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A new approach: LYSO based polarimetry for the EDM measurements

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Abstract. One of the fundamental questions of modern particle physics is the existence of finite electric dipole moments (EDM) of the hadrons. In case of charged particles, like protons and deuterons, the proposed method is the precise determination of the precession of the beam polarization vector in a storage ring. For that purpose, the JEDI (Jülich Electric Dipole moment Investigations) collaboration is developing a precise polarimeter detector based on LYSO scintillator coupled to SiPM modules. They are capable of stopping 300 MeV elastically scattered deuterons and protons. Precise measuring of the kinetic energy of the scattered projectiles ensures the accurate reaction identification leading to a precise polarization determination. To create the long-term reliable detector system, we have performed four iterations of the detector development. Currently, we are operating 52 LYSO modules with a dedicated dead-time less sampling ADC readout system. The modules are very compact, due to modern high pixel density SiPM readout.

1. Introduction

The EDM measurement of elementary particles like proton and deuteron requires very precise instrumentation from the accelerator and particle detector system. The JEDI [1] collaboration is currently utilizing polarized beams of deuterons and protons from cooler synchrotron COSY [2]. A polarimeter newly developed for an EDM dedicated detector system will be installed (see fig. 1). The general concept is based on long-term stability, high accuracy, and modularity of the detector [3, 4, 5, 6, 7]. It is based on LYSO crystals [8, 9] coupled to large area SiPM arrays [10, 11]. The modules are very compact and can precisely measure the total energy of elastically scattered polarized beams (p or d) on the carbon target. All this is achieved without using a strong magnetic field (as in magnetic spectrometers) and without high electric field (used for conventional PMT based scintillator detectors).

2. LYSO-SiPM based detector system

As it is shown in figure 1, the final version of the detector will be installed at the COSY beam beginning of 2019. The full polarimeter consists of three main parts: the target chamber, vacuum chamber (with incorporated degrader) and detector part. Each extracted particle after exiting the vacuum chamber (500μm thick steinless exit window) loses energy in two

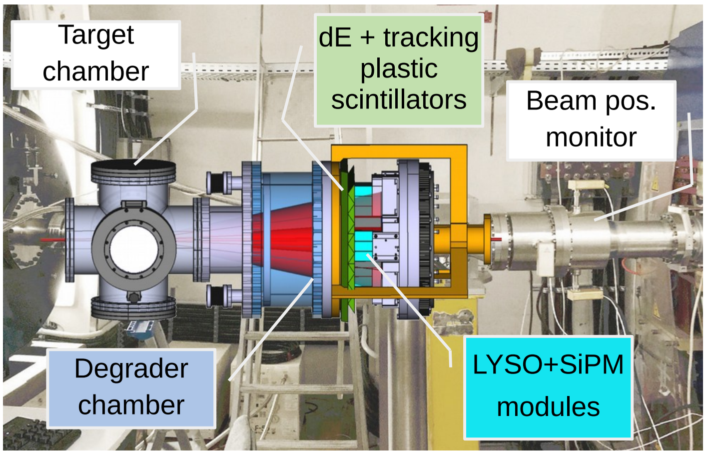

Figure 1. The JEDI polarimeter inserted at the former ANKE detector location. Left to right: (i) target cross flange; (ii) vacuum flight chamber with degrader in a closed position; and (iii) the polarimeter with the tracking system. The total length is 127 *cm*.

orthogonally oriented plastic scintillator layers [12]. Each layer consists of overlapping triangular bars, such that each particle crosses two horizontal and two vertical bars. The difference over sum between overlapping bars gives the precise crossing point and the sum of amplitudes (after energy calibration) gives the energy loss information. Both layers make in total 4 (2+2) cm ΔE path. Finally, each particle will be stopped in the eight cm thick LYSO layer where its

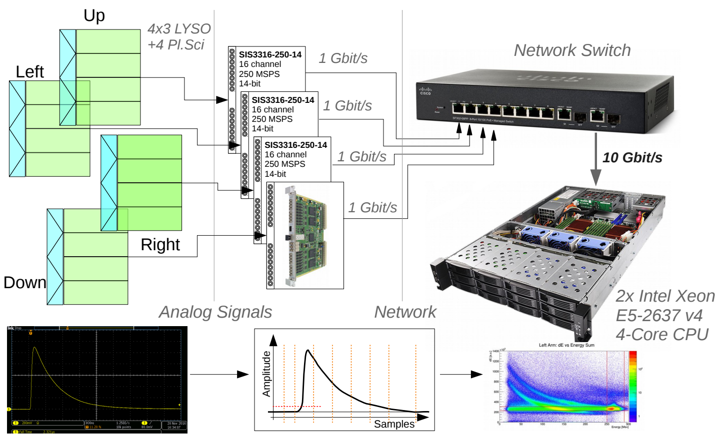

Figure 2. The data acquisition system for the dedicated polarimeter. The full signal shape is in eight integrals divided and transferred to the server computer for online analysis. For the precise tracking, the triangular plastic scintillator bars are used. Finally, $\Delta E/E$ histograms are constructed for the clean elastic reaction selection.

full energy will be measured. Using this two $\Delta E/E$ determinations, a very precise elastic reaction identification is obtained, these with precise scattering angle information the beam polarization will be extracted. The readout of the detector (see fig.: 2) is flash ADC based [13] continuously sampling trigger-less system. It gives the polarimeter enormous advantages for the EDM measurement where the event timing information is very crucial [15, 16, 17, 18, 19]. The whole slow control of the detector is based on EPICS [14] system which integrates detector with the COSY accelerator control system.

2.1. Front and side scans of the LYSO crystals

Figure 3 shows clear sub-percent resolution for the SiPM-based LYSO modules but with quite big error bars. Partly these error bars come from a significant deviation between modules caused by light sensors sensitivity, optical coupling, and readout channels. Also, the energy distribution histogram fitting procedures are a substantial problem since the line shapes differ from module to module. But we also have many LYSO modules where the signal distribution histograms demonstrate 0.3% energy resolution (see Fig: 4) when injecting focused beam directly into specific regions of the crystal front face. This was mostly seen during the energy calibrations.

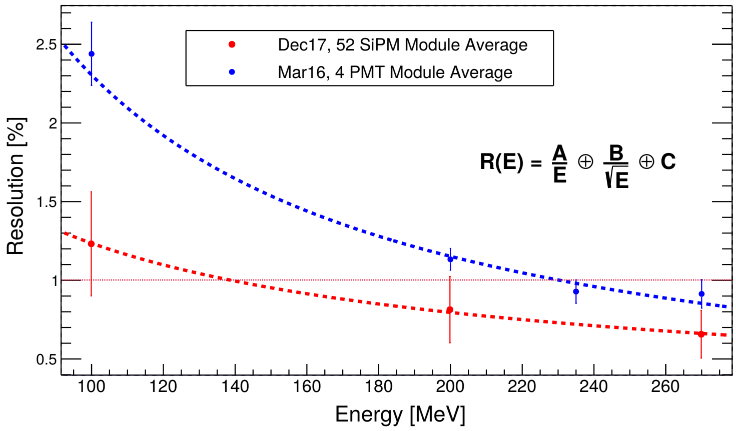

Figure 3. The comparison of energy resolutions as a function of incoming deuteron beam energy. Blue data points are the first measurement of the LYSO crystals with PMT readout. The red data points are averages of all modules with SiPM readout from December 2017 beam time. Note: here the resolution is defined as a FWHM divided by amplitude.

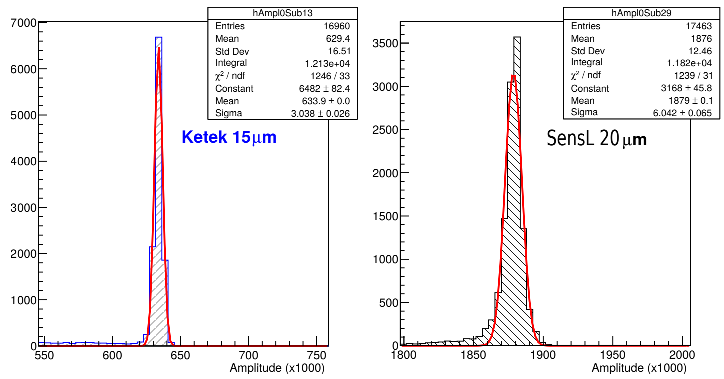

Figure 4. A typical charge distribution spectra at $200 MeV$ deuteron beam energy aimed at the middle point of a crystal. Left: Ketek array with 15 μm pixels at 29 V having relatively low gain. Right: our standard SensL 20 μm pixel array, also with 29 V reverse bias voltage.

During the scattering experiments, sometimes we also saw a double peak with each peak being very narrow with about a third of the present resolution. The integrals of the peaks were very dependent on beam spot location when aiming at crystals. This motivated us to make more careful crystals scans which were easily possible with the current setup.

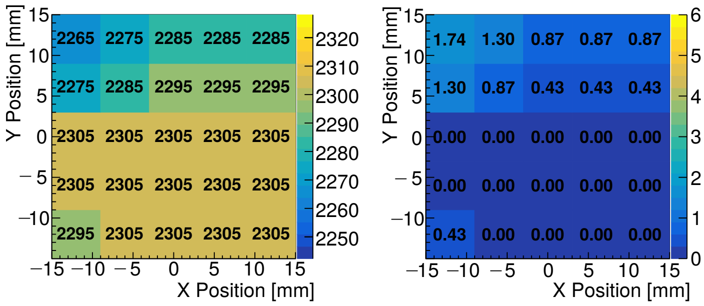

Figure 5. A typical 5×5 front face map of a LYSO crystal with a $300MeV$ deuteron beam. Left: the absolute values of peak position of the beam energy. Right: the relative deviation from the maximum value showing the homogeneity of the energy reconstruction to be within two percent.

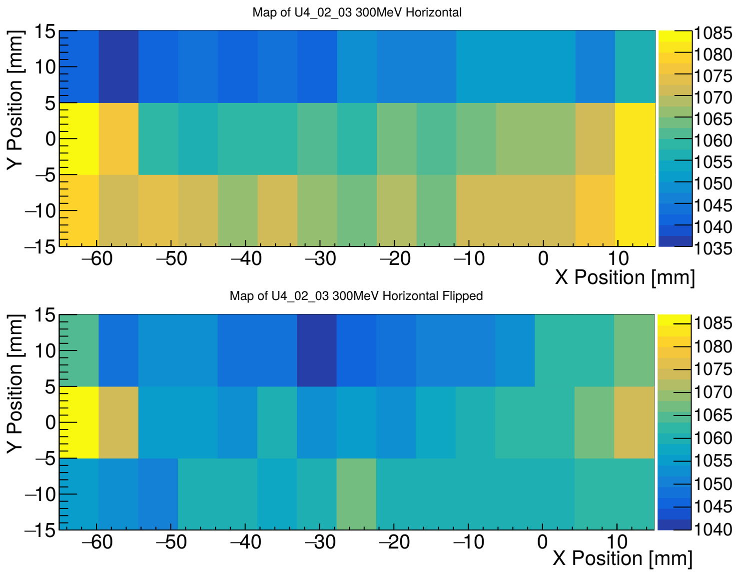

Figure 6. A 15×3 side face map of a LYSO crystal at $300MeV$ deuteron beam. In both measurements, the sensor is located on the right side. Upper: The same orientation as for the Fig. 5. Clear lowering of the light output can be identified in the upper part of the crystal. Lower: The 90° rotated map of the same crystal showing a different light output distribution from the upper face. Note: the crystals are only 3 cm thick, so deuterons are punching through.

Fig: 5 and 6 show the front face and the side face scanning of the same crystal. We found significant deviations in the light output homogeneity. All necessary cross-checks were done and the non-homogeneity of some LYSO crystals were identified. Now we have front face maps of all 52 LYSO modules measured at one energy. Some of the crystals were also scanned with all available beam energies, and no energy dependence was found.

2.2. Comparison between different types of SiPM

Figure 7 shows the comparison between typical amplitude dependence on deuteron energy for SensL and two different types of Ketek silicon photomultiplier arrays. As expected, the smaller pixel 15 μm^2 size leads to a higher number of pixels per area and thus to a higher dynamic

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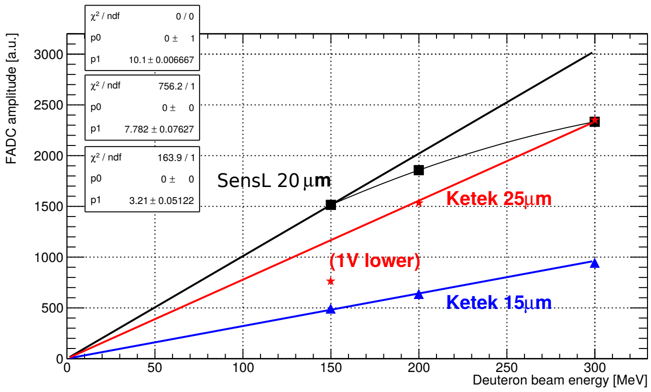

Figure 7. Typical measured amplitudes for SensL 20 μm (*black*), Ketek 25 μm (*red*) and Ketek 15 μm (*blue*) pixel size array vs. deuteron beam energy. All points are pedestal subtracted. That's why all linear fits are zero normalized ($y = g \cdot x$). Black line: only 150MeV measurement is fitted and extrapolated to 300MeV. Red line: only the measurements at 200 and 300MeV are in fit. Blue line: only the measurements at 150 and 200MeV are fitted and extrapolated.

range. Both arrays have very similar size roughly 27×27 mm. Even though the pixel size is bigger for the 25 μm Ketek than for the 20 μm SensL, the amplitude vs. energy function for the Ketek is more linear within the operating range. This effect can be explained by the pixel architecture and PCB layout of the SiPM arrays. The so-called trench technology of the new Ketek SiPM's reduces optical crosstalk as well as dark current drastically. Typically from several hundred μA for SensL to below 40 μA for Ketek. In general, all three types of sensors can be used successfully. Maybe for a future modules, we will prefer 15 μm Ketek arrays due to their higher dynamic range. We obtained the first prototype two samples in our beam time through a special order. Also, the fact that Ketek arrays have separated SiPM connectors gives us more flexibility to design and test different readout PCB schemes for a signal including data reduction.

3. Conclusion

Currently, we are successfully operating a LYSO polarimeter utilizing the extracted deuteron beam of COSY. In total, we have had more than five weeks of test beam time; three of them with a polarized deuteron beams. We have gained valuable information from detector tests and measurement of elastic deuteron scattering of six different targets materials (C, Mg, Al, Si, Ni, Sn). Also, several different beam energies (100, 150, 200, 270, 300 MeV) with very different intensities (from several Hz to several MHz) have been used. Figure 8 demonstrates the online deuteron beam polarization monitoring of the COSY cycle by cycle. The detector hardware is very reliable and the software is operational. More improvements are expected after its installation at the COSY internal beam where the count rate will be continuous and smooth compared to external experiments. The 2D maps of all crystals can be used for energy loss correction for each individual crystal, leading to minimizing the energy resolution.

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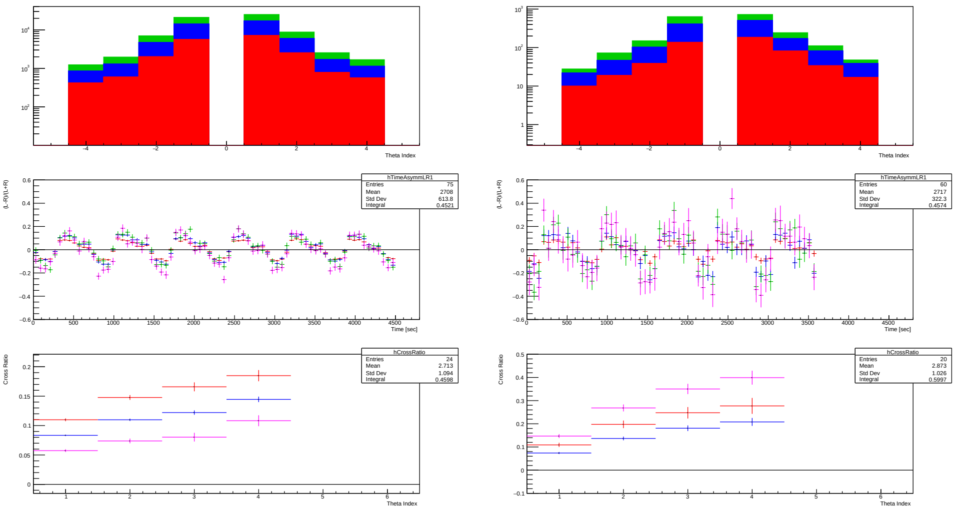

Figure 8. Online monitoring of the COSY deuteron beam polarization cycle by cycle. Left the deuteron-nickel and right deuteron-tin elastic scattering is shown. Upper row the stacked histogram of left and right arms, middle the left-right asymmetry cycle by cycle and the lower so-called cross ratio (combined asymmetry for different spin states) are shown.

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