Semesterthesis AX-PET

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1 Abstract

The AX-PET group at CERN is trying to improve the design of the current positron-emission-
tomographs by changing the alignment of the scintillation crystals and thus eliminating the
parallax error. This report illustrates the functionality of the detector and my work as a four
week semester thesis. In the first week the experimental setup was reassembled in order to
move it to Zürich. The rest of the time was mainly used for analyzing the data of previous and
current test runs to localize the radioactive sources and dealing with the technical problems of
the increased temperature due to the high power consumption of the readout electronics.

2 Introduction

2.1 Study of metabolic processes

The main idea of a PET is to find tumors inside the human body. The patient receives a radio
traces attached to a metabolic active substance, typically sugar, that accumulates at the tumor
due to it’s increased metabolism. The radioactive isotope decays in a $\beta^+$ decay, it emits a
positron. The positron annihilates with an electron and emits due to conservation of energy and
momentum two photons of 511keV, the rest mass of an electron. The two photons are emitted
back to back as the momentum of the positron and the electron are negligible. One can measure
the emitted high energetic photons by some scintillating crystals, in our case Lutetiumyttri-
moxoorthosilicat ("LYSO", LuYSiO$_5$:Ce$^{3+}$), a new material that has various advantages against
the common NaI. It is easier to work with due to better mechanical proprieties, "has a high
light out put, quick decay time, excellent energy resolution and low cost"[1]. 511 keV is enough
energy to excite an inner electron of a heavy atom. By deexciting, the atom emits a lot of
low energetic photons in arbitrary direction. Due to the law of refraction, some of the photons
remain inside the crystal, so they can be detected easily by a photomultiplier on one end. By
measuring the detected photons and using some statistics, one can calculate the energy of the
detected radiation.

2.2 The typical PET

In a typical positron-electron-tomograph (PET) there are many such crystals radially orientated
around the center axis. By detecting two photons in coincidence one can "draw a line" between
the places of the two detections. The two photons in coincidence can be measured as time
between two decay is usually much lower than the time it takes to detect a photon. As the
photons are emitted back to back the detection must have taken place somewhere on this line.
The time resolution of the detector is not high enough to measure the time difference of the two
detections, so the exact coordinate on this line is not known. Since the photons are emitted
in arbitrary direction and one uses a lot of such crystals arranged around the source, there are
such many lines crossing at a single point where the radioactive source is, see figure 1. In reality

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{A short overview how a PET works [2]}
\end{figure}

the resolution is reduced by various effects. The positron scatters inside the source before it
annihilates and the size and arrangement of the crystals reduces the accuracy of the coordinates
per hit. For a very high number of detections this error can be reduced, using statistics. The
LYSO need to have a certain size to increase the efficiency. The scintillating crystal have a
certain chance per unit length to detect the photon. The remaining photons are the incoming ones minus the detected ones. So there is an exponential decay of the photon flux inside the detector. The photon flux of parallel incoming photons is then $\Phi(x) = \Phi_0 e^{-x/x_0}$, where $x = x_0$ is the required length of the crystal to detect 63% of the incoming photons. For LYSO, the attenuation length $x_0$ is 1.2 cm. The cross section of the crystals determines the resolution of the module and thus of the detector. The length of the crystals doesn’t matter if the source is exactly in the middle as one just draws a line along the crystal, but if it’s close to the border, the radial coordinate of the hit gets more important and there is the so called parallax error. The line differs if the hit took place at the inner or the outer end of the scintillating crystal by a distance of $\delta_p$, see figure 2. The parallax error $\delta_p$ is small for regions in the middle if the detector but increases for off center regions.

As the only important value is the angle resolution one could also increase the size of the detector ring and add some more modules but this would increase the cost of the apparatus enormously. So one has the choice between high accuracy and small crystals, low accuracy and big crystals or a very expensive apparatus. For economical reasons a real PET is as small as possible and one chooses a mix of accuracy and detection efficiency. The decay rate of the source should not be increased as the radiation is unhealthy for the patient.

![Figure 2](image)

**Figure 2:** If a decay takes place at the center of the detector, accuracy is determined by the cross section of the crystal. For decays at off center regions, the length of the crystal decreases the resolution due to the parallax error labeled by $\delta_p$.

2.3 Our improvements, the AX-PET

The parallel arrangements of the LYSO to the central axis practically eliminates the parallax error. They are read out by Multi Pixel Photon Counters (MPPCs) from Hamamatsu, type S10362-11-050C with 3600 pixels of (50x50) $\mu$m$^2$ and an active area of (3x3) mm$^2$ [3]. Wavelengthshifters (WLS) added perpendicular to the LYSO gain us the coordinate along the crystal. They absorb the photons leaving the LYSO in a high angle due to the refraction law and the measure them with MPPCs custom designed by Hamamatsu with dimensions of (3.22x1.19) mm$^2$.
Figure 3: The alignment of the WLS and LYSO. The MPPCs of the WLS are in reality octagonal.

The leaving photons hit usually three or four neighboring WLS, a so called cluster. By calculating the center of gravity of these hits, we find the precise coordinate of the hit along the WLS. Like this we have a three dimensional lattice absorbing the photons and thus all the coordinates of the detection. One coordinate is discrete due to the discrete number of LYSO, the other one along the WLS is continuous as the center of gravity is for a high number of hits continuous.

The main problem is that everything gets more complicated due to the additional elements. The crystals need to be calibrated due to the saturation of the gain at high energy. Therefore we can use the 202 and 307 keV peaks of the Lutetium due to the radioactive decay at this energy and the 511 keV peak of the $e^+e^-$ annihilation. As the gain is linear for low energies, for a hit with 0 keV there should be no photons be detected at all. The peak at 63 keV could not be measured.

With these layers of LYSO and WLS there is a higher resolution of the detections and thus of the detector. But as we are not theoretical physicists, the most difficult part is not the idea itself, but the implementation of it. As always, there turned out to be a lot of unexpected problems.
Figure 5: The peaks at 202 and 307 keV of Luthetium are used to calibrate the WLS.

Figure 6: Due to the saturation of the MPPC at 511 keV, the energy of the hits is not linear to the energy of the detections but slightly higher.
3 Experimental setup

3.1 The detection modules

Figure 7: A module for detecting the radiation, on the top the green WLS and perpendicular to it the LYSO crysralls are visible.

Each module consists of six layers of LYSO/WLS lattice and a black light shield between the layers. In each layer there are 8 LYSO and perpendicular on it 26 WLS. For the read out they have the MPPCs on alternating ends to improve the packing fraction as the MPPC are bigger than the crystals. The different layers of LYSO crystals are slightly shifted against each other to avoid line ups of the gaps. This increases the detection efficiency slightly as no photon can escape the detector without passing a scintillating crystal. As the energy of the hits can be calculated, one can distinguish between a photoelectric effect and Compton scattering. There are attempts to find the first hit by some calculation but they are not yet completely successful.

The gain of the MPPC depends very strong on the supply voltage and the temperature. It is very important to have a constant gain to calculate the energy of each hit exactly. The BIAS voltage supplying it has been measured before the experiment and is adjusted to the temperature.

3.2 Onto the chariot

Because we are dealing with very light sensitive apparatus, the LYSO, WLS and MPPC are inside a light impenetrable box. For our experiments there are only two modules. To stimulate the round arrangement of a real PET, one of the modules can be rotated around the probe by up to 60°, see figure 8. The mounting of the module is fixed in the center and moved by a linear motor pushing the module some cm distant from the rotational axis. The source is placed onto a motor in the center to rotate our probes instead of all the apparatus. This allows to simulate the round alignment of all the detectors around the center. The modules can also be moved against each other. One could optimize the size of the crystals for a certain radius but this was not done with our modules. Behind the black boxes, there is the front end electronics to read out the data from the MPPC. Every single multiplier has it’s own plug, but as long as every channel works we are only interested in the total output.

3.3 Data acquisition

The programs need the data of two photons in coincidence, thus exactly one hit per module and a good cluster of the WLS, this is also called a golden event. In order to measure only such events there are some thresholds to start the measurements of the detectors. The MPPCs gain a voltage as soon as they detect some photons. This voltage is almost proportional to the incident
energy and can be used to calculate the energy of the hit. As not all the photons are detected at the same time the voltage increases with time. If this voltage reached a certain value, one expects to measure a hit by a high energetic photon at the LYSO crystal. An output signal of 30 mV, the "low threshold", starts the internal trigger of the module. This threshold should cancel out the thermal photons and noise. If this trigger starts in both modules within some nanoseconds, data gets acquired. If both modules reach a value between the "high threshold" of 220 mV and the "very high threshold" of 350 mV the data is saved as a good hit. The very high threshold should avoid that measurement of very high energetic photons, e.g. two photons at the same time or cosmic radiation even though this is rather unlikely. Events with more than one hit per module are being discarded. It is not possible to find the two photons in coincidence if there are two 511 keV detections in one module at the same time. As long as the analysis of the Compton scattering is not completely successful these events need to be discarded as well. The time resolution of one single event is 200 ns because of the signal shape of the LYSO and the delay of the electronics [4]. The typical detection rate is around 3000 Hz, the number of golden events less then half of it. Thus typical measurement cycles take a few minutes and have some hundred thousand hits. For localizing a single source in the center, 30000 golden events are enough to get a reasonable result. But if we’d like to calibrate every single MPPC, e.g. for the energy resolution, we need up to a million hits to have good statistics.

3.4 Inside the chariot

The setup is arranged on a chariot hosting also the electronics. Just underneath the metal plate is the BIAS module and the low-voltage power supply for the electronics onto the chariot.
The metal box with all the green wires transfers the BIAS voltage to each individual MPPC. On the bottom of the chariot we have an analog crate (NIM) on the left to set the external threshold and ignite the trigger. On the right we have a digital crate (VME) to set the internal threshold and transfer the data between the mid end electronics and the computer, see figure 9. On the other side of the chariot we have the computer to adjust the BIAS voltage to the current temperature, read the data from the crate and control the motor for the rotations of the source and the module. Below the computer is the analogue control of the rotating motor, on the right side is the analogue control of the linear motor.

4 Analysis of data

For locating the radioactive source one needs some coordinates. They can be chosen in arbitrary direction. We chose the the x-coordinate to be the line from one module to the other. The y-coordinate is parallel to the modules and the z-coordinate is perpendicular to the surface of the table.
The LYSO crystal are then parallel to the z-coordinate, the WLS parallel to the y-coordinate.

Figure 10: The coordinate system used for the data processing. The y-coordinate is discrete due to the discrete number of LYSO, the z-coordinate is continuous as the center of gravity of the WLS is continuous and the x-coordinate is determined by the fit of the Gaussian in the z-coordinate.

The z-coordinate of the source is then given by the detection of the WLS and, as the center of gravity of the hit is continuous, a continuous coordinate. The y-coordinate is discrete as there are only few LYSO crystals, see figure 10.

### 4.1 Data processing

The main idea is to locate the radioactive source, located somewhere between the two modules. The data from the detector was analyzed with ROOT [5], an analyzing environment developed by CERN, including an own programming language, various visualization possibilities, curve fitting and much more. The binary data can be processed to so called ”trees”. The binary data itself can not be analyzed but the trees provide a lot of important data that can be processed efficiently.

The program axpet_analysis_2v0.C analyzes the tree. This gives us various histograms about every single crystal but also for the sum of it, here are some of the most relevant examples
Figure 11: Number of hits in the WLS per event of the two modules plotted against each other. The size of the rectangle is proportional to the number of hits. As expected there are the most counts at around 4 hits which is the approximate size of a good cluster.

Figure 12: Number of the LYSO instead of the WLS. Now there are the most events at one hit each. The two hits occur mainly because of the Compton scattering.

4.2 Line of response LOR

The analysis of the tree outputs also the LOR file. This has the coordinates of each hit. So the program “draws the lines” where the source should be. The program LOR.c displays this data graphically, see figure 14. We can display some hundred results with their lines of the photon propagation, or we make a cross-section with these lines. As the source for the test runs has diameter of 0.25 mm and photons are not emitted at precise the place of the decay the lines don’t intersect in exactly one single point but are Gaussian distributed around the center of the
Figure 13: Number of hits in the WLS per channel within one run for both modules. The rear WLS have less hits than the one in the front because some radiation gets absorbed of the module and the angular size of a single crystal decreases. One can also see the dead channels with no hits at all.

Figure 14: The LOR plotted with the modules, view from the side. This output can be used to see immediately if the results are reasonable.
source. We take the projection of the data to the z-coordinate because they are continuous due to the continuous coordinates of the WLS. The y-coordinate is discrete because there are only a discrete number of LYSO and usually has one sharp peak in the optimized plane. The fit of this Gaussian $\sigma$ changes as we move the plane in the x-direction between the two modules. The best fit is reached if the plane cuts the source. If the plane is displaced, the Gaussian widens up because of the arbitrary direction of the lines and the fact that they do not intersect in exactly one point. Thus the fit of the Gaussian gets worse. With the program loopLOR.c we can calculate the fit of the Gaussian for many planes at a time. As the $\sigma$ is supposed to be more or less continuous we can subdivide the region with the lowest $\sigma$ and find the best fit by iteration, see figure 15. With the peak of the Gaussian in $z$, the mean value in $y$ and $x$ with the minimized $\sigma$ we know all the coordinates of the source.

Unfortunately the case with only one source exists only as a test run. In reality one has many sources at various places. Even a two source setup is much harder to analyze. As one source was much stronger than the other it was still possible to find the $x$ with minimized $\sigma$, the center of the strong source. But the $x$-coordinate of the weak source remains unknown. For the $z$-coordinate we fitted the Gaussian over both peaks separately. In the $y$-direction, the mean value of both peaks separately yields the coordinate. The curve has too sharp peaks to be fitted with a Gaussian and both peaks at a time gives only the center of gravity of both peaks at a time. The area of interest can be defined by eye, because as the curves drops very fast and some changes in the border hardly change the result. If the $y$-coordinate of the two sources distinguishes only slightly it’s not possible any longer to discern the two sources and thus to find the mean value.

There were some runs made with the sources at various places and rotated them. The results gained with the line of response were quite precisely the same as measured mechanically. E.g. as the two sources were rotating around each other in a distance of 7.5mm (run3459-3477) with constant $z$ coordinate. The distance in $y$ evaluated with the software was an almost sinusoidal curve with a maximal distance of 7.6 mm. Only the alignment seemed to be imprecise. The strong source was supposed to start at $y=-3.75$ but the evaluated $y$ coordinate varied only be-

![Figure 15: The fit of the Gaussian gets better towards the plane intersecting the radioactive source, thus $\sigma_z$ gets lower.](image)
Figure 16: On the right side is the cross section of the LOR with the plane, in this case \( X = 7.6 \text{mm} \). Purple means there are only few LOR crossing a point, in the red central region are a lot of lines crossing, this is where the source is. The \( Z \)-projection is the sum of hits per point of resolution in the \( Z \) direction, the same for the \( Y \)-projection in the middle of the figure.

tween 0.6 and -1. In the runs 3440-3458 the distance in \( z \) between the two sources is stable, but the rotation axis is slightly tilted against the \( z \)-axis. In the runs 3363-3381 the distance of the source to the center in \( x \) and \( y \) was between 7.1 and 7.7 mm, see figure . The \( x \)-coordinate is not as accurate as the \( y \)- and \( z \)-coordinates. But a difference of \(< 0.4 \text{ mm} \) is still quite good.

The setup was maybe not that good aligned and the center not at \((0,0,0)\). The runs 3382-3400 couldn’t be evaluated properly because the source was located at the border of the measured area and thus we didn’t have a nice Gaussian, it was cut off at the upper end. But in the plots, the source was still visible where it was supposed to be.

Unfortunately we have only two sources. It would have been interesting to test the setup with more sources at a time or to find \( x \) with minimized \( \sigma \) for two equally strong sources. With many sources especially the \( x \)-coordinate needs a lot more sophisticated algorithms to be evaluated properly. One can not fit a many source problem with a single Gaussian.

5 Implications of temperature variations

Since there is all our electronic on the chariot and inside the dark room, the air conditioning is not anymore strong enough to cool down the room to 20°C. The typical temperatures are now at 27°C, thus the noise increases and disturbs the measurement. It can be canceled by increasing the low threshold but therefore new problems occur. The question is how high the new optimal threshold should be. Therefore we made some runs at different thresholds and compared the fit of the Gaussian at the LOR. For too low thresholds, the noise disturbs the fit and at too high thresholds we cut off a part of the Gaussian. We also compared the fraction of golden events of our runs. The \( \sigma \) has a minimum at 70 mV, the fraction of the golden events a maximum at 50 mV, so the new optimal threshold somewhere in this region, see figure . Fortunately, the ADC values are only chopped off at the lower end but not effected any further. The energy resolution also decreased. The FWHM was at around 13% at the previous runs and increased
Figure 17: Both sources are at the same position in y and z. The plane is in x where the strong source is. The x coordinate of the weak source can not be found by fitting the Gaussian as the strong source disturbs too much. The colors are plotted logarithmically to display the weak source better.

Figure 18: Here are x and y coordinate in mm of the runs 3363-3381 plotted against the angle of the rotation. Both curves (blue points) form almost a sinus (red curve $7.6 \cdot \sin(\alpha + \delta)$).

to approximately 14%. It is not clear what causes this increase exactly but it is highly likely that it is caused by the increased noise or not so accurate correction of the BIAS voltage. This additional energy might worsen the fit of the Gaussian.

We hope that the air conditioning in Zurich is better that we can continue working at 20°C and a threshold of 30 mV. The gained data can still be processed but the previous circumstances are definitely preferable.

6 Summary

The AX-PET is a very promising attempt to improve the common PET. The operational experimental setup is working and the various analysis programs provide a lot of different results about the single LYSO/WLS but also some data for the coordinates of the sources. The results are up to now at an accuracy of below 0.5 mm, but we measured only some simple arrangements
with a maximum of two sources. The difficult part remaining is to locate various small sources. The simple LOR approach won't work as the lines cross at various points. On the other side we took only data with the two modules at fixed positions but we can increase the resolution by rotating them and gaining more data. But therefore some more sophisticated algorithms to process this data are required.

7 References

[3] AX-PET, a demonstrator for PET imaging using long axially orientated scintillating crystals

On the homepage of the The AX-PET group are many more scientific papers listed.
https://twiki.cern.ch/twiki/bin/view/AXIALPET/WebHome