Particle Detectors for Hadron Physics and Applications

- **Introduction**
- **Detector Physics for HP, Examples:**
  - **CBELSA/TAPS, Bonn**
  - **$\bar{P}$ANDA at FAIR**
  - **(+ε miscellaneous)**
- **Summary**

Kai-Thomas Brinkmann

Genoa

Jan 30, 2018

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

II. Physikalisches Institut

HIC for FAIR Helmholtz International Center

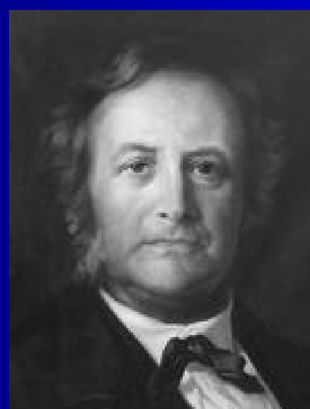
Bundesministerium für Bildung und Forschung

University of Gießen

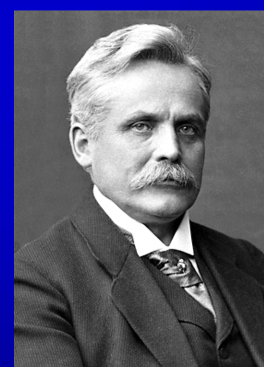
founded in 1607

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Justus Liebig

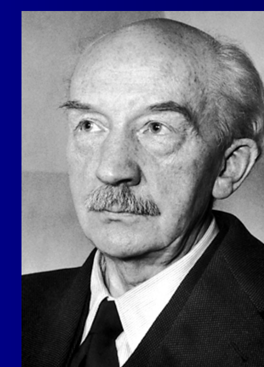


Heinrich Buff



Wilhelm Carl Werner Otto Fritz Franz Wien

Wilhelm Conrad Röntgen



Walther Bothe


VERO ESTRATTO DI CARNE LIEBIG.
RAZZE BOVINE : Jaco, Tibet.
Veggasi a tergo.

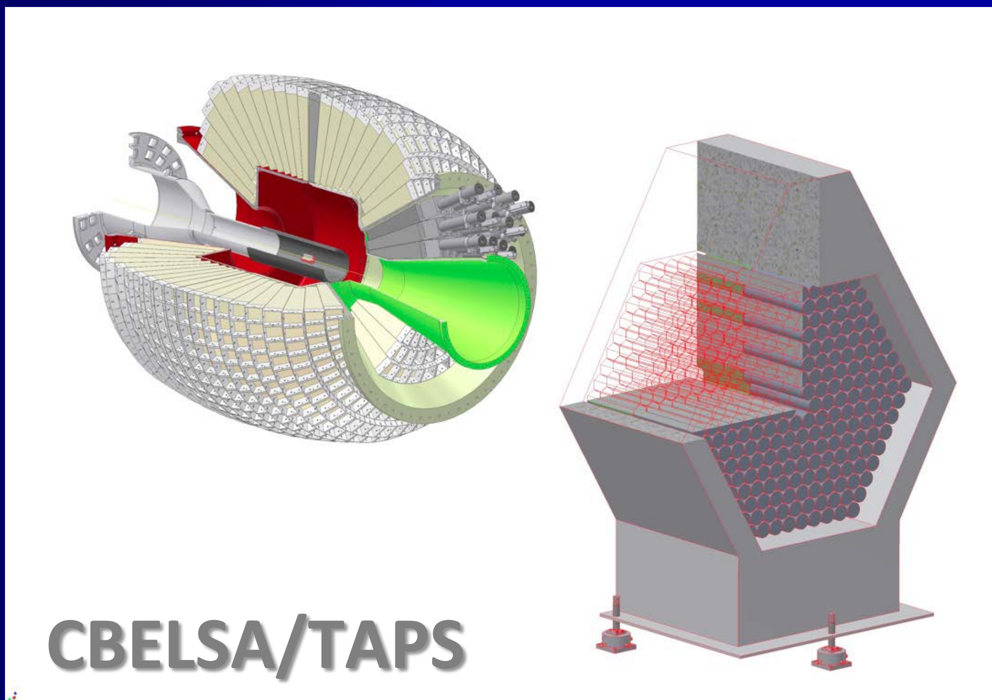

Höchste Auszeichnungen auf ersten Weltausstellungen seit 1867. Ausser Preisbewerb seit 1885.
LIEBIG Company's
FLEISCH-EXTRACT
AUS FRAY-BENTOS SÜD-AMERIKA.
NUR AECHT,
wenn jeder Topf den Namenszug
in blauer Farbe trägt.
Unentbehrlich in jeder Haushaltung. Verdirbt nie und ist unter strengster Kontrolle aus bestem Fleisch hergestellt.


ANNUAL SALE EIGHT MILLION JARS.
ASK FOR LIEBIG COMPANY'S EXTRACT OF MEAT.


VERO ESTRATTO DI CARNE LIEBIG.
RAZZE BOVINE: Toro selvatico, epoca degli antichi Germani.
Veggasi a tergo.

CBELSA/TAPS

(How to make an old work horse jump higher.)

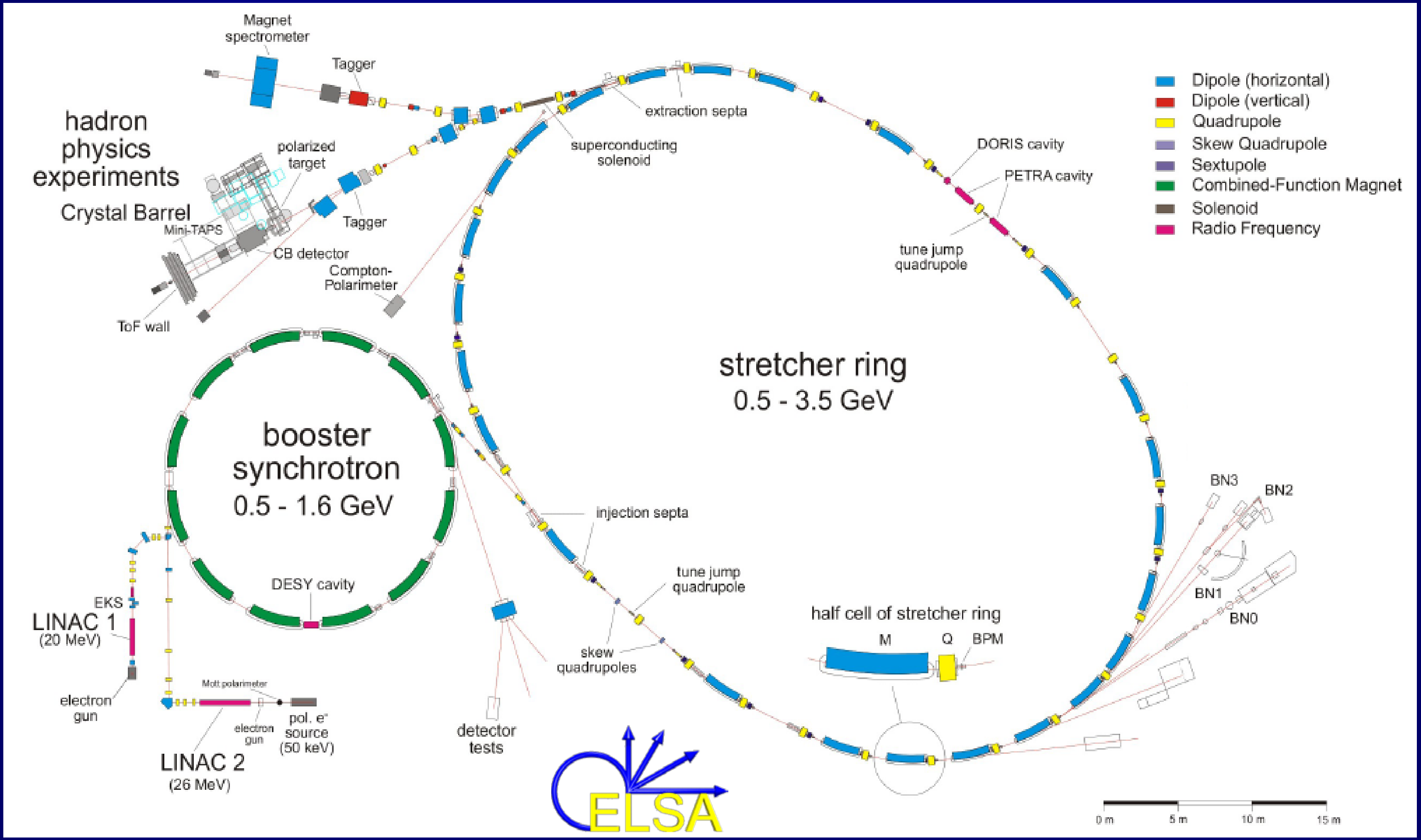


- **Double-polarized meson production in γp, γn**
- **Baryon resonances**
- **Meson production (η, ω, η‘) in nuclei**

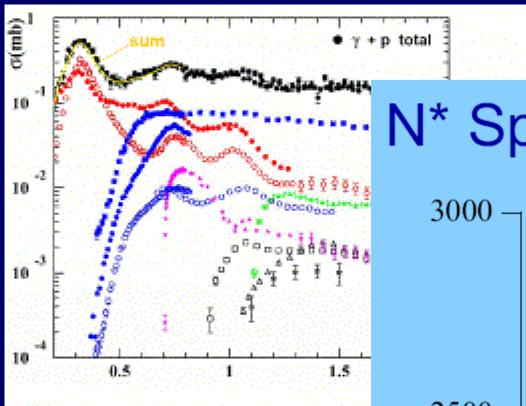
- Tagged photon beam

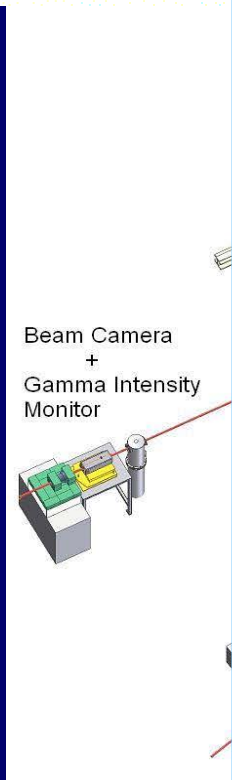
- $E_\gamma < 3.2$ GeV

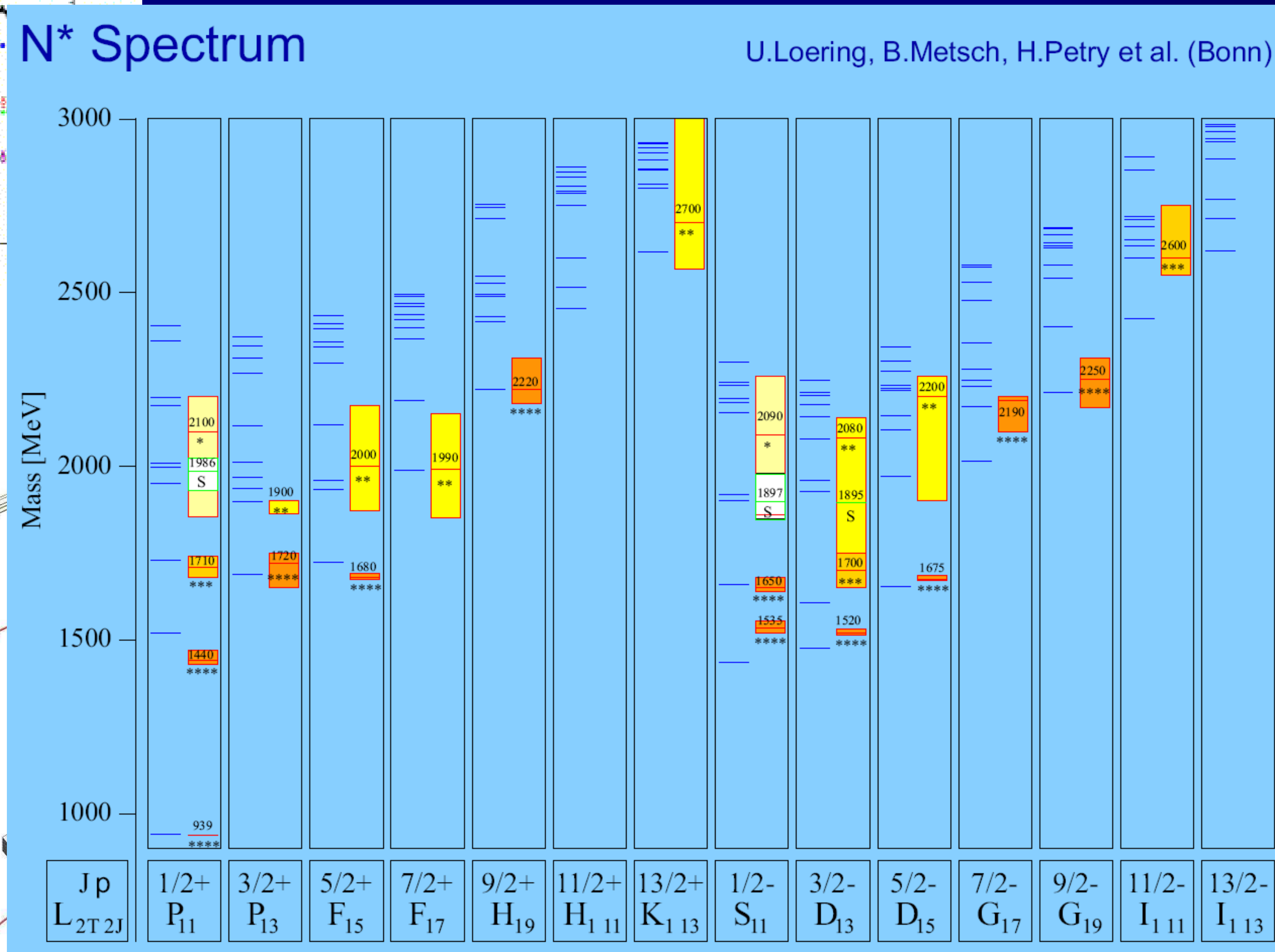
Systematic Study of the Excitation Spectra of Hadrons: Photoproduction at ELSA



Systematic Study of the Excitation Spectra of Hadrons



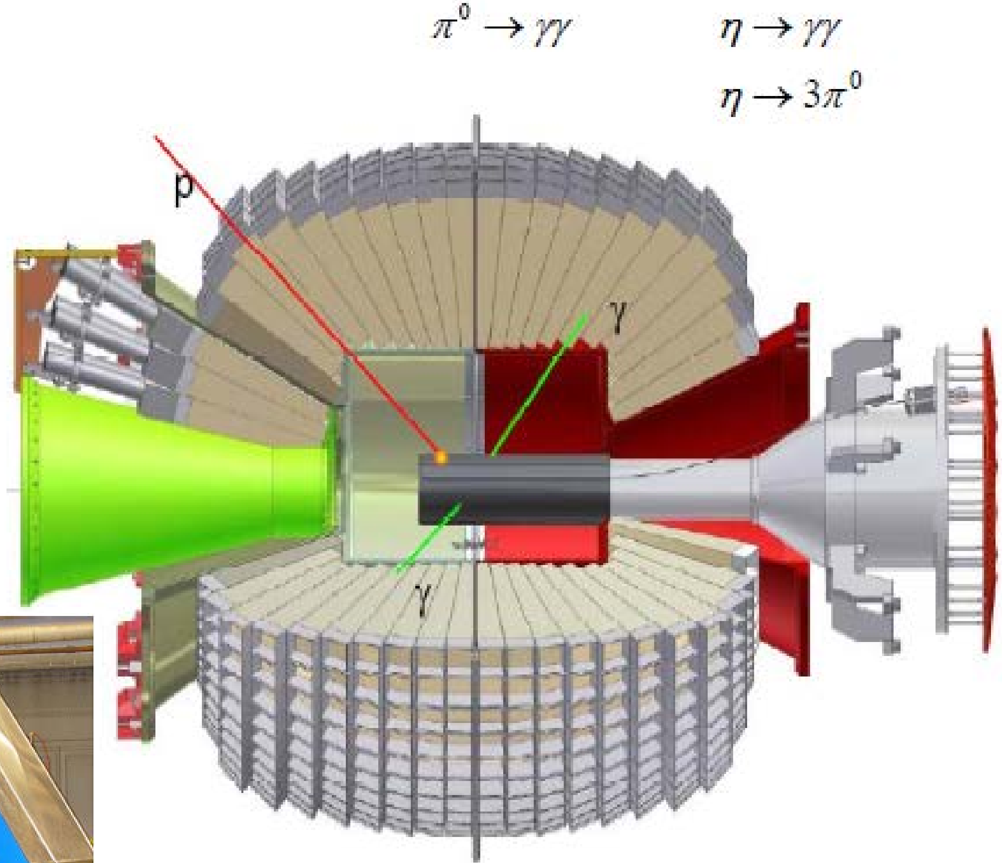


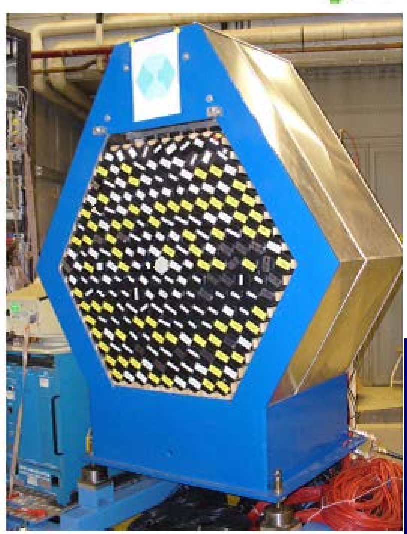


CBELSA/TAPS

- Crystal Barrel detector
  1230 CsI crystals
- Inner-detector
  cylinder of 513 scintillating fibers
- forward detector (FWPlug)
  90 CsI crystals with PM's, 12^0-30^0
- forward detector (MiniTAPS)
  216 BaF_2, 1^0-12^0

Close to 4π coverage

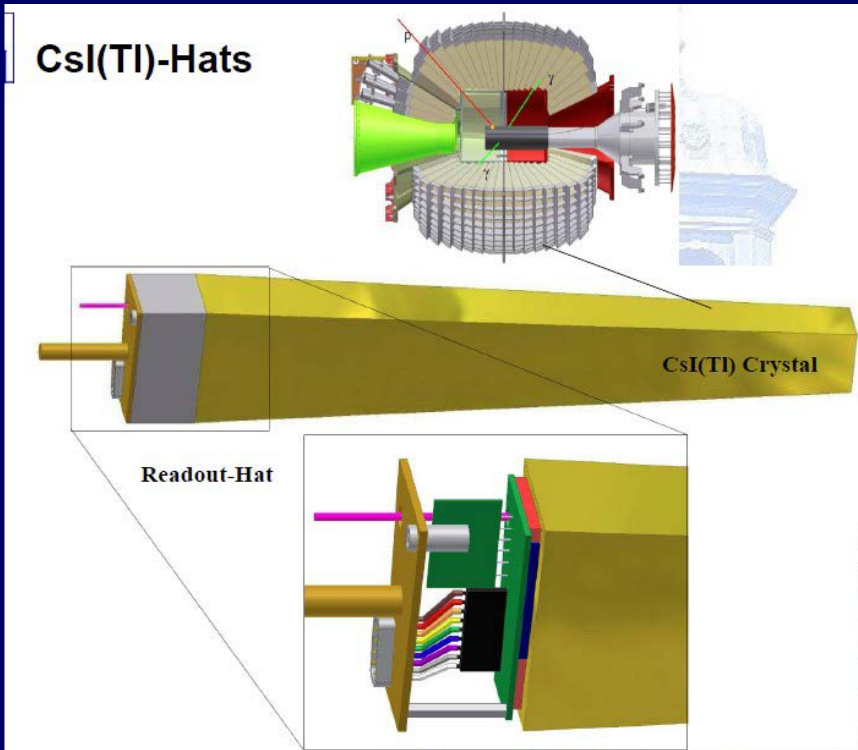


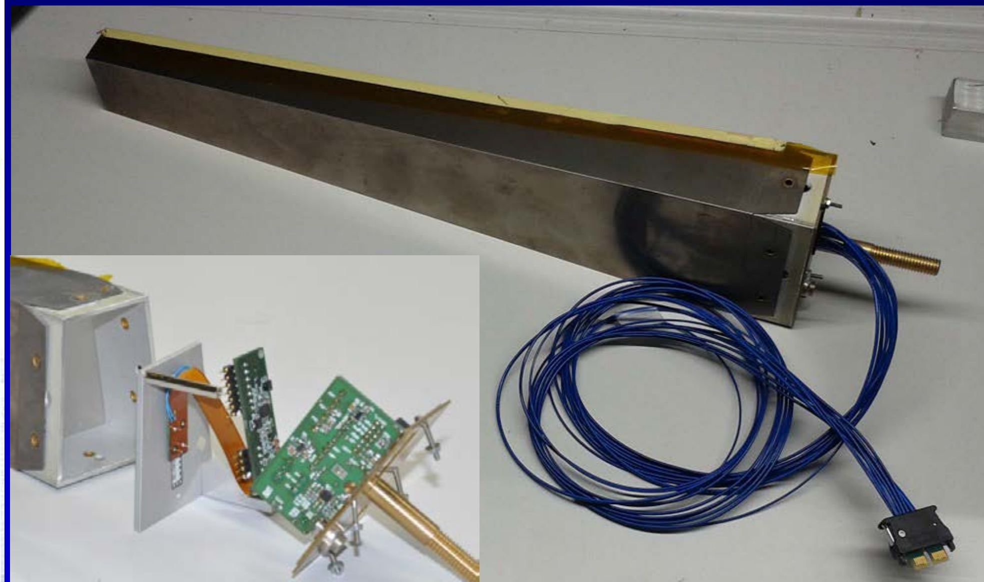


How to make an old work horse jump higher.

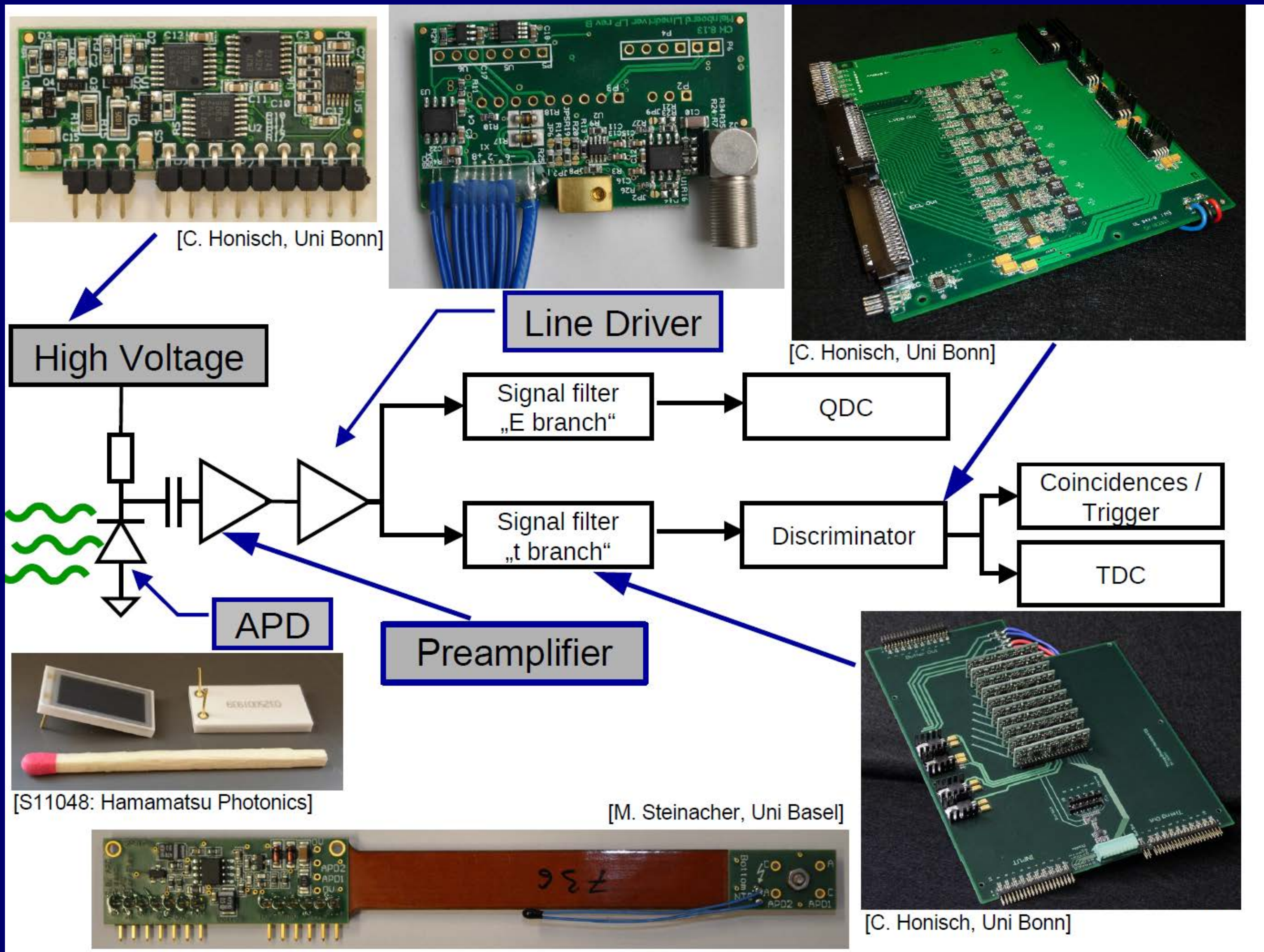
Physics	Problem
• experiments on neutrons	- neutron detection next to impossible
	$\longrightarrow$ identification of $\pi^0 \rightarrow \gamma\gamma$
	$\longrightarrow$ 2γ-coincidences on trigger level
• higher rates	- faster detectors
CsI: photodiodes	$\longrightarrow$ new readout: APD
BaF_2: PMTs	$\longrightarrow$ filters remove slow component
	- radiation hardness of detectors
	$\longrightarrow$ partly use $PbWO_4$ instead of BaF
	$\longrightarrow$ annealing

CBELSA/TAPS

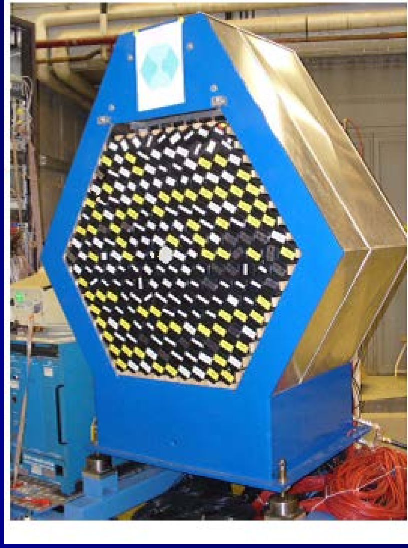




CBELSA/TAPS

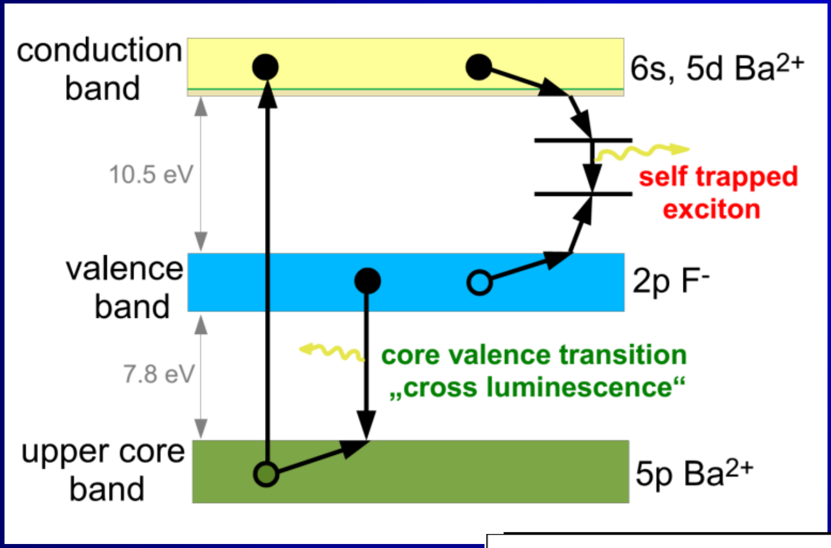

[C. Honisch, Uni Bonn]
High Voltage
Line Driver
[C. Honisch, Uni Bonn]
Signal filter „E branch“
QDC
Coincidences / Trigger
Signal filter „t branch“
Discriminator
TDC
APD
Preamplifier
[S11048: Hamamatsu Photonics]
[M. Steinacher, Uni Basel]
[C. Honisch, Uni Bonn]

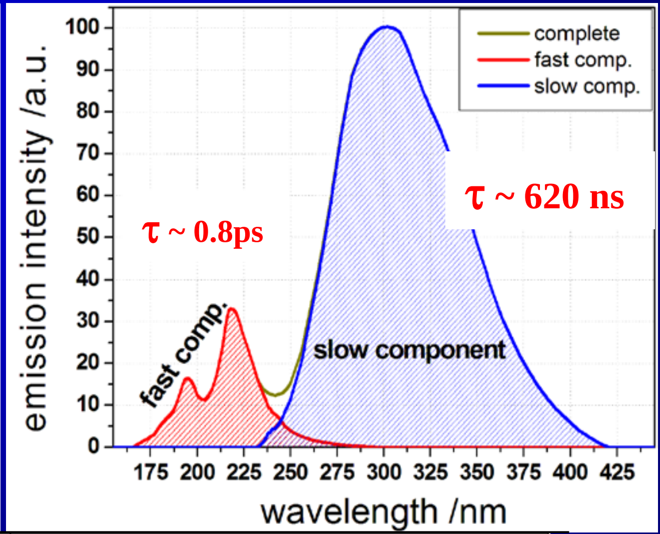
TAPS Upgrade (and "Repair")



- Upgrade of rate capability
- Performance survey and repair

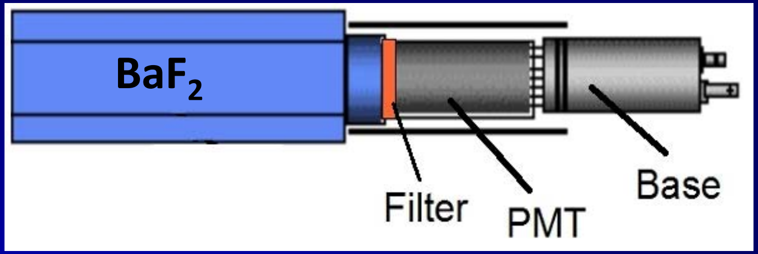
BaF_2: Scintillation mechanism





light yield for γ-rays	11300 ph/MeV	
	fast: 1300 ph/MeV	**slow:** 10000 ph/MeV

TAPS Upgrade

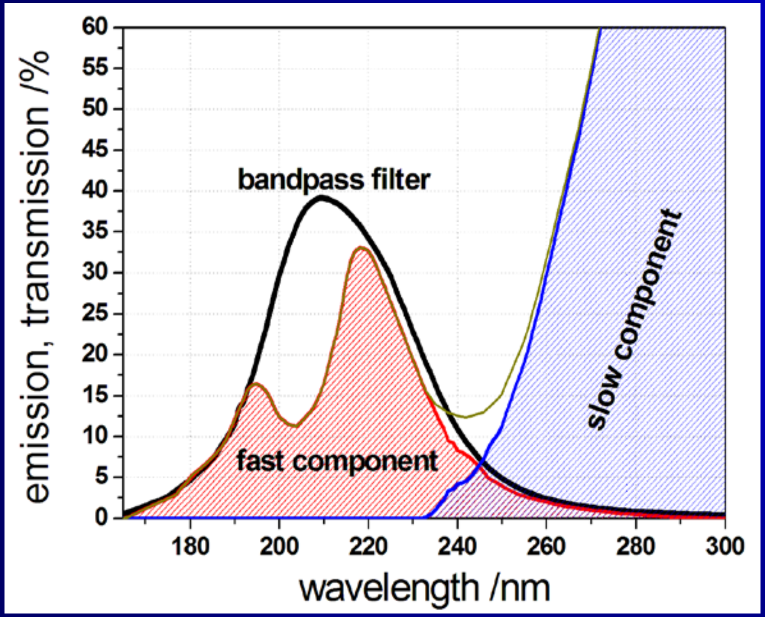


Optical filter between crystal and PMT

- high transmittance for fast component
- high grade of suppression for slow component

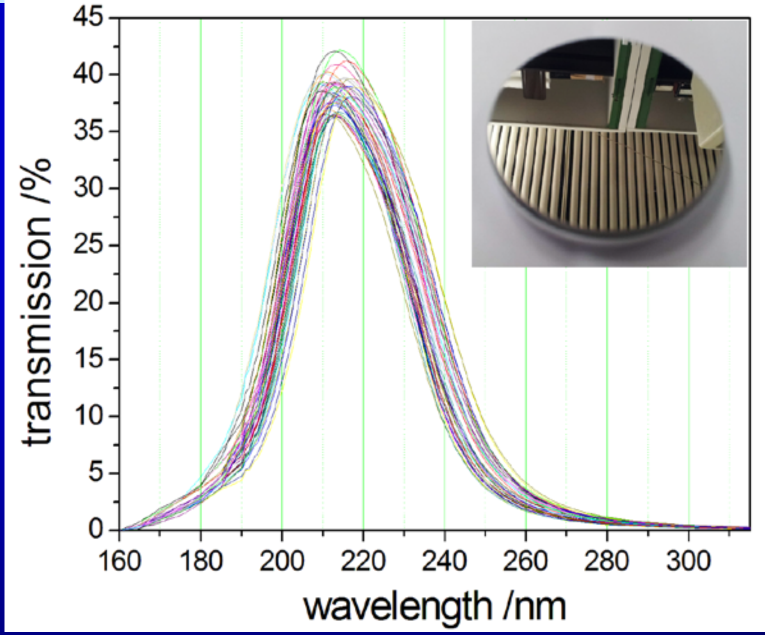
Bandpass filter

hard coated
quartz glass



- best price / performance ratio
  - LY_{fast} / LY_{slow} ratio > 5

Quality control of the filters

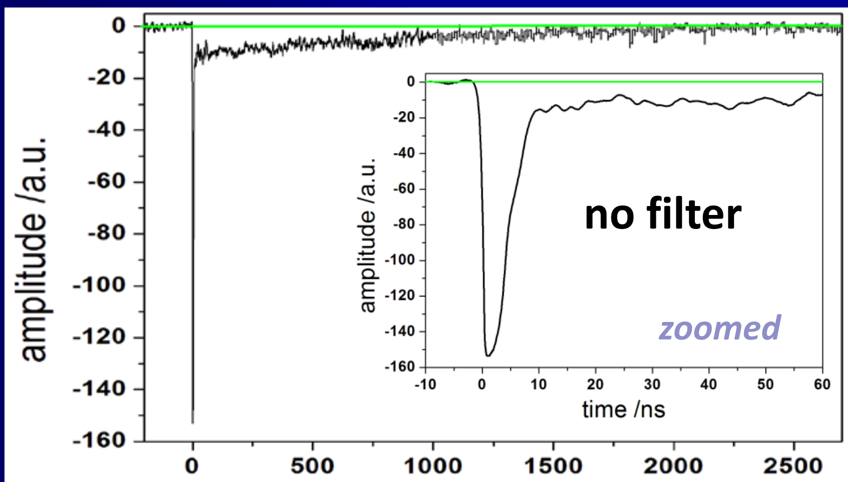


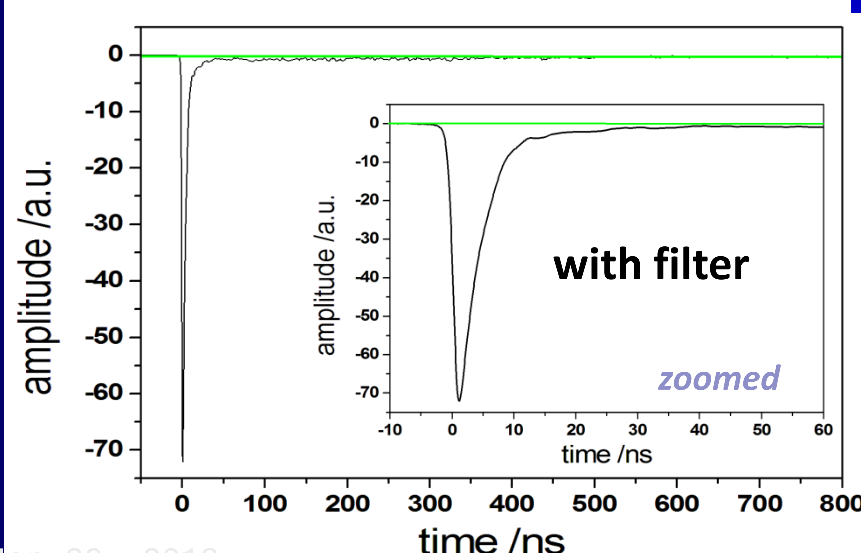
λ_{max}: 214 nm ± 3 nm

transmission @ λ_{max}: 36 % - 42 %

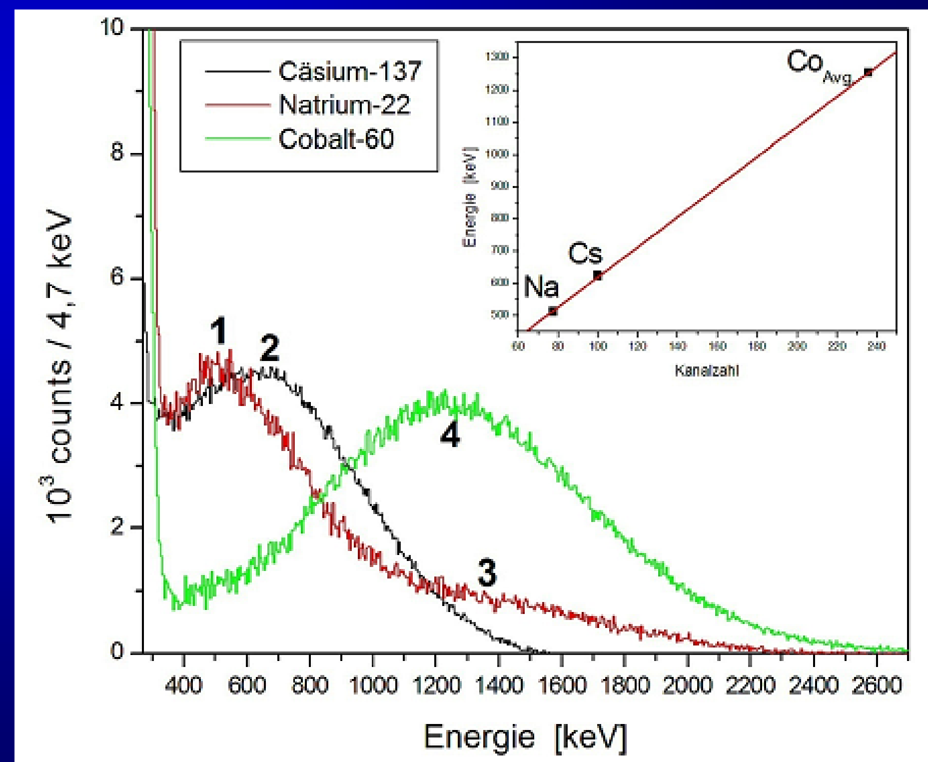
TAPS Upgrade

• Impact on signal shape





• Response to low-energy (MeV) photons

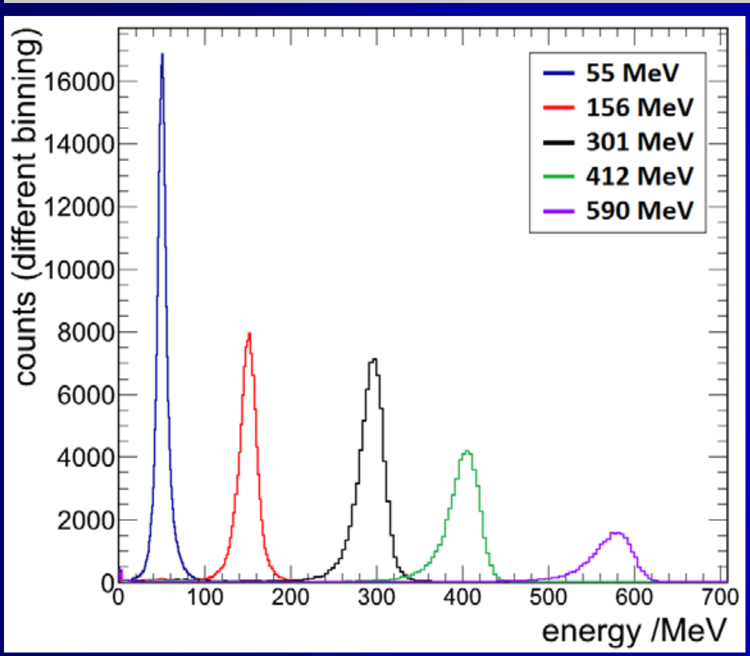


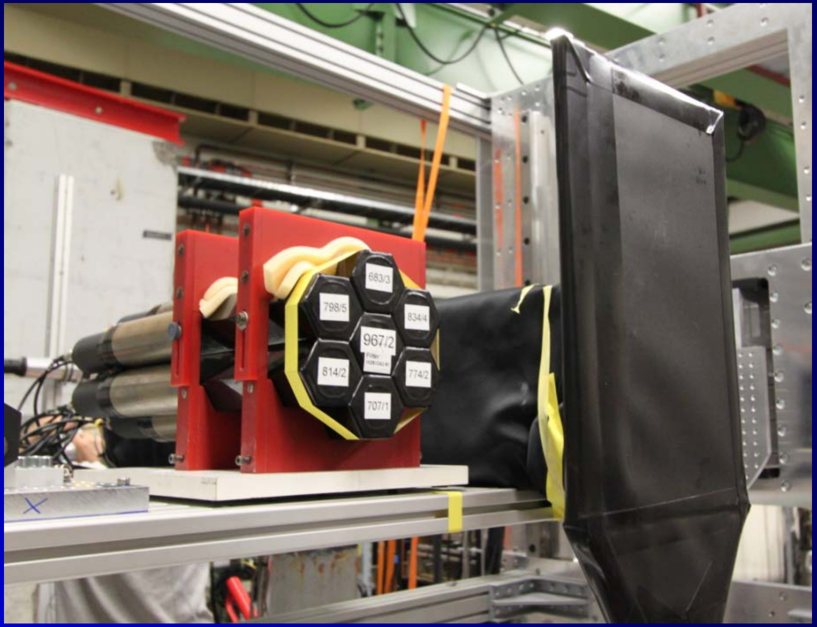
Test experiment @ MAMI-A2

E_γ : 50 – 650 MeV

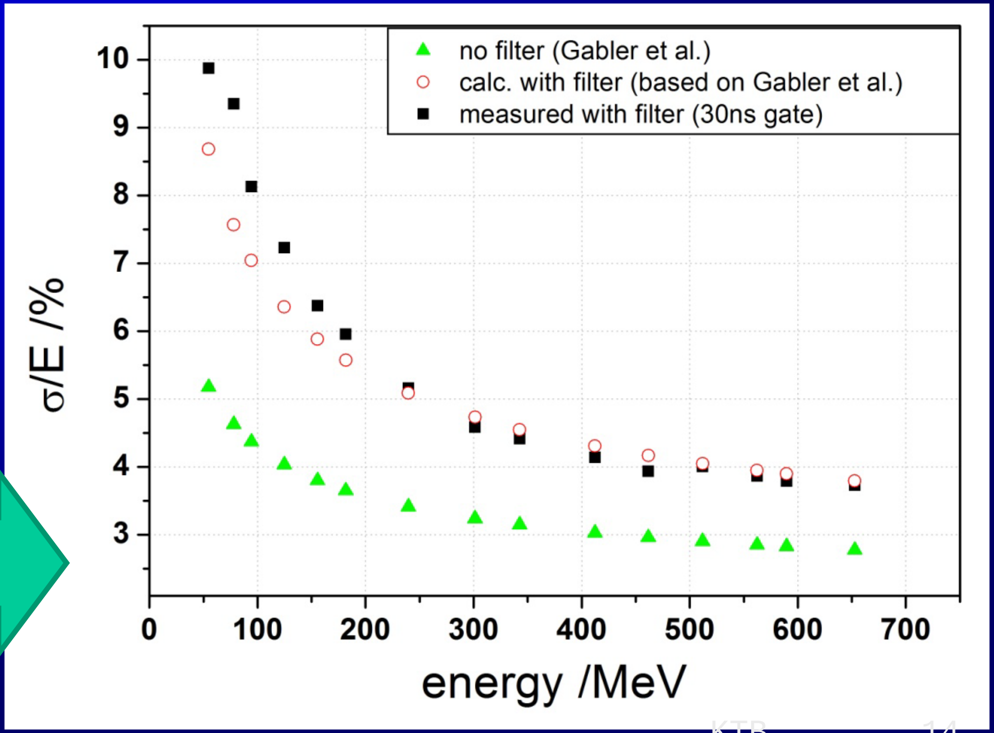
Relative calibration via cosmics

Reconstruction of the shower (7-array)

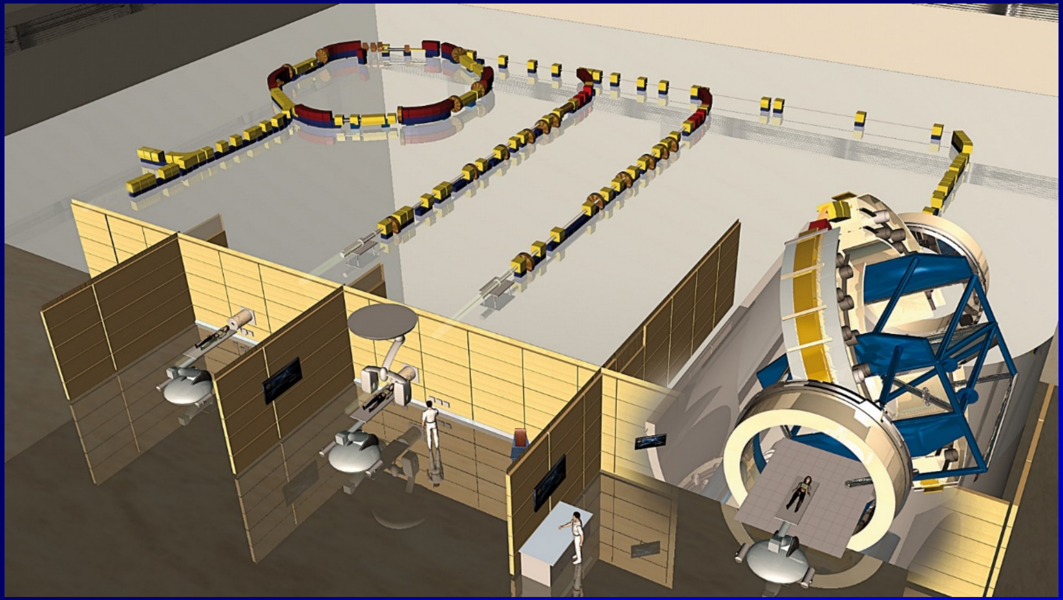




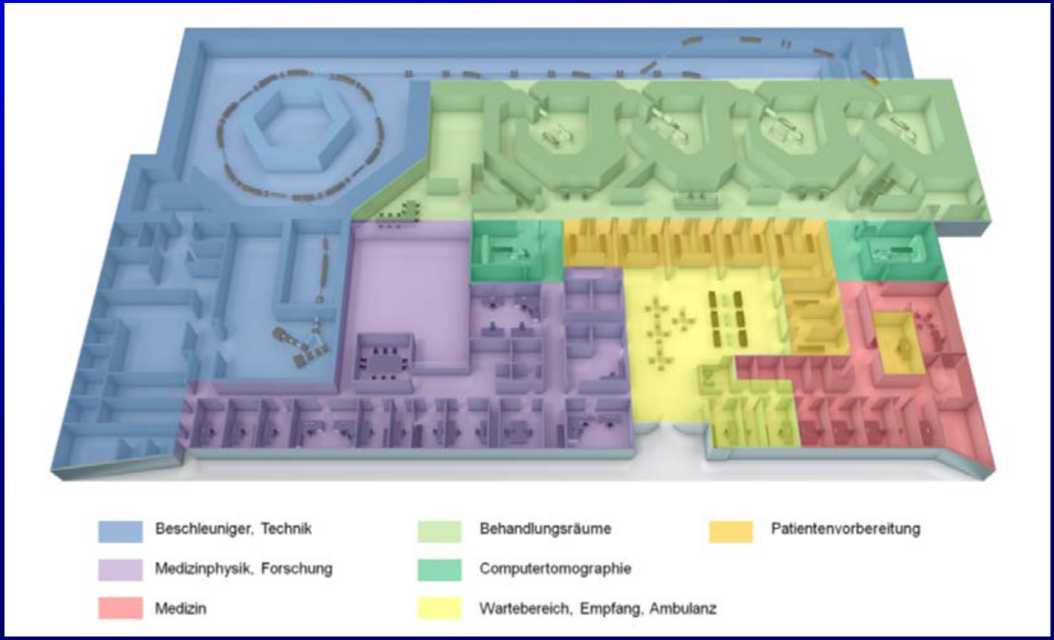
energy resolution achieved



Spin-Off: Measurements for Particle Therapy



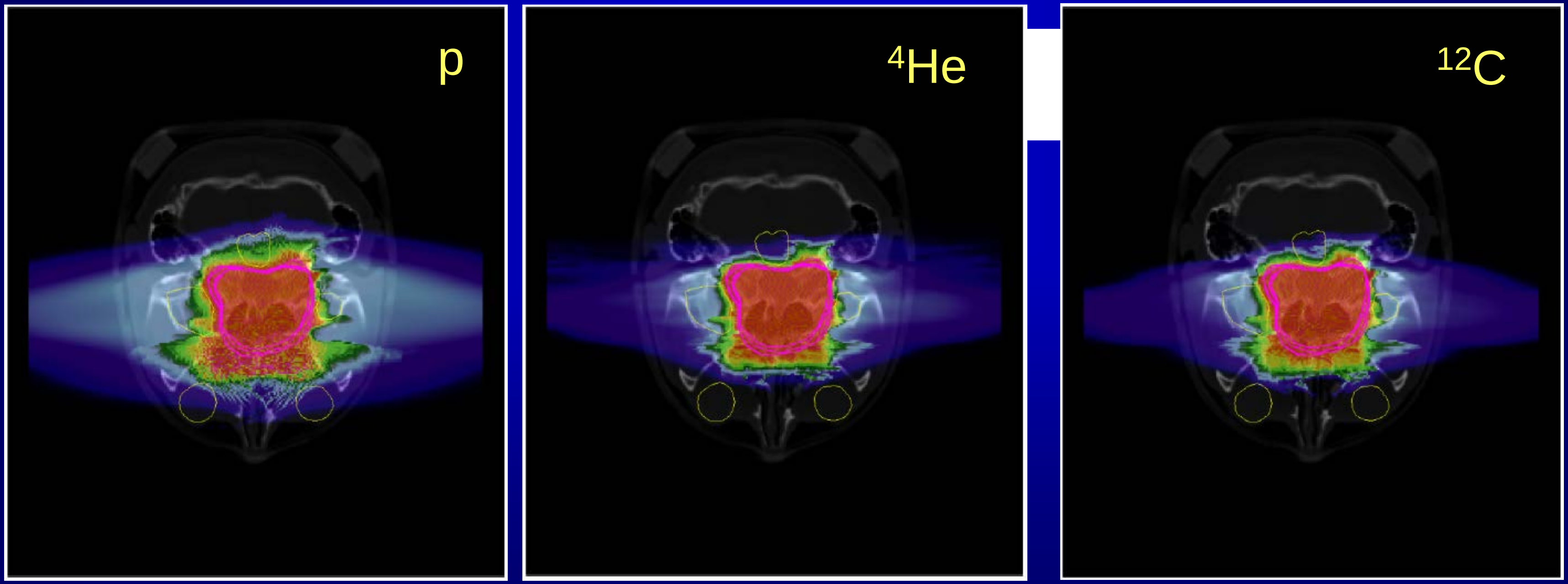
Heidelberger Ionenstrahl-Therapiezentrum (HIT)



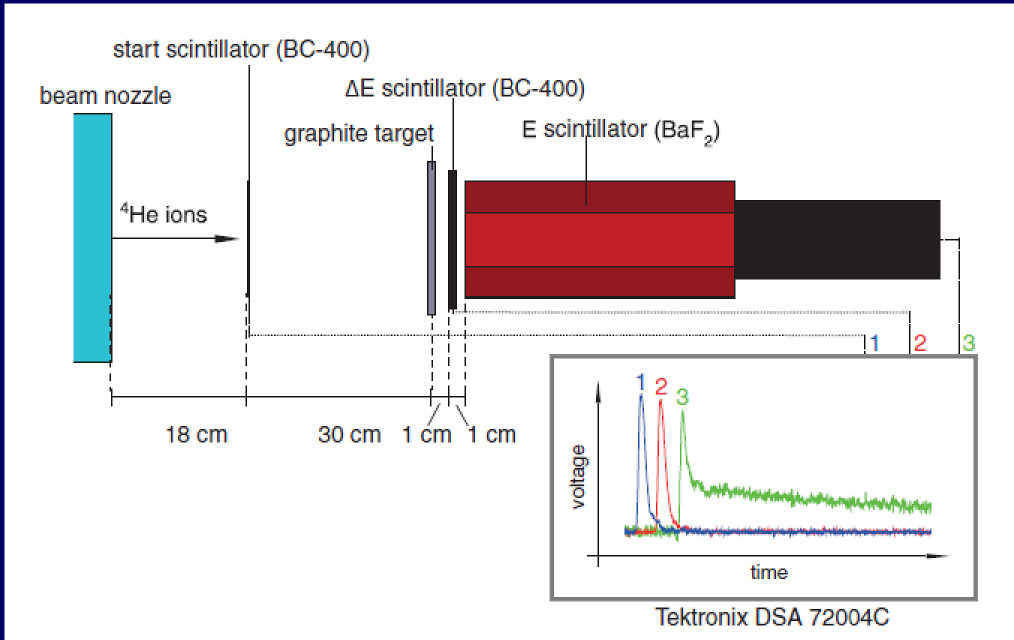
Marburger Ionenstrahl-Therapiezentrum (MIT)

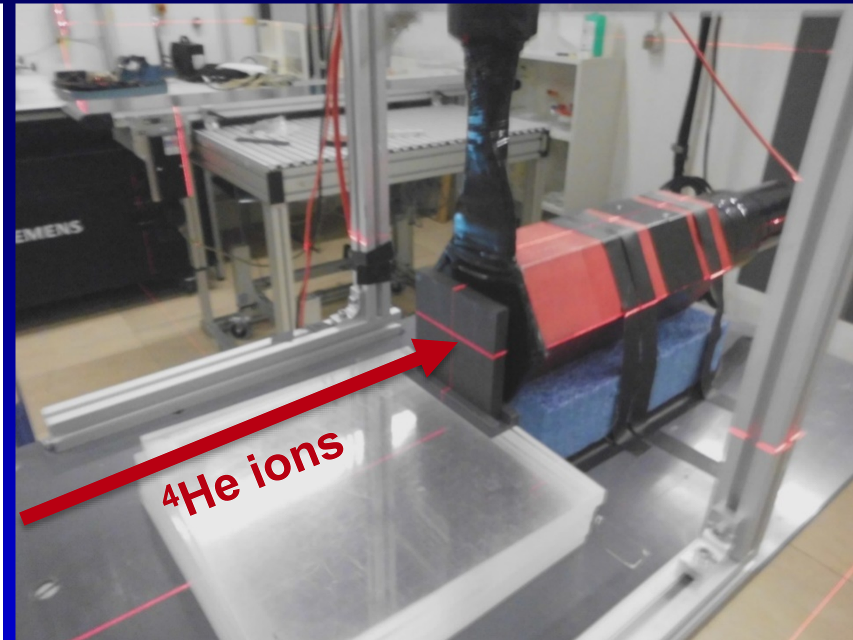
Radiotherapy With Light Heavy Ion Beams

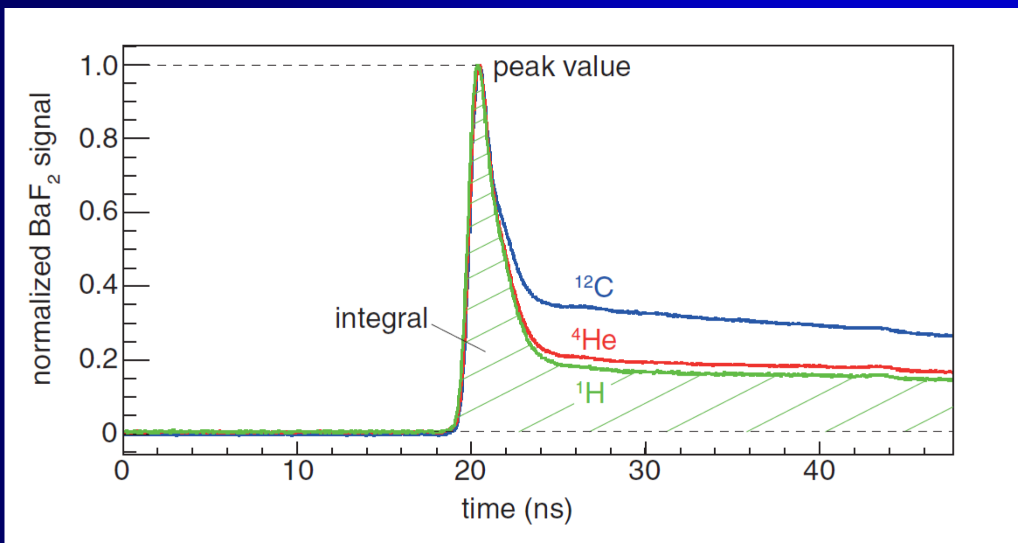
- Two proton/^{12}C clinical facilities in operation in Germany: HIT, MIT
- Clinical standard: protons (up to 220 MeV), ^{12}C (up to 430 MeV/u)
- Planned: ^{4}He (up to 220 MeV/u), ^{16}O (up to 430 MeV/u)



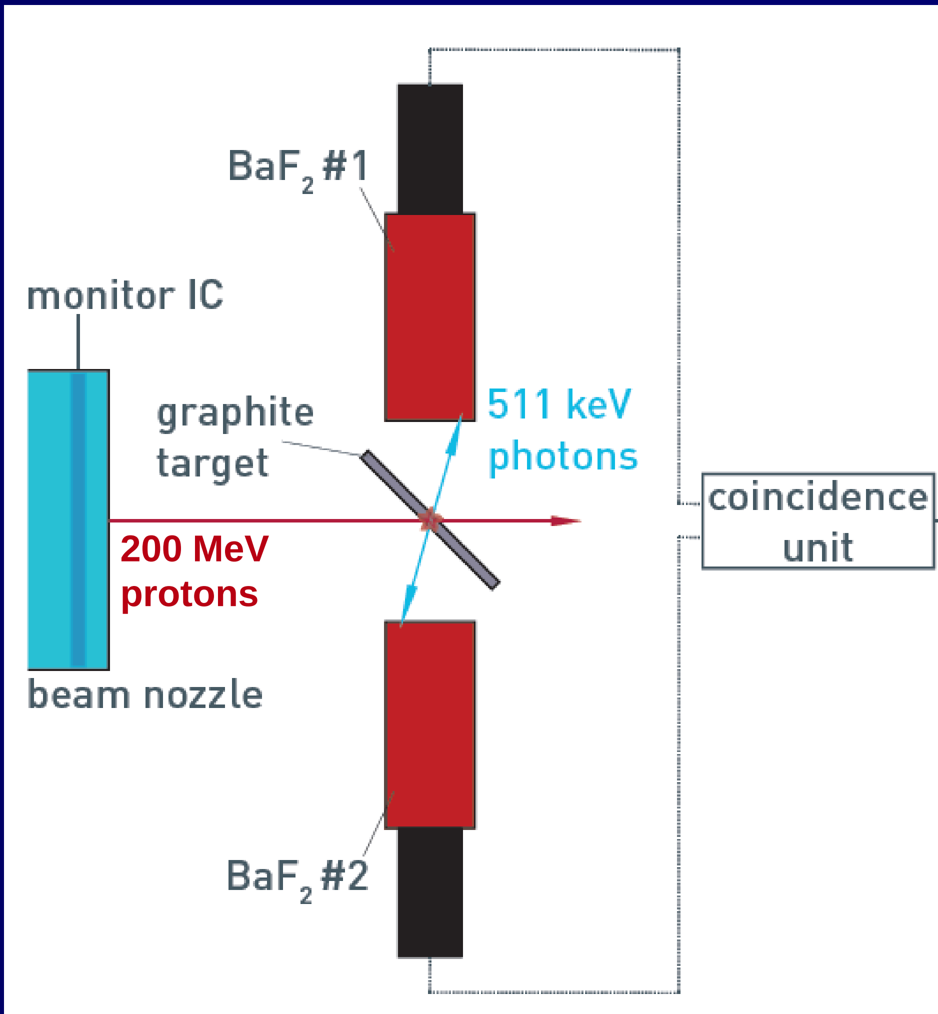
R. Grün et al. **Med. Phys.** (2015)

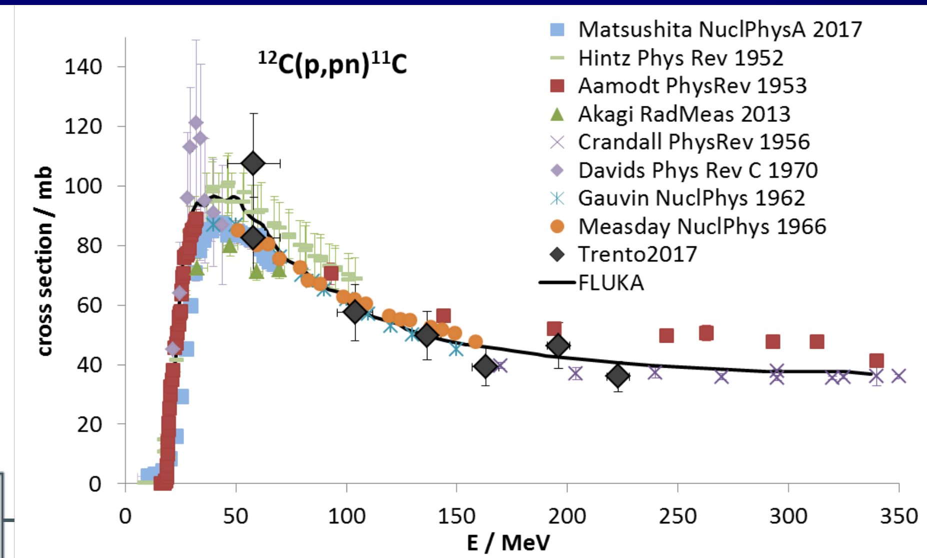

start scintillator (BC-400)
beam nozzle
ΔE scintillator (BC-400)
graphite target
E scintillator (BaF2)
4He ions
18 cm
30 cm
1 cm
1 cm
1
2
3
voltage
time
Tektronix DSA 72004C

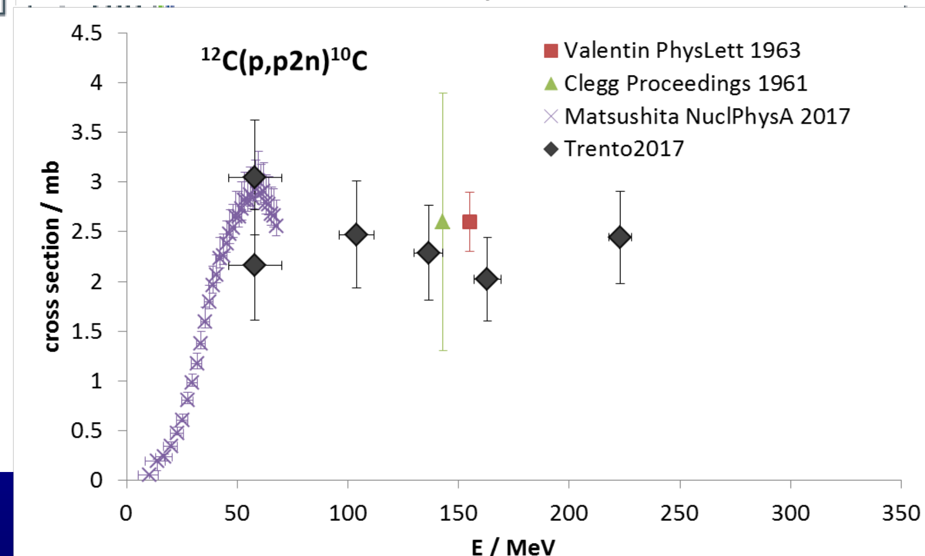

4He ions


peak value
normalized BaF2 signal
1.0
0.8
0.6
0.4
0.2
0
integral
12C
4He
1H
0
10
20
30
40
time (ns)

Production Cross Sections for Positron Emitters

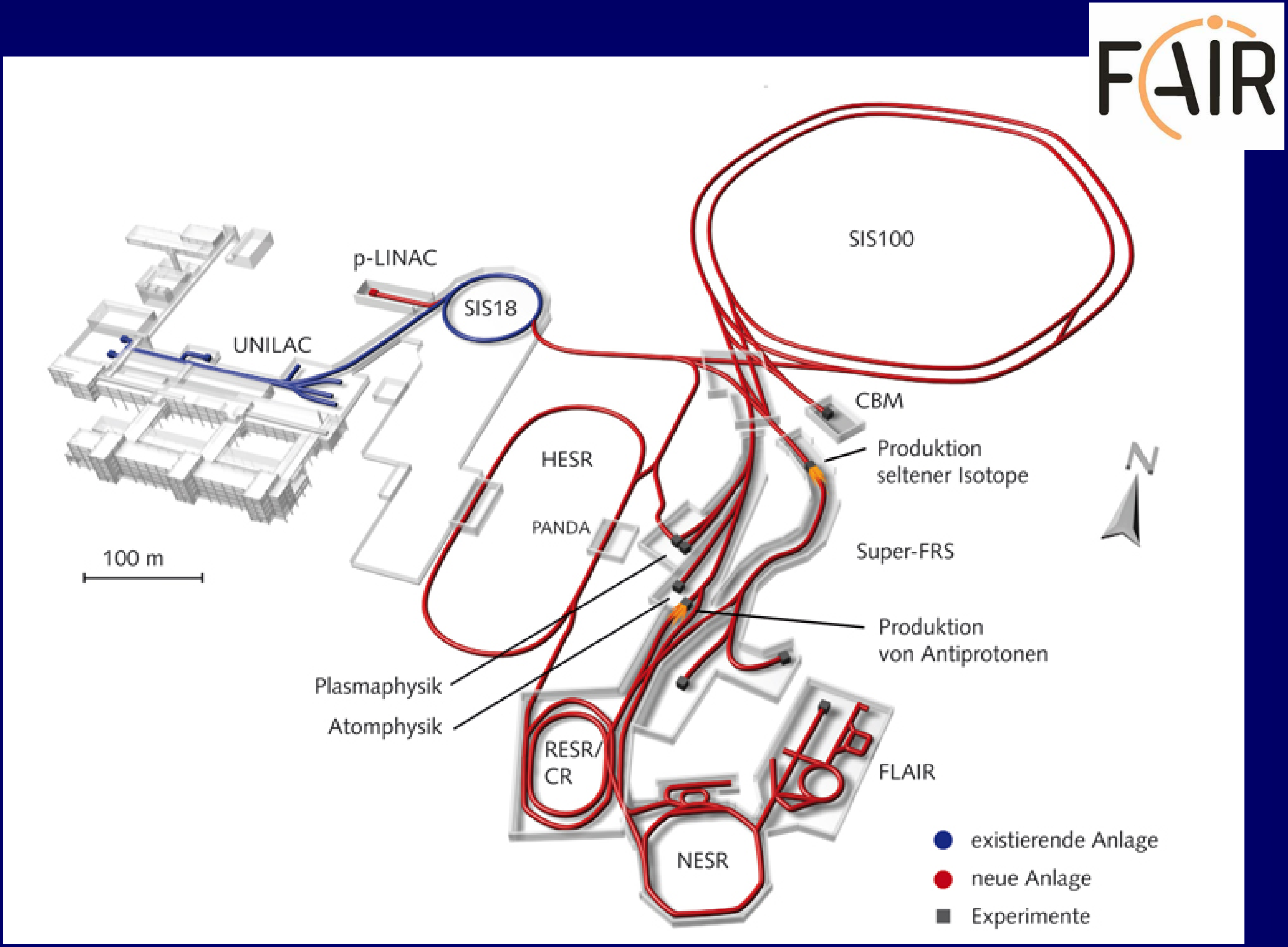






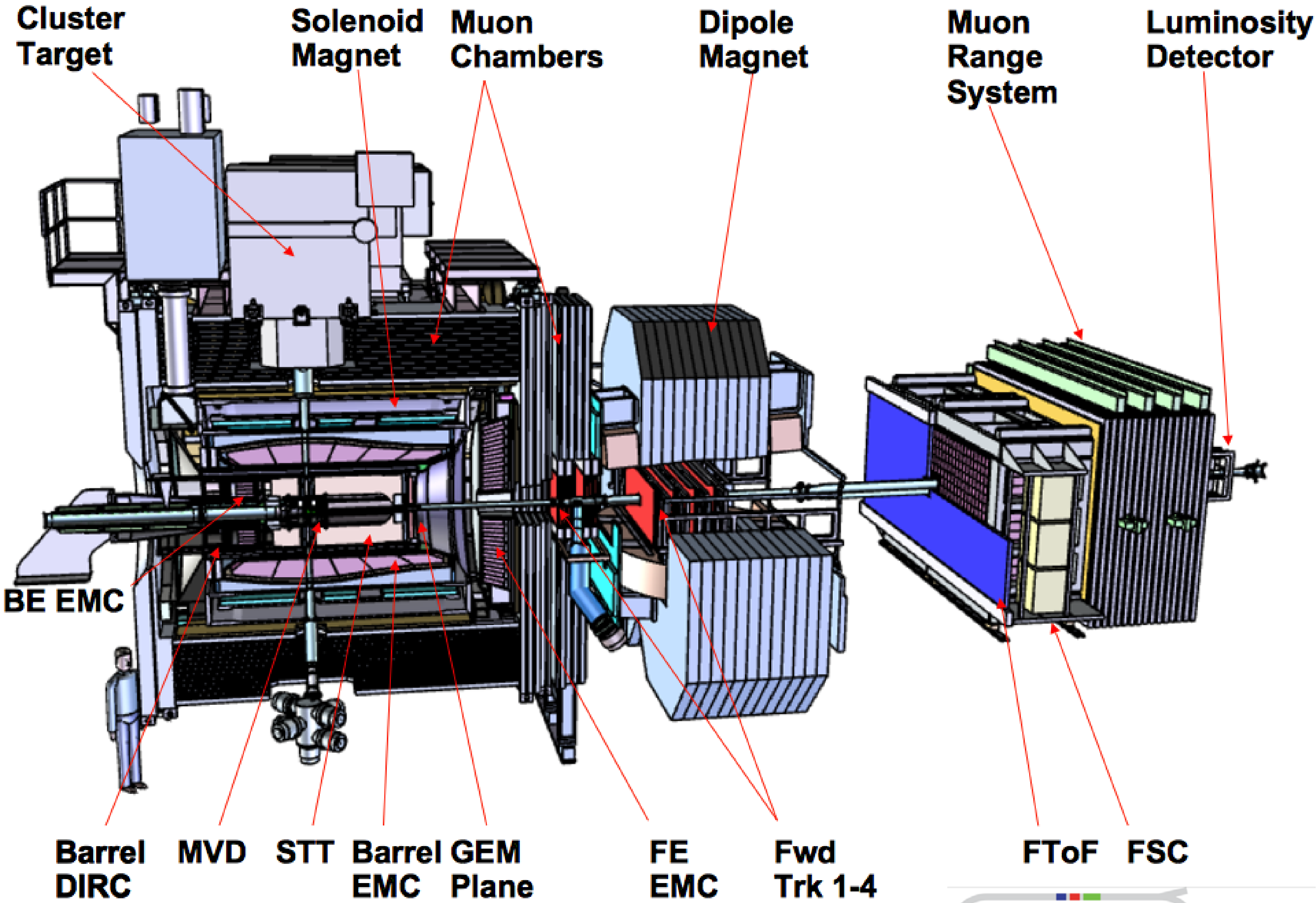
Developments for P̄ANDA

- Particle Tracking: P̄ANDA Micro-Vertex Detector
- Particle Calorimetry: P̄ANDA Electromagnetic Calorimeter



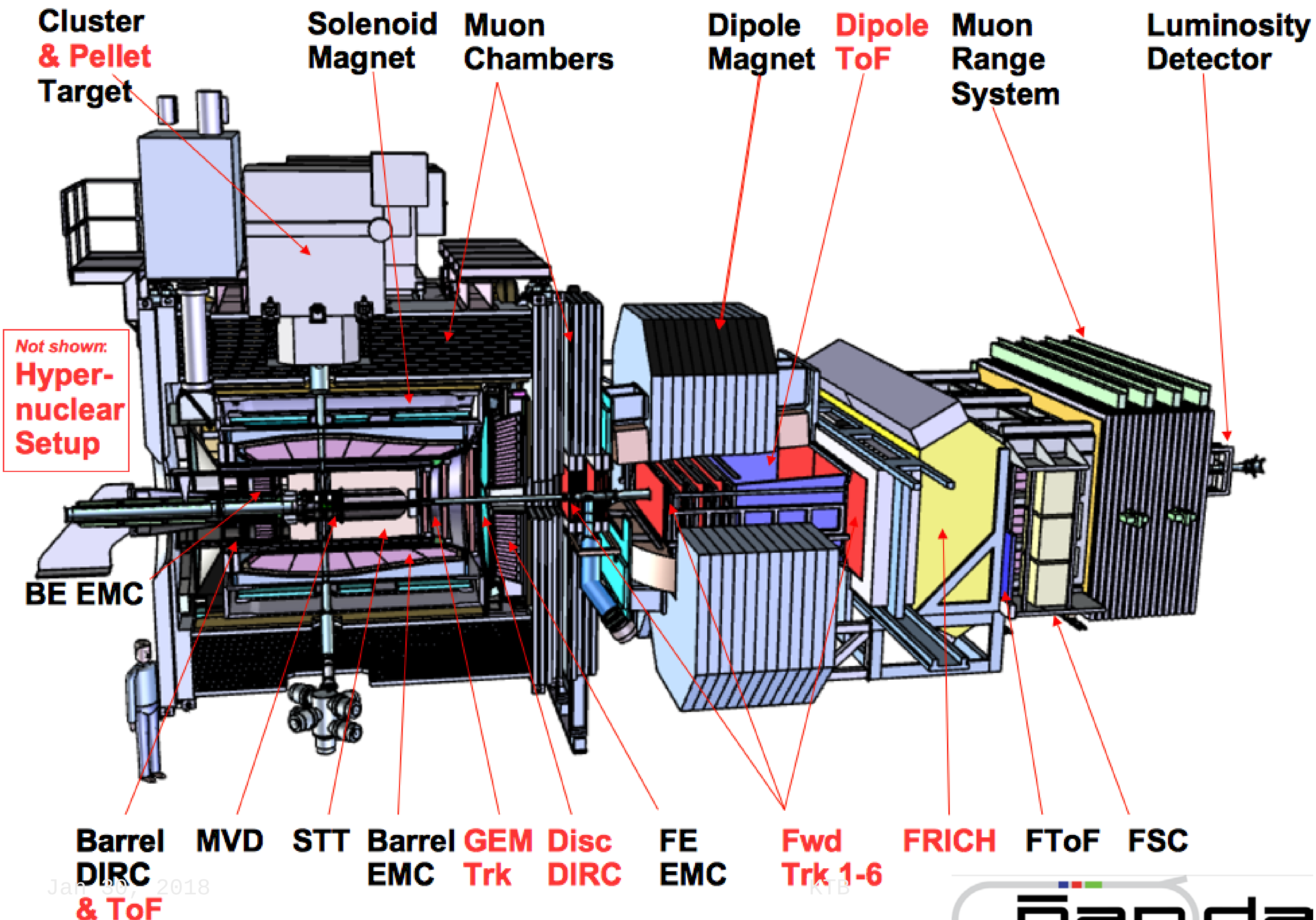
FAIR
p-LINAC
SIS18
UNILAC
SIS100
CBM
Produktion
seltener Isotope
HESR
PANDA
Super-FRS
100 m
Produktion
von Antiprotonen
Plasmaphysik
Atomphysik
RESR/
CR
FLAIR
NESR
existierende Anlage
neue Anlage
Experimente
N

Start Setup



Cluster Target
Solenoid Magnet
Muon Chambers
Dipole Magnet
Muon Range System
Luminosity Detector
BE EMC
Barrel DIRC
MVD
STT
Barrel EMC
GEM Plane
FE EMC
Fwd Trk 1-4
FToF
FSC

Full Setup


Cluster
& Pellet
Target
Solenoid
Magnet
Muon
Chambers
Dipole
Magnet
Dipole
ToF
Muon
Range
System
Luminosity
Detector
Not shown:
Hyper-
nuclear
Setup
BE EMC
Barrel
DIRC
& ToF
MVD
STT
Barrel
EMC
GEM
Trk
Disc
DIRC
FE
EMC
Fwd
Trk 1-6
FRICH
FToF
FSC

Physics Objectives

HEP: interference of coupled channels

HEP: underlying elementary processes

Spectroscopy

New narrow XYZ: Search for partner states

Production of exotic QCD states: Glueballs & hybrids

Bound States of Strong Interaction

Nucleon Structure

Generalized parton distributions: Orbital angular momentum

Drell Yan process: Transverse structure, valence anti-quarks

Timelike formfactors: Low and high E, e and μ pairs

Strangeness

Strange baryons: Spectroscopy Polarisation

Astro physics: Strange n-stars

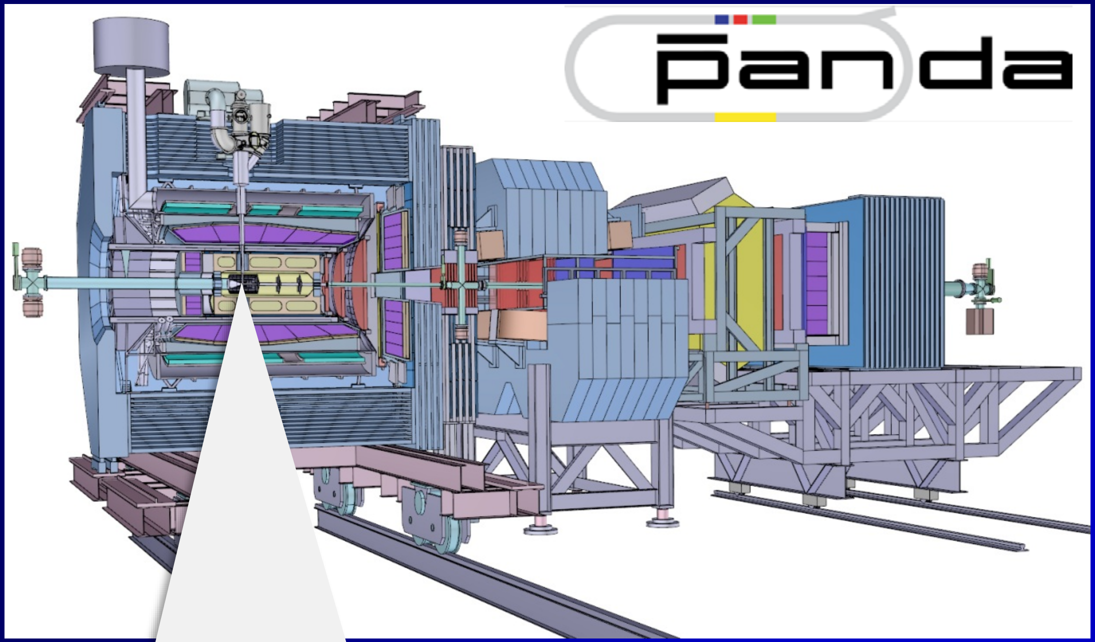
Nuclear physics: Hypernuclear spectroscopy

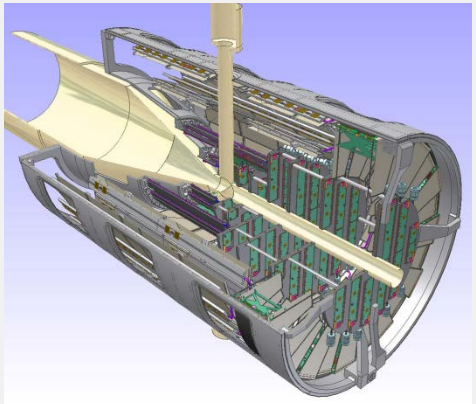
Nuclear Physics

Hypernuclear physics: Double Λ hypernuclei Hyperon interaction

Hadrons in nuclei: Charm and strangeness in the medium

HI collisions comparing QGP to elementary reactions





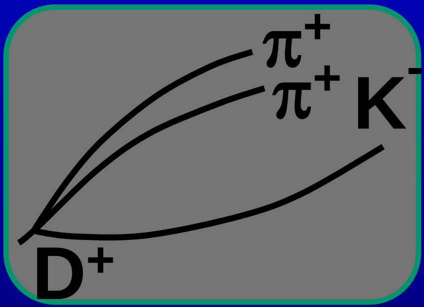
tracking

The P̄ANDA Micro-Vertex Detector

Design adopts state-of-the-art silicon sensor techniques

Focus on P̄ANDA-specific issues:

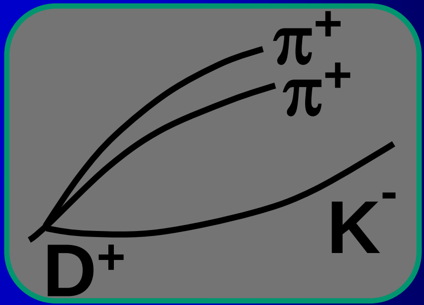
- High and asynchronous interaction rate
- Strongly asymmetric angular distributions
- Versatile experimental requirements
- D meson ID
- Minimum mass budget



Solutions:

- Heterogeneous design (pixel and strip sensors)
- Very compact design
- Limited number of space points / layers (default 4)
- Novel readout electronics (non-triggered readout)
- Tracklets real-time (fast on-line processing)

The $\bar{\mathrm{P}}$ANDA MVD Project

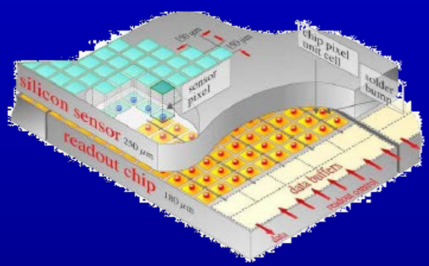


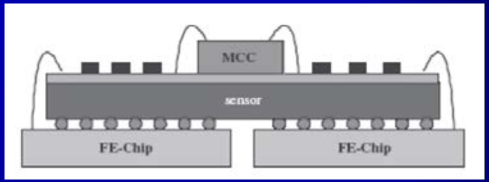
Silicon pixel sensors

Small pixel cells – 100 x 100 μm^2

Specialized custom hybrid ☞ ToPix

Features:
- .13 μ technology
- ToT to retain (some) energy information
- fast handling for high data rates
- "untriggered" readout of data
- rad hard within "typical" limits
- minimum material load ⬄ sensor technology (EPI)

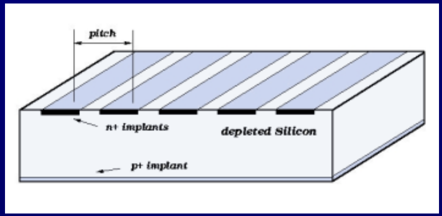




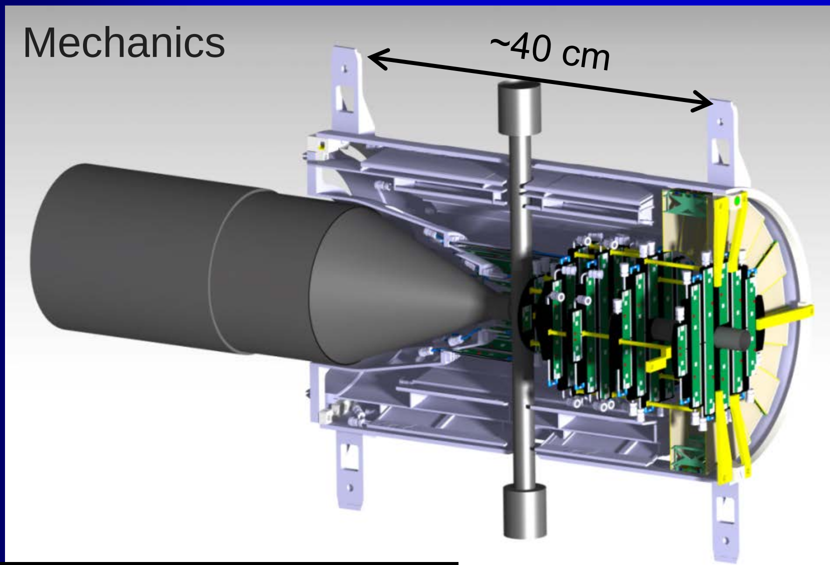
Silicon strip sensors

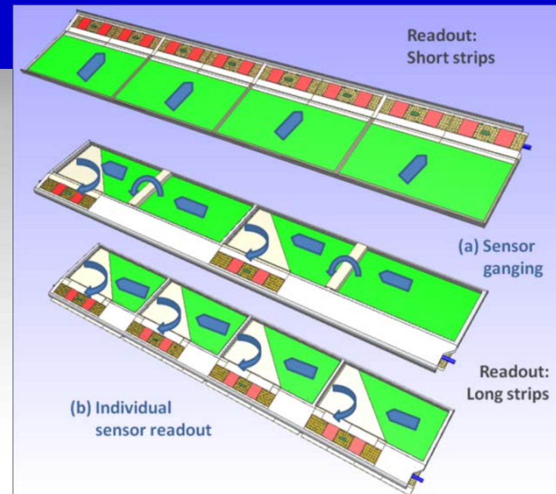
Less traversed material than pixels, smaller number of channels

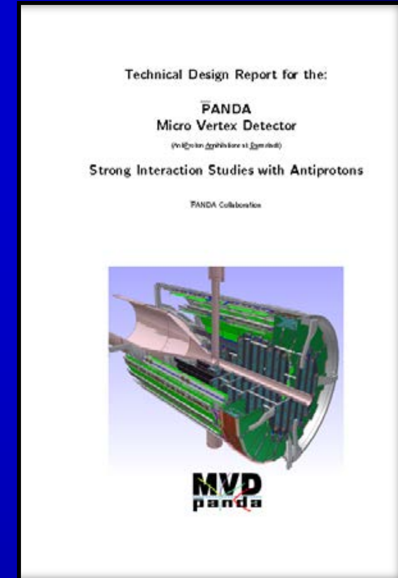
Features:
- pitch of 50 – 150 μm
- double-sided sensors, 300 μm thick
- specialized solution for front-end



The P̄ANDA MVD Project



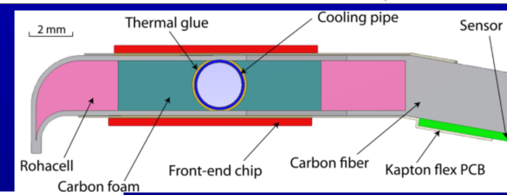


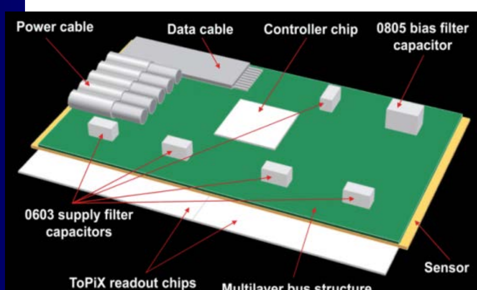

Technical Design Report for the:

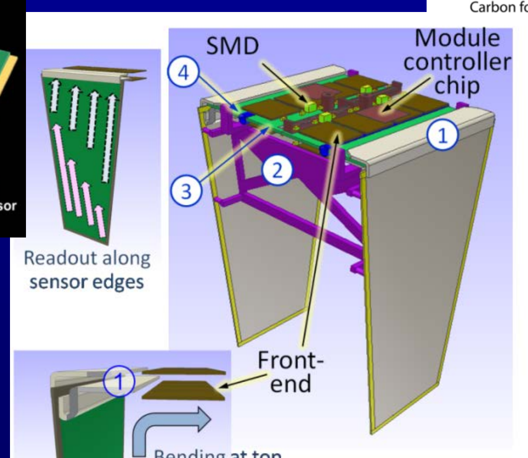
P̄ANDA
Micro Vertex Detector

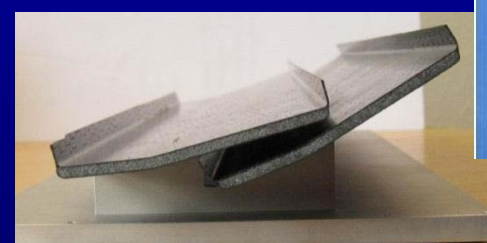
Strong Interaction Studies with Antiprotons

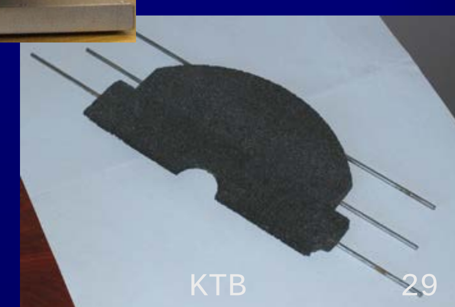
P̄ANDA Collaboration











The $\bar{\text{P}}$ANDA MVD Project

Hardware

Cleanroom facility (ISO class 6)

Automatic prober

Semi-automatic wedge wire bonder

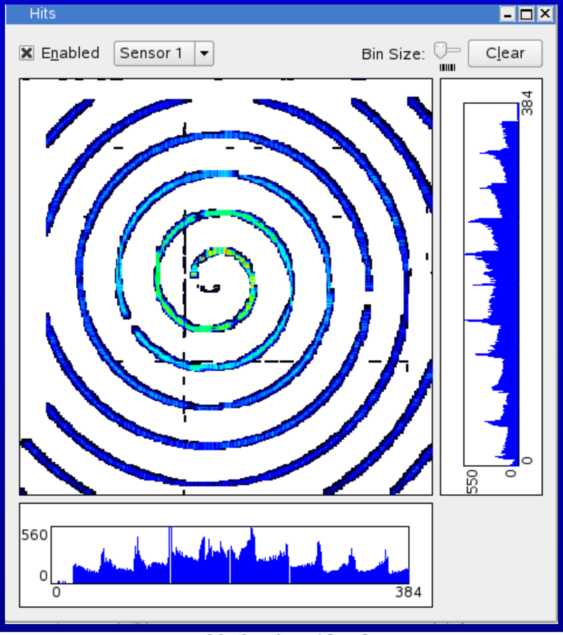
Workshop:
Specialized equipment in-house, customized, on short notice

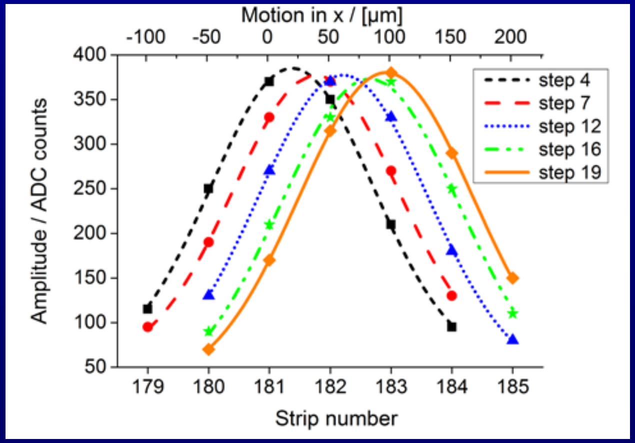
- Bonding tools
- Mounting tools

The P̄ANDA MVD Project

Hardware

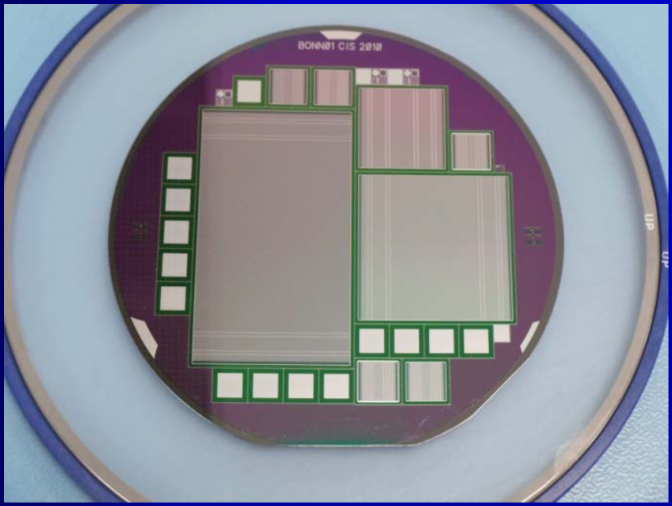
1060 nm laser test stand operational



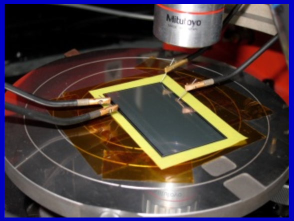


The P̄ANDA MVD Project

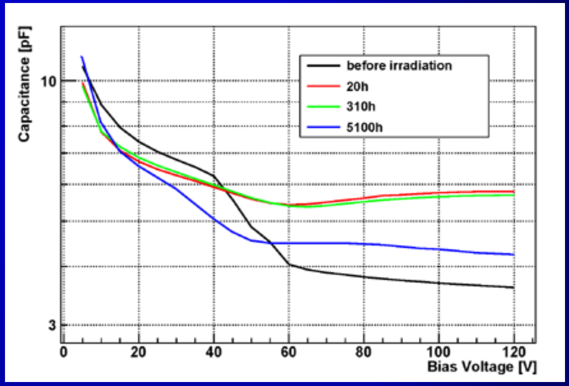
Hardware: double-sided Si strip sensors, P̄ANDA grade

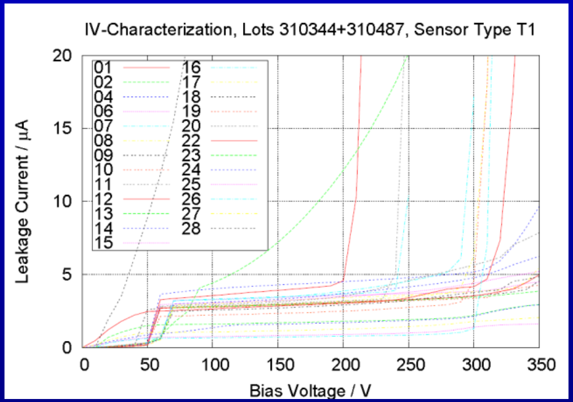


P̄ANDA wafer CiS Erfurt

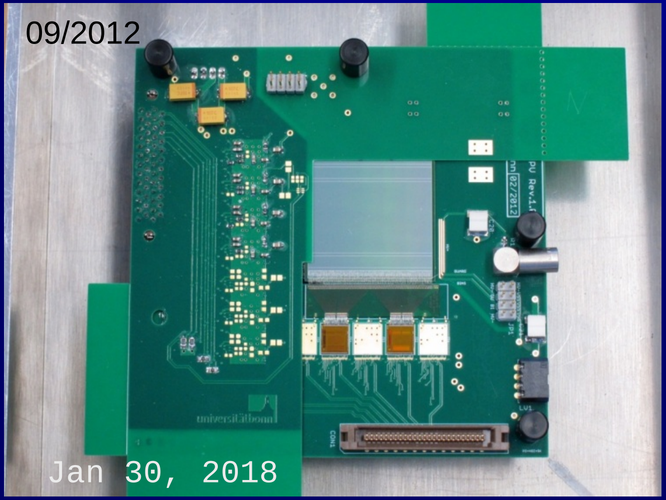


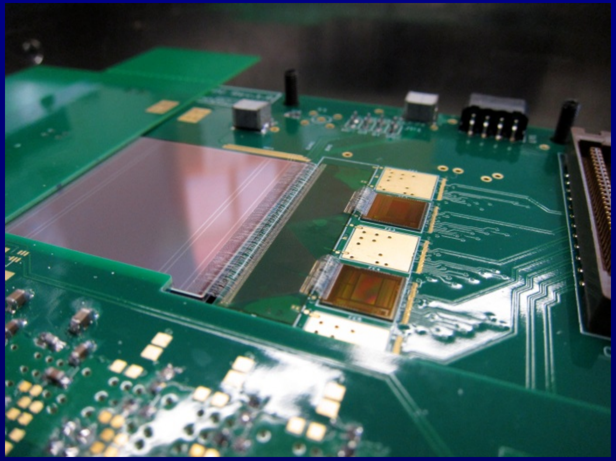
Radiation damage test

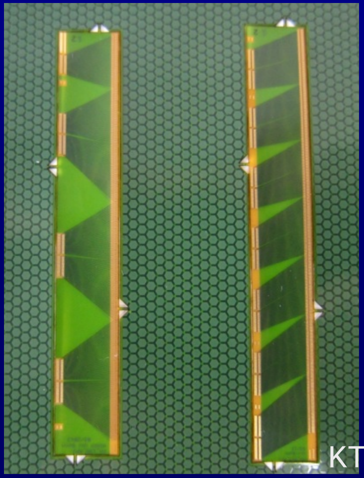




Probe station characterization







Flex PCB

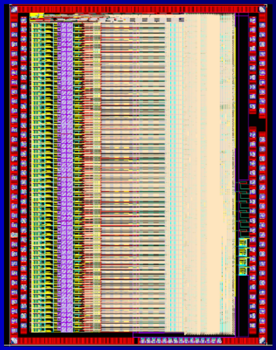
<25 µm Cu

30 µm solder resist,

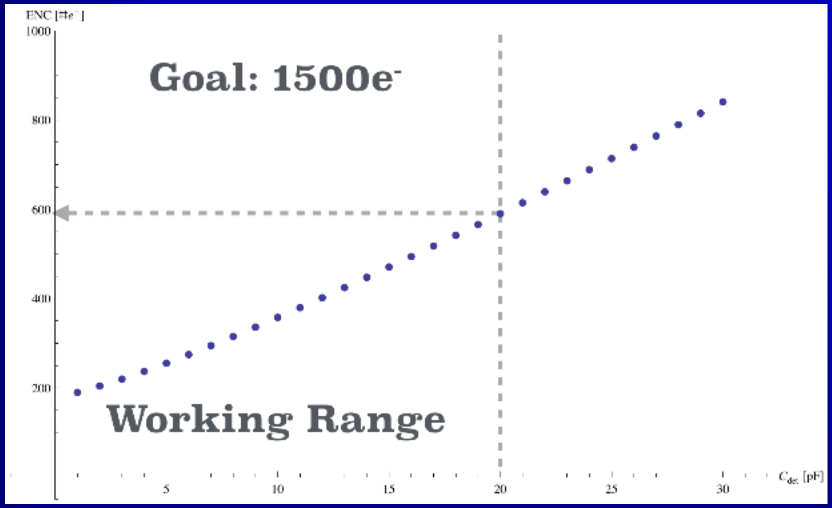
25 µm dielectric /carrier

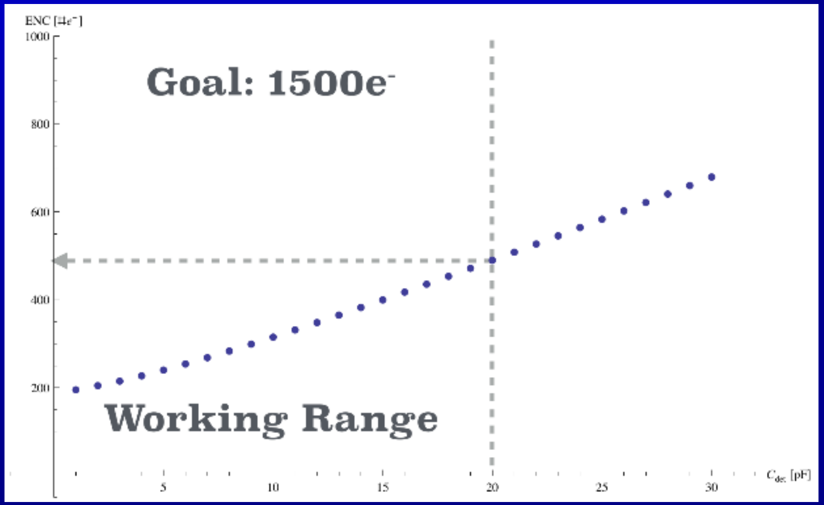
The P̄ANDA MVD Project

Hardware: development of a non-triggered Frontend readout chip (PASTA)



First prototype submitted to MPW run (04/2015)





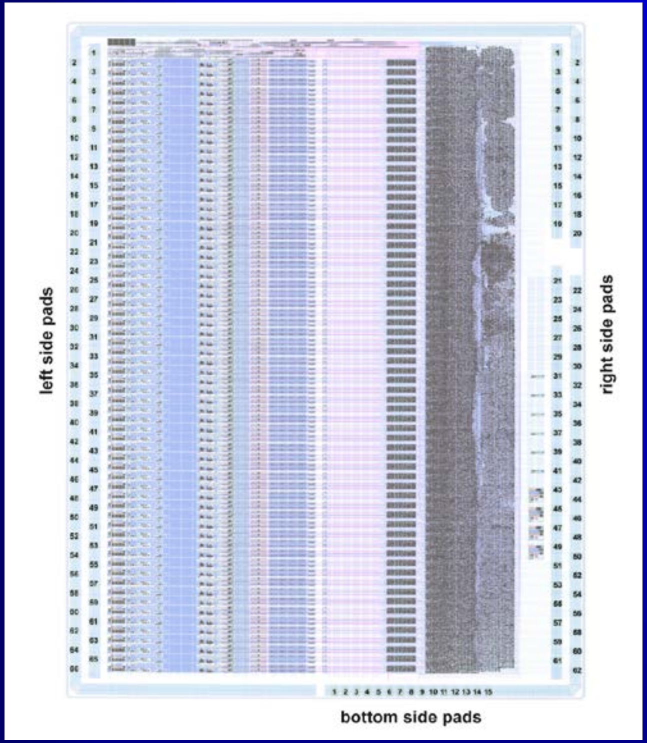
Features:

- 64 channels
- Time over threshold
- Small power consumption

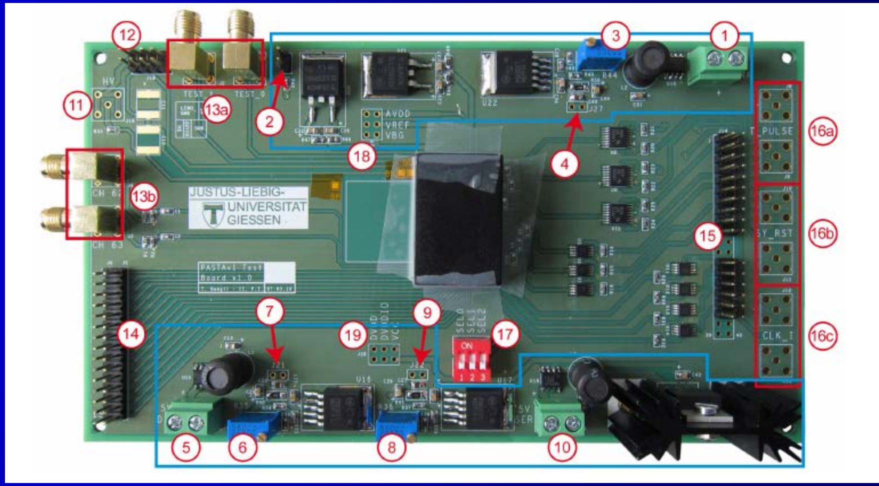
Delivery in Dec '15, tests ongoing
Re-submission envisaged
Final design planned in ~ 2 years
Module controller chip developed in parallel

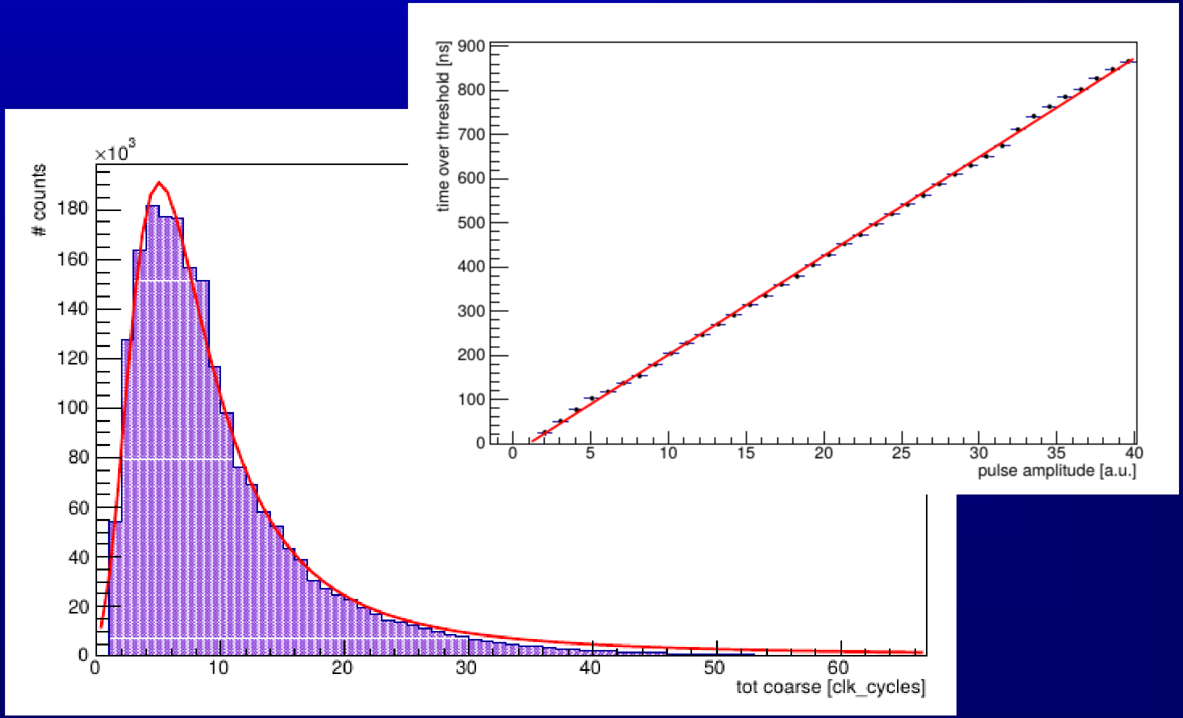
Torino, Gießen, Jülich, Iserlohn

PASTA



PASTA floorplan (4x6 mm²)



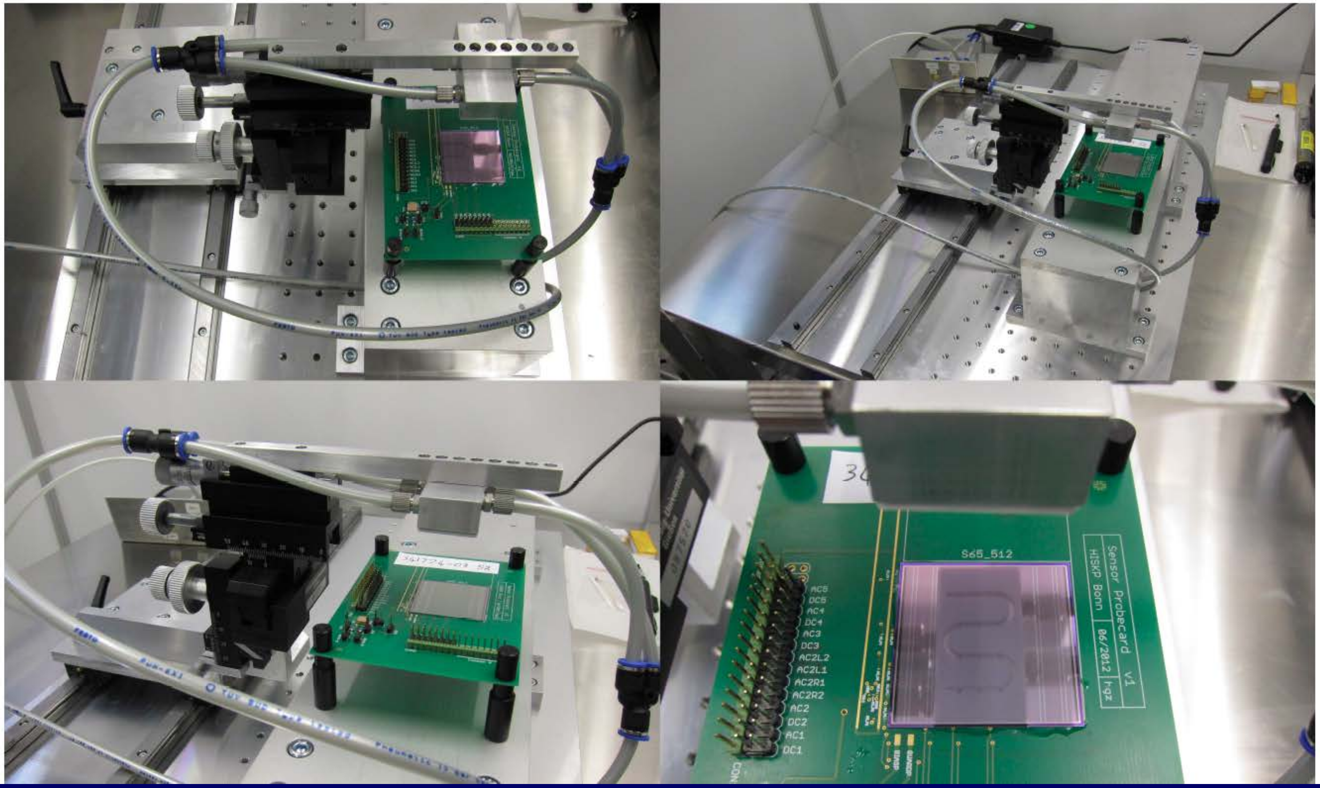


PASTA tests: Linearity and Time-over-Threshold response in beam on P̄ANDA strip sensor (pc = 800 MeV protons)

The $\overline{\mathrm{P}}$ANDA MVD Project

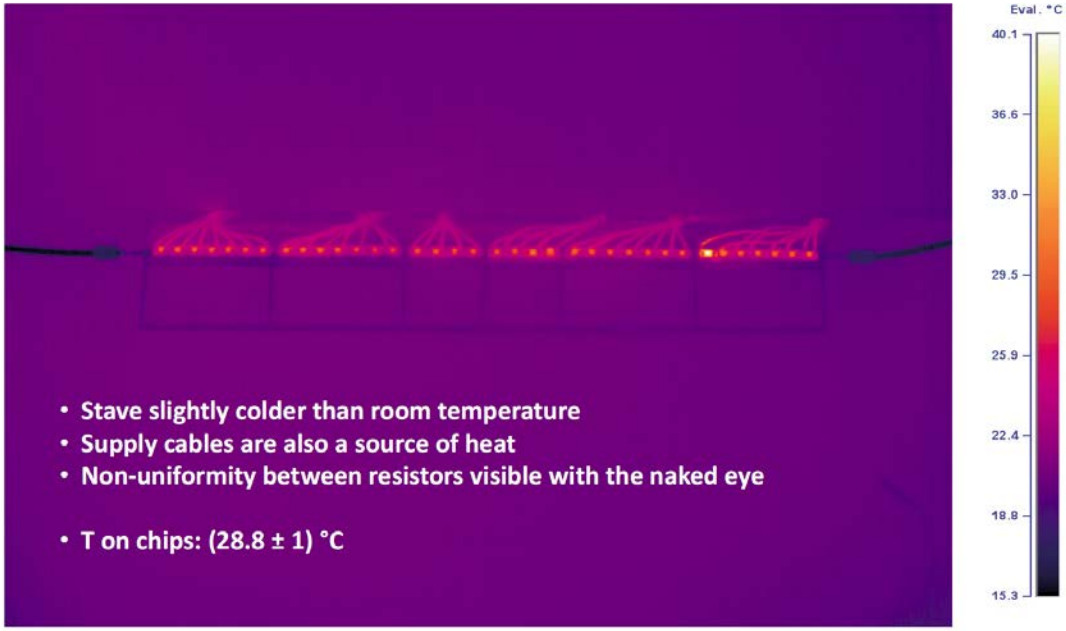
Manual stave assembly tool

- **3-axis manipulator mounted on rails**
- **Modular stave/board holder**
- **Vacuum operated sensor holder**



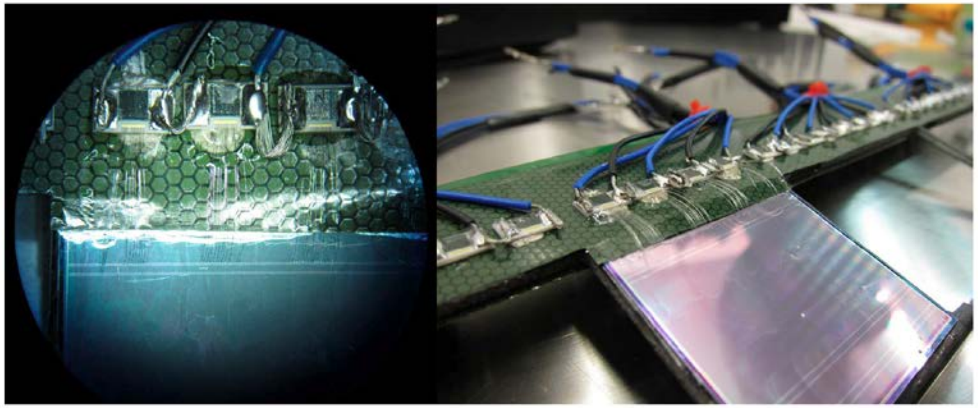
The P̄ANDA MVD Project

Cooling test

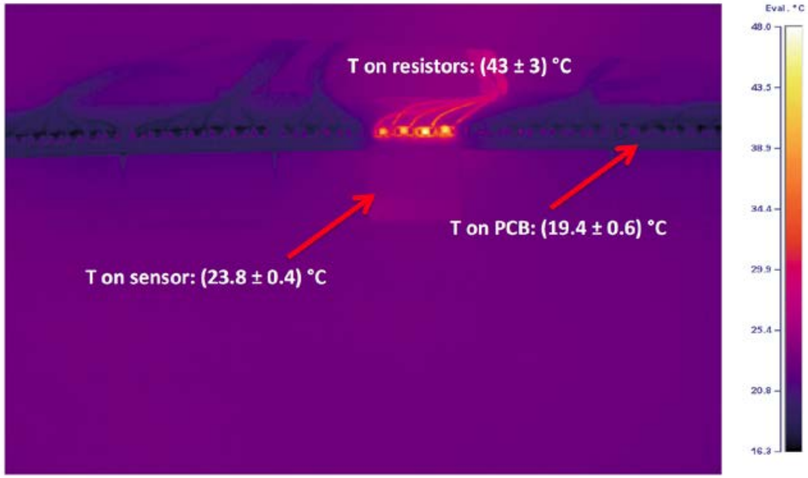


Test stave

4. Wire bonding (on p-side only) between resistors and sensor



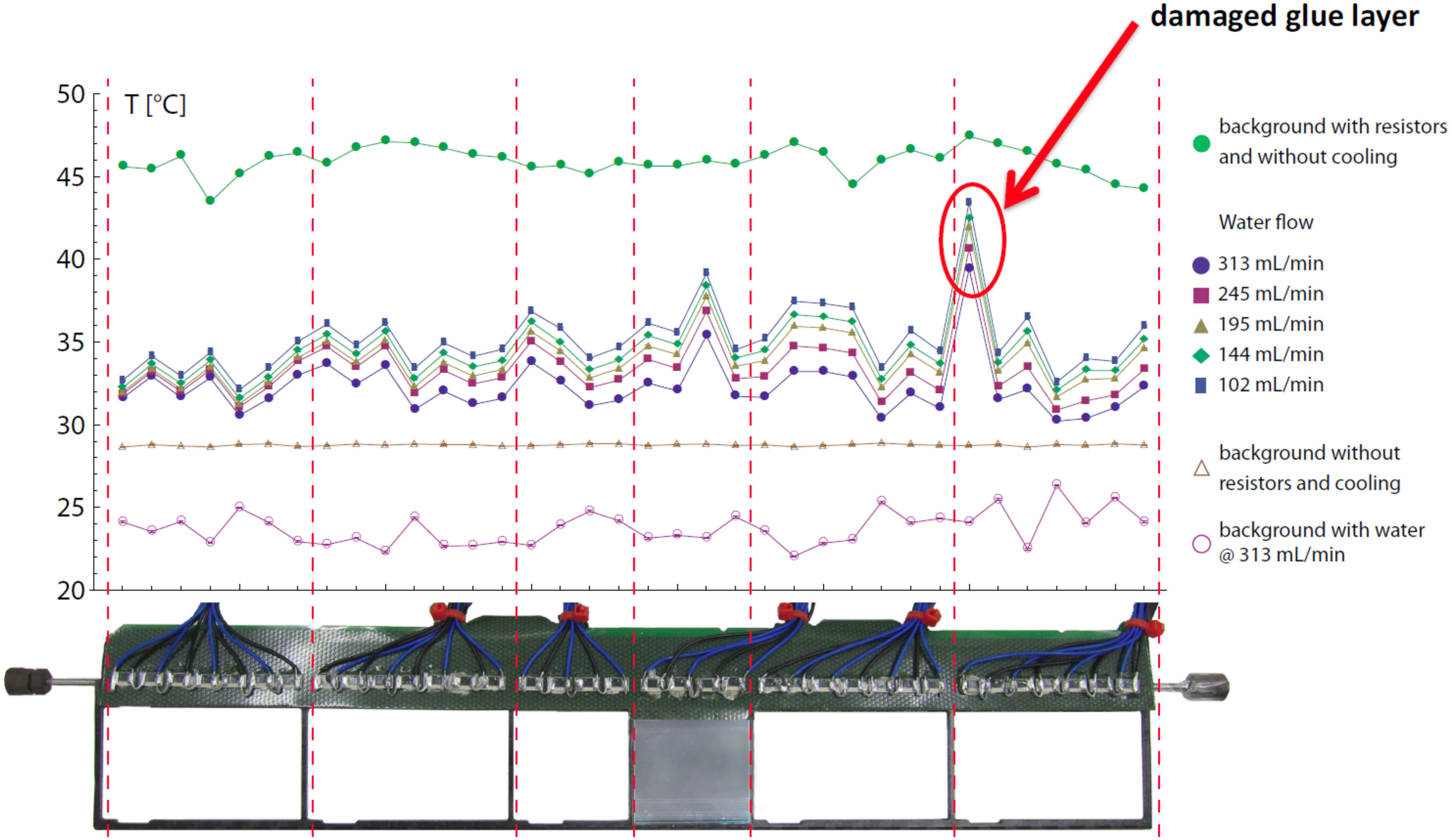
Additional test with double power (512 mW per chip), only on 9 resistors around the sensor



The P̄ANDA MVD Project

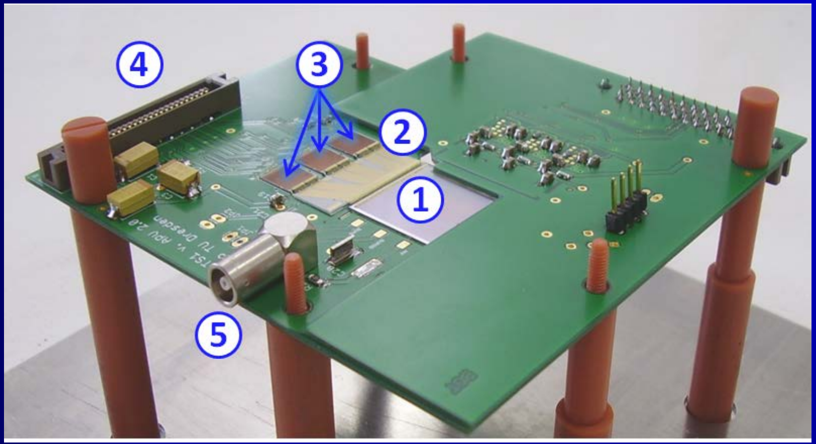
Cooling tests – Stave profile

Temperature profile with heating at nominal power (16.9 W); cooling water @ 20°C, different fluxes. Room temperature 28.5 °C



The P̄ANDA MVD Project

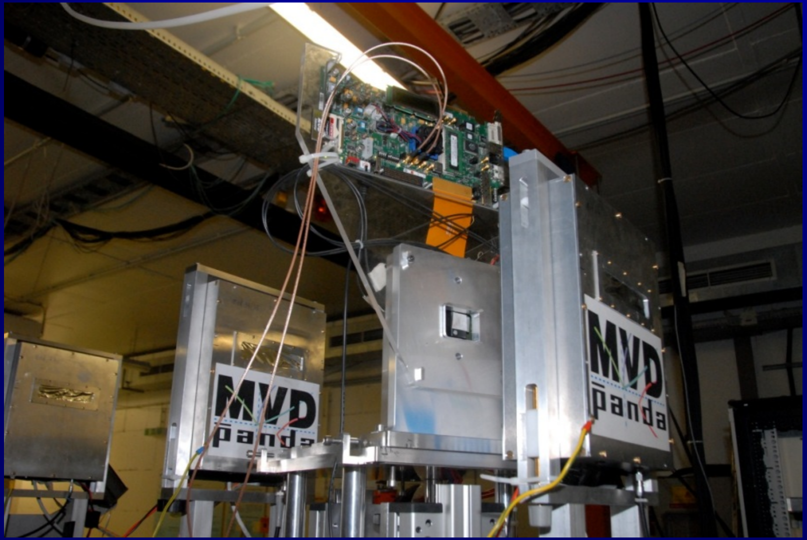
Hardware

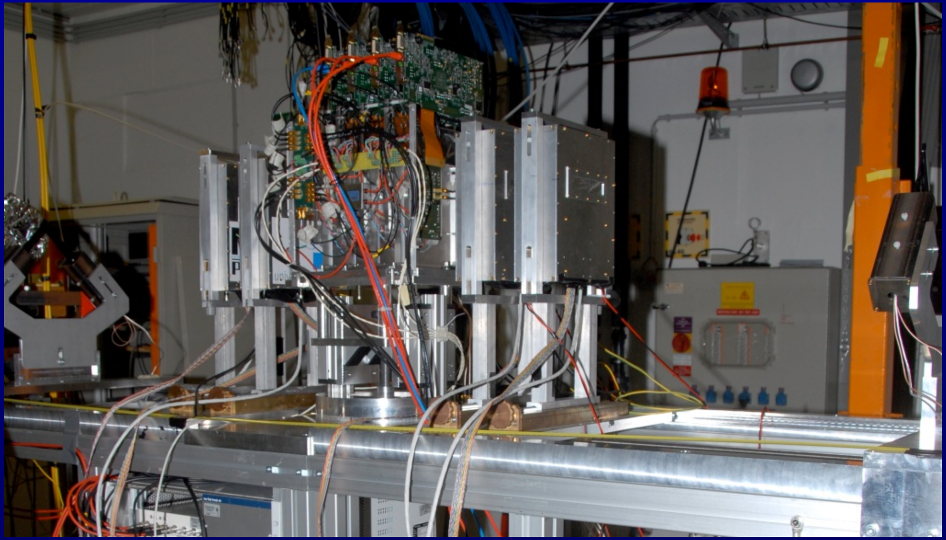


Tracking station:

Si strip sensors, 4 layers

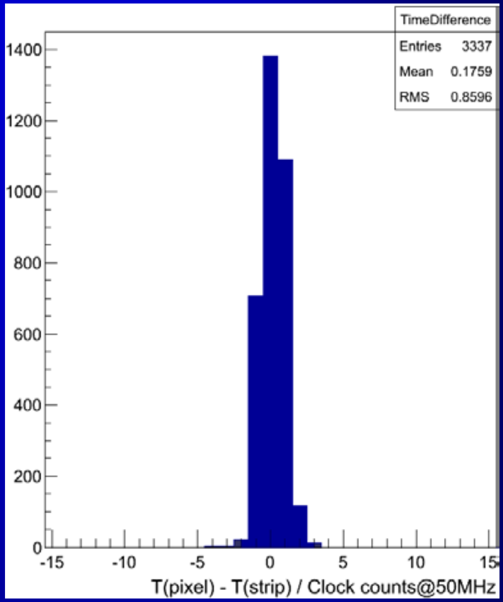
- Handling
- Sensor tests
- Tracking development (soft/hard)
- Infrastructure





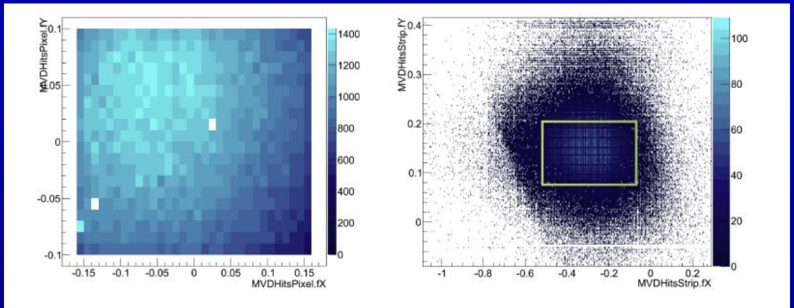
The $\bar{\text{P}}$ANDA MVD Project

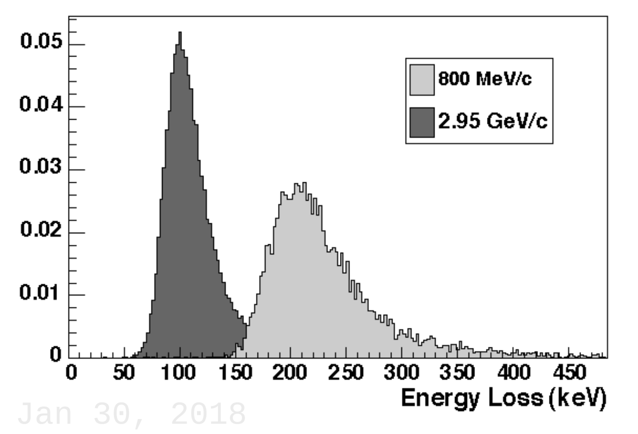
Measurements



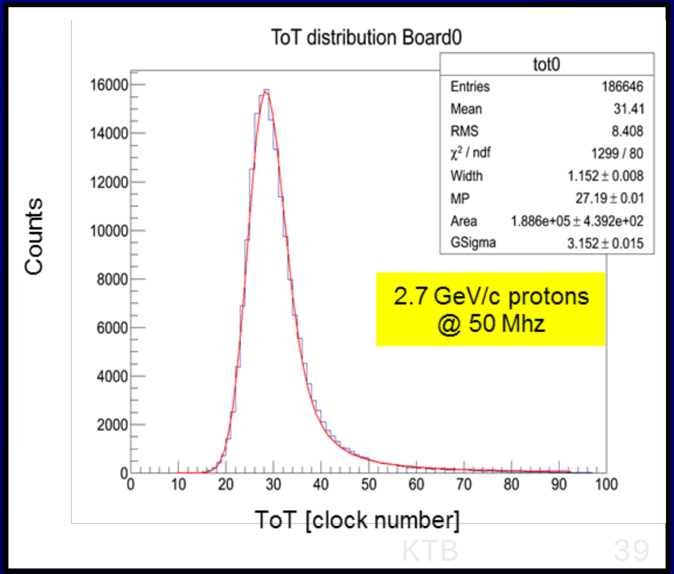
CERN, COSY, DESY, ELSA:

- Pixel tracking station – triggerless readout
- Synchronisation with the strip telescope @50 MHz
- 10 GeV/c pions, pixel + strips: residuals $\sigma_{x,y}$ = 18 µm



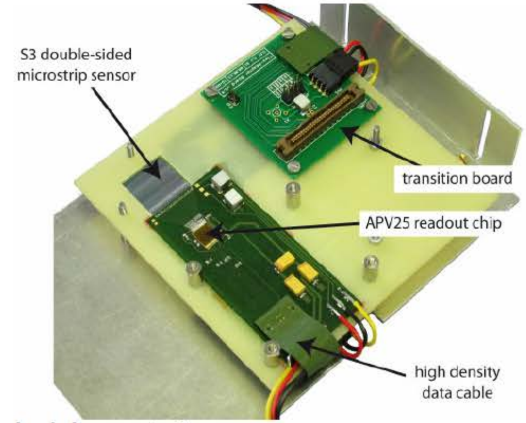


p, Si strips
APV S25



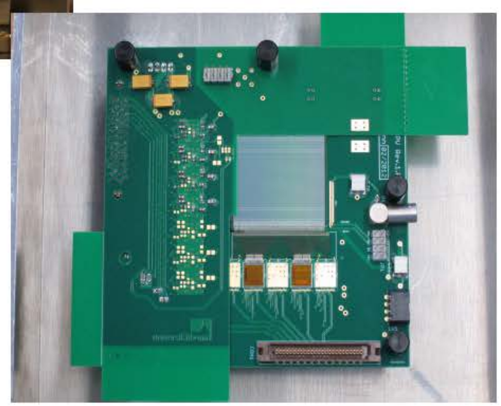
p, ToPix
pixel array

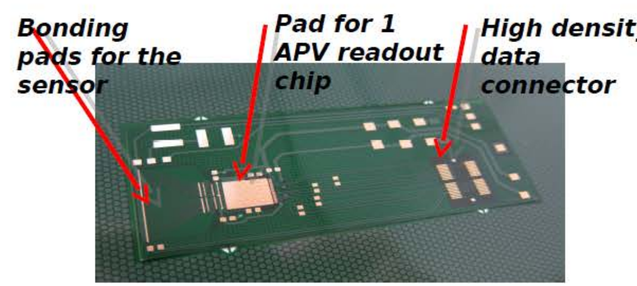
Prototypes



1st sensor-flex hybrid prototype

Full-size trapezoidal sensor module (fw disc strips)



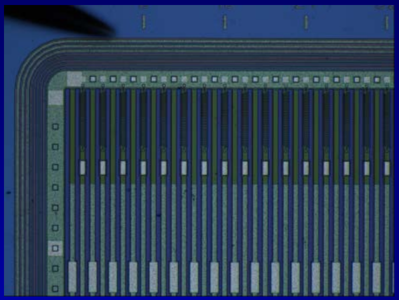


Full-size rectangular sensor module (barrel strips)

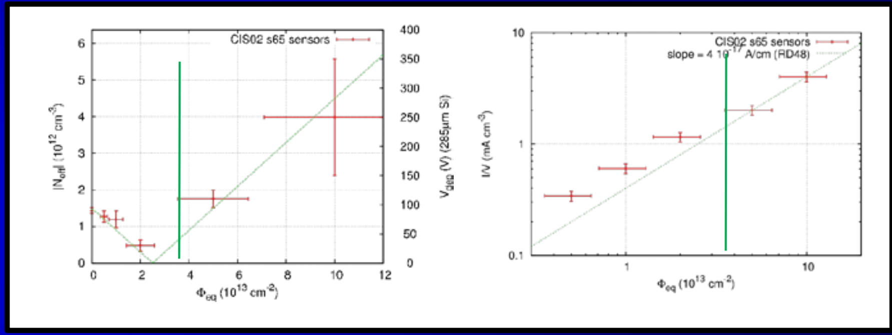
P̄ANDA MVD

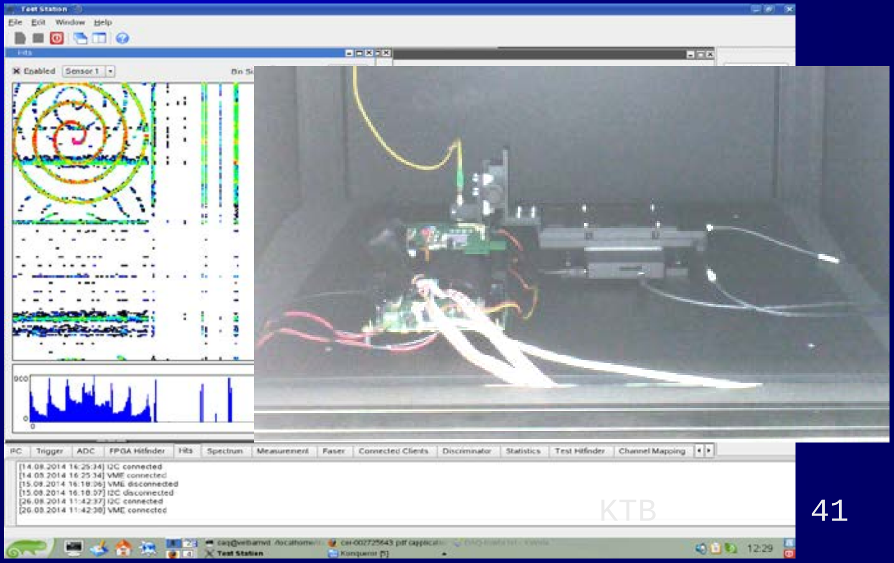
- Detector layout frozen
- Rad hardness verified
- Wafer selection finished

  ~50% of sensors for barrel ordered
- Laser probing operational
- PASTA design advanced, v.1 tests ongoing
- ThinFlex, mounting components available
- More beam tests
- Beam telescope infrastructure

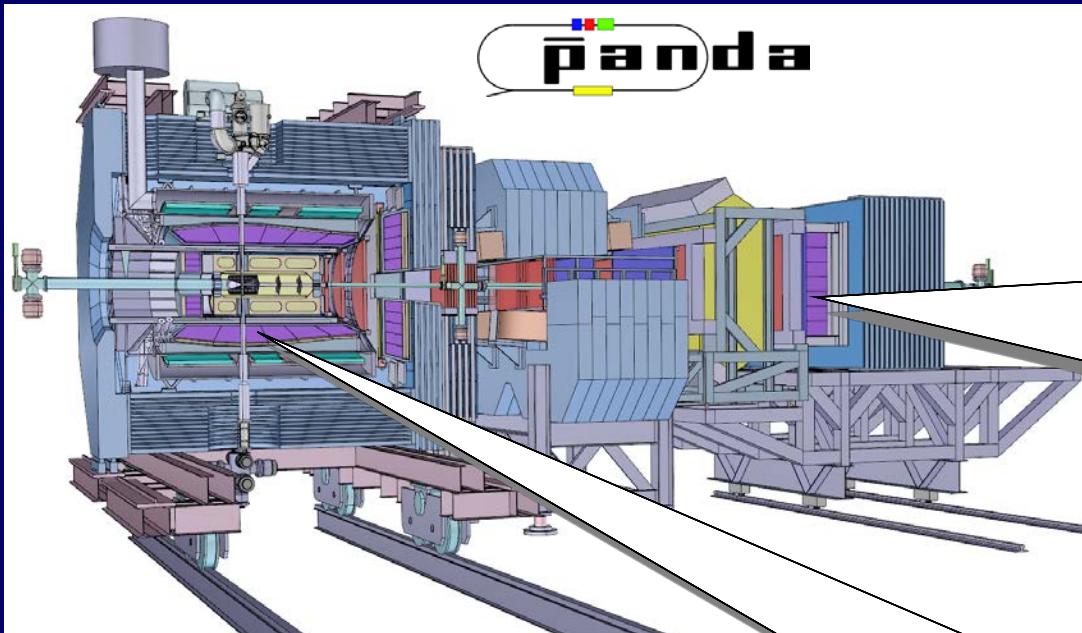


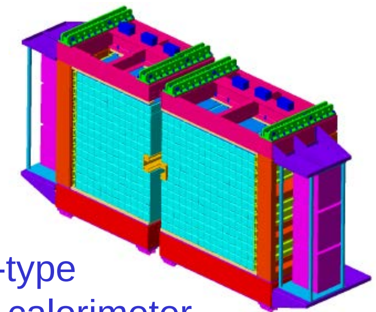
Poly-silicon biasing

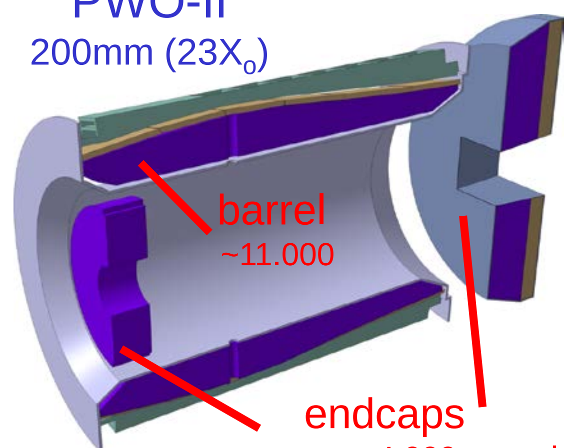




e.m. calorimetry: *e*, γ

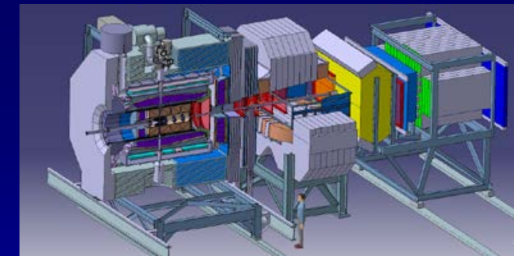






Target Spectrometer @ $\bar{\text{P}}$ANDA:

based on high-quality PWO-II



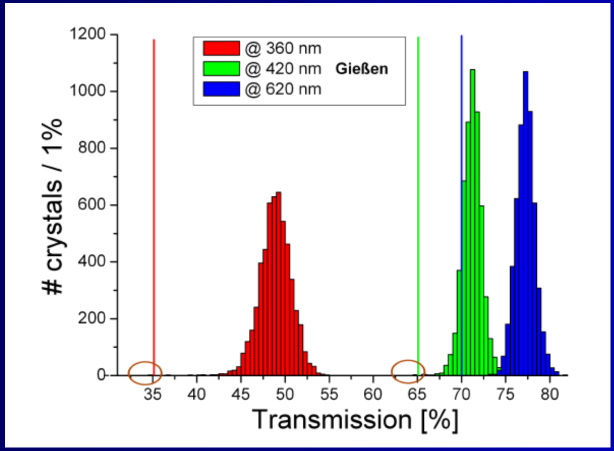
- physical goals of PANDA require further development

	PWO-I (CMS)	PWO-II (PANDA)
luminescence maximum, nm	420	420
La, Y concentration level, ppm	100	40
expected energy range of EMC	150MeV - 1TeV	10MeV - 10GeV
light yield, phe/MeV at room temperature	8-12	17-22
EMC operating temperature, °C	+18	-25
energy resolution of EMC at 1GeV, %	3,4	2,0

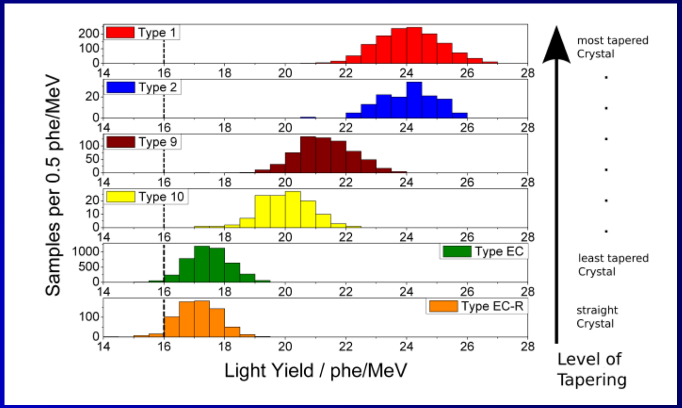
Contributions to the $\bar{\text{P}}$ANDA - EMC

In-house:

- Quality control of PWO-II crystals from BTCP
- R&D on PWO crystals from SICCAS



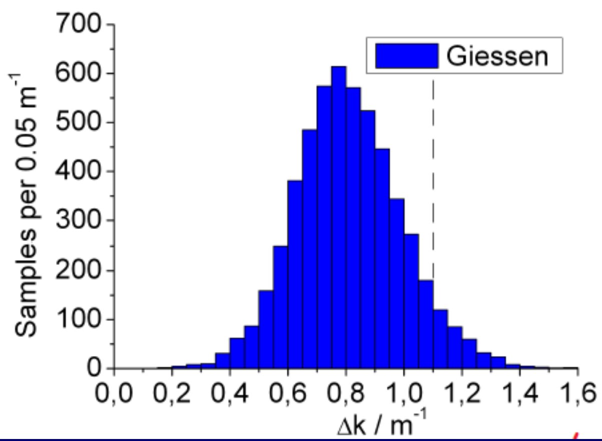
Optical transmission



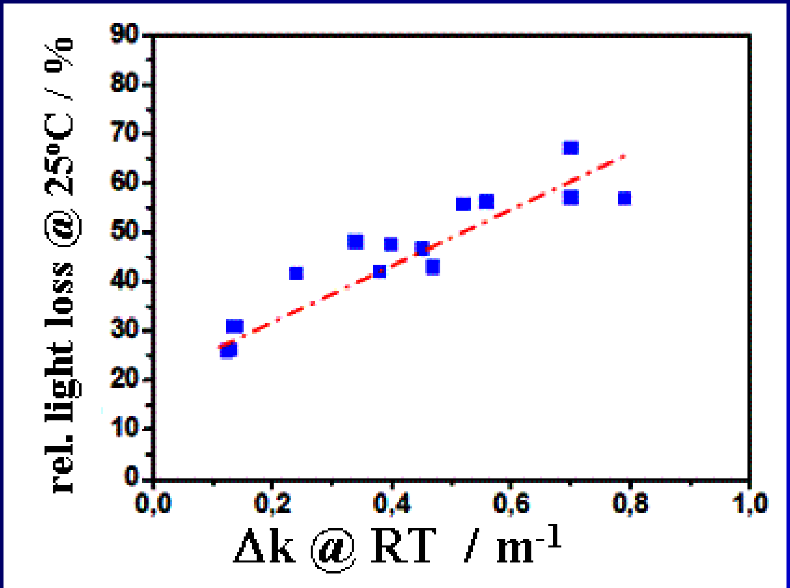
Light yield @RT

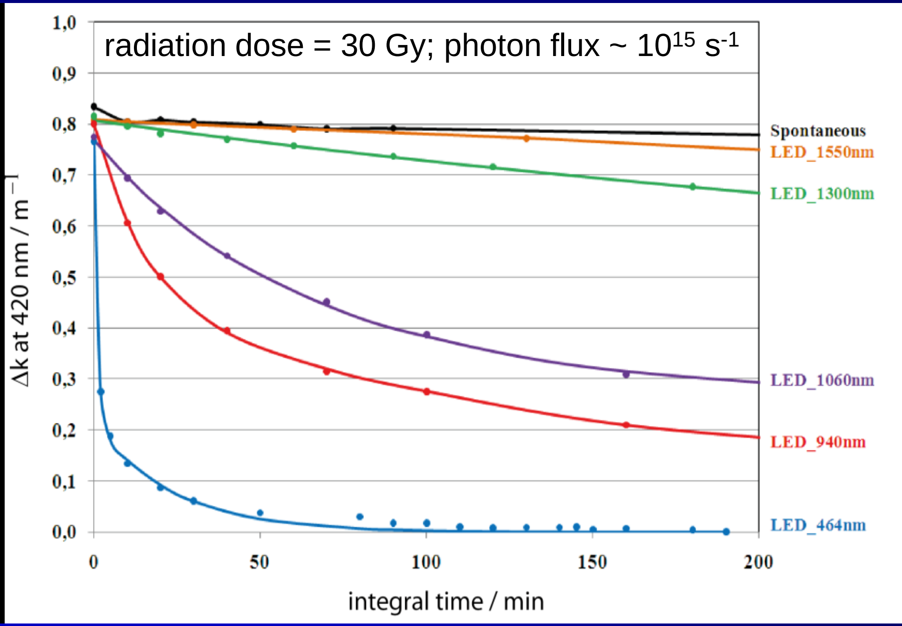
Radiation hardness

- $T = \exp(-k \cdot x)$ with $x = 20\text{cm}$
- $\Delta k = k_{\text{after irr.}} - k_{\text{before irr.}}$
- irradiation with an integral dose of 30Gy (^{60}Co source)

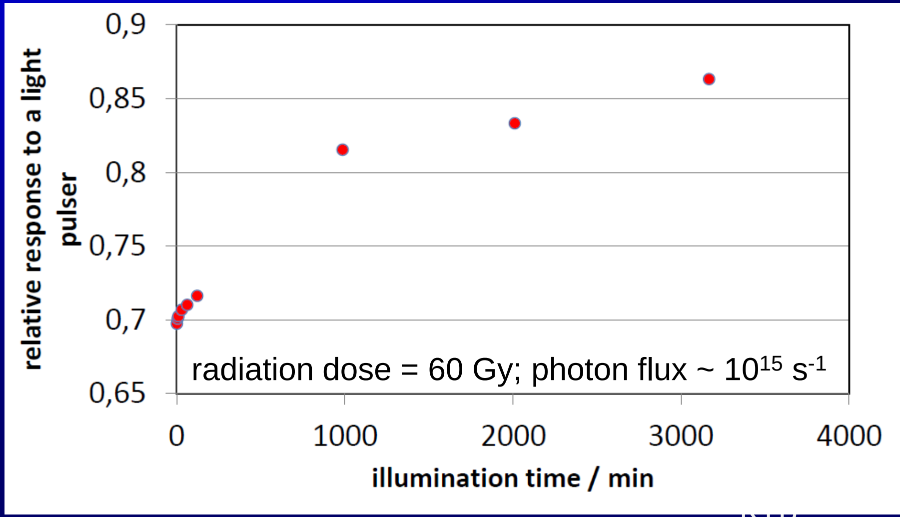


P̄ANDA EMC: Stimulated Recovery of Rad Damage





$$\Delta k = ln\left(\frac{T_{before}}{T_{after}}\right) \cdot \frac{1}{d}$$

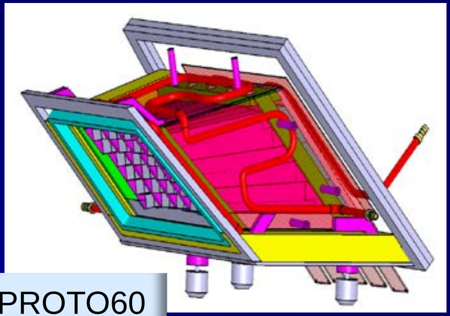


Stimulated recovery with
830 nm laser light at -25°C

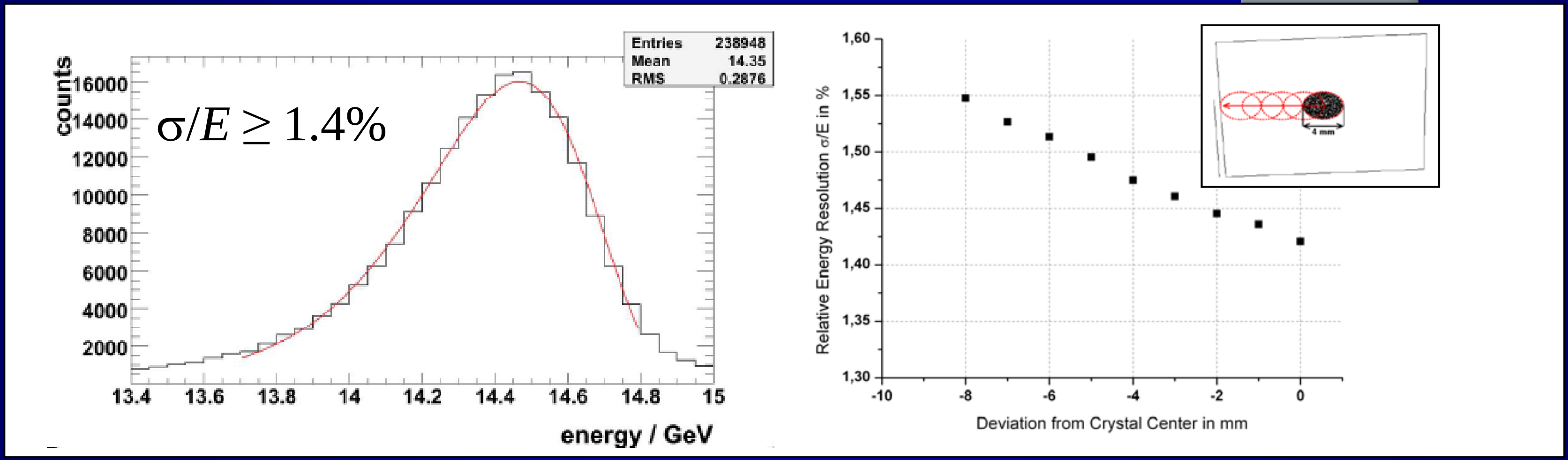
P̄ANDA - EMC

Prototype experiments:

- Response of PROTO60 to 15 GeV positrons @ CERN

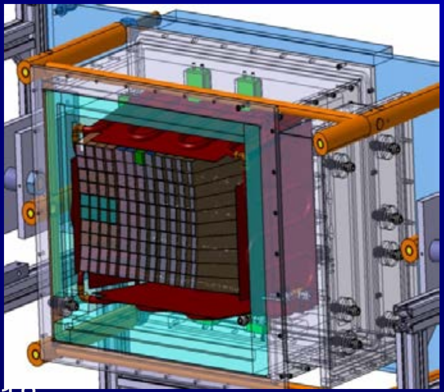


PROTO60



$\sigma(x,y)$~1mm

- Development of new prototype PROTO120

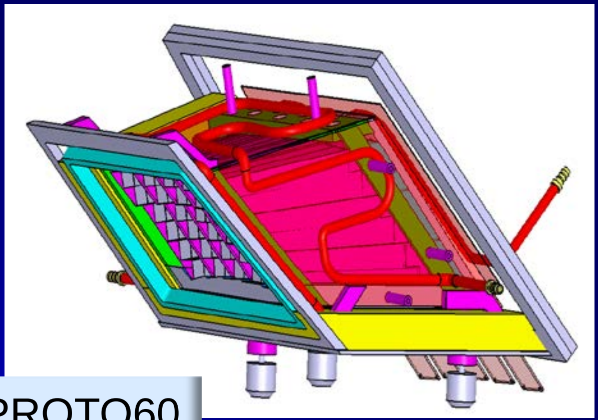


- 120 PWO crystals
- read-out with 2 LAAPDs
- APFEL 1.4 as PA
- individual carbon fiber alveolae
- implementation of final SADCs

P̄ANDA - EMC

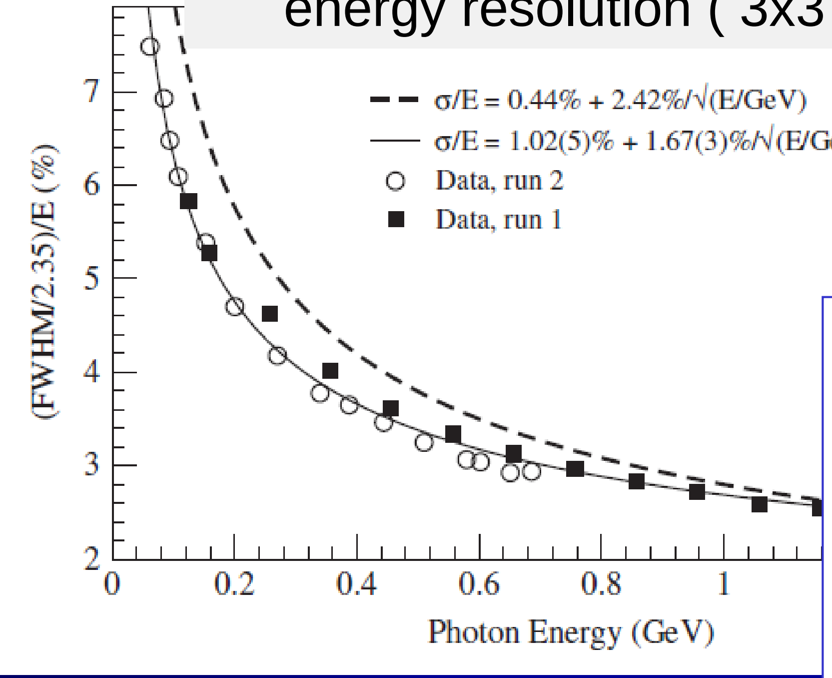
Prototype experiments:

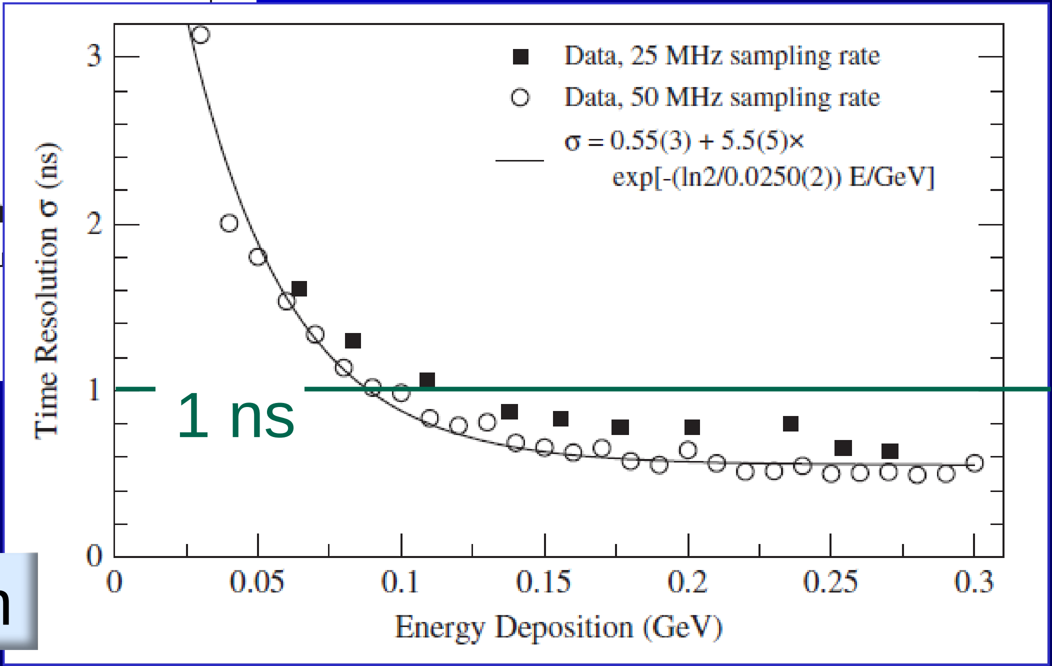
- Response of PROTO60 to photons



PROTO60

energy resolution (3x3 matrix)





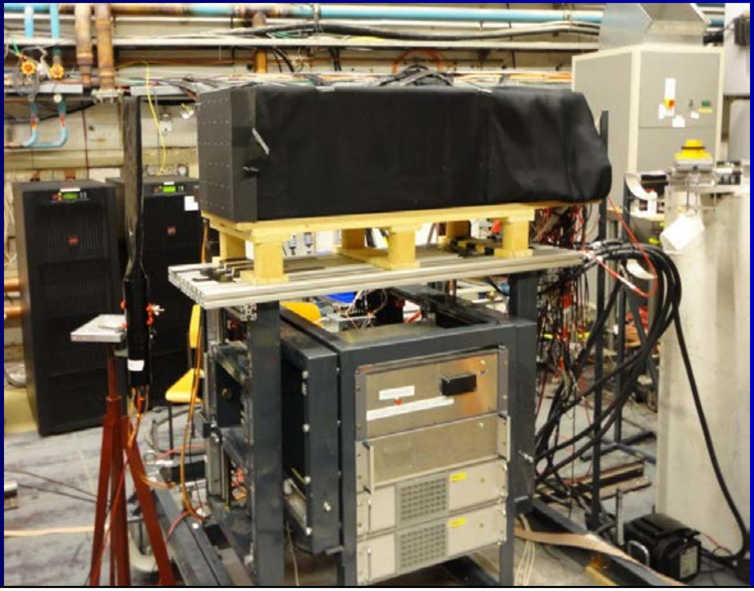
time resolution

P̄ANDA Forward EMC

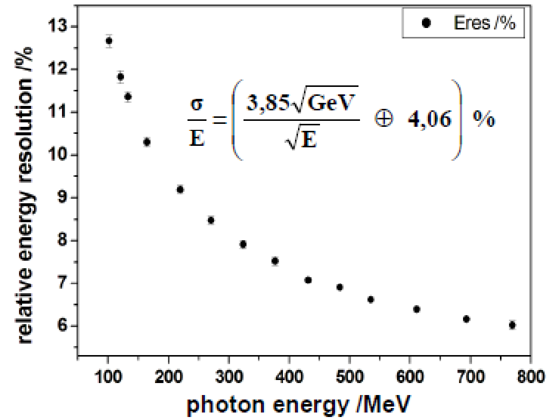
Prototype experiments:

test @ A2-MAMI

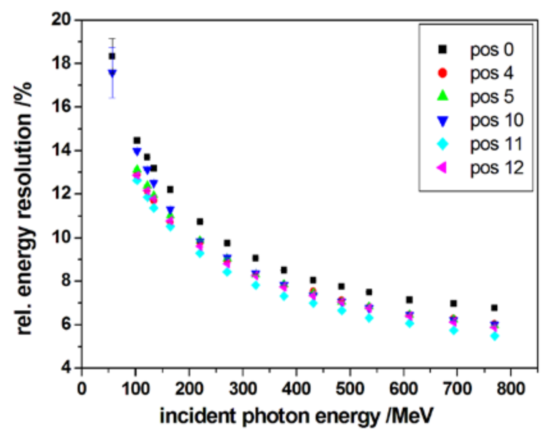
Tagged photons

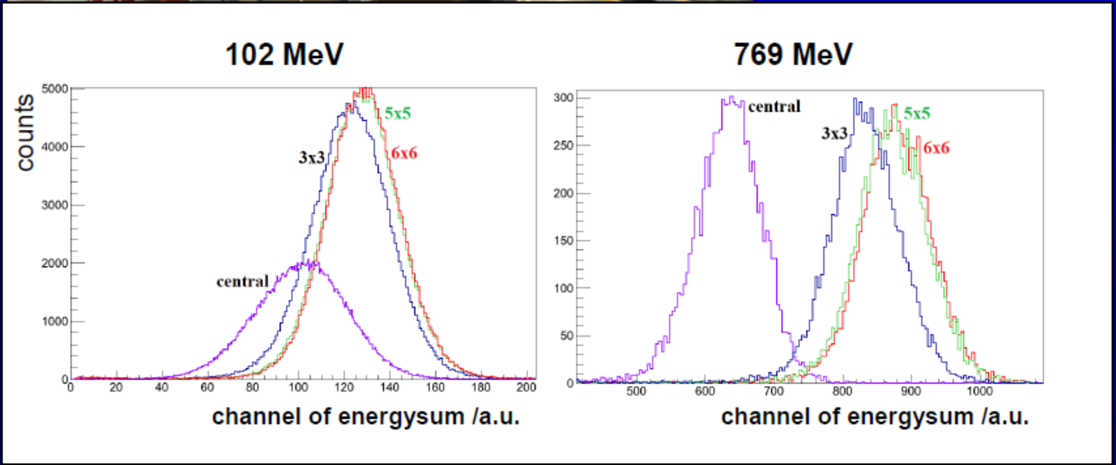


- ✓ time resolution: ~ 100ps/√E
- ✓ position resolution: ~ 1 cm
- ✗ E_{reco} = ***f***(impact position)

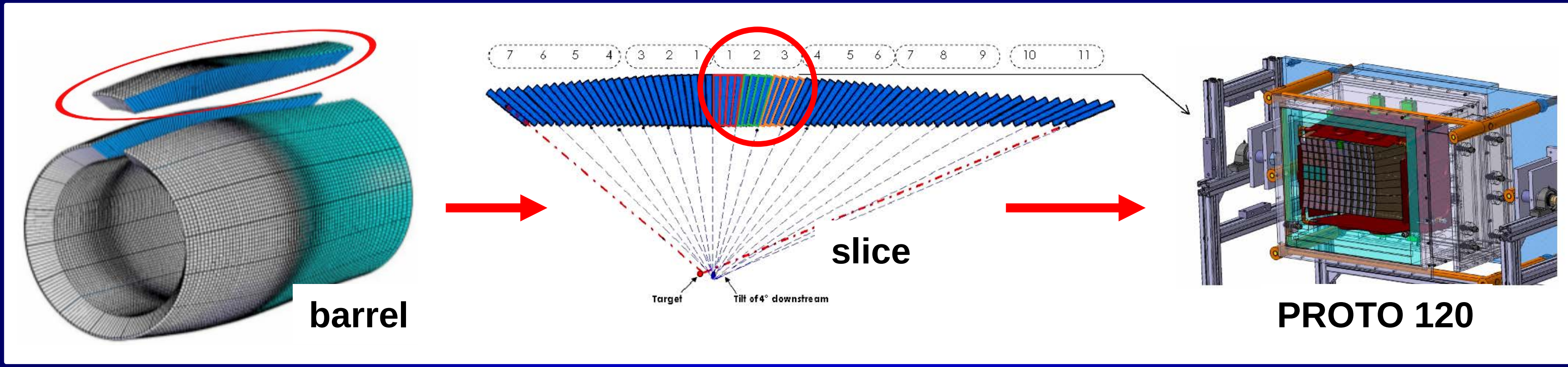


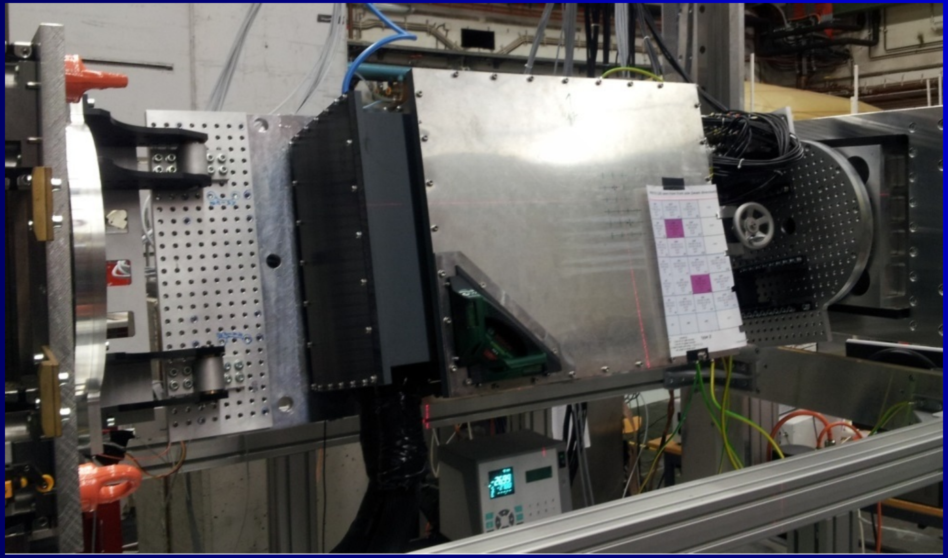
12,8 % @ 100 MeV
5,6 % @ 1 GeV





P̄ANDA PROTO 120 – Close-to-Final Prototype

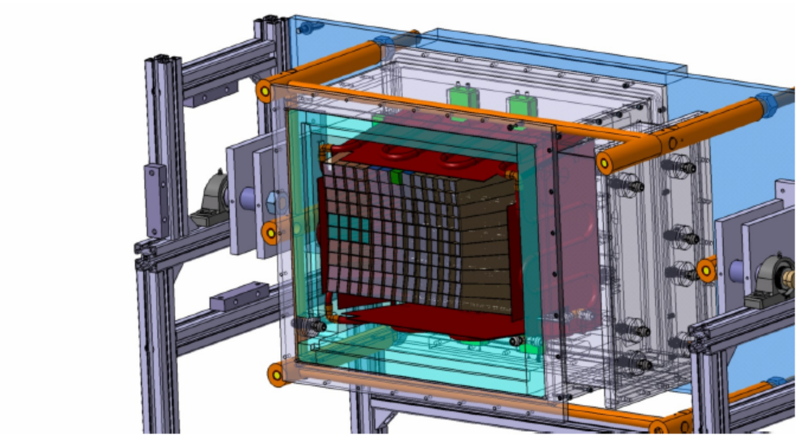


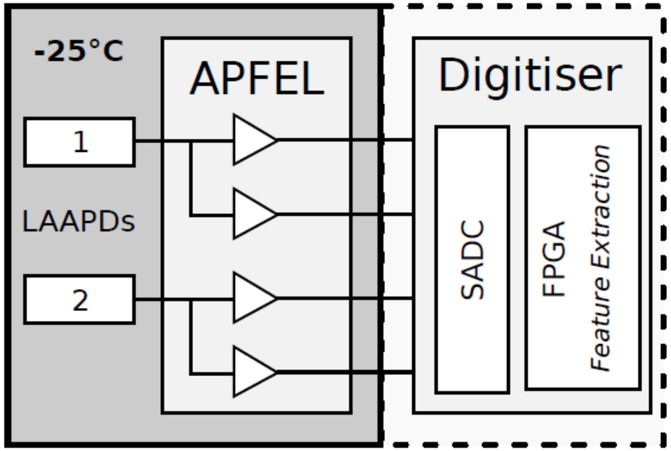


PROTO 120:

- close to final barrel design
- 120 $PbWO_4$ crystals
- operated @ -25°C
- readout with 2 LAAPDs
- APFEL ASIC v 1.5

P̄ANDA PROTO 120 – Close-to-Final Prototype



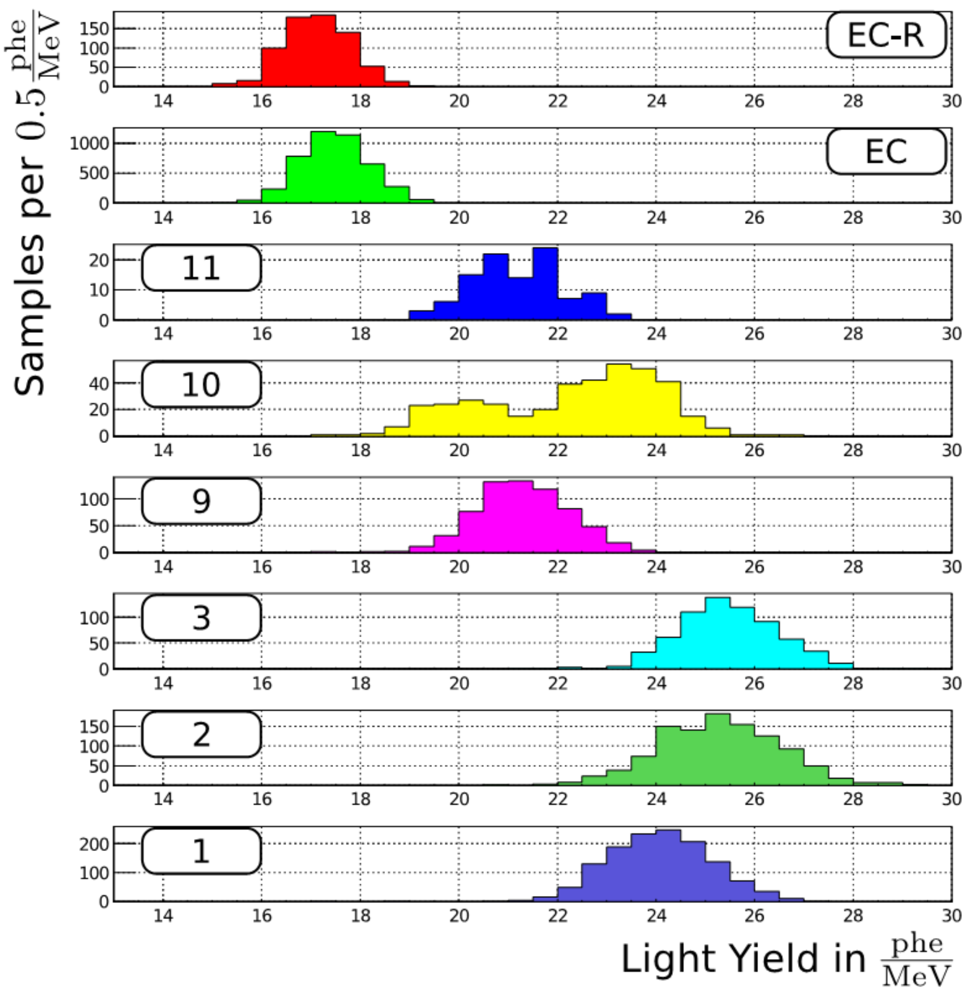


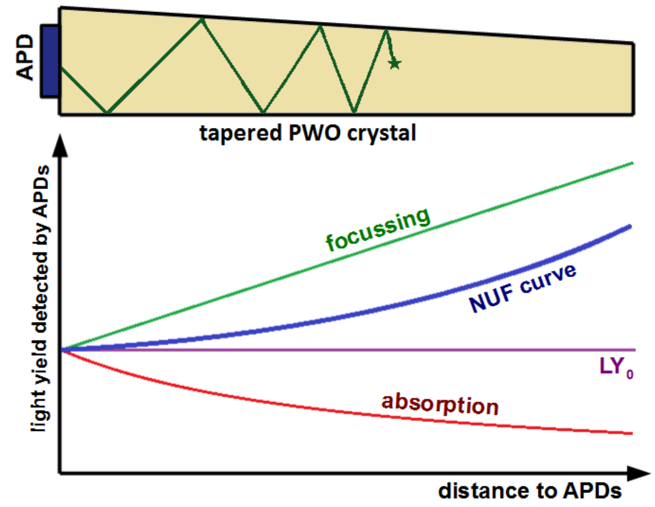
PROTO120

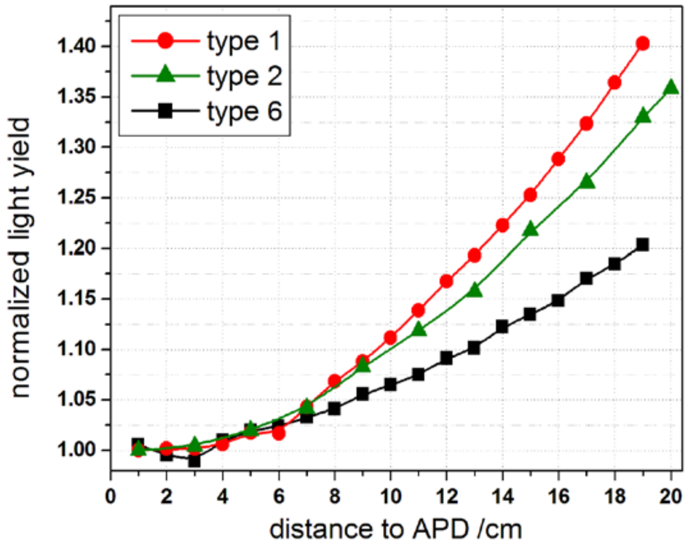
- 120 PWO crystals of type 1, 2 and 3
- 2 LAAPDs per crystal
- APFEL readout 1.4 with final dynamic range (dynamic range of 10000 and programmable amplification 16/32)
- close to final mechanics
- new x-y-z table

P̄ANDA PROTO 120 – Close-to-Final Prototype

Quality control:

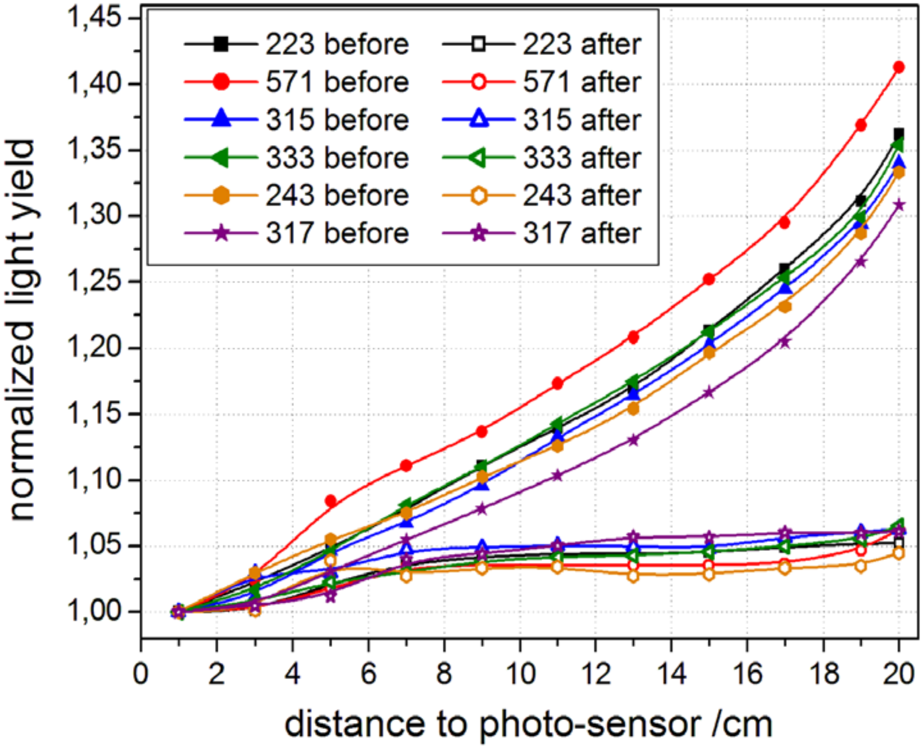






P̄ANDA PROTO 120 – Close-to-Final Prototype

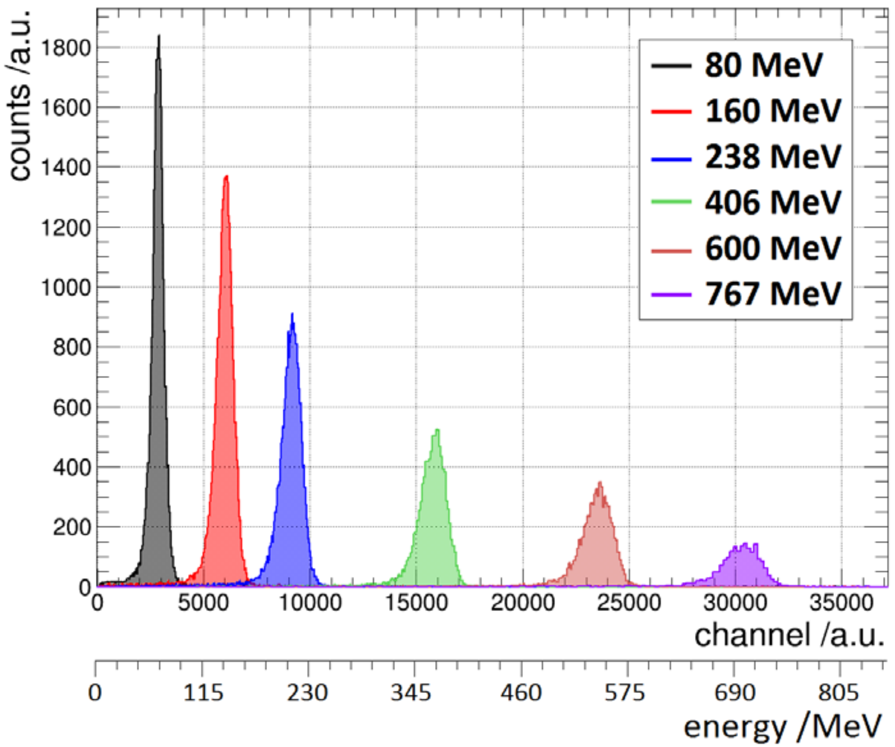
- NUF in light collection deteriorates the energy resolution
- Several concepts for a uniformization have been investigated
- De-polishing of one lateral side face (R_a = 0.3 µm) provides the best results (already investigated for the CMS ECAL)



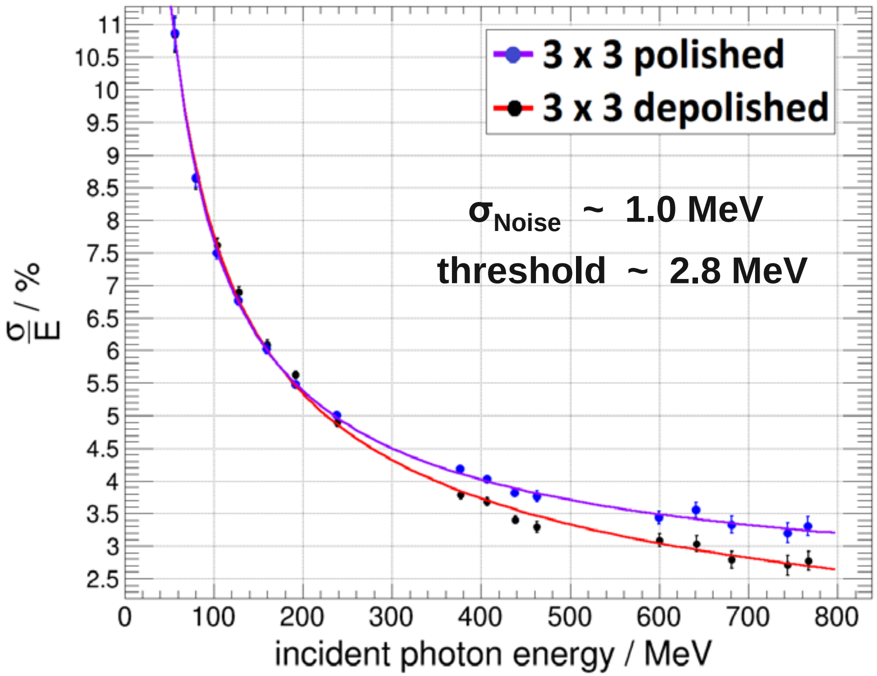
P̄ANDA PROTO 120 – Close-to-Final Prototype

- Tagged photons: 55 MeV < E_γ < 767 MeV
- 3x3 array of polished and de-polished crystals

energy response:



energy resolution:



$$\frac{\sigma}{E}_{polished} = \frac{0.34}{E} \oplus \frac{2.07}{\sqrt{E}} \oplus 2.18$$

$$\frac{\sigma}{E}_{depolished} = \frac{0.27}{E} \oplus \frac{2.30}{\sqrt{E}} \oplus 0.50$$

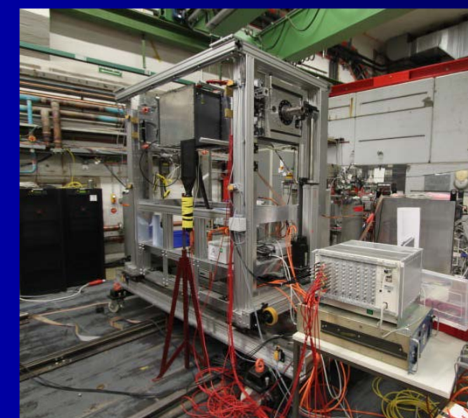
P̄ANDA EMC

- Prototyping of stimulated recovery of PWO crystals

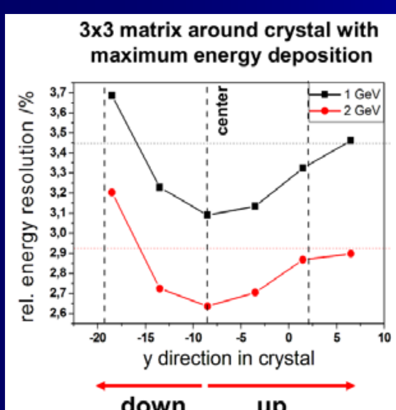
  => standard procedure
- Hadron rad damage studies
- Light-yield uniformity studies
- Rad hardness of laAPDs

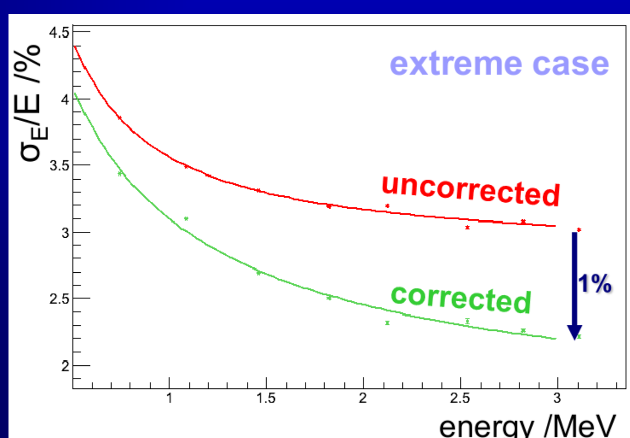
  => standard procedure under development
- Barrel prototype PROTO 120, many procedures and components standardized
- Proto analysis

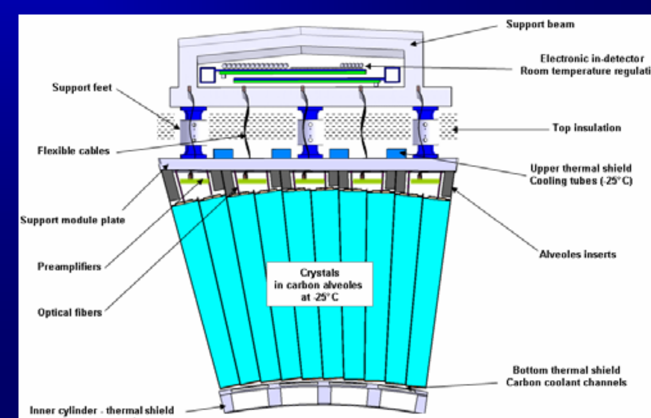
Co-60 irradiation, JLU



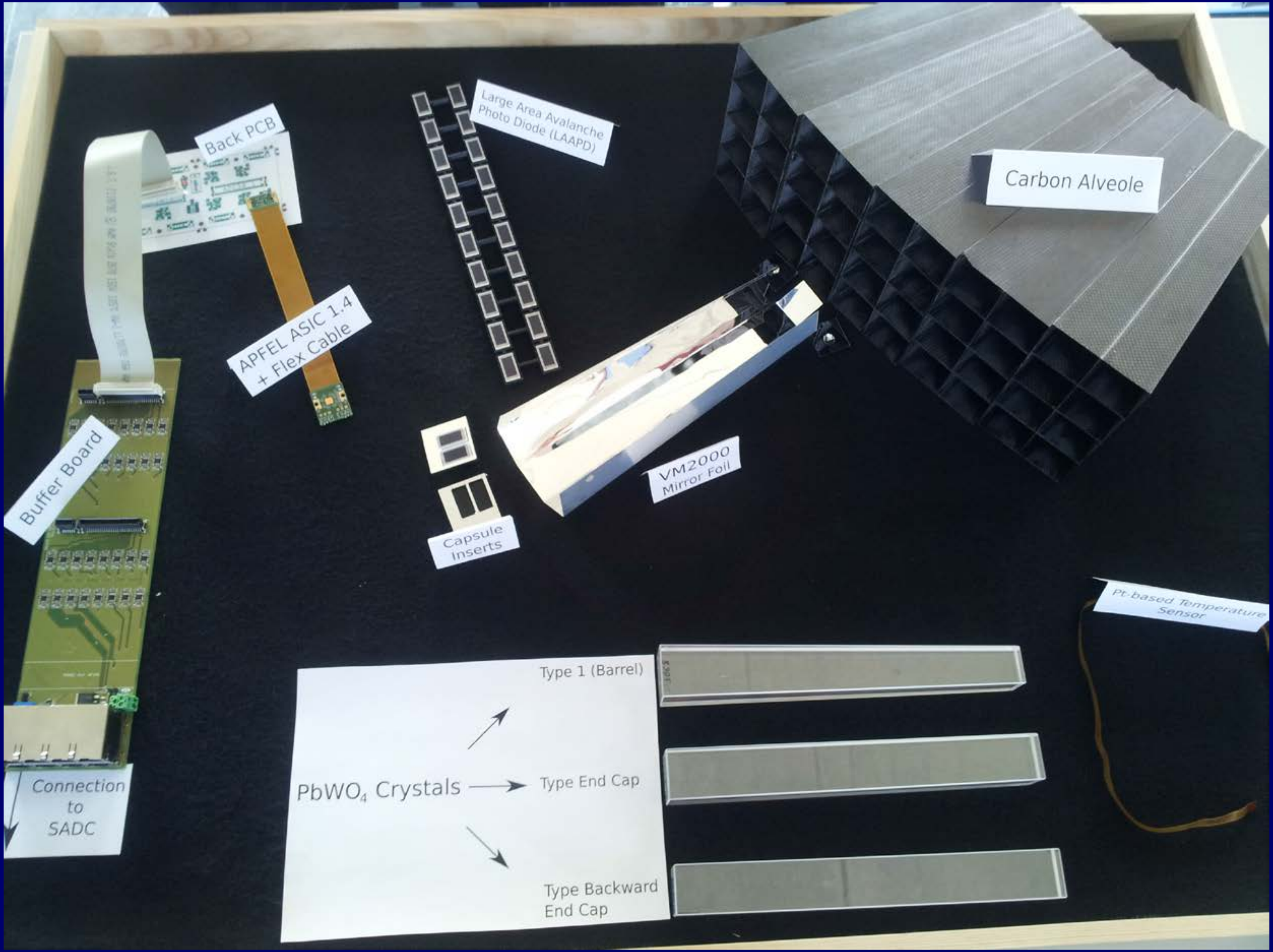
PROTO120@MAMI



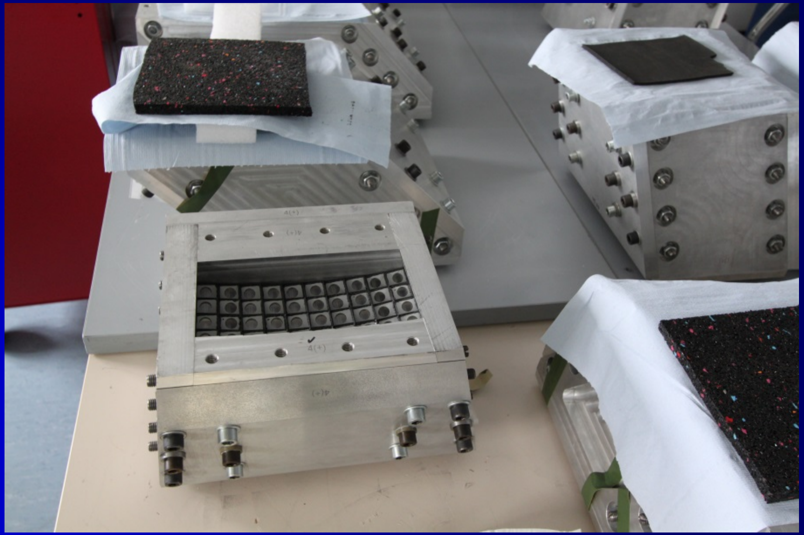


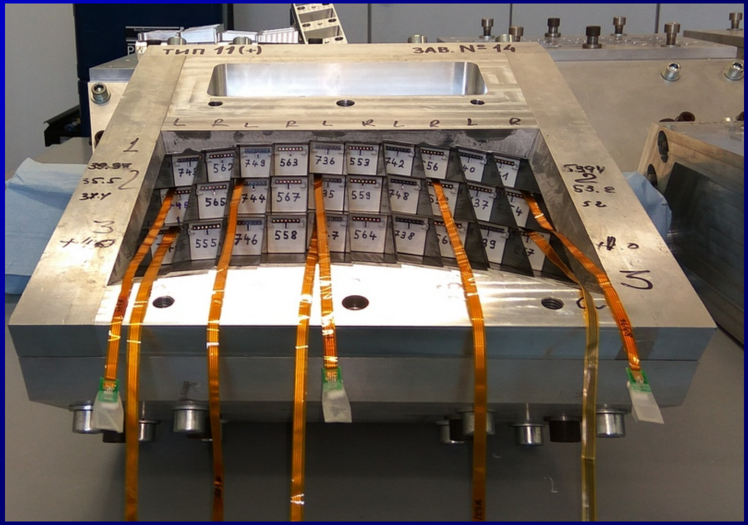


Next Step: $\bar{P}$ANDA Barrel Slice

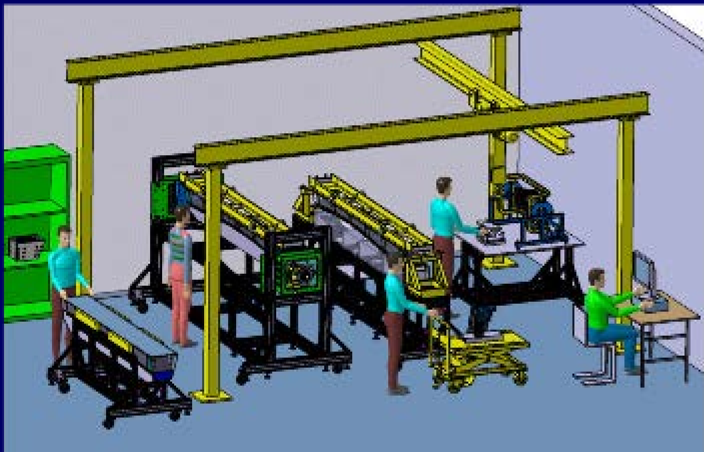


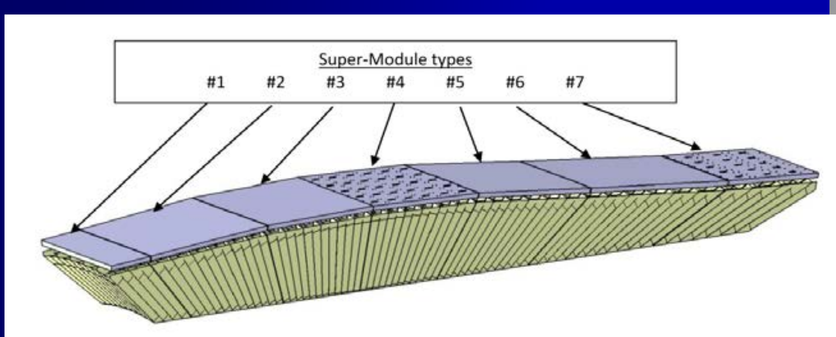
$\bar{\mathrm{P}}$ANDA Barrel Slice Module Assembly



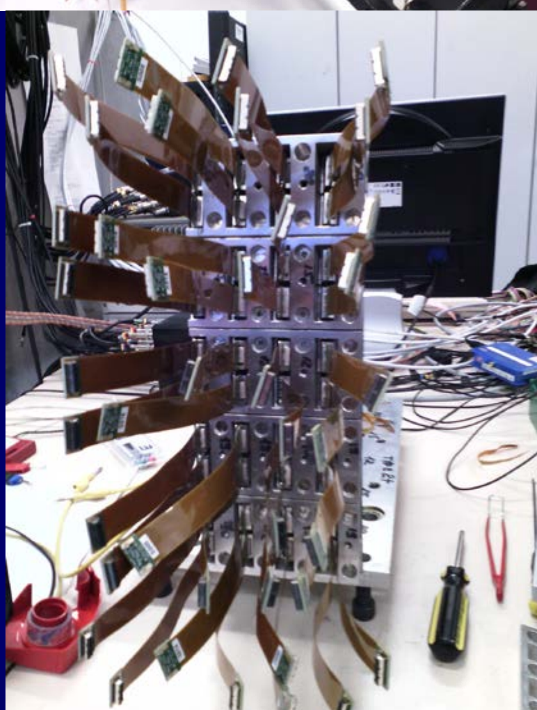


P̄ANDA Barrel Slice Assembly





$\bar{\text{P}}$ANDA Barrel Slice Assembly



The Panda and I in 2016 ….

Thank you.