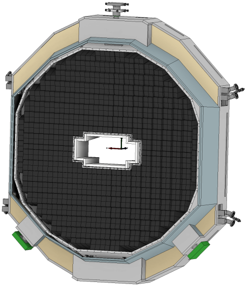
- Fibre and cable routing on back of backplate
- Patch panel PCBs to
  - Feed out preamp signals
  - Connect to temperature sensors
  - Power stimulated recovery LEDs
  - Supply HV, LV
  - Individually adjust APD HV (gain)

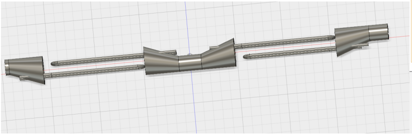


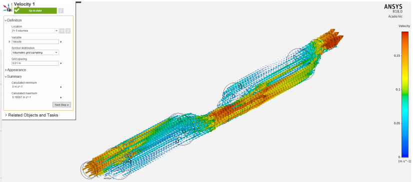


Temperature Regulation

- Reservoire temperature below operating temperature
- Controlled heating of subcircuits: Fast regulation

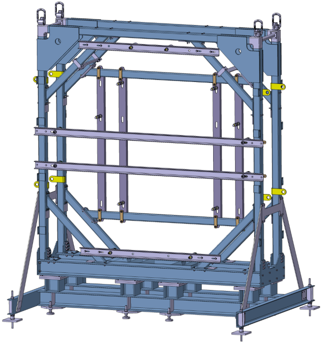






Build-up at FZ Jülich

- Assembly at COSY, FZ Jülich starting this year
- Dedicated suspension/transportation frame
- Pedestal to lift up on COSY beam height
- Manipulator arm borrowed from CMS



Summary

- Target calorimeter forward endcap most advanced $\overline{\text{P}}$ANDA detector component
- Several successful beam times with 200 crystal protoype
- Meeting TDR requirements
- Crystal submodule series manufacturing started
- Start of detector erection at FZ Jülich in 2018
- COSY beam time after finishing in Jülich ($\overline{\text{P}}$ANDA preassembly comprising different subdetectors)
- Transport to FAIR