A pre-shower detector for forward electromagnetic calorimeters

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Introduction

This proposal addresses the need for distinguishing neutral pions from other particles using a crystal-based electromagnetic preshower detector. The problem is universal at high energies, and is of particular interest to any Electron Ion Collider detector due to the relatively high rate of photons, electrons and positrons in the electron scattering environment. While silicon-tungsten based preshower calorimeters have been proposed for this purpose, it is of interest to also explore a crystal-based design in order to understand options with a very different radiation tolerance and a different cost point, and which could also be used in an hybrid design in conjunction with fine granularity readout technologies. Over the past two decades, cerium-doped silicate-based heavy crystal scintillators have been developed for the medical industry, and mass production techniques for LYSO and LSO crystals are now well-developed. The new LSO/LYSO crystals offer fast and bright scintillation in a high density format, allowing unprecedented compactness in sensitive calorimetric measurements. Because of these advantages, use of these crystals is being explored for electromagnetic calorimetry at the future ILC. Here, we propose to use this technology for a pre-shower detector for the EIC forward calorimeters.

Description of Project

Pre-shower detector with LSO/LYSO crystals for electromagnetic calorimeters.

This proposal is addressed to forward and very forward calorimeters and based on the experience of the proponents in design, construction, and operation of forward calorimeters for CMS (the quartz fiber Hadronic Forward calorimeter, HF) and the Inner Calorimeter (IC) and Forward Calorimeter for CLAS. The detector of the Electron-Ion Collider should have specialized forward calorimeters for the electron fragmentation region and for the ion fragmentation region.

The forward calorimeter for the electron fragmentation region will play a key role as a tagger for experiments with real photons and as an electron and gamma detector for DVCS experiments. This calorimeter should be able to discriminate electrons, higher energy photons and pairs of photons from high energy neutral pions. The CLAS IC was designed especially for DVCS experiments with a fixed target and a 6 GeV electron beam. The development of a prototype for a pre-shower detector for an electromagnetic calorimeter such as the IC is the focus of this proposal.

The discrimination between neutral pions and single gammas is extremely important for forward electromagnetic calorimeters in experiments seeking to find isolated photons at low rate, such as in DVCS. A pre-shower detector of 3-5 radiation lengths is a straightforward approach for the rejection of two close gammas. The standard design of a high resolution electromagnetic calorimeter is an assembly of tapered bars or bars in the shape of a parallelepiped. Scintillating crystals (such as PWO), lead glass blocks (c. f. the GAMS detector) and sandwiches of lead and scintillating plastic with WLS fibers (e.g., shashlik calorimeter) are optimal in price-performance considerations for such a calorimeter.

Each bar (or tower) is optically isolated and read out with optical sensors on the rear face. Such a calorimeter has transverse segmentation, and the performance depends on the knowledge of the transverse profile of the electromagnetic shower as a function of the energy. The optimal transverse segmentation of the electromagnetic calorimeters is approximately the Moliere radius. When the decay photons from neutral pions enter the same calorimeter tower, the efficiency of discriminating between two hits and one hit is problematic when the distance between gammas is less than half the tower width. To improve the situation the transversal space resolution and the longitudinal segmentation can be optimized; this is the conceptual basis for a pre-shower detector.

As an example of a possible forward calorimeter for the EIC detector which could be improved with the proposed pre-shower we use the IC of CLAS (Fig.1 and Fig.2) for illustration. The calorimeter has 424 tapered PWO crystals 160 mm (18 radiation lengths) in length, each with 13.33 x 13.33 mm^2 front size. PWO crystals are considered as the most radiation hard and the densest crystals with fast scintillation. The pre-shower design was selected from the following criteria:

1. 4 X0 pre-shower length was selected as reasonable for a 18 X0 (or more) + 4 X0 calorimeter

2. The pre-shower volume is equal to 15-20% of the total calorimeter volume. This could be an argument for selection of more expensive crystals for the instrumentation. The density of crystals for the pre-shower should be not far from PWO density but the light output of the crystals should be more than 10 times higher taking into account lower energy deposition in each crystal unit and lower light collection efficiency of a read out system in such configurations.

3. Crystals for the pre-shower should have about the same time decay constant parameters in combination with read out timing parameters.
4. Read out should be on the front side of the calorimeter, minimizing non-sensitive construction materials.
5. The calibration of the pre-shower and the calorimeter (or a longitudinally segmented calorimeter) is much more complicated than the calibration of a calorimeter without longitudinal segmentation. A calibration system has to be integrated from the beginning. For example, CMS HCAL uses the radioactive source calibration which gives the possibility make an inter calibration of different layers of the HCAL, LHCb hadron calorimeter uses 137 Cs radioactive sources embedded into the calorimeter structure. Some crystals have intrinsic radioactivity and if the read out system was sensitive enough the calorimeter or the pre-shower could have an intrinsic calibration.

We suppose that for the pre-shower of a calorimeter like the IC, commercially available LSO or LYSO crystals could meet the requirements described above. Moreover, a pre-shower with LSO/LYSO crystals could have 3 dimensional spatial resolution, as will be explained later. The proposed pre-shower consists of LYSO 4x4x45 mm^3 crystals matrix and read-out with WLS fibers.
In order to use a 4 X0 design, we have to use 45 mm long crystals and the crystal wrapping scheme is very important. According to measurements by the AX-PET collaboration, polished Saint Gobain LYSO 3x3x100 mm^3 crystals have an optical absorption length of 412 mm, despite the Saint Gobain nominal specification of 12 mm attenuation length. The standard application of such crystals is in Positron Emission Tomography with 10-20 mm length crystals, and we suppose that Saint Gobain shows the 12 mm attenuation length for crystals with-non polished surface and wrapped with Teflon as it is in the PET. A group from LBNL[1] reported a method of

[1] http://escholarship.org/uc/item/09w6f8nx

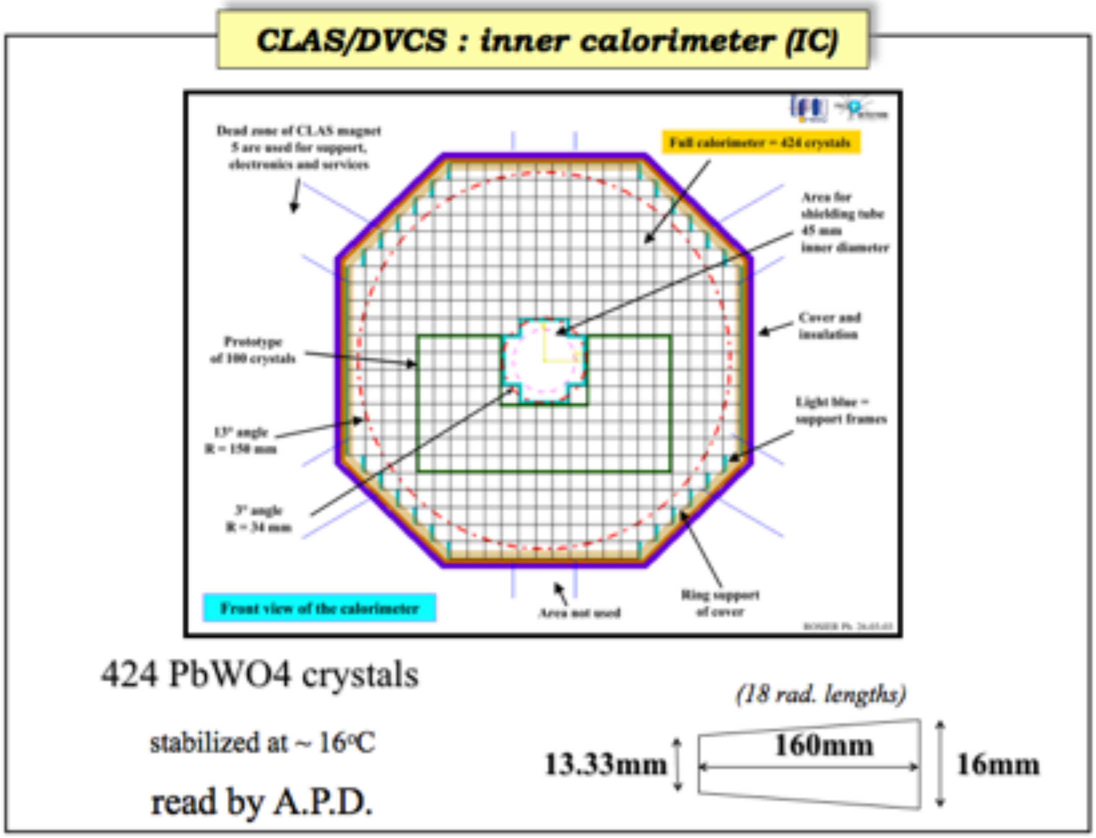

Figure 1. The CLAS DVCS inner calorimeter: an example of a forward calorimeter for which a preshower of the proposed type can be used.

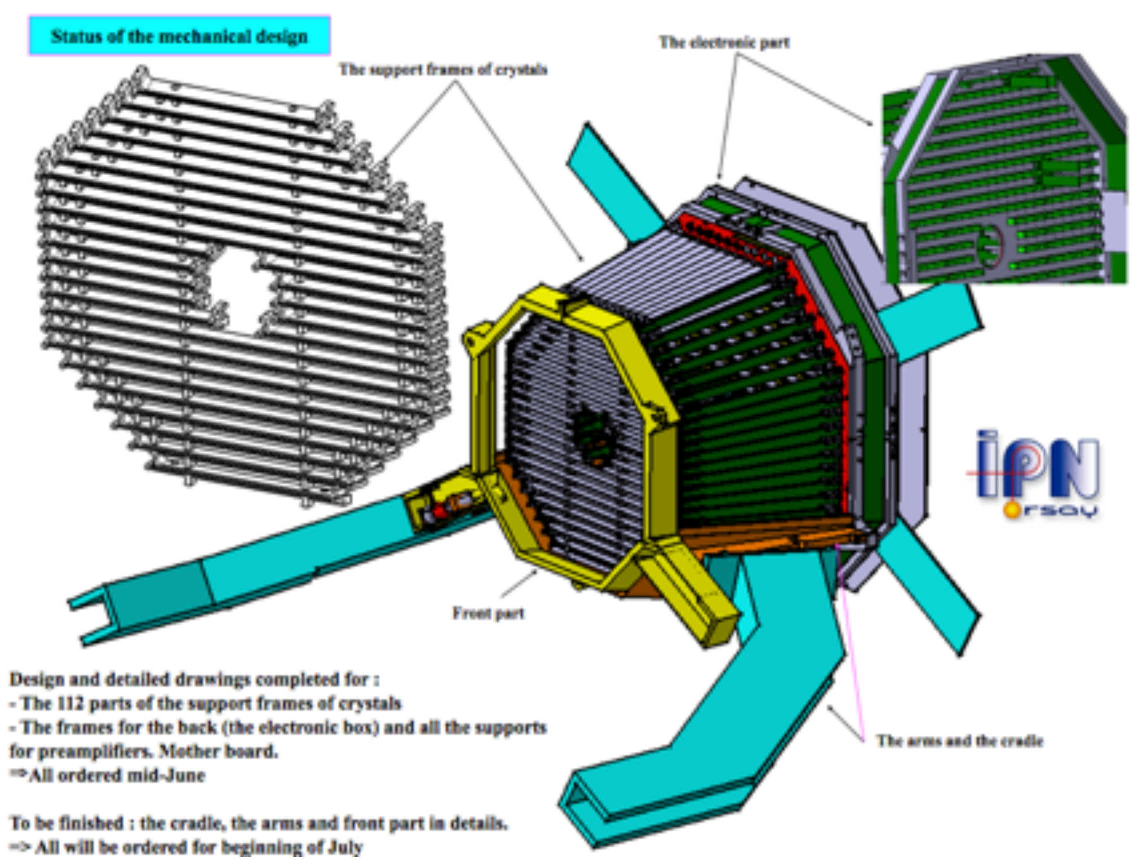

Figure 2. A three-dimensional view of the CLAS Inner Calorimeter (IC).

optimizing the attenuation length with different wrappings. We have two options - either select a design of the crystals matrix with an attenuation length much more than 45 mm and make the readout from the front side only, or make a matrix with a attenuation length about 30-45 mm and make the readout from both front and rear sides. Both options are shown in Figures 3 and 4.

Existing prototypes

A first effort has already been made to test the approach that is being proposed here. A small prototype with a matrix of 64 2x2x12 mm^3 LYSO crystals and 1 mm diameter WLS fiber (Kuraray Y11) readout contained from 8 X-coordinate and 8 Y-coordinate fibers was tested as a check of the pre-shower design idea. The crystal matrix and WLS fiber panel are shown in Fig. 5. 16 CPTA 151-30 MRS APD/SiPM[2] with fast current amplifiers were used for readout. The assembly with a “socket” for the WLS fibers, 16 SiPMs and 16 amplifiers are shown in Fig. 6. The prototype was placed in a dark box, shown in Fig. 7. The nuclide 176-Lu is naturally present in LSO/ LYSO crystals. This isotope is a radioactive β-emitter followed by a γ cascade and is very useful for calibration. The SiPM gains were adjusted to provide a 7 mV output pulse on the discriminator input from the amplifier for the 1-photoelectron signal of the SiPM. Pulses from all 16 amplifiers were split in two directions, to a discriminator and to a QDC. The gate for the QDC was generated when any one of the 8 channels of X- WLS fibers and any one of the WLS fibers provided a pulse with an amplitude of more than 4 photoelectrons. Because each channel was calibrated in photo electrons with the internal radiation of crystals, the uniformity of the calibration was well-controlled; the intrinsic LYSO radiation spectrum is shown in Fig. 8 (the data are from the AX-PET collaboration). Lutetium based scintillators contain ^{176}Lu, a naturally occurring beta emitter. ^{176}Lu beta decays to ^{176}Hf in 99.66% of the time to the 597 keV excited state and this state decays with 3 gamma ray cascade of 307, 202 and 88 keV. A 1 μCi ^{137}Cs source was installed on the front of the prototype. The distribution of the sum of amplitudes of all channels in photoelectrons is shown in Fig. 9. The distribution has two peaks; the left peak is the response from the internal radiation of LSO/LYSO with energy 202 and 307 keV (see Fig. 8). The right peak in Fig. 9 is the response from the 661.6 keV gamma from ^{137}Cs and

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[2] http://www.cpta-apd.ru/ENdocAPD/CPTA%20MRS-APD%20avalanche %20photodiode%20en151-30.html

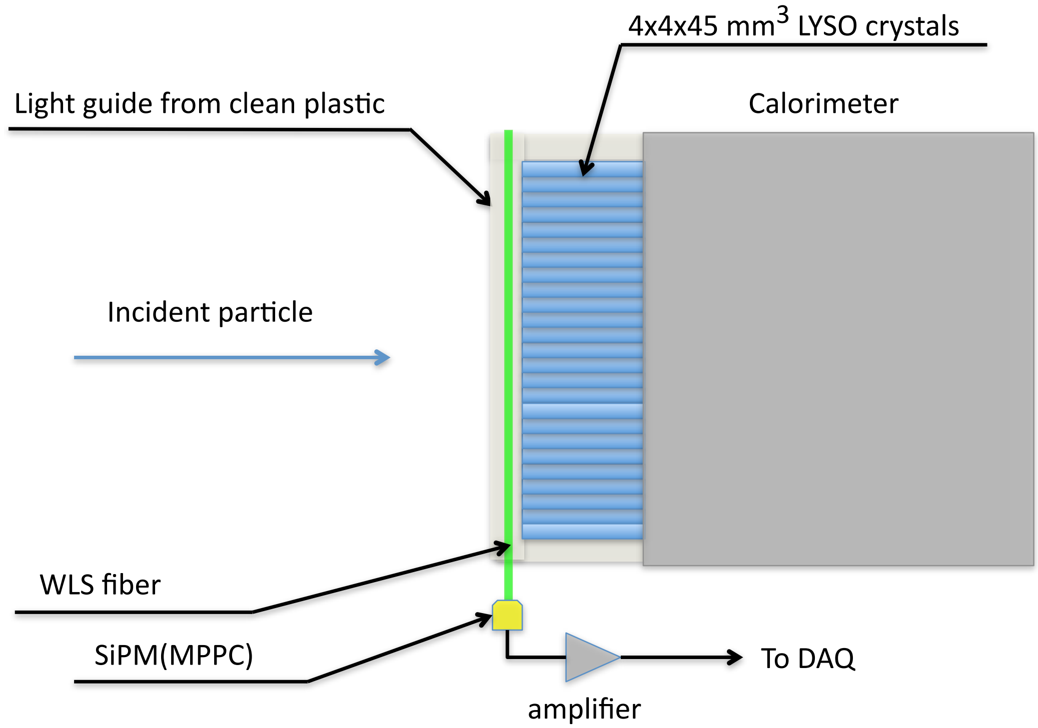


Figure 3. A schematic drawing of the pre-shower calorimeter with one-sided readout.

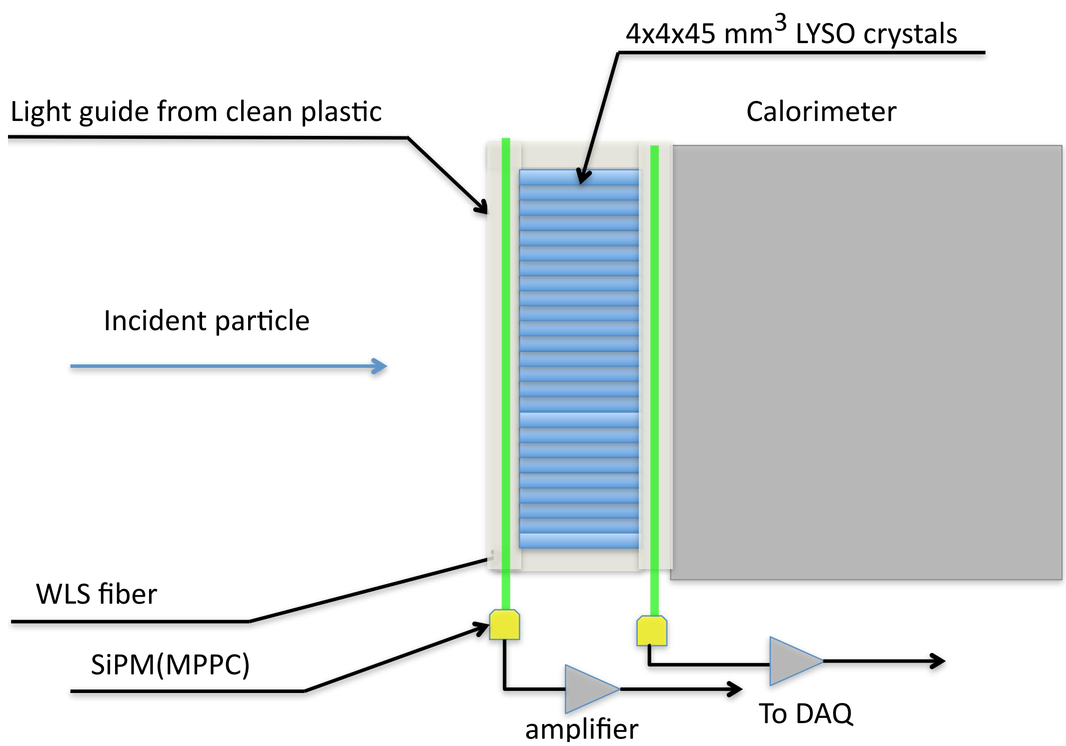


Figure 4. A schematic drawing of the pre-shower calorimeter with two-sided readout.

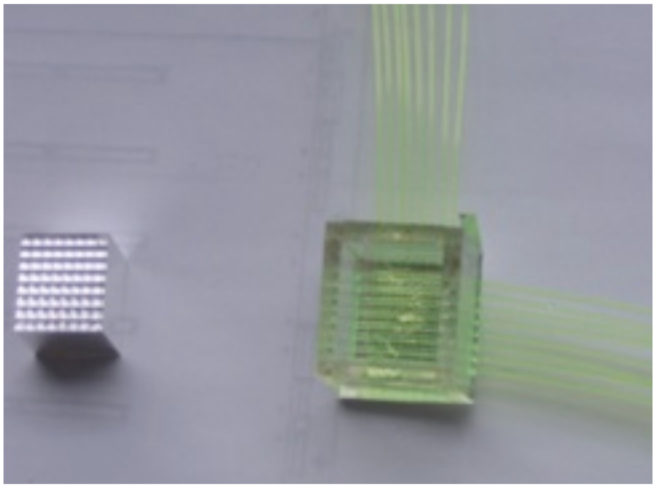


Figure 5. The crystal matrix and WLS fiber panel.

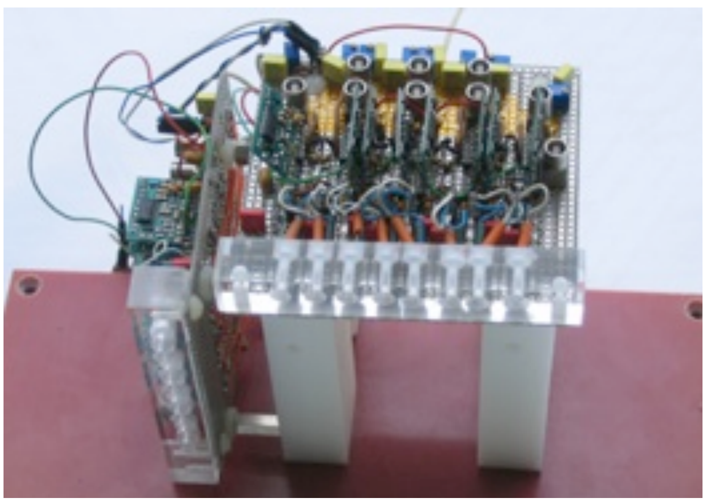


Figure 6. The assembly with a “socket” for the WLS fibers, 16 SiPMs and 16 amplifiers.

internal radiation (about 5-10% events in the peak). Thus, the 661.6 keV calibration peak gives 51 photoelectrons or about 77 photoelectrons per 1 MeV. Considering the amplitudes in each channel we concluded that each event from ^{137}Cs looks like a cluster of fibers and the average X-size and Y-size of the cluster was 1.5 crystals (x 2 mm distance between fibers).

In the proposed pre-shower we are going to use 4x4x45 mm^3 LYSO crystals and 1 mm diameter WLS fibers; based on the results from this first prototype, we expect to get 37.5 photoelectrons per MeV.

R&D program

The aim of the R&D program is to design and test a prototype of the pre-shower. First, we will make a setup for evaluating the LYSO crystals. The setup will include a tagging gamma source with Na^{22}. A schematic drawing of this gamma source is shown in Fig.10. The radioactive ^{22}Na isotope (1 µCi activity) decays with positron annihilated into two 0.511 MeV gammas coming in strictly opposite directions. One gamma is detected with the gamma detector consisting of a BrilLanCe™ 380 crystal (LaBr3Ce) and a HAMAMATSU R7525 photomultiplier. This detector has 3% energy resolution for 0.511 MeV gammas and a fast response, with a decay time constant (of the LaBr3Ce crystal) of 16 nS. There is a collimator between

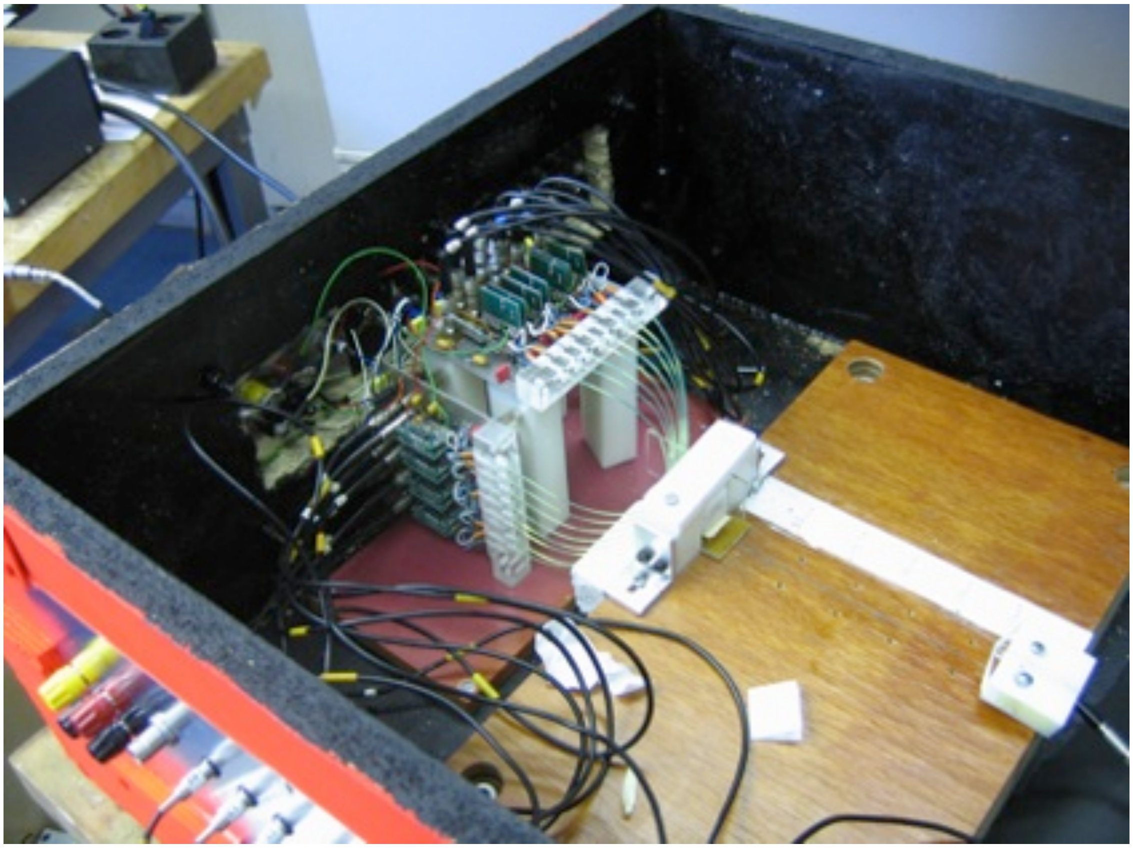


Figure 7. Dark box in which measurements for the existing prototype were performed.

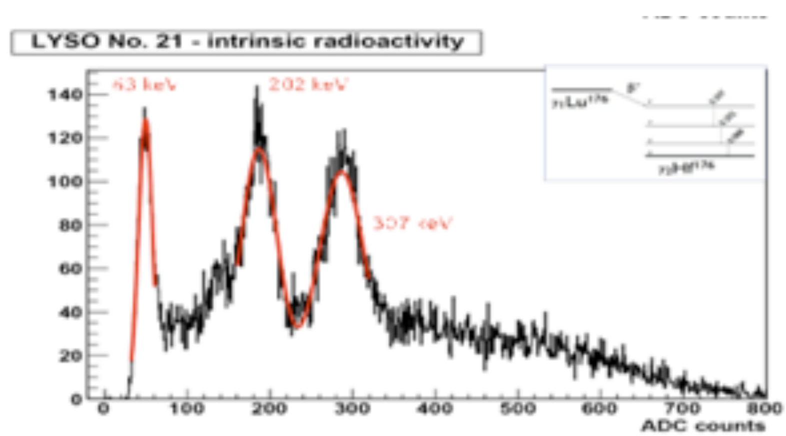


Figure 8. Intrinsic LYSO radiation spectrum (data from the AX-PET collaboration).

the ^{22}Na source and the gamma detector. The gamma detector will provide the trigger for the data acquisition system, and gammas from positron annihilation will be selected with an amplitude analysis - events with energy around 0.511 MeV in the gamma detector will tag gammas with 0.511 MeV energy in a tiny angle cone. The attenuation length of differently wrapped LYSO crystals will be measured with this system and the wrapping materials and technology will be selected.

The next step is the LYSO crystals matrix production. We have purchased 625 4x4x45 mm^3 LYSO crystals (see Appendix A). A 25 X 25 crystal matrix will be produced by our mechanical facility. The matrix will be contained in a plastic package with the two X-Y WLS fibers panels. Each panel consists of a UV-transparent optical plate with grooves for WLS fibers every 4 mm. The WLS fibers are not isolated optically and a spatial resolution analysis could be performed as for a gas-based wire chamber with a highly segmented cathode strip read out. It means that a cluster of fibers should be selected for the reconstruction and the particle position is the center of gravity in the cluster. 1 mm diameter KURARAY Y-11 fibers will be inserted into the plastic plate and glued with UV-transmitting optical glue.

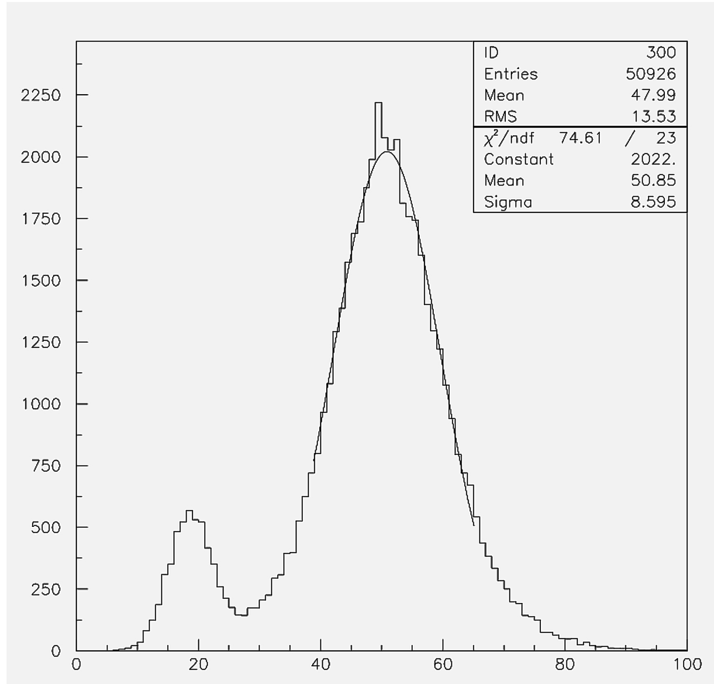


Figure 9. The distribution of the sum of amplitudes of all channels in photoelectrons from the existing prototype. The distribution has two peaks; the left peak is the response from the internal radiation of LSO/ LYSO with energy 202 and 307 keV (see Fig. 8). The right peak is the response from the 661.6 keV gamma from 137Cs and internal radiation (about 5-10% events in the peak).

Each X-Y fiber panel will be instrumented with 25+25 HAMAMATSU S10931 3x3 mm MPPC (SiPM) (See Fig. 11). 25 MPPCs will be assembled into a

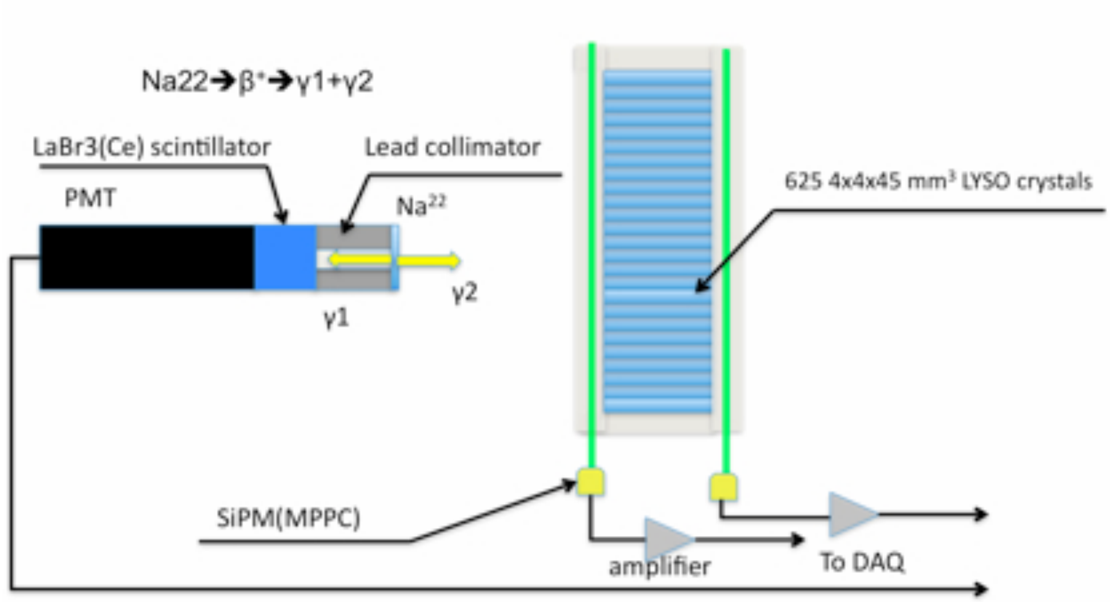


Figure 10. A schematic drawing of the ^{22}Na gamma source that will be used for gamma tagging.

package including small plastic light guides transmitting light from the 1 mm diameter fibers to 3x3 mm2 MPPC. The packages and light guides will be produced with a 5-axis milling machine and a polishing machine in our group's mechanical facility. We will also design and build the amplifiers and PCBs for readout electronics.

We will use one of our existing VME crates with 5 32-channel QDC modules (CAEN 792) and a VME controller. We will design and build the analog splitters and logic modules for the trigger.
Once assembling of the prototype is completed, an energy resolution and spatial resolution scan will be done with the tagged gamma source. We will also simulate the prototype in GEANT4.

The final version of the pre-shower prototype could be tested in a beam and could be used as an element of a detector in either in JLab or in BNL. It could be used as PET element or a gamma chamber as well.
The next step of R&D should be a maximization of the radiation robustness of different parts of the pre-shower.

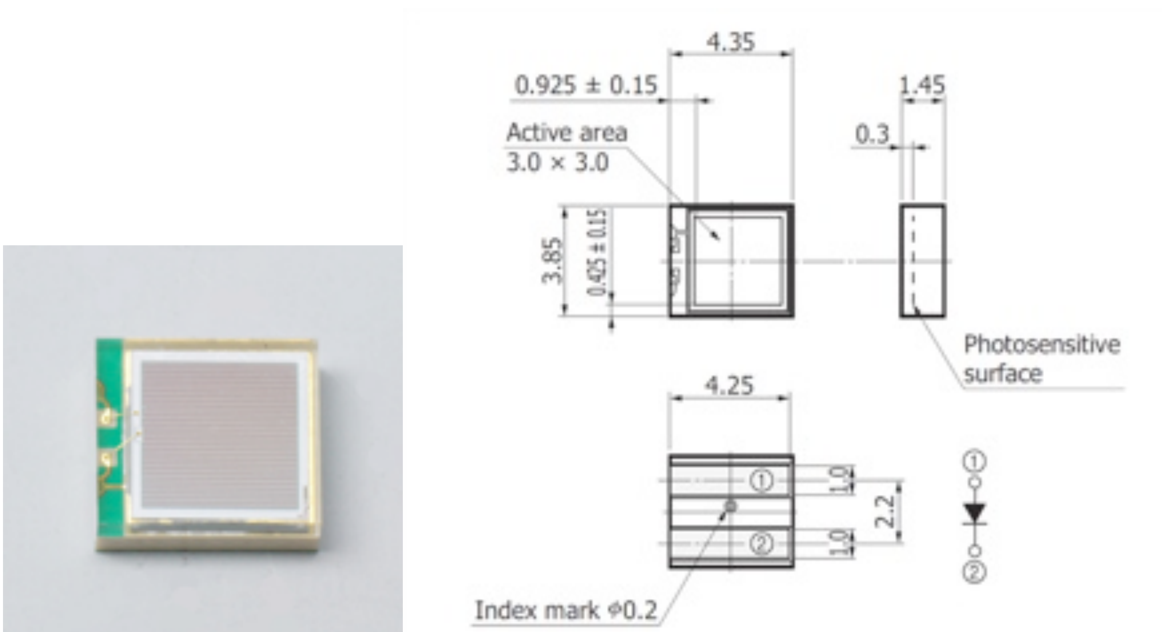


Figure 11. A photograph of the HAMAMATSU S10931 3x3 mm MPPC (SiPM) which is proposed to be used for this project, together with its dimensions and layout. (MPPC S10931-025P; active area:3 x 3 mm, pitch:25 um, surface mount type.)

Description of resources

Laboratory and Equipment

The experimental nuclear and high energy physics group of UTFSM has a modern, fully equipped mechanical and electronics fabrication facilities and extensive laboratory space for mounting test setups. This infrastructure was created during the last 4 years and is currently being used for testing 2800 HAMAMATSU large-area MPPC arrays and production of 4000 light guides for Hall D at JLab. The most recent versions of a DAQ system produced by CAEN are being used in this laboratory. The Valparaíso Center for Science and Technology (CCTVal in the Spanish acronym), a Chilean Center of Excellence located at UTFSM, is also currently negotiating to be the technical and business representative of CAEN in Chile. The members of the group have been involved since the inception of the CLAS detector at JLab, and of CMS and RD-40 at CERN. Our group participates in ATLAS, NA-61, RD-42 and RD-51 at CERN, GlueX and CLAS at JLab, and MINERVA at Fermilab.

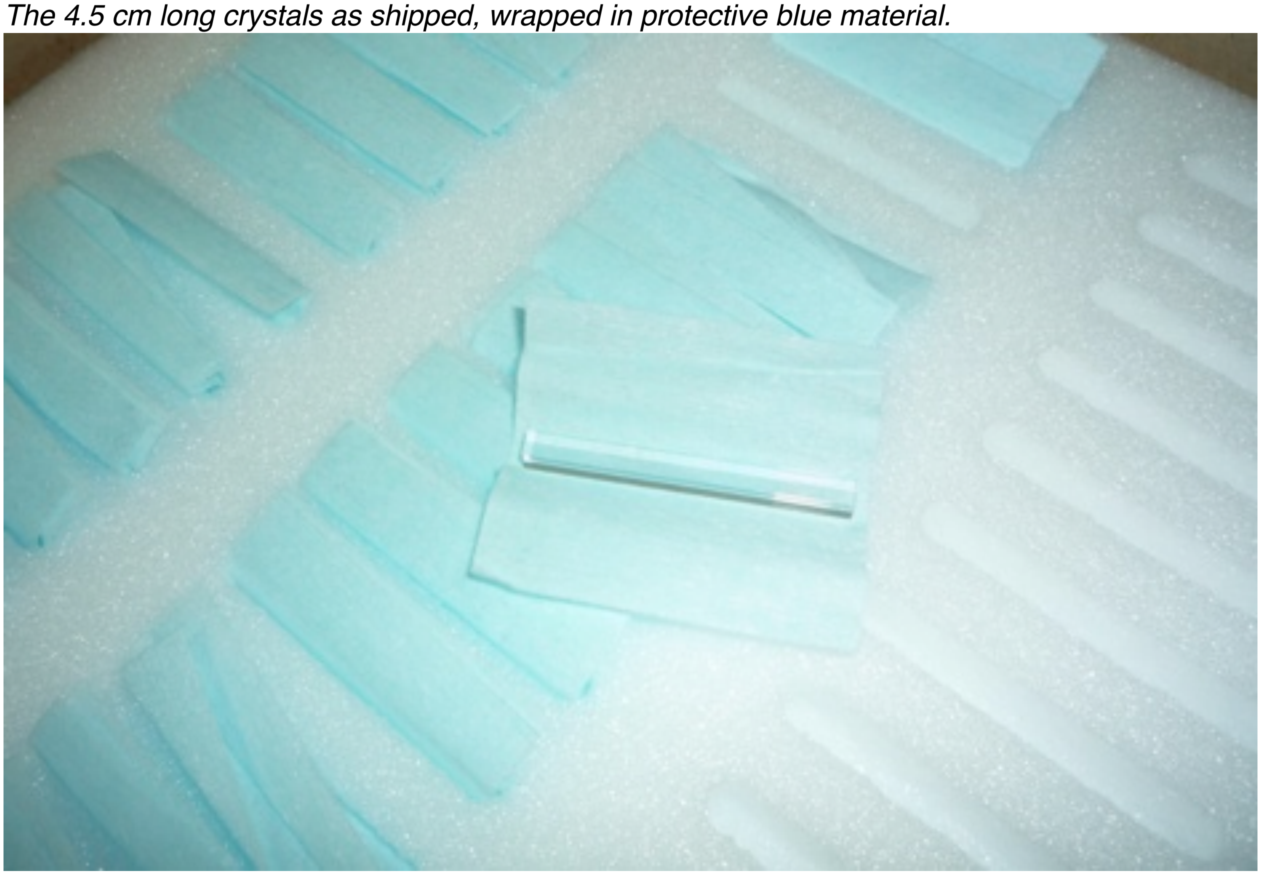
UTFSM Budget Request

Item	Cost (k$USD)
110 HAMAMATSU Series S10931 MPPC	12
500 m KURARAY Y-11 WLS fiber	5
Electronics components	7
Read out boards	5
Plastics, wrapping, optical glues	2
Moving table, precise mechanics, supports	10
Undergraduate student	5
Total:	46

APPENDIX A - In-house crystals available at UTFSM for this project.

Properties of PreLude420 (LYSO) crystals from Saint Gobain	
Density [g/cm3]	7.1
Hygroscopic	no
Attenuation length for 511keV (cm)	1.2
Wavelength of emission max.[nm]	420
Refractive index@emission max.	1.81
Decay time [ns]	41
Energy resolution [%]	8.0
Light yield [photons/keVγ]	32
Average temperature coefficient from 25 to 50 ^{o}C (%/^{o}C)	-0.28
Photoelectron yield [% of NaI(Tl)]	75

The 4.5 cm long crystals as shipped, wrapped in protective blue material.



The quality assurance certificate fron Saint-Gobain for the UTFSM crystals available for this project.