This chapter addresses the issues of crystal properties, specifications, production and testing. Section 2.1 gives an overview, whereas optical properties and radiation hardness of the crystals are discussed in Sections 2.2 and 2.3, respectively. Section 2.4 covers the crystal production, acceptance specifications, quality control, and production schedule.

2.1 Overview and Requirements

The CMS electromagnetic calorimeter will consist of over eighty thousand lead tungstate crystals (total weight of 93 tonnes), avalanche photodiodes or vacuum phototriodes and associated electronics operating in a challenging environment; 4 T field, 25 ns between bunches, radiation doses measured in kGy/year for LHC operation at maximum luminosity, difficult access for maintenance. Although several large crystal calorimeters have been built in the past, none of them has had to face the challenges of speed, radiation resistance and size that an LHC calorimeter will face. Thus, although much is known about the construction and operation of crystal calorimeters, significant R&D had to be undertaken to design the calorimeter.

PbWO$_4$ is a birefringent, tetragonal, scheelite-type crystal belonging to the space group I4 1/a or monoclinic raspite [2.1]. It is grown from a 50%–50% mixture of lead oxide (PbO) and tungsten oxide (WO$_3$) which melts congruently at 1123°C, without a phase transition during cooling. Properties of lead tungstate are listed in Table 1.1 and compared to those of other crystals used in electromagnetic calorimeters.

A combined effort between CMS and producers is under way to optimize mass-production procedures of long, high-quality PbWO$_4$ crystals and more than five hundred evaluation samples have been supplied by the Bogoroditck Techno-Chemical Plant in Tula, Russia, by the Shanghai Institute of Ceramics, by the Beijing Glass Research Institute in China and by CRYTUR in the Czech Republic. Milestones towards this goal have included: understanding the PbWO$_4$ scintillation mechanism; enhancing the light output; understanding the radiation damage mechanisms and developing techniques to produce radiation-hard crystals; understanding the mechanical properties of the crystals and producing stress-free crystals to avoid breakage during cutting and polishing; finding the most economical way of mass-producing these crystals. The optimization of production methods has been successfully tested on small production batches and is now ready for validation in a preproduction phase. The PbWO$_4$ crystal growth technology is very similar to the one used on an industrial scale for niobiate and molybdate crystals.

The standard method to grow PbWO$_4$ crystals is the Czochralski one in a platinum crucible. This method is currently used in Russia and Czech Republic where a significant production capacity already exists. Raw materials are first melted in a platinum crucible from which up to three ingots of 2 kg of polycrystalline PbWO$_4$ are grown. This polycrystalline PbWO$_4$ is then sintered and used as starting material for crystal growth. Up to seven crystals can be grown from the same initial load of the crucible by adding some new material between the crystallizations in order to maintain the level of the melt constant. The melt is then too contaminated by impurities and the crucible has to be cleaned. In China the modified Bridgman–Stockbarger technique in closed platinum foils, previously developed for the BGO production for the L3 experiment, has been successfully adapted to grow PbWO$_4$ crystals. This technique produces several ingots at the same time. Both methods have their own merits and drawbacks, but it is important to note that
crystals of the required quality have been grown using both technologies. This allows CMS to benefit from the already developed production infrastructure for lithium niobate and molybdate (Czochralski) and BGO (Bridgman) crystals. For cutting and polishing the crystals a precise and cost-effective method has been developed at CERN from the experience gained during the production of BGO crystals [2.2], and has been transferred to the producers. Samples of Czochralski ingots and machined full-size crystals are shown in the colour picture (Fig. 2.i).

The crystal is optically and mechanically anisotropic and care must be taken during the growing process to avoid formation of cleavage planes. This anisotropy, which can be a cause of mechanical instability, is well understood and its effects are controlled by a judicious choice of growth and annealing conditions. This crystal is intrinsically radiation hard, significant radiation damage has been observed at doses as low as 1 Gy on non-optimized crystals. Over the past three years, systematic R&D on the crystal growth parameters has led to a significant improvement in radiation hardness at low doses, as well as of transparency, light yield, and decay time.

2.2 Optical Properties

Most of the crystals of the tungstate family have an intense but slow emission in the millisecond range. PbWO$_4$ has a rather weak but fast emission because of a strong quenching of the scintillation process. This quenching is rather complex but to a large extent associated with high-temperature charge transfer process and thermal decomposition of excited states. The efficiency of these two mechanisms can be modified by the presence of some impurities, as demonstrated in 1995 [2.3].

Light emission spectrum

The scintillation emission spectrum (Fig. 2.1) results from the superposition of two broad and complex emission bands at 420 nm and 500 nm respectively. Interpretation of these bands has been given in various papers [2.4]. The present optimization of crystals leads to a Gaussian-shaped spectrum (140 nm FWHM) peaking at about 440 nm with a range from 360 nm to 570 nm at 10% of the maximum and matches the wavelength range where good quantum efficiency can be obtained for both APDs and VPTs.

Decay time

Towards the end of 1995 a sizeable improvement in light yield had been attained for lead tungstate crystals. Unfortunately, along with this increase, a large slow component was observed in the scintillation light. A few months later the main mechanism leading to such a slow component was found. Some traps in the crystals slowed down the usually very fast (picoseconds) recombination of the free carriers which yield the green luminescence. It was shown that molybdenum impurities were the main cause of this effect: after reducing the contamination by molybdenum by a factor ~10 (below 10 ppm), the slow component was considerably reduced. In recent batches of crystals the decay time can be fitted by a sum of three exponentials of typically 5 ns, 15 ns and 100 ns with amplitudes of 39%, 60% and 1% respectively. About all of the light is collected in 100 ns in recent crystals. A large effort to reduce non-radiative traps associated with other defects allowed the improved light yield to be maintained.
Transmission

The optical transmission of the crystals has been steadily improved, in particular in the region of scintillation, between 360 and 570 nm. The optical transmission of PbWO$_4$ crystals can be limited by the presence of macroscopic defects like inclusions, precipitates or veils which scatter the light in all directions, or by the existence of traps which induce absorption bands. The most frequent traps observed in PbWO$_4$ are located near the valence and conduction bands and affect the shape of the transmission edge. A band at 350 nm believed to be due to oxygen defects is frequently observed. Another band at 420 nm, believed to be caused by the presence of holes trapped by lead ions, is responsible for the yellowish coloration of some crystals [2.5]. A better control of the raw material preparation and of the growth and annealing conditions, as well as the introduction of dopants, have led to considerable improvement in the optical transmission of full-size PbWO$_4$ crystals. The attenuation length now exceeds 3 m in the whole range of emission spectrum.

Light yield

The improvement of the transparency of crystals (Fig. 2.2 and Fig. 2.3) has been associated with an increase in the amount of collected light. Light yield values in excess of 10 photoelectrons/MeV are now systematically observed in a gate of 200 ns on a photomultiplier (XP2262B) covering all the back face of 23-cm-long crystals. This corresponds to a 30% to 40% improvement as compared to crystals produced in 1995, with a much reduced dispersion from crystal to crystal.

The thermal quenching of the scintillation mechanism leads to a rather strong temperature dependence of the light emission, of typically – 2% per °C at room temperature. The temperature
coefficient of the light yield is shown in Fig. 2.4 as a function of temperature [2.4]. The temperature coefficient of the crystals, and of the APD, implies that the temperature of the calorimeter must be stabilized to a tenth of a degree.

**Fig. 2.2:** Typical longitudinal transmissions for 23-cm-long PbWO$_4$ crystals produced in 1995 and 1997, compared to the maximum achievable transmission taking into account Fresnel losses and assuming infinite absorption length.

**Fig. 2.3:** Statistics on intrinsic absorption coefficient at 500 nm for crystals produced in 1995 and for a batch of 20 crystals from July 1997.
**Longitudinal uniformity**

Another important characteristic of crystals is the collected light yield as a function of distance from the photodetector. Two opposing effects determine the light non-uniformity profile: crystal absorption and focusing effect due to the tapered crystal shape. These effects have previously been studied for the L3 and CLEO calorimeters.

The longitudinal light-collection curves have been measured and the results included in shower simulation programs in order to predict the contribution to the constant term. We have published the results of these studies [2.6], [2.7], which show a strong correlation between the observed constant terms and the predicted contributions from longitudinal non-uniformity. As explained in Chapter 12, a uniformity of better than 0.35%/X₀ must be obtained in order not to induce a contribution greater than 0.2% to the constant term. Better control of the longitudinal light collection, using improved techniques for uniformizing the crystals, has enabled us to reduce the mean constant term observed in test beam to 0.34%.

**Test-beam results on light yield and longitudinal uniformity**

Shower containment is predicted by GEANT shower simulation to contribute a little more than 0.1% to the constant term. In beam tests, beam momentum spread (nominally 0.1%), shower leakage into the APDs, and residual miscalibration effects, build this up to a combined floor of between 0.2% and 0.3%. In the test beam the remaining contribution to the observed constant term has come from longitudinal non-uniformity of light collection.
In April 1997 we measured the energy resolution with beam incident in 15 crystals. We obtained a mean stochastic term of 4.3%, a mean constant term of 0.40%, and a mean energy resolution at 120 GeV of 0.56%. In August 1997 we measured the energy resolution with the beam incident in 21 crystals (of which only 4 were the same as in the April sample) and obtained a mean stochastic term of 4.2%, a mean constant term of 0.34%, and a mean energy resolution at 120 GeV of 0.53% (Fig. 2.5).

Shower containment in a $3 \times 3$ array gives a contribution of $2\% / \sqrt{E}$ according to GEANT shower simulation. Thus the photostatistics contribution dominates the stochastic term measured in the test beam. The values obtained from the energy resolution fit can be compared with the values obtained from the width of an injected LED light pulse which provides a rather precise measurement of the photostatistics contribution. The agreement is very good — more details of such measurements can be found in Refs. [2.6] and [2.7].

The mean value of the stochastic term of $4.2\% / \sqrt{E}$ for a $3 \times 3$ array of crystals is compatible with an average of nearly 2000 photoelectrons per GeV released in the 25 mm$^2$ EG&G APD (excess noise factor $F = 2.2$) used in the test. This figure is consistent with measurements of the light yield made elsewhere (see discussion in Chapter 4). The baseline will employ APDs with an effective area of 50 mm$^2$. Hence the photostatistics contribution is expected to be $< 3\% / \sqrt{E}$.

![Fig. 2.5: Energy resolution at 120 GeV observed in August 1997. The energy is measured in a $3 \times 3$ array of crystals centred on the struck crystal.](image-url)
2.3 Radiation Hardness

2.3.1 Introduction

Lead tungstate is intrinsically radiation hard, but non-optimized crystals do suffer from radiation damage. The R&D carried out over the last few years has led to a better understanding of this damage mechanism. Tests with electrons, gammas and charged hadrons all confirm that the damage can only be attributed to electromagnetic interaction. Tests made with thermal and fast neutrons up to fluences of $10^{14}$ n/cm$^2$ have shown that the damage is compatible with that expected from the flux of gamma rays produced in the reactor with the neutrons. No specific neutron damage could be observed [2.8].

The R&D results can be summarized as follows:

**First**, radiation does not affect the scintillation mechanism in the crystals, at least in the range of doses and dose rates considered at LHC [2.9], [2.10].

**Second**, radiation damage affects the transparency of the crystals through the formation of colour centres related to defects in the crystals introduced by mismatched stoichiometry and creation of oxygen vacancies. This conclusion was reached by detailed material analysis [2.11], [2.12], [2.13]: a glow discharge mass spectroscopy (GDMS) analysis revealed no correlation between the detected trace impurities and the crystal’s susceptibility to radiation damage; electron microprobe (EMPA) and particle-induced X-ray emission (PIXE) analyses revealed that crystals with poor radiation hardness have a non-optimal Pb/W ratio [2.14], [2.15], [2.16]. Thus the light transport is changed by self-absorption of the crystals, and the effect of irradiation can be quantified by a radiation-induced absorption coefficient [2.16]. The loss of transmission due to irradiation will be monitored by a light injection system in the calorimeter, and a correction can be established and applied, as shown in Chapter 6.

**Third**, irradiation does not change the uniformity of collected light yield along the crystal, provided that the initial light attenuation length is long enough and the damage remains moderate (Fig. 2.6). This has been proven experimentally by a measurement of longitudinal uniformity after irradiation [2.14], [2.15].

**Fourth**, the loss in the amount of collected light stabilizes at a level dependent on the dose rate, an effect well described by the creation of colour centres under irradiation and their annihilation through room-temperature annealing [2.15], [2.17].

The shape of the crystal (small cross section of about 500 mm$^2$ and a length of 230 mm), the high refractive index of PbWO$_4$ (2.3 at 500 nm) [2.18] and the small size of the avalanche photodiode (APD) for the light readout (currently 25 mm$^2$) increase the average path length of the light rays if the transparency is good. The acceptable density of colour centres has therefore to be reduced to a very small level such that the amount of light collected by the APD is not reduced by more than a few per cent under irradiation, a level which was shown not to affect the energy resolution after correction by the monitoring system (Chapter 6) [2.19].

**Fifth**, there is no damage recovery with time constants of less than a few hours for dose rates that will be encountered at the LHC.
Fig. 2.6: Slope of the light collection curve in the region 4 to $-13 \times_0$ plotted against the attenuation length of the crystal. The line is a Monte Carlo prediction, while dots are data. The errors are statistical only. The plateau gives the range of acceptable final attenuation length.

### 2.3.2 Irradiation studies

Several hundred crystals have been tested so far at various facilities described in Table 2.1 with irradiation at various doses and dose rates, in order to

- reproduce conditions of irradiation at different places of the ECAL and different LHC luminosities (Fig. 2.7);

- accumulate doses equivalent to 10 years of LHC operation.

Extensive studies on the radiation-damage mechanism have led to the conclusion that it is not driven by extrinsic impurities but by host-structure defects acting as traps [2.14], [2.20]. Systematic work has been done by the producers to decrease the number of such defects. One way is to fine tune the stoichiometric ratio and to control it with precision during the growth process.
### Table 2.1: Irradiation facilities used to test lead tungstate crystals for CMS

<table>
<thead>
<tr>
<th>Facility/Source and irradiation method</th>
<th>Typical Dose/Dose rate in air</th>
<th>Type of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>JINR and Prague Microtrons/ e⁻ 25 MeV lateral</td>
<td>3 Gy, 9 and 30 Gy/h</td>
<td>Transmission several λ, Transmission all λ, Scintillation kinetics</td>
</tr>
<tr>
<td>Minsk/ ⁶⁰Co on top of ingots</td>
<td>1 kGy, 300 Gy/h</td>
<td>LY with weak ⁶⁰Co source</td>
</tr>
<tr>
<td>Geneva Hospital/ ⁶⁰Co lateral</td>
<td>1–500 Gy, 3.6–250 Gy/h</td>
<td>Longitudinal + Transverse, Transmission all λ, LY with weak ⁶⁰Co source</td>
</tr>
<tr>
<td>CERN-TIS/ ⁶⁰Co front</td>
<td>9 Gy, 0.15 Gy/h</td>
<td>LY by HPMT current during irradiation, Transmission all λ</td>
</tr>
<tr>
<td>CERN-X5/ ¹³⁷Cs lateral and front</td>
<td>2 Gy, 0.15 Gy/h</td>
<td>Transmission several λ, LY with weak ⁶⁰Co source, LY with beam</td>
</tr>
<tr>
<td>HEFEI/ ⁶⁰Co lateral</td>
<td>4 Gy, 0.25–0.9 Gy/h</td>
<td>LY in irradiation room with weak ⁶⁰Co source for calibration</td>
</tr>
<tr>
<td>PSI-Eichlabor/ ⁶⁰Co lateral</td>
<td>130 Gy, 0.15–4 Gy/h</td>
<td>LY in irradiation room with weak ⁶⁰Co source for calibration</td>
</tr>
<tr>
<td>Saclay/ ⁶⁰Co lateral, masks</td>
<td>3 Gy, 0.15 and 0.58 Gy/h</td>
<td>Transmission during irradiation several λ, Transmission all λ</td>
</tr>
<tr>
<td>CALTECH Cs and Co gamma ray Sources All lateral irradiations</td>
<td>Cs–1 ≤ 1 Gy/h, Cs–2 = 157 Gy/h, Co-1 ≤ 10 Gy/h, Co-2: 5–400 Gy/h</td>
<td>Transmittance, Emission, LY versus time gate, light response uniformity</td>
</tr>
<tr>
<td>ENEA-Casaccia/ ⁶⁰Co lateral, neutrons</td>
<td>1–500 Gy, 0.8–900 Gy/h</td>
<td>Transmission all λ, LY with weak ⁶⁰Co source</td>
</tr>
<tr>
<td>PSI pions, E &lt; 250 MeV protons, E &lt; 400 MeV</td>
<td>0.1–2 kGy, 10 Gy/h, 0.1–10 kGy, 100 Gy/h</td>
<td>LY uniformity, Decay time, energy spectrum</td>
</tr>
</tbody>
</table>
Another way to decrease defects is to optimize the post-growth annealing process to compensate deficiencies in the oxygen sublattice. Annealing dependence studies have been carried out with crystals cut in pairs from the same ‘father’ crystal; oxygen-annealed crystals appear more radiation-resistant than air-annealed crystals, (Fig. 2.8a). Further work on oxygen-annealing has shown that the process can be optimized to produce quite radiation-resistant crystals (Fig. 2.8b). Reproducibility of the process has been demonstrated on a few samples (Fig. 2.8c) and radiation hardness even at higher dose rates is promising (Fig. 2.8d and Fig. 2.9).

Another approach to crystal optimization was investigated by specific doping, either pentavalent on tungsten site (niobium), or trivalent on lead site (lanthanum, yttrium, lutetium) in order to compensate for the defects remaining after optimization of stoichiometry. The effect of pentavalent doping is a direct suppression of defects, whereas trivalent doping compensates the charge imbalance of existing defects [2.20]. In both cases, systematic tests on several tens of full-size crystals have shown a significant improvement in the sharpness of the transmission band edge which has resulted in increased transparency. All crystals doped in conditions of optimized raw materials show a considerable improvement of radiation hardness with a light-yield decrease of less than 5% after several days of irradiation at a dose rate similar to that expected in most of the calorimeter at high luminosity (Fig. 2.10).
Fig. 2.8a: Relative light-yield loss of two undoped 50-mm-long crystals from the same ingot, one air-annealed and the other oxygen-annealed. The crystals were irradiated laterally over their full length with $^{60}$Co at 0.15 Gy/h. The light yield is measured using a weak calibration source placed at the tip of the crystals.

Fig. 2.8b: Relative light-yield loss of two undoped 50-mm-long crystals from the same ingot, both oxygen-annealed for a different length of time. The same measurement method is used as for crystals in Fig. 2.8a but at a slightly higher dose rate of 0.25 Gy/h.

Fig. 2.8c: Reproducibility of relative light-yield loss for 50-mm-long oxygen-annealed crystals. Same measurement method and dose rate as for Fig. 2.8b.

Fig. 2.8d: Radiation hardness of a 50-mm-long oxygen-annealed crystal at a higher dose rate.
Fig. 2.9: One of the 50-mm-long crystals shown on Fig. 2.8c is being exposed to much higher dose and various dose rates up to 157 Gy/h and has shown excellent behaviour. This crystal will be irradiated to reach an integrated dose of two hundred thousand gray, the highest dose expected at LHC after 10 years of operation.

Fig. 2.10: Example of a low dose rate irradiation on 23-cm-long La-doped crystals grown in conditions of mass production ($^{60}$Co front irradiation, 0.15 Gy/h).
To illustrate the recovery kinetics of La- and Nb-doped crystals, two full-size crystals of medium quality have been exposed to radiation cycling so as to simulate the cycle of filling the LHC machine; a remaining fluctuation of about 0.8% has been observed for the Nb-doped crystal during a succession of 15 h irradiation periods followed by 8 h recovery after an initial irradiation period of 3 days. In similar conditions, the La-doped crystal has a remaining 1.2% fluctuation. After a one week stop, the Nb-doped crystal recovers 21% of its initial damage, and the La-doped 72% (Fig. 2.11a, Fig. 2.11b).

**Fig. 2.11a:** Damage/recovery cycle of a Nb-doped crystal at 18°C.

**Fig. 2.11b:** Damage/recovery cycle of a La-doped crystal at 18°C.
For longer shutdowns (one month or more) it is expected that La-doped crystals will almost completely recover, whereas Nb-doped crystals will only recover 30% to 40% of the initial damage and show therefore less variation.

These techniques have led to the production of several crystals, both in Russia and in China, with a light yield decrease of less than 5% after several days of operation in conditions similar to LHC. The fact that these crystals do not show self-annealing time constants of less than an hour makes them rather insensitive to normal operating conditions.

2.3.3 Test-beam results on radiation damage

The test beam has been used to check the radiation hardness of crystals as work has proceeded in the development of harder crystals. The ability of light monitoring systems to track the resulting calibration changes has also been studied and this work is described in Chapter 6. Details of studies made in 1996 are given in Ref. [2.7]. It has also been possible to verify that if the loss of light collected is relatively small the energy resolution itself is not noticeably degraded by the radiation damage, so that radiation damage can be regarded essentially as a calibration issue. As discussed at greater length in Section 2.3.1, irradiation of lead tungstate creates colour centres which reduce the light attenuation length. The change of attenuation length can affect the longitudinal uniformity. The energy resolution is not degraded if the longitudinal non-uniformity is not affected.

Figure 2.12 shows the energy distribution for 120 GeV electrons measured just before and just after an irradiation that caused a loss of 8% of the collected scintillation light. The energy resolution is unchanged within fitting errors.

**Fig. 2.12:** Energy distribution seen in the sum of 9 crystals for 120 GeV electrons incident in a $4 \times 4$ mm$^2$ area centred on the central crystal before and after irradiation to 6.5 Gy, which caused a light output loss of 8%.
Using data obtained with radiation-soft crystals in 1996 we have verified that damage which results in a moderate loss of collected light does not degrade much the energy resolution. The average resolution of six rather soft crystals was measured before and after an irradiation which caused their light output to drop by an average of 27% (range of losses between 18.6% and 33.3%). The average resolution at 120 GeV degraded from 0.52% to 0.61%, a degradation equivalent to adding a contribution of about 0.3%. Some of this loss (about 0.19%) can be understood as being due to an increase in the stochastic term because of the reduced number of photoelectrons collected, but a larger loss must be attributed to an increase in the constant term owing to induced longitudinal non-uniformity. By contrast, three harder crystals irradiated at the same time, and suffering an average light output loss of 5.1%, had an average resolution at 120 GeV of 0.52% before, and 0.50% after irradiation. Interpolating between these results leads to the conclusion that damage which results in a loss of collected light of less than about 15% will cause a resolution degradation of less than 0.2%.

2.4 Crystal Production

Optimization of growth parameters has been pursued to maximize the crystal yield. The growth yield has reached 70%, and further improvements aim at a final growth yield of 80%. Initially crystal breakage was a problem during mechanical processing. This was solved in 1996 by optimizing the cutting process, the corresponding machines and technologies have been transferred to the producers. It has been demonstrated that with this new technology the mechanical tolerances of processed crystals can be considerably improved [2.2].

2.4.1 Crystal mechanical specifications

There are seventeen right-handed and seventeen left-handed crystal shapes in the barrel and only one shape for the endcaps.

The barrel crystal dimensions are given in Table 3.2 of Chapter 3. The technology developed for cutting and polishing the crystals [2.2] will allow us to attain mechanical tolerances of +0, –100 μm on the lateral dimensions and on the length. In addition, a planarity of better than 50 μm will be required on all faces. The perpendicularity must be better than 50 μm. The edges will be chamfered to a minimum of 0.5 mm and a maximum of 0.7 mm.

2.4.2 Optical specifications

Optical transmission

One very important parameter which is relatively easy to measure and strongly correlated with the optical and radiation-hardness properties of the crystal is the optical transmission spectrum. The longitudinal measurement through the 23-cm-long crystal allows the detection of even weak absorption bands which give a good indication about the light yield and radiation hardness of the crystal. Particularly important is the control of the sharpness of the optical transmission edges and the absence of the 420 nm absorption band. The transverse measurement at different points along the crystal also gives the longitudinal uniformity of the optical parameters of the crystal. Therefore, a maximum spread of the transverse transmission edge at different points along the crystal is part of the specification. The final specifications will be set after a thorough investigation of the first thousand preproduction crystals.
The preliminary specifications are (including the Fresnel losses at both ends of the crystal):

- **Longitudinal transmission:**
  - > 10% at 350 nm
  - > 50% at 420 nm
  - > 70% at 600 nm.

- **Transverse transmission:**
  for each of the 6 points spaced by 4 cm and starting at 1.5 cm from the small end:
  - > 50% at 350 nm
  - > 60% at 420 nm
  - > 70% at 600 nm.

The wavelength dispersion of all the points corresponding to a 50% transverse transmission has to be smaller than 10 nm.

**Light yield**

A minimum light yield of 10 photoelectrons per MeV will be required, as measured with an XP2262B photomultiplier covering all the back face of the crystal, wrapped in Tyvek, in a gate of 1 μs, with over 90% of this light being contained in a 100 ns gate and with no detectable afterglow.

The conditioning of the PbWO$_4$ crystals must ensure that as much light as possible is collected by the photodetectors in order to guarantee sufficient photostatistics and a high signal over electronic noise ratio, while keeping to a minimum the thickness of material between crystals.

Each crystal will be mounted in an individual alveolus which is part of the mechanical structure of the calorimeter (see Chapter 3).

Directly inserting the uniformized crystals in an Al-lined alveolus has been shown to be a practical solution. However, there is an ongoing study to improve the level of collected light. Different variants are being studied, such as preparing Al sheets with a thin sputtered silver layer or a layer of white diffusing paint. Alveoli were produced successfully with both methods and such tests will be continued.

**Uniformity**

Highly transparent crystals have a non-uniform light-yield response due to the tapered shape of the crystals and the high refractive index of lead tungstate ($n = 2.3$ at 500 nm). Light yield uniformity can be restored by roughening the lateral faces to reduce total reflection [2.21].

Numerous studies performed in laboratories with sources or with particle beams showed in particular that:

- an adequate light-collection uniformity can be achieved by depolishing one or several faces of the crystals,
- the choice of the wrapping does not significantly affect the uniformization.
With the highly transparent crystals delivered in summer 1997, which can be considered to be near production quality, it is now possible to define a uniformization method for the PbWO$_4$ calorimeter. The proposed scheme is to have crystals delivered with 5 faces optically polished, but one of the side faces only polished to a certain degree of roughness. The roughness specification will be the same for all crystals of the same geometrical type. Their non-uniformity profile will then be checked and a small fraction of them may need a correction. A series of crystals for the 1997 beam tests were treated with predefined polishing conditions and found to give an adequate constant term for the energy resolution. The resulting light yield non-uniformity in the region of shower maximum is less than (0.3 ± 0.1)% per $X_0$.

### 2.4.3 Quality control

It is the producer’s responsibility to control the production chain and to organize proper monitoring of the crystal quality during the different phases of the raw material preparation, growth, annealing and mechanical processing. On the other hand it is the responsibility of CMS to define the crystal specifications and the testing protocols for the characterization of the finished crystals. Some parameters, such as radiation hardness [2.22] and afterglow, will be tested on a sampling basis.

The choice of the parameters to be controlled, the measuring device, and the protocol of measurement will be defined by CMS. Automatic and compact quality-control devices [2.23], [2.24], [2.25] (ACCOS) have been designed to measure the following parameters at a minimum rate of 40 crystals per device per day:

- crystal dimensions and planarity of each face with a precision of ± 5 μm,
- transverse optical transmission in the range 300 nm to 700 nm at 10 points along the crystal with an absolute precision of ± 0.5%,
- longitudinal optical transmission in the range 300 nm to 700 nm with an absolute precision of ± 0.5%,
- decay-time characteristics,
- light yield at more than 10 points along the crystal in order to measure its uniformity with an accuracy of 0.1% per $X_0$.

One ACCOS machine will be installed in each of the production centres, as well as in each regional centre (two for the barrel and one for the endcaps, see Chapter 8), so that the above-mentioned parameters can be systematically measured on each crystal before and at reception in the regional centres. Quality-control data will be provided by the producer for each crystal.

A centralized database [2.26] will be built at CERN with a link and automatic transfer procedure from the local databases in the regional and production centres. It is also foreseen to have at CERN a company representative of the producer who takes part regularly in the crystal measurements to give fast feedback. Details of this organization are discussed in Section 8.1.

### 2.4.4 Production schedule

The production of large size monocrystals at this unprecedented scale cannot be started before systematic investigation of all the technical parameters that influence the crystal
performance and the cost. This is the reason why ambitious R&D programmes were started in 1995 in China (Shanghai Institute of Ceramics (SIC) and Beijing Glass Research Institute (BGRI)), Russia (Bogoroditsk Techno Chemical Plant (BTCP)) and Czech Republic (CRYTUR) with proper funding and well defined milestones.

A preproduction phase will start mid 1998 for about 18 months until the end of 1999. This period will allow producers to start with their production equipment and to progressively increase the capacity up to an average production rate of 1700 crystals per month. Production of a total of 7000 crystals is foreseen during the preproduction phase. All crystals for the barrel shall be produced by September 2003 and those for the endcaps by February 2004.

 Suppliers will be selected following applicable Purchasing Rules. Table 2.2 shows, as an example, a possible annual production rate for the anticipated scheme involving two producers. Potential suppliers involved in the R&D programme have confirmed that these production rates are technically feasible.

Table 2.2: Possible annual production rate$^a$)

<table>
<thead>
<tr>
<th>Potential suppliers</th>
<th>Preproduction</th>
<th>Production</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998</td>
<td>1999</td>
<td>2000</td>
</tr>
<tr>
<td>BTCP</td>
<td>1000</td>
<td>5000</td>
<td>8000</td>
</tr>
<tr>
<td>SIC &amp; BGRI</td>
<td>1000</td>
<td>6000</td>
<td>9000</td>
</tr>
</tbody>
</table>

$^a$) It should be noted that the multiple pulling furnaces developed in China require more time to be operational than the existing Czochralski furnaces from Bogoroditsk. On the other hand they will allow a higher production capacity after 2001 with a smaller number of machines.

References


[2.5] Paul Lecoq, Private communication from Bogoroditsk.


[2.11] Charles Evans and Associates, 301 Chesapeake Drive, Redwood city, CA94063, USA.

[2.12] Shiva Technologies West Inc., 16035 Caputo Drive, suite C, Morgan Hill, CA95037, USA.


