WORKSHOP ON PICOSECOND PHOTON SENSORS

Clermont - Ferrand, 12-14 March 2014

TOF - PET concept with axial geometry and digital SiPM

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Outline

TOF - PET concept with axial geometry and digital SiPM readout

Outline:

The AX-PET Demonstrator
- why axial geometry?
- AX-PET detector concept
- Characterization measurements and performance
- Results (small animal imaging reconstruction)

[AX-PET collaboration]

Extension towards TOF
- usage of long axially oriented 10 cm long crystals, readout by dSiPMs
- TIMING PERFORMANCE

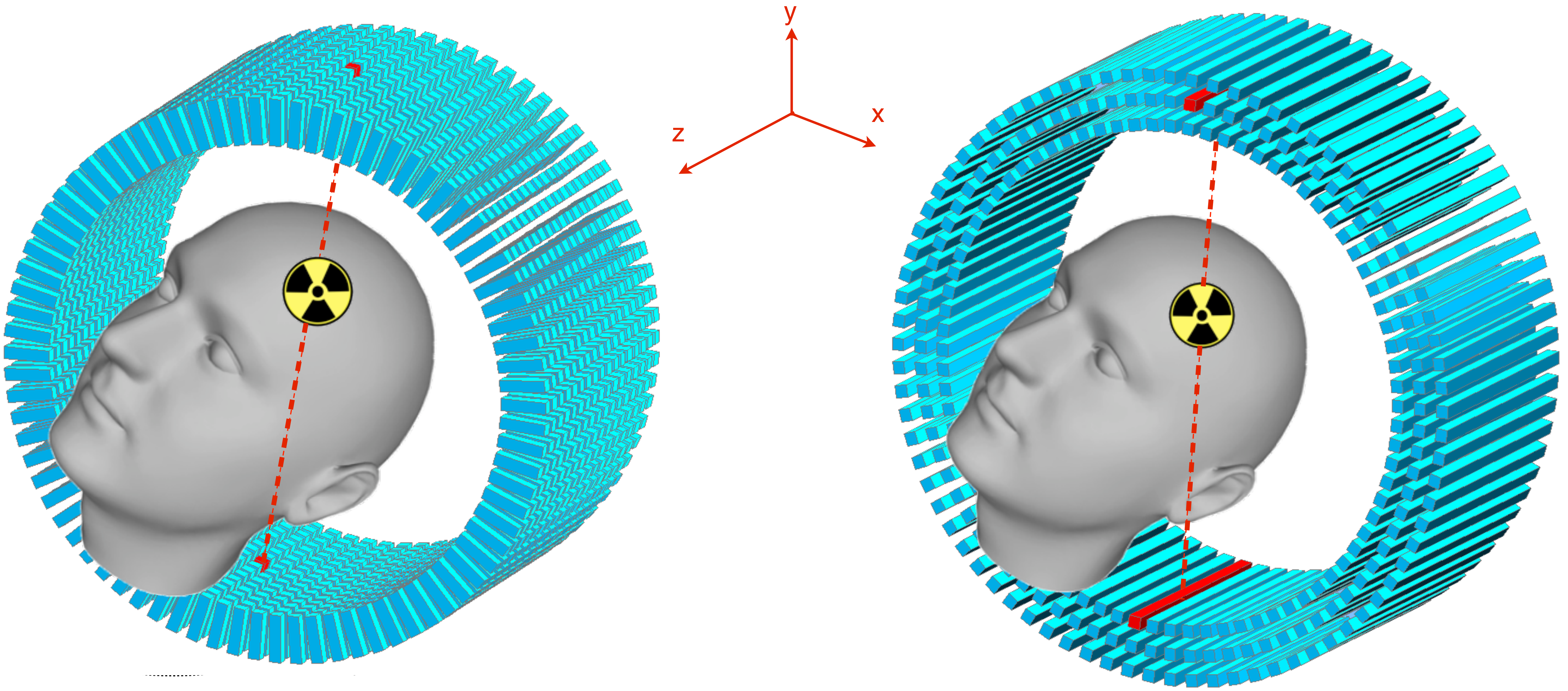
[C.Casella, M.Heller, C.Joram, T.Schneider]

Axial resolution
- usage of long axially oriented 10 cm long crystals, dual sided readout and surface treated

[C.Casella, M.Heller, O.Holme, C.Joram]

Axial arrangement of crystals in a PET

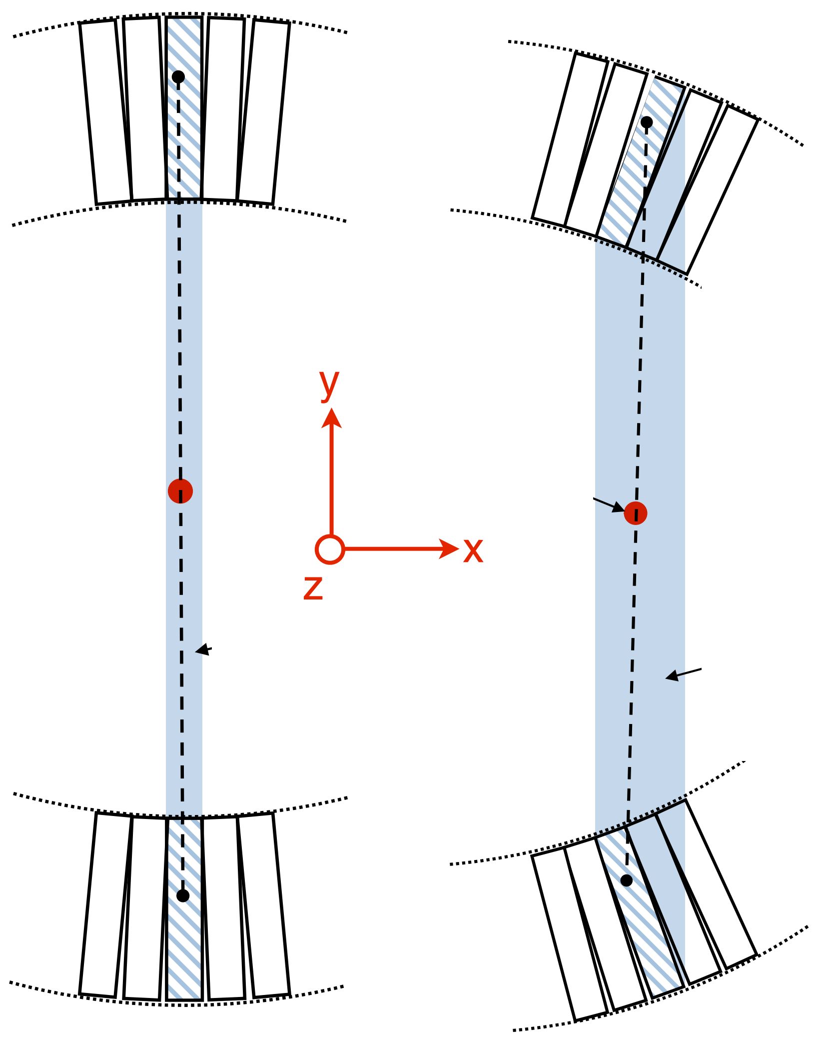
Conventional radial arrangement | **Novel AXIAL arrangement**



Which is the advantage of axially oriented crystals?

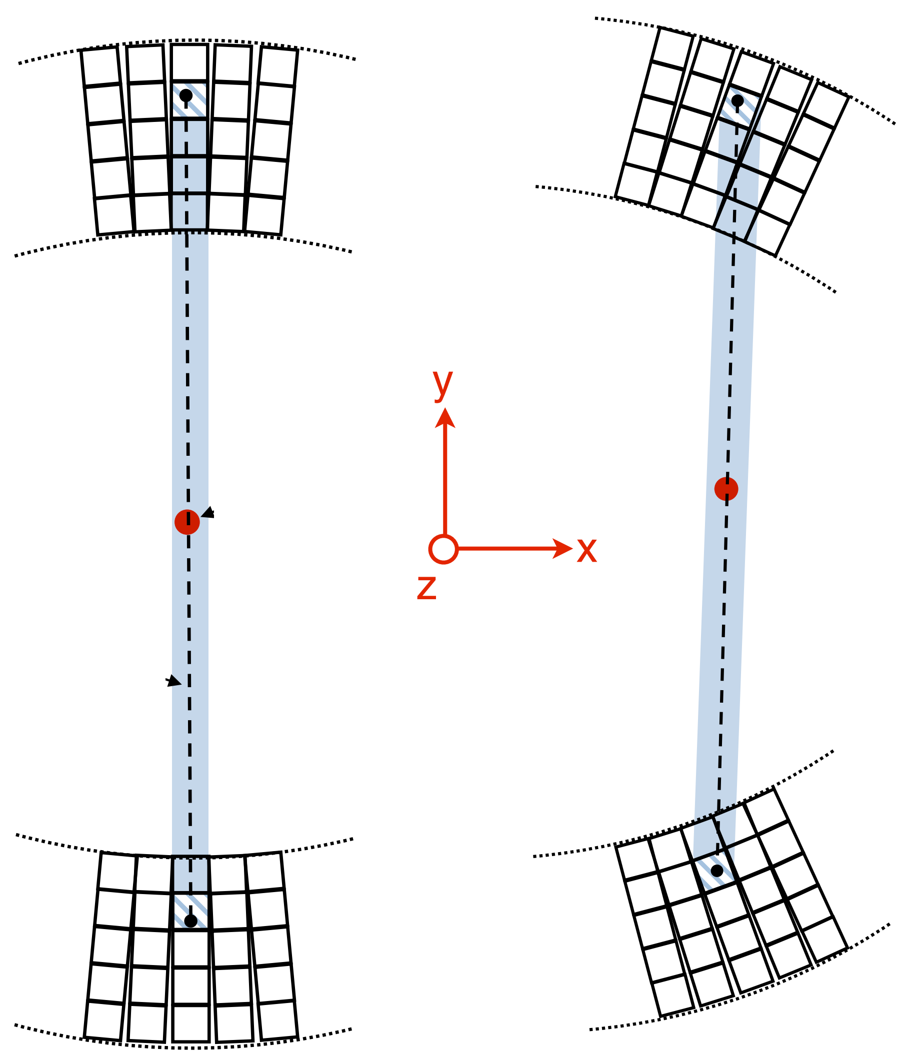
Axial arrangement of crystals in a PET

Conventional radial arrangement



- parallax error
- compromise between spatial resolution and sensitivity (length of the crystal)
- DOI techniques required

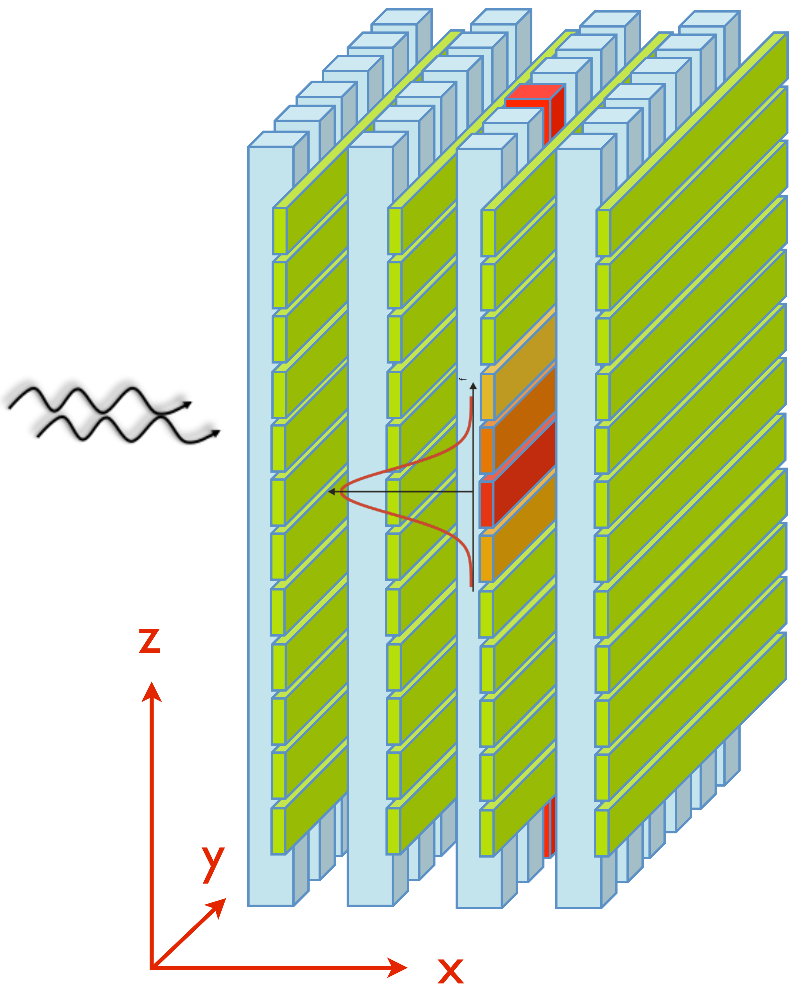
Novel AXIAL arrangement

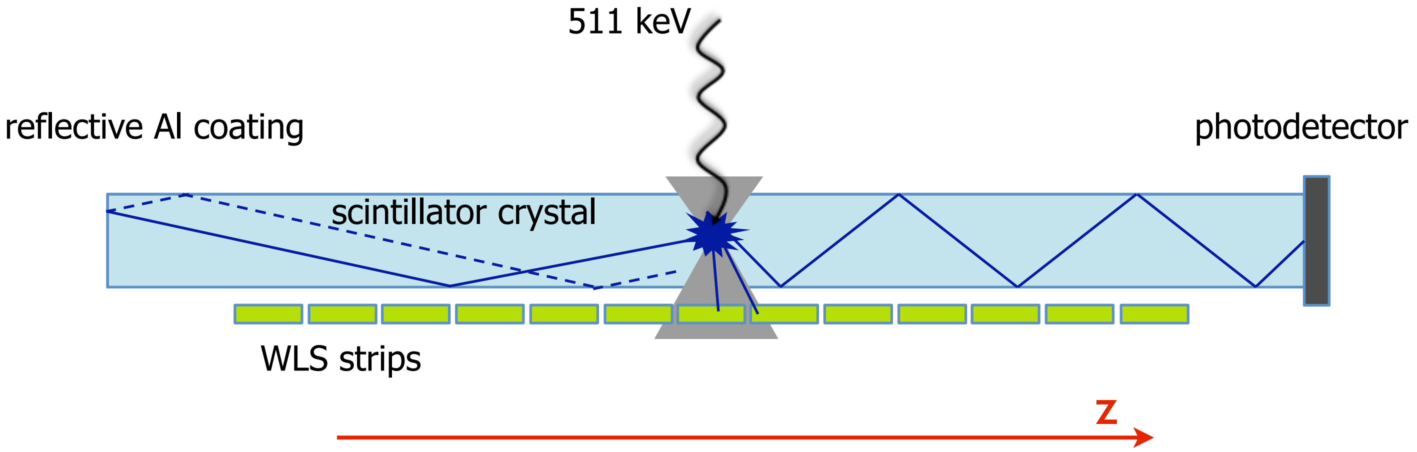


- parallax error contribution significantly reduced
- decoupled sensitivity and resolution
  - sensitivity <=> nr of layers
  - spatial resolution <=> crystal cross-sectional(x,y) size
- need to define the axial(z) coordinate

The AX-PET detector concept : Axial coordinate definition

- AX-PET : axial coordinate definition using **arrays of Wave-Length Shifting** (**WLS**) **Strips**
- technique from calorimetry in High Energy Physics



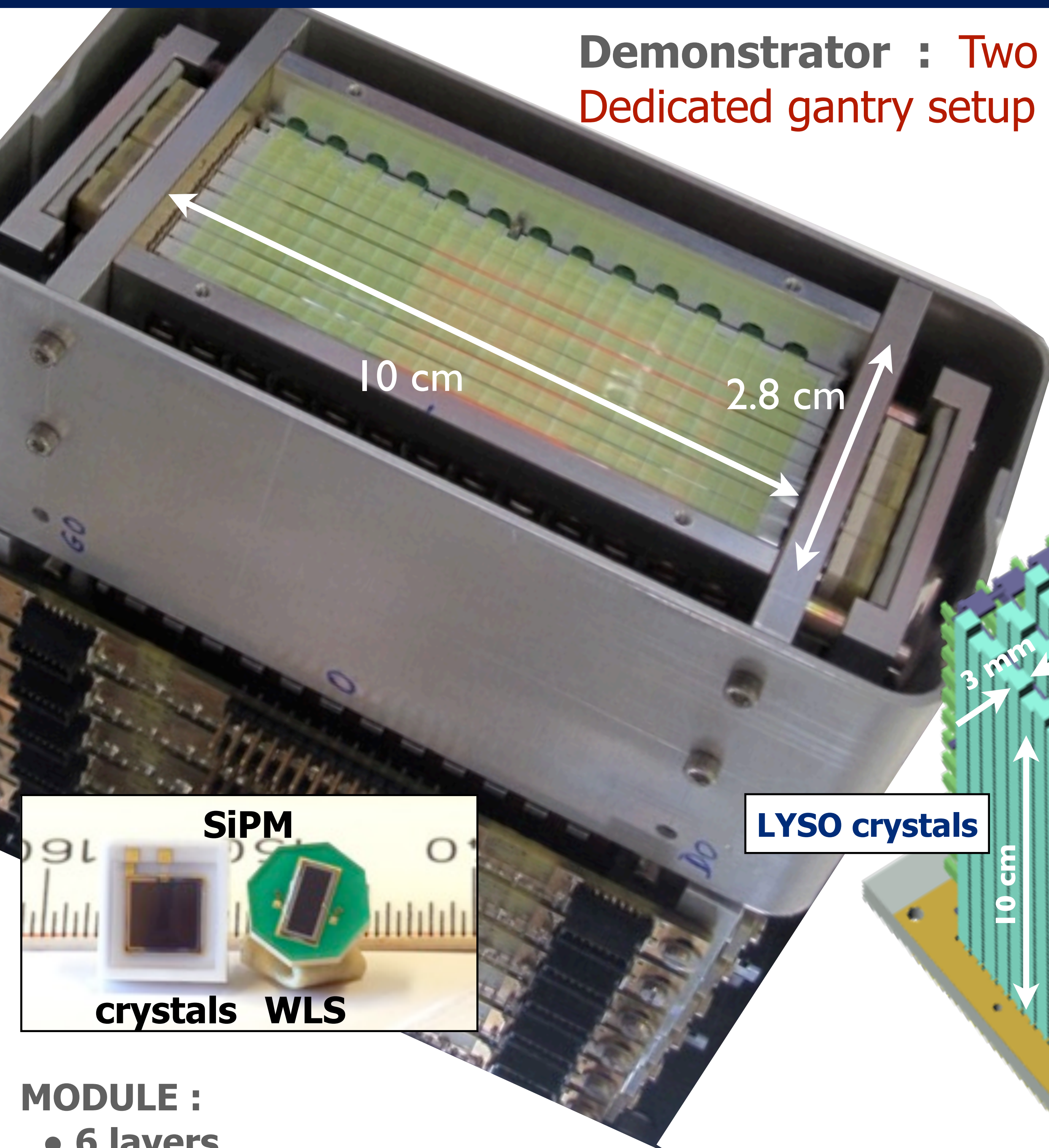


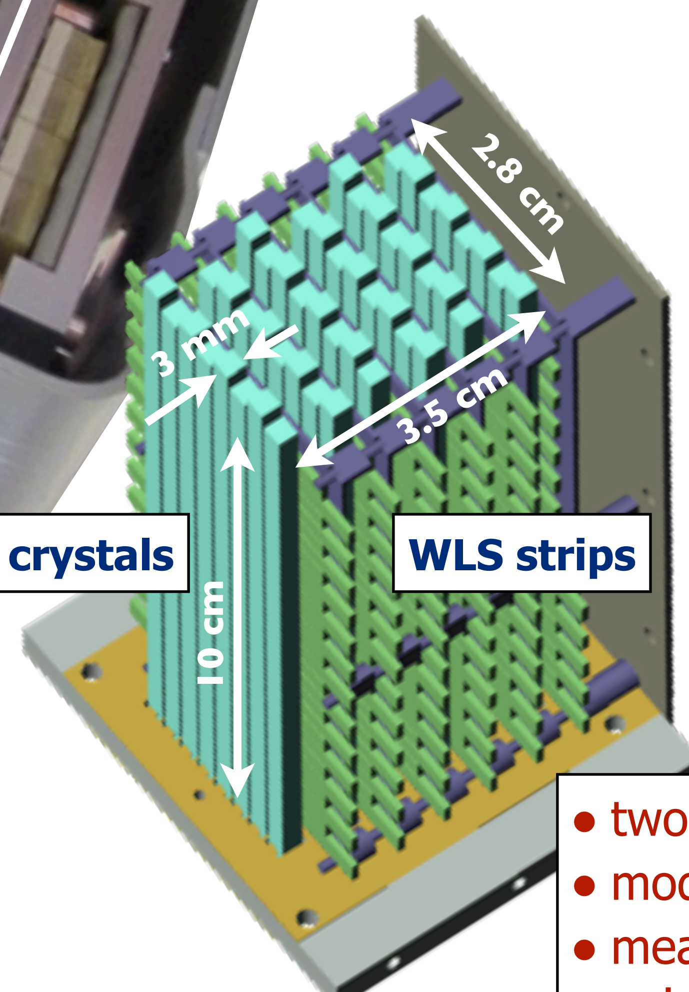
- WLS strips to detect the scintillation light that escapes the crystal
- center of gravity (CoG) on the few strips interested by the event => z (axial) coordinate

- AX-PET detector : **matrix of layers of LYSO scintillator crystals and WLS strips arrays**
  - LYSO crystals and WLS strips
    => **3D localization of the photon interaction point**
    crystal position => (x,y) ; WLS CoG => z
  - LYSO crystals => **energy measurement**

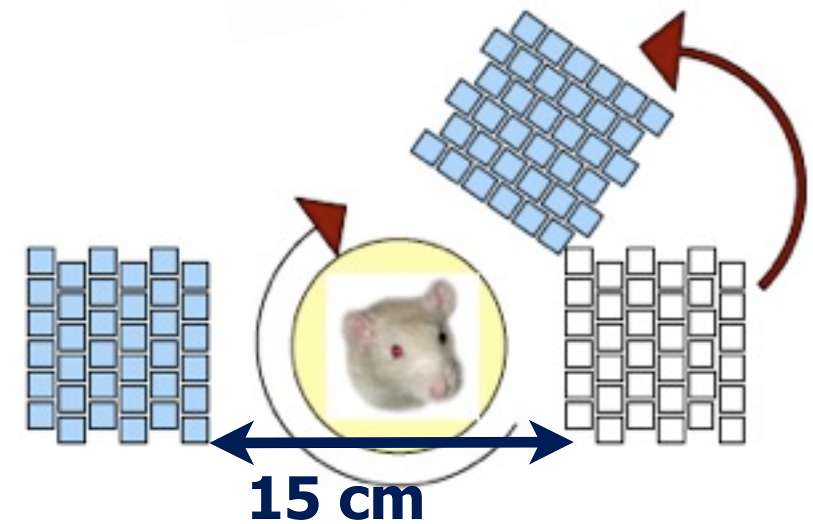
The AX-PET Demonstrator

Demonstrator : Two identical AX-PET modules, used in coincidence. Dedicated gantry setup to mimic a full ring scanner with **2 modules only**.





x2 ⇒



MODULE :

- **6 layers**
- **8 crystals** / layer (**3 x 3 x 100mm³ LYSO** xtals, **St.Gobain**)
- **26 WLS** / layer (**3 x 0.9 x 40 mm³** WLS, **ELJEN Technology**)
- 48 crystals + 156 WLS = **204 channels**
- all channels **individually readout by SiPMs** (MPPC, **Hamamatsu**)

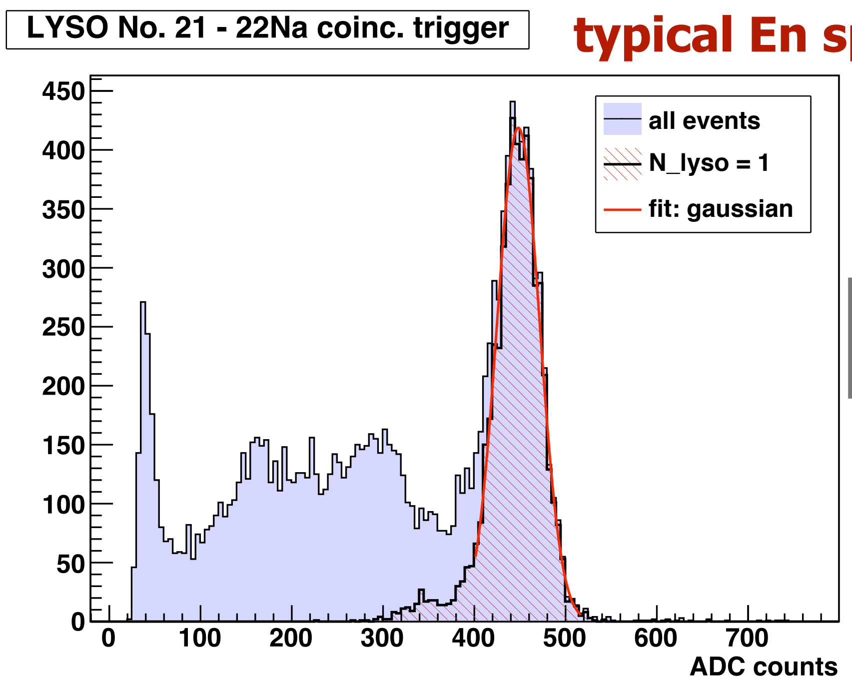
- two modules built
- module performance assessed
- measurements campaigns (phantoms and animals)
- tomographic image reconstruction (our own software)
- all stages fully supported by simulations

AX-PET detector performance

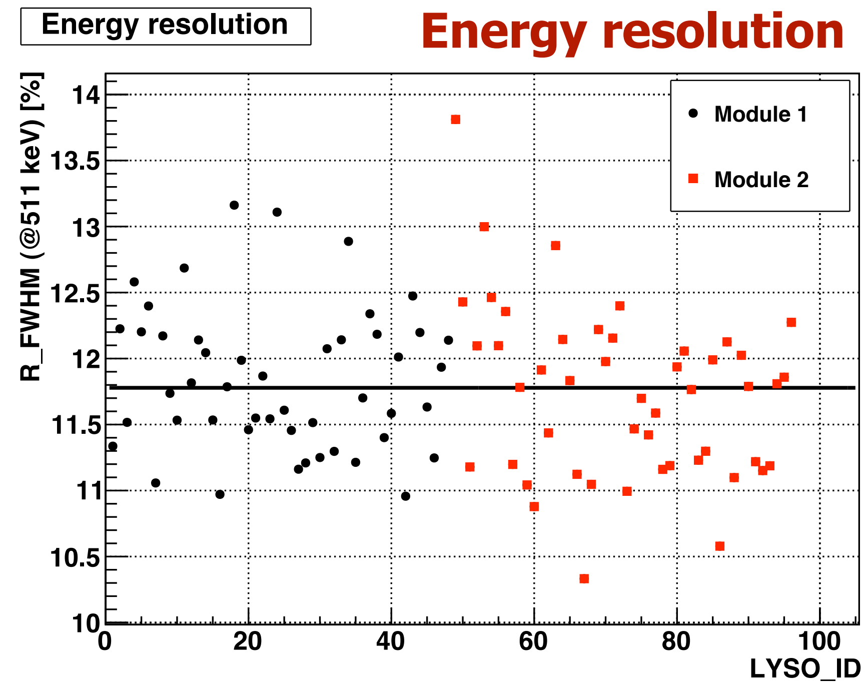
- characterization measurements with ^{22}Na (point-like) sources
  - individual module characterization (+ tagging crystal)
  - two-modules coincidence characterization

Methods and results:
P. Beltrame et al, NIM A 654 (2011) 546-559

one LYSO crystal, typical En spectrum

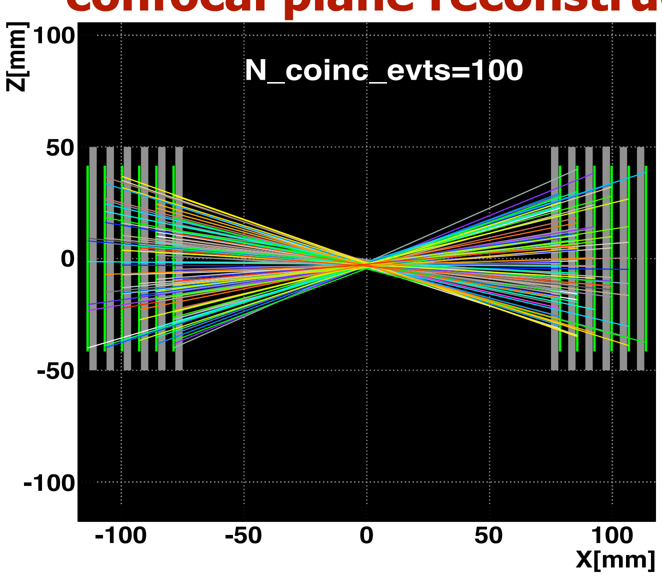


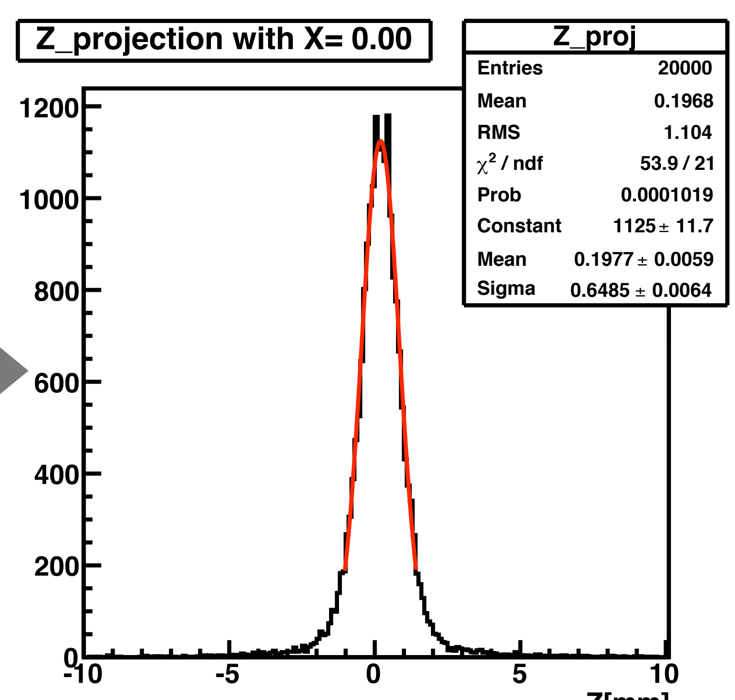
Energy resolution



<ΔE/E> ~ 11.8%
FWHM, 511 keV
(after en.calibr.)

Two modules coincidence, confocal plane reconstruction





contributions from the physics of the positron annihilation

$$R_{intr} = \sqrt{R^2_{meas} - R^2_{\rho} - R^2_{180}}$$

≈ **1.35 mm**, FWHM **(in coincidence)**

Detector spatial resolutions :

$R_{Z,mod}$ ~ 1.91 mm, FWHM (measured)

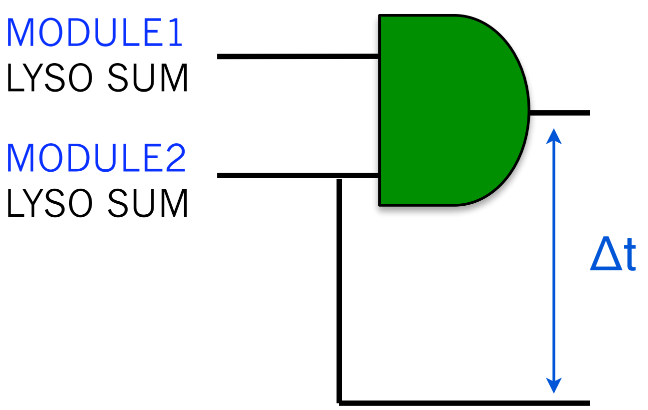
$R_{X,Y,mod}$ ~ 2.03 mm, FWHM (= (3mm/√12)x2.35)

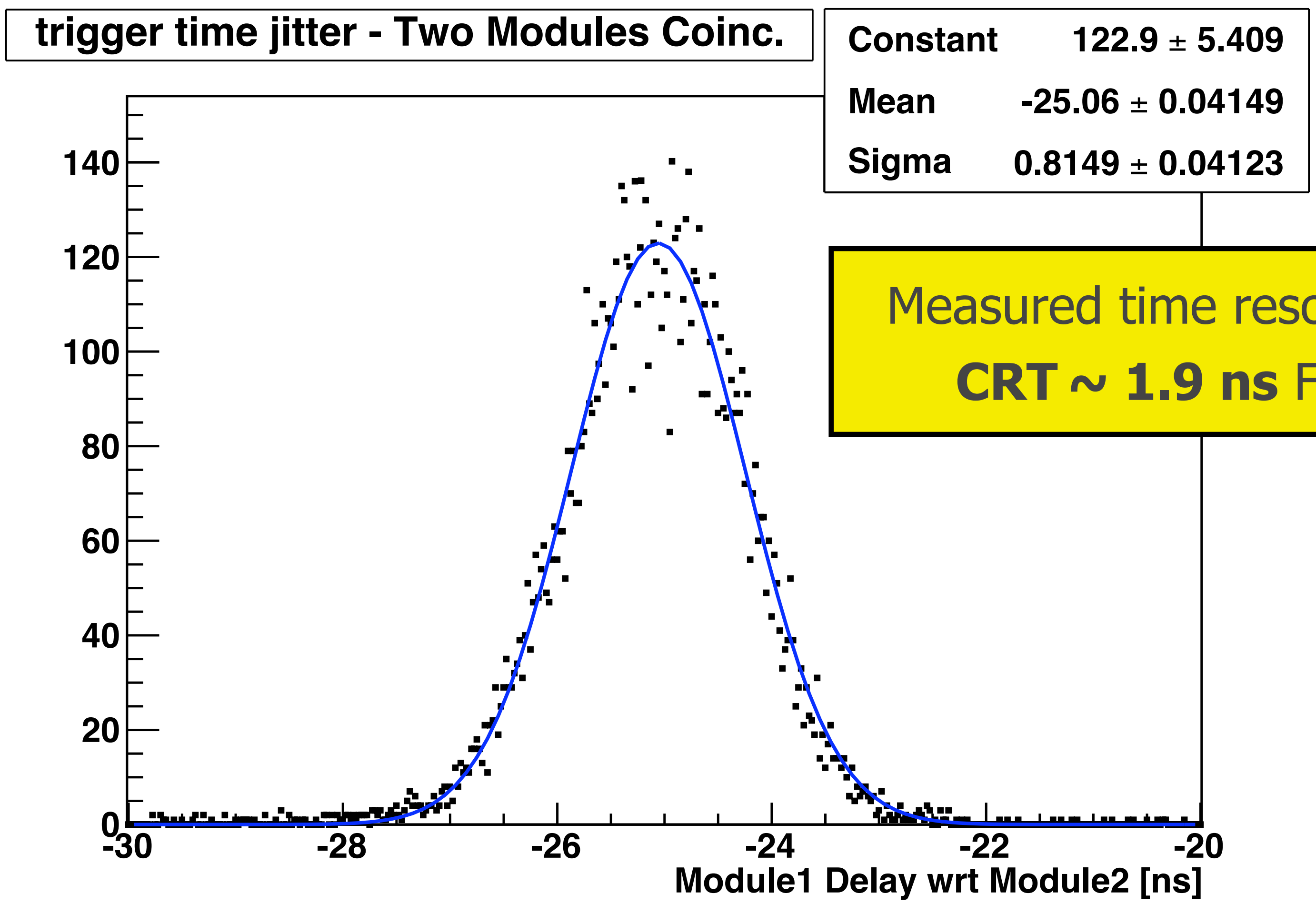
AX-PET timing performance

- **no timing information available in the AX-PET readout (fully analogue readout chain)**

measurement from the scope [Lecroy Waverunner LT584 L 1GHz]

delay of coincidence wrt Mod2

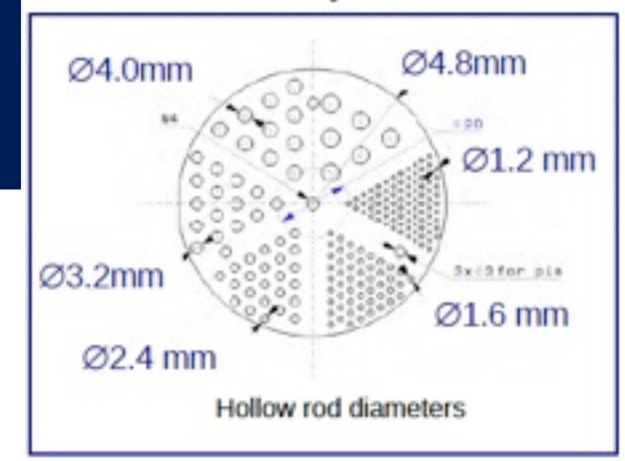




Measured time resolutions :
CRT ~ 1.9 ns FWHM

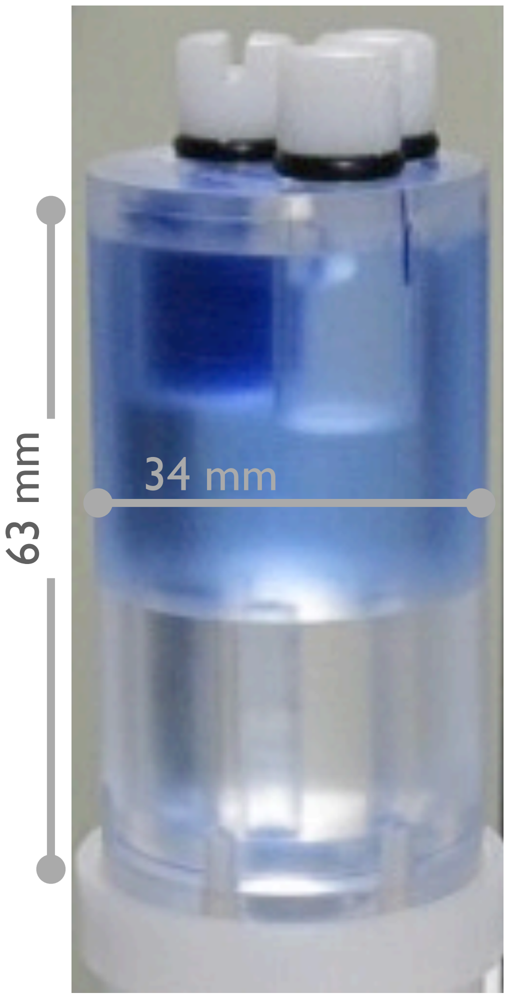
modest TOF potential in the original AX-PET layout
(but anyhow not foreseen)

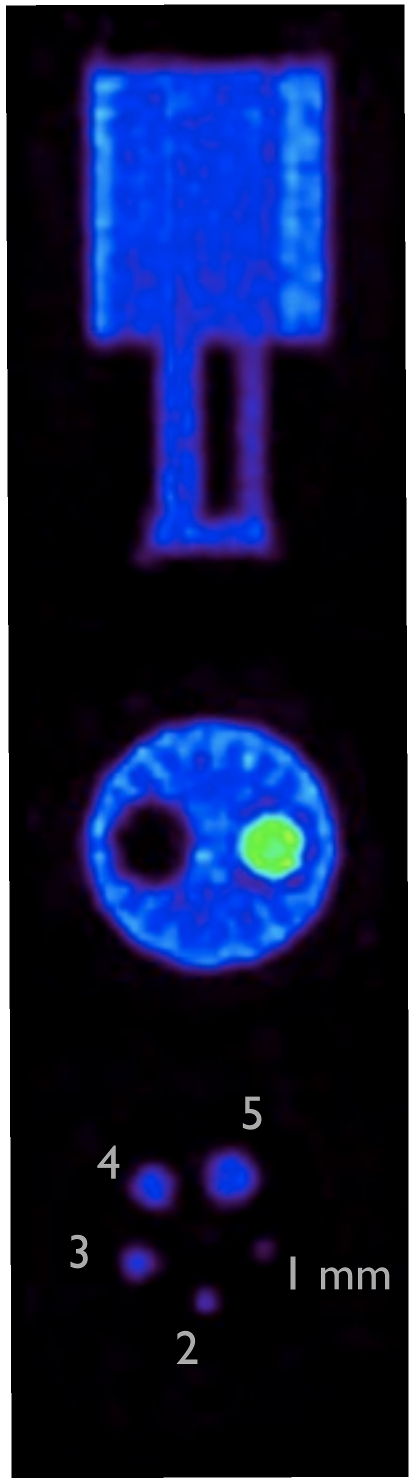
Phantoms reconstructed images



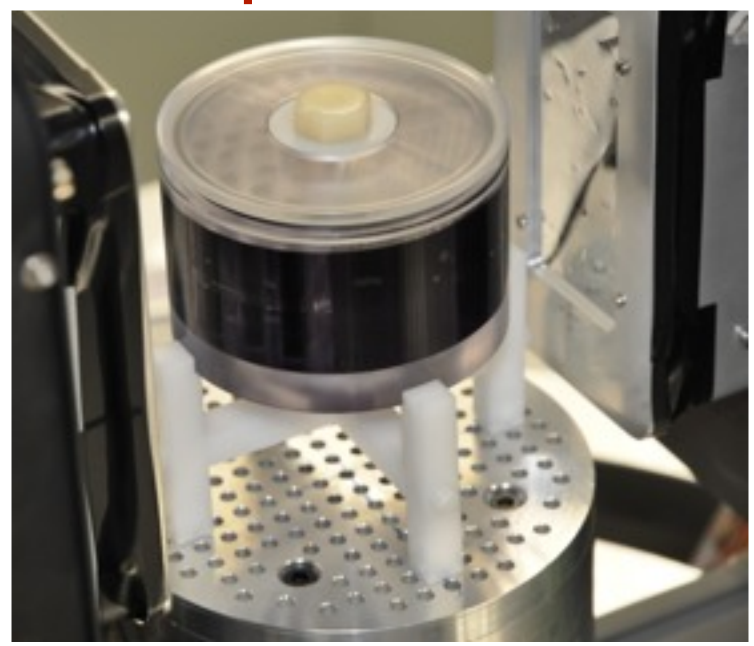
- **F-18** in water solution
- at AAA (Advanced Accelerator Applications), St Genis, France

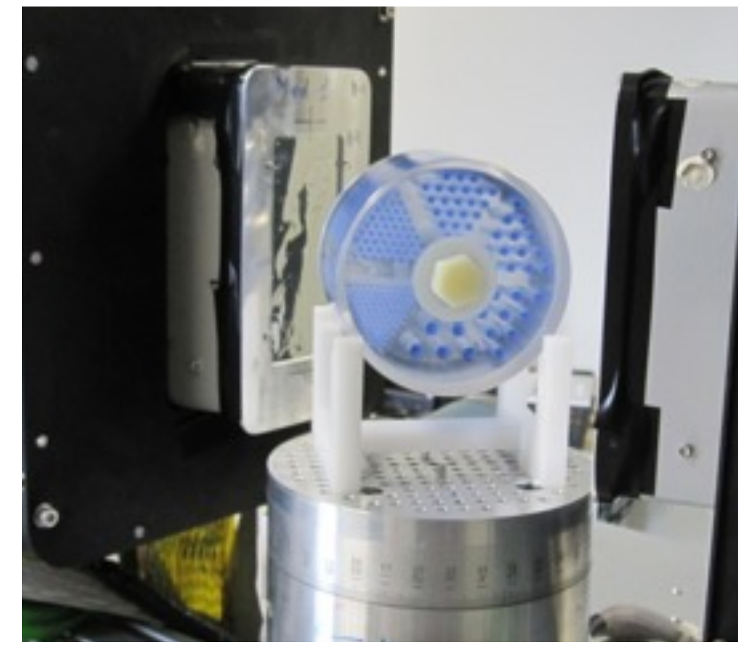
NEMA phantom

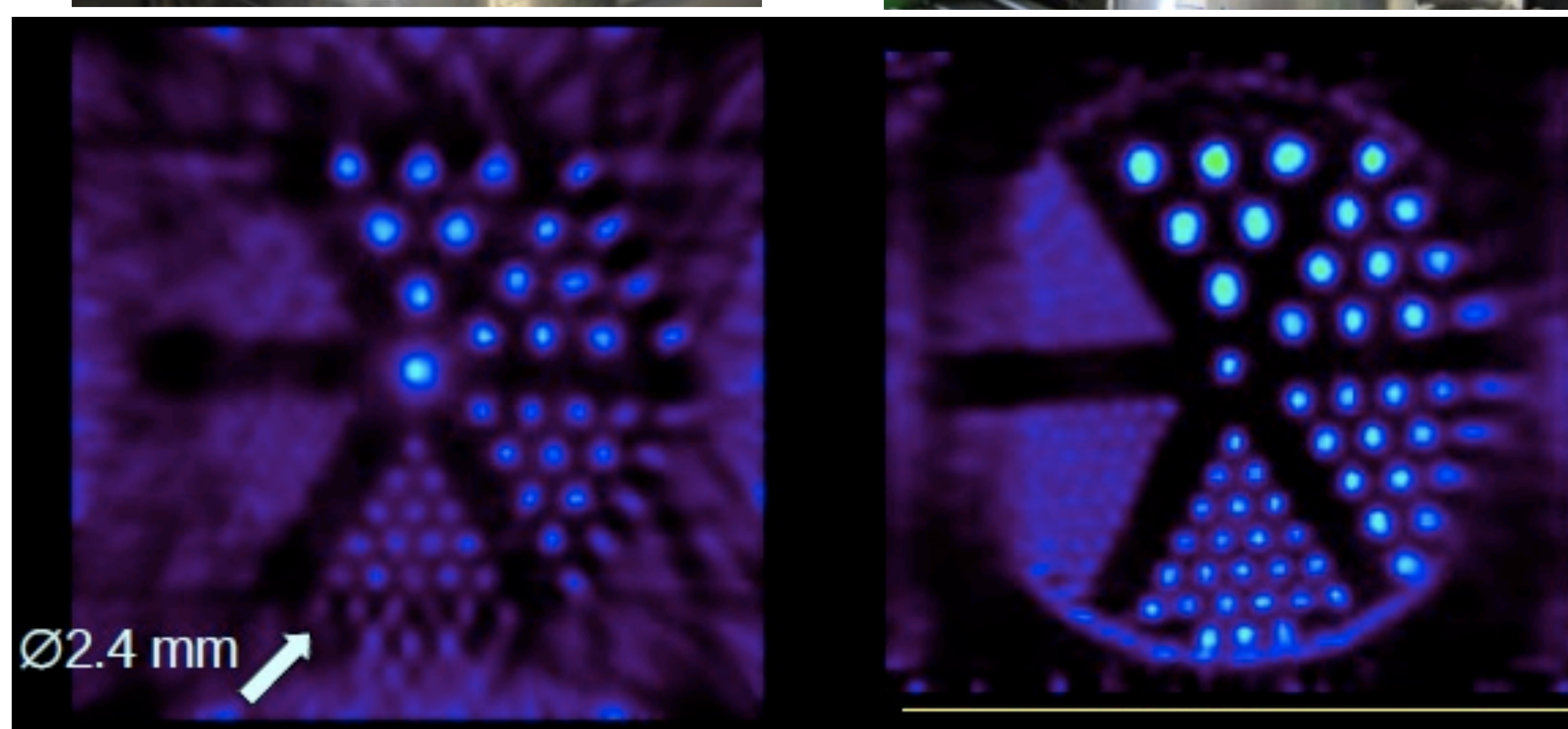




Mini Deluxe phantom







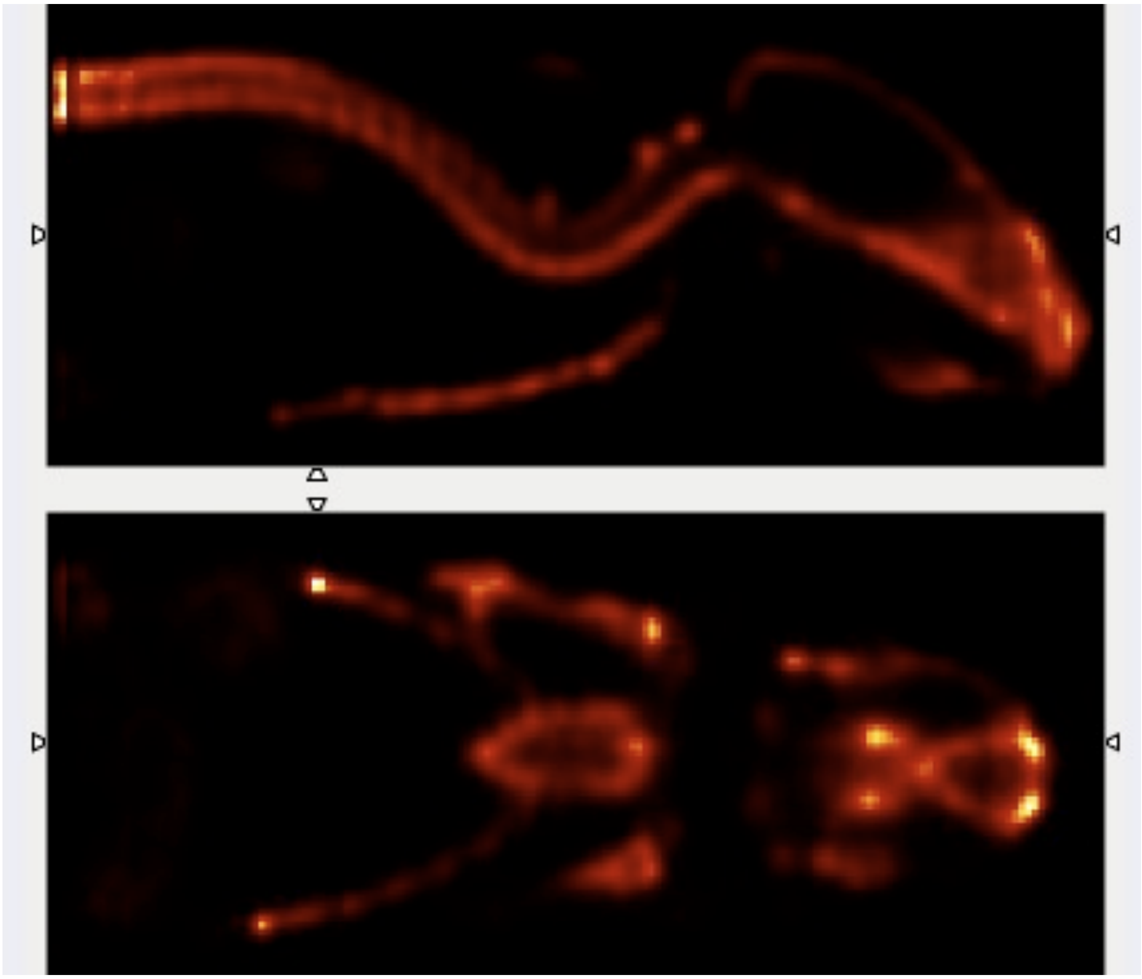
P. Beltrame et al, 2011 IEEE NSS Conference Record MIC 22-5

Small animal reconstructed images

- **SMALL ANIMAL IMAGING CAMPAIGN**

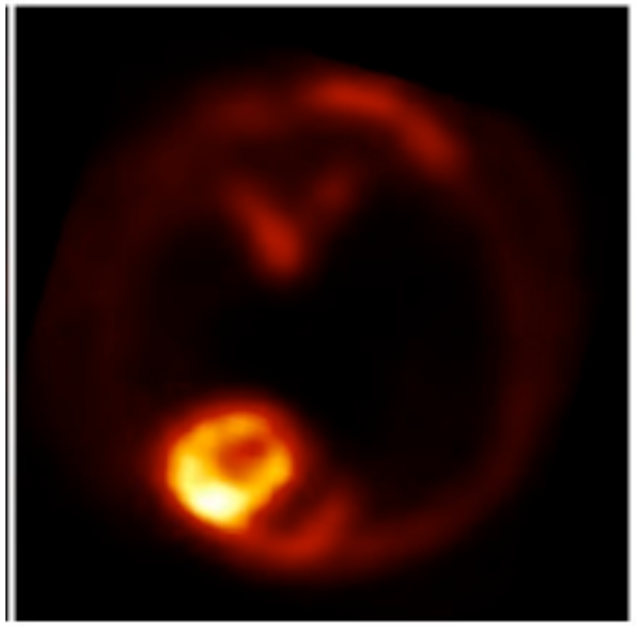
- **F-18 bone scan** of one young rat (post-mortem)
- two **FDG studies**, one young rat, one mouse (post-mortem)
- at Animal Imaging Center - PET @ ETH Zurich, June 2012

Rat F-18 => Bone scan



- **fine structure visible (high spatial resolution)**
- **large axial coverage (single step acquisition)**

Rat FDG => zoomed coronal image of the rat hearth



low contrast regions (ventricular myocardium) visible

first rodent images from a PET with axial geometry !

satisfactory quality of the reconstructed images – despite the limitations of the experimental setup (i.e. two modules only, large crystals cross section)

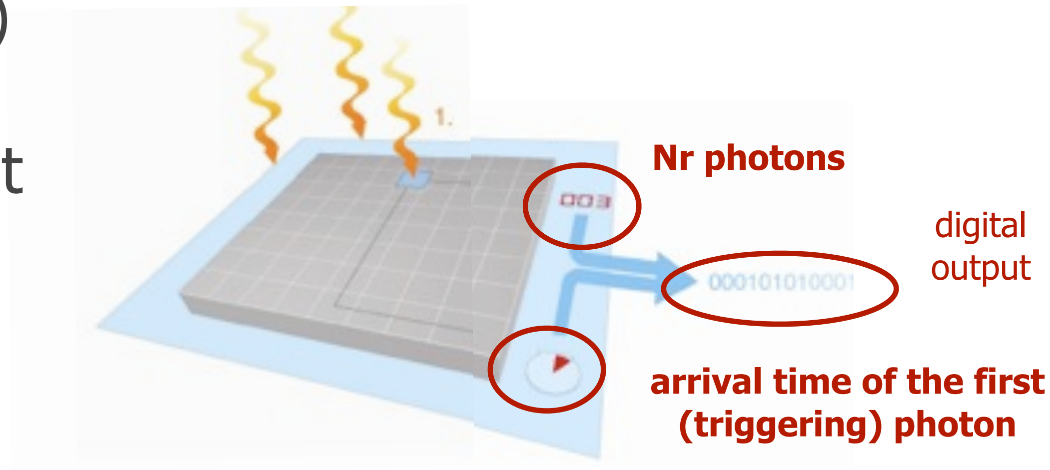
paper in preparation!

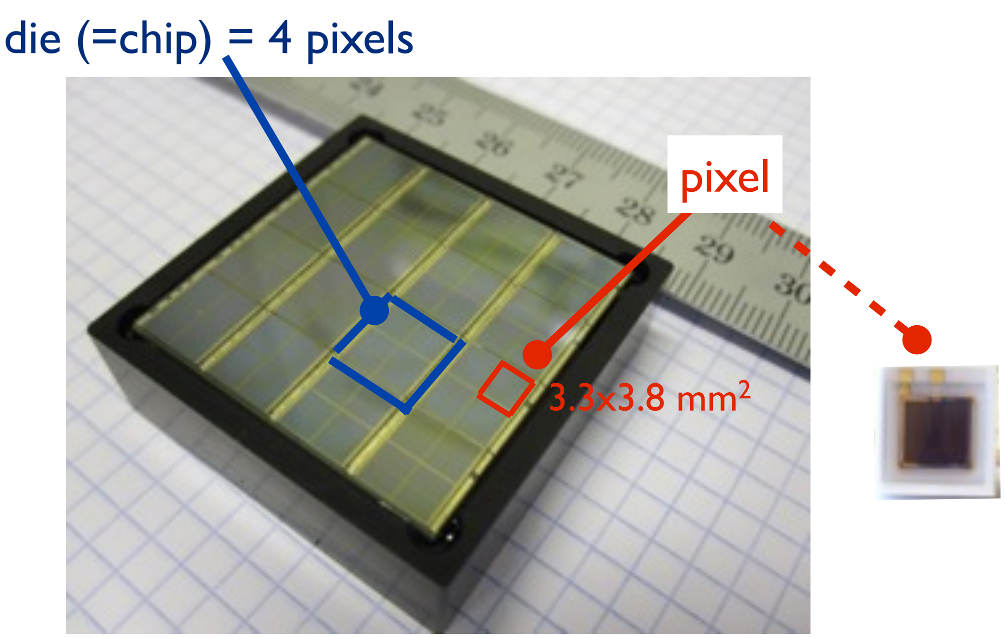
Extension of AX-PET concept toward TOF

Is it possible to add TOF capabilities to an "AX-PET like" detector?

- excellent timing resolutions are needed (few 100 ps)

- yes, with the proper choice of photodetector / readout
  => usage of **digital SiPM (dSiPM)** from **Philips**
    - fully digital implementation of SiPM
    - high resolution TDC (19.5 ps resolution)
    => time information ; ~ 50 ps intrinsic time resolution

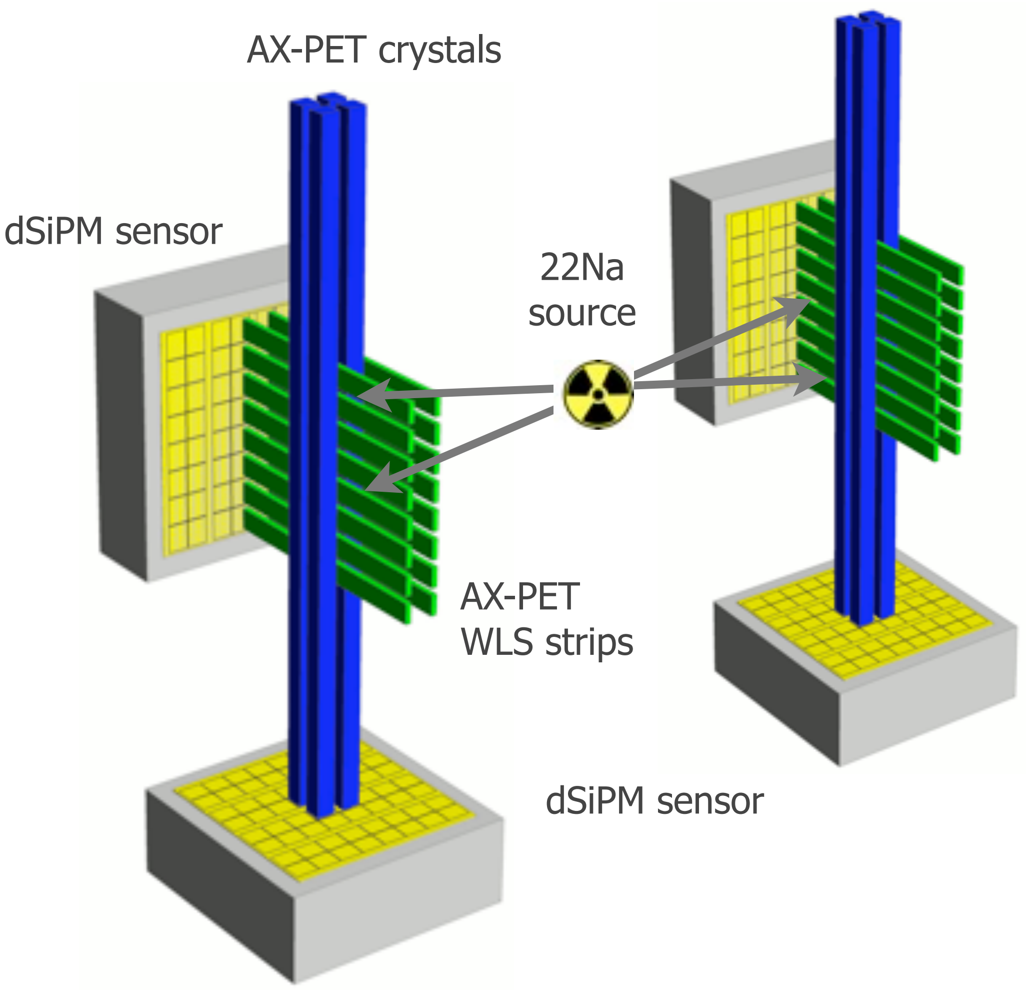




interest of dSiPM for PET applications :

- **High resolution timing information** => TOF-PET
- Small; **high level of integration** (e.g. bias supply included); **compactness**
- Digital => **Temperature and gain stability less crucial** than in analogue devices.
- Digital => Low noise.
- Active quenching => no Afterpulses.
- Possibility to disable individual cells => Significant **reduction in the dark count rate** (but lower PDE)
- MRI compatible

dSiPM as alternative photodetectors



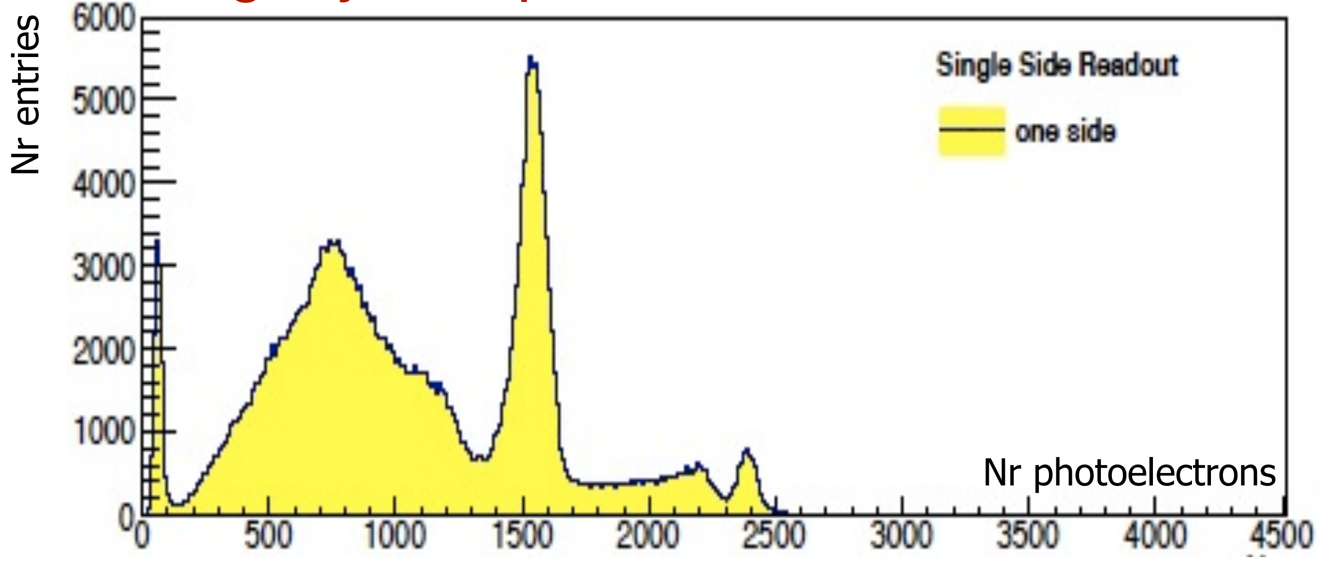
22Na source characterization measurements
(both individually and in coincidence)

Results of the characterization measurements:

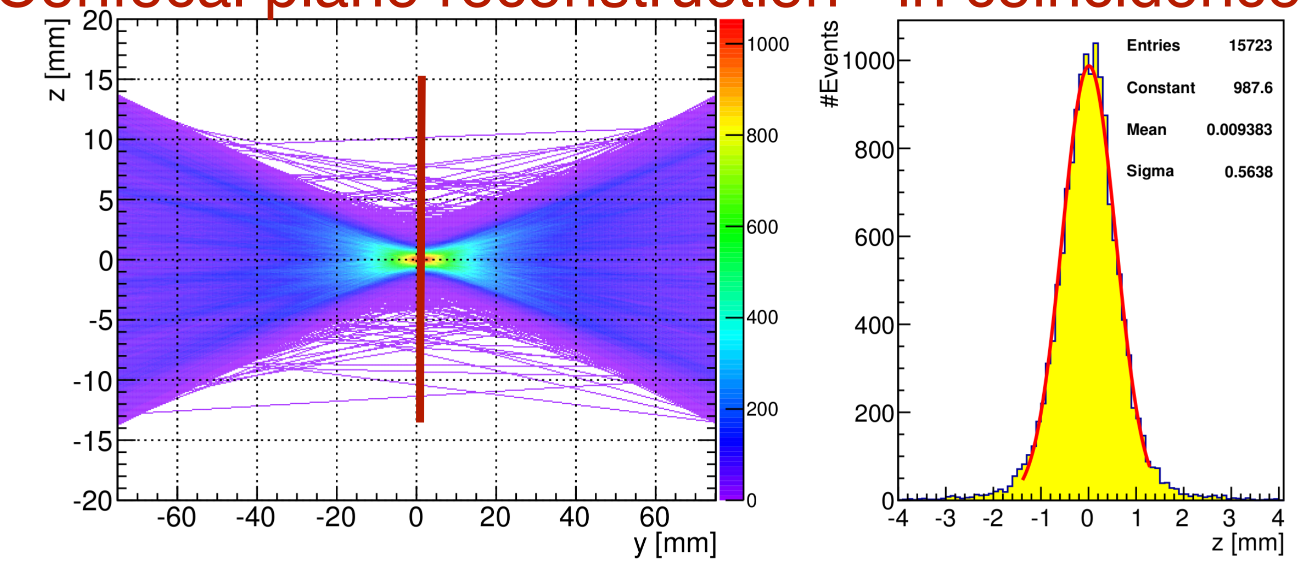
- **Light yield : ~ 1500 pe** (at 511 keV)
- **ΔE/E ~ 14%** @511 keV (after en.calibr.)
- **R_z ~ 1.22 mm**, FWHM (**in coincidence**)
- **$R_{z,mod}$ ~ 1.71 mm**, FWHM

- **two "digital" small-scale modules**
- **identical detector elements as AX-PET coupled to dSiPM**
- reduced Nr channels
- 2 Layers; 2 LYSO and 8 WLS / layer

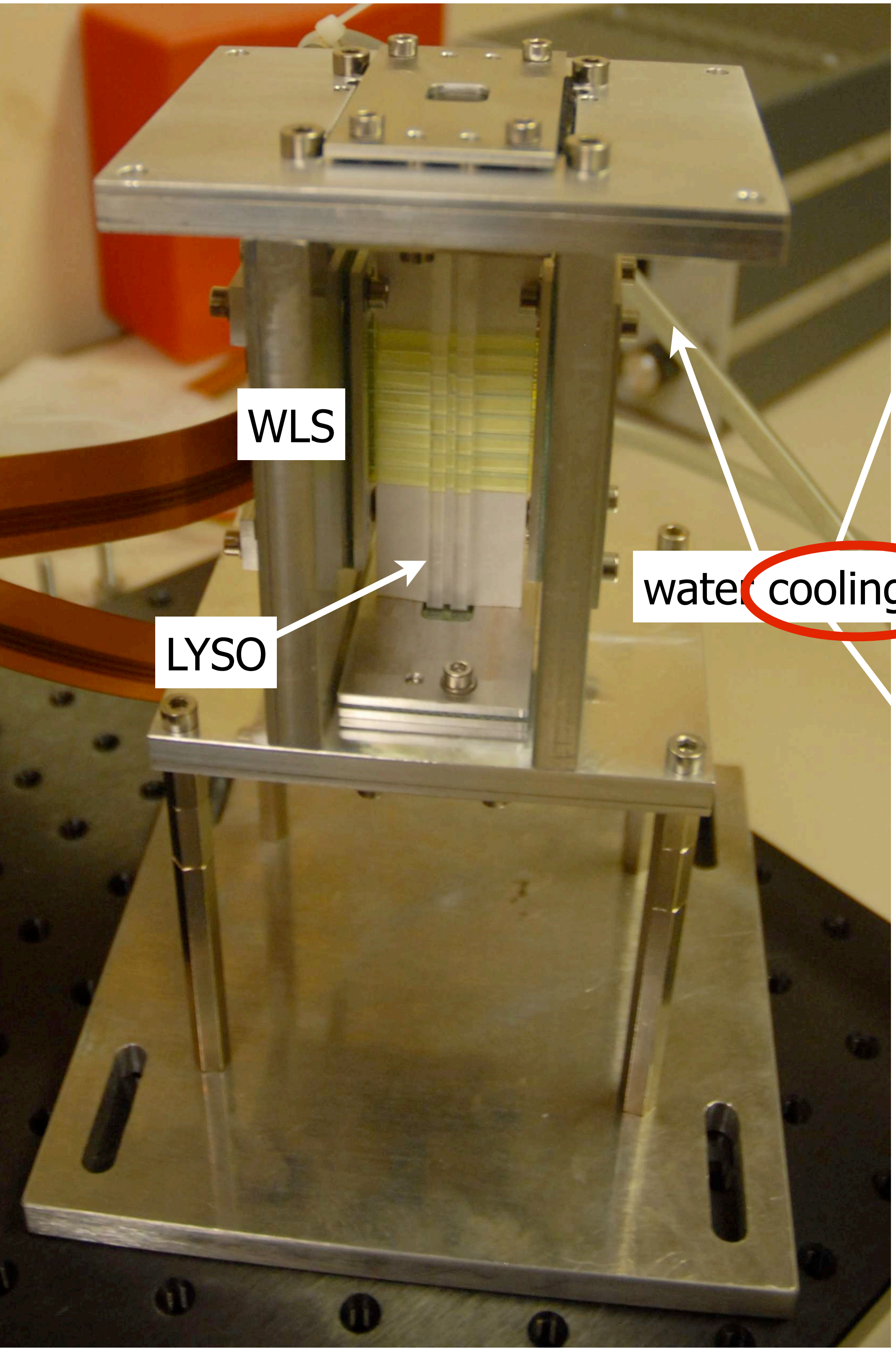
Light yield spectrum - no coincidence



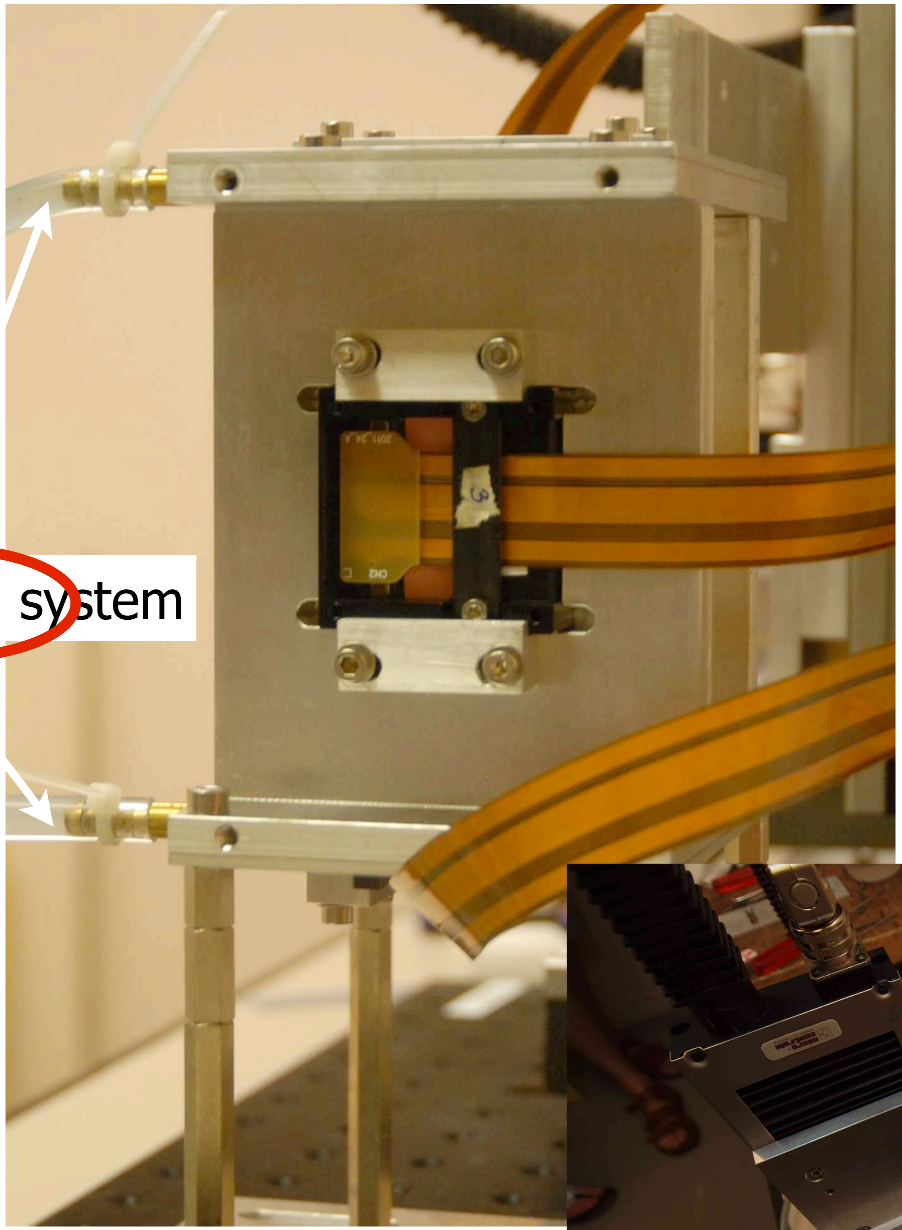
Confocal plane reconstruction - in coincidence



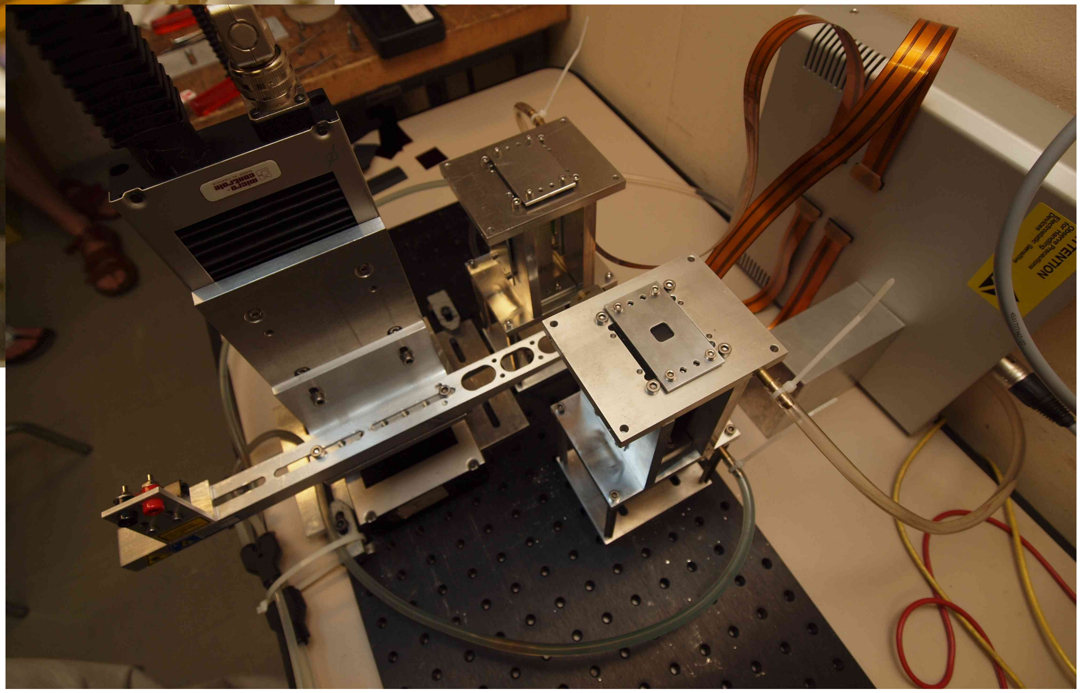
dSiPM as alternative photodetectors



small scale digital axial module



coincidence setup

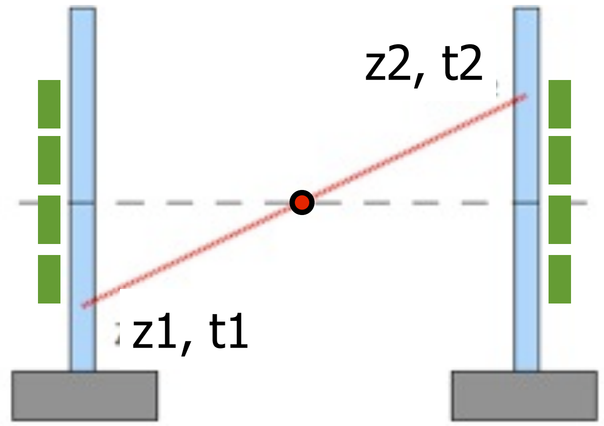


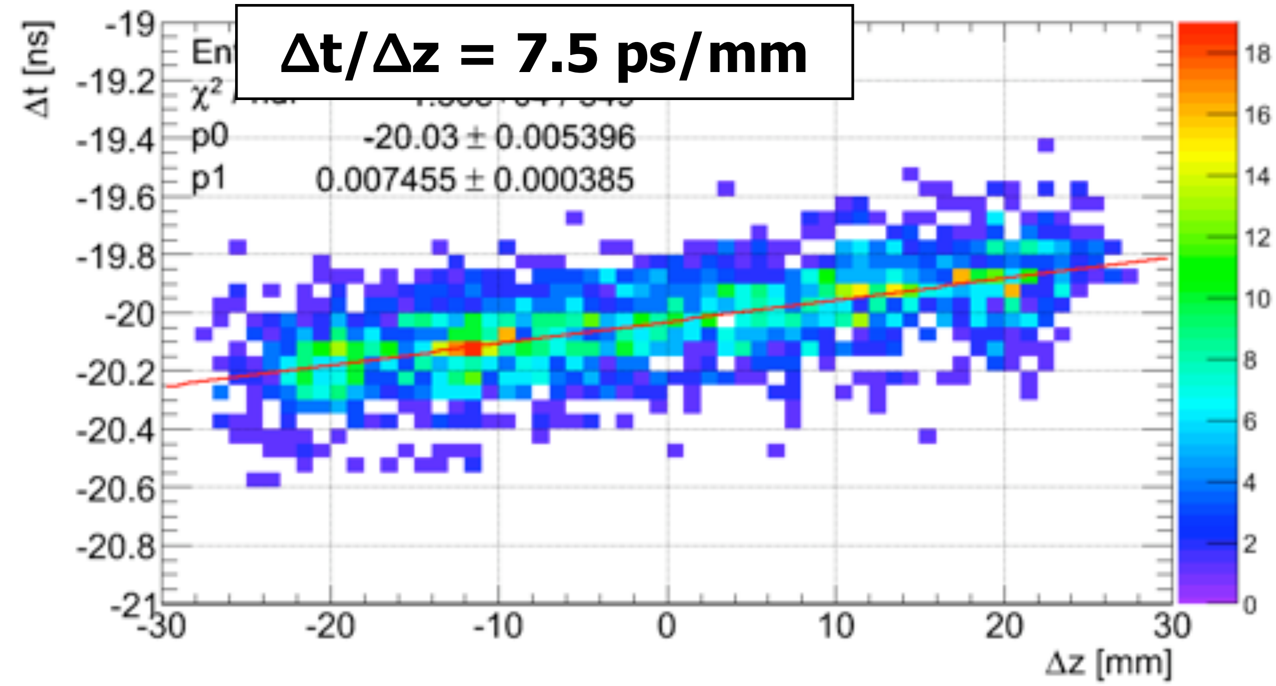
"Digital AX-PET modules": Timing performance

10 cm long crystals

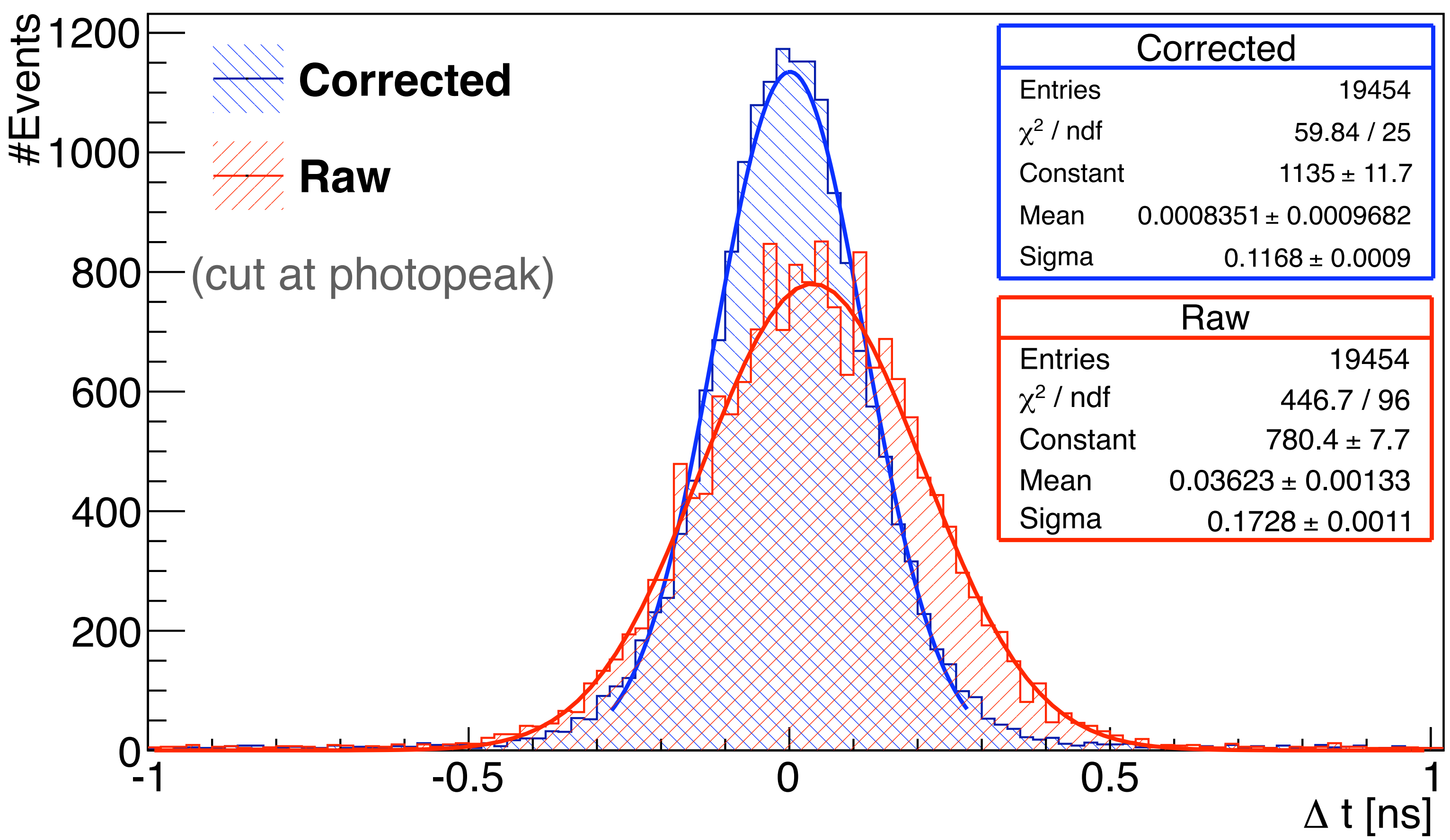
=> the arrival timing of the photons at the photodetector strongly depends on the axial position

=> need to correct for the axial coordinate





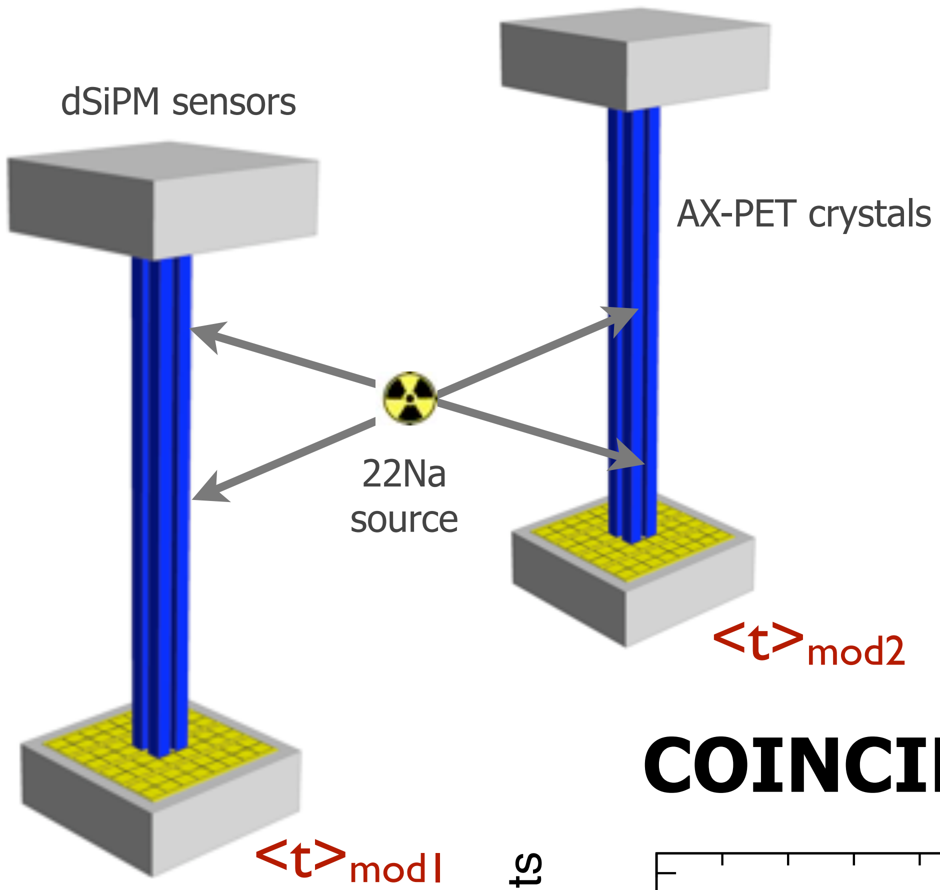
COINCIDENCE RESOLVING TIME



not corrected for axial coord.
CRT ~ 406 ps FWHM
module t_res ~ 287 ps FWHM

corrected for axial coord.
(using information from the WLS)
CRT ~ 269 ps FWHM
module t_res ~ 190 ps FWHM

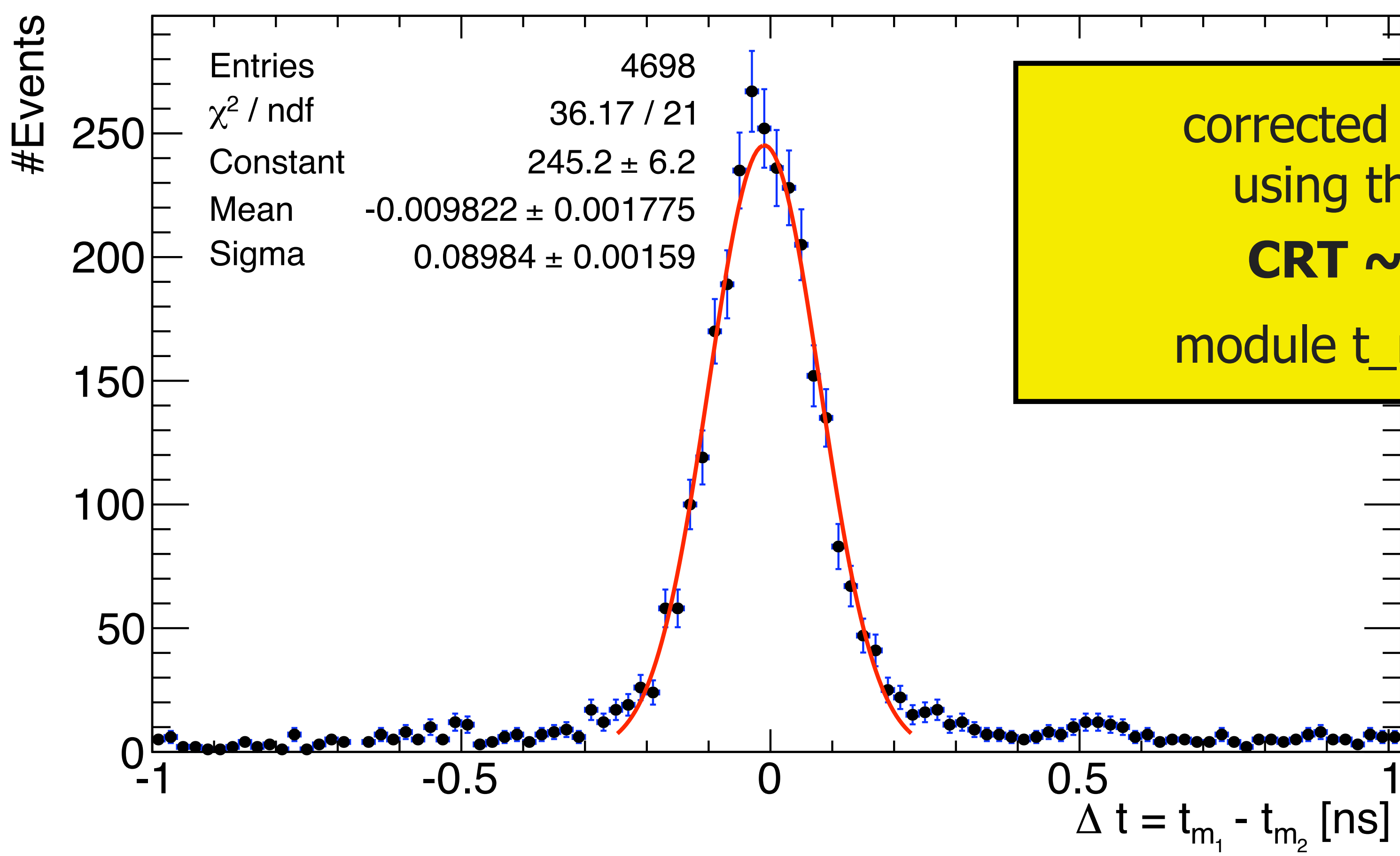
Dual sided readout axial modules



Dual side readout => Average timing definition

By definition corrects for the path length dependence on the axial coordinate.

COINCIDENCE RESOLVING TIME $\langle t \rangle_{mod1} - \langle t \rangle_{mod2}$



corrected for axial coordinate using the average timing

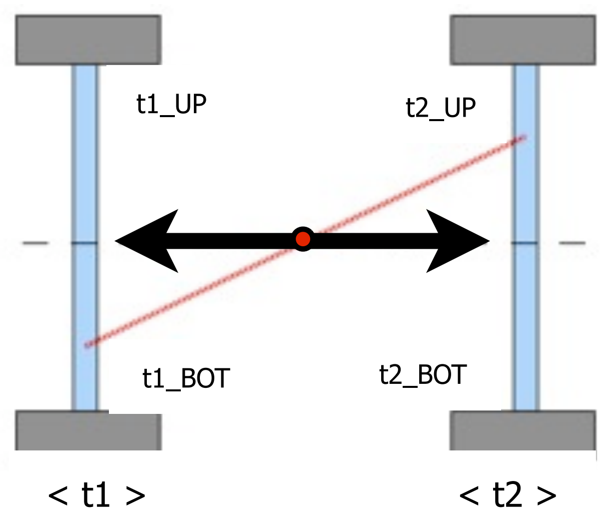
CRT ~ 211 ps FWHM

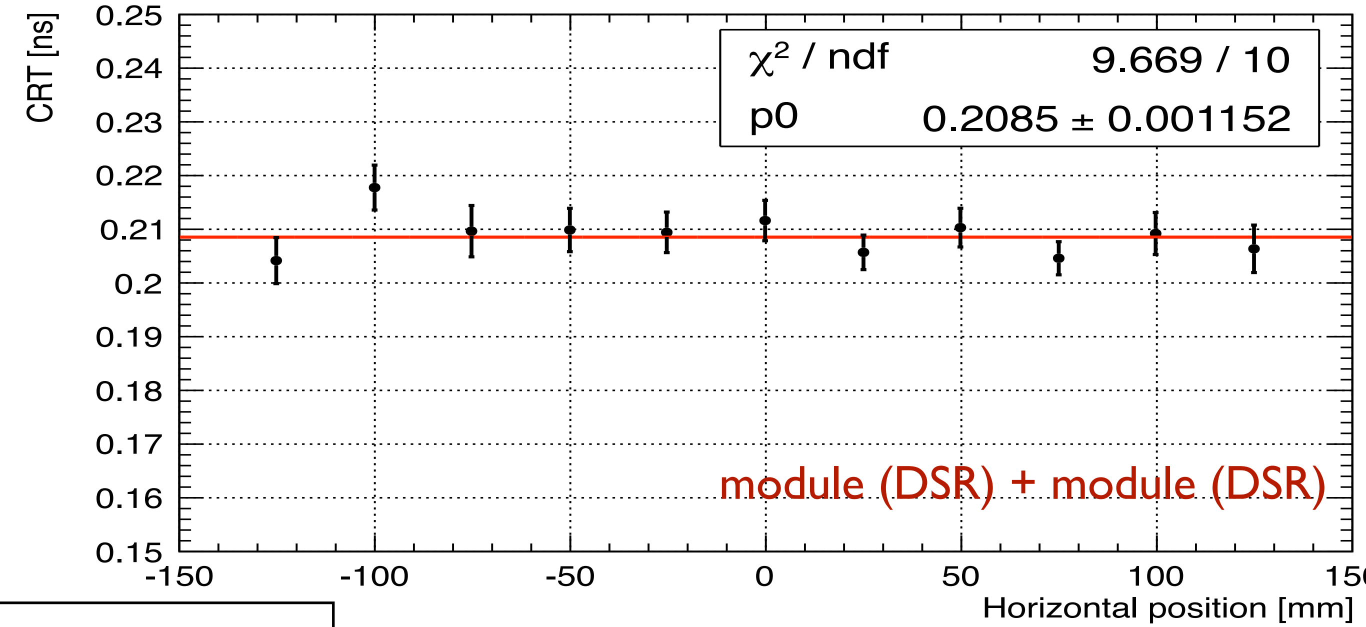
module t_res ~ 149 ps FWHM

NIM A 736 (2014) 161-168

Dual sided readout axial modules

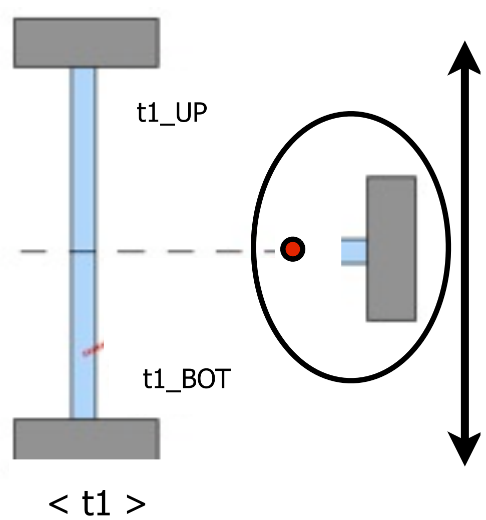
HORIZONTAL scan

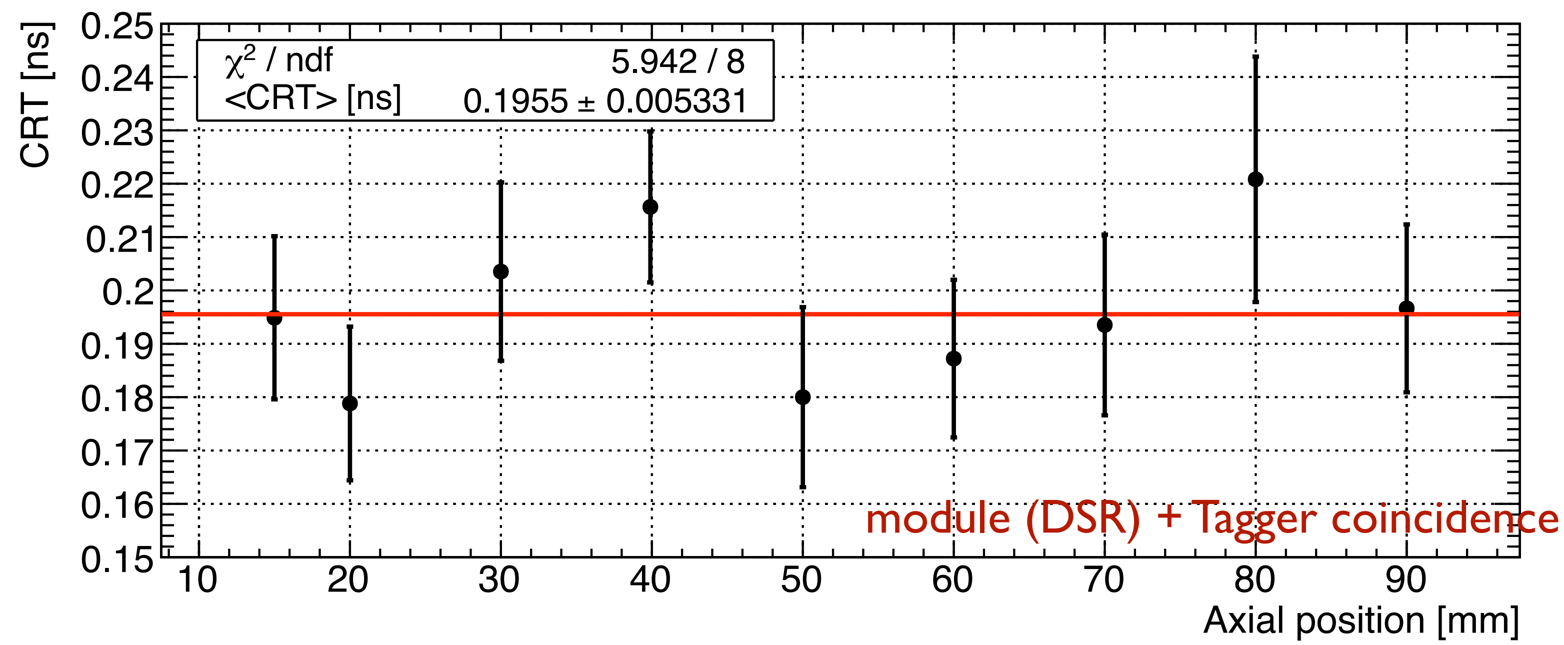




independent on the horizontal position along the FOV

AXIAL scan



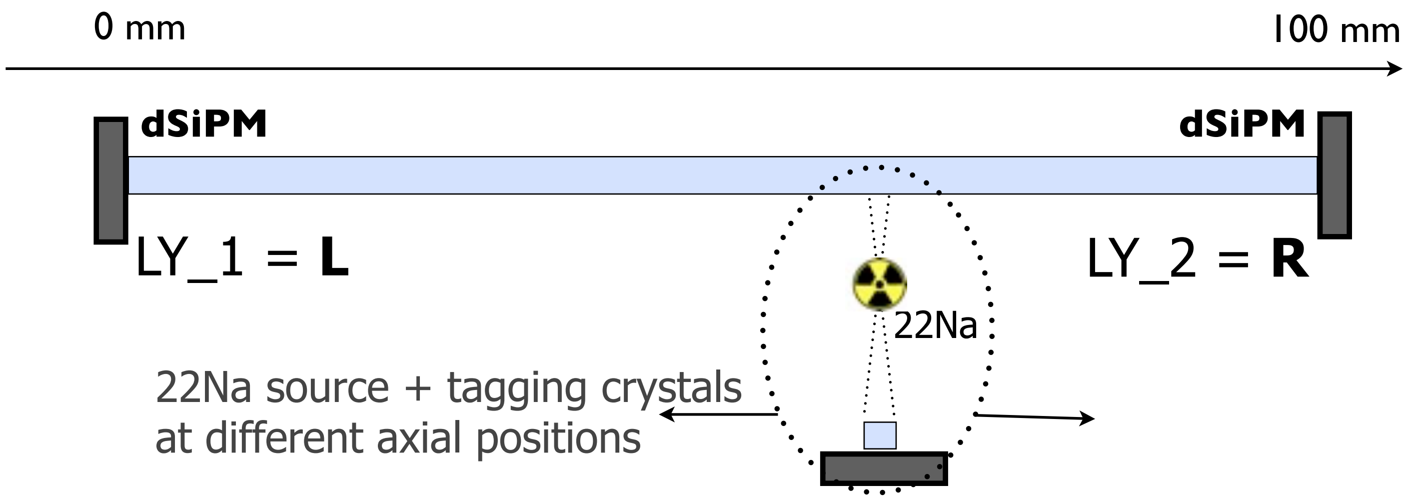


independent on axial coordinate

C. Casella et al, NIM A 736 (2014) 161-168

Very good CRT demonstrated. Uniform along the FOV.

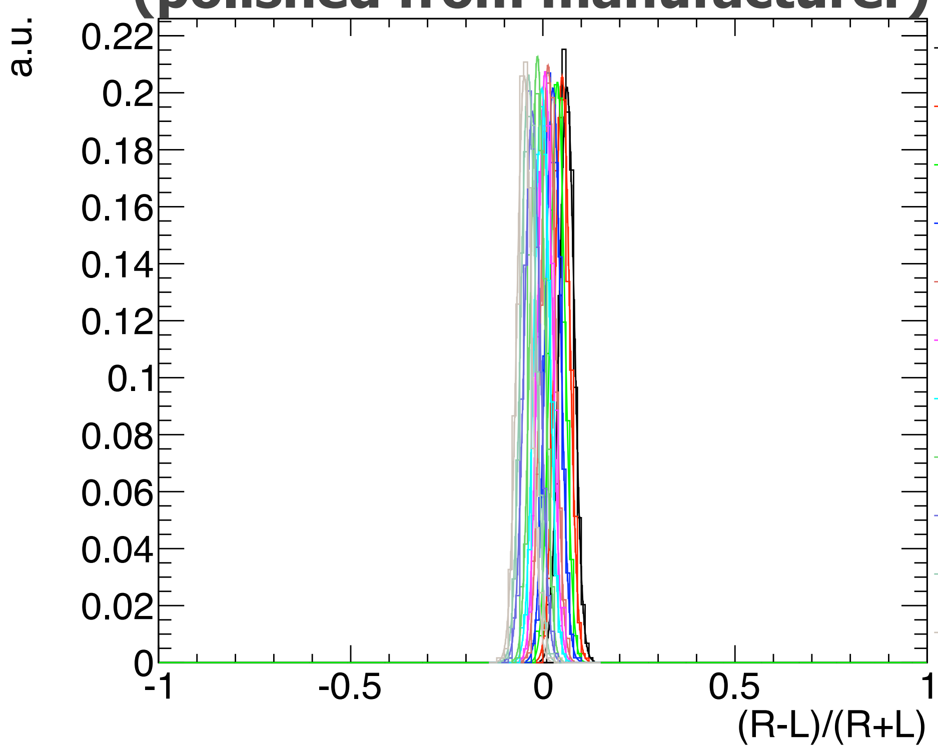
Long crystals, dual sided readout: axial resolution ?



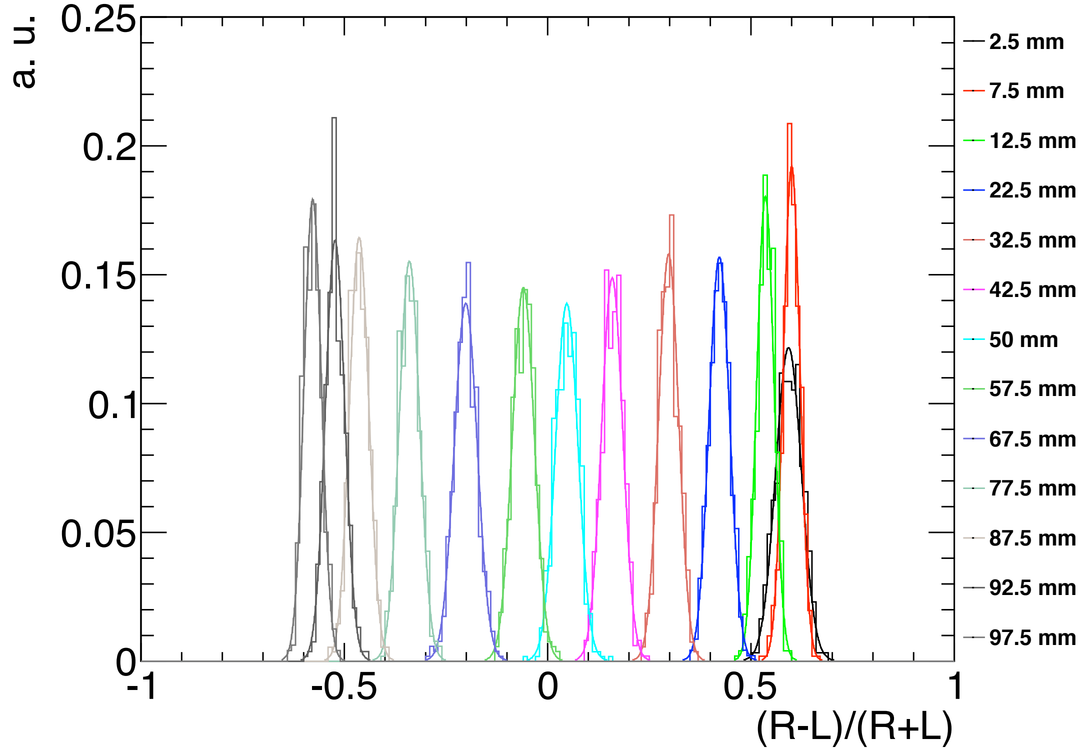
Which is the spatial resolution achievable by light sharing techniques on dual sided readout long crystals ?

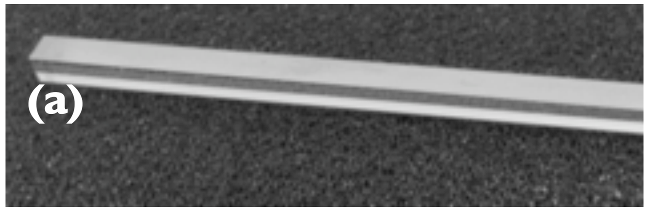
dSiPM still used for this study, but not strictly needed

untreated crystal (polished from manufacturer)

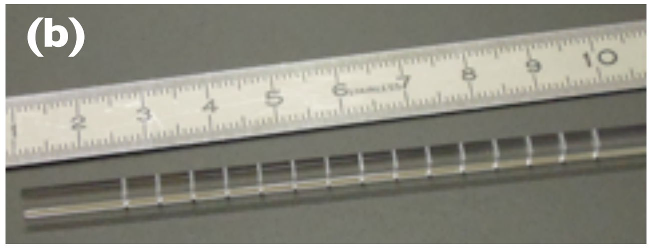


crystal with treated surface

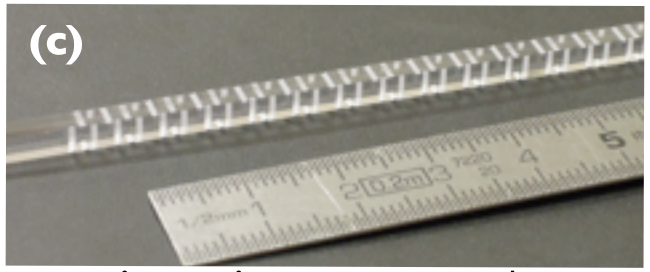




continuous, two depolished surfaces



discrete pattern



semi-continuous, staggered pattern

crystal treatment: mechanical CNC etching (diamond tool) @ CERN

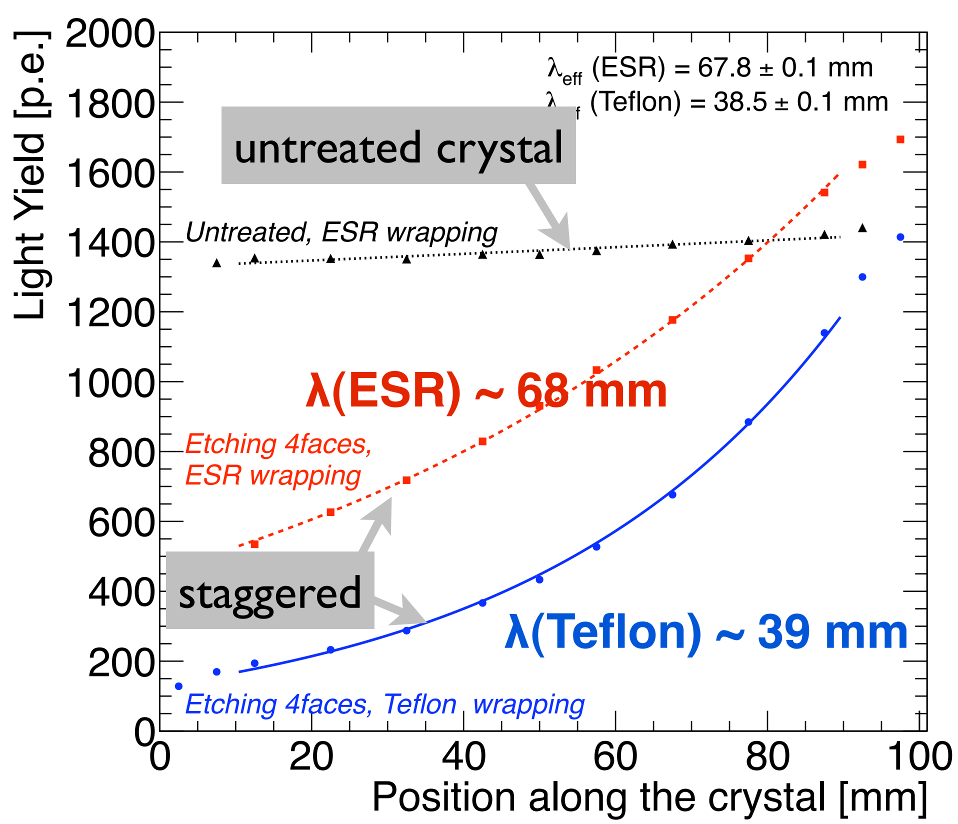
Needed to "destroy" the crystal to reduce its optical attenuation length and be able to appreciate differences in the LY for different axial coordinates !

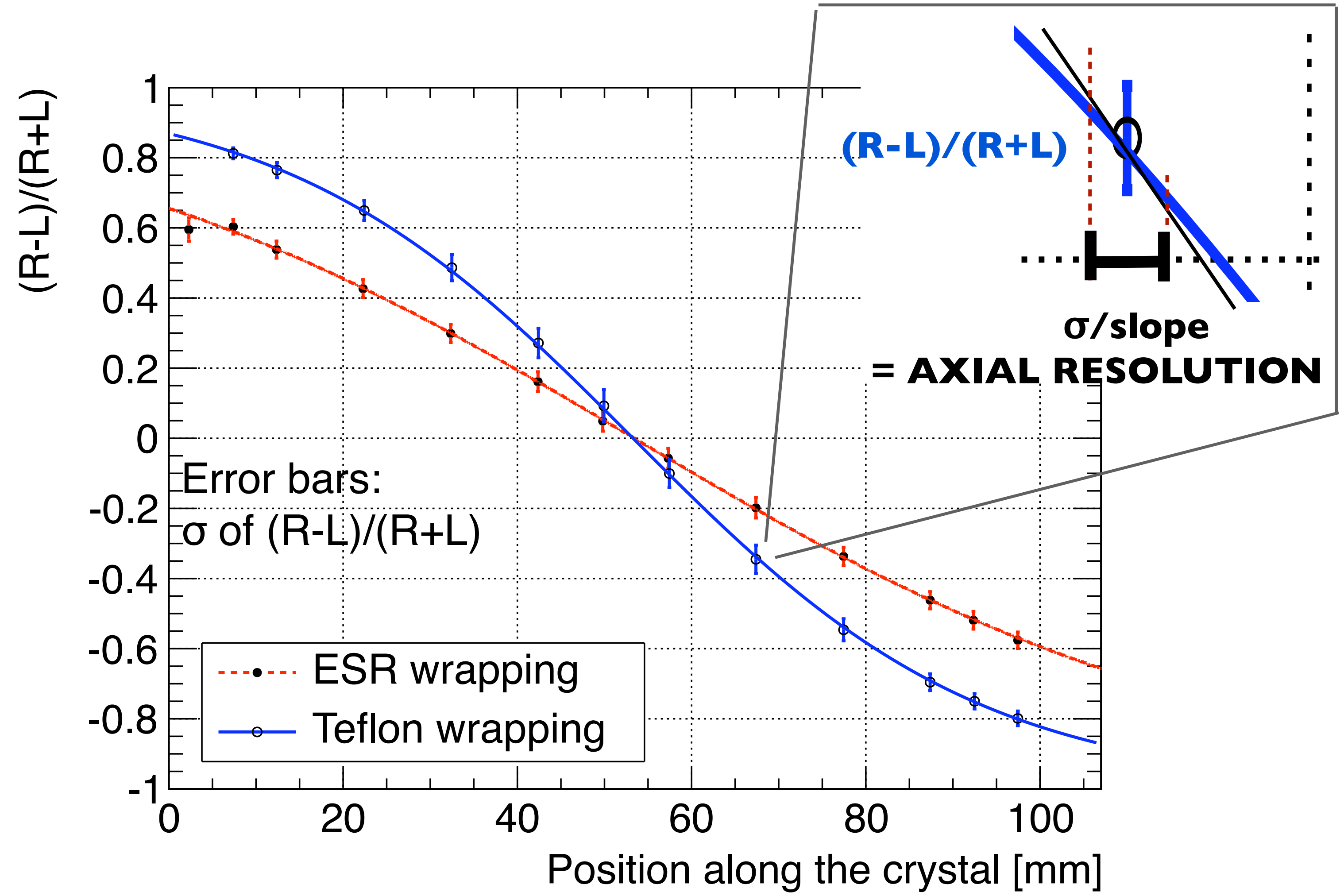
Axial resolution without WLS readout (staggered pattern)

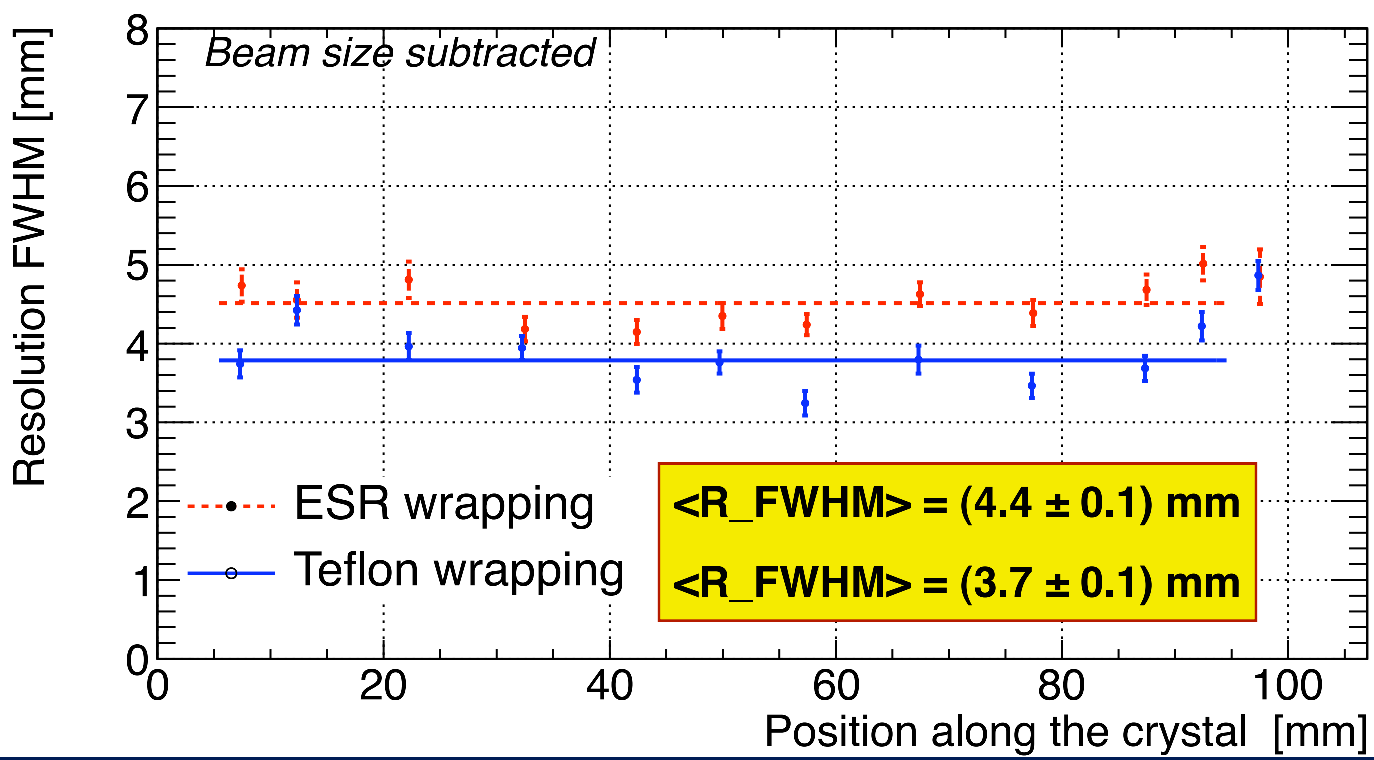
representative of the general results

100 mm long

Detected **light yield** (one side)







Dual Sided readout / No-WLS solution :

- still good spatial res
- not competitive with WLS solution (at the achieved λ and LY)
- advantages: compactness, simplicity, nr channels...

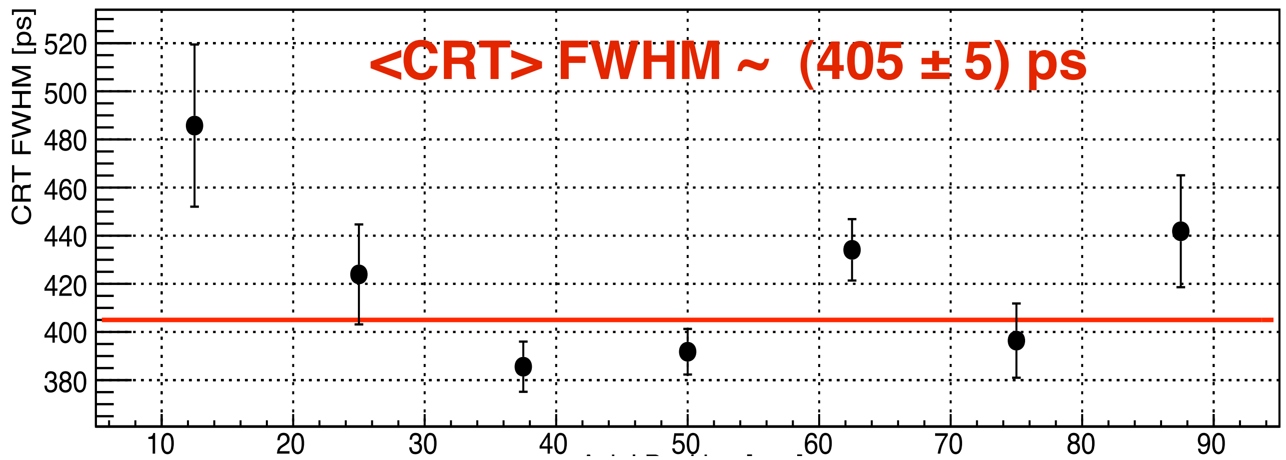
Timing performance of surface treated crystals

Which timing performance can be achieved with surface treated crystals ?

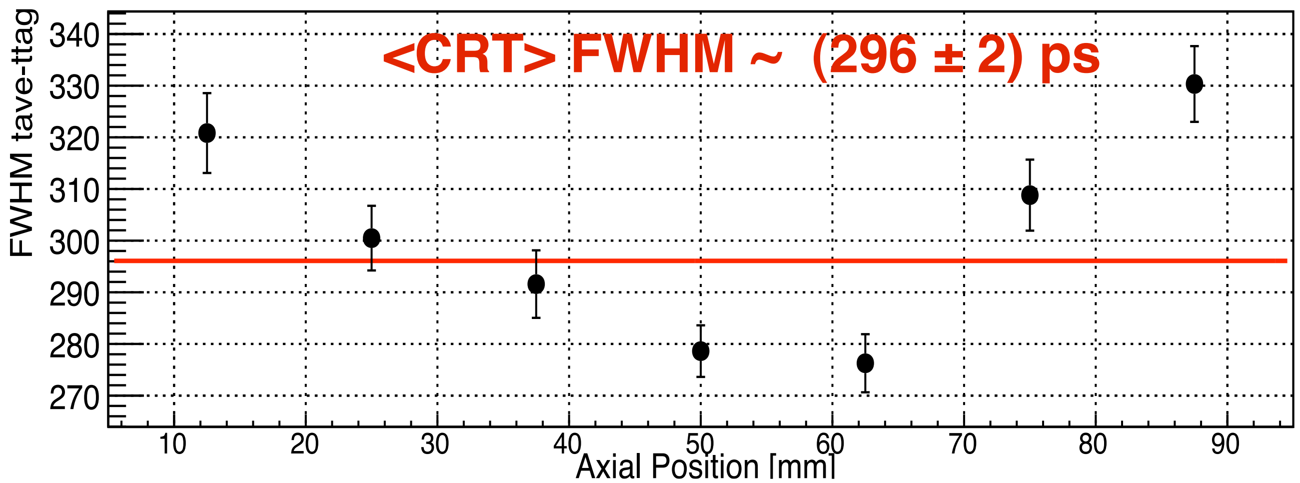
100 mm long crystal (t_ave) + tagging crystal

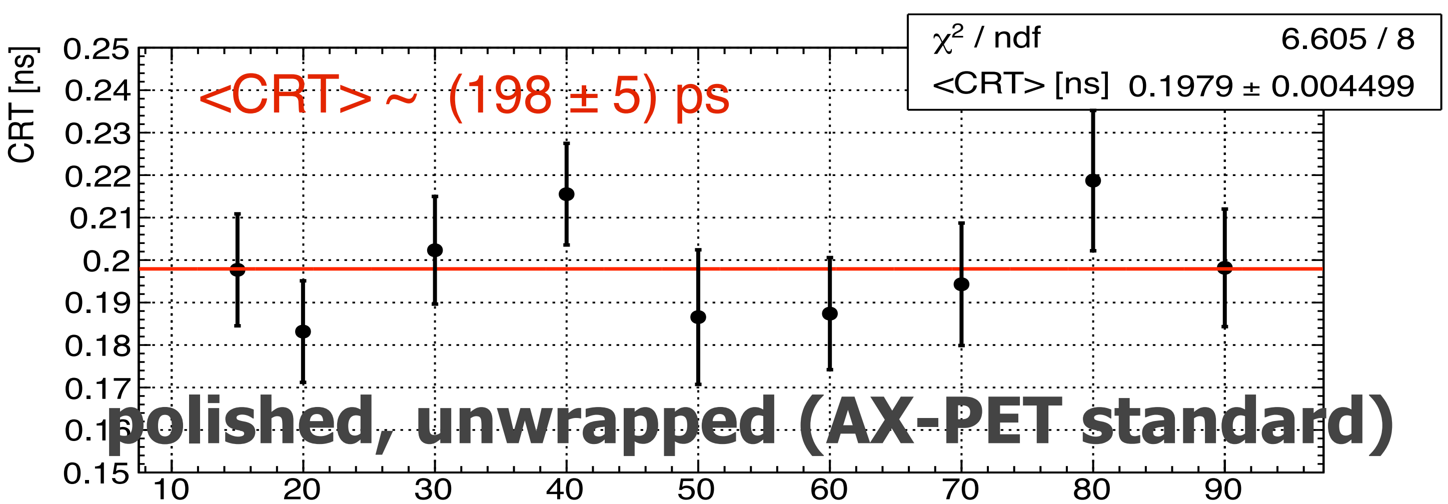
tested crystal: aligned etching,
4 faces, teflon/ESR wrapping

teflon



ESR





polished, unwrapped (AX-PET standard)

<u>intrinsic resolution FWHM</u>

- polished ~ 149 ps

- treated surf, teflon ~ 383 ps
- treated surf, ESR ~ 266 ps

Surface treated crystals
wrt polished crystals :

~ x2 deterioration of absolute timing resolution
(on average)

and
non uniformity

Usage of long axially oriented crystals for PET applications: AX-PET Demonstrator and beyond

AX-PET Demonstrator :
fully operational demonstrator for a PET detector (not a real scanner!), based on the novel axial geometry. Characterized. Successfully used in several image reconstructions.

Time Of Flight capabilities :
Axial geometry (long axial crystals) and time of flight capabilities can both coexist !
Need proper photodetector and readout system.
Need to correct for the path length dependence of the arrival time of the photons.
(our measurements : **dSiPM dual sided readout**, average timing => **CRT ~ 211 ps**)

If we would be ready to compromise on the axial resolution as well as on the timing **satisfactory axial resolutions with dual sided readout** (by light sharing technique) is achieved, **without the WLS strips solution**
(our measurements : Resolution ~ 4 mm FWHM (100 mm long xtals))

If new generation timing resolutions will be within reach (few 10's ps)
=> very interesting for axial coordinate definition in long crystals with dual sided readout **by timing considerations** (and without "destroying" the crystals)
(our measurements : $\Delta t/\Delta z$ ~ 15 ps/mm from dual sided readout)

Usage of long axially oriented crystals for PET applications: AX-PET Demonstrator and beyond

AXPET collaboration
CERN, ETH Zurich,
IFIC and University of Valencia,
INFN Italy (Bari, Cagliari),
Ohio State University,
University of Michigan, University Oslo,
Tampere University