# COSY Beam Time Request

For Lab. use

| Exp. No.: | Session No. |
|---|---|
| **E2.6** | **8** |

Collaboration **JEDI**

# Towards the EDM Polarimetry


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| Total number of particles and type of beam (p,d,polarization) | Kinetic energy (MeV) | Intensity or internal reaction rate (particles per second) | |
|---|---|---|---|
| | | minimum needed | maximum useful |
| **Extracted beam of polarized deuterons** | **100, 200, 270, 300 MeV** | **$10^3$** | **$10^7$** |
| Experimental area | Safety aspects (if any) | Earliest date of installation | Total beam time (No.of shifts) |
| **LYSO crystals at external BIG KARL area** | **none** | **1st November 2018** | **2 weeks (+ MD)** |

JEDI Beam Time Request for the next period

# Towards the EDM Polarimetry (Progress report)

for the JEDI collaboration

*http://collaborations.fz-juelich.de/ikp/jedi*

June 24, 2018

**Abstract**

In this beam time request, we would like to finalize our system development in the extracted beam area. The next step will be a COSY internal beam test, which we plan to start early in 2019. At the beginning of this document, we will review the recent results, especially our last detector test which took place in the second week of May. The LYSO-SiPM module development is in a fully operational state and has shown very reliable operation during the last years. A polarimeter tracking system has been tested and also shows promising first results. The next iteration is also a necessary step before the installation on the COSY internal beam line. Namely, the mechanical constructions need to be implemented as they will be in the final detector assembly. The fully assembled two-dimensional tracking system must be attached to the crystals, and the vacuum chamber needs to be combined to the detector. The DAQ system needs also further software and slow controls optimization and will be finalized for the operation of the internal beam experiments. Using the $2D$ plastic scintillator tracker, we can substantially improve our previous measurements of $\vec{d}X \rightarrow dX$ differential cross section and analyzing power for all target materials $(C, Mg, Si, Al, Ni, Sn)$ for several beam energies.

For the planned measurements using the polarized deuteron beam, we request **two weeks** of COSY beam time preceded by one week of machine development (MD). Four beam energies between 100 and 300 $MeV$ will be explored with six different target materials at the BIG KARL experimental area.

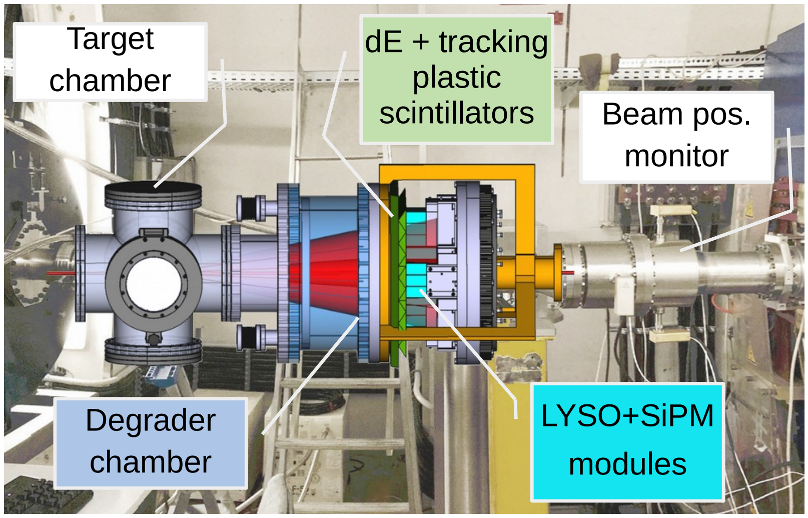


Figure 1: The JEDI polarimeter inserted at the former ANKE detector location. Left to right: (i) target cross flange; (ii) vacuum flight chamber with degrader in a closed position; and (iii) the polarimeter with the tracking system. The total length is 127 *cm*.

# 1 Introduction

Since the last CBAC meeting (*December 2017*) [1], the primary emphasis has been on further development of the final polarimeter design for use with the internal COSY beam. The design requirements and restrictions are matched to the former ANKE target section. The length of the whole polarimeter fits into the space (1.27 $m$) between a superconducting solenoid and the COSY beam position monitors (BPM) (see Fig. 1).

According to our earlier plan, we expected to install an entire tracking system and the mechanical structure. The detailed information about the tracking system based on triangular plastic scintillator bars, read out using $6\times6\ mm^2$ Ketek SiPM's, eight per bar, will be given in the next section. The mechanical construction was planned to test the exit window welded to the 88 $mm$ (outer diameter) beam pipe. Unfortunately, the exit window has been delayed due to manufacturing problems. We ordered three and the company made only two perfect and one damaged window that is not appropriate to

Figure 2: Damaged exit window during delivery.

use in UHV applications. The two that were sent to us were bent (see Fig. 2) in unknown circumstances that we are trying to clarify. The window itself is (shown as light green in the left insert of Fig. 2) 500 $\mu m$ stainless steel with a slight bowing radius to withstand atmospheric pressure. Taking into account this accident, we will test the new exit window and other mechanical parts during the coming beam time.

# 2 Results from the last beam time

At the beginning of the last beam time, the COSY polarized deuteron source showed weak performance with low polarization in one state and very low intensity in both polarized states. The decision was made to use unpolarized beam and perform as much hardware adjustment as possible. During the experiment, all 52 LYSO-SiPM modules were installed and continuously tested. To review, we have 48 crystals from Saint Gobain [3] and 4 crystals from Sichuan Tianle Photonics [4]. The remaining 48 LYSO modules were unchanged (among them 4 Tianle crystals) and equipped with SensL 20 $\mu m$ SiPM arrays [5]. Two of the modules are equipped with new 15 $\mu m$ Ketek [6] SiPM arrays. Another two already from the last beam time had Ketek 25 $\mu m$ SiPM arrays attached. Also, one module with the Ketek array was equipped with a digital thermometer, permanently reading the temperature inside the module.

The readout for the 6 FADC modules, new software for data acquisition, and slow-control has been tested. Continues voltage and temperature monitoring was successfully implemented and included in the general COSY EPICS archiving system.

It has to be mentioned that we faced two long weekends (each with four holidays), at the beginning of the machine development week and the end of measurement week. The consequence of that was the development of only three energies 150, 200 and $300 MeV$. Our wish was to have $100 MeV$ instead, but it was not possible due to extraction difficulties.

Now we will discuss the recent achievements in this section.

## 2.1 Energy Calibration

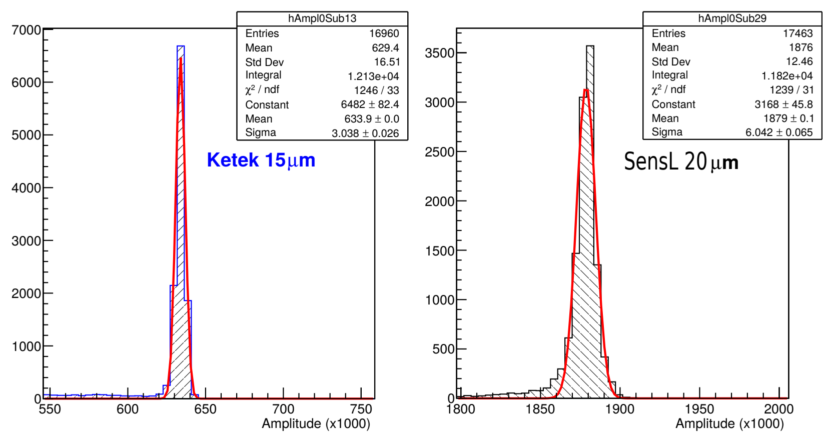


Figure 3: A typical charge distribution spectra at $200 MeV$ deuteron beam energy aimed at the middle point of a crystal. Left: Ketek array with 15 $\mu m$ pixels at 29 $V$ and relatively low gain. Right: our standard SensL 20 $\mu m$ pixel array, also with 29 $V$ reverse bias voltage.

After the successful installation of all modules and before attaching the $dE$ plastic scintillator bars (in front of the LYSO modules), the energy calibration was made using the direct beam. The available deuteron kinetic energies were only three: 150, 200 and $300 MeV$.

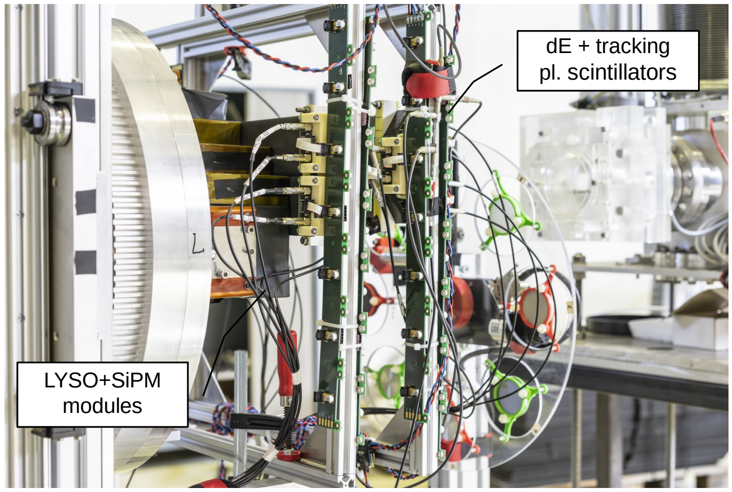


Figure 4: The experimental setup, similar to last beam time. In this setup, in addition to the last setup, six triangular plastic scintillator bars, three per plane, are used. The 2D scans of LYSO modules and the relative position scan for the plastic scintillators were made using this setup.

## 2.2 First test of $2D$ position sensitive $dE$ detector

The aim of using triangular plastic scintillator bars with SiPM readout is to achieve an EDM-compatible $dE$ detector system. The SiPM low voltage supply ($< 30V$) ensures microampere level current consumption. Consequently no strong electric and magnetic fields are created. This is a definite advantage over using systems with conventional PMT's or using gaseous tracking detectors. Energy and position resolution is not compromised.

In this beam time, we tested two layers of triangular plastic scintillator bars. Each layer consisted of three scintillating bars overlapped as shown in Fig. 5. Each bar has eight Ketek $6 \times 6$ $mm$ SiPM's, four on each end. Each end has especially designed two channel fast opamp based preamplifier, each attached to a shared reverse bias and supply voltage. For the first test beam time, each preamp output was sampled individually, four readout channels per bar. This was to find an optimal way to simplify the system, by reducing the FADC readout channels. We were seeking to reduce readout channels without losing the energy resolution. Maybe, we can reduce the SiPM number per bar from eight $(4+4)$ to six $(3+3)$ or even lower. One can

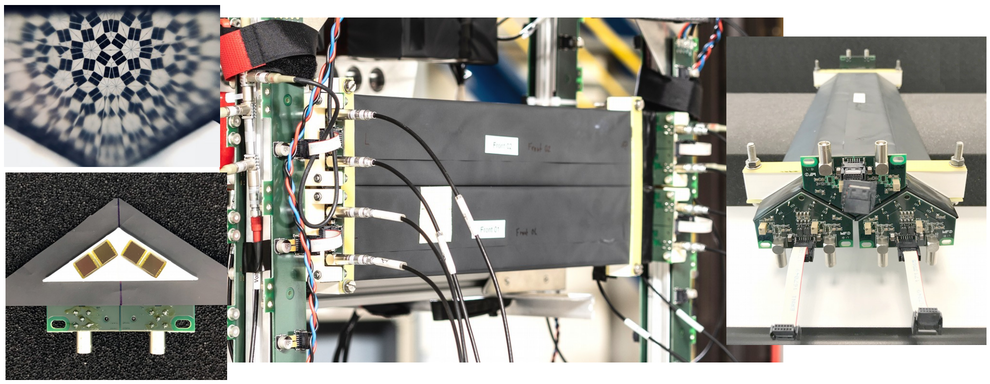

Figure 5: Picture gallery of the plastic scintillator tracker. Left-up: the view through the wrapped triangular scintillator bar where the kaleidoscopic picture of the SiPM's is seen from another end. Left-down: the end cup of the bar is shown with four SiPM's split into two independent preamplifier channels. Middle: already attached tracker in front of LYSO modules. Right: one of the layers with three bars after assembly. Each counter has four independent preamplifier output, two each end, and eight $6 \times 6\ mm$ SiPM's four each end.

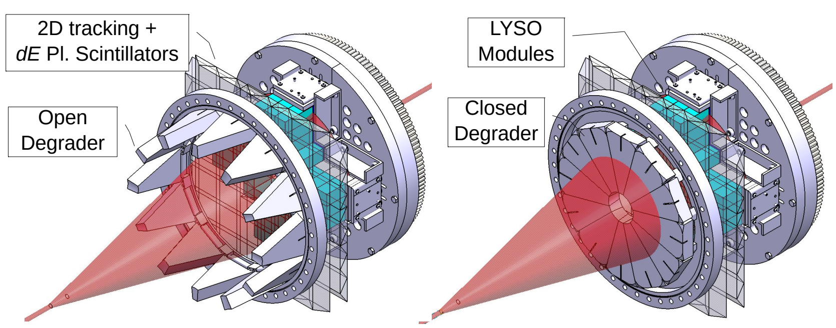


Figure 6: The JEDI polarimeter forward system consisting of the degrader system, the $dE$ scintillating layer, and the LYSO modules. The $dE$ layer consists of two layers $(X, Y)$ of overlayed triangular bars with $2D$ position sensitivity.

also try the asymmetric distribution of SiPM's (1+3) for the scintillator ends. Also, we expect to use one channel per bar, since, in the final construction, an $X$, $Y$ configuration will be realized (see Fig. 6). This will allow us to self-correct attenuation functions for each layer on an event by event basis.

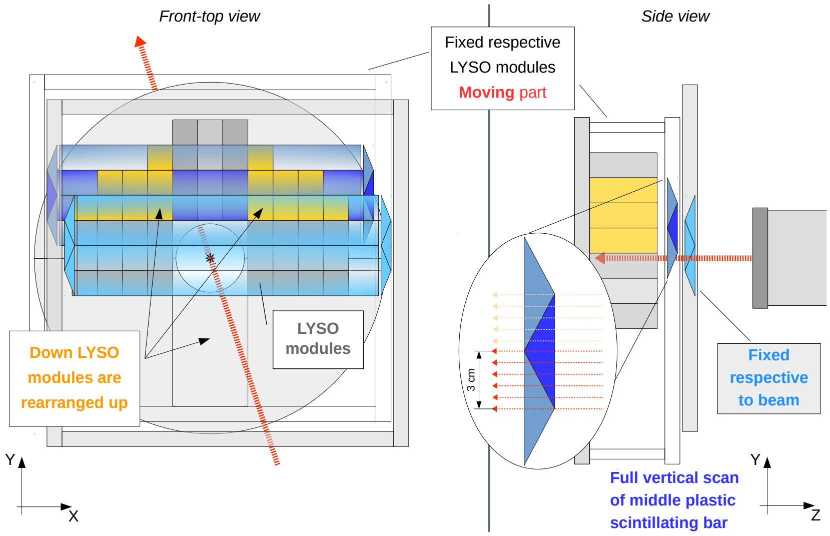


Figure 7: Schematic drawing of the plastic scintillator tracker consisting of the overlapping triangular scintillator bars. The upstream (forward) frame is installed to be fixed vertically relative to the beam while the downstream (backward) frame can scan the beam. Left: the front view, showing the crystal rearrangement for the tracker scanning. All plastic scintillators were scanned vertically and horizontally (along the bar). Right: the side view, showing a full vertical scan of the backward middle (dark blue) scintillating bar.

As it is demonstrated in Figs. 8 and 9 the scan of the vertical profile (see Fig. 7) without careful offline analysis shows less than two-millimeter resolution. We expect, based on Geant 4 simulation and the acquired promising data, to reach a submillimeter resolution after correcting attenuation functions and finding the proper algorithms for weighting and summing the preamp channels accurately.

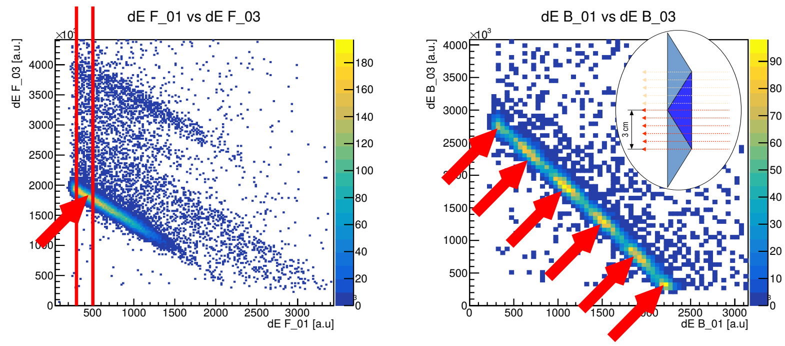


Figure 8: The amplitude correlation histograms for the forward and backward layers of two overlapping triangular scintillator bars. Left: a forward layer which is fixed relative to the beam and showing only the beam spread. The red lines show the cut area to choose a relatively focused beam for the second layer. Right: the correlation in the second layer while scanning along the overlapped side. The apparent correlation between the amplitudes is demonstrated.

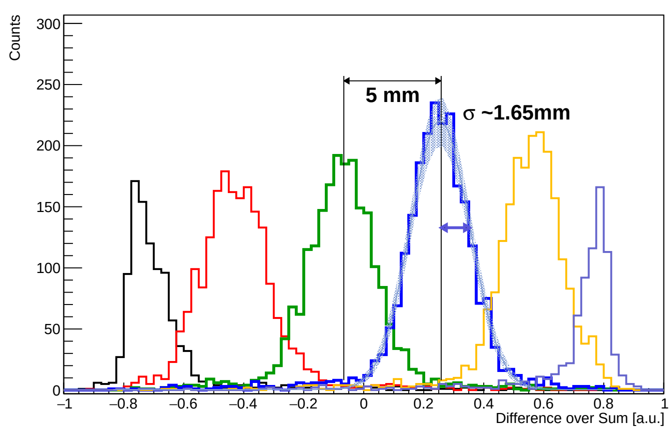


Figure 9: The difference over sum ($\frac{A_1-A_2}{A_1+A_2}$) between the bars for six different positions along the overlapping sides (5 $mm$ steps over a 3 $cm$ side) of a backward layer is shown. Without much effort, the few millimeter resolutions can be achieved. This is a preliminary result from the online analysis. In the offline analysis we expect to reach millimeter level position resolution.

## 2.3 Front and side scans of the LYSO crystals

Figure 10 shows clear sub-percent resolution for the SiPM-based LYSO modules but with quite big error bars. Partly this 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 defer from module to module. But we also have a lot of cases where the signal distribution histograms demonstrate 0.3% energy resolution (see Fig: 3) when shooting focused beam directly into specific regions of the crystal front face. This was mostly seen during the energy calibrations. During the scattering

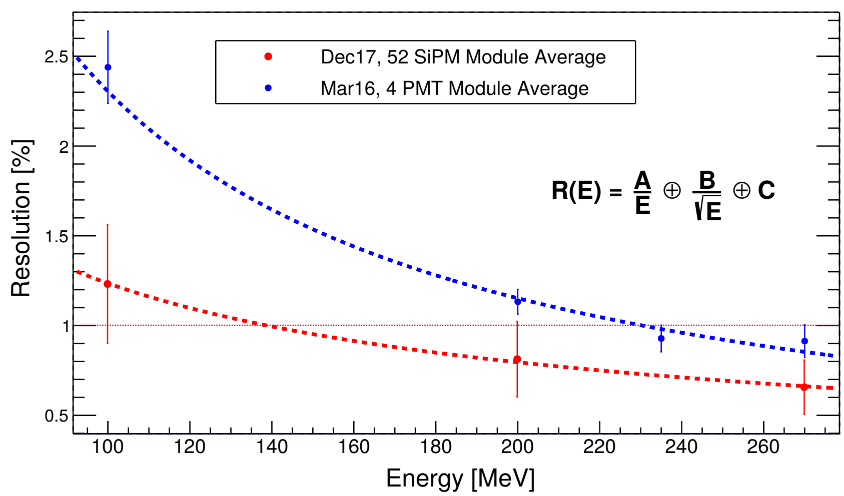


Figure 10: The comparison of energy resolutions as a function of incoming deuteron beam energy. Blue data points are a very first measurement of the LYSO crystals with PMT readout. The red data points are average of all modules with SiPM readout from December 2017 beam time. Note: here the resolution is defined as a FWHM over all modules divided by amplitude.

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.

Fig: 11 and 12 show the front face and the side face scanning of the same

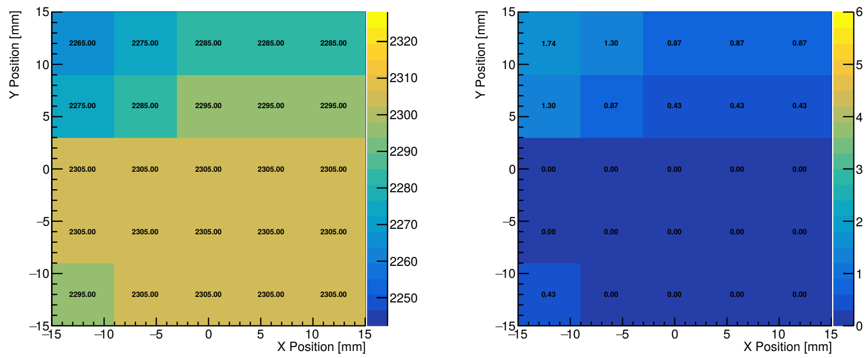


Figure 11: A $5 \times 5$ front face map of a LYSO crystal with a $300 MeV$ deuteron beam. Left: the absolute values of peak position of the beam energy. Right: the relative deviation from the maximum value showing the homogeneity of the energy reconstruction to be within two percent.

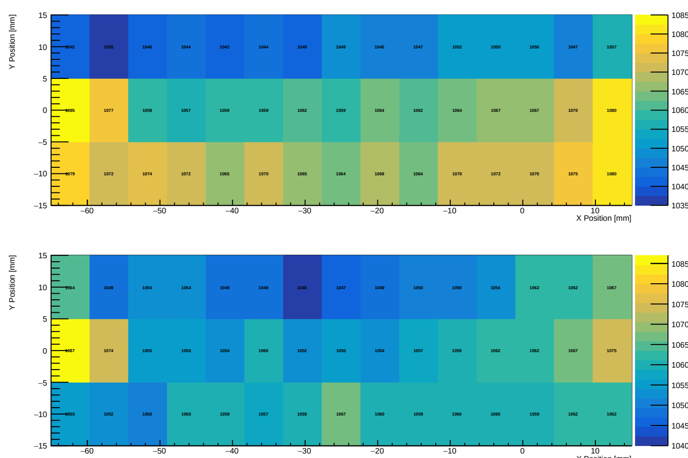


Figure 12: A $15 \times 3$ side face map of a LYSO crystal at $300 MeV$ deuteron beam. In both measurements, the sensor is located on the right side. Upper: The same orientation as for the Fig. 11. Evident lowering of the light output can be identified in the upper part of the crystal. Lower: The $90°$ rotated map of the same crystal showing a different light output distribution from the upper face.

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. These results will be discussed in more details during the oral presentation.

### 2.4 Laboratory test using radioactive $^{60}Co$ and $^{22}Na$ sources

Before installing the modules in the beam position, all modules were tested in the laboratory environment for light tightness. Also, three measurements were always recorded with high statistics for archiving purposes to compare with previous performance. The internal $^{176}Lu$ and external $^{60}Co$ and $^{22}Na$ radioactive sources were used. All 52 modules show excellent performance and only a few had a little bit of damage on the covering at the corners of the Tedlar wrapping.

### 2.5 Input threshold individual adjustment

During the experiment, we tested a new software control system that allows us to adjust individual thresholds for all channels in an effortless way. It can be changed using a graphical user interface (GUI) or using an automatized procedure which in the future will take into account online information about the elastic peak position and adjust the fixed energy cut position for every module.

### 2.6 Extending data acquisition system (DAQ)

During this beam time, we have tested six Struck FADC [7] modules with parallel readout, capable of reaching 6 $GBit/s$ data transfer rate. Four modules were dedicated for sampling LYSO module signals (52 in total) and two FADC modules for plastic scintillator bars (24 readout channels in total). At the next step, the settings (gate length, triggering mode, integration regions) for LYSO and plastic scintillators will be adjusted differently. The triggering threshold was already individual for each channel. The rest of the available channels are used for a start counter and one input channel in each module was connected to 100 $Hz$ generator rectangular signal for continuous synchronization monitoring.

## 2.7 Comparison between different types of SiPM

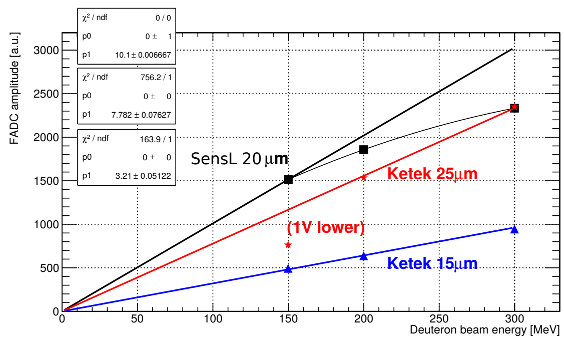


Figure 13: Typical measured amplitudes for SensL 20 $\mu m$ (*black*), Ketek 25 $\mu m$ (*red*) and Ketek 15 $\mu m$ (*blue*) pixel size array vs. deuteron beam energy. All points are pedestal subtracted. That's why all linear fits are zero normalized ($y = g \cdot x$). Black line: only 150$MeV$ measurement is fitted and extrapolated to 300$MeV$. Red line: only the measurements at 200 and 300$MeV$ are in fit. Blue line: only the measurements at 150 and 200$MeV$ are fitted and extrapolated.

Figure 13 shows the comparison between typical amplitude dependence on deuteron energy for SensL and two different types of Ketek silicon photomultiplier array. As expected, the smaller pixel 15 $\mu m^2$ size leads to a higher number of pixels per area and thus to the higher dynamic range. Both arrays have very similar size roughly $27 \times 27mm$. Even though the pixel size is bigger for the 25 $\mu m$ Ketek than for the 20 $\mu m$ 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 $\mu A$ for SensL to below 40 $\mu A$ for Ketek. In general, all three types of sensors can be used successfully. Maybe for the future modules, we will prefer 15 $\mu m$ Ketek arrays if the serial production will be started. We had the first prototype two samples in our beam time through a special order. Also, the fact that Ketek arrays have separated SiPM connectors makes us more flexibility to design and test different readout PCB schemes for a signal including data reduction.

## 2.8 EPICS based temperature and voltage monitoring and archiving system

We have implemented the EPICS (Experimental Physics and Industrial Control System) [8] based system compatible with a default COSY archiving environment. It gives us the possibility to implement a shared architecture with the accelerator control software. Figure 14 shows the module internal temperature correlation with the experimental hall temperature. This indicates a small power dissipation inside the module. On the other hand, we see the voltage dependence of the modules is also fully correlated with temperatures. The expectation is, either the reference voltage regulator or the voltage regulator for each channel has a substantial temperature dependence. The temperature change over the day is roughly one-degree $\Delta T \sim 1^{\circ}$ and the voltage change around 5 $mV$.

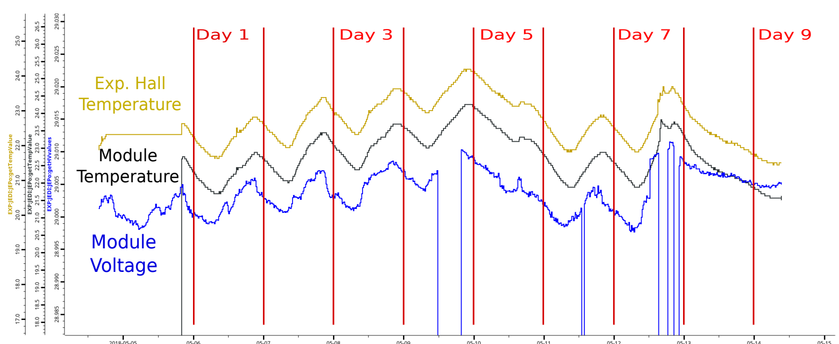


Figure 14: The module internal (black) and Big Karl experimental hall (yellow) temperature variation vs. time over the whole beam time. With the blue graph, the supply voltage for the same module is shown. The apparent correlation between all the values is evident.

To investigate this problem, we have already launched a laboratory test process, and we will identify which active elements of the power supply are temperature dependent. In parallel, we will enclose the power supply modules inside an aluminum box with internal temperature regulation a few degrees above the experimental hall value. This will provide the long-term voltage stability down to the micro-volt level.

# 3 Beam Time Request

In order to finalize this very successful development, we ask the CBAC committee to grant us **two weeks** of polarized deuteron beam time in the fourth quarter of the 2018 with several beam energies up to $300 MeV$.

# References

[1] November 14, 2017, Towards the EDM Polarimetry (E2.5)
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[2] Experiment electronic log book.
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[3] Cerium doped Lutetium PreLude420 crystal.
($http://www.crystals.saint{-}gobain.com/PreLude\_420\_Scintillator.aspx$)

[4] Sichuan Tianle Photonics Co., Ltd.
($http://tianlephotonics.com/$)

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($http://sensl.com/products/sipmarrays/arrayj/$)

[6] OEM arrays based on KETEK WB Series silicon photomultipliers .
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[7] SIS3316-250-14 16 channel 250 MSPS 14-bit.
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[8] The Experimental Physics and Industrial Control System (EPICS)
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$https://eljentechnology.com/products/plastic-scintillators/ej-200-ej-204-ej-208-ej-212$