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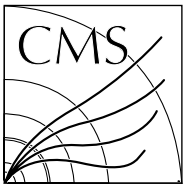

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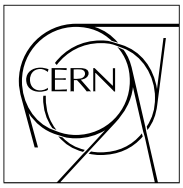

January 26, 2001

Development of a Uniformisation Procedure for the $PbW0_4$ Crystals of the CMS Electromagnetic Calorimeter

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ECAL

Abstract

The CMS electromagnetic calorimeter will consist of nearly 80,000 lead tungstate crystals, with 18 different geometries. The contribution of any non-uniformity in the light collection to the constant term in the energy resolution must be limited to 0.3%. A procedure capable of achieving this for the full calorimeter has been developed in the CERN EP-CMA group. A description of this method and the results obtained with the first few hundred pre-production crystals from Bogoroditsk, Russia are given in this note.

1 Introduction

The energy resolution, σ/E, of the CMS electromagnetic calorimeter (ECAL) can be parametrized by:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

where E is in GeV, a is the stochastic term, b is the noise term and c is the constant term.

To allow us to take advantage of the excellent stochastic term in a crystal calorimeter, the added constant term must be limited to 0.5% - this represents one of the major challenges for the ECAL. A major contribution to the constant term is the non-uniformity of the light collection along the length of the crystal. The effects of the longitudinal light collection curve have been studied in detail in ref [1]. As a result of this work we have to place stringent requirements on the crystal longitudinal non-uniformity (NUF). In particular, if we approximate the variation in light collection in the shower maximum region (5-10X_0) by a linear fit then we must require that this slope is less than 0.35%/X_0 to limit the contribution of the NUF to the constant term to less than 0.3% .We shall refer to the slope (non-uniformity) in this region as the front non-uniformity or FNUF (%/X_0). A slight increase (~10%) towards the rear of the crystal helps to compensate for rear leakage from late developing showers. We shall refer to this slope as the rear uniformity or RNUF (%/X_0). The longitudinal uniformity can either be measured in the lab or in a testbeam. In the former, a radio-active source is scanned along the crystal and the light produced detected with a photomultiplier (or similar device). In the latter the higher energy deposited allows one to use the final photodetector i.e. a twin Avalanche PhotoDiode for the barrel and a Vacuum PhotoTriode for the endcaps. For further details of testbeam studies see ref [2].

The arrangement of the crystals within ECAL is governed by the desire to contain a large fraction of the energy of an incident photon or electron in a single crystal (or small group of crystals). The transverse granularity is chosen to match the Moliere radius, ~22mm, of lead tungstate. This compact value reduces the effect of pileup and gives rejection of Π^0 photons in the barrel. Such a choice of crystal size optimizes the energy and angular resolution as well as the power of any isolation cuts placed on an energy deposit. The crystals are arranged so as to point approximately to the interaction point (IP) - they are in fact offset from the IP itself by 3^o to reduce the effect of energy loss between the crystals. A total thickness of about 26X_0 (at η=0) is required to limit the longitudinal shower leakage to an acceptable level, corresponding to 23cm of lead tungstate.

As a consequence of these constraints, the crystals have a pyramidal shape and taper of up to 4mm from the small ‘front’ end to the larger, rear photodetector end. This tapering produces a natural non-uniformity in the longitudinal light collection. This is accentuated by the high refractive index of lead tungstate, 2.2, and so the light is ‘focused’ towards the photodetector. The focusing is compensated for by the light absorption within the crystal as illustrated schematically in Fig.1.

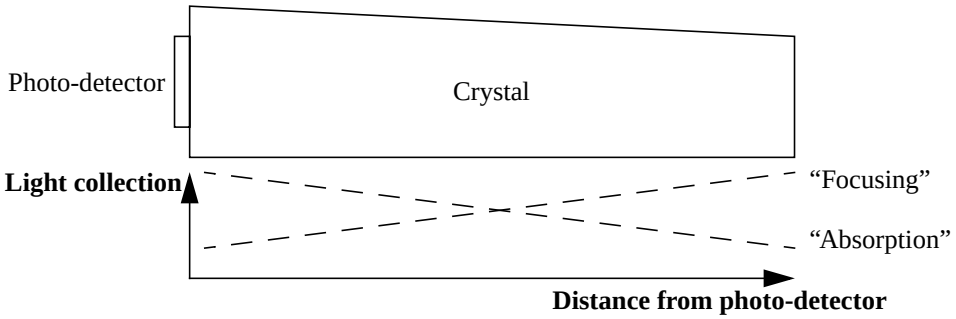

Figure 1 Illustration of competing effects of crystal absorption and focusing.

The attenuation length has evolved from 30-50cm in 1995 to several metres in recent Russian[a)] crystals, thus modifying the behaviour of the light collection. Earlier crystals were often spontaneously uniform with all their faces optically polished, due to the compensation in the front half of the crystals of the focusing effect by the strong light attenuation. Later, with typical attenuation lengths of 50-80cm, a U-shaped NUF profile was observed, requiring some correction. Recent crystals, exhibiting attenuation lengths of 1- 5m, are dominated by the focusing effect, yielding typically a slope of ~1.5%/X_0, with most light being collected from the small end of the crystal, as illustrated in Fig. 1.

a. Bogoroditsk Techno-Chemical Plant, Bogoroditsk, Russia.

Various methods, tuned according to the initial “all-polished” NUF were developed at CERN in the EP-CMA group to uniformise the crystals.

Now that a suitable technique has been identified, this technology has been transferred to the producer who is then responsible for its application. In the barrel, there are 17 different geometries, with the effective taper changing from ~ 2-4 mm; the aim is to have a single technique which requires minimum changing for the different geometries.

The layout of this note is as follows. The method is described in Section 2, results are given in Section 3 and we conclude in Section 4.

2 Uniformisation Procedure

Initially various methods were tried to uniformise the crystals, these are discussed in Section 2.1. Any potential method must not only ‘uniformise’ the crystal but satisfy the secondary requirements of not reducing the light yield significantly and being suitable for mass application to 80,000 crystals. Only one of the initial techniques, the roughening/depolishing of one lateral face, effectively satisfied these secondary criteria. It is this procedure that we have optimized, mechanized and transferred to the producer with extremely encouraging results. This procedure is discussed in further detail in Section 2.2 and subsequently.

2.1 Initial Studies

In this section the results of the initial tests, obtained with differential wrapping (a), deposits on the crystals (b) and depolishing (c) are discussed.

(a)Differential wrapping

This method was studied and used for U-shaped NUF curves, for which it appeared that a local correction had to be applied to the front end of the crystal, with the rise at the rear end remaining unchanged. The crystals were usually wrapped in Tyvek[a)] paper as this was found to give the best light yield. The comparison of various wrappings also showed that no significant change in the NUF is to be expected as long as the wrappings are homogeneous. To modify the NUF, one has to use different wrappings on different parts of the crystal. Several alternatives were tried: black tape on the crystal or on the inside of the tyvek, or ink stripes on the tyvek. Several units of the 25 crystal matrix for the early 1996 beam tests were uniformised this way and gave adequate results apart from significant light losses (10-20%). Furthermore such a method involves a significant amount of trial and error for each crystal and it is thus difficult to envisage using it for the full calorimeter. For further details see ref [3].

(b) Deposits on the crystal

As is well known, a direct deposit on a crystal which prevents the formation of the airgap around the crystal reduces drastically the total internal reflection and thus should reduce the focusing effect. Very thin deposits of silver were applied under vacuum [4] on five faces of the crystals, directly or on some intermediate layer, with the secondary aim of obtaining a high light yield (LY). Interesting results were obtained but with some technical difficulties. A change in slope of the NUF curve was observed, but fine tuning of the uniformity seemed very difficult. Also, thin deposits of reflective Sol-Gel[b)], aiming at a resistant coating with good LY, gave encouraging results but proved problematic. Reflective mineral white paint[c)] has been used successfully in many scintillator applications, in particular on the BGO crystals of L3 [5], not only to obtain a good LY, but also to uniformise the crystals. In fact, the NUF profile could be adjusted by varying the relative thickness of the paint on the two halves of the BGO crystals. The use of reflective paint on PWO has been studied. A decent LY was only observed with 5 faces painted but the response stayed non-uniform. Paint on one or several faces can be used to tune the NUF but with an unacceptably large loss in LY. A new series of painting tests on recent crystals with attenuation lengths of several metres confirmed these observations.

a. High density Polyethylen fibres, Du Pont Engineering Products S.A., 2894 Luxembourg.
b. Sol-Gel optical coatings, H.G. Floch & P.F. Belleville, CEA-Limeil, 94195 Villeneuve Saint-Georges, France.
c. BI 620, Bicron Corporation, Markstraat 271A, P.O. Box 271, Netherlands.

(c) Depolishing of a crystal face

Extensive studies to uniformise lead tungstate crystals in an ‘intrinsic’ way by modifying their surface state have been carried out. The depolishing of one or several end or lateral faces has been investigated. Whilst encouraging results were obtained generally, the best combination of uniformity and light yield was obtained by depolishing one lateral face. Fig. 2 shows the uniformity before (a) and after (b) for one of the earlier crystals (attenuation length ~ several metres) treated in this manner - in both cases the crystal is wrapped in tyvek.

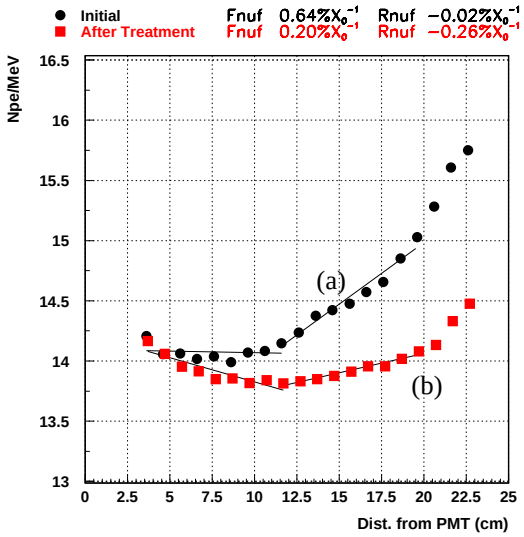

Figure 2 Uniformity before (a) and after treatment (b).

Clearly a much improved uniformity is obtained, without a major loss in light yield. As this technique showed the greatest promise it was investigated further. Its development in general, including the importance of using a high quality reflector, is discussed in detail in Section 2.2a. The mechanization of the technique is described in Section 2.2b

2.2a Technique Development

Roughening one lateral face greatly reduces the internal reflection and re-scatters the light so reducing the focusing. The extent to which the surface is roughened controls the magnitude of the change - we shall see that the way in which this ‘roughness’ is achieved is significant. The standard way to quantify the roughness of a surface is using the Ra parameter, measured in microns. It corresponds to the mean height of the inhomogeneities on the surface and is defined as shown below. The roughness was measured using a Taylor Hobson Surtronic 3+ meter.

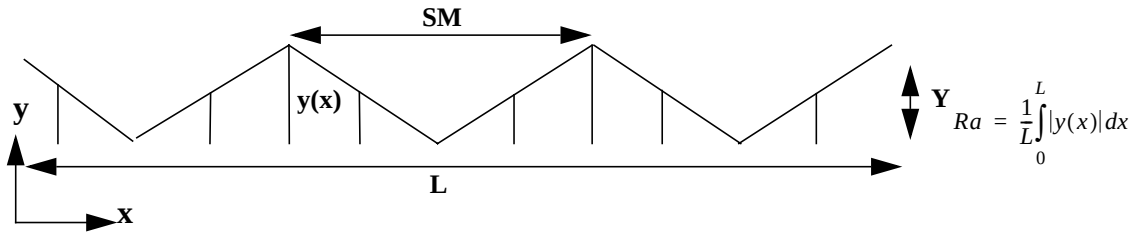

Figure 3 Schematic of a roughened surface and definition of Ra parameter.

Although when one face of the crystal is depolished a significant fraction of the light leaves the crystal, it can be recovered by surrounding the crystal with a suitable reflector. Figs. 4a and b show the light yield for two crystals, one with all faces optically polished (a) and the other with one lateral face depolished (b), for various wrappings. It can be seen that the choice/quality of reflector is far more important for the crystal with the depolished face. It should be noted that the uniformity, for both crystals, is independent of wrapping.

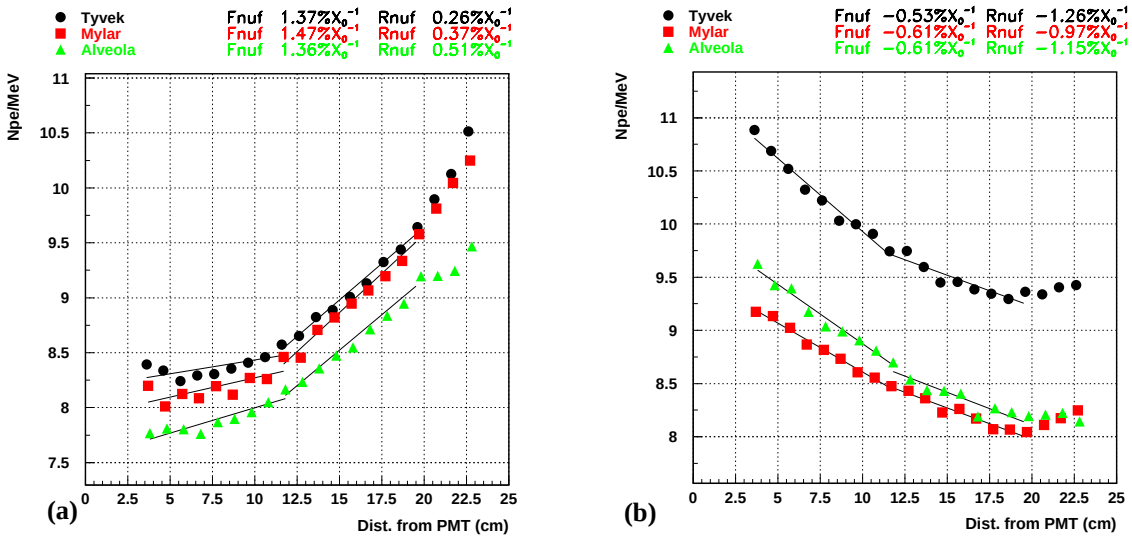

Figure 4 Light yield for a crystal with all faces optically polished (a) and for a crystal with one face depolished (b) for various wrappings (mylar was aluminized). The barrel ECAL crystals will be supported within ECAL in alveoles.

As depolishing one lateral face looked the most promising a larger number of crystals, ~20, had one lateral face ground with 4μm diamond paper. The crystals were moved in circles, by hand, on a glass plate wetted with the alcohol based diamond solution. Effectively the procedure was iterative in as much as the 'roughness' of the surface was increased, the crystal uniformity measured and so on until the desired uniformity was achieved. The improved uniformity measured in the lab was confirmed in high energy testbeams so confirming the proof of principle [2]. Concurrently ray tracing programs were developed to study/help optimize the procedure [6]. Whilst such programs can be reliably used to study the light collection in a polished crystal the complexity here is modelling the depolished surface. The angular dependence of light scattered from a 'diffuse' surface not only depends on the particular element but also critically on the details of the surface finish. Thus the value of the 'roughness' used in the Monte Carlo needed to be normalized to an experimental measurement. However once this 'normalization' is done the programs can, and were, used to predict the change associated with a change in roughness or in crystal geometry. Table 1 shows the expected change in front (FNUF) and rear (RNUF) uniformities for some of the various types of barrel crystal. Type 2 has the greatest tape (~4mm), whilst Type 17 the least (~2mm).

Type	FNUF (%/X0)	RNUF (%/X0)
2	0.14	-0.15
6	0.00	-0.20
9	-0.05	-0.25
17	-0.15	-0.44

Table 1 Predicted uniformities for various types of barrel crystal. The Monte Carlo response to a depolished surface was optimized/tuned to the experimental Type 6 results described later. A negative gradient for the RNUF indicates an increase in light yield towards the back of the crystal.

We can see that only a limited 'tuning' of the procedure should be required for different crystal types. Type 2, and similar will need to be slightly 'rougher' than the Type 6's, whilst the Type 17's will need to be 'smoother'. We also note that the progression is sufficiently slow that similar types, such as 6-9, can be treated in the same way.

Clearly an iterative, hand-depolishing is not applicable to the full crystal set and so we mechanized the procedure, using automated polishing wheels.

2.2b Mechanization

The crystals, initially with all faces optically polished, are first lapped on the face that will be depolished. This procedure 'roughens' the crystals to a greater extent than required but allows us to start from a common state and

removes any surface effects. Three crystals at a time are held rigid within plastic supports with a weight of 30kg uniformly distributed from above on a rotating resin surfaced polishing wheel. The edges of the crystal that are not to be treated are protected with masking tape. 15 μm diamond powder in solution is applied over the surface of the wheel and the crystal's bottom face ground. After 5 minutes the face being treated has a uniform roughness, characterized by Ra =0.50μm +/- 0.03μm and the process stopped.

The crystals are then cleaned and prepared for 'depolishing' on a second polishing wheel. The crystals are held in a similar manner. A soft 'tissue' is placed this time on the polishing wheel surface so that there is far less roughening of the crystal and so effectively the surface is polished to a state, with a roughness in between that of the lapped and fully polished crystal. Initially 4μm diamond powder was used as it had been used in the first, hand-depolished tests. The final roughness is controlled by the duration of the depolishing - as illustrated in Fig.5. Thus by combining the results of Fig. 5 with tests of front uniformity (FNUF) vs. roughness, as shown in Fig.6, we fixed upon a roughness of 0.25-0.30μm, corresponding to a 'depolishing' time of ~100s.

In fact the weight (30kg) applied to the crystals was chosen so that the time required to achieve the desired roughness is in a reasonable, practically achievable range. Each point in Fig. 6 corresponds to a group of three crystals treated in that particular way, and as such represents the first mechanized uniformisation, all be it on a limited number of crystals.

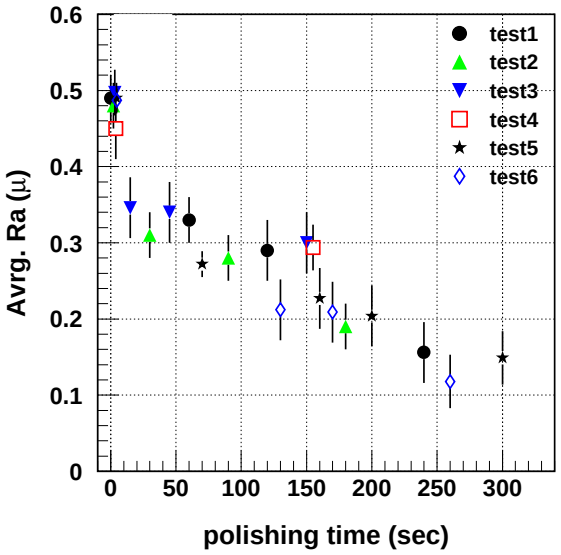

Figure 5 Roughness vs. polishing time.

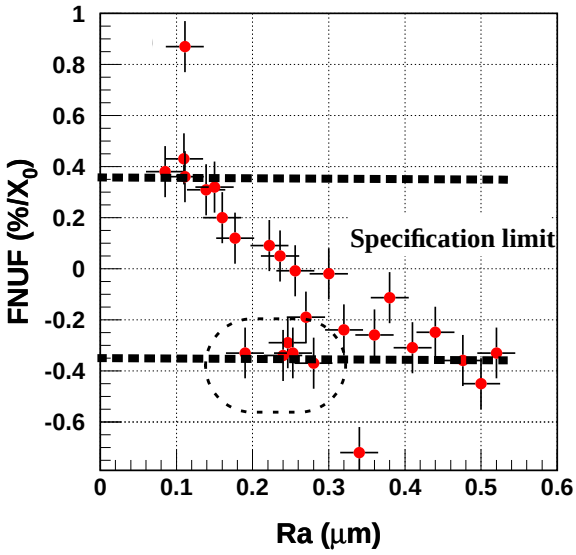

Figure 6 Front non-uniformity (FNUF) vs. roughness. Circled subgroup of crystals were subsequently found to have an abnormal variation in the transversal transmission and hence are non-representative.

For simplicity and economic reasons we made the decision to use 15μm powder at the 'depolishing' stage as well as the lapping stage before treating a larger number of crystals. The weight applied at the depolishing stage was changed to 15kg to allow us once again to be in a reasonable time range. The Ra value required to give a uniform response for crystals of type 6,7,8 and 9 (similar geometry) is 0.38μm using this new procedure. The results obtained using this process are described in the following section.

Note that the optimum Ra for the new procedure is significantly different to that required with 4μm powder, illustrating the process dependence of the Ra specification. Thus at the same time considerable effort was made to try and find a process independent way of specifying the surface state. The parameters defined below were tested. Recall Fig. 3, we can form the angle θ, as defined below.

$$\theta = \frac{Y}{0.5SM} \sim \frac{4Ra}{SM}$$

Following the notation of Fig. 3, Rq can be defined as,

$$Rq = \sqrt{\frac{1}{L}\int_0^L y(x)^2 dx}$$

Consider Fig.7.

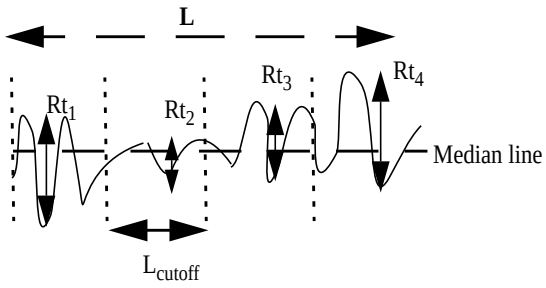

Figure 7 Schematic-2 of a roughened surface.

L_{cutoff} is the length you choose to be representative of that surface. Rt_i is the maximum "height", measured from peak to valley, within each L_{cutoff}. Ry is the maximum value of Rt_i measured over the full length L, Rz is the mean value of Rt_i over the full length L and S_M is the mean separation between peaks above the median line, again over the full L. The parameters Ry, Rz and S_M were tested.

As for the previous studies, pre-production crystals, i.e. crystals with comparable, good optical properties, of types 6,7,8 and 9 were used as they are of similar geometry. The Type 6's were uniformised at CERN using the mechanized procedure described above i.e. 15μm powder and an Ra value of 0.38μm. Whilst the Type 7,8 and 9's were uniformised by hand at the producer with 4μm powder to our pre-requested roughness of 0.25μm. The above parameters were measured for crystals having similar FNUF's, but uniformised with the different procedures. No parameter was found to be process independent. For all crystals, the correlation between the above parameters and FNUF was also studied. Whilst the θ parameter was the most sensitive, the correlation was also visible in Ra - as previously illustrated - Fig 6. As it is far easier/quicker to measure, and barely less sensitive, it was decided to keep Ra as the parameter used in the crystal specifications.

3 Results

The mechanized process described in the previous section was applied to ~ 50 pre-production Type 6 crystals. The results obtained for the front (FNUF) and rear (RNUF) uniformities are shown in Figs 8a and 8b.

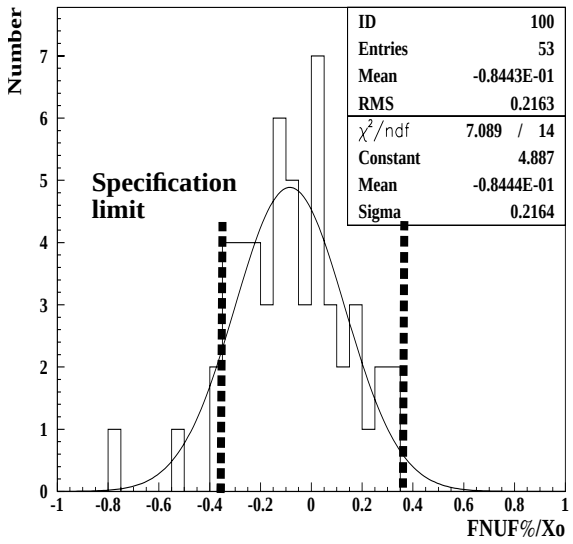

Figure 8a Front uniformity (FNUF) for Type 6 crystals mechanically treated at CERN.

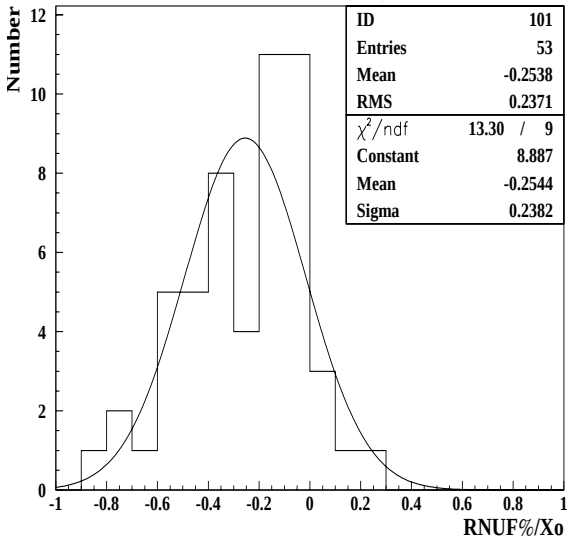

Figure 8b Rear uniformity (RNUF) for Type 6 crystals mechanically treated at CERN.

Clearly the majority of crystals have an FNUF value between the acceptance criteria of $-0.35\%/X_0 < FNUF < 0.35\%/X_0$. The RNUF values are mainly negative, which is favourable for a good energy resolution as discussed earlier. Following the success of this and the earlier tests it was decided to confirm this procedure as the official crystal treatment. This technology was transferred to the producer in Bogoroditsk, Russia over a period of months and the necessary equipment installed. Until this equipment was fully commissioned it was decided that the producer would continue to supply hand depolished crystals using 4μm powder, to a roughness chosen by the CERN EP-CMA group and determined from this work. The next pre-production crystals, being Types 7,8 and 9 and hence of similar geometry were supplied with the same 'equivalent' (0.25μm) roughness parameter as the Type 6's. Figs. 9 and 10 show the uniformities for ~80 of the Type 7 crystals received in batch 2 and ~150 of the Type 8 and 9 crystals received in batch 3. Over 90% of the crystals fall within the specifications - illustrating that the

method and its application to pre-production crystals is satisfactory. This ratio can still be improved by restricting the Ra specification and making it type dependent.

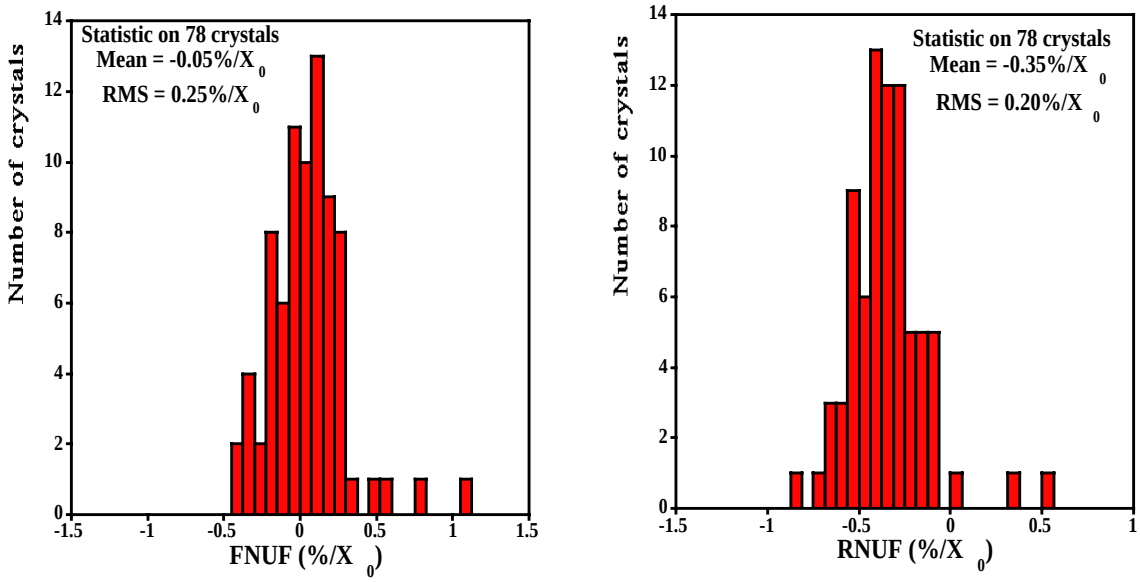

Figure 9 Front (a) and rear (b) uniformity for Type 7 crystals (batch2), supplied to the pre-requested roughness.

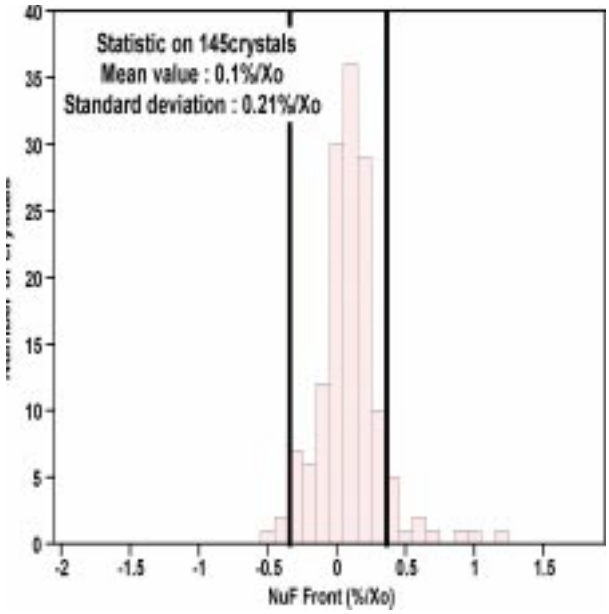

Figure 10 Front uniformity for Type 8/9 crystals (batch 3) supplied to the pre-requested roughness.

4 Future Plans and Conclusion

We have developed and demonstrated a technique suitable for uniformising the CMS ECAL lead tungstate crystals - this is critical for the ECAL's performance. We have shown that this technique can be carried out successfully at the Producer and are finalizing the technology transfer.

This method is sufficiently adaptable to allow the slight modifications required for the different crystal types to be easily achieved. When the method was well established, we requested crystals from the ends of the geometrical range to allow us to calibrate the slight changes in roughness predicted by the Monte Carlo for such crystals. An

example of the flexibility of, and our experience with, this method is the recent modification required by the move from single-doped (Nb or La) to double-doped (Y,Nb) crystals. This move has been made as these crystals have improved radiation tolerance [7]. As a consequence the uniformity was affected. Fig 11a shows the front uniformity for the first batch of double doped crystals (batch 6) finished to the usual roughness - clearly an increased roughness is required. From previous tests it was known that roughening to an Ra value of 0.5μm with the 15μm powder treatment at CERN (or equivalently Ra=0.35μm using 4μm powder) shifts the FNUF by -0.45%/X_0; the effect of doing this on a subset of these crystals, selected from the peak of the distribution is shown in Fig. 11b. As can be seen the crystals are now uniformised. This modified roughness parameter was passed back to the Producer and the next set of crystals produced to this modified specification. The front uniformity for this batch is shown in Fig. 12.

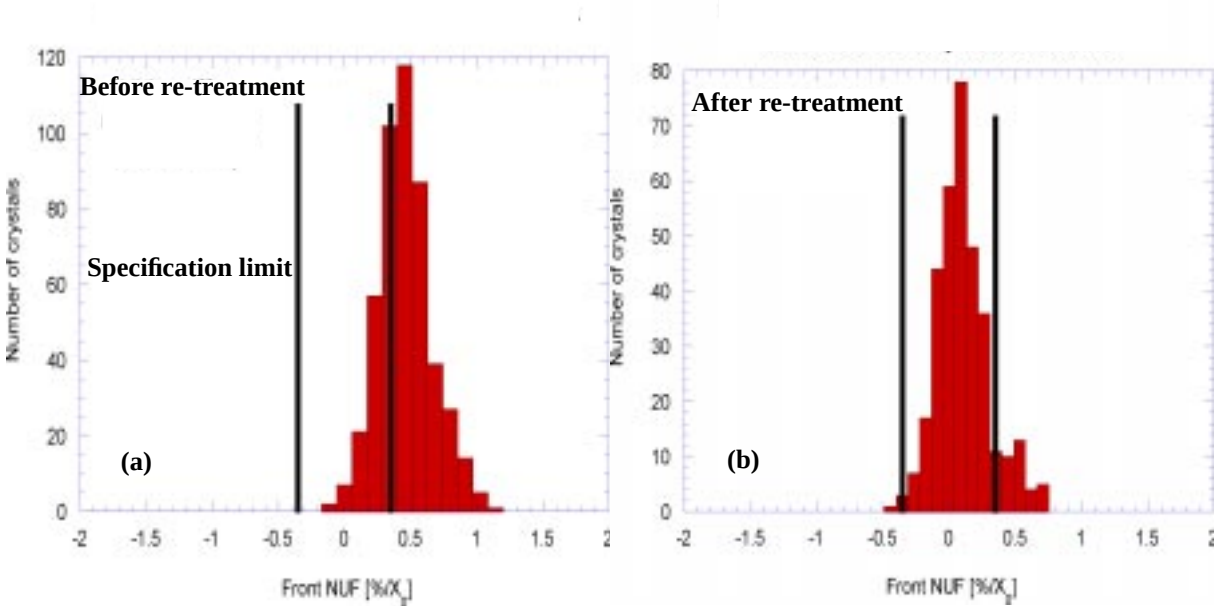

Figure 11 Front uniformity for first batch of fully double doped crystals, supplied to the usual pre-requested roughness (a) and after re-treatment at CERN (b).

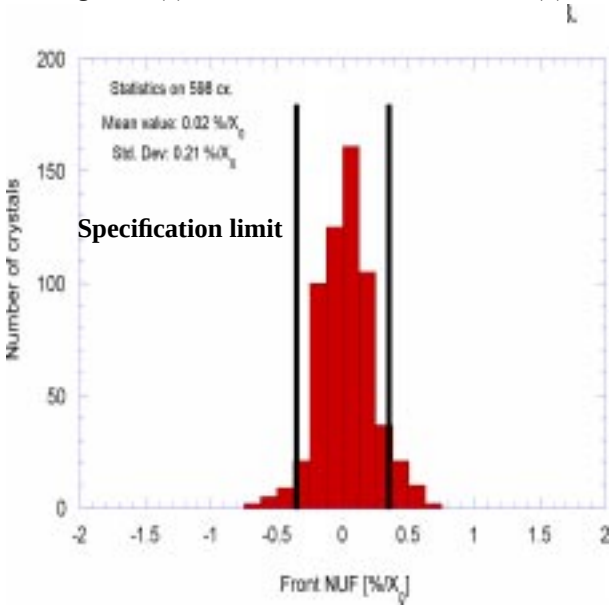

Figure 12 Front uniformity for crystal batch with modified roughness parameter, as applied at the Producer.

The baseline scheme is thus that the Producers deliver crystals to the Regional Centres with five faces optically polished and one of the lateral faces polished only to the degree of roughness pre-specified for each type of crystal at ordering. Most crystals treated in this way should then have a uniformity in the correct range, when measured on the Automatic Crystal COntrol Systems (ACCOS) [8] installed in the Production and Regional Centres. If a

crystal is found out of range, the roughness of its non-polished face is measured. If found to be out of the range specified to the Producer, the crystal is rejected. If it is inside the roughness range but not uniform, a correction to the surface state will be applied at the Regional Centre.

5 Acknowledgements

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