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	Contributors:	**Marcin Jastrząb**, M. Ciemała *IFJ PAN*, D. Jenkins, P. Joshi, *UYork* **Benjamin Heiss**, R. Gernhäuser, *TUM*
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Disclaimer

This milestone has been prepared by Work Package 9 (PASPAG - Phoswich scintillator assemblies: Application to the Simultaneous detection of Particle and Gamma radiation) of the Project in accordance with the Consortium Agreement and the Grant Agreement n°654002. It solely reflects the opinion of the parties to such agreements on a collective basis in the context of the Project and to the extent foreseen in such agreements.

LIST OF ACRONYMS AND ABBREVIATIONS

$LaBr_3$:Ce	A transparent scintillator material that offers the best energy resolution obtained so far. Hygroscopic, has to be encapsulated. Emission at 380 nm
$CeBr_3$:Ce	An alternative to LaBr, not exhibiting the internal radiation of La
CsI(Tl)	A transparent scintillator material, economical, doped with Tl with emission at 550 nm, which is better suited for LAPD and SiPM
APD	Avalanche Photo Diode
LAPD	Large Area Avalanche Photo Diode
SiPM	Silicon photomultiplier
PMT	Photomultiplier Tube
PARIS	http://paris.ifj.edu.pl/ Photon Array for studies with Radioactive Ions
CALIFA	the R3B CALorimeter for In-Flight emitted pArticles detection
R3B	Reactions with Relativistic Radioactive Beams https://www.r3b-nustar.de/

EXECUTIVE SUMMARY

Research and development have been carried out into hybrid scintillator array for nuclear physics and societal applications. The focus is on the need to combine different scintillator material, readout system, and electronics depending upon the characteristics of the gamma rays and particles to be detected. In one case is studied the application of SiPMs to replace standard PMTs for light collection. Their excellent performance has been demonstrated in terms of energy resolutions comparable to the best obtained with regular PMTs – close to 3% at 662-keV when coupled to $LaBr_3$. SiPMs facilitate innovative solutions for light collection unachievable with PMTs and show excellent promise for realising the determination of point of interaction within large scintillator crystals. The second case is related to the performance of the CALIFA (**CAL**orimeter for the **I**n **F**light detection of γ-rays and light charged p**A**rticles) Hybrid Array for the R3B experiment at GSI-FAIR. In this case test experiment has been performed at the proton cyclotron at IFJ PAN using different scintillators, readout techniques in combination with pulse shape analysis in order to separate gamma ray and particle response at high energy. Our hybrid prototype designs are advancing on the basis of these results.

INTRODUCTION

Hybrid detectors employing two or more scintillators are an interesting possibility for nuclear physics and societal applications. Phoswich detectors, where two different scintillators are coupled and the light is collected with a common photomultiplier tube (PMT), are a technology of long standing. This technique works best when the two scintillators differ strongly in terms of the decay time of their scintillation light output, i.e. where one is fast and the other is slow. The recent advent of fast digital data acquisition suggests scope for improvement in separating scintillation components. An alternative, so far largely unexplored in terms of hybrid detectors, is to use layers of scintillator read out by silicon photomultipliers (SiPMs). Such sensors are intrinsically compact and low profile affording the possibility of new, compact geometries for hybrid detectors. Moreover, SiPMs operate at low voltage (typically 30-60 V), and are cheap and robust compared to PMTs which have an evacuated tube.

Further it has been shown that (p,2p) reactions in normal kinematics is ideal for calibration experiment. A water jet target has been used in order to simultaneously obtain high energy gamma rays and charged ions. The reaction with the water target works fine; the obtained data can be clearly separated from the background, very good calibration points are obtained a very good starting point for proton and gamma calibration of the CALIFA petals.

This milestone is related to the deliverable D9.2 of Task 2 Sensor characterisation and base design of hybrid detectors. The work presented has mainly been performed by the participating groups of IFJ PAN and UYork in considerate collaboration INFN Milan in the case of PARIS development and the groups of TUM, TUD, USC and U Lund in the case of the CALIFA developments.

SECTION 1 TOWARDS SIPM READOUT FOR THE PARIS PHOSWICH ARRAY

SiPM technology is becoming a standard for scintillators and light applications, replacing PMT's which are getting more difficult to buy. Although trey are still some applications where PMT's demonstrate better results in terms of spectrometry and timing resolutions, the SiPM performance in terms of dark count rate, dynamic range, chip-to-chip uniformity (breakdown voltage) is becoming very good. Considering also the immunity to the magnetic field it makes it a good candidate for the replacement of current PMT's for the PARIS detector.

The SensL company produces a J-series SiPM array 2x2", which is geometrically well suited to 2x2x2" LaBr3 or CeBr3 crystals, has a fill factor of ~ 75 % and 50 % PDE at 420 nm. The array has 64 pixels (6x6 mm) and each pixel is composed of 22,292 microcells (dynamic range), Fig. 1.1.

Fig. 1.1: SensL J-series array attached to the LaBr3 2"x2"x2" scintillator from Krakow

We have performed several laboratory tests with 2x2x2" LaBr3 crystal and Co60 and Na22 sources in order to measure energy and time resolutions. The below picture shows the energy and time outputs form SiPM array pixels, together with reference, fast signal from very small LaBr3 crystal coupled to ultrafast, small PMT, Fig. 1.2 & Fig 1.3 show obtained signals. As can be seen from the figures, the PMTs are for sure faster, but the SiPM gives a more stable signal with less noise that is better adapted for the digital pulse shape analysis

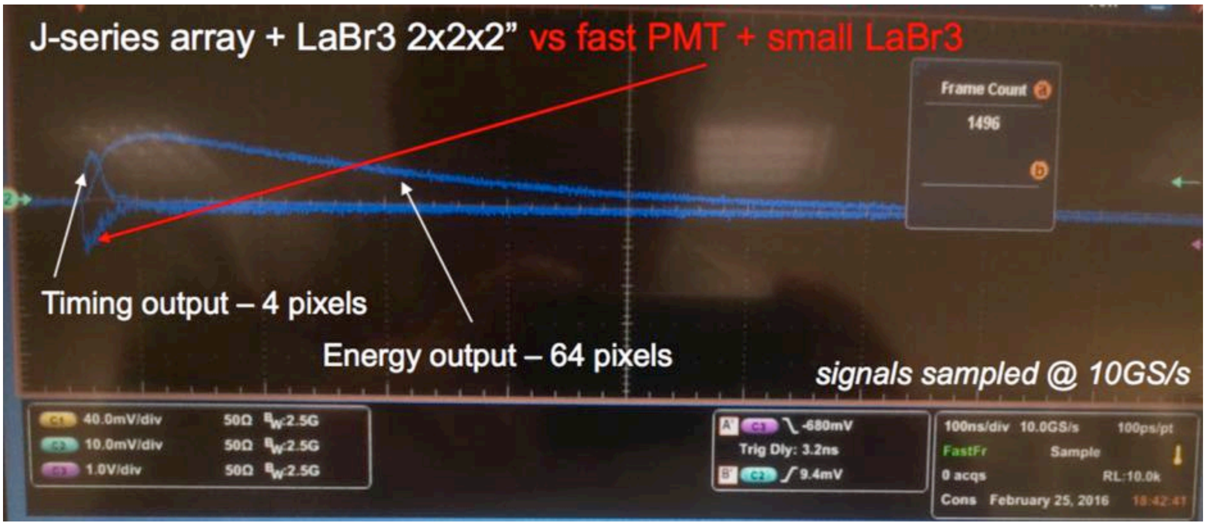

Fig. 1.2: SensL J-series array + LaBr3 2x2x2" vs fast PMT + small LaBr3

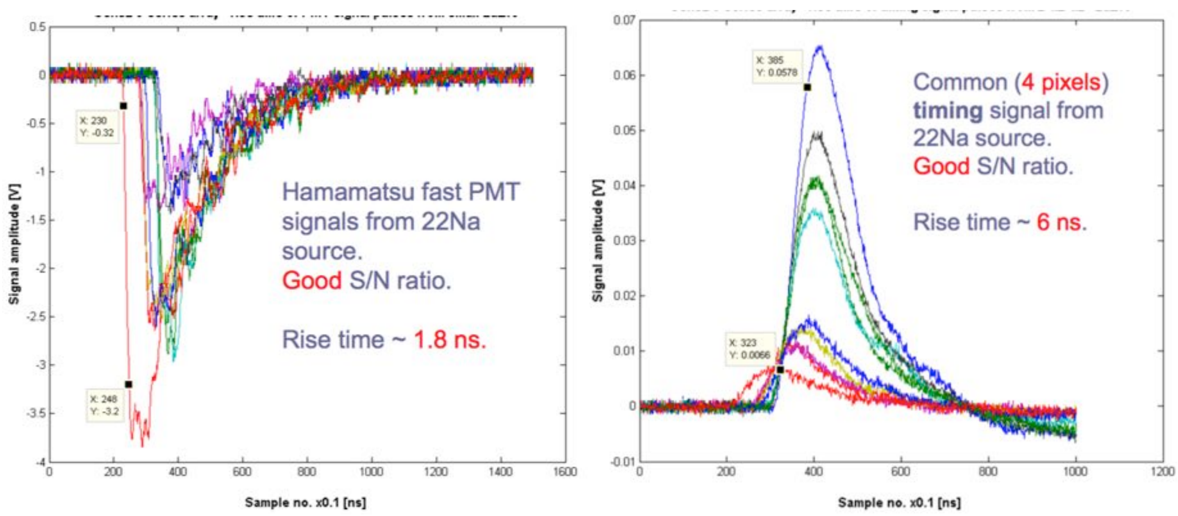

Fig 1.3: Comparison of timing output from Hamamatsu fast PMT and SensL J-series SiPM

The results of the timing measurements demonstrated in the below plot, show that the performance depends on no. of pixels connected together (passively) for timing signal. As for energy measurements, it is crucial to collect all the light (all pixels connected together), for timing there is a trade off, between fast rise time and high S/N.

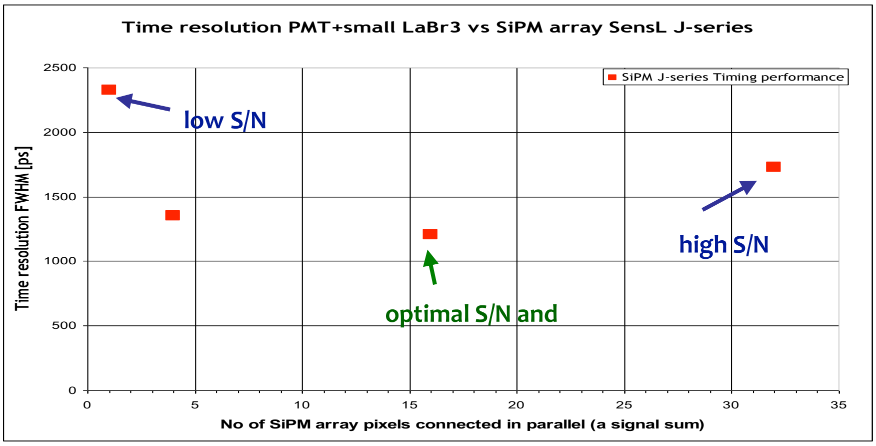

Fig.4: Time resolution op PMT vs SiPM readout

Measurements of energy spectra with Cs137 and Co60 have been performed with traditional, analog chain (MCA and shaping amplifier Ortec 671) as well as with digital processing of sampled signals with LeCroy HDO6104 1GHz 2.5 GS/s oscilloscope. The energy resolution achieved at 662 keV peak, is satisfactory and comparable to results obtained with reference setup with high quality PMT (~ 3 %).

The obtained results show an important progress in development of SiPM technology. There are still some effects to be considered as for final solution as gain stability vs temperature, pulse duration of signals when all pixels connected together or optimization of timing circuitry.

Section 2 The CALIFA Hybrid Scintillator Array

CALIFA is a calorimeter intended for the high-efficiency detection of gammas and light charged particles produced in secondary reactions at relativistic velocity in the R^3B target. A large resolution both in the individual strongly Doppler shifted gamma energy as well as the total energy (up to 30 MeV) is requested. Protons (up to 700 MeV) produced in the target region crossing the crystal bulk should also be detected with good energy resolution.

The main properties of this device, high efficiency and good angular resolution, are imposed by the very particular kinematics of energetic gamma rays emitted by sources moving with relativistic velocities and by the typically low intensities of the secondary beams involved.

As the energy of the involved irradiation is strongly angular-dependent the detector array can be divided into 3 regions as described below.

The ***Barrel*** *40 – 140 degrees, where* the gamma rays, due to emission in flight, are detected with strong Doppler Broadening but rather flat Doppler shifted energies; finger like 15cm long CsI(Tl) crystals coupled to LAPD are used enough to stop 250 MeV protons.

The ***iPhos*** 20 – 40 degrees, region with strong Doppler shift and protons of > 250 MeV will no longer be stopped, also here long 17cm CsI(Tl) crystals coupled to LAPD are used, but a special reconstruction pulse shape analysis has to be performed to obtain the full proton energy deposit.

The ***Cepa*** 7 – 20 degrees, region with the highest rate and Largest Doppler shift, and not space enough for longer crystals. Here a faster scintillator is needed and Phoswich technique in combination it pulse shape analysis has to be done. A Phoswich combining LaBr with LaCl couple to a metal package PMT is chosen for the readout.

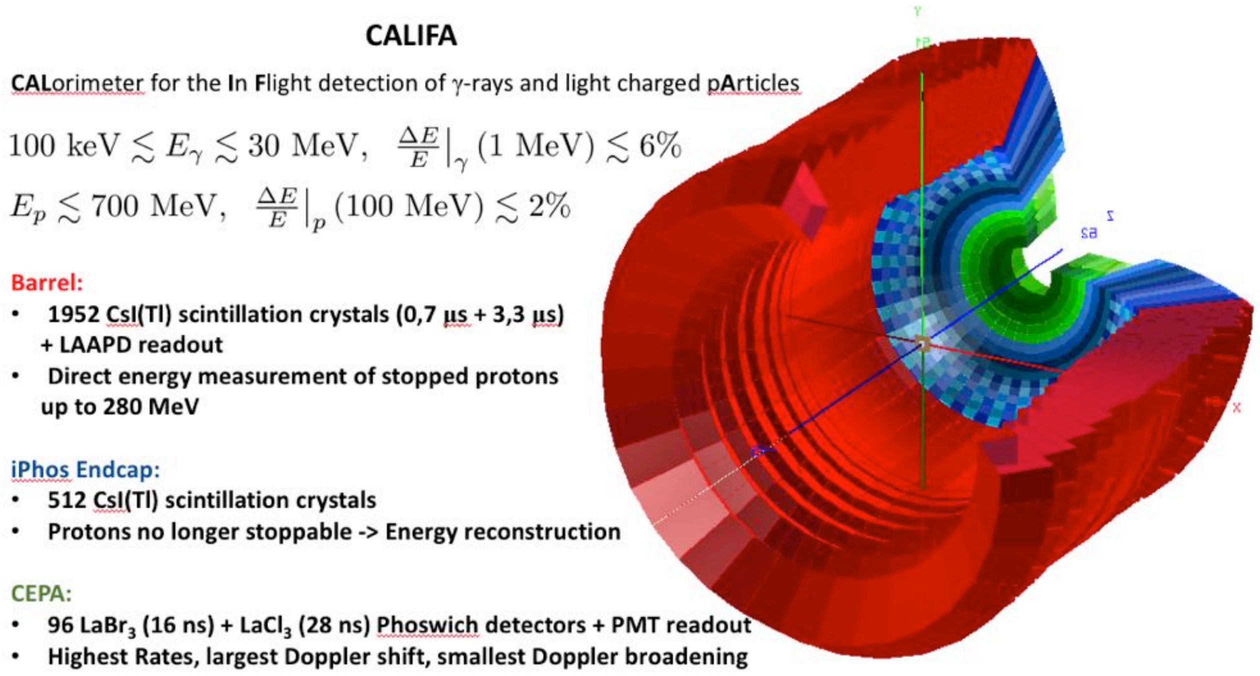

Fig. 2.1 CALIFA divided into 3 sectors. Barrel, iPhos and CEPA

In the process of constructing CALIFA the CsI(Tl) crystals are pre-assembled in smaller units, *petals,* of 64 crystals. Three such petals were taken to IFJ PAN for test experiment with high energy protons impinging on graphite and on a water-target. The experimental set-up is shown in Fig. 2.2 & 2.3.

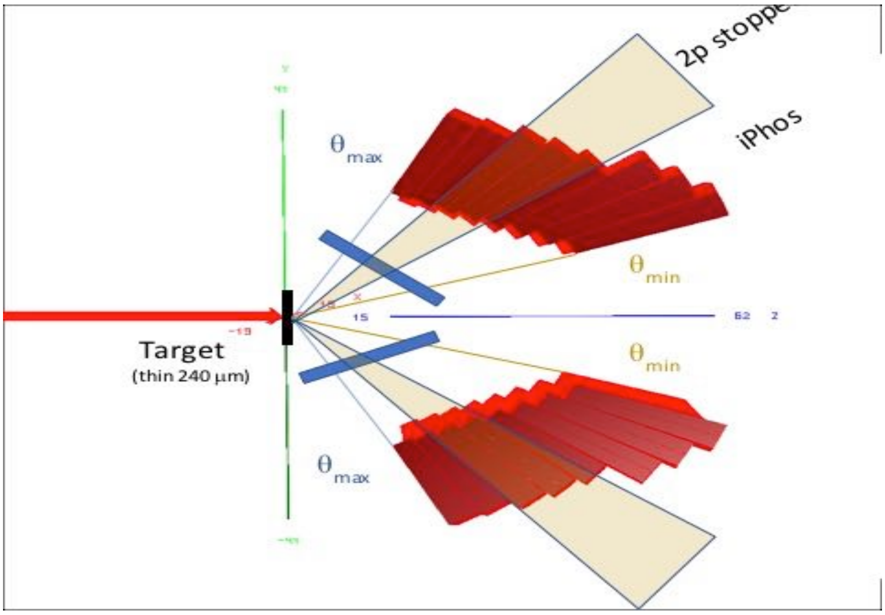

Fig. 2.2 Schematic view of the experimental set-up

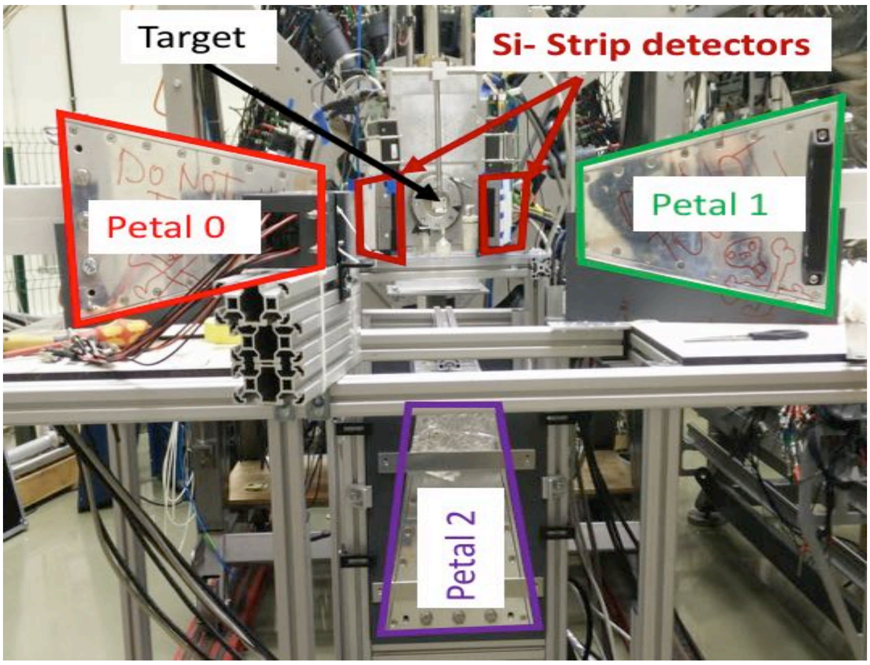

Fig. 2.3 Photo of the experimental set-up at IFJ PAN.

The Graphite block irradiated with 70 MeV protons, was in order to excite 2+ state at 4439 keV of 12C to test calibration at higher gamma energies. Photo-peak, single and double escape peaks are clearly visible, well separated and most importantly well calibrated. Also, the 511 keV peak is visible as well. The figures 2.4,2.5 & 2.6 show the results.

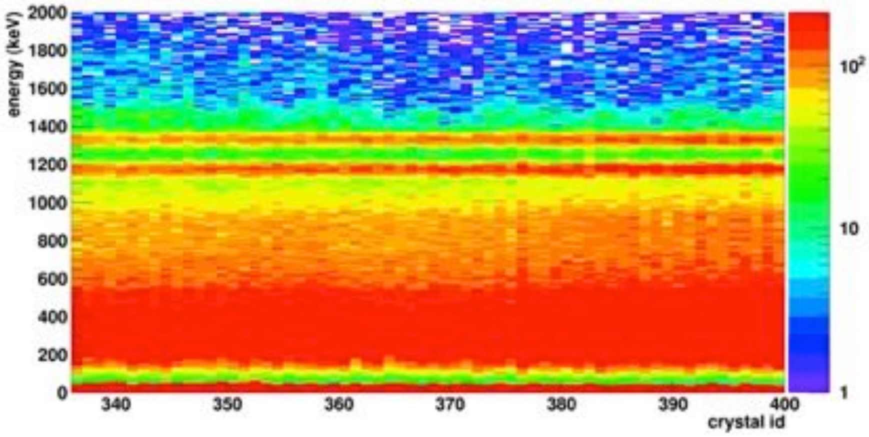

Fig. 2.4 Co-60 source calibration of one petal. All 64 crystals precisely calibrated.

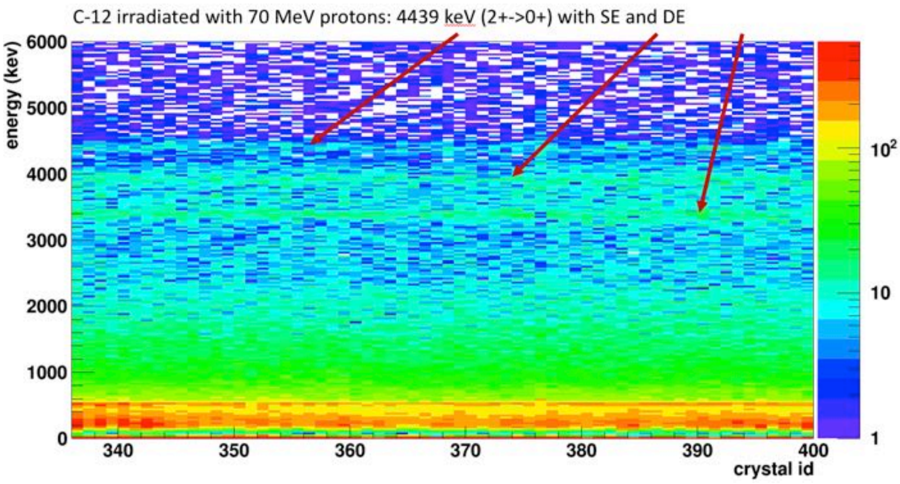

Fig. 2.5 Graphite block irradiated with 70 MeV protons to excite 2+ state at 4439 keV in12C. Photo-peak, single and double escape peaks are visible. Also, the 511 keV visible.

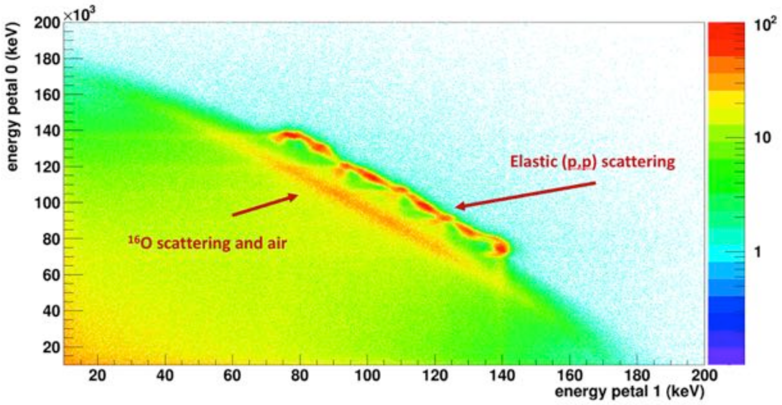

Fig. 2.6 First results from water target 500 um, 200 MeV protons.

Second experiment was to irradiate the 500 micrometer thick water target with 200 MeV protons. Petal 0 vs Petal 1 correlations without any cuts. Anti-correlation from protons scattered elastically on hydrogen in water, well separated the background band from air and below the background hidden we can assume the 16O(p,2p)15N signal, Fig 2.6. Applying a vertex cut the plot looks completely different Fig. 2.7. Below instead of a broad band two smaller lines are visible and the 16O(p,2p) reaction signal is visible here. Next step get rid of elastics to further clean plot.

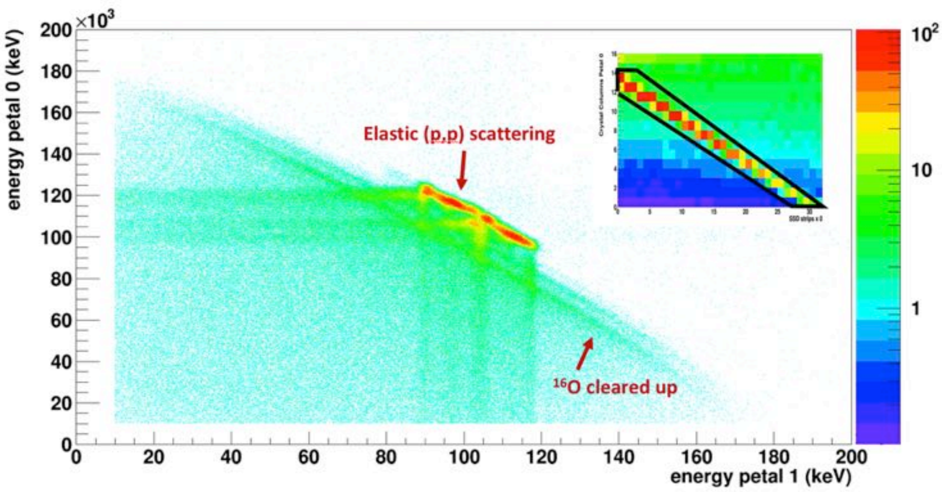

Fig. 2.7 First results from water target 500 um, 200 MeV protons.

Reduced PID plot where N_red is the slow component N_s reduced by the correlation with the fast component N_f. A cut on the stopped proton band (inside black polygon) with 4 peaks from elastic scattered protons, cleans the events of all non-proton contributions. Also bands corresponding to deuterons, tritons, 3He and alphas are visible, Fig 2.8.

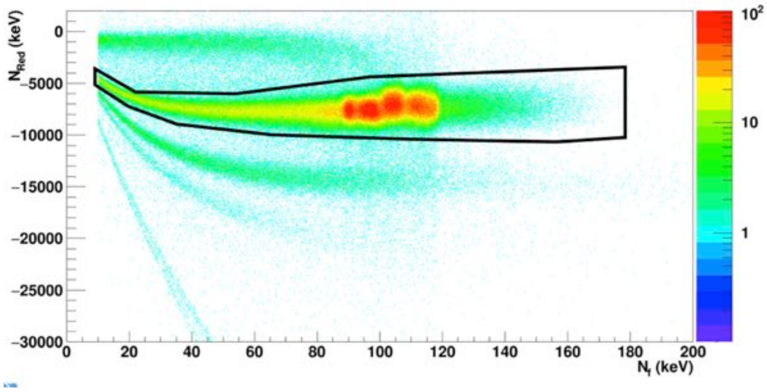

Fig. 2.8 A cut on the stopped proton band (inside black polygon) with 4 peaks from elastic scattered protons, cleans the events of all non-proton contributions.

It has been shown that (p,2p) in normal kinematics is ideal for calibration experiment. The water jet target works fine, data can be clearly separated from the background calibration good starting point for proton calibration ongoing work!

First results from the water target look promising,1/2- and 3/2- states are clearly separated γ-energy resolution under realistic circumstances (1,6 %).

Further, a universal hardware readout-platform has been developed for the full CALIFA array. In order to accumulate also the readout of the CEPA having the much faster scintillators and where the interest is in small differences between LaBr3 and LaCl3 signal If using the same readout as for the CsI crystals, the sampling frequency would be only 50 MHz due to the inherent ADCs.

Obviously this is insufficient for any conclusions on total deposited energy and ratio of LaBr3 and LaCl3 signal, an Add-on board with 1GHz sampling chip DRS4 is under development to solve this situation, Fig. 2.9.

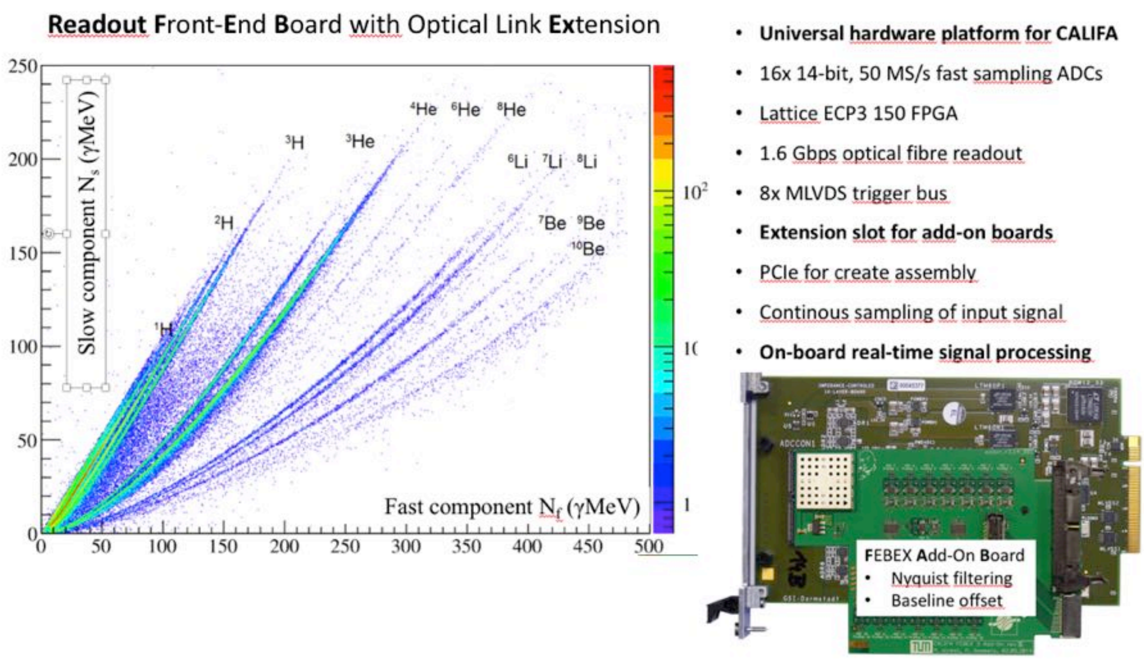

Fig. 2.9 Universal hardware readout-platform has been developed for the full CALIFA array.

SECTION 3 SUMMARY

Research and development have been carried out into hybrid scintillator detectors. Here we have focused on the development of the scientific research tools. The outcome will pave the way towards smaller units for applications in medical physics and homeland security.

In the first part related to R&D for the PARIS array, the focus is to study the potential for the application of SiPMs for light collection. Their excellent performance has been demonstrated in terms of energy resolutions comparable to the best obtained with regular PMTs. In the second part R&D on different scintillator crystals in combination with versatile readout in order to obtain detection modules able to simultaneously detect and distinguish between high energy gamma rays and charged particles.

4 PUBLICATIONS AND OUTREACH

4.2 Conference contributions and Outreach:

- Marcin Jastrząb “*Towards SiPM readout for Phoswich”,*
  The Annual PARIS Collaboration Meeting 2018, Warsaw ŚLCJ 25-26.01.201
- Benjamin Heiss “CALIFA Demonstrator @ Krakow”, PSI Seminar January 10th 2018
- Nuclear Inst. and Methods in Physics Research, A 879 (2018) 92–100 Response function and linearity for high energy γ-rays in large volumen LaBr3:Ce detector.