

Performance study of single undoped CsI crystals for the Mu2e experiment

R. DONGHIA⁽¹⁾(²) on behalf of the MU2E CALORIMETER GROUP

⁽¹⁾ *INFN, Laboratori Nazionali di Frascati - Frascati (RM), Italy*

⁽²⁾ *Dipartimento di Fisica, Università Roma Tre - Rome, Italy*

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Summary. — The Mu2e experiment at Fermilab aims to measure the neutrinoless muon-to-electron conversion, which is a charged-lepton flavor-violating process. The goal of the experiment is to reach a single event sensitivity of 2.5×10^{-17} , to set an upper limit on the muon conversion rate at 6.7×10^{-17} in a three-year run. For this purpose, the Mu2e detector is designed to identify electrons from muon conversion and reduce the background to a negligible level. It consists of a low-mass straw tracker and a pure CsI crystal calorimeter. In this paper, the performance of undoped CsI single crystal is reported. Crystals from many vendors have been characterized by determining their Light Yield (LY) and Longitudinal Response Uniformity (LRU), when read with a UV extended PMT, and their time resolution when coupled to a silicon photomultiplier. The crystals show a LY of ~ 100 photoelectrons per MeV when wrapped with Tyvek and coupled to the PMT without optical grease. The LRU is well represented by a linear slope that is on average 0.6%/cm. Both measurements have been performed using a ^{22}Na source. The timing performance has been evaluated exploiting cosmic rays, with MPPC readout. A timing resolution lower than 400 ps has been achieved (at ~ 20 MeV, which is the energy released by a minimum ionizing particle in the crystal).

1. – Introduction

The Mu2e experiment [1] at Fermi National Accelerator Laboratory, will search for the charged-lepton flavor-violating (CLFV) process of muon-to-electron conversion in an aluminum nucleus field, $\mu + N(Z, A) \rightarrow e + N(Z, A)$.

Mu2e measures the ratio, $R_{\mu e}$, between the muon conversion and the muon capture rates, by the Al nucleus, with a single event sensitivity (SES) of 2.5×10^{-17} . This corresponds to setting an upper limit of the ratio

$$R_{\mu e} = \frac{\mu^- N(Z, A) \rightarrow e^- N(Z, A)}{\mu^- N(Z, A) \rightarrow \nu_\mu N(Z-1, A)} < 6 \times 10^{-17} \text{ (at 90\% CL),}$$

improving by four orders of magnitude the previous result from SINDRUM II [2].

The signature of this neutrinoless conversion process is a mono energetic electron, with an energy slightly lower than the muon rest mass (~ 104.96 MeV).

The Standard-Model predicted rate for this process is $\mathcal{O}(10^{-52})$, so that, observation of these processes is a clear evidence for New Physics.

2. – The Mu2e Calorimeter

The Mu2e detector consists of a low-mass straw tracker and a crystal calorimeter. Both are located inside the evacuated bore of the Detector Solenoid, in a uniform 1 T magnetic field, that is surrounded by a cosmic ray veto.

The detector is designed to identify the ~ 105 MeV/ c electrons from muons conversion, reducing the background to a negligible level.

The calorimeter, located behind the tracker, provides information about energy, timing and position in order to validate the charged particles reconstructed by the tracker and to perform a particle identification.

In order to reach the SES required by the experiment and to maximize the acceptance for ~ 105 MeV conversion electrons, a crystal calorimeter with an energy resolution of $\mathcal{O}(5\%)$ and a timing resolution better than 500 ps in the energy region around 100 MeV are required. Moreover, the Mu2e environment implies the use of solid-state photodetectors, which are immune to the presence of the magnetic field.

The baseline calorimeter is composed of 1400 pure CsI crystals, distributed in two annular disks and readout by two silicon photomultipliers (SiPMs) each.

This paper reports the tests done on the light yield (LY) and the longitudinal response uniformity (LRU) of single CsI crystals. Moreover, the timing performance has also been evaluated for some crystals, by coupling them to a SiPM.

2.1. Pure CsI crystals. – Undoped Cesium Iodide (CsI) is a slightly hygroscopic crystal with an emission maximum at 315 nm, characterized by a relatively short decay time of ~ 20 – 30 ns [3]. Along with this fast component, a much slower component with a decay time of about $1 \mu\text{s}$ is present, which represents less than 30% of the total light output. The intensity of this slow component depends on the purity of the crystal since contamination tends to degrade the fast-to-total ratio. This contribution is less than 20% of our CsI samples.

2.2. Silicon Photomultiplier, MPPC. – Due to the high magnetic field, the CsI crystals readout is made by high-gain solid-state photodetectors, such as SiPMs.

SiPMs are photon-counting devices made by one planar matrix of several avalanche photodiode (APD) pixels of the same shape, dimension and construction features that are operated in Geiger mode, with an inverse polarization above the breakdown. Each pixel is coupled to a quenching resistor [4].

At 315 nm the UV extended Hamamatsu SiPM, named Multi-Pixel Photon Counter (MPPC) is a good choice for the Mu2e calorimeter, due to its good photon detection efficiency at this wavelength ($> 40\%$). In particular, the performance of S13361 series MPPCs is underway. It allows precision measurements, using the TSV (Through Silicon Via) technology [5]. There is no wire bonding, so the package outline is very close to the MPPC array. The outer gap from active area edge to package edge is only 0.2 mm.

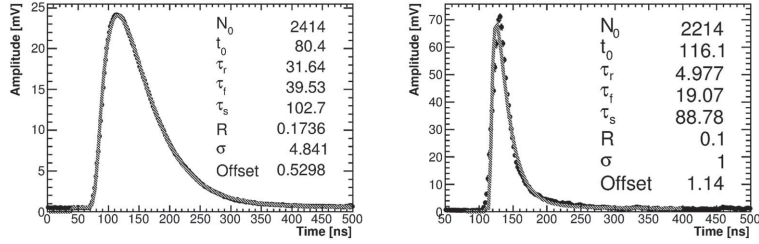


Fig. 1. – Digitized waveform for few events of the tag (left) and of one Tyvek-wrapped Opto Materials 01 crystal (right) acquired by the CAEN digitizer.

3. – Tests on single pure CsI crystals coupled to a UV extended PMT

To test the crystal production quality, we procured 13 samples of pure CsI crystals from different high-quality producers: 2 from Opto Materials (Italy), 7 from ISMA (Ukraine), both with a crystal dimension of $(3 \times 3 \times 20)$ cm³ and 4 additional longer crystals $(2.9 \times 2.9 \times 23)$ cm³ from ISMA. Tests have been performed at the INFN National Laboratory of Frascati (LNF) using a dedicated station for crystals testing.

3.1. Experimental setup. – To study the LY and LRU of each crystal, we used a low-intensity collimated ²²Na source which irradiates the crystal in a region of few mm². The ²²Na source produces 511 keV photons, caused by electron-positron annihilation, and it is placed between the crystals and a small tagging system, constituted by a $(3 \times 3 \times 10)$ mm³ LYSO crystal, readout by a (3×3) mm² MPPC.

One of the two back-to-back photons produced by the source is tagged by this monitor, while the second one is used to calibrate the crystal under test, which is readout by means of a 2" UV extended photomultiplier tube (PMT) from ET Enterprises. This PMT has a quantum efficiency of $\sim 30\%$ at 315 nm. The whole system is inside a light tight black box.

The data acquisition system is composed of a trigger board, which starts recording events applying a threshold of 20 mV on the tag signal, and a CAEN DT5751 digitizer at 10⁹ samples per second, which acquires both tag and test signals.

For each crystal, a longitudinal scan is executed irradiating eight points, by a 2 cm step from the edge of the crystal where the readout system is located. During the scan, the source and the tag are moved together along the axis of the crystal under test. All crystals have been wrapped with a material, which covers both the four surfaces along the longitudinal axis and the side opposite to the readout system.

The digitizer has 1024 samples in the acquisition window, each sample corresponding to 1 ns. Examples of the pulse shapes, obtained for both LYSO tagging system (left) and a CsI crystal under test (right), are shown in fig. 1. The generic emission time distribution for a scintillator can be described as a fast component, generated by a two-step scintillation mechanism (absorption, emission) and a slow component [6]

$$(1) \quad E(t) = \frac{\frac{e^{-t/\tau_f} - e^{-t/\tau_r}}{\tau_f - \tau_r} + \frac{R}{\tau_s} e^{-t/\tau_s}}{1 + R},$$

where τ_f , τ_s , τ_r are the time constants of respectively the fast and slow scintillation process and of the rising part. R is the ratio between the slow and the fast component.

If we assume that the time resolution of our system can be described by a Gaussian, then the resulting distribution used to fit the waveforms is the convolution of $E(t)$ with a Gaussian, as follows:

$$(2) \quad V(t) = \frac{1}{1+R} \left[\frac{\tau_f f(t, \tau_f) - \tau_r f(t, \tau_r)}{\tau_f - \tau_r} + R f(t, \tau_s) \right],$$

where

$$(3) \quad f(t, \tau) = \frac{1}{2\tau} \left[1 + \operatorname{erf} \left(\frac{1}{\sqrt{2}} \left(\frac{t}{\sigma} - \frac{\sigma}{\tau} \right) \right) \right] e^{-(t/\tau - \sigma^2/2\tau^2)};$$

erf is the error function, defined as:

$$(4) \quad \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

and σ is the Gaussian standard deviation.

The profiles of the waveforms have been fit with eq. (2) to evaluate the decay time of each crystal. The fit results are reported in fig. 1. R parameter has been fixed to 0.1, since the CsI samples tested have a slow component of less than 20%, while the resolution function of our system has been set to $\sigma = 1$ ns. As shown in the same figure, in our setup, signals produced in CsI crystals are typically within 300 ns from the trigger, with a 50 ns delay offset, so that the charge Q is obtained integrating in the range (50–300) ns. The baseline is evaluated using the interval region between 700 ns and 1000 ns.

In fig. 2, the charge distributions for one of the crystals under test (Opto Materials 01), wrapped with Tyvek, are reported for the eight points of a single scan. The charge spectra are very clean and the peak due to the 511 keV photon is clearly visible. A Gaussian fit is applied to extract the mean values (μ_{Q1}): these values are then reported as a function of the distance of the source from the PMT, obtaining a linear slope parametrized as 39.5 pC + 0.1 pC/cm (fig. 2, bottom right).

3'2. Light emission and longitudinal response uniformity performance. – All crystals have been tested with the ^{22}Na source, coupling just one of the two squared faces with the readout system. For some of the crystals, the effect of the optical grease contact with the PMT has also been studied.

A reflector material wrapping is needed to improve the detection efficiency of scintillation photons. The Opto Materials pure CsI crystal number 02 has been tested with different wrapping materials: aluminum (Al), Tyvek, Teflon. The charge distributions have been fit with a Gaussian function to extract the peak position and evaluate the LY, defined as the number of photoelectrons produced per MeV, $N_{p.e.}/\text{MeV}$:

$$(5) \quad \frac{N_{p.e.}}{\text{MeV}} = \frac{\mu_{Q1}[\text{pC}]}{G_{PMT} \cdot E_{\gamma}[\text{MeV}] \cdot q_{e^-}[\text{pC}]},$$

where $q_{e^-} = 1.6 \times 10^{-19}$ pC is the charge of the electron, $E_{\gamma} = 511$ keV is the energy of the annihilation photon and $G_{PMT} = 3.8 \times 10^6$ is the PMT gain.

The Al wrapping provided the worst LY (~ 79 $N_{p.e.}/\text{MeV}$ with the source in the central position of the Opto Materials 02), while for every scan point the best performance

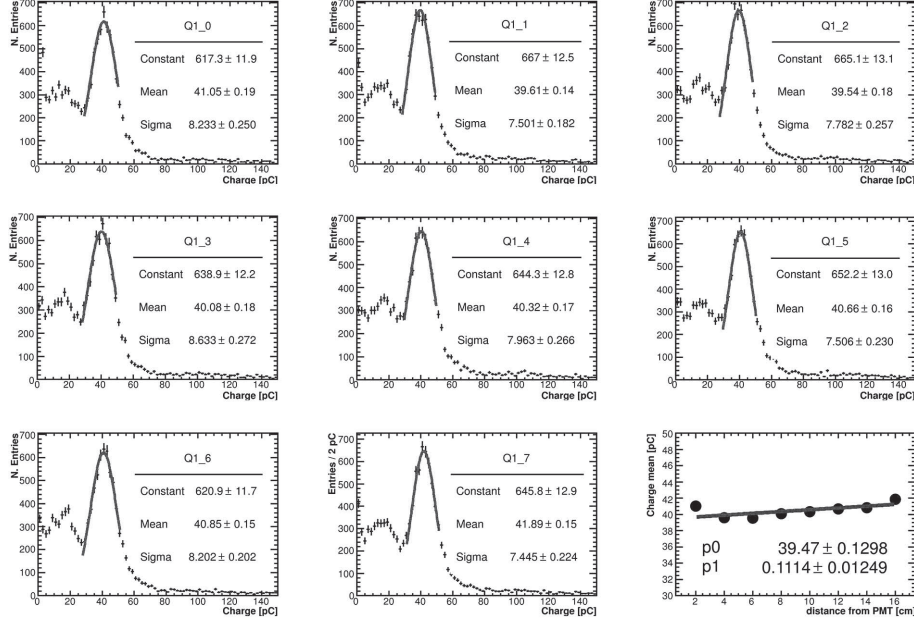


Fig. 2. – Fits used to extract the charge peak position during the scan of the Opto Materials 01 crystal, wrapped with Tyvek and plot of these values as a function of distance.

has been obtained with Teflon ($\sim 91 N_{p.e.}/\text{MeV}$) and Tyvek wrapping ($\sim 89 N_{p.e.}/\text{MeV}$), which provide a LY increase of a factor about 20% with respect to the configuration with Al. Therefore, tests on all the other crystals have been carried out with Tyvek wrapping, due to the fragility and difficulty of repairing Teflon, especially when using optical grease [7].

Examples of scan results are reported in fig. 3. In the top-left figure, a comparison between optical grease and air coupling is also shown, an improvement of about 80% is clearly visible for all the scan points.

To resume the features of all the 13 crystals tested, in fig. 4 (bottom left), the LY obtained with the source in the central scan position has been reported. To evaluate crystals LRU, the LY, normalized to its value in the central position, has been plotted as a function of the scan position and fit with a linear function (fig. 3). Fits angular coefficients are reported in fig. 4, showing a LRU lower than 0.5%/cm in most of the crystals.

To summarize, tests on all the 13 crystals show that:

- relevant differences between crystals from the same company do exist. For instance, we observe a major LY of 45% with Opto Materials sample 01 with respect to sample number 02 (fig. 3);
- similar performance for ISMA crystals, both long and short ones, and Opto Materials 02, while Opto Materials 01 has much better uniformity and LY ($130 N_{p.e.}/\text{MeV}$ with respect to $\sim 100 N_{p.e.}/\text{MeV}$);
- larger signals are observed closer to the PMT, because of the collection of direct light;
- the charge resolution is $\sim 18\%$ ($\sim 25\%$) with (without) optical grease (fig. 4).

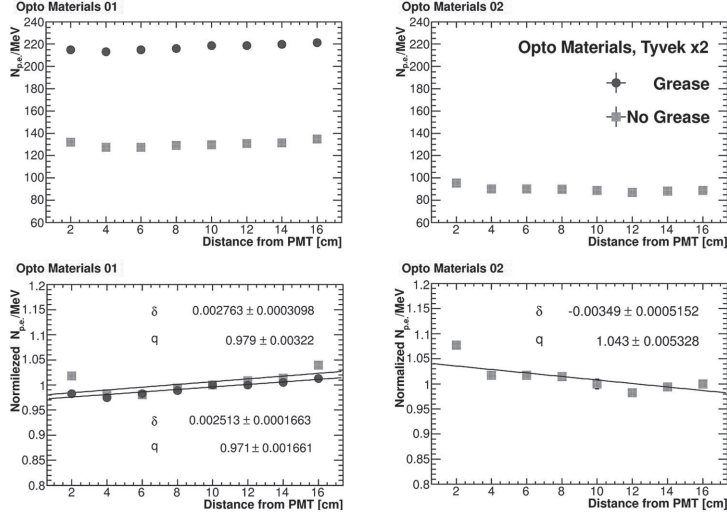


Fig. 3. – Top: Number of photoelectrons per MeV produced in the Opto Materials 01 (left) and 02 (right) crystal samples as a function of the distance of the source from the PMT. Bottom: LY normalized to the number of photoelectrons per MeV produced in the central scan position and fitted with a line function to evaluate the LRU (δ) in $\%/cm$.

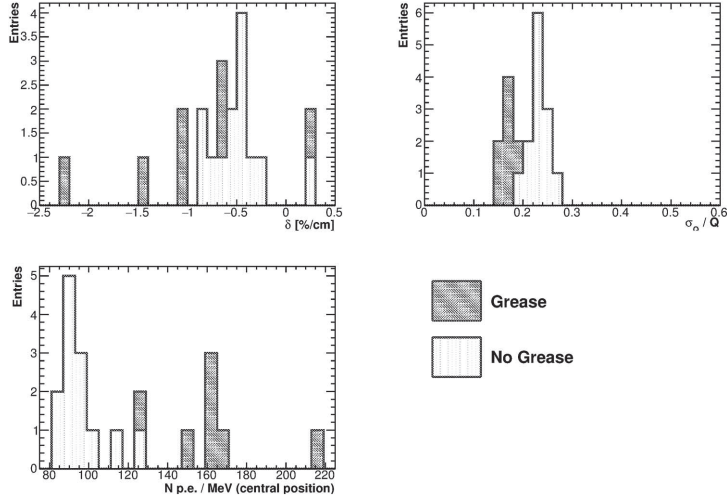


Fig. 4. – Slopes distribution (in $\%/cm$) provided by the linear fit on the LY normalized as a function of the distance from the PMT (top left), resolution distribution (top right) and LY distribution (bottom left) obtained with the source in the central scan position (10 cm far from PMT) for all the crystal samples tested.

4. – Single-channel timing performance

A $(3 \times 3 \times 20)$ cm³ sample from each company, Opto Materials and ISMA, has been coupled to a SPL MPPC and tested with cosmic rays to evaluate the timing resolution.

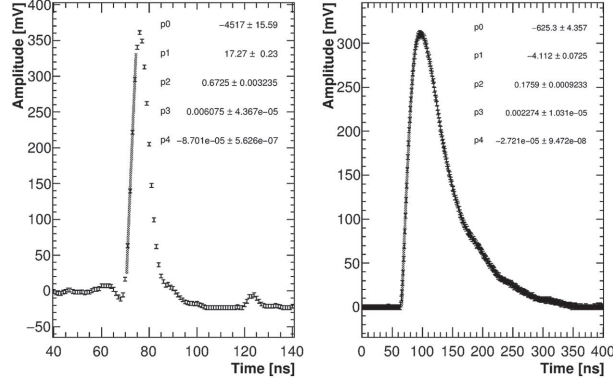


Fig. 5. – Signals of the top finger (left) and of the Opto Materials 01 crystal (right) acquired by the CAEN DT5751 digitizer at 1 Gsps rate. Also the 4th-order polynomial fit is shown.

4.1. *Experimental setup.* – As in the previous tests, five crystal surfaces have been wrapped with Tyvek foils. Each crystal has been placed between two *fingers* (small plastic scintillators), which are perpendicular to each other and positioned one below and one above the crystal under test. In this way, the two finger coincidence covers 1 cm^2 area on the long surface of the crystal. For some crystals, the effect of the Rhodosil Paste 7 optical grease coupling has also been studied. The whole system has been assembled inside a light tight black box.

The data acquisition system is composed by a trigger board, that makes the coincidence between the two discriminated finger signals, and a CAEN DT5751 digitizer at 1 Giga samples per second, which acquires finger and crystal signals.

The goal of this test is to measure the time resolution achieved at the energy released by a minimum ionizing particle (MIP) in the crystal. In order to set the energy scale, we compare the charge spectra of the MIP with that from a radioactive source. Our ^{22}Na source emits 511 keV back-to-back photons from annihilation and its charge spectrum has a corresponding mean value of $(11.57 \pm 0.17) \text{ pC}$. For the cosmic rays charge plot, the most probable value is $(463.3 \pm 1.13) \text{ pC}$. Comparing these two values, the energy released by a MIP in a crystal results to be around 20 MeV.

The amplifier used for the CR test was a prototype version with a gain of 3.

4.2. *Timing analysis.* – Waveform examples obtained for one finger and for the crystal, are shown in fig. 5 (left and right, respectively). To extract the time, the maximum value of pulse height for the finger and crystal signals has been evaluated and then a fit with a 4th-order polynomial function has been performed between the times at two fixed thresholds: *i*) the position of the time sample corresponding to a pulse height of 10 mV above the signal baseline and *ii*) the one at maximum pulse height minus 1 ns ($t_{max} - 1$).

The measured time for both fingers and crystals is taken as the position of the fit function at a constant fraction (CF) value, set at 25%, of the maximum signal amplitude. In order to eliminate the jitter due to the trigger, the half sum of the finger time has been subtracted,

$$(6) \quad t = t_c - \frac{t_1 + t_2}{2} ,$$

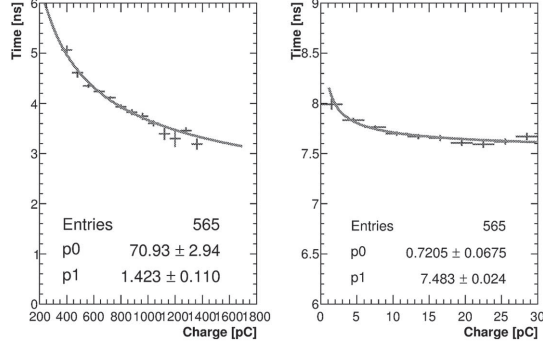


Fig. 6. – Left: crystal time evaluated as $t = t_c - \frac{t_1+t_2}{2}$ as a function of the signal charge, where t_1 and t_2 are the bottom and top finger times respectively. Right: half difference of finger times as a function of the signals charge. The fit reported is used to evaluate the slewing correction.

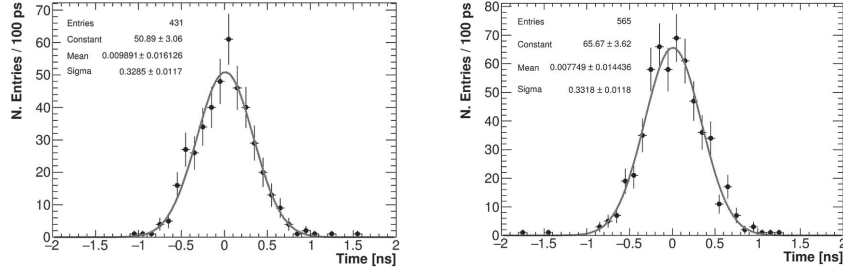


Fig. 7. – Time distributions obtained with the constant-fraction method after the slewing correction of the Opto Material 01 crystal, coupled to the SPL MPPC with optical grease. This crystal has been tested wrapped with Teflon (left) or Tyvek (right).

where t_1 and t_2 are the time of the bottom and top fingers respectively and t_c is the crystal time. The time jitter of the trigger, $(t_1 + t_2)/2$, is evaluated as the σ_f provided by the Gaussian fit that is $\sim (168 \pm 6)$ ps.

The detector timing properties are determined primarily by time slewing (or time walk) resulting from the signal rise time, shape and amplitude. The dependence of the time, t , from the charge, Q , is shown in fig. 6. This behavior is described by the function

$$(7) \quad t = \frac{p0}{\sqrt{Q}} + p1,$$

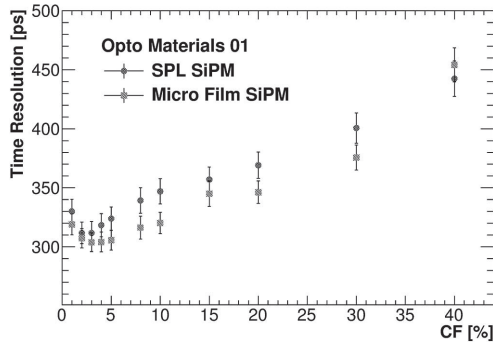
where $p0$ and $p1$ are parameters evaluated by a fit to the dependence in fig. 6 minimizing the χ^2 .

After the time slewing correction, the time distributions of the Opto Material 01 crystal tested, wrapped with Tyvek and Teflon and coupled with and without optical grease to the SPL MPPC, are reported in fig. 7. The time resolution, σ_c , is the ‘‘Sigma’’ value of the Gaussian fit, reported in the same figure.

The best performance is obtained with optical grease coupling: (328 ± 12) ps with Teflon and (333 ± 12) ps with Tyvek wrapping. Coupling in air deteriorates the resolution: (409 ± 16) ps with Teflon and (455 ± 13) ps with Tyvek wrapping, as expected by the loss

TABLE I. – Time resolution, at ~ 22 MeV, given in ps. The value reported are jitter subtracted. The symbol “–” means that this case has not been measured.

	Tyvek	Tyvek and grease	Teflon	Teflon and grease
Opto Materials 01	~ 410	~ 270	~ 375	~ 260
Opto Materials 02	–	~ 280	–	–
ISMA 05	–	~ 265	–	–

Fig. 8. – Time resolution as a function of the constant-fraction threshold value of the Opto Material 01 with grease coupling. For both the SiPMs, the best resolution is obtained with $CF = 3\%$.

of collected light. Then the time resolution after jitter subtraction is evaluated as

$$(8) \quad \sigma = \sqrt{(\sigma_c^2 - \sigma_f^2)}.$$

In table I, all the jitter-subtracted time resolutions obtained testing crystal + SPL MPPC exploiting cosmic rays are summarized.

Other Hamamatsu MPPCs with a different cover layer have also been tested: Micro Film MPPCs.

In this final test, the time has been evaluated in a similar manner, by using two variable thresholds for the fit range (the fit function remains a 4th-order polynomial) at, respectively, 1% and 85% of the signal maximum amplitude. These threshold values are obtained performing a scan and minimizing the time resolution. The fit is shown in fig. 5.

Therefore, a scan on the time resolution as a function of the CF threshold has been carried out (fig. 8). The CF value used for all tests has been chosen as the value which minimizes the time resolution of the crystal, that is $CF = 3\%$. For this purpose, only the Opto Material 01 coupled with grease to both SPL and Micro Film photosensors has been tested, the optimized CF value is similar in both cases.

For the same configuration the SPL MPPC (the Micro Film SiPM) shows an improvement of $\sim 2\%$ ($\sim 8.5\%$) of the time resolution with respect to the previous method.

5. – Conclusion

Every tested undoped CsI crystal shows a good LY $\sim (100\text{--}130) N_{pe}/\text{MeV}$, which is increased by a factor ~ 1.7 when coupled with grease. The LRU has an average of $\sim 0.6\%/cm$.

The time resolution obtained with cosmic rays is ~ 375 ps (~ 270 ps), without (with) grease at ~ 22 MeV (energy deposited by a minimum ionizing particle in a pure CsI crystal) using Hamamatsu MPPC as readout.

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