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Mechanical design and photodetector system of the first calorimeter prototypes based on oriented scintillating crystals

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Abstract: Scintillating crystals are a well-established technology for electromagnetic (EM) calorimetry. When their crystalline lattice is properly oriented with respect to the incoming particle beam, however, coherent interactions with the periodic potential can strongly modify the EM shower development. For high-energy electrons and photons, the Lorentz-boosted electric field experienced along atomic strings or planes can approach the quantum electrodynamical strong-field regime, enhancing bremsstrahlung and the pair production probability and effectively shortening the radiation length. This leads to

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earlier and more compact EM showers compared to the amorphous case. The ORiEnted calOrimeter (OREO) project exploits these strong-field effects in ultra-fast $PbWO_4$ (PWO-UF) crystals to realise an ultra-compact, longitudinally segmented electromagnetic calorimeter. In this paper, we present the mechanical design and photodetection system of two OREO prototypes: a first configuration with an oriented upstream layer followed by a non-oriented layer, and a second configuration in which both layers can be operated in the oriented mode and aligned independently. The prototypes employ 3×3 matrices of PWO-UF crystals read out by SiPM arrays, with dedicated mechanics to achieve microradian-level control of the crystal orientation and to ensure light-tight operation. Possible applications include forward calorimetry at future colliders, fixed-target and beam-dump experiments, and space-based γ-ray detectors.

KEYWORDS: Calorimeter methods; Calorimeters; Overall mechanics design (support structures and materials, vibration analysis etc); Photon detectors for UV, visible and IR photons (solid-state)

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1 Introduction

In detector physics, compact and homogeneous electromagnetic calorimeters are often realized using scintillating or Čerenkov crystals [1]. Prominent examples include the CMS experiment at CERN, which employs about 75 000 lead tungstate ($PbWO_4$, PWO) crystals in its electromagnetic calorimeter [2]; the KOTO experiment at J-PARC and the Mu2e experiment at Fermilab, which use undoped cesium iodide (CsI) crystals [3, 4]; the Fermilab g-2 experiment, which adopts PbF_2 crystals. The ORiEnted calOrimeter (OREO) project exploits coherent effects in oriented crystals to develop a novel calorimetric concept [5, 6]. The interaction of ultra-relativistic electrons and photons with oriented crystals leads to a substantial acceleration of the electromagnetic shower development [7], enabling a more compact detector design, reduced longitudinal leakage, and improved photodetection performance as well as enhanced γ/hadron discrimination. Within OREO, an entire electromagnetic calorimeter layer has been realized, consisting of a 3×3 matrix of oriented $PbWO_4$ crystals, each with a length of $5X_0$ [8] (where X_0 denotes the material radiation length, i.e. the mean distance over which an electron loses all but $1/e$ of its energy via bremsstrahlung [9]). After a brief introduction on electromagnetic shower development in oriented crystals (section 2) and on the experimental programme investigating these effects (section 3), this contribution presents the two mechanical prototypes of the OREO calorimeter (sections 4 and 5) and the characterization of its photodetection system (section 6), discussing both the initial prototype and an upgraded configuration tested during a two-week campaign at the CERN SPS. To fully exploit the potential of OREO as a fine-granularity calorimeter, a detailed study of the response as a function of the independent orientation of the two layers is required, which in turn motivates the development of the new mechanical design.

2 Electromagnetic shower development in oriented crystals

In the standard description of electromagnetic shower development in inorganic scintillators, the medium is treated as amorphous, meaning that the atoms are assumed to be randomly distributed in space. Within this picture, the shower formation is driven by the Bethe-Heitler bremsstrahlung from

electrons and by the $e^{\pm}$ pair production from γ-rays, both processes being described as interactions with the Coulomb field of isolated atoms. Such models, however, ignore the role of the crystalline structure and its orientation. When a charged particle propagates close to a crystallographic axis, i.e. along a string of atoms, it is subjected to an electromagnetic field that is nearly uniform in the axial direction, arising from the coherent superposition of the fields of many atoms. This coherent field substantially modifies the underlying electromagnetic processes [10, 11]. At very high energy, in the rest frame of the incident particle, due to Lorentz contraction [10–13], the boosted electric field $E^* = \gamma E$, where γ is the Lorentz factor, can overcome the Schwinger critical field [14]

$$E_c = 1.32 \times 10^{16}\ \text{V/cm} \tag{2.1}$$

It is convenient to introduce the dimensionless parameter

$$\chi = \frac{E^*}{E_c} \tag{2.2}$$

which quantifies the effective field strength in units of E_c. Values of $\chi \geq 1$ define the strong-field (SF) regime [11], in which nonlinear QED effects become significant [14]. In the SF regime, the spectrum of the radiation emitted by a charged particle and the probability of pair production by a photon are enhanced [10, 11, 15–17], stimulating the emission of secondaries and further accelerating the development of the electromagnetic shower.

Dense inorganic scintillators such as PWO, BGO, BaF_2, and CsI are widely employed in compact electromagnetic calorimeters because their larger effective atomic number leads to radiation lengths of the order of 1 cm [1]. When the crystal lattice is aligned with the incoming particle beam, these high-Z materials do not simply behave as amorphous media: the strong electromagnetic fields associated with atomic strings or planes can significantly modify the development of electromagnetic showers, in close analogy with the case of single-element crystals [18]. Among these materials, PWO stands out as one of the most compact scintillators, with $X_0 \simeq 0.89$ cm [9]. It combines high density, good radiation hardness, and industrial availability. At the same time, its excellent crystalline quality and large atomic number make it an ideal candidate for exploiting SF phenomena in oriented crystals and, in turn, for investigating compact, high-performance electromagnetic calorimetry. PWO has a scheelite-type structure with a tetragonal symmetry and lattice constants $a = b = 5.456$ Å and $c = 12.020$ Å [5]. When the crystal is aligned along the $\langle 100 \rangle$ axis, the axial potential well depth is $U_0 \sim 500$ eV, corresponding to a maximum axial electric field of about $E \simeq 10^{11}$ V/cm [5]. In this configuration, the SF threshold for electrons and positrons is around 25 GeV, with a characteristic acceptance angle defined as

$$\Theta_0 = \frac{U_0}{m_e c^2} \tag{2.3}$$

of ≈ 0.9 mrad. Less pronounced radiation and pair production enhancement effects are still visible up to one degree of misorientation between the particle and crystal directions [11]. A visual representation of the acceleration of the electromagnetic shower is shown in figure 1, which displays the simulated development of the shower initiated by a 120 GeV primary electron in an amorphous 4.6 X_0 PWO and in an oriented PWO of the same thickness [7]. A clear shift of the shower maximum toward the first radiation lengths is observed, illustrating the accelerated development of the cascade.

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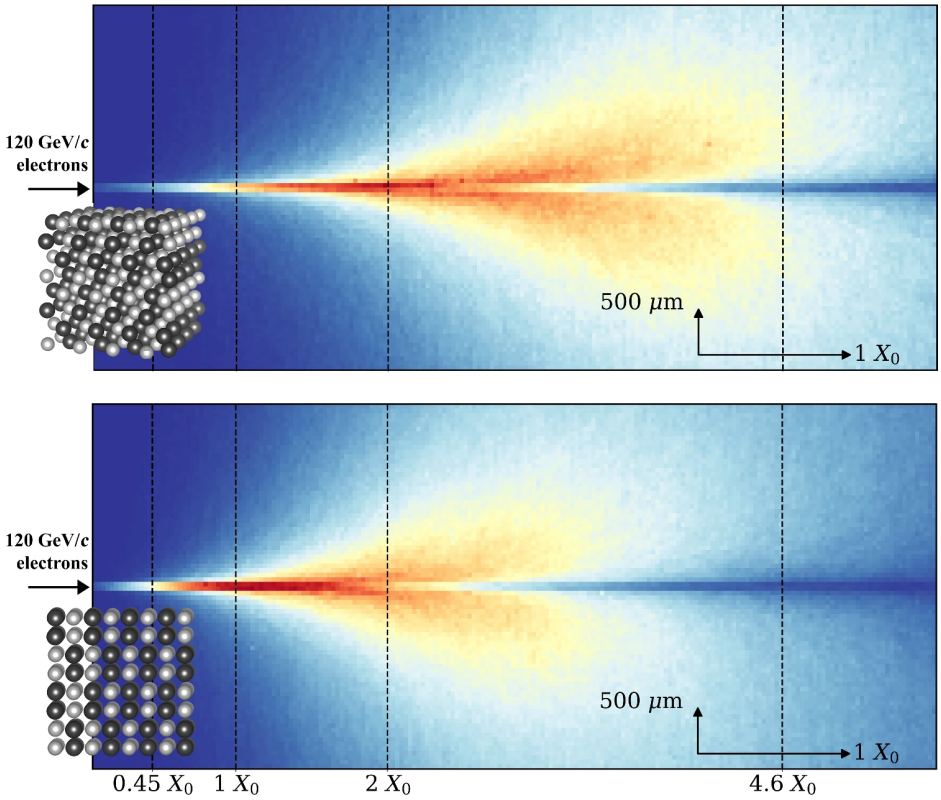

Figure 1. Simulated energy density deposit by an electromagnetic shower initiated by 120 GeV electrons as a function of depth in a PWO crystal, for a randomly oriented (top) and an axially oriented (bottom) configuration. Reproduced from [7]. CC BY 4.0.

3 Experimental evidence for shower acceleration in oriented scintillators

The first indications of an accelerated electromagnetic cascade in oriented scintillators came from measurements in 1999, in which 26 GeV electrons crossing an axially oriented PWO showed an increase in the radiative energy loss of about 10% with respect to the random orientation [19]. These results highlighted the importance of extending the investigation to higher energies, in the hundreds of GeV to TeV range, where SF effects are expected to be much stronger, and of developing dedicated Monte Carlo tools going beyond the amorphous approximation of standard shower codes.

A decisive step was achieved starting from 2017 with a series of experiments on single PWO crystals. The first measurements in the SF regime ($\chi \sim 4$) were performed at the CERN SPS H4 beamline with 120 GeV/c electrons and positrons impinging on a 4 mm-thick PWO$^{\langle 001 \rangle}$ sample ($\simeq 0.45\ X_0$) [18]. When the crystal was aligned, the photon spectrum hardened markedly, with an enhanced emission at high energies and a suppression of the low-energy photons compared to the random case, leading to an effective reduction of the radiation length by about a factor of five for 120 GeV $e^{\pm}$s in axial configuration [18].

To probe directly how shower development is modified, subsequent measurements with 120 GeV electrons investigated the energy deposit in PWO samples up to 4.6 X_0, corresponding to the early, high-energy stages of the shower. The deposited energy, inferred from the scintillation light read out by SiPM matrices, increased up to a factor of three in axial configuration with respect to the

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amorphous case for the thickest sample [7]. A measurable enhancement persisted even for incidence angles larger than the nominal acceptance $\theta_0 \sim 1$ mrad for PWO$^{\langle 100 \rangle}$ (see eq. (2.3)), with observable effects with angles up to 1° [7, 20]. Similar orientational enhancements, up to about a factor of three, were also observed at lower energies in oriented BGO$^{\langle 100 \rangle}$ and CsI$^{\langle 111 \rangle}$ crystals [21–23], indicating that these effects are relevant for a broad class of scintillators.

To interpret these measurements and define a realistic detector design, a dedicated simulation framework was developed. Since standard `Geant4` [24–26] treats crystals as amorphous media, a modified version of the `FTFP_BERT` Physics List was implemented, in which the differential cross sections for bremsstrahlung and pair production are rescaled by energy-dependent factors that encode the orientational dependence [6, 18]. These factors are derived from full Monte Carlo calculations based on the quasiclassical Baier-Katkov formalism applied to particle trajectories in the axial field of the PWO lattice [6, 18]. After validation against data, the model was incorporated into `Geant4` as a dedicated module for oriented crystals [27, 28].

Simulations with this framework show that, for primary electrons from several hundred GeV to the TeV scale, the fraction of energy deposited as a function of depth (in units of the nominal radiation length X_0) is enhanced in the first few X_0 when the PWO crystal is axially aligned, and the shower maximum is shifted towards smaller depths [5]. For instance, for 3 TeV electrons, the maximum moves from about 12.5 X_0 in random orientation to roughly 7.5 X_0 in axial configuration. The ratio between axial and random configurations is largest in the first 5–10 X_0 and decreases at larger depths, reflecting the progressive loss of energy and the escape of secondary particles from the SF angular acceptance defined by eq. (2.3).

These experimental and simulation results demonstrate that oriented scintillating crystals can substantially accelerate the electromagnetic shower development and compress the longitudinal profile of the energy deposit. Motivated by these findings, the OREO collaboration designed a first prototype of electromagnetic calorimeter explicitly exploiting SF effects in PWO. The active medium is ultra-fast lead tungstate (PWO-UF), a third-generation variant optimized for timing performance: co-doping with yttrium and lanthanum suppresses slow scintillation components, achieving sub-nanosecond decay times and improved radiation hardness [5, 29]. Although the light yield is smaller than for standard PWO, these crystals retain high density, compactness and excellent radiation resistance, making them well suited for granular, fast homogeneous ECALs in high-rate environments.

4 Design of the first OREO calorimeter prototype

The OREO calorimeter prototype consists of two separate modules, each implemented as a 3×3 matrix of ultra-fast $PbWO_4$ (PWO-UF) crystals. The first module is oriented and has a thickness of about 5 X_0, optimized to exploit strong-field effects and to initiate a compact electromagnetic shower. The second, non-oriented module, with a thickness of about 11.2 X_0, completes the shower development and provides a conventional measurement of the shower tail. The SF enhancement is expected to be strongest in the first few radiation lengths, where the particle energy is highest and the condition of axial alignment is fulfilled. Consequently, a fully oriented calorimeter is not required to obtain a more compact shower: orienting only the first few X_0 (of order 4–5 X_0) is in principle sufficient. This depth also matches the typical front longitudinal segment foreseen for future high-energy experiments such as FCC-ee [30] and the Muon Collider [31]. The present configuration therefore allows us to

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emulate these layouts and to assess whether the addition of an oriented preshower can yield a more compact shower and a more sensitive calorimeter.

Their crystallographic quality and orientation were characterized using high-resolution X-ray diffraction with laser autocollimation and photoelastic laser conoscopy, as detailed in refs. [5, 8]. These studies demonstrated low mosaicity and tightly controlled miscut angles, with deviations of the crystal axes below $\sim 100\,\mu$rad and inter-crystal misalignments below $\sim 200\,\mu$rad within the 3×3 matrix with $25 \times 25\,\text{mm}^2$ transverse sections, well inside the SF angular acceptance for PWO$^{\langle 100 \rangle}$. An external silicon mirror, mechanically referenced to the crystal matrix, is used as an alignment aid with respect to the incoming beam during beam test campaigns [8].

The mechanical structure for the first OREO prototype, shown in figure 2, was produced at the University of Ferrara using a 3D printer and Polylactic Acid (PLA) filament. Its primary goal is to fully enclose the OREO calorimeter, thereby mitigating light losses after the interaction of the particle beam with the crystals. Figure 2 left shows the OREO mechanical structure open during the assembly. The layer labelled `ORIENTED` $5X_0$ is placed upstream with respect to the beam, while the layer labelled `NOT ORIENTED` $11.2X_0$ is located downstream. The two layers are read out from opposite sides: the upstream oriented layer is read out from the front, whereas the downstream matrix is read out from the back. This arrangement was chosen to achieve a more uniform and efficient optical coupling between the two crystal matrices and to substantially reduce light losses, thereby improving the calorimeter energy resolution. In this way, it is possible to build a highly granular calorimeter with performances that approach those of a fully homogeneous detector. Figure 2 right shows the completed OREO mechanical structure before installing the photodetection system. Compared to the configuration shown in the left panel of figure 2, three additional PLA side panels have been added to completely enclose the calorimeter crystals. This feature further suppresses the entry of external light, which would otherwise increase the noise level and degrade the energy measurement. In addition to minimizing both stray light entering the system and scintillation light escaping it, the mechanical structure must be compatible with its installation on a high-precision goniometer. The support is therefore designed to be mounted on a system comprising two translational stages, with millimetre resolution, and two rotational stages, with microradian resolution, which together allow the precise alignment of OREO with respect to the beam.

An accurate alignment is essential to correctly locate the crystallographic axis and to enable a reliable comparison between the oriented and amorphous configurations of the calorimeter. The alignment of the calorimeter with respect to the particle beam is performed using a laser that is first aligned to the nominal beam position along the beamline. Using a pentaprism, the laser spot reflected by the silicon mirror mounted on the upstream $5X_0$ matrix, shown in figure 2 left, can be observed. Knowing the relative angle between the upstream matrix and the silicon mirror then allows to align the calorimeter with respect to the beam.

The OREO prototype with the first mechanical structure was tested in two beam test campaigns. At the CERN PS on the T9 beamline with electrons up to 6 GeV, the oriented configuration of the calorimeter was validated: all the crystals in the upstream $5X_0$ oriented layer exhibited the same increase in the deposited energy for the same relative incidence angle of the particle beam. The calorimeter was then tested at the CERN SPS on the H4 beamline with electrons in the 20–150 GeV range. This second campaign allowed us to operate the calorimeter in the strong-field regime and to study its performance in both the amorphous and oriented configurations. The full analysis of

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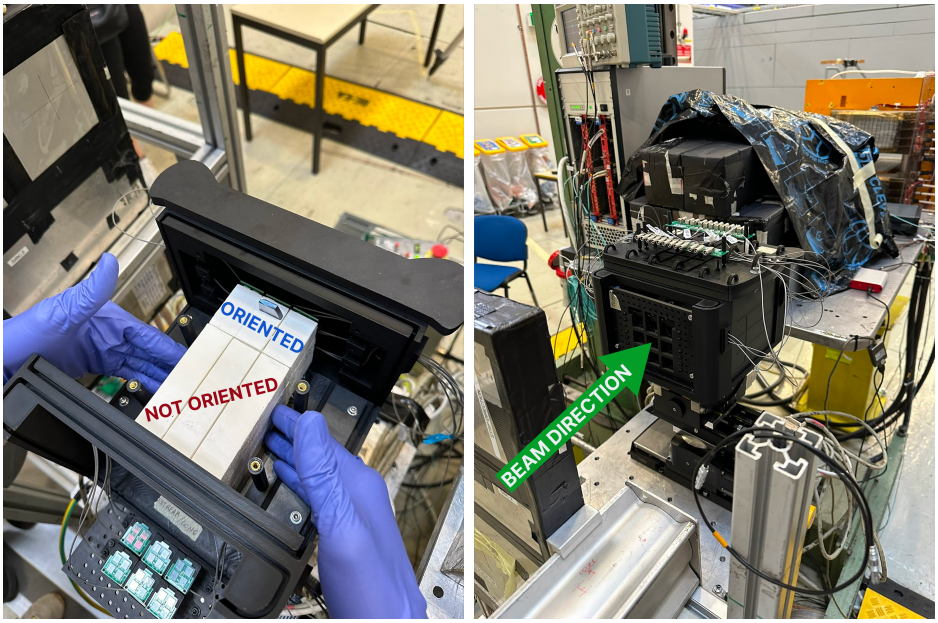

Figure 2. Pictures of the first OREO calorimeter prototype. Left: mechanical structure with the cover removed. The two calorimeter layers are visible and labeled `ORIENTED` (upstream $5X_0$ layer, in blue) and `NOT ORIENTED` (downstream $11.2X_0$ layer, in red). A silicon mirror mounted on top of the upstream layer is used as an external reference for the alignment with the particle beam. Behind the non-oriented layer, six of the nine photodetection modules are visible. Right: complete mechanical structure of the first OREO prototype before the installation of the photodetection system. The beam direction, which also defines the upstream side, is indicated by the green arrow.

beam test data, preliminarily presented at the conference, is still ongoing, and the corresponding results will be presented in a separate publication.

5 Design of the second, fully oriented and longitudinally segmented OREO prototype

To exploit this technology for high-efficiency γ-ray detection, as required for instance in high-intensity fixed-target experiments [32] and in beam-dump experiments for light dark matter searches [33], all calorimeter layers should be oriented so as to maximise the detector sensitivity by enhancing the photon-conversion probability over the full detector depth. We therefore developed a new prototype in which both the upstream and downstream crystal matrices operate in the oriented configuration. The original mechanical structure, optimised for a single oriented layer, could not be reused, and a dedicated mechanical design was thus implemented.

A new mechanical prototype for the second OREO prototype was therefore fabricated at the mechanical workshop of the INFN and the University of Ferrara and is shown in figure 3. The complete structure consists of two plastic cases, each housing the nine crystals of one calorimeter layer. Each case is individually closed by two external covers, one of which hosts the mechanical support for the photosensor modules (with the same positioning as in the first design). The two cases are mechanically independent, so that each layer can be aligned by its own rotational stages. The upstream layer has manual adjusters for fine-tuning the spacing, and its alignment is performed by the global goniometer described in section 4, which holds the whole mechanical structure. The downstream layer is mounted on Thorlabs motorized tip/tilt stages. By decoupling the mechanics of the two layers, each

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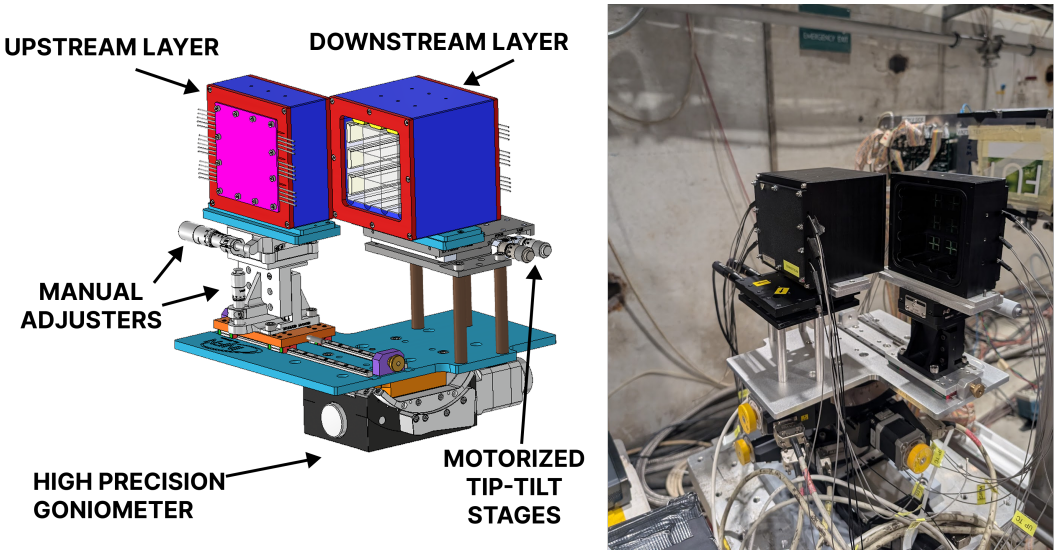

Figure 3. Left: CAD model of the second OREO prototype. The upstream and downstream layers, the manual adjusters, the motorized tip-tilt stages and the high-precision goniometer are labelled and indicated by arrows. Right: photograph of the mechanical structure of the second OREO prototype before installation of the calorimeter layers. The setup is shown with the upstream layer translated out of the beam, and the photodetection system of the upstream layer visible inside its case. The left and right panels are mirror views of the same configuration.

matrix can be oriented independently with respect to the beam direction and to the crystallographic axis. In this configuration, the cases are designed to be as hermetic as possible, which requires the removal of the silicon mirror previously used as an alignment reference. The front covers of the cases were therefore made easily removable to provide access for the alignment laser to the crystal faces of each layer. In the new structure, the upstream layer can also be translated laterally and moved completely out of the beam. The second prototype was tested in a dedicated beam test campaign at the CERN SPS on the H4 beamline. This configuration made it possible to study OREO in several settings: random-random, axis-random, and axis-axis, where the first term refers to the upstream layer. In addition, the downstream $11.2X_0$ layer was characterized independently. The preliminary results, presented at the conference, are promising and will be presented in a separate publication.

6 Photodetection system and performance characterization

The OREO calorimeter is read out by eighteen identical photosensor modules, one per crystal (nine for the upstream layer and nine for the downstream layer). In the first prototype, the SiPM modules were housed in custom plastic holders with a spring-loaded system that ensured stable and uniform contact between the sensors and the crystal end faces (see figure 4, left). In the second prototype, the modules are inserted into square apertures machined into one of the case covers; dedicated feed-through holes allow the cables to exit, and the covers are screwed to the cases with a thin rubber gasket in between to guarantee light-tight sealing. The photodetection modules are visible inside the case of the upstream layer in figure 3. Each module is based on four Hamamatsu Multi-Pixel Photon Counters (MPPCs), type S13360-6050VE [34], mounted in a 2×2 array. The MPPCs were specifically selected because their compact footprint and high active-area fraction allow the photodetector assembly to remain as

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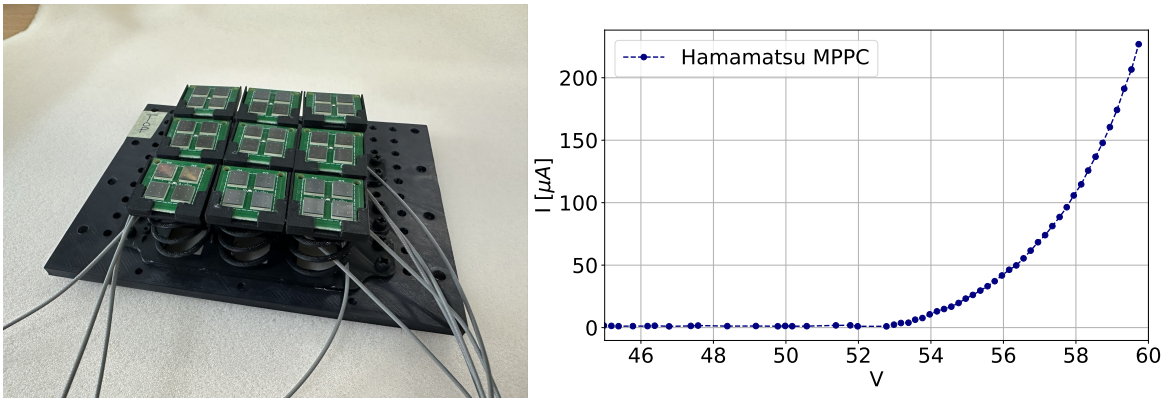

Figure 4. Left: picture of the nine photodetection modules of one calorimeter layer mounted in the mechanical structure of the first prototype. Springs ensure the proper optical coupling to the crystals and help to reduce the light leakage. Right: example of a I-V curve obtained in for the characterization of MPPC sensor, showing a breakdown voltage of about 53 V.

compact as possible, in line with the tight space constraints of the calorimeter design. Each device has an active area of $6 \times 6\,\mathrm{mm}^2$, segmented into 14 336 microcells with a pitch of 50 µm and an effective fill factor of about 74%. The four MPPCs are soldered on a dedicated PCB that uses a BGA package to route the signals. In this layout, the four cathodes are connected together and biased through a 1 kΩ resistor, while the anodes are kept at a ground potential. At the centre of the PCB, between the four SiPMs, a dedicated LED is integrated to provide controlled light pulses for in situ monitoring and calibration of the SiPM response during data taking. The front-end boards were designed and developed at the InsuLab laboratory, whereas sensor mounting and PCB assembly were performed by SCEN s.r.l. On the readout board, the nine cathode lines from a given layer are AC-coupled to the digitizer inputs through 100 nF capacitors; together with the 50 Ω input impedance of the digitizer, this results in a high-pass coupling stage. Figure 4 right displays a representative IV curve for one photosensor unit. During the beam test campaigns, the SiPMs were biased at 53 V on the T9 beamline, at 56 V during the H4 campaign with the first prototype, and at 55 V during the second H4 campaign with the second prototype. On T9, the devices were operated close to breakdown in order to minimise saturation effects at the relatively low beam energies. In contrast, on H4 the much higher electromagnetic shower required an additional attenuation: combination of two Kodak neutral optical density (O.D.) filters (O.D. 0.7 and O.D. 1 for the first prototype and O.D. 1 and O.D. 2 for the second prototype) were placed in front of each calorimeter layer to reduce the light reaching the SiPMs and thus extend the linear response range.

7 Conclusions

The main objective of the OREO project is the construction of a new type of ultra-compact electromagnetic calorimeter, consisting of an oriented array of scintillating PbWO4 crystals, in which the radiation length and, consequently, the electromagnetic shower are significantly reduced with respect to calorimeters currently employed in high-energy and astroparticle physics. When axially oriented, the enhanced probability of photon conversion into e^+e^- pairs increases the γ-detection efficiency and improves γ/hadron separation, thereby strengthening the overall particle-identification

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capabilities. This paper has presented the mechanical design and photodetection system of the first OREO calorimeter prototypes. The first OREO prototype consists of two modules, each implemented as a 3×3 matrix of ultra-fast $PbWO_4$ (PWO-UF) crystals. The upstream module is oriented and has a thickness of about 5 X_0, optimized to exploit SF effects and to initiate a compact electromagnetic shower, while the downstream, non-oriented module ($\sim 11.2\ X_0$) completes the shower development and provides a conventional measurement of the tail. Since the enhancement of the e.m. shower is maximal in the first few radiation lengths, where the particle energy is highest and axial alignment is fulfilled, it is sufficient to orient only the first $\sim$ 4–5 X_0. This depth is comparable to the front longitudinal segment foreseen in future high-energy experiments such as FCC-ee and the Muon Collider, so that the present layout emulates these designs and allows us to assess the impact of an oriented preshower on shower compactness and calorimeter sensitivity.

To exploit this technology for high-efficiency γ-ray detection in high-intensity fixed-target experiments and in beam-dump searches for light dark matter, all calorimeter layers should be oriented so as to maximize the photon-conversion probability over the full detector depth. We therefore developed a second prototype in which both the upstream and downstream crystal matrices operate in the oriented configuration. As the original mechanical structure, optimized for a single oriented layer, could not be reused, a dedicated mechanical design was implemented, providing motorized and independent motions of the crystal matrices.

We have also described the characterization of the OREO photodetection system, based on photosensor modules hosting arrays of four Hamamatsu MPPCs. The choice of S13360-6050VE devices, with their compact footprint and large active-area fraction, was driven by the stringent space constraints of the calorimeter and by the need to keep the photodetection modules highly compact. In combination with the oriented crystal sections, this readout scheme supports a fast development of the electromagnetic cascade and enables a reduction of the shower size at fixed material budget, while preserving calorimetric performance. An intensive experimental campaign is currently underway within the DRDCALO international collaboration [35] to develop innovative calorimeters and to demonstrate the feasibility of the OREO concept in realistic conditions. These studies aim to establish OREO as a competitive option for the forward regions of future colliders, for high-intensity beam-dump and fixed-target experiments, and for space-borne detectors with pointing capability aimed at the observation of gamma rays with energies above 1 GeV.

Acknowledgments

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