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LIST OF ACRONYMS AND ABBREVIATIONS

CEPA	Califa Phoswich Array. 96xPhoswich($LaBr_3/LaCl_3$) in eight Al-encapsulations
CEPA4	CEPA demonstrator; 4 Phoswich($LaBr_3/LaCl_3$) crystals in one Al-encapsulation
CALIFA	Calorimeter for In Flight Gamma and proton detection
CsI(Tl)	Scintillator crystal material, Tl doped: CsI(Tl)
DT5730	Digitizer: 14-bit at 500MS/s and 2Vpp input range
DT5751	Digitzer: 10-bit at 1GS/s and 1Vpp input range
FEBEX3B	Digitizer board developed at GSI
LaBr	Scintillator crystal material, Ce doped: $LaBr_3$(Ce)
LaCl	Scintillator crystal material, Ce doped: $LaCl_3$(Ce),
LAAPD	Large Area Avalanche Photo Diod
MPRB-32	MESYTEC, Charge Sensitive Preamp with temperature compensated voltage supply to the LAAPD
Phoswich	Sandwich of two scintillator crystals with single readout
iPhos	*intrincsic PHOSwich*
FPGA	Field-Programmable Gate Array
SiPM	Silicon Photo Multiplier

EXECUTIVE SUMMARY

The PASPAG-JRA exploit novel scintillator materials and explore new techniques and concepts such as phoswich detectors and segmented or hybrid scintillators. We focus on developing the capability to simultaneously detect high-energy gamma rays, neutrons and charged particles.

As was discussed in the project application in order to separate the different components in the light emission, in the case of different response to light of the different crystals used in Phoswich detectors and/or the difference in light output due to the impact of different particles, digital systems based on flash ADCs may be the most flexible solution. The amount of data has to be reduced by digital pre-processing at the frontend. Optimized algorithms have to be developed to deliver sufficient performance and throughput.

A variety of different read-out sensors has been tested in order to measure high energetic protons and low energy gamma rays at the same time with Phoswich material LaBr/LaCl. The iPhos method was further investigated and benchmarked in an experiment measuring 16O(p,2p).

INTRODUCTION

This deliverable is related to Task 2.2 **Phoswich detectors** and have partly been reported in the milestone M3.3. The work presented has mainly been performed by the associated groups of TUM and CTH and the participating group of IEM and with considerate help from the collaboration especially IFJ PAN, TUD, and USC. Further, a considerable input from our colleagues of university of Lund is acknowledged.

In Phoswich detectors two different scintillators are optically coupled. Typically, the scintillators are chosen such that the light output of the two materials have very different timing properties. Therefor the energy deposited in the two materials of the phoswich can be extracted. Phoswich detectors are an attractive solution for discriminating high-energetic charged particles and gamma rays. They can also be a good solution for making economic use of novel scintillators to make detectors which have high energy resolution for low-energy gamma rays and high efficiency at the expense of resolution for high-energy gamma rays [1,2].

The idea of the Phoswich detectors as well as with particle identification in general is to be able to extract more information than just deposited energy from analysing each signal. Our collaboration is working on two complementary solutions; first the Phoswich, where two or more crystals are coupled together and their different light response can be used to identify particle type, and detection depth and secondly the iPhos method where one by analysing the signal-shape can identify which type of particle did interact in the crystal.

In both cases, digital electronics and pre-processing of the signals at an early stage of the read-out chain is necessary in order to reduce the data-stream and improve on the data through put. However, the first step in this R&D is done by computer processing of the digitized data, once the algorithms are proven to work these can be implemented in an integrated circuit (FPGA) in the frontend electronics of the detector readout in a second step.

Section 1 Phoswich

We have been working on the LaBR/LaCl Phoswich solution for quite some time, the concept has been proven and several articles have been published [1] [2] over the years. The LaBr/LaCl Phoswich will be used for the more forward angles (7^{O} – 20^{O}) of the CALIFA [3] calorimeter at the R3B experiment at FAIR. The R3B setup is built to study reactions of radioactive nuclei at relativistic energies. Particles and gamma-rays emitted in such reactions extend over an extreme dynamic energy range (100 keV-350 MeV). Moreover, the reaction rate will be very high and thus the intensity of particles hitting the detectors. Further, the CALIFA detector is situated very close to the GLAD super conducting magnet giving a stray field in the region of <100 mT.

LaBr/LaCl-Phoswich have been selected because of the very fast scintillator response; signal decay-times of 16ns and 28ns respectively, which can cope with a very high intensity without signal overlap. The very dense materials also make possible relatively short crystals (7+8 cm) necessary due to the lack of space between target and GLAD magnet. As mentioned above, both the response to gamma rays and protons of high energy has been tested and shown to work. However, the detection (within the full dynamic range) of low energy gamma rays (100 keV) with high energetic protons (300 MeV) is still being investigated and a good solution has not yet been found. The last few years work has been dedicated to find a suitable readout sensor and readout electronics.

Due to the surrounding magnetic field standard PMtubes cannot be used, the LAPDs are considered to be too slow to be able to do the pulse shape separation between the LaBr and LaCl response. Two options are still being tested SiPM and metal-package photo tubes. The main activity so far has been put onto the metal-package photo tubes. These are very compact units where the metal channel dynodes are made by micro processing technology and the electron path between dynodes is only 1mm, which makes these devices relatively insensitive to magnetic stray field, and very fast 1.5 ns (transit time spread <0.8 ns).

Two different metal-package tubes together with several different voltage-dividers were tested. The problem has been the dynamic range. The LaBr is a very bright scintillator light emission 63 kphotons/keV which means that a tube excellent for standard gamma sources with 10 dynodes yields huge signals in the order 1V leading to signal saturation at higher energies. We have obtained new tubes with only 8 dynodes, where both, the last dynode and the anode were read-out in order to choose different amplification. We reached a solution without signal saturation, however, the 2nd problem is the acceptance voltage of the digitizer that are $2V_{pp}$ and again we are saturated but now in the digitizer. **Part of this investigation was reported in the Milestone M3.3**

The latest step has been to ask Hamamatsu for a new development and in a few months from now we will have a 6 dynode metal-package photo tube with its voltage divider having last dynode and anode readout. This tube should be able to cope with the full dynamic range of the particles and gamma rays emitted in the experiments.

In order to reach a functional digital pre-processing, we need to identify precisely all parameters of the crystals, especially the time resolution, and from there decide upon the necessary characteristics (number of bits and sampling frequency) of the digitizers to be used. To experimentally “simulate” the response to high energy protons we detect cosmic muons, as MIPS interact similar to protons and in the size of crystals will deposit some 10 MeV/cm.

For this purpose, a setup for detecting muons was prepared, see Fig. 1, where we trigger muons in the four plastic scintillators, 2 on top and 2 below the CEPA4 LaBr/LaCl Phoswich array.

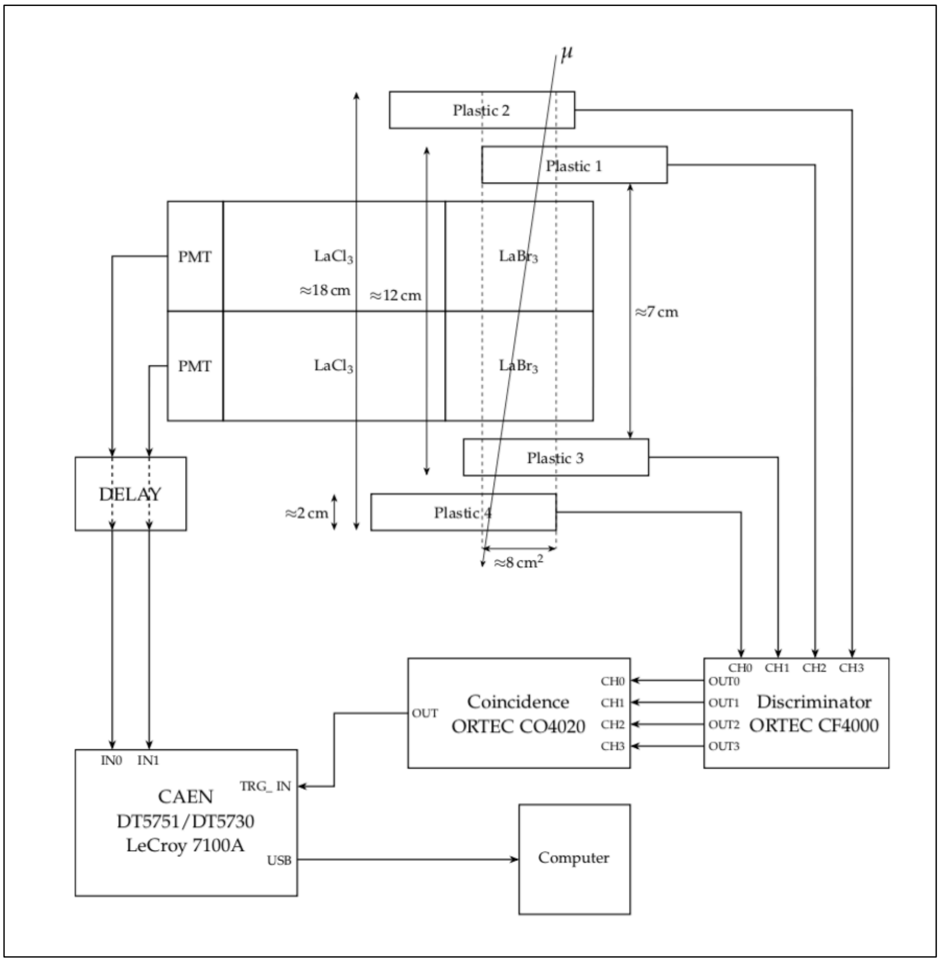

Figure 1. Schematic view of the setup for detecting and tracking cosmic muons passing through the CEPA4 demonstrator.

Different digitizers were used: the CAEN DT5730, which has 14-bit at 500MS/s and 2Vpp input dynamic range and the CAEN DT5751 which is a 10-bit at 1GS/s and 1Vpp input dynamic range. The time difference between two crystals detecting the same muon was determined to be < 100 ps. By choosing different sampling periods one could simulate a digitizer of less sampling frequency, and compare the influence of sampling frequency, see Fig. 2. [6] Further, as the devices have a fixed bit resolution of *bits* dividing the amplitude of every sample by $1/2^{\mathrm{Bits}-\mathit{bits}}$, being *bits* the number of bits we want to simulate, we can simulate a digitizer with a lower bit resolution and thus, the influence of the number of bits on the time resolution, see Fig. 3.

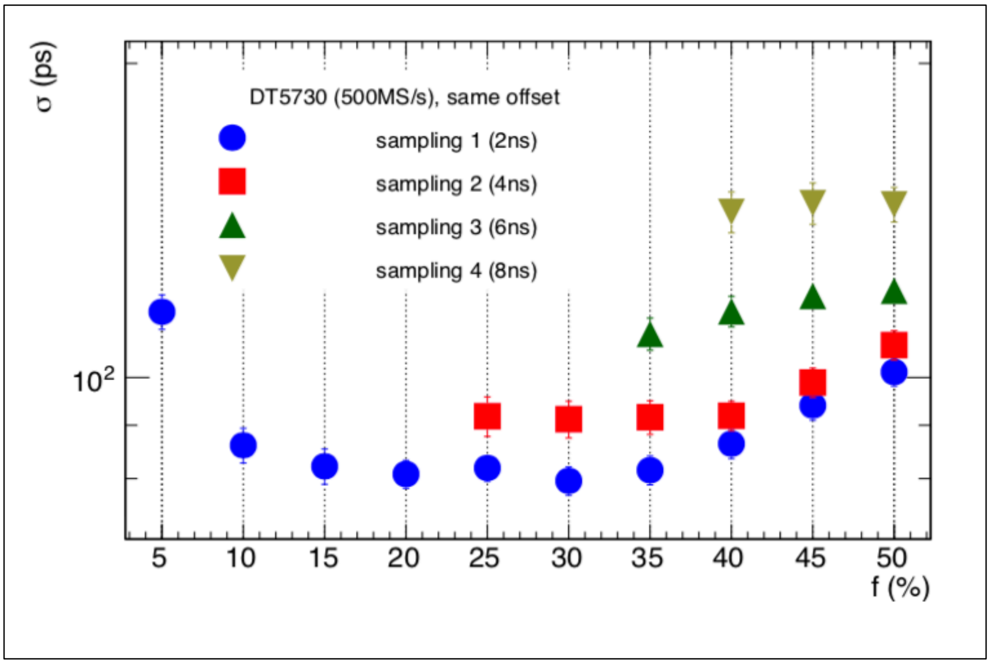

Figure 2. Sigma from the Gaussian fit to the time differences obtained for the DT5730 versus fraction of different samplings. The fraction f is a parameter of the algorithm which is used to determine the time of each signal. The sampling describes how much the signal sampling period was increased, to simulate a slower ADC.

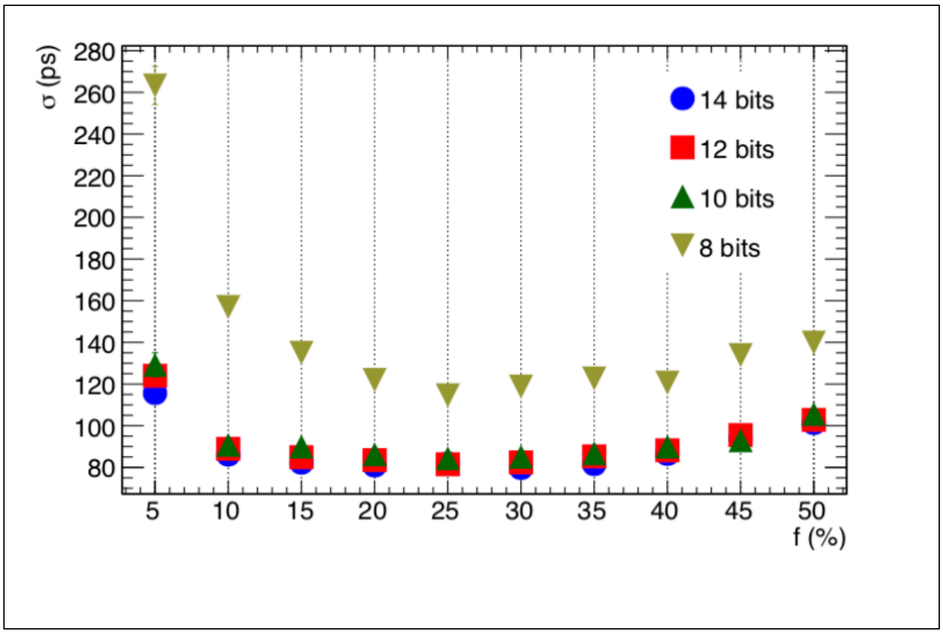

Figure 3. Sigma from Gaussian fit to the time differences obtained for the DT5730 versus the fraction f for different bit resolutions.

The time resolution of the LaBr3 crystals of the CEPA4 was successfully determined for muons obtaining values of less than 100 ps. Small variations in the time resolution obtained for muons were observed depending on the digitizer used.

The time resolution was also studied as a function of the sampling period T and the bit resolution. The studies showed that a digitizer with 1 GS/s or 500 MS/s provide time resolution compatible within error bars. The studies of the bit resolution showed that there is almost no difference between 10, 12 and 14 bits.

From this we can conclude that the minimum requirements needed for the digitizer are 10 bit resolution and a sampling frequency of 500 MS/s. Details of this investigations are parts of the master thesis of G. Bruni http://publications.lib.chalmers.se/records/fulltext/251988/251988.pdf. Chalmers University of Technology, Göteborg Sweden.

SECTION 2 IPHOS

In the case of iPhos, where the "I" stands for intrinsic i.e. *intrincsic PHOSwich,* one depends upon the different Pulse Shape as response to different particles or gamma rays interacting in the crystal. It is known for decades that CsI(Tl) scintillation light is dominated by two different components, a fast one with a decay time constant of $\tau f \approx 600$ ns and a slow one with $\tau s \approx 3.5$ µs. Evaluating these two components of the obtained signal allows for particle identification.

Making use of the RPID [5] – a fast pulse shape analysis algorithm already implemented in hardware - results in a nearly constant separation for stopped and punch through protons, which is N = 13 times larger than the width of the correlation of fast and slow component of the light emission. This feature allows to identify protons up to 480 MeV. This favours the use of the iPhos method up to these energy regions. However, due to the relatively slow response of CsI(Tl) and the very long crystals (22 cm) that are needed for the high energy protons, this method is chosen for the 2^{nd} forward-region [20^{O} – 43^{O}] of CALIFA, where both, less particle energy and less intensity is expected.

The iPhos solution for CALIFA is more matured than the Phoswich, it is fully based on the same crystal material, sensors, and readout electronics as the rest of CALIFA. The R&D for iPhos has been more directed to the development and implementation of the readout algorithm and analysis. Especially an experiment was performed at the Cyclotron Center Bronowice of the Henryk Niewodniczñánski Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow. This experiment was partly reported in the Milestone M3.3.

The facility features a proton cyclotron of type "Proteus C-235", with the possibility to change the beam energy quickly within a range of 70MeV < E_{Beam} < 230MeV. Three Petals representing 64 CsI(Tl) crystals of the forward half of the final CALIFA detector each (polar angle-range of 43° - 93°), were used. For the readout each individual crystal is equipped with a Hamamatsu S8664-1020 LAAPD. The scintillation light is collected on an active area of 2 x 10 x 10 mm^2 with a capacitance of C = 2 x 300 pF. The signals are connected to charge sensitive preamplifier MPRB-32 by Mesytec, which is specifically designed for CALIFA and CsI(Tl)/LAAPD readout. It houses two individual preamplifiers with 16 channels each, integrated HV supply to the LAAPDs, temperature dependent gain compensation for LAAPD and switchable gain stages (30MeV and 300 MeV). The resulting signals are digitized by the FEBEX3b board developed by GSI. The FEBEX3b board carries two 50MHz sampling ADCs and a LFE3-150 FPGA (from Lattice Semiconductor Cooperation) for the usage of customized online analysis firmware. For the 16 readout channels per board, the ADCs supply a 14-bit resolution with an input range of 1 V_{pp}. In addition a FEBEX Add-on Board (FAB) with Nyquist filtering and baseline adjustment features was attached. Figure 4 show raw signal traces of first measurements with E_{beam}= 200MeV on a polypropylene target.

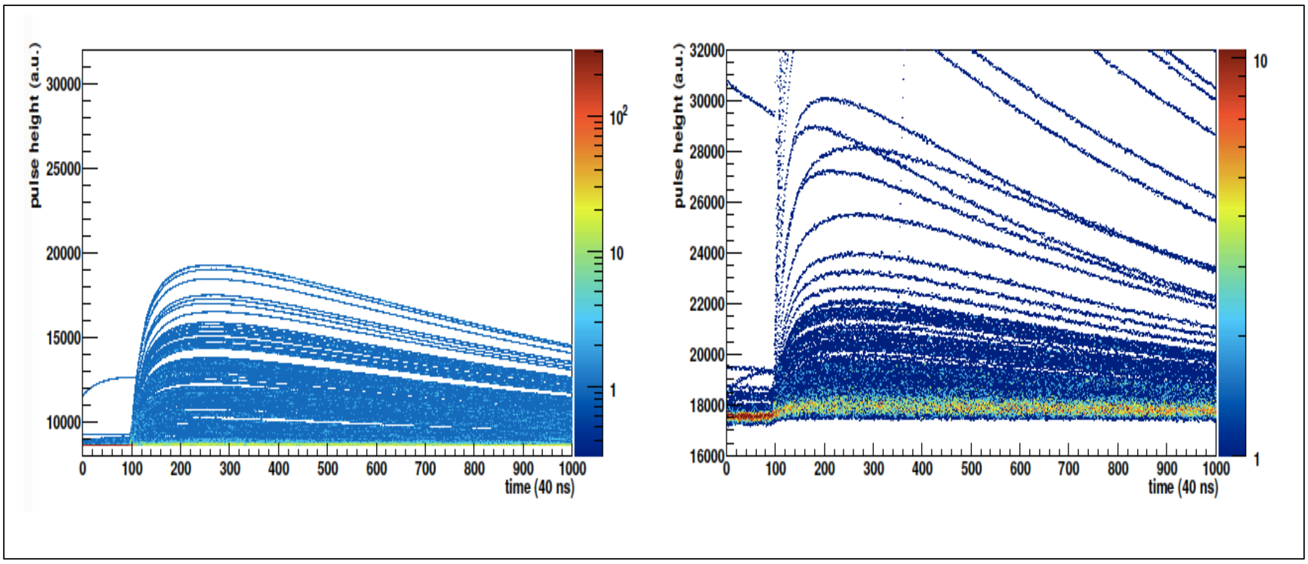

Figure 4. Raw signal traces of one selected detector sampled with FEBEX3B. Summed pulse height of two consecutive ADC samples is plotted versus the time in 40 ns samples. On the left side Petal 2 configured in high range mode (300MeV) is shown, while on the right side the petal is configured in low range mode (30MeV). Both traces show the characteristic slow rising edge of the CsI(Tl) scintillator as well as the preamplifier decay with τ=35 µs. Only a few pileups and baseline distortions are visible in both trace histograms. The data was taken with E_{beam} = 200MeV on a polypropylene target.

Experiment: excitation levels in ^{15}N populated in ^{16}O(p, 2p)^{15}N reaction

A liquid water (H_2O) fiber target with diameter dH_2O = 460 µm was used. This target provides on one hand a simple method of creating a stable and easily usable oxygen target to investigate the ^{16}O(p, 2p)^{15}N reaction and on the other hand delivers through elastic scattering on the hydrogen nuclei an intrinsic calibration capability. Figure 5 shows the correlation between the energy deposition in the petals mounted opposite to each other 0 and 1. As we know from the purely kinematic simulation of a ^{16}O(p,2p) reaction two strong lines corresponding to the ground state and first excited $3/2^-$ state of the ^{15}N nucleus should dominate the spectrum. A third strong line from proton-proton elastic scattering in the water target was canceled here by an opening angle cut on the two measured protons. Further, as the CALIFA crystals can detect simultaneously the protons and gamma rays we can gate on the specific proton line and see which gamma rays are in coincidence or vice versa gate on gamma and project proton energy, see figure 6. In order to reach this stage of results a lot of calibration and analysis work has been performed.

Especially, the particle identification (PID) capabilities intrinsic to CsI(Tl) are used to select only protons in both petals. The PID plots for petal 0 and 1 are shown in Fig. 7. The figures shows the PID plot in a reduced representation, where the reduced slow component $N_{red} = N_s - \alpha N_f$, (with α as the slope of the N_f vs. N_s plot) is plotted against the fast component N_f of the scintillation in CsI(Tl) summed over the full petal. This representation emphasizes the separation of the branches for different particles and particle stopped or punching through. The method is working for single crystals as well as for larger groups of crystals. In both figures the branches of stopped and punch through protons are separated very well down to the threshold visible at 10 MeV. Furthermore, deuterons, tritons, ^{3}He and ^{4}He can be identified as well. Individual peaks stemming from elastically scattered protons are nicely aligned on the stopped proton branch in both figures and were used for calibration for both petals. The details of this investigation are part of the Doctoral thesis of Benjamin Heiss, Technische Universität München, in preparation.

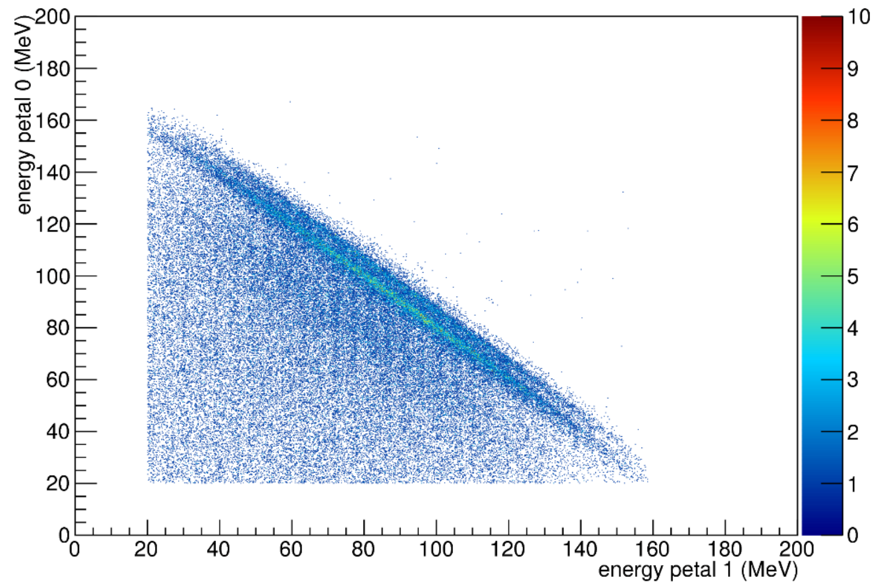

Figure 5. Correlation of the energy depositions in the petals 0 and 1 mounted opposite to each other. Here multiple anti correlations are observed in the data. As we know from kinematic simulation of a ^{16}O(p,2p) reaction two lines corresponding to the ground state and first 3/2^{-} excited state of the ^{15}N nucleus dominate the spectrum. The elastic proton - proton scattering was suppressed by an opening angle cut.

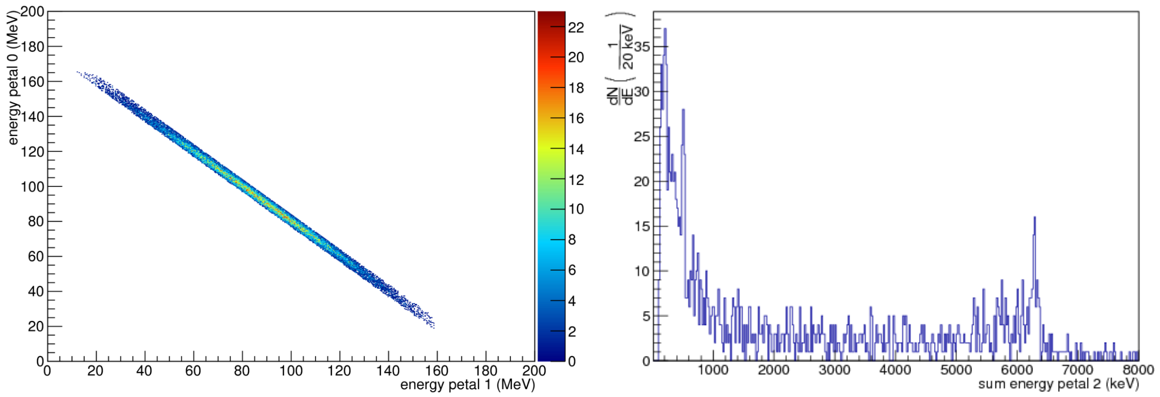

Figure 6. Event selection on the particle energy sum indicating the first excited state (left) and corresponding coincident gamma ray spectrum detected in petal 2 (right). Clearly, the expected line at 6.3MeV and its single and double escape peak dominate the spectrum.

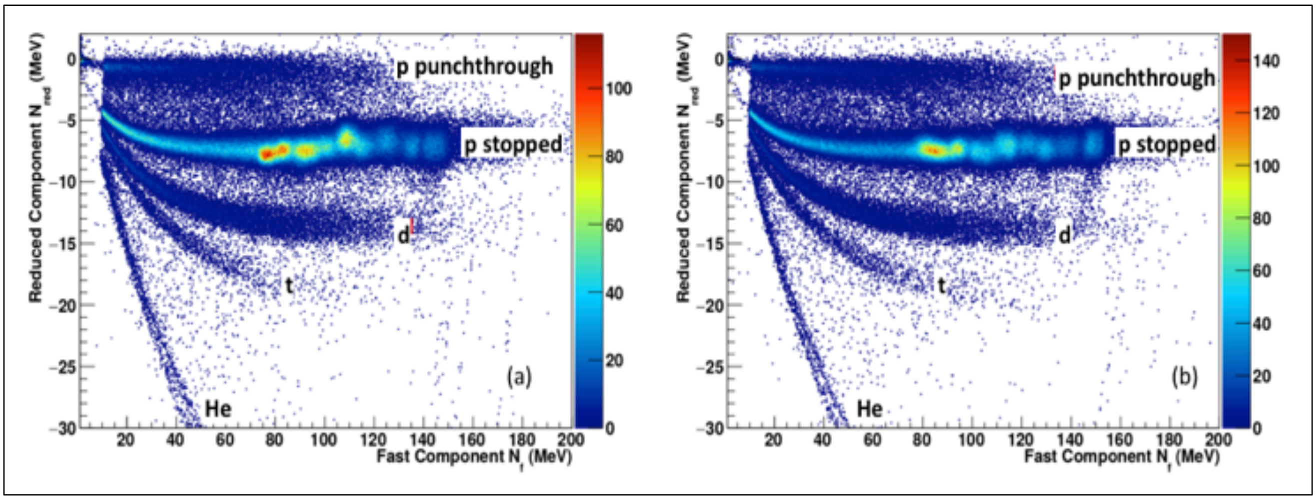

Figure 7. The figures shows the PID plot in reduced representation, as explained in the text above. In both petals the branches of stopped and punch through protons are clearly separated down to an artificial threshold visible at 10 MeV. Furthermore, deuterons, tritons, and He are identified as well.

CONCLUSION

The development and testing of new digitizing and analysing methods has been has been initiated. The features of sensors and readout together with different digitizer options are being characterized especially for the possibility to disentangle and separate the combined crystal-response that is obtained in the phoswich. There is still a major R&D work and comparisons of the different methods to be done before an actual performing detection system can be obtained. In the case of iPhos the results are more matured and the system is ready for data taking. The first real experiment will be the commissioning run S444 of the R3B set-up at GSI-FAIR scheduled for mid-October 2018.

The work is ongoing; we are on the point where we believe a real system is achievable. The work will continue in the timescale new sensors and digitizers can be obtained, an update of the report will be made along the time of the PASPAG project.