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Crystal conditioning for high-energy physics detectors

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Abstract

In homogeneous high-resolution calorimetry for particle physics, scintillating crystals can now be considered as a mature technique. In the past decades, several large high-energy experiments have included crystal calorimeters from which a considerable harvest of physics results could be made. To extract the ultimate precision from such calorimeters, great care must be taken in the crystal conditioning, i.e. machining and wrapping or coating. These operations have a strong influence on some key crystal properties for the calorimeter energy resolution, such as light yield and light collection uniformity. In this note, some aspects of machining and of the techniques for uniformizing light collection will be discussed in the light of a recent experiment: L3 at LEP collider, using bismuth germanate crystals and an experiment in construction: CMS for LHC collider, using lead tungstate. To illustrate these techniques, results obtained on medium-scale crystal productions will be shown.

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1. Introduction

Crystals can now be considered as a mature technique in homogeneous high-resolution electromagnetic calorimetry. In the two last decades, several HEP experiments have used crystal calorimeters and made a fruitful harvest of physics results, such as: Crystal Ball (NaI), Babar (CsI) and L3 (BGO). Moreover, a new calorimeter for LHC with unprecedented dimensions and performance challenge, the CMS calorimeter with $\sim$80,000 $PbWO_4$ crystals, is now in construction.

To extract the ultimate precision from such calorimeters, particular care must be taken of crystal conditioning, i.e. machining and wrapping or coating. These operations have a strong influence on crystal properties such as light yield and light collection uniformity, which are crucial parameters for the calorimeter performance. In this note, several aspects of crystal machining and of the techniques for uniformizing light collection along the crystals will be discussed in the light of a recent experiment, L3 at LEP using bismuth germanate (BGO) and an experiment in construction, CMS at LHC using lead tungstate (PWO)

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crystals. To illustrate these techniques, results obtained on medium-scale crystal productions will be shown. This note being based on an oral presentation to the Scint 2001 conference, for which the audience was pluridisciplinary, some well-known aspects of physics and crystal preparation will be explained in some detail.

2. Physics considerations

For the BGO calorimeter of the L3 experiment [1] at LEP, the physics goal was to have near 1% energy resolution for e/γ between 1 and 50 GeV. The PWO electromagnetic calorimeter of the CMS experiment [2,3] for LHC aims at an energy resolution for e/γ of $\leqslant 0.6\%$, down to energies of ~ 50 GeV for Higgs search in the intermediate mass region.

Let us parameterize the energy resolution of an electromagnetic calorimeter as

$$\sigma/E \approx a/\sqrt{E} \oplus b/E \oplus c. \quad (1)$$

The stochastic term a, is usually small for crystals when enough light is collected. For BGO, it is effectively small ($a \approx 2\%$) due to its relatively large light yield (see Table 1). But, the amount of light collected in PWO is marginal, even when read out by two $5 \times 5\,\mathrm{mm}^2$ Avalanche photodiodes (APD) per crystal ($a \approx 3-4\%$).

The noise term b is small only if the light yield is large enough: for BGO, read out by one $1\,\mathrm{cm}^2$ pin photodiode (no gain), the signal/electronic noise ratio is a critical contribution. For PWO, the term b should be acceptable with APDs, but again the light yield (LY) is critical.

The constant term c is small only in a "dedicated" detector, i.e. a calorimeter for which all critical contributions, such as shower leakage and intercalibration errors, have been carefully minimized without compromises in quality. For BGO (goal: $c \leqslant 0.8\%$) and PWO (goal: $c \leqslant 0.5\%$) crystals, due to their high refractive index and tapered shapes, the longitudinal light non-uniformity (NU) is one of the critical contributions to the c-term, as is shown by simulations in Section 4.

We can conclude that crystal LY and NU are critical parameters both in L3 and CMS calorimeters.

3. Crystal machining

The crystal cutting and polishing methods have strong influence, not only on the precision of the dimensions, thus on the calorimeter hermiticity, but also on the surface state of all six faces and on the residual stresses under their surface [4], i.e. finally on LY and NU of the crystals. Moreover, polishing one or several faces to a certain degree can be a method for adjusting NU profiles, as we will see later. Let us summarize the main features of the techniques developed at LAPP and CERN in the past 20 years.

The original machining method was developed for the processing of BGO for L3 experiment in 1984 at LAPP, Annecy [5] and transferred to the Shanghai Institute of Ceramics, where 11 000 BGO crystals were produced and machined from 1985 to 1989. The construction of CMS–ECAL brings a new challenge of a total of 80 000 crystals to be produced and machined in ~ 5 years. Also, the high anisotropy and fragility of PWO have to be faced. Since 1996, a close collaboration on full size crystals machining is established with the Bogoroditsk TechnoChemical Plant (BTCP) Russia, where most of the 80 000 PWO crystals will be produced and machined [6].

Table 1

Crystal	Density ($\mathrm{g/cm}^3$)	X_0 (cm)	Length of 25 X_0 (cm)	Molière radius (cm)	λ_{max} (nm)	Refractive index at λ_{max}	Light yield (photons/MeV)	Decay time (ns)
$Bi_4Ge_3O_{12}$	7.1	1.11	27.7	2.4	480	2.15	~ 4000	300
$PbWO_4$	8.3	0.90	22.5	2.2	420	2.25	~ 80	5/15/100

The main characteristics of the cutting method (see Fig. 1) are:

- The effort is put on quality and accuracy of the cutting operations, so that no shape correction is required after cutting.
- Starting from a raw "boule", cutting provides the crystal's shape to design accuracy (0–100 μm) in all dimensions. In fact, a cutting precision of $\sigma \approx 20\,\mu m$ (distribution in each dimension) is obtained for a batch of several hundred crystals.
- The cutting parameters produce regular, isotropic surface finish of roughness [7] $R_a \approx 2\,\mu m$, ready for the first stage of polishing, the lapping. This results in considerable savings in processing time, manpower and equipment investment.
- A crystal is attached to the same reference base for the six cutting operations. For each cutting operation, disk, table and position tooling are calibrated with the same setting tool, made of precision sphere and reference base. This provides machining accuracy to minimal investment cost.
- The fixation with special high-precision transfer adhesive film gives cheap and stable fixation with minimum handling and adjustments. It does not hamper crystal cutting and lubrication and a fool-proof tooling can be designed to save qualified manpower.

The polishing process is performed in two steps:

- The lapping which brings "rough from cut" ($R_a \approx 2\,\mu m$) to lapped surfaces ($R_a \approx 0.5\,\mu m$). It is executed on a large resin wheel, with a 30 kg weight and 15 μm diamond grain, in ~ 5 min (Fig. 1).
- The polishing, which brings lapped surfaces to optical polish state, is executed on a wheel covered with a hard fabric, with 30 kg weight, 4 μm diamond grain, for ~ 10 min.

This method results in excellent precision in dimensions and face planarity and gives good surface finish with acceptable stresses. It also allows good control over intermediate values of surface roughness for NU adjustment (see Section 6 for PWO).

4. Light yield and light collection non-uniformity

Table 1 gives the main properties of BGO and PWO crystals. Extensive R&D performed on BGO and later on PWO allows to make some general observations. For instance, measurements with a photodetector on one end face and five-face-polished crystals wrapped in various materials show that:

- Diffusing wrappings give highest LY. This can be explained by the long attenuation length obtained in good crystals, from which light rays have several chances to escape by the rear face, with enhanced probability for randomized reflection angles. In fact, Millipore [8] and Tyvek [9] give highest LY for BGO and PWO, respectively.
- There is no significant change in NU profile of a crystal using different wrapping material. In fact, profiles are nearly parallel curves for Tyvek, Teflon, aluminized Mylar, white paper, as will be shown on PWO in Section 6. This means that the optimization of LY and NU can be studied independently.

On the contrary, deposits or paint applied directly on one or several polished crystal faces have strong effects on NU profiles. So, one has to optimize first NU profiles studying various methods and then to compare the measured LY obtained.

As is well known, when an electromagnetic shower develops in a long scintillating crystal, the main energy deposit occurs at a depth, which fluctuates with shower shape and with energy of the incoming particle. Any dependence of the amount of light collected at a crystal's extremity on the position of the emission along the crystal may induce an additional contribution to the energy resolution and a non-linearity of the response as a function of energy. The non-linearity can be corrected for by adequate calibrations, but the only way to reduce the effect of the shower to shower fluctuations in depth is to have the light collection as uniform as possible along the crystal, particularly in the region around the shower maximum: $4-12\ X_0$.

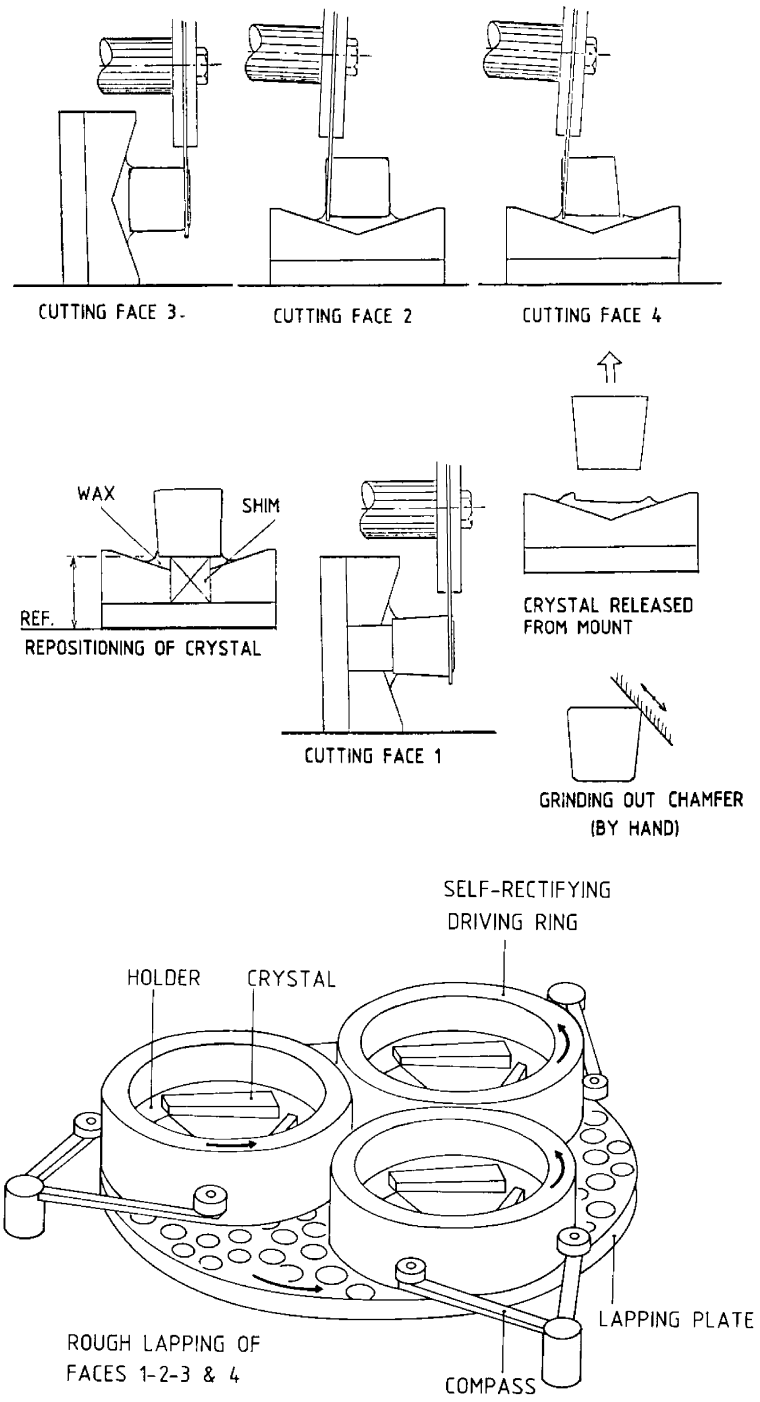


Fig. 1. Cutting and polishing BGO as developed at LAPP and transferred in 1985 to SIC China for L3 experiment.

A non-uniform light response along the crystal length, called longitudinal NU of light collection, can occur due essentially to two competing effects:

- The light attenuation along crystals, due to intrinsic absorption inside the material but also to diffusion on scatter centers such as bubbles or impurities in the bulk of the crystals and to losses by multiple reflections on faces. This effect tends to decrease the light collected when produced far from the photodetector.
- A "focusing effect" due to the crystal's tapered shape and high index. In a barrel + end-cap geometry, all crystals point to the collider interaction region and thus are truncated pyramids with θ and ϕ taper angles decreasing with θ along the barrel. Such tapered crystals give maximum light collected on a photodetector viewing their large end face when all six faces are optically polished. But, the light collection then favours light produced near to their small end, since more reflections of the light rays on the polished sides yield angles more favourable for escaping through the crystal's large end, as illustrated in Fig. 2.

The second factor depends only on crystal geometry, but the crystal light attenuation length (Λ) usually increases along R&D periods, due to progress in optical quality. Thus the behaviour of light collection evolves with time as illustrated in Fig. 3. In fact, "early" crystals with $\Lambda \approx 20-50$ cm are often spontaneously uniform with all faces optically polished, due to compensation, at least in their front half, of the focusing effect by the strong light attenuation. Later, with typical $\Lambda \approx 50-100$ cm, U-shaped profiles are observed, requiring small correction in the front half of the crystals. In the beginning of mass production, crystals of high optical quality ($\Lambda \approx 1-5$ m) are usually obtained, thus dominated by the focusing effect. They yield typical front NU factors: $F_{\mathrm{NUF}} \approx 1.5\%/X_0$ (slope of relative LY variation per X_0 for front half of the crystal) and need strong correction.

Monte-Carlo simulations [10] indicate how uniform the crystal response must be to obtain an acceptable contribution to the constant term of the energy resolution. Simulations of the effect on this contribution when the NU slopes vary independently in three regions along a crystal show that:

- Varying the slope in the region: $4-12\ X_0$, where the electromagnetic shower is well developed, has a quite critical effect, as is shown in Fig. 4 for PWO. In fact, to keep the contribution to the c-term below 0.25%, F_{NUF} has to be in the range:

$$-0.35\%/X_0 < F_{\mathrm{NUF}} < +0.35\%/X_0.$$

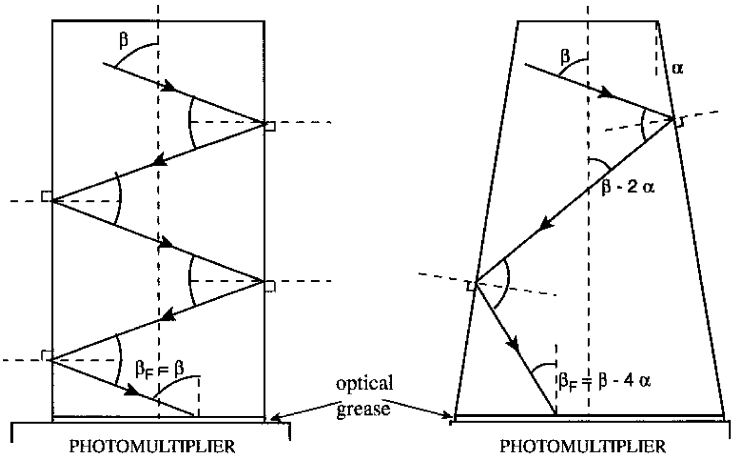


Fig. 2. Focusing effect in a tapered crystal.

Fig. 3. Typical NU profile for "old" (1), "middle-age" (2) and final quality (3) crystals.

For BGO, similar curves showed that to keep this contribution below 0.5%, F_{NUF} had to be in the range:

$$-0.5\%/X_0 < F_{\mathrm{NUF}} < +0.5\%/X_0.$$

- Varying the slope in the crystal rear half: 12–25 X_0, makes an effect only on late developing showers. In fact, a rise of $\sim 10\%$ to the rear end of the crystal is desirable since it provides some compensation for the late showers rear leakage, thus reducing the low energy tail in the energy spectrum.
- Varying the slope in the region: 0–4 X_0, where the shower has hardly started its development, is rather uncritical.

These simulation results were confirmed in several test beam campaigns [11].

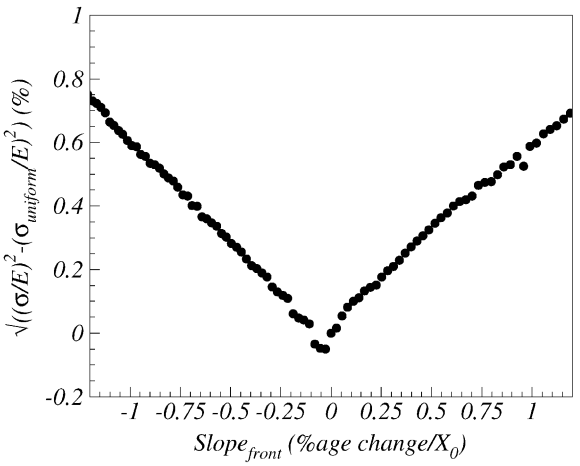


Fig. 4. Contribution of F_{NUF} to the energy resolution versus F_{NUF}.

5. Crystal uniformization methods

Different methods were studied during the R&D performed for BGO and for PWO:

5.1. Inhomogeneous wrapping

Different materials can be used along the crystal length or applied in well-defined places. Such a method was studied and used on "middle-age" PWO crystals, presenting U-shaped NU profiles for which a local correction was needed on their front end only.

Several alternatives were tried: black tape glued inside Tyvek (or directly on crystal) or optimized black ink stripes on Tyvek in the relevant region. The last method was used in early PWO beam tests (1996) and gave adequate physics results apart from significant light losses ($\sim 30\%$). Moreover, nearly each crystal required tuning of the method, which makes difficult to envisage such a method for a large calorimeter. It can nevertheless be very useful for small NU corrections on a homogeneous crystal batch.

5.2. Deposits on crystals

Direct deposits on crystals without air gap reduce drastically the total reflection and thus cause a strong reduction of the focusing effect and a large change in NU profiles.

- Very thin deposits of silver [12] were applied under vacuum on five faces of PWO crystals, directly or on some intermediate layer. Interesting results in LY were obtained, but severe technical difficulties were experienced. Large effects on NU slopes were observed, but found

to be not reproducible and fine tuning was difficult.

- Also, thin deposits of reflective sol–gel [13], aiming at a resistant coating with good LY, gave encouraging results on PWO crystals, but nothing conclusive could be obtained due to technical complexity and again poor reproducibility of the results.
- Reflective mineral white paint NE560 [14] was studied extensively on BGO. It gave adequate NU with high LY and was chosen as the final method for the L3 calorimeter (see Fig. 5b). With this method, the LY could be improved if necessary by increasing the thickness of paint (from 40 up to 70 μm). Also, the NU could be

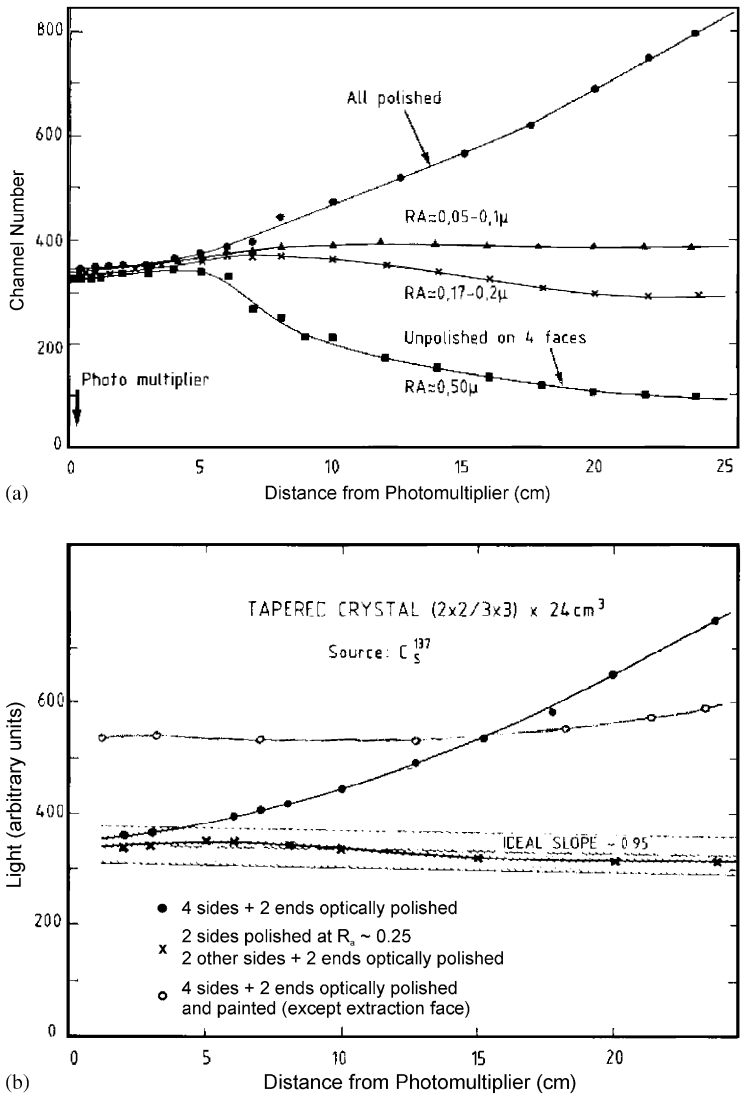


Fig. 5. (a) Studies of the NU profiles versus crystal surface state; (b) optimal conditions for uniformizing BGO crystals by depolishing and superposed curve for painted (NE560) crystal.

corrected by varying the relative paint thickness along the crystals.

- Paint NE560 was also studied on PWO and gave acceptable LY values with five faces painted. But then, the NU profiles obtained were not in the correct range and moreover not reproducible. A possible explanation could be that the existence of stressed PWO layers below the polished faces prevents full reflection on the paint layer.

5.3. Depolishing crystal faces

The method was first studied and optimized for BGO in 1984 (before paint): many tests of depolishing one or two faces "by hand" to different roughness values (see Fig. 5a) showed good control and reproducibility of the results. The best conditions (Fig. 5b) were obtained with two faces depolished to $R_a \approx 0.25\,\mu m$. The LY profile obtained on the same crystal with five faces painted with NE560 is superposed and shows clearly a higher LY, thus justifying L3's final choice of the paint method.

Since paint did not give good results for PWO, extensive studies to uniformize PWO crystals by modifying the surface state of one or two faces were performed [15] and led to the procedure explained in Section 6.

6. Procedure for PWO/ECAL uniformization

Fig. 6a illustrates that focusing largely dominates in a fully polished PWO crystal of "final" quality. Such a crystal would give a contribution to the c-term of at least 0.7% [10]. But, when one face is lapped ($R_a \approx 0.5\,\mu m$), absorption usually dominates (Fig. 6b). Note that, in both cases, curves for three different wrappings are well parallel, thus confirming our earlier statement that wrappings did not affect NU significantly. The gaps between curves are wider for one face lapped, since much more light escapes from a lapped face, making the wrapping material more critical.

To obtain uniform crystal profiles, i.e. F_{NUF} values within limits of $\pm 0.35\%/X_0$, it was necessary to find an intermediate state of roughness: $R_a \approx 0.3\,\mu m$, as shown in Fig. 6c. The procedure and optimum R_a value were defined on first pre-preproduction crystals 2 years ago. The mechanized treatment is applied to three crystals simultaneously in two steps: lapping on resin wheel, with 30 kg, 15 μm diamond grain for 5 min, followed by polishing on hard fabric wheel, with 15 kg, 15 μm diamond grain, for 10–20 min.

The dependence of F_{NUF} on R_a of one face is shown in Fig. 7a, on which a best value of $R_a \approx 0.25 \pm 0.05\,\mu m$ can be read. A few crystals (in circle) reacted in a different way, due to an additional parameter mentioned in Section 8. The evolution of R_a with polishing time is shown in Fig. 7b.

LY, front and rear NU together with dimensions and transmissions are measured at CERN for all delivered crystals on Automatic Crystal COntrol Systems (ACCOS) [16]. LY relative values are deduced from the decay time spectra recorded in 21 positions along crystals. Samples are also measured on "classical benches" (PMT and ^{60}Co source) in order to derive a set of coefficients allowing to obtain absolute values of LY in number of photons/MeV for all crystals. These values were compared to measurements at PSI proton test beam [17] in quasi-final conditions of wrapping and readout: aluminium-coated glass fibre alveoles and two APDs glued on each crystal. A very good correlation is observed between measurements as can be seen in Fig. 8.

7. Results on uniformization of PWO for ECAL

Since the end of 1998, 6000 pre-production PWO crystals [18] were received in 12 batches and measured at CERN. The data are compared to the contractual specifications [19]. We can classify the batches according to their measured F_{NUF} distribution:

- Batches 1–4: The treatment defined at CERN and transferred to producers worked well. The F_{NUF} distribution is well centered as Fig. 9a shows for batch 3.
- Batches 5–7: The producer tuned slightly the growing method to further improve crystal

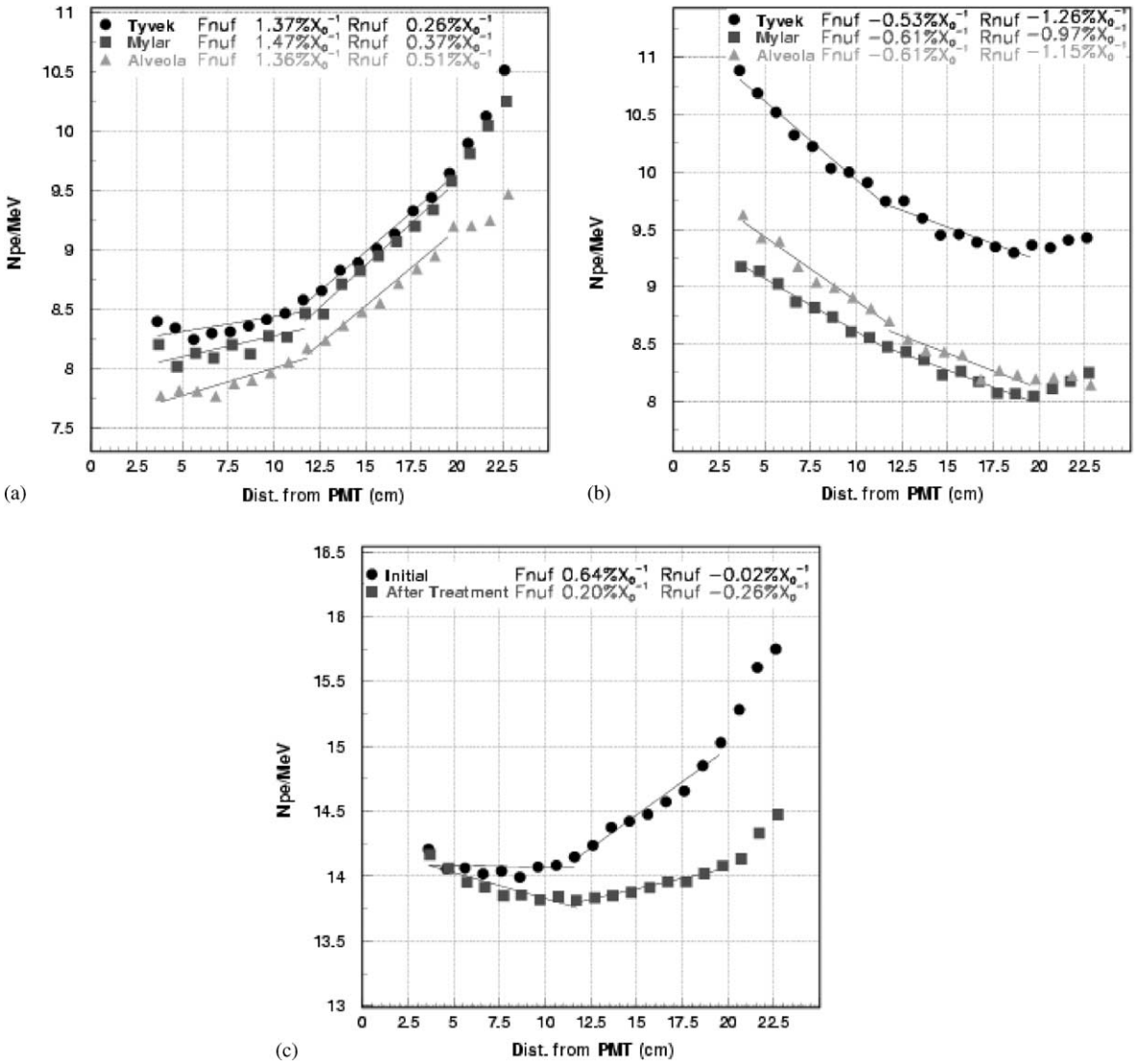


Fig. 6. NU profiles for an all-polished crystal in three different wrappings (a); NU profiles for a lapped crystal in three different wrappings (b); NU profiles before and after uniformization (c).

quality. The consequent decrease of light absorption shifted the F_{NUF} distribution, as Fig. 9b shows for batch 6.

- Batches 8–12: After some studies, a higher R_a value $\sim 0.35\,\mu m$ was given to the producer resulting in a well-centered F_{NUF} distribution (Fig. 9c for batch 9).

Non-uniformity corrections for batches 1–4 and 8–12, with F_{NUF} distributions well centered, concern typically $<10\%$ of the crystals to be retreated. For batches 5–7, with F_{NUF} distribution shifted, more than half of the crystals had to be corrected. For all these crystals, the treatment applied to one face by the producer was corrected

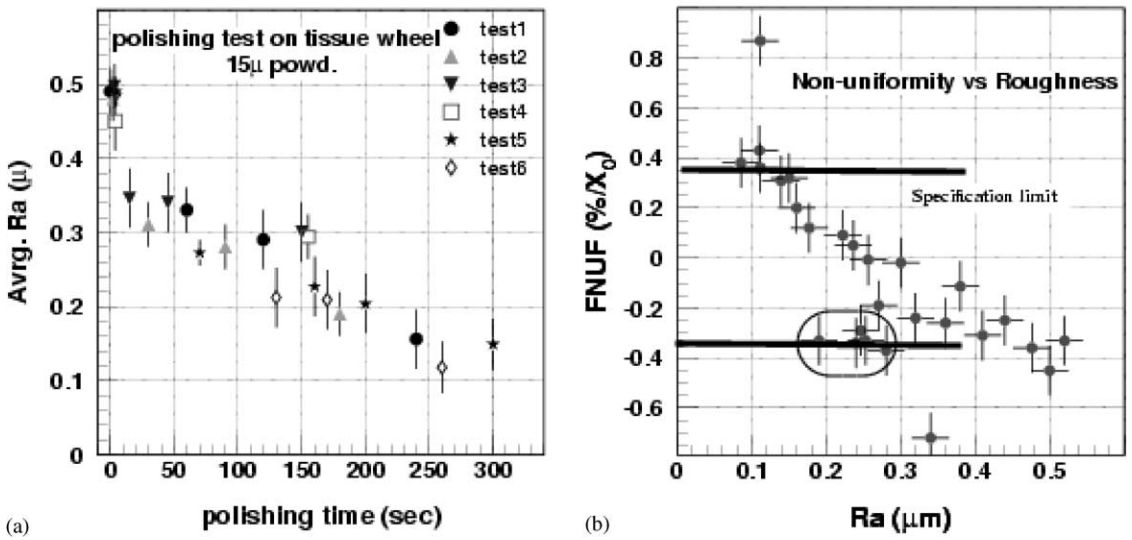


Fig. 7. Average roughness versus polishing time (a); variation of front NU with roughness R_a (b).

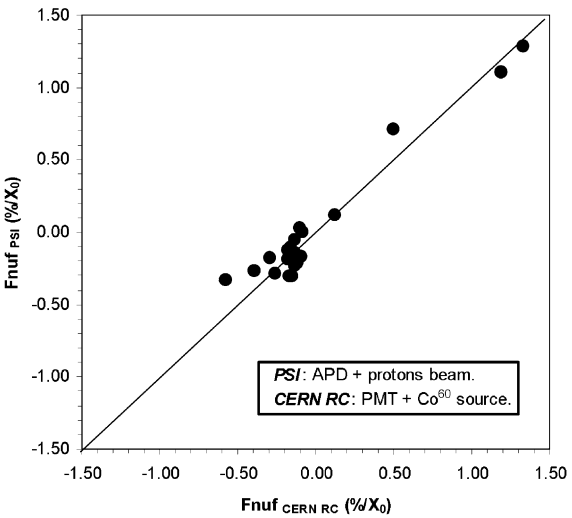


Fig. 8. Correlation between front NU measured in PSI proton beam and CERN source set-up.

at CERN, with a technique depending on the sign of the slope:

- If $F_{NUF} > 0.35\%/X_0$, R_a has to be increased. Standard lapping is usually adequate, followed in some cases by a short repolishing if the effect is too severe.
- If $F_{NUF} < -0.35\%/X_0$, R_a had to be decreased by a short polishing.

8. Other parameters affecting PWO uniformity

ECAL endcap crystals should be naturally quasi-uniform due to their small tapering angle. Studying a sample of 10 end-cap crystals, 4 were found nearly uniform but 6 behaved differently (Fig. 10). This is attributed to strong gradients in longitudinal transmission with opposite signs depending on the orientation of the ingot during the cutting operations. To get rid of this effect, specifications had to be put on the maximum value of the transmission gradient and the cutting orientation is now strictly controlled.

9. Conclusions

To summarize this review on crystal conditioning for HEP detectors, we can make a few comments:

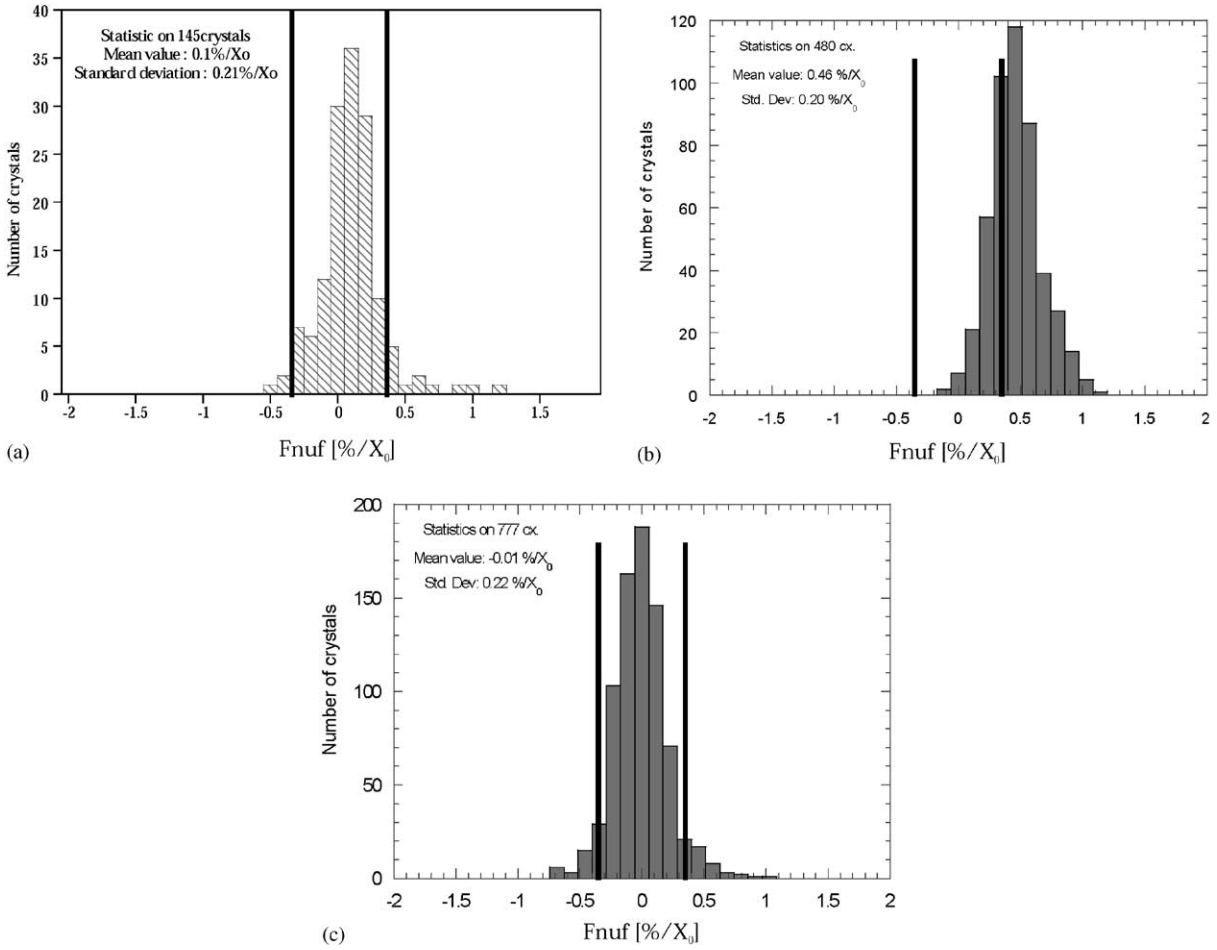
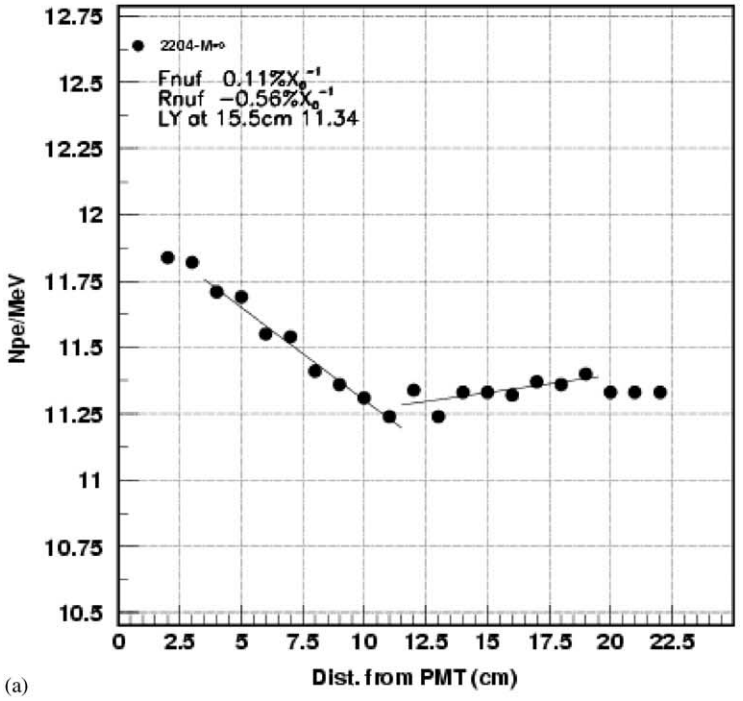
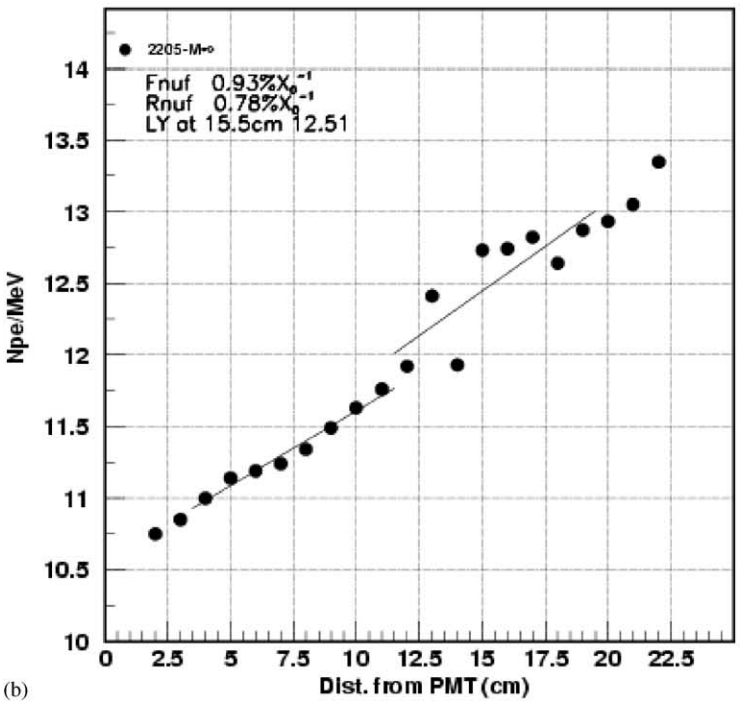


Fig. 9. Front NU distribution for batches 3 (a), 6 (b), and 9 (c).

- For present and future crystal calorimeters, as the detected e, γ energies increase, the c-term of the energy resolution and in particular the non-uniformity of light collection become more and more critical. The producers can no more be responsible for the crystal uniformization as was sometimes the case in the past.
- Due to their effect on light yield and light collection non-uniformity, machining procedures as well as wrapping/coating methods have strong impact on crystal performance for physics.
- Methods for obtaining optimum light yield and uniformity in crystals may be quite different for each type of crystal, even with similar optical properties. Specific R&D for each type of crystal is required.
- Nevertheless, depolishing with controlled roughness of one or several faces of a crystal is a rather general method usually yielding adequate uniformity.
- For wrappings, LY and NU parameters can be studied and optimized independently.
- For high-index polished crystals, LY is highest for white diffusive wrappings: Millipore, Tyvek, Teflon.
- For coatings (deposits or paint), NU must be first adjusted and then LY levels measured and compared.



(a)



(b)

Fig. 10. NU profiles for two samples of end-cap PWO crystals.

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