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Development of a MCP-based timing layer for the Upgrade 2 of the LHCb experiment(*)

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Summary. — The High-Luminosty LHC era will provide remarkable opportunities for the physics program of the LHCb experiment. However, various technological challenges are currently open. Concerning the electromagnetic calorimeter, the measurement of the time of arrival of the impinging particles will be a crucial new feature to effectively deal with the foreseen high pile-up. A dedicated timing layer, based on LAPPD technology, is currently under investigation for this purpose. This proceeding summarises the motivations for this option and the state of the art of the ongoing R&D programme.

1. – Motivations and R&D concept

The LHCb collaboration is designing an ambitious upgrade of its experiment, to fully exploit the occasion arising from of the High-Luminosity LHC [1]. The project, named "LHCb Upgrade 2", aims to collect a total integrated luminosity of about 300 fb^{-1}, to probe with unprecedented accuracy a wide range of observables [2]. To achieve its targets, the LHCb Upgrade 2 will have to keep the current detector performance, and even improve them in some domains, but dealing with a peak instantaneous luminosity of 1.5×10^{34} cm^{2}s^{-1}: a factor 7 higher than the design value of the current detector.

The main challenges for the electromagnetic calorimeter (PICOCAL) [3] will be the resistance to radiation damage and the control of high-occupancy effects. The current Shashlik technology [4] can sustain up to 40 kGy, whereas the most central region is foreseen to integrate up to 1 MGy. Therefore, new SPACAL modules [5] are candidates to equip the inner region of the future PICOCAL, while Shashlik technology will still be used to equip the outer regions. This solution will permit the PICOCAL granularity to increase with relevant benefits in the reconstruction performance of the much higher number of $e^{\pm}$ and photons. To increase the efficiency, another relevant new feature will be the double readout, namely the longitudinal segmentation of the PICOCAL with independent energy measurements for the front and back sections. Another critical consequence of the increased instantaneous luminosity will be the much higher combinatorial background. Simulation studies have shown that the reconstruction of the time of PICOCAL hits may be a powerful tool to handle it [6]. The studies set at around 10-20 ps

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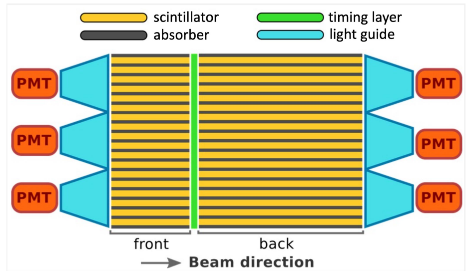

Fig. 1. – Schematic view of the SPACAL module for the LHCb Upgrade 2. The same longitudinal split with the presence of the timing layer can be applied also to Shashlik modules.

the target time resolution to resolve the pile-up profiting from the time spread of primary *pp* interactions. The timing performance of SPACAL and Shashlik modules in the test beam is encouraging, but further developments are still necessary [7]. In parallel, another option is currently under investigation. It is the inclusion of a dedicated timing layer between the front and back sections of the calorimeter, as illustrated in fig. 1. The ongoing R&D programme is investigating the feasibility of realising such a layer based on Large Area Picosecond PhotoDetectors (LAPPD). Off-the-shelf, these devices are the largest microchannel-plate (MCP) photomultiplier ever built (up to 20×20 cm^2 of active area), entirely made with inexpensive materials and capable of time resolutions of a few tens of picoseconds per single photoelectron [8]. The cost is traditionally one of the main limiting factors for the usage of the MCP technology in large areas. A breakthrough, that permitted the substitution of the usual lead-glass of the MCP substrate with common borosilicate, came from the deposition of resistive and emissive layers of material on the MCP substrate using the Atomic Layer Deposition (ALD) technique. A second source of cost and fragility of the traditional MCPs is the photocathode. This project proposes to use the LAPPD without the photocatode, exploiting the primary ionisations occurring in the MCP tiles. This configuration reduces the reconstruction efficiency, but such an effect may be compensated by the high particle multiplicity of the electromagnetic showers. Previous studies of this idea are available in ref. [10] and thanks to the *i-MCP* collaboration [11], but further work is necessary to assess the LAPPD behaviour in this case. For instance, the lifetime analyses of ALD-based MCPs available in the literature consider a maximal integrated charge of 35 C/cm^2 [12], whereas ≈ 300 C/cm^2 are expected in LHCb-Upgrade-2 conditions.

2. – R&D status

So far the R&D program has tested various MCP and LAPPD apparatuses, to measure their radiation hardness, ageing, and time resolution. The following sections summarise the experimental procedures and report the main results. The data were collected in the laboratory of INFN Bologna Division and at test-beam areas of accelerator facilities at DESY and CERN. All MCP and LAPPD devices were provided by Incom$^{\text{TM}}$ [13]. Two generations of the LAPPD were available: `Gen-I` tiles with internal stripline readout and `Gen-II` tiles with external pixelated readout, both equipped with MCPs with a pore diameter of 20 or 10 μm. The usual configuration involved a Chevron stack of two MCP layers, but a prototype with three layers (called *z-stack*) was also studied.

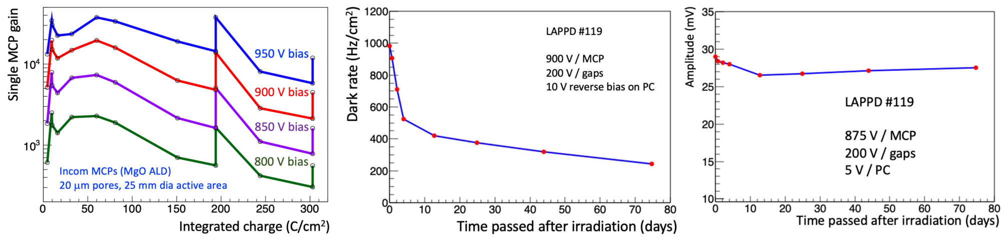

Fig. 2. – Left: Gain of Incom Inc. MCPs as a function of integrated emitted charge for different bias voltages; center and right: dark rate and signal amplitude of the irradiated LAPPD described in the text, depending on the time passed after the irradiation. Circles are the data points, whereas continuous lines are added to connect them and guide the eye.

Where not differently specified, the LAPPD photocathode was always disabled, namely a small negative voltage was applied between it and the surface of the first MCP layer, to prevent photoelectrons from reaching the multiplication stage. A `CAEN v1742` digitizer was always exploited for signal acquisition at 5 GS/s [14].

2·1. *Ageing and radiation hardness.* – The MCP ageing was studied in the laboratory with a Chevron stack of two circular MCPs with a pore diameter of 20 μm. Their substrate was analogous to the LAPPD one (borisilicate+ALD), but their active area was just 5 cm^2. The stack was placed in a vacuum chamber, whose upper flange was equipped with a viewport. A mercury lamp was located on the top of it, to trigger the extraction of primary electrons from the material of the top MCP. The stack configuration multiplied the emitted charge, and a metallic anode collected it below the bottom MCP. Two multimeters were used both to measure the anodic current and to calibrate the output current of the top MCP when measuring the gain of the bottom MCP. In about ten months of operations, a total emitted charge of 300 C/cm^2 was integrated. Figure 2-left illustrates the results of the gain measurements depending on the integrated charge and the voltage applied to the bottom MCP. An overall factor seven reduction of the gain was observed, but a tension increase of 100 V was sufficient to recover it. The discrete jumps visible at 200 and 300 C/cm^2 are due to measurements repeated after turning off the UV light for about a week. The rest made the MCPs recover part of the lost gain, but then it went back to the previous trend.

The irradiation campaign of a `Gen-II` LAPPD was executed at IRRAD [15]. This facility provided bunches of protons at 24 GeV extracted from the CERN Proton-Synchrotron (PS). The full width at half maximum of the beam was about 1 cm and 10^{16} protons were integrated in one week. The LAPPD comprised two MCP layers with pores diameter of 10 μm and the readout was segmented in 2.5×2.5 cm^2 pixels. During the irradiation, high voltage was provided to the MCP plates (900 V) and the gap between them (200 V). After the irradiation, the LAPPD was moved to a storage area. The dark rate and gain of the irradiated pixel were monitored for 75 days. Before the irradiation, the dark rate was 10 Hz/cm^2. Right after the irradiation it increased by two orders of magnitude. Then, it decreased steeply in the first few days, with a much slower long-term trend. Figure 2-center displays the results. After 75 days, the dark rate was significantly higher than prior to irradiation, but not problematic for the purposes of this project. To measure the gain, a blue LED was inserted in front of the irradiated spot. The MCP and gap voltages were set to 875 and 200 V, respectively. A 5 V active bias was set to the photocathode. The LED was powered by a pulse, whose width and amplitude were adjusted to produce single isolated photoelectrons. Before irradiation, the average amplitude of the signal was measured to be 30 mV. Just after the irradiation it was essentially unchanged (29 mV). The average signal amplitudes measured in the subsequent 75 days are shown in fig. 2-right. No relevant gain modification is observed.

2˙2. *Time resolution.* – The time resolution of the LAPPD prototypes was measured at the test-beam areas of DESY and SPS accelerators. The two facilities provided electron beams, whose energy ranged from 1 to 5 GeV and from 20 to 100 GeV, respectively. The experimental setup included: two thin scintillators for triggering, two MCP devices providing the reference time, and a system of three delay wire chambers (DWC) to localise the trajectory of the primary electrons. After crossing these detectors, the beam hit the front section of a SPACAL prototype with 5×5 cm^2 transversal section. The LAPPD prototype was placed behind it to collect the particles of the electromagnetic shower. The reference MCPs had a circular shape with a diameter of 2.5 cm. The timestamps of the reference MCPs were extracted from the digitalised signals using a constant fraction discrimination (CFD) algorithm. The position information from the DWC was used to reject the primary electrons passing close to the border of reference MCPs and exhibiting poor time resolution. The reference time was calculated as the average of the timestamps of the reference MCPs. Its resolution was 12 ps. The best performance was obtained with the *z-stack* LAPPD. It was equipped with three MCP layers, pores with a diameter of 10 μm, and 2.5×2.5 cm^2 readout pixels. Hence, only four LAPPD pixels were covered by the SPACAL prototype and instrumented. To study an approximatively uniform distribution of the primary electrons, the DWC, SPACAL, and LAPPD devices were placed on a movable table and a position scan was executed for each energy of the electron beam. The information from the DWCs was used to select the primary electrons crossing the fiducial region, defined as the square with vertices at the centers of the instrumented pixels. The resolution on the position from each DWC was of the order of 1 mm. The LAPPD timestamp was obtained as the output of a *Random Forest Regressor* algorithm [16]. It combined information from the four instrumented pixels and the DWC. The regressor target was the reference time from the MCPs. The digitalised signals from the LAPPD pixels were preliminarily analysed with a CFD algorithm. The input variables of the regressor were: the signal amplitudes, the time stamps from the CFD algorithm at 10%, 50%, and 90% of the amplitude, and the vertical and horizontal coordinates from a single DWC([1]). Figure 3 illustrates the time resolution of the *z-stack* LAPPD as measured in October 2022 at SPS and in December 2022 at DESY. In the SPS case, all three MCP layers were active. The tensions of each MCP layer and gaps between them were 685 V and 200 V, respectively. The measured time resolution ranged from 20 ps at 20 GeV to 16 ps at 100 GeV. In the DESY case, a performance improvement was observed with just two active MCP layers. Their tension was 875 V, while the tension of the gap was 200 V. The measured time resolution ranged form 48 ps at 1 GeV to 19 ps at 5 GeV. Measurements at SPS energies with two active MCP layers are foreseen for summer 2023.

([1]) The position resolution from the baricenter of the energies measured by the SPACAL cells is expected to be comparable with the resolution of a single DWC.

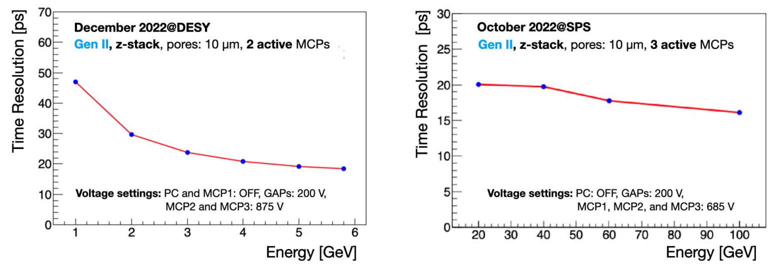

Fig. 3. – Time resolution of the *z-stack* LAPPD as measured at DESY (left) and SPS (right) test beams. The resolution of the reference time is already subtracted in these plots.

2·3. *Operations at high rate*. – In the hottest region of the PICOCAL fluxes of charged particles from 30 to 100 MHz/cm^2 are expected between the front and back sections of the SPACAL modules. However, a high input rate degrades the LAPPD performances. In fact, each multiplication depletes the MCP pores of electrons. It implies a dead time for each pore, which dumps the signal amplitude and worsens the time resolution. To study this case, a high-occupancy environment was mimicked in the laboratory using two lasers. The first laser imitated the effect of a shower produced by electrons impinging on the SPACAL front (hereafter referred to as *signal*), while the second one generated the background flux. Both lasers were defocused with a diameter of 15 mm on the LAPPD surface and had a wavelength of 405 nm. A 50 V positive bias was applied to the photocathode to generate photoelectrons with low kinetic energy and reproduce the effect of the electromagnetic showers. The knowledge of the quantum efficiency of the photocathode and simulation studies permitted the pulse power of the first laser to be adjusted to mimic showers of different energies (for instance, 20 photoelectrons roughly corresponded to 5 GeV). The pulse power of the second laser was set to have 10 photoelectrons per cm^2, and its pulse rate was varied to mimic particle fluxes for different regions of the calorimeter. Figure 4 plots the time resolution measured depending on the energy of the signal and the background occupancy. Already above a few MHz/cm^2 a relevant degradation of the time resolution was observed. The effect is mitigated at high signal energy. The LAPPD used for this test had pores with a diameter of 10 μm and direct readout with strip-line anodes, 1-mm wide. It comprised two MCP layers, whose voltages were set to 840 V. The voltage of the gap was 200 V. No relevant improvement was observed by modifying the voltages. Instead, an important advantage came from the pore size: similar tests with a pore diameter of 20 μm returned poorer results. For example, the time resolution corresponding to 5 GeV signal and 30 MHz/cm^2 background was estimated to be 90 ps, to be compared with 50 ps of the latest test. Further developments are needed to meet the requirements of LHCb Upgrade 2. The next test will focus on the performance of the *z-stack* LAPPD.

3. – Conclusions

A LAPPD-based timing layer is a candidate component for the electromagnetic calorimeter of LHCb Upgrade 2. This solution takes advantage of a relevant cost reduction compared to the traditional MCP technology. Several tests have already been carried on in the laboratory and at test-beam facilities. The lifetime of the MCP wafers

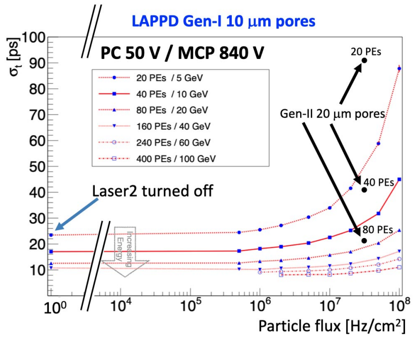

Fig. 4. – LAPPD performance at a high incident rate as estimated in the laboratory of INFN Bologna Division. Blue points correspond to the measurement with the `Gen-I` LAPPD with a pore diameter of 10 μm. The red lines are added to connect them and guide the eye. The black points summarise the results of a similar test with a LAPPD with a pore diameter of 10 μm. The conversion between the number of photoelectrons (PE) and energy of the mimicked electromagnetic shower is reported in the legend.

exploiting the ALD technique met the requirement of 300 C/cm^2 of integrated charge. The LAPPD radiation hardness effectively passed the irradiation test. Good time resolution was observed in a wide energy range, even without the photocathode. However, intense R&D is ongoing to overcome the performance limits at high incident flux.

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