WP4. Position Sensitivity in Large Crystals & Applications

This research program addresses the development of technology needed to localize the interaction points of gamma-rays inside a large volume scintillator crystal and to set the basis for the construction of a position sensitive large volume scintillator detector.

The project requires the simulation, production and test of a Position Sensitive prototype which is capable to provide, on an event by event basis, the image produced by the scintillation light on the photocathode. Possible scintillators which can be used in the project are NaI, LYSO, CsI(Tl) and the very promising novel materials $LaBr_3$(Ce) and $CeBr_3$[1-11].

Almost nothing is known on the imaging properties of position sensitive detectors that use several centimeters thick scintillator crystals and medium-high energy γ rays. In fact, even though gamma imaging is a hot topic in applied physics [12-15], the crystals used in such applications have a front surface of 50-100 cm^2 and thickness of few millimeters only, which reduces the detector efficiency down to zero for medium and high energy γ rays. In addition the surfaces are treated to completely absorb the scintillation light and this significantly worsens the energy resolution of the detectors, as approximately 10% of the scintillation light is collected by the photo-sensors. Figure 1 shows the percentage of photons which arrives on the photocathode in the case of incident 662 keV γ rays which have deposited all the energy in a 3”x3” $LaBr^3$:Ce detector [17]. The value is plotted versus the Z coordinate of the γ-ray first interaction point. The plot in the left panel is relative to a 3”x3” LaBr3:Ce detector with fully absorbing surfaces while the plot in the right panel correspond to a detector with fully diffusive surfaces.

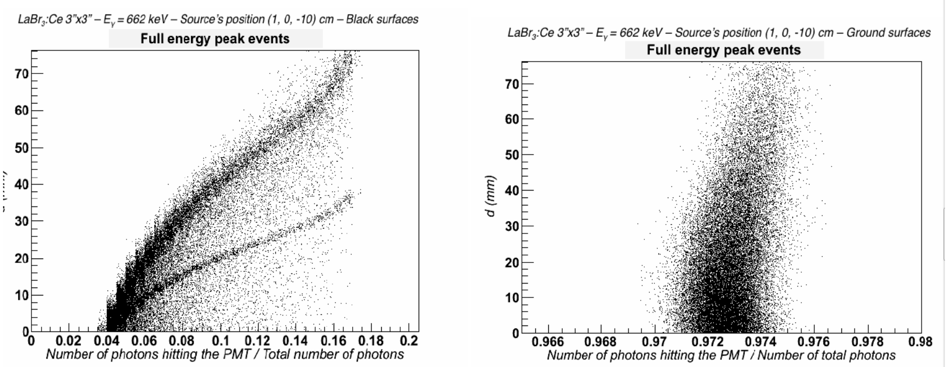
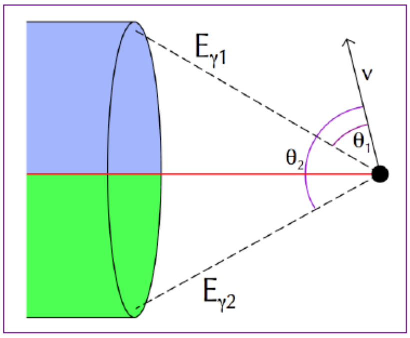


Fig 1: *Left panel: the simulated percentage of scintillation photons which arrive at the photocathode in a cylindrical 3”x3” LaBr3:Ce crystal with dark surfaces. Between the crystal and the photocathode a layer of 8 mm glass has been inserted to take into account the crystal encapsulation and the PMT glass window. Right panel: the same plot as in the left panel but, in this case, the crystal has diffusive fully reflecting surfaces. Note the difference in the x axis values. The quantity d represents the distance from the front face (d=0) along the Z axis of the detector; d = 73 mm corresponds to the end face of the crystal coupled to the PMT through a 8 mm glass window. In the simulation a collimated beam of 662 keV γ rays was used. The γ-ray beam enters into the detector 1 cm away from the center of the crystal front face [17].*

The application fields of such kind of devices range from fundamental research to astrophysics, homeland security and medical areas. In nuclear physics basic research and in particular in γ-ray spectroscopy, the efficiency for medium-high energy γ rays and the energy resolution are critical parameters. The imaging properties of a detector are extremely useful to reduce the Doppler Broadening effect in experiments where the γ-ray source moves with relativistic velocity (see figure 2). These beams are, for example, used in the study of nuclei far from the stability line and may reach velocities up to v/c = 0.6 and more. In such kind of measurements, the energy of the γ rays emitted by the moving source in the laboratory system (even though monochromatic in the CM system) is Doppler shifted and in the energy spectra the full absorption peak is broadened and degraded because of the size of the detector front face. Such effect becomes larger i) as the v/c of the source increases and ii) as the distance source-detector decreases. The localization of the interaction point of the γ ray inside the crystal (even with a position resolution of 1-2 cm) could reduce or eliminate such effect, recovering the intrinsic performances of the detector. In the case of sources with a low v/c an imaging detector will allow the reduction of the distance from the target increasing, consequently, the total efficiency of the apparatus and the identification of the γ-ray interaction point will allow the reduction of the Doppler Broadening effect.



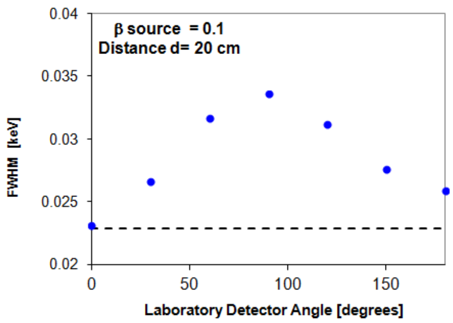


Fig. 2: *left panel: a schematic view of the Doppler Broadening effect. The drawing shows a γ-ray source moving with velocity v. The γ rays emitted at angles θ_1 and θ_2 enter and interact in the detector. Even though their energies are identical in the CM system, they are different in the laboratory system. The energy difference $E_{\gamma 2}$-$E_{\gamma 1}$ is the Doppler Broadening effect. Right Panel: The expected energy resolution for a 3"x3" LaBr3:Ce detector placed at 20 cm distance from the target at various laboratory angles. Calculations have been performed using a source of monochromatic 1 MeV* γ rays *moving at v/c = 0.1. The straight line indicates the detector intrinsic energy resolution. The Doppler Broadening induced energy resolution at 1 MeV in the CM system for a source moving at v/c=0.5 with the detector at 60° is approximately 5 time larger, 180 keV. The error bar for each point is 1 keV. The front-back anisotropy in energy resolution is due to the different energies of the measured γ rays [18].*

One important aspect in these kind of measurements is the presence of internal radiation which can be, however, reduced as it is inside the detector and spatially uncorrelated with the γ-ray 'source' which is to be 'identified'. Such kind of background can be rejected i) selecting the γ-ray energy (in this case a good energy resolution is required) or ii) through Pulse Shape Analysis techniques. In the case of $LaBr_3$:Ce crystals the internal radiation is a strong source of background as (approximately 2 evt/sec/cm^3). Such radiation is generated by ^{138}La and the decay chain of its heavy homologue ^{227}Ac. In the case of alpha induced background from the ^{227}Ac decay chain, as figure 3 evidences, PSA techniques are capable to identify and rejects the alpha induced events [19].

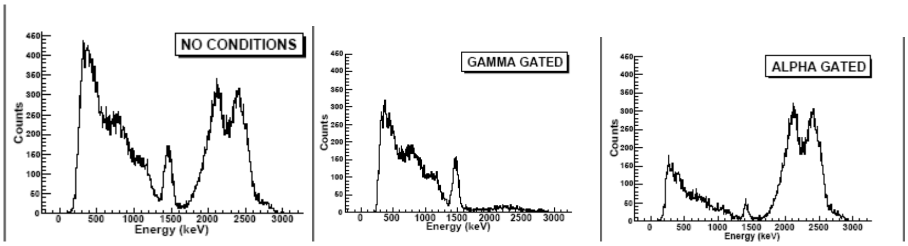


Fig 3 – *The internal radioactivity and natural background spectra measured with the $LaBr_3$:Ce detector. The left panel spectrum shows the measurement in single with no condition in the PSA. The middle and right panels show the spectra obtained requiring an alpha or* γ-ray *signal through Pulse Shape Analysis [19].*

An extremely powerful tool to analyze the position sensitivity of large volume scintillator is MonteCarlo simulations. The SCIDRA [ref] and GEANT4 [ref] libraries have been used as a tool to understand the way scintillation photons arrive at the photo-sensors (see for example figure 1). In case of detection of high energy γ rays it is important to stress that the scintillator surfaces must reflect the scintillator light, to maintain the best possible efficiency and spectroscopic performances, although reflections make more difficult to retrace the interaction points (see figure 4).

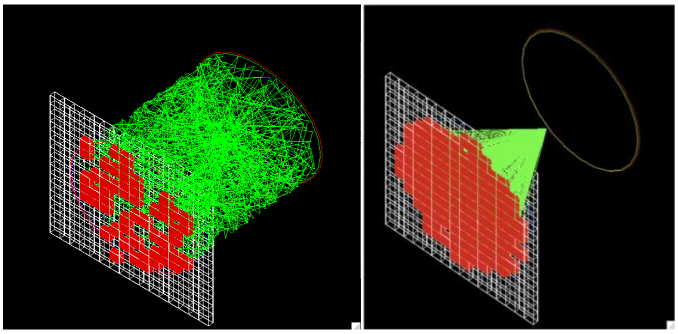


Fig. 4: *Left panel: the tracks followed by the photons in the case of fully diffusive surfaces from a simulation with GEANT4. Right Panel: the tracks followed by the photons in the case of perfectly dark surfaces from a simulation with GEANT4 [20].*

Within this project several solutions are planned to be tested to verify their performances and the optimal position resolution, photo-sensor technologies and algorithm, namely:

1) Cylindrical medium 1”x1” and large volume 3”x3” $LaBr_3$:Ce scintillator coupled to position sensitive photomultiplier (PSPMT)
2) CsI (of various thicknesses) and Cylindrical large volume 3”x3” $LaBr_3$:Ce scintillator coupled to an array of Silicon Drift Detectors (SDD)
3) Rectangular large volume scintillator with multi-face photon-detection

Cylindrical medium 1”x1” and large volume 3”x3” $LaBr_3$:Ce scintillator coupled to position sensitive photomultiplier (PSPMT)

In this part of research activity the position sensitivity of one cylindrical small volume (1”x1”) and one cylindrical large volume (3” x 3”) $LaBr_3$:Ce crystals have been measured and simulated using collimated beams of 662 keV γ rays.

In the first test, the PMT used was a standard Photonis CLARITY XP5031 with lime glass window. The PMT front window was covered by black tape leaving unshielded only a small region of the photocathode (see figure 5 and 6). The right panel of figure 5 shows how the energy resolution scales with the size of the window. The smaller is the windows the worse is the energy resolution as a reduced number of scintillation photons are measured by the PMT. As expected, using the unshielded PMT a value of 3.5% at 662 keV was found.

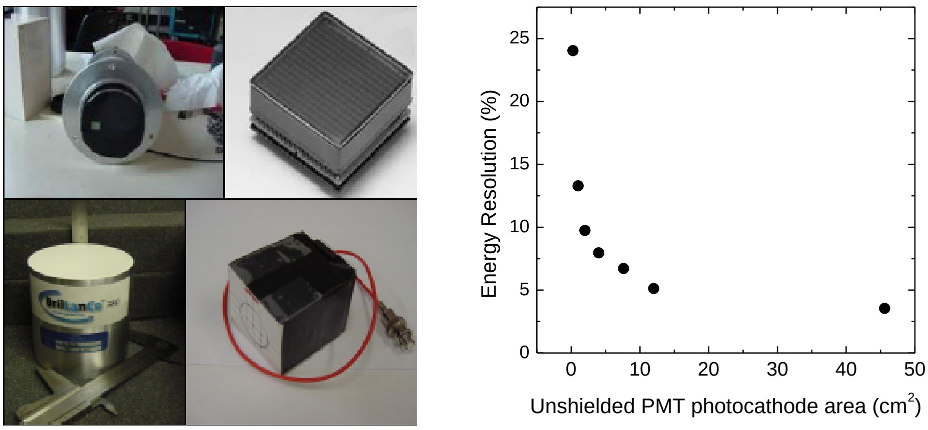


Fig 5: *Left panel: a composition of 4 pictures showing the shielded PMT (left upper picture), the PSPMT (right images) and the 3”x3” LaBr3:Ce crystal. Rigth panel: the energy resolution at 662 keV measured in a 3”x3” $LaBr_3$:Ce crystal varying the size of the window on the shielded PMT (the photocathode has a surface of 46 cm^2). As expected the energy resolution improves as the open window in the PMT increases in size [17-21].*

The position sensitivity using this kind of simple device has been measured using a collimated source of 662 keV γ rays moving along the crystal diameter and changing the position of the unshielded window on the photocathode. The plots in figure 6 show the measured position of the full energy peak, namely the average number of measured photoelectrons. In each plot a picture of the position of the window on the PMT is shown in the upper left part and each of the 5 points correspond to the x coordinate of the collimated 662 keV γ-ray collimated beam. A clear signal of position sensitivity is evident in the plot. In fact γ rays which enter in different positions produce different intensity patterns on the photocathode .

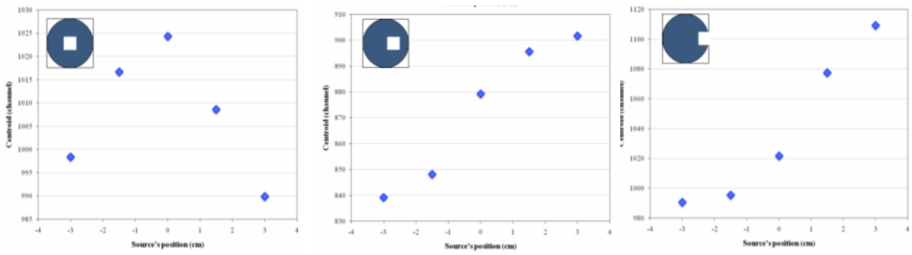


Fig 6: *The plots show the measured position of the full energy peak, namely the average number of measured photoelectrons, when 662 keV have been deposited in the detector. In each plot, the position of the window on the PMT is shown in the left upper part and each of the 5 points corresponds to the x coordinate of the collimated γ-ray beam* [20-21].

The previous measurements clearly show that, in average, the image produced by the γ rays on the PMT photocathode changes with the γ-ray interaction point [20-21]. In a second phase of the work the LaBr3:Ce crystal has been coupled to a PSPMT tube (Hamamatsu XP5300-100 Mod8, see the right images of the right panel of figure 5).

As a first step the PSPMT was coupled to a small 1"x1" $LaBr_3$:Ce. In this case only 16 (out of 64) segments are coupled to the $LaBr_3$:Ce detector. The measured average position of the 662 keV full energy peak measured in each segment was plotted relative to the segment x-y coordinates. In figure 7 the measured contour plots are shown: a position sensitivity is evident also in a 1"x1" detector and a PSPMT.

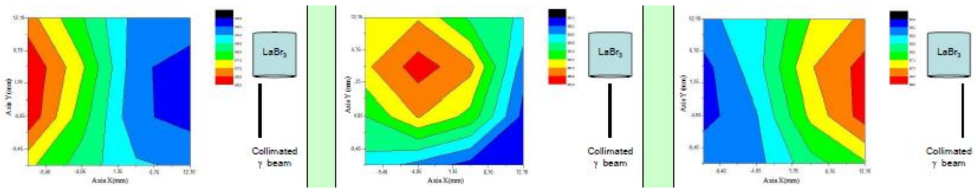


Fig. 7: *The plots show the image produced in a 1" x 1" LaBr3:Ce scintillator with a collimated 662 keV γ-ray beam measured on the segmented anode of a H8500C-100 Mod 8 phototube. In the central plot the collimation pointed approximately at the central position, in the left and right plots the collimated beam of γ rays was at -7 and +7 mm away from the centre. The values on the Z axis represent the position of the centroid of the full 662 keV energy peak [17-22].*

The position sensitivity in a 3"x3" LaBr3:Ce crystal have been also simulated using the GEANT4 libraries. The size of the detector is large enough to provide good full energy peak efficiency, even in the case of high energy γ rays.

In the simulations, a collimated monochromatic γ-ray beam of energy E=662 keV enters into the detector. For each incident γ ray the positions of the interaction points (IP) and the energy there deposited are extracted. Each IP generates a flash of scintillation light which, photon by photon, is followed up to its absorption or detection by a photosensor . In this way it is possible to simulate the spectra measured in both the shielded PMT and in the PSPMT. Figure 8 compares the measured results already shown in figure 6 with the simulations of the same system [20,23]. Measurements and simulations produce very similar curves. The error bars do not have any statistical origin but indicate the size of the PMT window.

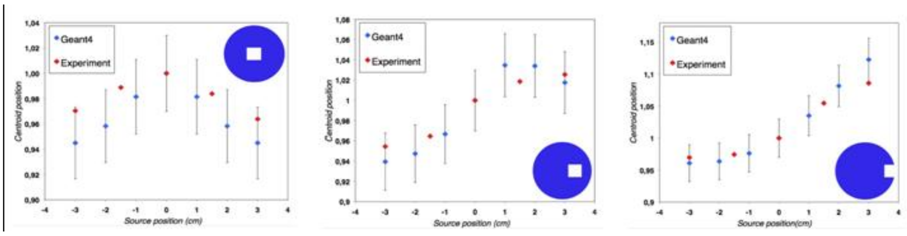


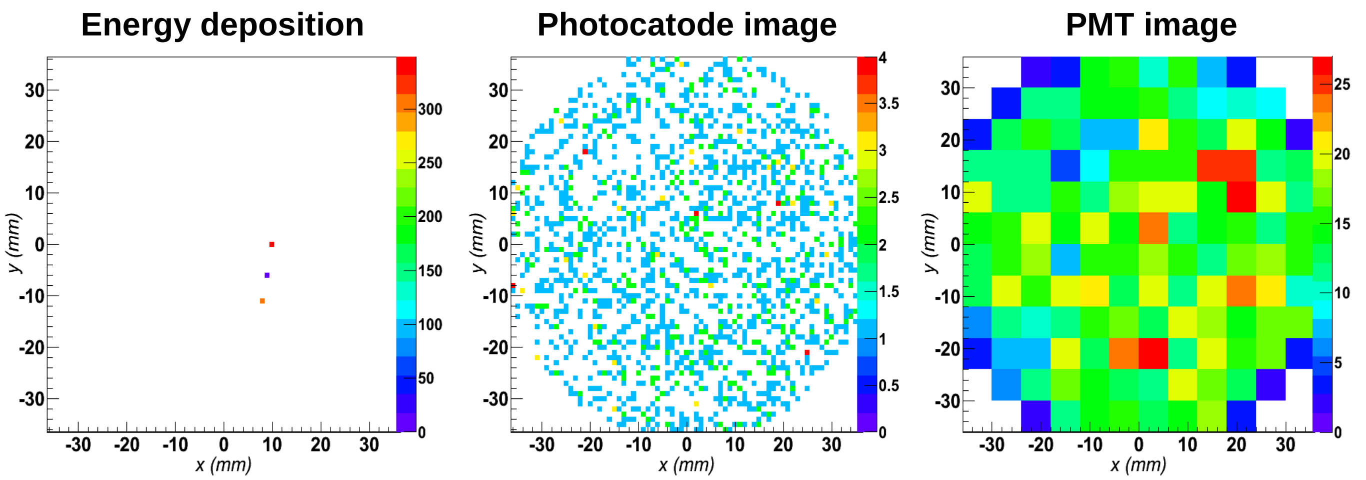
Fig. 8: *the comparison between the measurements of fig. 6 and the simulated (using GEANT4) results. In particular in the plots the measured and calculated relative position of the full energy peak (the average number of photoelectrons) for different positions of the collimated beam and PMT window is shown. The energy of the used γ rays is 662 keV. In each plot the position of the window on the PMT is shown in the upper left part and the 5 points correspond to different x coordinate of the collimated 662 keV γ-ray beam [20,23].*

A more detailed example of the results of GEANT4 simulations for a 3"x3" $LaBr_3$:Ce crystal is shown in figure 9. Two different detector configurations have been simulated : in the left panel a detector with dark surfaces and in the right panel a detector with diffusive surfaces are assumed. The graphs show all the processes of the simulation for six selected events, from the energy deposited by the incident γ rays up to the image produced on a segmented photocathode.

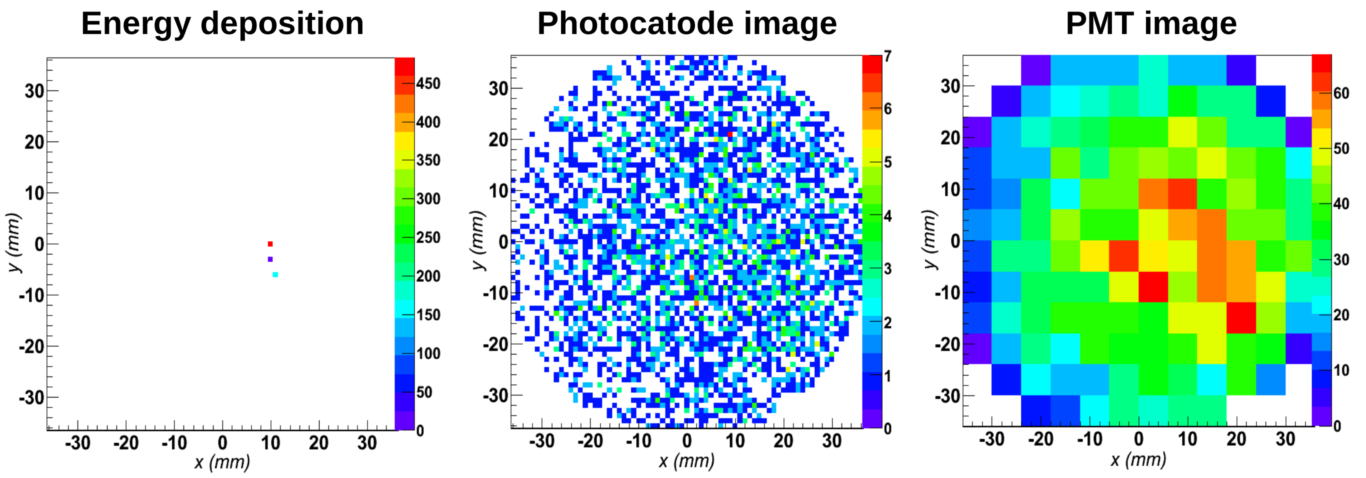
it is evident from the plots that dark surfaces provide in average the best imaging performances on an event by event basis but, as 90% of the scintillation photons are lost, scarce energy resolution. In the case of diffusive surfaces, the depth of interaction of the incident γ-ray is critical, namely the distance between the γ-ray interaction point and the photocathode [20,23]. In general, if a γ ray interacts in the second half of the detector depth, the position sensitivity on an event by event basis is evident. In case of interaction in the first half, the position sensitivity can be recovered on an event by event basis only using algorithms.

3”x3” – 662 keV – Source position (1, 0, -10) cm – DARK SURFACES

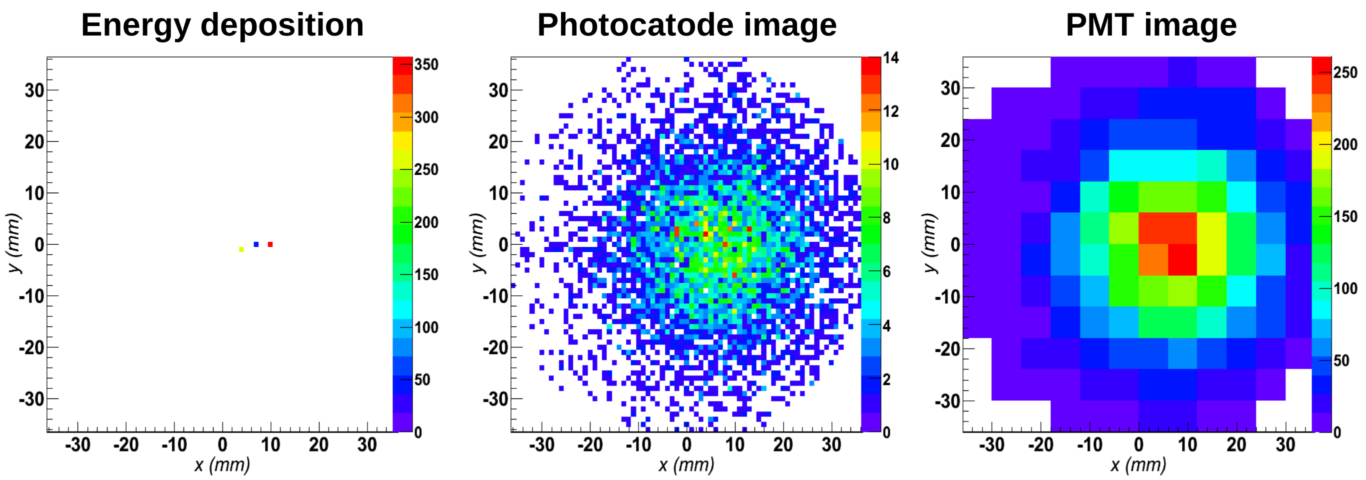
d = 0 - 5 mm



d = 40 - 45 mm

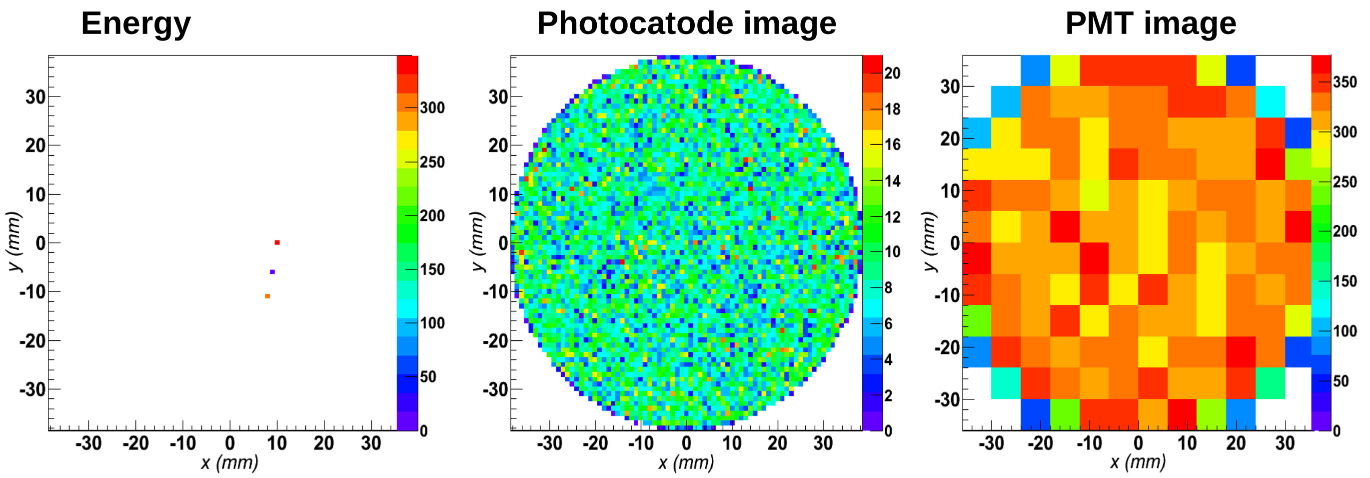


d = 60 - 65 mm

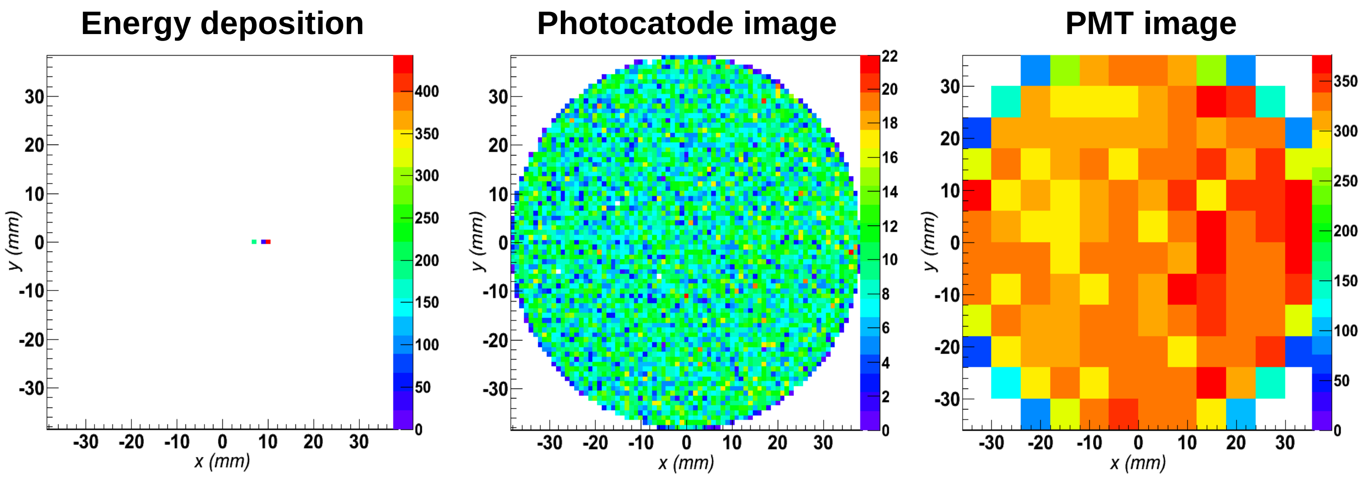


3”x3” – 662 keV – Source position (1, 0, -10) cm – FULLY DIFFUSIVE SURFACES

d = 0 - 5 mm



d = 40 - 45 mm



d = 60 - 65 mm

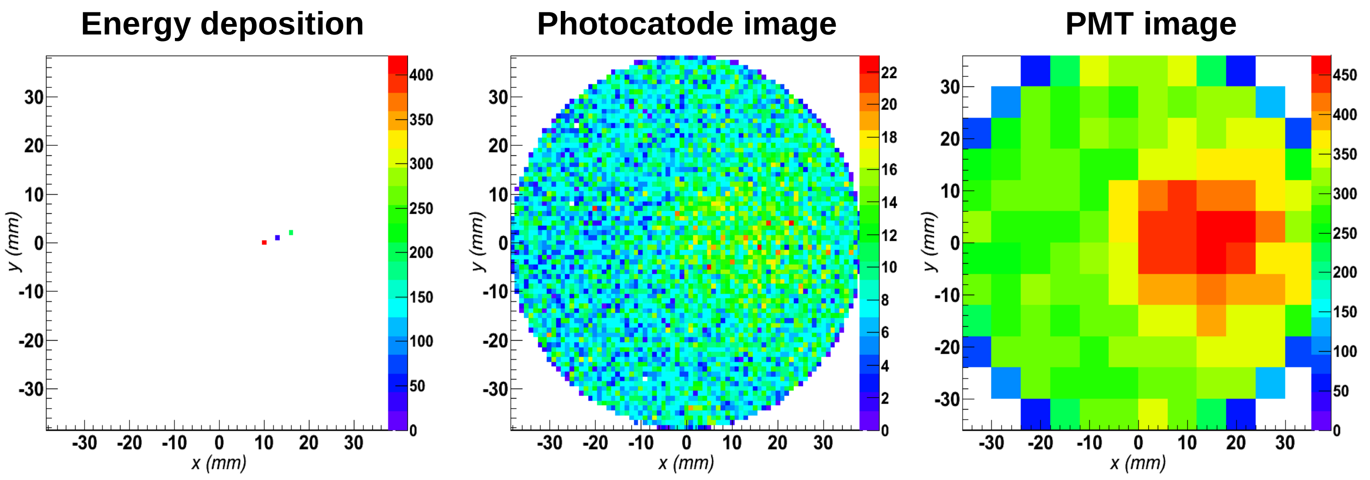


Fig. 9: *The plots show the position in the x-y axis of i) the energy deposition (first column), ii) the light sensor (middle column) and iii) the segment (right column) hit position of the scintillation photons for a typical γ-ray event which deposit 662 keV. The plots shows that in the crystal with dark surfaces (left panel) the position sensitivity is much better than in the fully diffusive crystal (right panel). It is also evident that the sensitivity improves as the hit position approaches the light-sensor [20,23]*.

CsI (of various thicknesses) and Cylindrical large volume 3"x3" $LaBr_3$:Ce scintillator coupled to an array of Silicon Drift Detectors (SDD)

In this second approach the work has been done in collaboration with the "Politecnico di Milano" and Prof. C.Fiorini [24-26]. This approach uses the innovative solution of SDD as a photo-sensor coupled to a 5 cm x 5cm CsI scintillator block with thickness of 1,2 cm. Measurements with a 5 cm thick CsI scintillator and with a a $LaBr_3$:Ce scintillator are also foreseen in the near future.

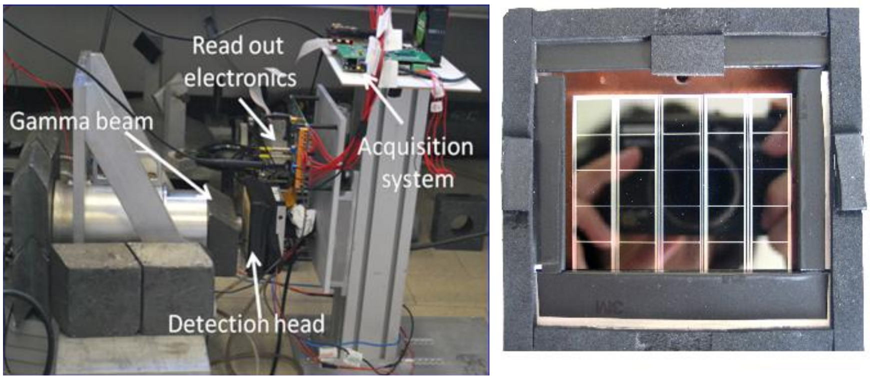


Fig. 10: *left panel: a picture of the experimental setup used for the measurement of position sensitivity with CsI and Silicon Drift Detector (SDD) [24]. Right panel: a picture of the SDD matrix used in the measurements.*

The picture in figure 10 shows the experimental setup used for the measurements. The collimated 662 γ-ray source (the same used for the measurement discussed in the previous sections) is on the left. The detector is in the middle of the picture while the holder and the electronics are on the right part. The measurements have been performed using a cylindrical collimator of 1 mm diameter hole and using different algorithms. The left panel of figure 11 shows the results of the analysis for a 60x50x10 mm CsI detector. The 8 spots visible in the figure correspond to the superposition of 8 measurements. In each measurement the γ-ray beam was shifted 5 mm and the FWHM of each spot was ~ 2.5 mm. The right panel of figure 11 is equivalent to the left panel but using a 20 mm thick detector. The width of each spot, also in this case, was ~ 2.5 mm.

A new measurement campaign is foreseen in 2013 using a 5 cm thick CsI and a 3”x3” $LaBr_3$:Ce scintillators.

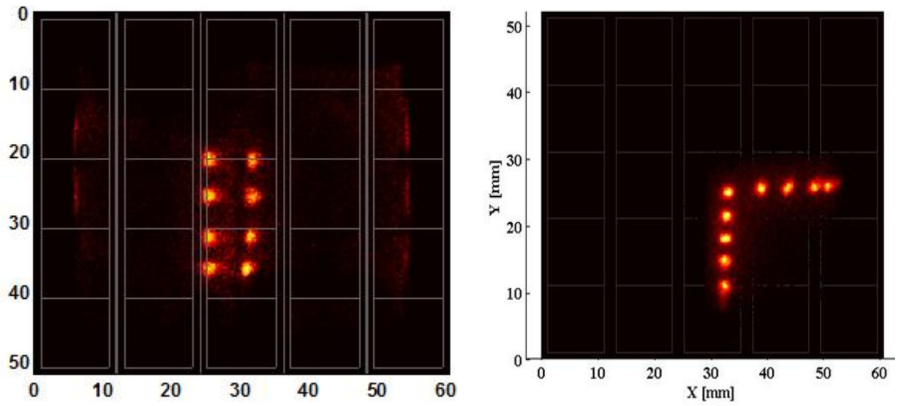


Fig. 11: The results of the position sensitivity measurements achieved using a 10 mm (left panel) or a 20 mm (right panel) thick CsI crystal coupled to an array of Silicon Drift Detectors. [24].

Rectangular large volume scintillator with multi-face photon-detection

The principal idea of this approach is to cover several faces of a cuboid scintillator crystal with position sensitive photo-sensors in order to determine the interaction points of penetrating γ rays in 3D. This solution provides the best possible position resolution for the initial interaction point, as required for Doppler correction of γ-ray energies in nuclear structure experiments with fast moving emitters. In addition, tracking of the path of γ rays through the scintillator may be possible. Thereby events with more than one γ ray entering a scintillator crystal at the same time can be identified and either discarded or even corrected, resulting in improved spectrum quality in experiments where high γ-multiplicities occur. γ-ray tracking provides also the possibility of gamma imaging, exploiting the Compton camera principle.

Within this project a 3D position-sensitive scintillation detector is planned to be developed, which will serve as part of a hybrid detection system composed of a position-sensitive scintillation front-detector and a conventional Ge back-detector. This hybrid-detector is intended to be used for in-beam spectroscopy of exotic atomic nuclei produced by fragmentation reactions at relativistic beam energies. The main characteristics of the hybrid-detector are an intrinsic energy resolution of 1-2% in the interesting energy range from 300 keV to 3 MeV and a position resolution of about 3 mm for the first interaction point in the scintillator. For typical velocities of the gamma emitting nuclei of $v/c = 0.4 – 0.6$ and source-to-detector distances of 10 cm to 15 cm, as previously discussed, the energy resolution after Doppler correction is dominated by the intrinsic resolution of the system.

Simulation showed that a scintillator thickness of 15 mm yields the largest efficiency when coupled to a Ge detector with at least 70 mm thickness. Using $LaBr_3$ as scintillator detector revealed an energy resolution of about 1 % at 1 MeV gamma energy when adding the contributions of both detectors event-by-event. The intrinsic efficiency for full energy absorption requiring the first interaction in the scintillator and the subsequent interactions in the Ge crystal is about a factor 4 to 5 lower than the efficiency of a large volume Ge detector of the size of a EUROBALL crystal without front scintillator. However, for the intended application EUROBALL detectors would need to be placed at least 70 cm away from the source to limit their solid angle in order to maintain 1-2 % energy resolution. Thus the hybrid system covering 20-30 times larger detection solid angle per hybrid-detector unit provides a factor five larger total full energy efficiency despite the lower intrinsic efficiency.

The close proximity to the gamma source leads to considerable parallax effects in a 15 mm thick front-detector. Therefore 3D position sensitivity is mandatory to achieve 3 mm position resolution of the first interaction point.

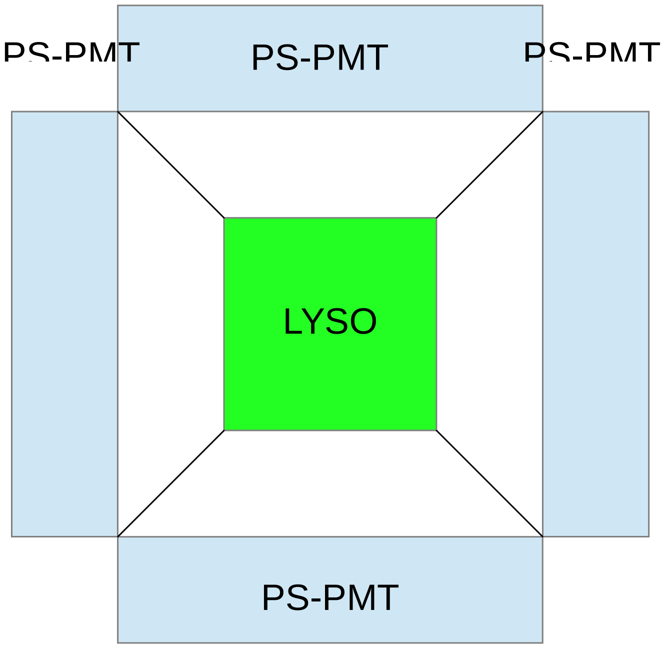


Fig. 12: Schematic layout of the LYSO Cube-Detector system.

To investigate the potential of the multi-face photon-detection a test system has been built, using a 34x34x34 mm^3 LYSO crystal coupled to position-sensitive PMTs (Hamamtsu 8500 series). Truncated square plastic pyramids served as light guides between crystal and PMT as shown schematically in fig. 12. The centroid of the light distribution on each side was obtained employing a conventional resistive chain network on each PMT. The obtained centroids and the relative light intensity provide a measure of the interaction position in 3D. LYSO like $LaBr_3$:Ce has the drawback of severe self-activity. To effectively suppress this self-activity a ^{22}Na source coupled to a reference gamma detector was employed for all investigations. Demanding one 511 keV γ ray to be detected in the reference detector in coincidence with the signals of the cube detector allowed to study the pure response of the other 511 keV γ ray in the cube. Absorption in the PMT material was negligible.

The PMT amplitude signals were first calibrated by uniformly illuminating the crystal with the ^{22}Na source. Then the source was collimated using a Pb block with a 2 mm hole. Fig. 13 shows the projection of the light distribution obtained for three different hole positions, being about 7 mm apart from each other. The intensity drop from left to right corresponds to the attenuation of the 511 keV γ rays in the depth of the crystal. A sum energy of 511 keV was demanded in the analysis for both the cube-detector and the reference detector.

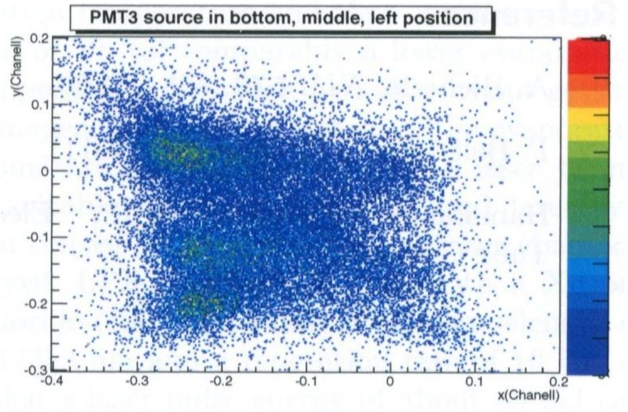


Fig. 13: Relative x,y distribution for three different y positions of the source situated at the left side of the cube.

Employing all channel information enables the reconstruction of the interaction points in 3D as shown in fig. 14. Already in the test runs a 3D position resolution of 3-4 mm FWHM has been achieved. Next steps will be to optimize the position determination by individual anode readout of the PMTs. It has been shown previously [28] that this can significantly improve the light centroid measurement because the strong gain differences of the anodes can be corrected for. At the same time the optimal pixel number will be determined in order to reduce the number of electronics channels to the needed minimum.

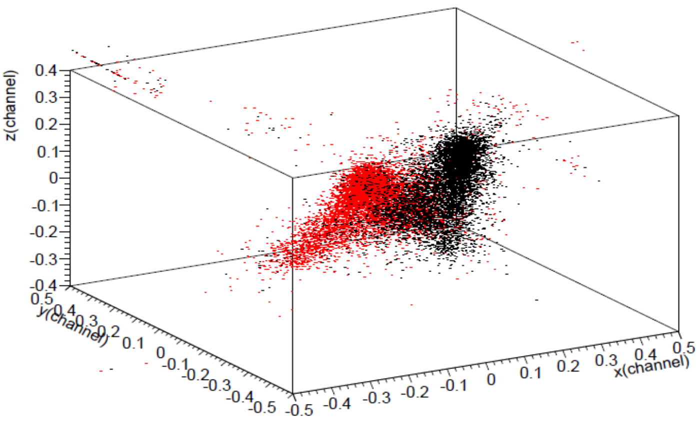


Fig14: 3D position reconstruction for two different source positions being 7 mm apart from each other.

Position Sensitivity in novel Hybrid semiconductor-scintillator detector

The investigations of light response for gamma rays performed in Kraków in relation to the PARIS project comprised simulations of light propagation in detectors of different sizes.

Using GEANT4 Monte Carlo software the propagation of light produced by gamma rays in scintillation detectors have been simulated for two detectors: cubic $LaBr_3$ crystal (2”x2”x2”) and PARIS phoswich detector $LaBr_3$ (2”x2”x2”) / NaI (2”x2”x6”). The light responses for the 1 MeV gamma rays emitted into the center of the crystal or into the left side position have been calculated for each detector.

The obtained light response of cubic $LaBr_3$ crystal (2”x2”x2”) for 1 MeV gamma rays presented in Fig. 15 shows the possibility of the interaction point discrimination by the light output. The differences visible on Figure 15 (left and right panel) indicate the possibility of obtaining precise gamma energy deposit information by usage of segmented photodetector.

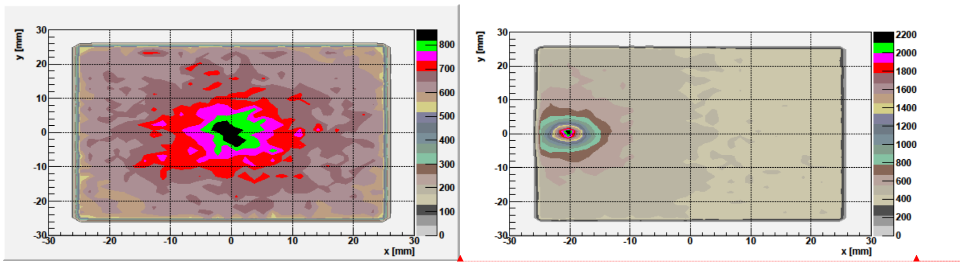


Figure 15. Distribution of scintillation light measured on back side of cubic 2”x2”x2” $LaBr_3$ crystal. Scintillation light was produced by absorption of 1 MeV gamma ray, which was emitted: left panel - into the center of the $LaBr_3$, right panel - into left side of the crystal (point x,y = [-2 cm, 0]).

In the case of response for 1 MeV gamma rays of phoswich detector, composed of 2”x2”x2” $LaBr_3$ connected to 2”x2”x6” NaI, simulation results show no dependence on the interaction point. Obtained results presented in Fig.16 for this detector are very similar for different irradiation (into the center and to the side). They indicate that there is no possibility to get information of the energy deposit positions by measuring the scintillation light distribution.

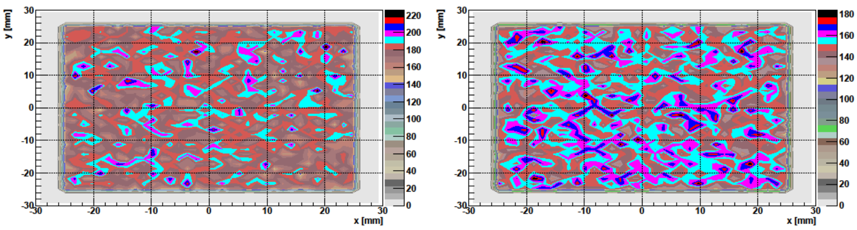


Figure 16. Distribution of scintillation light measured on back side of phoswich detector (2”x2”x2” $LaBr_3$ + 2”x2”x6” NaI). Scintillation light was produced by absorption of 1 MeV gamma ray, which was emitted: left panel - into the center of the $LaBr_3$, right panel - into left side (point x,y = [-2 cm, 0]).

Obtaining information on energy deposit position by the light measurement depends mainly on length of detector and is not possible for longer phoswich detector (LaBr3+NaI). Due to longer path of light from the gamma interaction point to the photodetector information on interaction point is lost.

Summary Table:

	Italy	Germany	Poland
Money used in 2012	0	0	
People	Simone Ceruti (Student) 2 weeks, Stefano Lodetti (student) 2 weeks, Agnese Giaz (student) 4 weeks Franco Camera (4 weeks) Nives Blasi (2 weeks) Sergio Brambilla (2 weeks)	Tugba Arici (master student) full time, Ivan Kojouharov 4 weeks, Frederic Ameil 4 weeks, Edana Merchan 4 weeks and Simone Ceruti 6 weeks working on the project	
Activity	See text	See text	
Publications	One in preparation	no	
Talks	2 Talks in Bormio 1 Talk in Varenna conferences		

[1] C.M.Rosza et al available at www.detectors.saint-gobain.com
[2] A.Iltis et al. NIM A563(2006) 359
[3] M.Moszynski et al. NIM A567 (2006) 31
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