Performance and upgrade plans of the ALICE Photon Spectrometer

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Abstract. PHOS is a highly granulated precision spectrometer, one of the two electromagnetic calorimeters of ALICE (A Large Ion Collider Experiment) at the LHC. It is based on scintillating PbWO₄ crystals and is dedicated to the precise measurements of spectra, correlations and collective flow of neutral mesons, thermal and prompt direct photons in ultra-relativistic nuclear collisions at LHC energies. PHOS participated in LHC Run 1 (2009–2013) and Run 2 (2015–2018), during which a large amount of physical data were collected in pp, p-Pb and Pb-Pb collisions.

We present an overview of the PHOS performance during Runs 1 and 2 and plans for an upgrade for future LHC runs.

1. Introduction

ALICE (A Large Ion Collider Experiment) at the LHC is designed for studies of nuclear matter at extreme temperatures and energy densities, the so-called Quark-Gluon Plasma (QGP). It incorporates two kinds of electromagnetic calorimeters for the measurements of electromagnetic signals of QGP: a highly granular photon spectrometer PHOS and a large acceptance calorimeter EMCal/DCal. Both are located in the barrel part of the ALICE detector.

PHOS is an electromagnetic calorimeter based on scintillating PbWO₄ crystals dedicated for precise measurements of spectra, correlations and collective flow of neutral mesons and direct photons in ultra-relativistic nuclear collisions at LHC energies. The choice of the PHOS active media allows for the ability to reconstruct π⁰ mesons up to very high transverse momenta, operation in a high multiplicity environment, and for excellent spatial and energy resolutions. PHOS is operated at a constant temperature of −25°C in order to increase light yield of crystals and further improve the energy resolution. PHOS consists of 12544 channels in 3 + 1/2 modules. Rejection of charged particles from the cluster spectrum is done with a Charged Particle Veto (CPV) detector which is located in front of PHOS. First module of CPV was installed into the ALICE during the Long Shutdown 1 (LS1) between Run 1 and Run 2. Two more modules were installed during the current Long Shutdown 2 (LS2) and will be operational in the future Run 3 (2022–2025).

Avalanche PhotoDiodes (APD) S8664-55 produced by Hamamatsu are used as photodetectors in PHOS. The readout system is based on ADCs called ALTRO which provide digitization and sampling and then pass signal to scalable readout units (SRU) via 20-Mb/s point-to-point links. In order to obtain wide dynamic range, two signal amplification modes, high and low
gains (HG and LG), are implemented in separate ADCs. The readout time is 172 $\mu$s independent from the event size. Properties of PHOS are summarized in Table 1.

| Table 1. Summary of PHOS properties. |
|------------------------------------|
| Active element | Homogeneous crystals PbWO$_4$ |
| Molière radius | 2.0 cm |
| Photodetector | APD $5 \times 5$ mm$^2$ |
| Depth | $20 \ X_0$ |
| Acceptance | Run 1: $|\eta| < 0.12, 260 < \phi < 320^\circ$ |
| | Run 2: $|\eta| < 0.12, 250 < \phi < 320^\circ$ |
| Granularity | Cell $2.2 \times 2.2$ cm$^2$ |
| | $\Delta \phi \Delta \eta = 0.0048 \cdot 0.0048$ rad |
| Modularity | $3+1/2$ modules |
| | 12544 cells |
| Dynamic range | 0–100 GeV |
| Energy resolution | $\sigma_E/E = 1.8\% / \sqrt{E} \oplus 3.3\% / E \oplus 1.1\%$ |
| Distance from IP | 460 cm |
| Material in front of the detector | 0.2 $X_0$ |

2. Trigger system and its performance
PHOS provides triggers at levels L0 and L1 in order to increase luminosity of high energy signals in data taking [7,8]. If the sum of the energy of $4 \times 4$ cells is larger than a threshold, PHOS L0 trigger is fired. Typical threshold of L0 trigger is 3 GeV. L1 trigger provides 3 thresholds which are useful to study Pb-Pb collisions. Thresholds are adjustable depending on collision rate, required trigger rejection factor, and readout time. The ratio of the uncorrected $p_T$ spectra of clusters normalized to the number of events reconstructed with a trigger to that with the minimum bias trigger is called trigger turn-on curve. Example of turn-on curve for PHOS L0 trigger is shown in figure 1 (bottom panel).

Figure 1. Top: uncorrected $p_T$ spectra of clusters reconstructed in PHOS with minimum bias and PHOS L0 triggers normalized to the number of events of the corresponding triggers. Bottom: an example of turn-on curve for PHOS L0 trigger.
3. Detector calibration

Excellent energy calibration is required for precise measurements of neutral mesons and direct photons, especially at low-$p_T$. Energy calibration in PHOS was performed in four mutually dependent procedures: relative gain calibration, absolute energy calibration, non-linearity correction, and time-dependent calibration correction [9]. Pre-calibration based on APD gain equalization and fine energy calibration based on $\pi^0$ peak position were used for relative gain calibration. A dedicated Monte Carlo study was performed in order to obtain fast iterative procedure for relative energy calibration in PHOS [9]. Thanks to this procedure, 2–3 iterations were enough to produce final calibration. Absolute energy scale was checked with electrons $E/p$.

Stability of $\pi^0$ peak position over time is important for good energy calibration. While PHOS is thermostabilized with precision $\sim 0.3^\circ$, still there are long-term modulations of this parameter. This effect is corrected for in the calibration procedure using $\pi^0$ peak position dependence over time.

At LHC, minimal interval between bunch crossings (BC) is 25 ns. In order to select photons produced only in the triggered BC, it is important to have good timing calibration. Front-end electronics (FEE) sampling clock frequency is 10 MHz and is synchronized with LHC clock at 40 MHz, but the phase remains unknown. Both relative cell-by-cell and per-run random phase were calculated from physical data, separately for HG and LG channels. Timing distribution and resolution ($\sigma_t$) in PHOS after calibration are shown in figure 2. $\sigma_t$ is about 2 ns at 6 GeV increasing to 8 ns at 1 GeV. These rather large values don't allow for separation between photon clusters and hadron ones. Front-end electronics with a dedicated timing channel should be installed if one wants to perform this task.

4. Photon identification

Two criteria of photon identification are implemented in PHOS: shower shape and anti-track matching [10]. Shower shape selection criterion is based on two components of cluster dispersion. Typical distribution of these parameters is shown in figure 3 (top), where region with large density of clusters corresponding to electromagnetic showers is clearly seen. Anti-track matching selection criterion is based on the distance to the closest extrapolated track from the ALICE central tracking system [1]. Distributions of the closest distance between a reconstructed track and a cluster in PHOS are shown in figure 3 (bottom) for two centrality classes of Pb-Pb collisions. The efficiency of the charged-particle rejection can be further improved with CPV detector [11], and, thanks to the enlarged CPV acceptance coverage, these possibilities will be fully exploited in the future LHC runs.

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Figure 2. (a) Timing distribution in PHOS after timing calibration procedure. (b) Timing resolution dependence on cluster energy obtained from physics data (Run 2).
5. Physics performance

Constraints on hadron fragmentation functions and parton distribution functions parameterizations can be provided with precise measurements of $p_T$ spectra of neutral mesons $[12,13]$. Both low and high multiplicity environments, and a wide $p_T$ ranges can be explored with PHOS. Typical two-photon invariant mass distributions are shown in figure 4. Excellent resolution of PHOS results in $\pi^0$-peak width as low as $\sigma_{\pi^0} = 4.56 \pm 0.03 \text{ MeV}/c^2$ in pp collisions $[9]$. PHOS can be used to identify electrons with high purity by $E/p$ ratio in conjunction with tracking system via $dE/dx$. Example of $E/p$ distribution for PHOS is shown in figure 5.

Figure 3. Top: distribution of cluster dispersion parameters $[10]$ in PHOS in pp collisions at 13 TeV. Bottom: distributions of the closest distance between a reconstructed track and a cluster in PHOS for 0–5% and 60–80% centrality classes of Pb-Pb collisions. Combinatorial background is estimated with mixed event distributions. They are obtained by matching clusters and tracks from different events.

Figure 4. Examples of two-photon invariant mass distribution in PHOS in pp (a) and Pb-Pb (b) collisions.
Figure 5. Distributions of the cluster energy to track momentum, \( E/p \) ratio, for PHOS. The electron contribution results in a peak around unity in these distributions. The distribution denoted as 'EM clusters' corresponds to the application of PID criterion based on a cluster shower shape.

6. Upgrade plans
There are no plans to change acceptance of PHOS in the future Runs 3 and 4. But in order to comply with high luminosity requirements of LHC after LS2 upgrade, software for online and offline reconstruction, calibrations, and data quality control is being developed within O2 framework [14]. The readout time will be reduced with firmware modifications of readout and trigger electronics.

In Run 4, an upgrade of PHOS is considered. The main goal is to improve energy and time resolution and open possibility to measure \( \pi^0 \) mesons and direct photons at \( p_T \) below 1 GeV/c. The upgrade is planned in three directions: upgrade of front-end cards (FEC) using modern components to improve timing resolution and operation reliability; upgrade of photodetectors to increase sensitivity for low-energy photons and to improve timing resolution; upgrade of module structure to ease access to FEC and improve operation reliability.

The main purposes of FEE upgrade is to add a timing channel in order to improve time resolution, increase energy dynamic range and produce cards based on recent components. The latter is important for prolongation of the lifespan of the whole detector system. Improvement of time resolution opens possibilities to study direct photons with higher precision. Currently, the prototype of the new FEC is being developed with timing channel on the base of CERN’s HPTDC chip [16]. It was tested at CERN during 2017–2018, and energy and time resolutions were measured. Measured timing resolution with Hamamatsu multi-pixel photon counter (MPPC) S12572 as photodetector is shown in figure 6 (a): \( \sigma_t \sim 200 \) ps at 1 GeV was obtained at room temperature. The energy resolution of the prototypes was also measured during these tests, see figure 6 (b). It was shown that a MPPC array with size 6 \times 6 mm\(^2\) provides energy resolution about 5.5% at 1 GeV without cooling. Excellent timing resolution together with this energy resolution and fair cost makes MPPC S12572 a good choice for the upgraded PHOS photodetector.

The purpose of the upgrade of the PHOS module structure is to give access to PHOS FEE during short technical stops of LHC. This requires modifications to the airtight cases of the PHOS modules in order to keep a cooled down and thermostabilized zone only for detector units, while makes FEC accessible by experts.
Figure 6. (a) Time resolution dependence on the beam energy obtained at beam test with new PHOS FEC prototype and MPPC S12572 as photodetector at CERN. (b) Energy resolution of upgraded PHOS prototypes with MPPC array, APD 5 × 5 mm² size (Hamamatsu S8664-55) and APD 10 × 10 mm² size (Hamamatsu S8664-1010). All measurements were done at temperature 17.5°C with 0.1°C stability. The curve represents current PHOS energy resolution (at –25°C).

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