Construction and tests of an in-beam PET-like demonstrator for hadrontherapy beam ballistic control

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Outline

1. The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

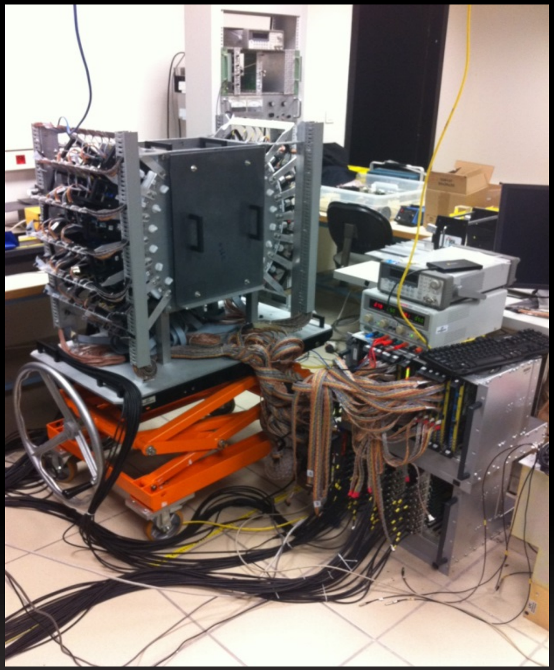
2. Design of the LAPD Demonstrator

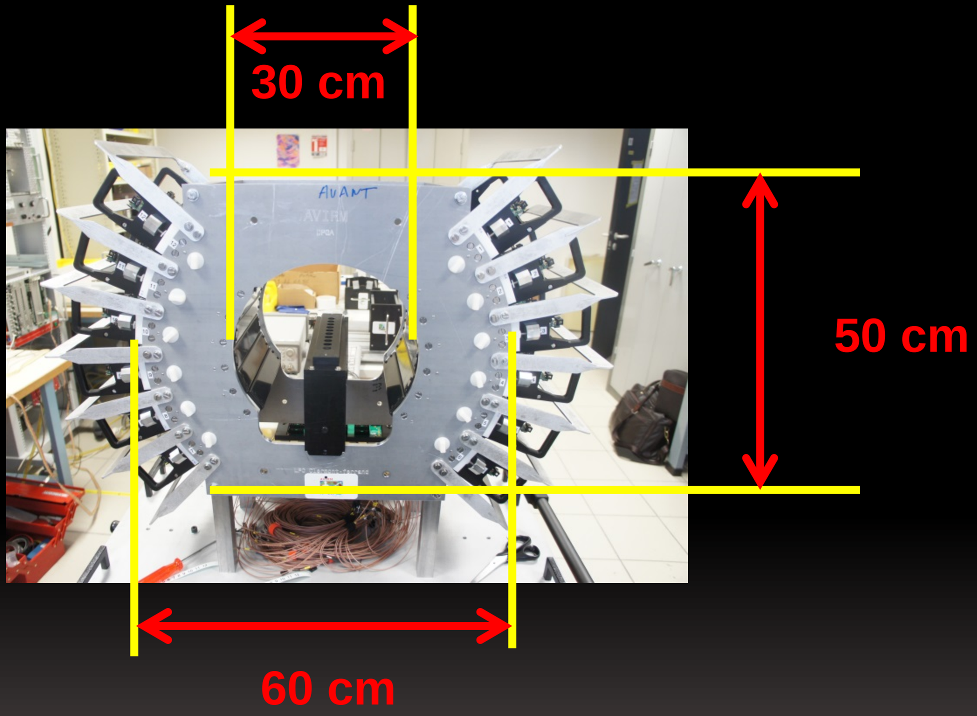
3. Estimation and simulation of the LAPD performances

4. First In-beam Test at Heidelberg Ionenstrahl Therapiezentrum (HIT)

5.Conclusions and Perspectives

1. The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments





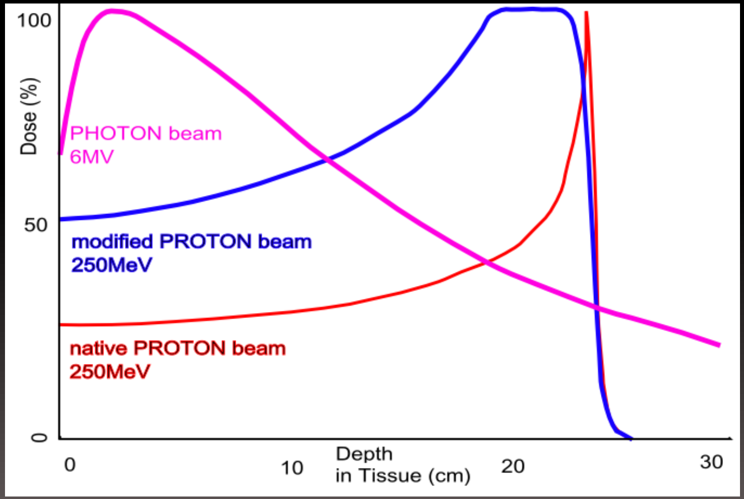
Objectives → Design of a demonstrator in order to test technical choices (electronic DAQ,…), test of trigger for selection of good events, in-line and off-line analysis, event's reconstruction

1.The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

Particle therapy is a reliable treatment of unresectable and radioresistant tumors that uses light ions (p, He^4, Li^7, C)

Particle therapy is based on specific interaction of hadron with matter
➔ Bragg peak which plots the energy loss of ionizing radiation during its travel through matter

- ✓ Highest dose in the volume of the tumor while sparing the surrounding healthy tissue
- ✓ Better biological efficacy to kill tumors (C)



The dose produced by a native and by a modified proton beam in passing through tissue, compared to the absorption of a x-ray beam

Quality assurance of the treatments

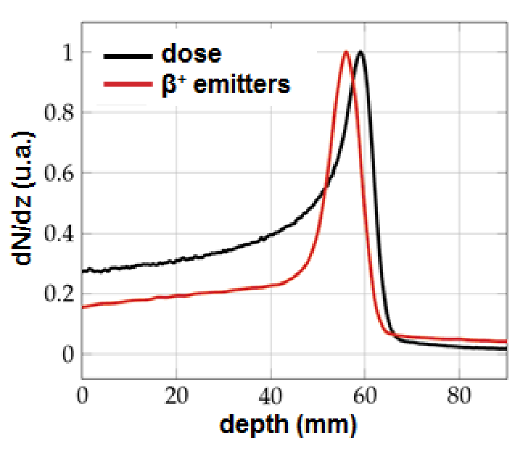
Need to monitor the range of the beam up to the Bragg's peak

1.The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

Unlike conventional radiotherapy, many secondary particles are produced during the treatment (nuclear reactions)

The Quality assurance of treatments is based on the measurement of these secondary particles

- β^+ emitters from induced radioactive isotopes
- Prompt gammas (Synchronous emission with beam spill)
- Secondary protons



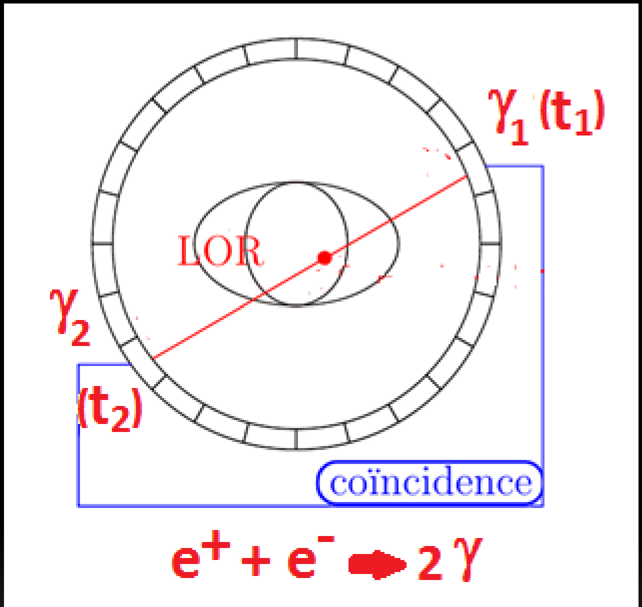
Geant 4 simulation : 163 MeV.u^{-1} C^{12} dose profile and secondary β^+ rate induced by the beam in water equivalent material [PhD Lestand 2012]

We concentrate on the production of secondary radioactive isotopes

- Short half-life : ^{11}C (20 min), ^{15}O (2 min), ^{10}C (20 s)
- Low activity induced ~ 100 Bq/Gy/cm^3 (MBq / Gy /cm^3 for clinical PET)

1.The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

β^+ activity detection (as in clinical TEP)



β+ emitters

- ➔ asynchronous disintegration
- ➔ a pair of annihilation gamma rays
- ➔ Energy = 511 keV

Emission

- ➔ In opposite direction (≈180°)
- ➔ At the same time (correlation in time)

One Event define 1 line of response (LOR)

However significant production of other particles γ, n, p

- ➔ Simultaneously in time with the beam spill
- ➔ Spoil the measurement of the "true" coincidence with "random" coincidences

➔ Contribution of the noise is function of the beam time structure

1.The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

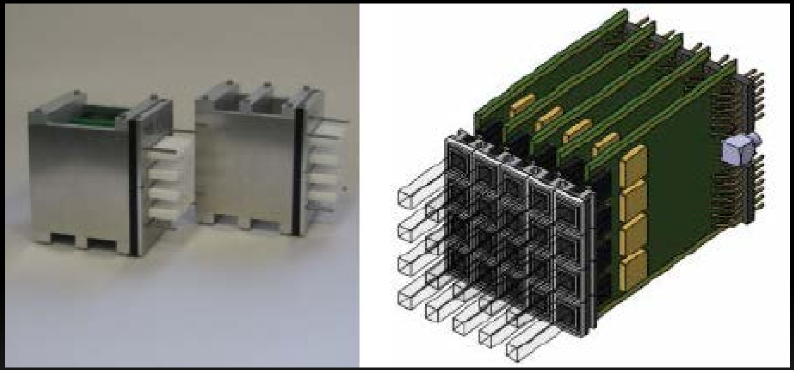
On-line measurement (during treatment) ➔ Measurements could be in-room and off-line

➔Reduce the influence of metabolic washout (biological diffusion of β+ emitters)

➔But physical noise (prompt gammas)

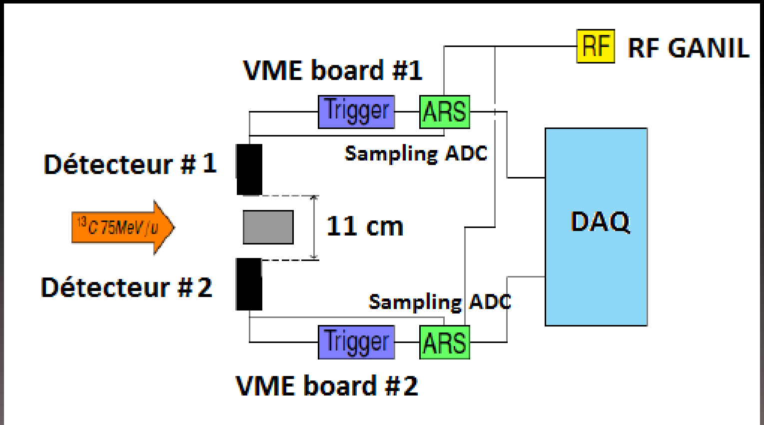
➔ Selection of good coincidences

First tests on beam with a small acceptance demonstrator



2 Detection Head (2x20 channels)

APD Hamamatsu + LSO crystal

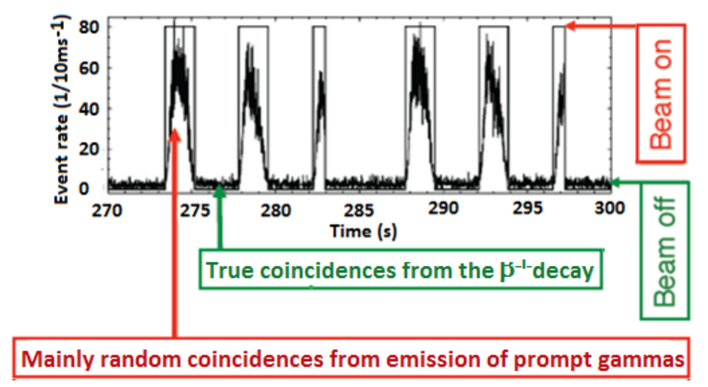


1.The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

$\mu=2$

$t_{event}=(t_1+t_2)\backslash 2$

$\tau=(t_1-t_2)\in[-7ns,+7ns]$



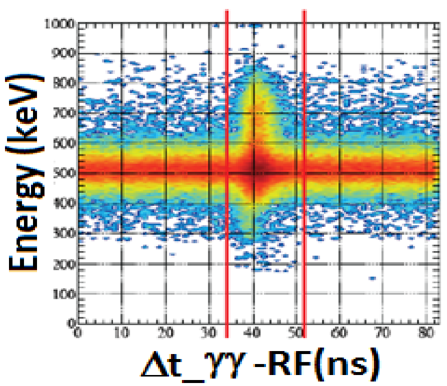
$\mu=2$

$t_{event}=(t_1+t_2)\backslash 2$

$\tau=(t_1-t_2)\in[-7ns,+7ns]$

GANIL C^{12} Pulsed beam

Energy (MeV.u $^{-1}$)	Intensity ions.s -1	Beam Spill (ns)
75	1×10^8	83



At GANIL, sufficient statistic of good events between two successive spills

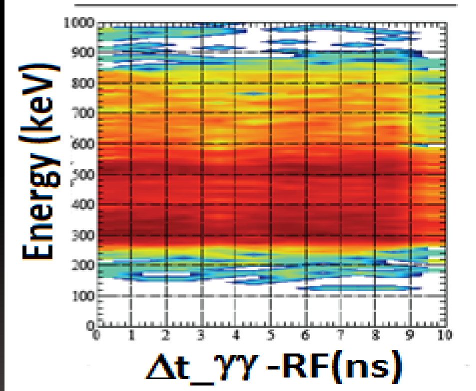
Use of the RF signal representing the accelerator radio frequency as time reference

$$\Delta t_{\gamma_1\gamma_2}\text{- RF} = (t_{event} - t_{RF})$$

The development of an effective online PET system needs to define and implement an effective in-line "trigger" to select the true coincidences

CP Orsay (C230 IBA) proton continuous beam

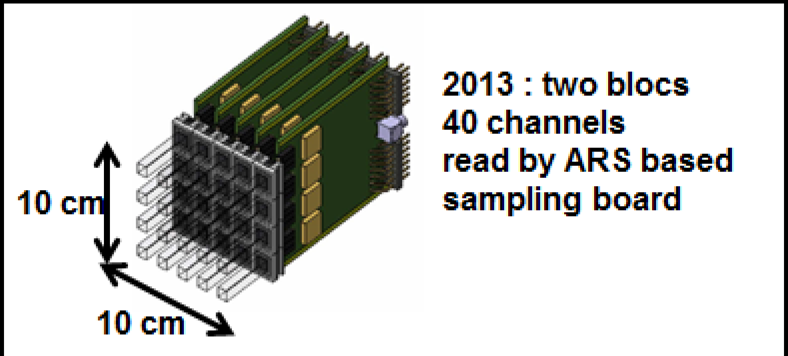
Energy (MeV.u $^{-1}$)	Intensity ions.s -1	Beam Spill (ns)
86	6.25×10^{11}	9.4

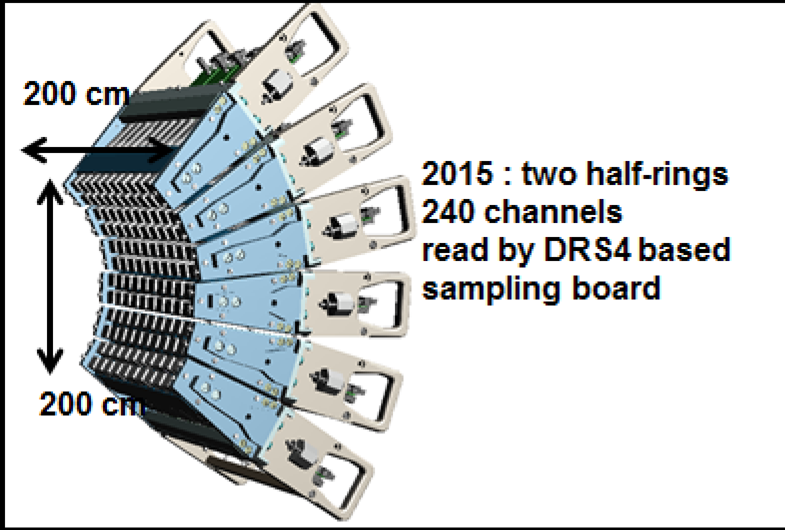


At CPO many "random coincidences" as well as a large acquisition dead time

1.The LAPD : A demonstrator of *in-beam* PET for quality assurance of hadrontherapy treatments

2015 : Assembly of a second demonstrator

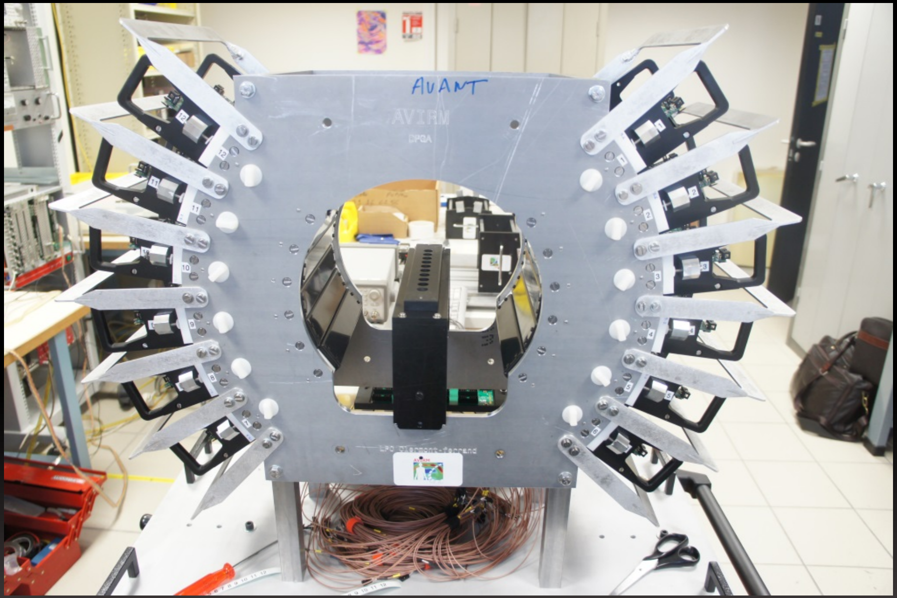




Improvements

- ✓ to get a larger number of channels (2x20 → 2x120)
- ✓ As in first demonstrator photodetector's signal read by sampling electronics but with higher bandwidth (2 GS/S → 5 GS/S)
- ✓ Replace VME based DAQ by xTCA based DAQ (decrease dead time)

2. Design of the LAPD Demonstrator



2.Design of the LAPD Demonstrator

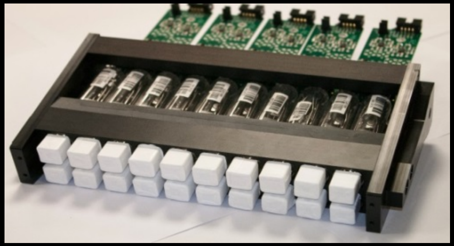
Mechanical Assembly

1 Channel = 1 crystal (LYSO) + 1PMT

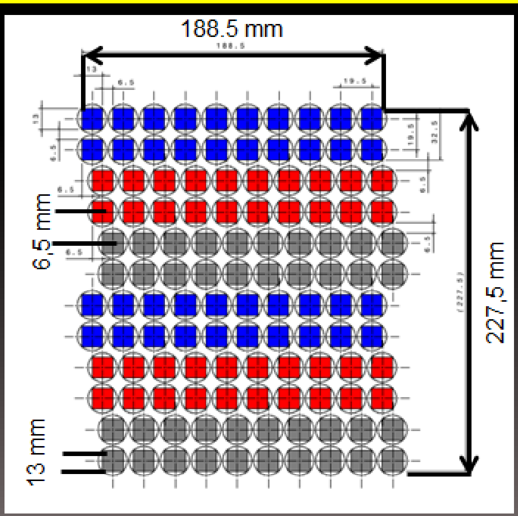
1 Quartet = 4 Channels

4 PMTs are welded together in a Quartet with a single HV power supply

1 Row = 5 Quartets



20 channels are put together in a detection row



Schematic view of the crystals of one half ring

Each row are shifted in *z* direction

- to minimize the dead zone
- 2 Lines Of Response (LOR) can't have the same coordinates

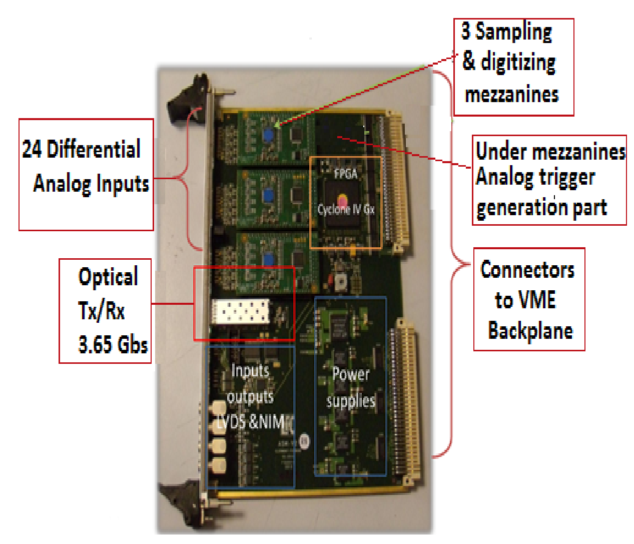
2.Design of the LAPD Demonstrator

Read-out electronic

Sampling Electronic (SCA technology)

ASM custom boards : sampling electronics based on DRS4 chips (PSI)

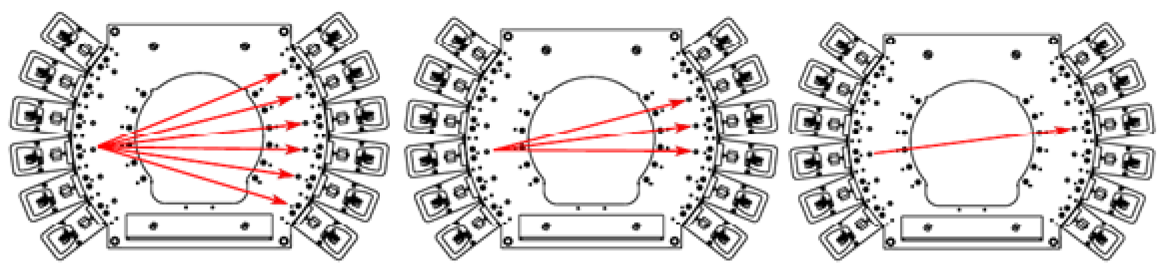
- switched capacitor array
- buffer depth : 1024 samples
- sampling rate : up to 6 GHz
- Digitizisation :ADC 33 MHz, 12 bits



3 levels of Trigger

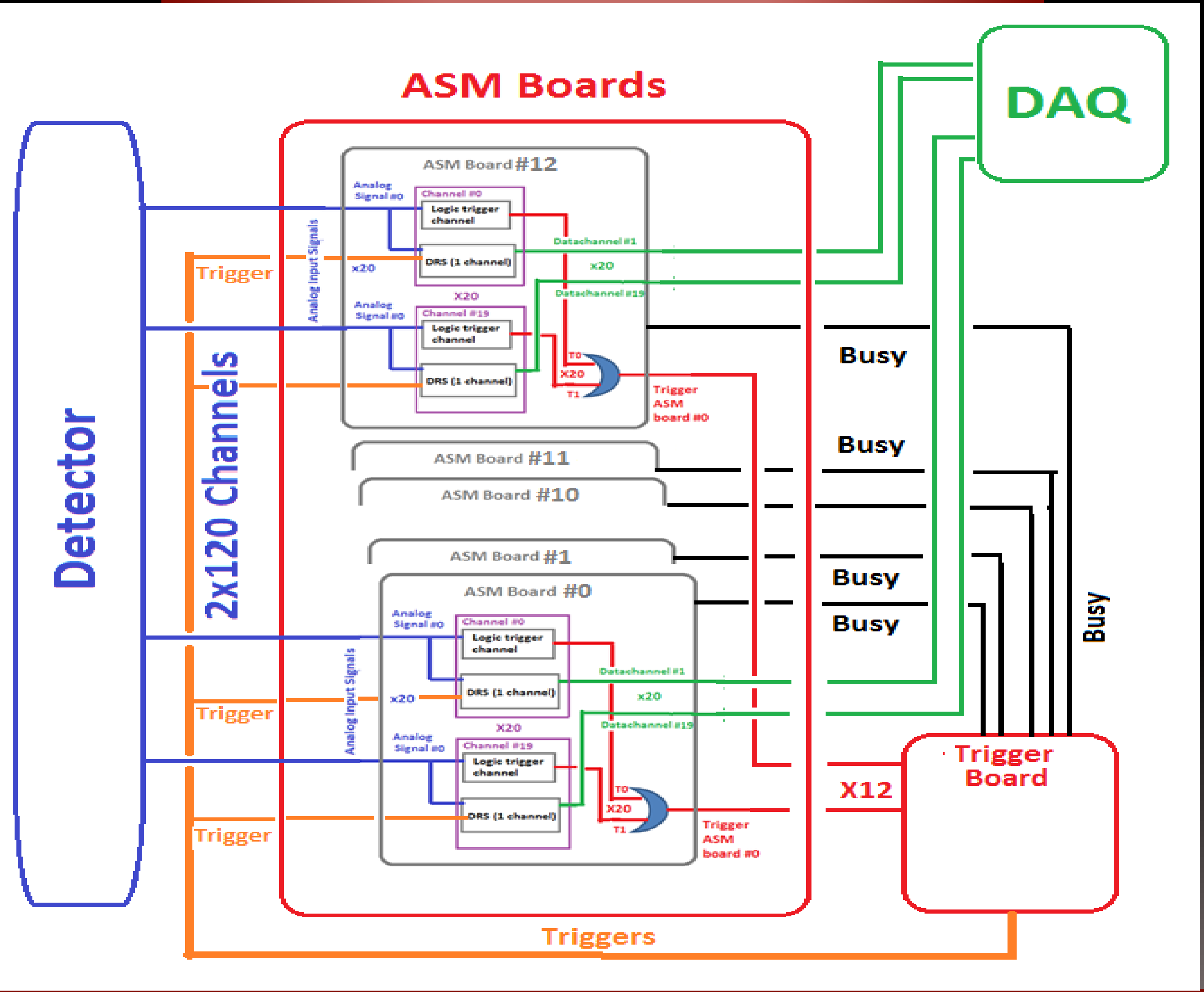
- energy selection with two thresholds
- temporal selection : 2 events in less than 20 ns
- geometrical selection through Trigger Board

Geometrical Selection



2.Design of the LAPD Demonstrator

Read-out electronic



2.Design of the LAPD Demonstrator

DAQ

Up to now

- ✓ The data are transferred via a VME bus between the ASM boards and a CPU in the same VME crate
- ✓ Data transfer between the CPU (Server) and a dedicated PC (Client) via an Ethernet link

The VMEbus induces a large dead time

Ongoing work

- ✓ Use of modular and open MicroTCA standard for building a high performance DAQ system in a small form factor.
- ✓ Data transfer between ASM boards and the MicroTCA crate by optical fibers (3.2 Gb/s for 24 channels)

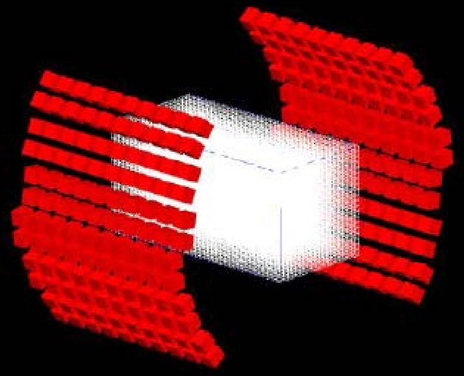
μTCA Crate

MicroTCA was originally intended for smaller telecom systems and has high bandwidth performances

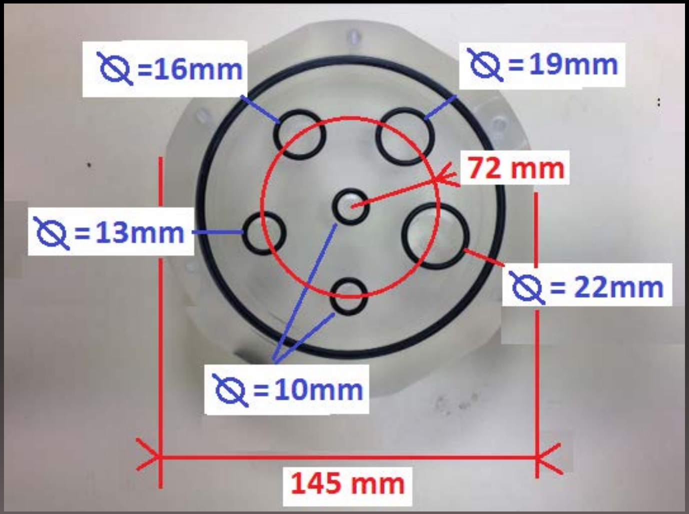
AMC Board

3. Estimation and simulation of the LAPD performances

Simulations of the DPGA performed using GEANT4



Matrix of the crystals used in simulation and reconstruction algorithms



Measurements performed using PMMA Phantom filled with FDG in hospital environment

3.Estimation and simulation of the LAPD performances

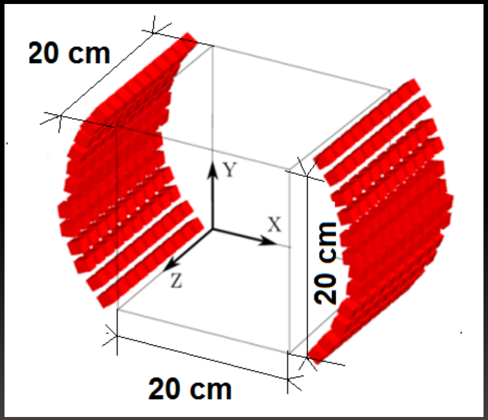
Full detector performances

Measured performances with FDG

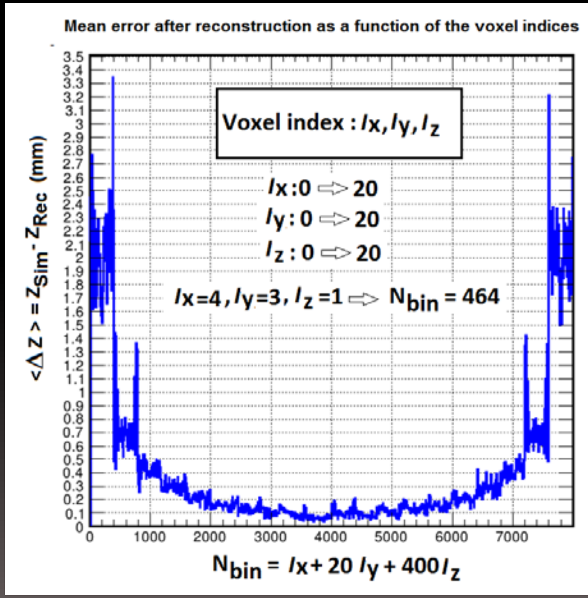
- energy resolution at 511 keV : 14 %
- coincidence resolving time : 3 ns

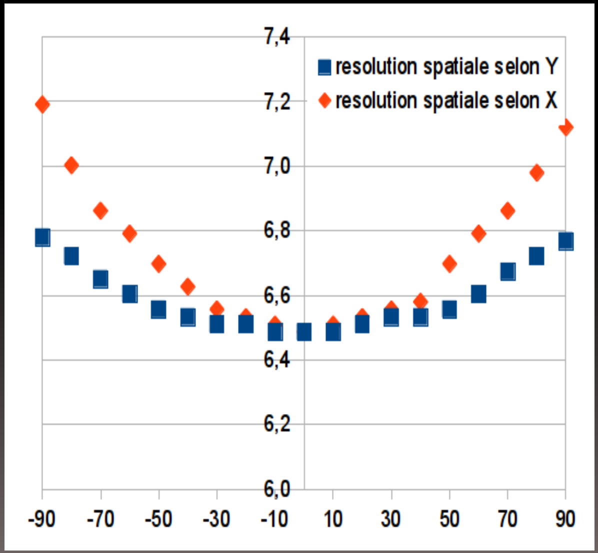
Mean error after reconstruction
very low (<0,5mm) except near the edges

Spatial resolution for fixed value of x and y
Spatial resolution between 6,5 mm and 8 mm



Annihilation positions distributed simulated uniformly in a 20x20x20 voxelized cubes





Iterative reconstruction algorithm

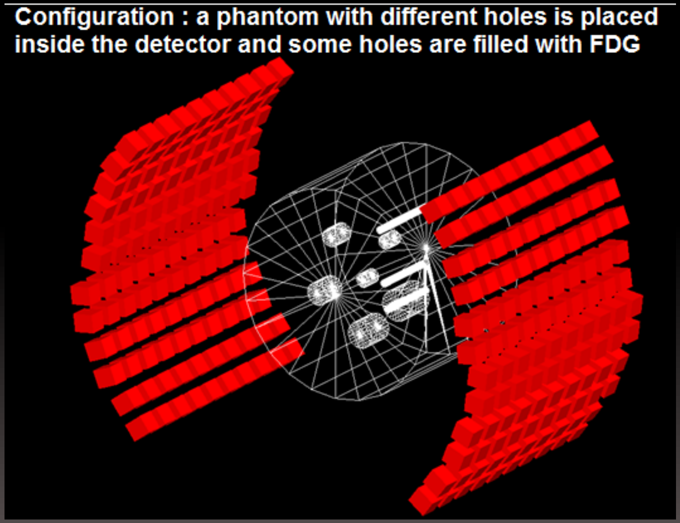
Use of MLEM algorithm

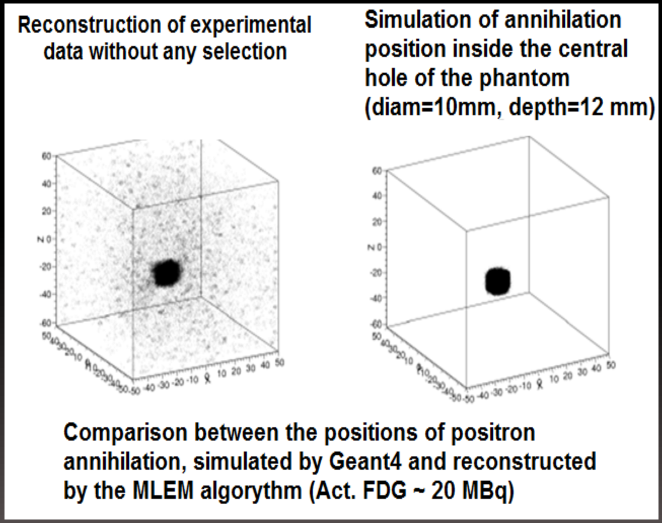
Known
Matrix of hits in crystals

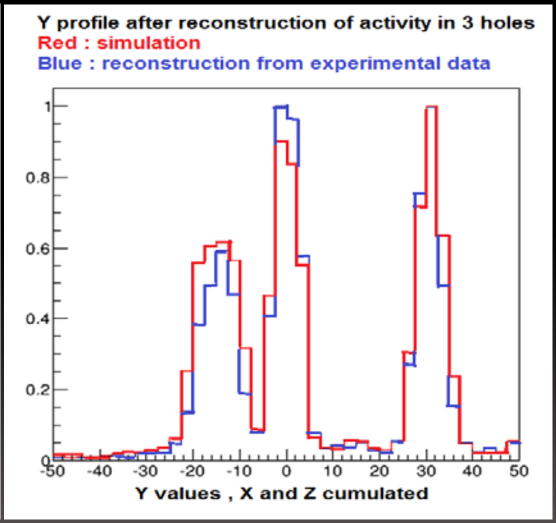
➡

To reconstruct
β^+ activity distribution

Projector (voxels 2x2x2mm^3)
Calculated by full Monte-Carlo Simulation





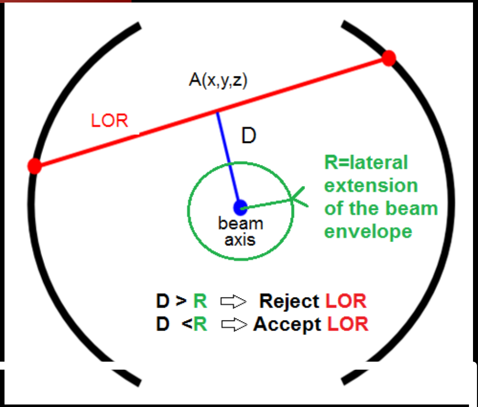


3.Estimation and simulation of the LAPD performances

"Minimal approach" reconstruction

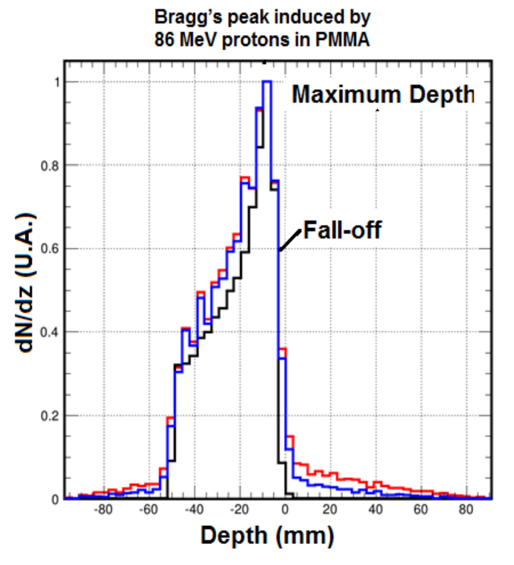
"Minimal approach" Algorithm

- ✓ Compute the position of the point A on the LOR with D minimum
- ✓ Define the maximum extension R of the beam envelope
- ✓ Reject or accept the LOR if D is less or greater than R

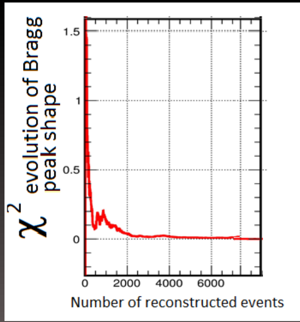


Algorithm convergence

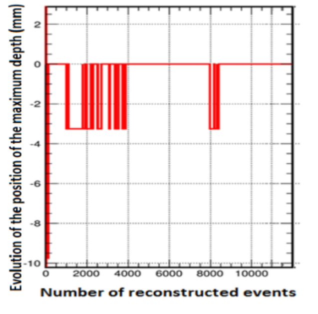
- ✓ convergence of the $\chi 2$ of Bragg's peak shape
- ✓ Z of the maximum depth
- ✓ Z of the fall-off depth
- ➔ Convergence in less than 10.000 events (50.10^6 protons)



Black : Position of annihilation
Blue : Reconstruction from true coincidences
Red : Reconstruction from all events

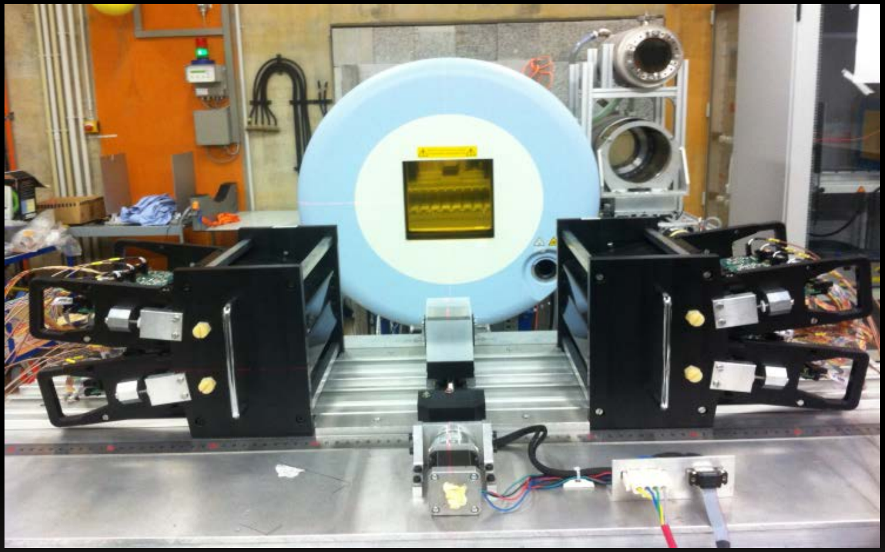


Convergence of the $\chi 2$ of te Bragg's peak shape



Evolution of the position of the maximum depth (mm)

4. First In-beam Test at Heidelberg Ionenstrahl-Therapiezentrum (HIT)



1/3 of the LAPD tested at
Heidelberg Ionenstrahl-Therapiezentrum (HIT)

4. First In-beam Test at HIT

Specificity of HIT beam

- ➔ Beam produced by synchrotron
- ➔ RF knock-out slow extraction method
- ✓ the spills are not always extracted at the same RF phase
- ✓ the RF is not usable as time reference

➔ Need a time monitoring in the Beam for time reference

Beams Used for Test

150 MeV	proton	1.2 x 10^9 p/s	➔	0.5 proton/bunch	period	252 ns
100 MeV.u-1	carbon e	2x10 ^{6} ion/s	➔	3 22 ion/bunch	period	267 ns

4. First In-beam Test at HIT

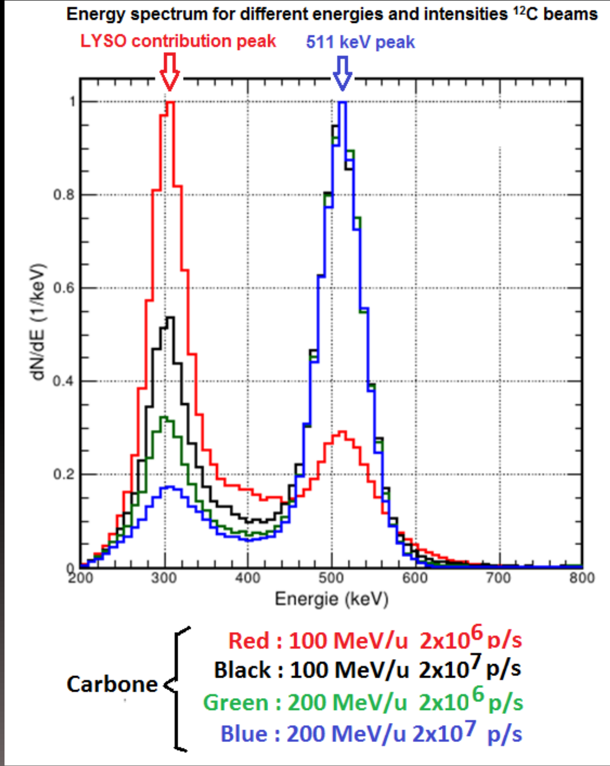
Useful characteristics for events selection

- Measurement of 511 keV Spectra after target irradiation and activation
- Only β+ disintegration (no beam induced background)

- energy resolution at 511 keV : 14 %
- coincidence resolving time : 1,8 ns

LYSO contribution

- increase with acceptance and crystals number
- decrease with energy and intensity (increased β^+ activity)



^{12}C run 100 MeV/U & 2 x10^6 p/s (0.5 p/bunch)

- too few induced β^+ activity
- signal dominated by LYSO coincidences (LYSO+LYSO or LYSO+other)

➔ Need a Selection algorithm against LYSO noise

proton run 150 MeV & 1.2x 10^9 p/s (322 p/bunch)

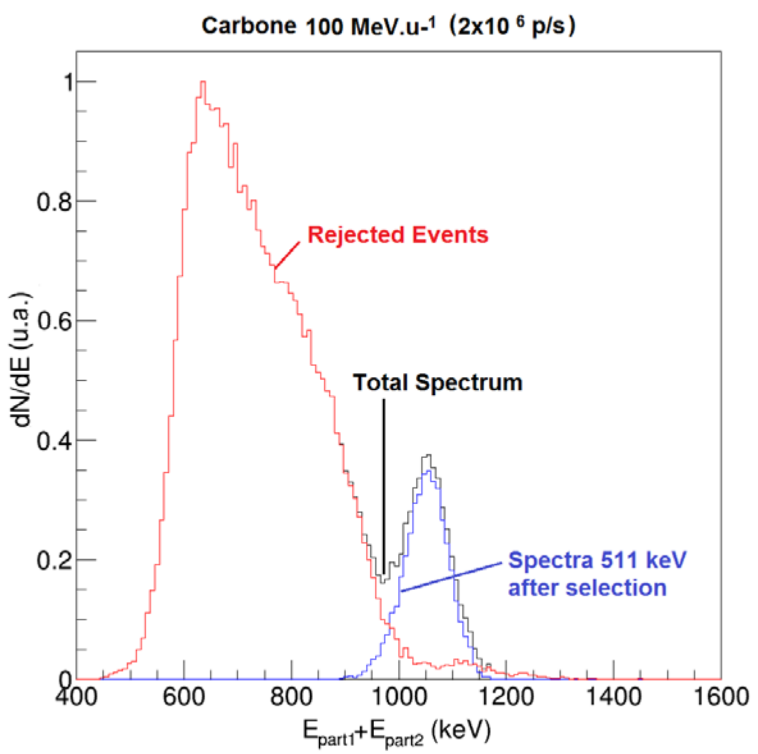
- Beam extraction configuration decrease dead time
- Detection during beam spill extraction

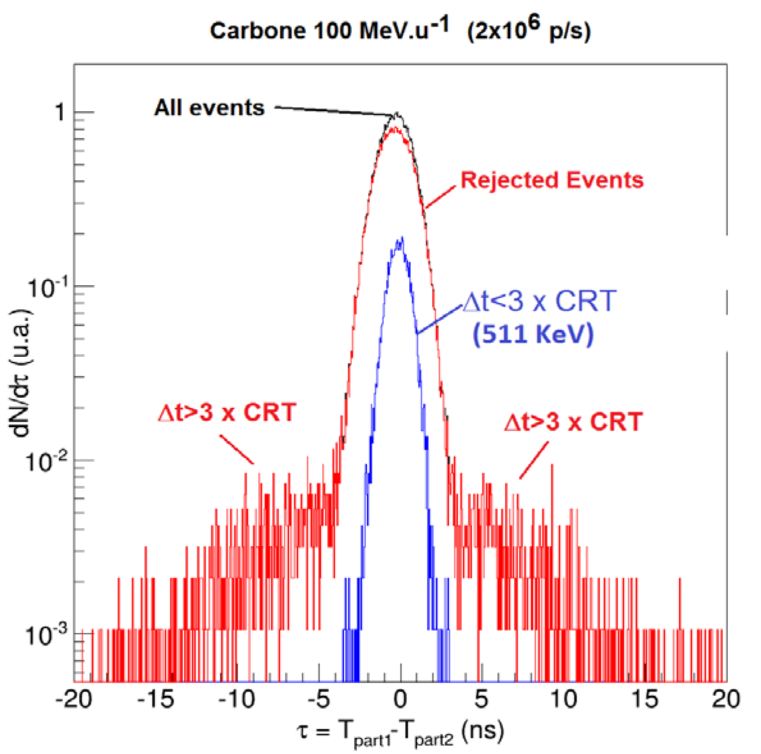
➔ Need a Selection algorithm again prompt noise

4. First In-beam Test at HIT

Data selection using cuts

Event's multiplicity = 2
Cut on Energy : 511 KeV +- 3 σ
Cut on time : +- 3 Coincidence Resolving Time





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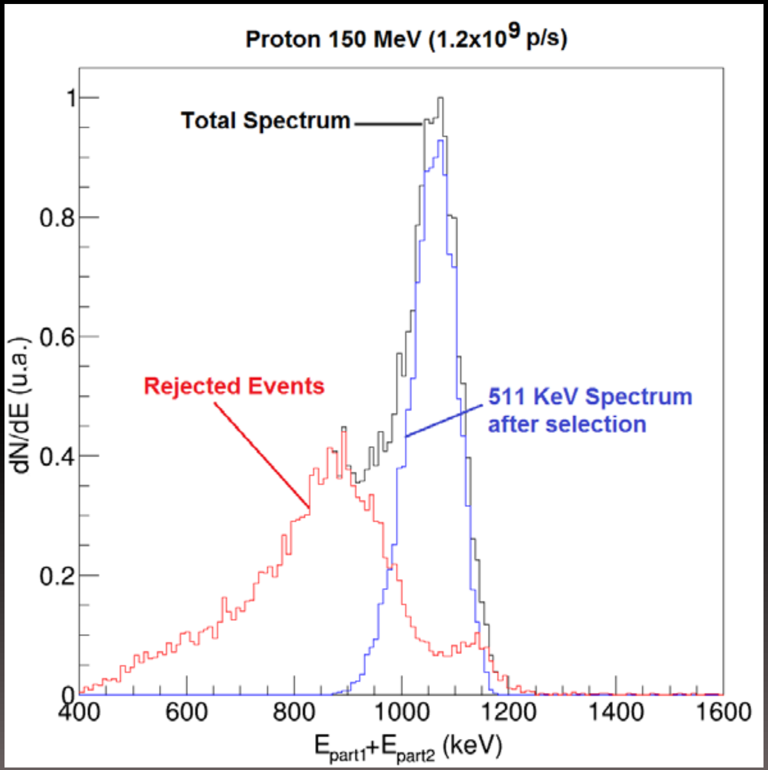
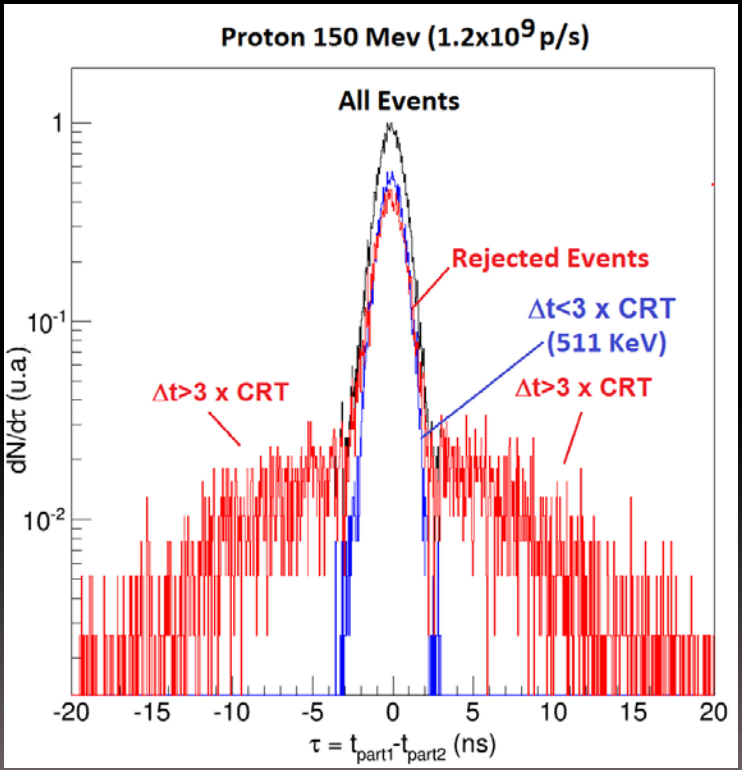


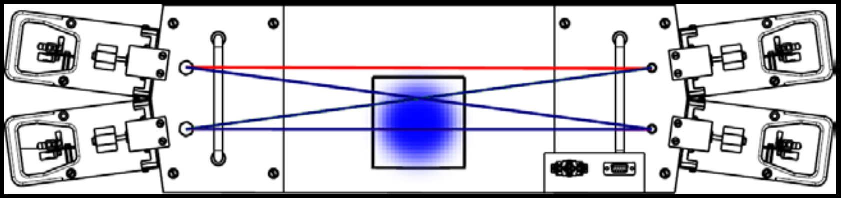


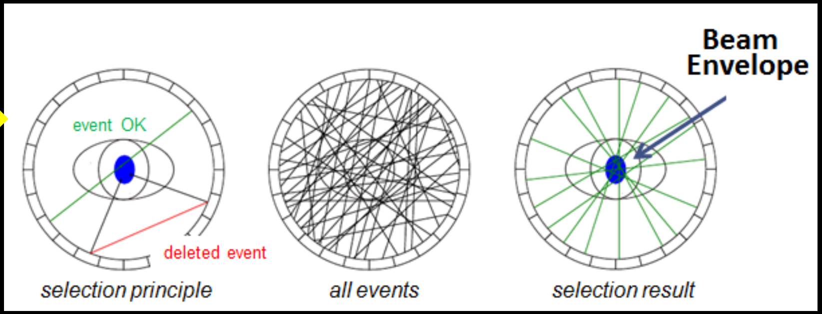
Data selection using Minimal Approach

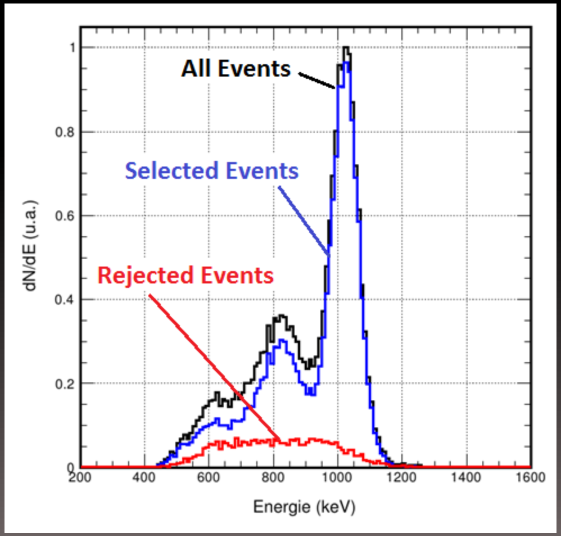
Geometric selection not very efficient in this test configuration

- **β^+ activity is induced in close vicinity to beam path**
- **HIT beam cross section: protons ≈ 4,5 cm, ^{12}C ≈ 2,5 cm**

➔ almost all the line of response detected intersect the beam path







5. Conclusions and Perspectives

Main Problem ➔ Dead time (about 70%) ➔ Highest Priority

➔ Acquisition rate : maximum (with 4 boards) : 96 Hz

- strongly limited by VME DAQ
- time for reading ASM boards on VME backplane

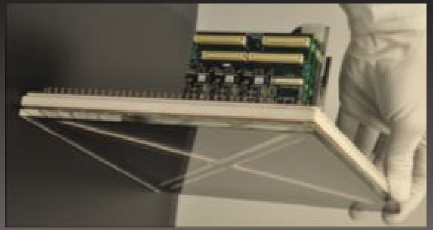
➔ On Going Solution : fast µTCA data acquisition (DAQ)

- data transfer via optical link
- data rate : up to 3Gb.s-1 for 24 channels

Test of the demonstrator on proton beam at Centre Antoine Lacassagne (Nice) using a S2C2 230 Mev proton beam (Proteus ONE)

Multimodal configuration combining the detection of γ and β + in a the clinical environment (Project *ProtoBeamLine* France Hadron)

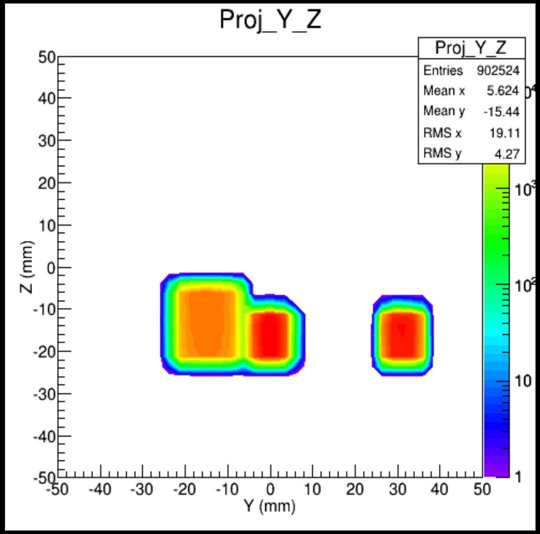
Test of large aera MCCPMT
➔ use the TOF for event selection and reconstruction



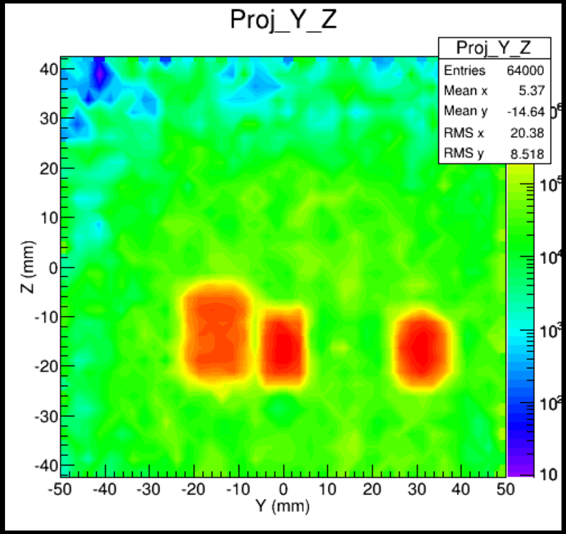
thank you for your attention !!!

Estimation and simulation of the LAPD performances

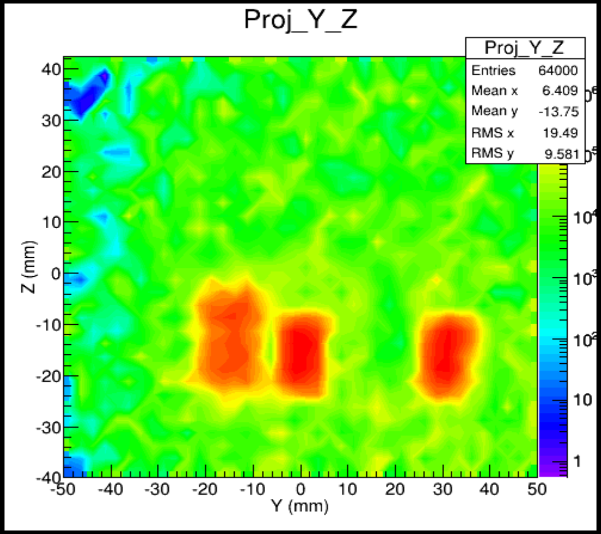
Iterative reconstruction algorithm



Simulation



Reconstruction of the Simulation



Reconstruction of the Experimental Data