High-precision alignment techniques for realizing an ultracompact electromagnetic calorimeters using oriented high-Z scintillator crystals

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ABSTRACT

Electromagnetic calorimeters used in high-energy physics and astrophysics rely heavily on high-Z inorganic scintillators, such as lead tungstate ($PbWO_4$ or PWO). The crystalline structure and lattice orientation of inorganic scintillators are frequently underestimated in detector design, even though it is known that the crystalline lattice strongly modifies the features of the electromagnetic processes inside the crystal. A novel method has been developed for precisely bonding PWO crystals with aligned atomic planes within 100 μrad, exploiting X-ray diffraction (XRD) to accurately measure miscut angles. This method demonstrates the possibility to align a layer of crystals along the same crystallographic direction, opening a new technological path towards the development of next-generation electromagnetic calorimeters.

1. Introduction

High-Z inorganic scintillators like lead tungstate (PWO) are widely used in the design of homogeneous electromagnetic calorimeters for high-energy physics (HEP) and astrophysics [1]. Understanding the crystalline nature and lattice orientation is essential as they strongly modify the features of the electromagnetic processes inside the crystal [2,3]: when a particle moves close to one of the strings (axes) of atoms in the lattice, it experiences an intense electromagnetic field [4], that induces an enhancement of the radiation emission [5–9] and pair production probability [10,11] with respect to the Bethe–Heitler description typical of amorphous media [12]. The enhancement of radiation and pair production caused by the strong crystalline field results in the acceleration of the electromagnetic shower development [13], leading to potential advancements in calorimeter resolution, photon detection efficiency, and particle identification capabilities [14]. This enhancement extends over an angular range of more than 1 mrad

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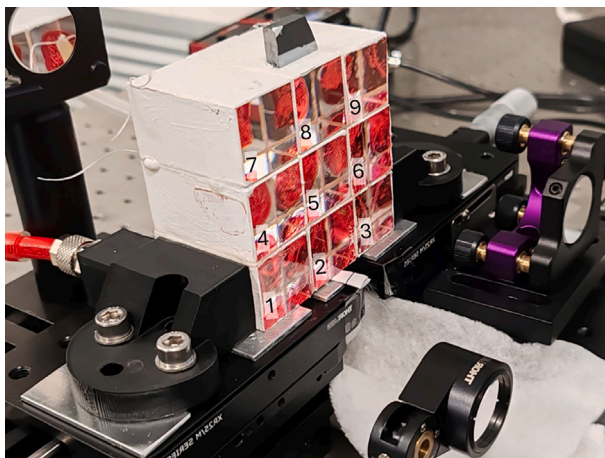
Fig. 1. 3 × 3 matrix formed by oriented crystals with each crystal numbered.

Fig. 2. Variation of the horizontal and vertical angle relative to the ideal bonding angle for each crystal.

(within which it is maximal), with a detectable effect up to 1° [5]. The development of oriented detectors are promising for applications in forward geometry in accelerator based experiments and space-borne gamma-ray telescopes [6]. For instance, in case of fixed-target experiments, these effects lead to an improvement of the shower containment in the active volume of the detector, which will result in a major improvement of its energy resolution and a better discrimination of hadronic and electromagnetic signals. In this work, the feasibility of bonding a 3 × 3 matrix of PWO crystals (Fig. 1) with the same atomic plane alignment within 100 μrad has been demonstrated.

2. Material and methods

Nine samples of PWO Ultra-Fast [15] were purchased from Crytur. A thorough characterization was carried out using a Panalytical High Resolution X-ray Diffractometer (HR XRD) [16] especially equipped with a laser autocollimator [17]. The miscut angle, i.e. the angle between the lattice planes and the sample surface, was measured at the center of each of the crystals with microradian precision and accuracy using the procedure described in [17,18] and previously employed in [19]. A second crucial characterization was the variation of the crystallographic axis orientation at different positions on the sample, that was measured along the two 25 mm directions to estimate the mosaicity of the crystal. Such characterizations were performed on both 25 × 25 mm^2 faces to identify the upstream surface for each sample in order to minimize the contribution coming from mosaicity and the miscut difference between samples. Indeed, large mosaicity would hinder optimal alignment between samples, while misalignment due to miscut angles may result in gaps in the millimeter range between the faces of adjacent crystals, so it is essential to rotate and adjust these faces to reduce gaps. Before bonding, all lateral surfaces have been coated with a white, radiation-resistant reflective paint (Eljen EJ-510). This ensures optimal light collection and cancels light loss through the other surfaces, enhancing the overall efficiency of the scintillator. During the alignment and bonding procedure, samples were mounted on two separate systems of rotation and linear optomechanic stages via a finely engineered vacuum fixture.

A wide-field-of-view laser interferometer (Zygo Verifire HDX [20]) was employed to measure simultaneously the profile of the samples' 25 × 25 × 45 mm^3 surfaces with nanometric precision and accuracy, hence allowing estimation of their reciprocal inclination with few micro-radian uncertainty. Thanks to the previously measured miscut angles, the angle between atomic planes of any pair of crystals can be estimated. Once axes alignment was achieved, an epoxy resin was applied on lateral surfaces and the samples were put in contact. To
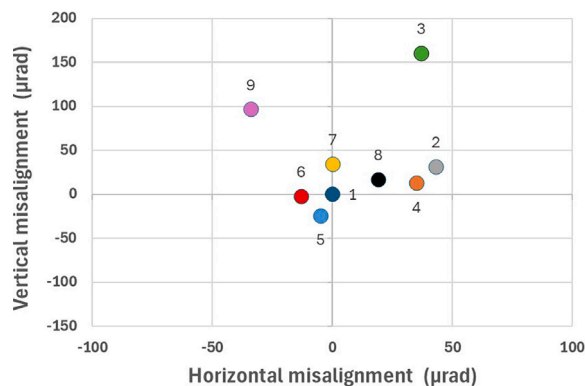
minimize displacement during curing, resin was applied at the gel point and active adjustment was carried out during initial solidification. Assembly of the nine crystals, with each crystal numbered accordingly, to a 3 × 3 matrix resulted in the prototype compact calorimeter of Fig. 1.

3. Results

All PWO crystals for both the 25 × 25 mm^2 faces present miscut angles within a range of 5000 μrad, and a crystal mosaicity up to 300 μrad. Based on these two quantities, the best surface of each crystal has been selected to be used as a reference during the bonding phase. The alignment achieved between crystals in the final 3 × 3 matrix, taking crystal 1 as reference, is shown in Fig. 2. It is clearly visible that almost all crystals have misalignment lower than 50 μrad, well below the approximately 1 mrad range of the maximum electromagnetic shower acceleration effect observed in PWO. The measurements have been repeated after several months and after handling and transportation, highlighting the robustness of the assembly and absence of any measurable variation in the alignment of the crystals. These results demonstrate that our bonding process has achieved a high level of precision and stability over time.

4. Conclusions

In this study, we have developed and tested a novel bonding method for crystals, aimed at obtaining an oriented matrix of PWO. Our method has demonstrated the capability to align a set of crystals with a typical precision and accuracy within a few tens of microradians. Considering that the enhancement of phenomena of interest, such as radiation and pair production, has an angular acceptance on the order of several milliradians, our achieved alignment falls well within the desired region of interest. These results pave the way for the realization of ultra-compact electromagnetic calorimeters based on oriented crystals, which may have significant applications in fixed target experiments and space-borne telescopes [6].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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