Ce:LaBr$_3$ crystals with SiPM array readout and temperature control for the FAMU experiment at RAL

M.Bonesini, a,1 R.Benocci, a, R.Bertoni, a, M.Clemenza, a, D.Ghittori, a, R.Mazza, a, E.Vallazza, a A.deBari, b A.Menegolli, b M.Prata, b M.Rossella, b M.Baruzzo, c,2 E.Mocchiutti c

a Sezione INFN Milano Bicocca, Dipartimento di Fisica G. Occhialini and Dipartimento di Scienze dell’Ambiente e della Terra, Università di Milano Bicocca, Milano, Italy
b Sezione INFN Pavia and Dipartimento di Fisica, Pavia, Italy
c Sezione INFN Trieste, Trieste, Italy

E-mail: maurizio.bonesini@mib.infn.it

ABSTRACT: Compact X-rays detectors made of 1/2” Ce:LaBr$_3$ crystals of cubic shape with SiPM array readout have been developed for the FAMU experiment at RIKEN-RAL, to instrument regions of difficult access. Due to the high photon yield of Ce:LaBr$_3$ it was possible to use a simple readout scheme based on CAEN V1730 digitizers, without a dedicated amplification stage. The drift with temperature of SiPM gain was corrected by using CAEN A7885D regulated power supply chips with temperature feedback. Energy resolutions (FWHM) around 3.5% at the $^{137}$Cs peak and around 9% at the $^{57}$Co peak were obtained.

KEYWORDS: X-ray detectors; PET

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1 Corresponding author.
2 Also at Dipartimento di Scienze Informatiche, Matematiche e Fisiche, Università di Udine.
1 Introduction

The FAMU (Fisica degli Atomi Muonici) experiment at RAL [1] is designed to measure the hyperfine splitting (HFS) in the ground state (1S) of the muonic hydrogen. It aims at a high accuracy determination of the proton Zemach radius [2], [3]. This experiment may contribute to solve the so-called “proton radius puzzle”: a large and still unsolved disagreement between the proton charge as measured with electrons or muons [4].

A high intensity pulsed low-energy muon beam, stopping in a hydrogen target, is used to produce muonic hydrogen (in a mixture of singlet F=0 and triplet F=1 states). A tunable mid-IR (MIR) pulsed high power laser then excites the hyperfine splitting (HFS) transition of the 1S muonic hydrogen (from F=0 to F=1 states). Making use of the muon transfer from muonic hydrogen to another higher-Z gas in the target (such as O₂), the (\(\mu^-\text{p}\))₁S HFS transition will be recognized by an increase of the number of X-rays from the (\(\mu\text{Z}^+\)) cascade, during a laser frequency scan around the resonance value \(\nu_0\) (\(\Delta E_{\text{HFS}} = h\nu_0\)). From the measurement of \(\Delta E_{\text{HFS}}(\mu^-\text{p})_1\text{S}\) the Zemach radius \(r_Z\) of the proton may be computed with a precision up to \(5 \times 10^{-3}\), thus casting new light on the proton radius puzzle.

The FAMU experiment is performed in steps, starting from the study of the transfer rate from muonic hydrogen to another higher-Z gas and ending with the full working setup including the pump MIR laser and a multipass optical cavity. The preliminary steps have allowed to determine the best mixture to be used inside the cryogenic target and optimize the operating conditions. A schematic layout of the experimental setup for the preliminary steps is shown in figure 1.

The RIKEN-RAL muon facility [5] at Rutherford Appleton Laboratory (UK) provides high intensity pulsed muon beams at four experimental ports. The primary proton beam at 800 MeV/c impinges on a secondary carbon target producing pions and then high intensity low energy pulsed muon beams. The muon beams reflect the primary beam structure: two pulses with a 70 ns FWHM and a 320 ns peak to peak distance are delivered, with a 50 Hz repetition rate. The FAMU experiment

\(^1\)to enhance the probability of laser light-muon interactions
Figure 1. Left panel: layout of the setup for the 2015-2016 data-taking (R582); 1) is the 1 mm pitch beam hodoscope, 2) the crown of eight Ce:LaBr$_3$ detectors with PMT readout and 3) the cryogenic target. The four HPGe detectors, also used in this run, are not shown. Right panel: picture of the 2018 setup where the two half-crown of the Ce:LaBr$_3$ detectors with PMT readout (A) were displaced along the beam axis (z) and complemented with 4+4 1/2” Ce:LaBr$_3$ detectors with SiPM array readout (B).

makes use of a negative decay muon beam at $\sim 60$ MeV/$c$. For this experiment, an important issue is the optimal steering of the incoming high intensity pulsed muon beam onto the hydrogen target, to maximize the muonic hydrogen production rate. A system of three beam hodoscopes has been developed for this scope. The first two are based on square $3 \times 3$ mm$^2$ Bicron BCF12 scintillating fibers read by SiPMs, while the last one is based on square $1 \times 1$ mm$^2$ scintillating fibers of the same type, with white EMA coating, to avoid light cross-talk [6]. The muon beam intensity is around $6 \times 10^4 \mu^-/s$ in a typical size $4 \times 4$ cm$^2$. The energy spread is around 10 % and the angular divergence around 60 mrad.

To extract the characteristic muonic X-rays lines (around 100 keV) with a good energy resolution and a minimal events pile-up, a system based on Ce:LaBr$_3$ crystals and HPGe detectors has been developed. Even if they have better energy resolution, the HPGe detectors are slower, work at cryogenic temperatures and are more expensive. Therefore the main X-rays detector system for the experiment was based on 1” circular Ce:LaBr$_3$ crystals, 1” long, read by UBA Hamamatsu R11265U-200 PMTs with active divider (up to eight arranged in two detachable half crowns). In addition, an R & D was pursued to complement these detectors with crystals equipped with SiPM readout to instrument regions of more difficult access, see reference [7] for further details.

2 X-rays detectors with SiPM arrays readout

For our aims it is essential to detect low-energy X-rays in the range 100-200 keV. Pr:LuAG [8] and Ce:GAAG [9] crystals with respect to more conventional Ce:LaBr$_3$, CeBr$_3$[10] and NaI(Tl) crystals, have the advantage to be non hygroscopic and thus do not need encapsulation.

Results on their performances are reported in references [11], [12]. From laboratory tests a solution based on Ce:LaBr$_3$ crystals was shown as still to be preferred. A crystal thickness of 0.33 (1.54) cm for 88% attenuation at 100 (200) keV was computed from X-ray attenuation coefficients,
as reported in [13]. It is apparent that for the detection of the O$_2$ characteristic lines in the region 100-160 keV, corresponding to muon transfer, 1/2" long crystals are adequate. A more complete Monte Carlo simulation based on MNCP[14] provided an estimate of absorption for cubic crystals of 1/2" side with a source at a distance corresponding to the center of the foreseen target. Even in this case 1/2" long crystals were considered adequate.

The structure of a detector with a SiPM array readout is shown in figure 2. The optical contact between the crystal and the SiPM arrays is done through a Bicron BC631 silicone optical grease. The crystal/PCB holder, realized with a 3D printer, is made in two pieces: one contains the crystal

![Figure 2](image)

**Figure 2.** Components of the detectors with SiPM readout. 1) is the Hamamatsu SiPM mounted on the custom PCB, 2) the Ce:LaBr$_3$ crystal in the Al encapsulation, the optical window is seen in the front. 3) is the holder containing the crystals and the PCB, in two pieces seen from the top. 4) is the cap to guarantee detector’s light tightness. The full mounted detector (5) is shown in the back of the picture. The 3.5 mm stereo jack cable (6) connects the temperature sensor (TMP37) on the backside of the SiPM array PCB to the power supply module.

under test, while the other holds the readout electronics with the custom PCB, where a SiPM array is mounted on. The analog signals of the 16 SiPM of one array are summed together on the custom PCB. Signal acquisition may be realized with a standard spectroscopic chain (based on a Ortec 672 spectroscopic amplifier or a fast Ortec 579 Ortec amplifier) or with a fast digitizer. Due to the signal amplitude ($\sim$ 100 – 200 mV at the $^{137}$Cs peak ) no amplification is needed and a direct readout via a digitizer may be used. In our case we made use of a CAEN DT5730 digitizer (desktop version) or a V1730 digitizer (VME format). Both have been used via an optical link and have a bandwidth of 500 MHz with a $\pm$1 Vpp dynamic range.

In the first instance, we used different 4 × 4 arrays made from 3 × 3 mm$^2$ SiPM array from Sensl, Advansid and Hamamatsu for their readout. Their main operation characteristics are resumed in
Hamamatsu SiPM make use of the TSV (“through Silicon via”) technology that eliminates the need of a wire bonding pad, thus reducing dead space problems. The anode of each channel is traced to the backside pad by TSV. Typical gains are in the range $1.7 \times 10^6$ and depend on the applied overvoltages ($\Delta V_{ov}$), while the dark count rate is around $0.5 \text{ Mcps}$ for all the considered SiPM arrays.

Table 1. Main characteristics of the SiPM arrays used for our tests. Photon detection efficiency (PDE) are at typical overvoltage values, at $\lambda_{max}$. $V_{op} = V_{bd} + \Delta V_{ov}$ is the typical voltage used in our tests. $\Delta V_{op}$ is the variation in the suggested voltages for operations, between the 16 different SiPM making a SiPM array. (E) or (S) are used for an epoxy or silicon window.

| Array Type           | $V_{bd}$ | $\Delta V_{ov}$ | $V_{op}$ | $\Delta V_{bd}/\Delta T$ | $\Delta V_{op}$ | $\lambda_{max}$ | PDE ($\sim \lambda_{max}$) | Range (nm) |
|----------------------|---------|-----------------|---------|--------------------------|-----------------|-----------------|--------------------------|------------|
| SenSL Array          | 24-25   | 1-5             | 26      | 21.5                     | 420             | $\sim 30\%$    | 300-800                  |            |
| SB-4-3035-CER        |         |                 |         |                          |                 |                 |                          |            |
| Advansid NUV3S-4x4TD | 26      | 2-6             | 29      | 26                       | 420             | $\sim 43\%$    | 350-900                  |            |
| Hamamatsu S13361-3050-AE (E) | 53 ± 5 | $\sim 3$        | 53.8    | 54                       | 450             | $\sim 35\%$    | 320-900                  |            |
| Hamamatsu S13361-3050-AS (S) | 53 ± 5 | $\sim 3$        | 54.2    | 54                       | 450             | $\sim 35\%$    | 280-900                  |            |
| Hamamatsu S14161-3050-HS (S) | 38      | $\sim 2.7$     | 40.8    | 34                       | 450             | $\sim 50\%$    | 270-900                  |            |

Preliminary results obtained with a standard spectroscopic chain were reported in references [11], [12] and show resolution at 662 keV from 3.1% (Ce:LaBr$_3$ crystals with Hamamatsu S13361-3050-AS SiPM arrays) to 8.4% (NaI crystals with the same readout). At lower X-rays energy ($\sim 122$ keV), FWHM energy resolutions between the different crystals become more compatible: as an example while at 662 keV a Ce:LaBr$_3$ crystal has a resolution a factor $\sim 2$ better than a NaI(Tl) crystal, at 122 keV this factor reduces only to $\sim 30\%$.

The best results were obtained with Ce:LaBr$_3$ crystals with a readout based on Hamamatsu SiPM arrays with a silicone window, that has a better transmission around 380 nm.

As the SiPM gain has a drift with temperature ($\sim 54$ mV/°C for the breakdown voltage of Hamamatsu S13361 SiPM) a temperature correction had to be implemented.

2.1 Temperature control of SiPM gain
The gain of SiPM depends on the applied voltages $V_{op} = V_{bd} + \Delta V_{ov}$ where the overvoltage is kept fixed: typically around 2-4 V. The breakdown voltage depends from temperature, according to equation:

$$V_{bd}(T) = V_{bd}(T_0) + c \times (T - T_0) \quad (2.1)$$

where $c$ is the temperature coefficient $\Delta V_{bd}/\Delta T$ of table 1 and $T_0$ a reference temperature, tipically 25 °C [15]. By correcting for the increase of breakdown voltage with the previous equation 2.1 one may obtain an excellent gain stabilization. The temperature correction may be obtained offline, by recording the temperature, or online with an active feedback.
The effect to be corrected is shown in figure 3 (black circles) for two different Hamamatsu SiPM arrays. Data have been taken inside a Memmert IPV30 climatic chamber, with a temperature resolution of 0.1 °C between 10 °C and 40 °C. A typical detector is irradiated with a $^{137}$Cs source and data are read by a CAEN V1730 digitizer. The position of the pulse height peak is computed and then plotted as a function of temperature. We initially used single desktop power supply CAEN DT5485P$^2$, where the temperature feedback was based on a temperature sensor (TMP37 from Analog Devices) put on the backside of the PCB holding the SiPM array (see figure 2 for details). This temperature sensor is connected via a 3.5 mm stereo cable to the power supply module. Between 10 °C and 40 °C the detector pulse height response had a variation up to 60%. This effect is reduced to ~ 6% after temperature correction, via a CAEN DT5485P desktop module.

All results, based on laboratory tests, were made using such modules for powering the SiPM arrays. For the next future we have developed custom made NIM modules with up to eight HV channels each, based on CAEN A7585D chips. The communication with the host computer is done via an I2C protocol, followed by an USB-I2C converter, using on the computer side a proprietary software$^3$ that may control the setting of the power supply chips, monitor their erogated voltages and currents and record results on an Excel file. These modules realized with a wire wrap technique are shown in figure 3 and their use is foreseen for the next spectroscopic run of FAMU in late 2020. In these modules the primary voltage to feed the power supply chips is taken from the NIM backplane and the interface USB-I2C is realized via a FDTI C232HM-EDSHL-0 module. For data

$^2$ 0.1 mV (pp) voltage ripple, ±20 mV setting precision, 1.2 mV setting resolution, with USB control

$^3$ Zeus software from Nuclear Instruments srl.
taken in December 2018 six DT5485P CAEN modules connected to an USB hub were used instead.

3 Results from laboratory tests.

Results for a typical crystal are shown in figure 4 for both linearity and FWHM resolution (in %) using different laboratory sources in the range between 80 and 1300 keV. At the $^{137}$Cs peak a resolution $\sim 3.5\%$ was found, compatible with best results with the standard PMT readout. Results on linearity and FWHM resolution (%) are also shown in figure 5 for several Ce:LaBr$_3$ detectors with size $14 \times 14 \times 14$ mm$^3$ from Kinheng Ltd (no. 12-17) and $12 \times 12 \times 12$ mm$^3$ from Ost Photonics (no. 21-32). Detectors with worse energy resolutions are equipped with Hamamatsu S13361 arrays with epoxy windows, that have a reduced transparency to the UV signal emitted from Ce:LaBr$_3$ or have suffered from ageing problems (such as some older detectors from Kinheng, PRC). Around 122 keV FWHM energy resolutions up to 8% are obtained.

4 Analysis of performances in beam

In the December 2018 run at Port 1 of RIKEN RAL, the two half-crown of 1” Ce:LaBr$_3$ crystals with PMT readout were displaced of $\sim 10$ cm along the beam direction. They were complemented with four 1/2” Ce:LaBr$_3$ detectors with SiPM readout, each. The first six detectors were powered via CAEN DT5475 modules with temperature feedback, the last two were powered by conventional ISEG NIM NHS-6001x power supply for cross-check. As the temperature in the experimental hall was quite stable (the run was done in winter) no appreciable temperature excursions were seen.

Calibration results in situ with $^{137}$Cs, $^{133}$Ba, $^{57}$Co sources are reported in figure 6 and are roughly compatible with laboratory measurements, even if FWHM resolutions are a little worse. This may be due to worse positioning of sources with respect to the detectors to be calibrated and environmental noise.

\[ p_0 = 1.7309 \pm 0.0456, \quad p_1 = 0.9938 \pm 0.0002 \]

\[ p_0 = 0.6994 \pm 0.0261, \quad p_1 = 0.0115 \pm 0.0017 \]

\[ \text{p0} = 0.0455 \pm 1.7309 \quad \text{p1} = 0.0002 \pm 0.9938 \]

\[ \text{p0} = 0.0261 \pm 0.6994 \quad \text{p1} = 0.0017 \pm 0.0115 \]

**Figure 4.** Left panel: linearity for a typical 1/2” Ce:LaBr$_3$ detectors with SiPM array readout, from OST Photonics (CN). Right panel: FWHM resolution with different test sources for the same detector. Fits are performed with a straight line for linearity and with the expression $p_0 + p_1/\sqrt{E}$ for the FWHM energy resolution.
Figure 5. Top panel: linearity for the used 1/2" Ce:LaBr₃ detectors with SiPM array readout. Detectors no. 12-17 are from Kinheng Photonics (PRC), while detectors no. 21-32 are from OST Photonics (PRC). Bottom panel: FWHM resolutions with different test sources for the same detectors.

Figure 6. Calibration results obtained with a $^{137}$Cs, $^{133}$Ba and a $^{57}$Co source during the December 2018 run at RAL. FWHM resolutions are slightly worse as respect to what obtained in laboratory measurements.
Data were then taken with a target filled with pure H$_2$ for background studies and a mixture of O$_2$ and H$_2$ at various concentrations (from 0.3 to 4.6 % weight) at a temperature around 80 K, at various pressures.

The timing properties of one typical detector are shown in figure 7. The two peaks structure of the beam is clearly visible with FWHM and peak-to-peak distance compatible with what expected. In figure 7 the full energy spectrum is reported for the same detector. Characteristic X-rays lines,

![Figure 7](image)

**Figure 7.** Top panel: X-ray time evolution spectrum of the H$_2$-2% O$_2$ mixture with a 56 MeV/c moun momentum. Bottom panel: energy spectrum for a SiPM array readout 1/2" Ce:LaBr$_3$ detector using a 2 % O$_2$ mixture, at 7 bar and 80 K. Background is not subtracted. Characteristic spectral lines at 347 keV and 66 keV from Al (a,f), Nickel at 310 keV and 107 keV (b,e) and Oxygen at 158/167 keV and 133 keV (c,d) may be seen.

mainly Nickel and Aluminium from materials present in the target, are evident from ~ 100 keV to around 400 keV.
5 Conclusions

Ce:LaBr$_3$ detectors with SiPM array readout and temperature control for the power supply have been assembled and tested both in laboratory, at Sezione INFN Milano Bicocca and in beam at Port 1 at RIKEN RAL. Results show good performances and FWHM resolutions compatible with more bulky conventional detectors with PMT readout. Their use is foreseen, together with the NIM power supply module with temperature feedback, for the coming 2020 FAMU spectroscopic run.

Acknowledgements

We would like to thank S. Banfi, M. Gheigher (INFN Milano Bicocca) for help in mechanics setup. We acknowledge the help of Dr. M. Saviozzi of CAEN, Dr. A. Abba and Dr. V. Arosio of Nuclear Instruments for issues related to the regulated power supply chips for SiPM and their control program Zeus.

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