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Status of the lead tungstate crystal calorimeter of CMS

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In this talk, the main design features of the electromagnetic calorimeter of the CMS experiment at LHC are briefly reviewed and the current state of the production and R&D on lead tungstate crystals is summarized. The planned steps for the realisation of the calorimeter until installation in the LHC pit are indicated.

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1. INTRODUCTION

It was stated many times in recent years [1] that very high-resolution calorimetry is needed at least in one of the LHC experiments. Only homogeneous and 'dedicated' calorimeters may reach the ultimate resolutions desirable in particular for Standard or Supersymmetric Model Higgs search. Amongst the homogeneous techniques, crystals [2] are certainly the most tried and reliable technique, provided a dense, fast, radiation hard and relatively cheap crystal can be developed.

The Compact Muon Solenoid (CMS) Collaboration [3] decided to put the emphasis on very good muon, photon and electron detection. In October 1994, CMS chose to use a new, very dense and fast crystal, already grown in Russia and Ukraine in large dimensions: the lead tungstate (PbWO_4 or PWO). This crystal has been studied since 1991 by the LAPP-Kharkov-Minsk-Protvino collaboration [4] and since 1993 by the 'Crystal Clear Collaboration' [5]. Extensive R&D on PWO is still going on in these collaborations in the frame of CMS. After reviewing the main areas of the ECAL design, the status of generic crystal R&D and of beam test performance, as well as present ideas on crystal preparation and assembly, will be summarized.

2. PHYSICS GOAL

A high resolution calorimeter will be very valuable for all the LHC physics involving electrons and gamma-rays. But, searching for SM or SUSY Higgs bosons of mass between 80 and 150 GeV/c^2 can only be performed by detecting $\gamma\gamma$ or $\gamma\gamma l$ final states. The difficult observation of $H \rightarrow \gamma\gamma$ signals over a very large background was taken as benchmark for the CMS electromagnetic calorimeter (ECAL), since the detector performance completely dominates the observed mass resolution, due to the low natural width (≈ 10 MeV) of the Higgs below 200 GeV.

In the detection of the two-photon decay mode of a Higgs boson in the intermediate mass region, the photon energies are such (30 ~ 80 GeV) that the stochastic term (a) of the energy resolution parametrized as: $\sigma/E = a/\sqrt{E} \oplus b$, has to be low as well as the constant term (b). A small a-term (2-3%) is readily obtained with homogeneous calorimeters if enough light is collected. A low b-term ($\sim 0.5\%$) is difficult to reach for any calorimeter and implies a 'dedicated' detector, i.e. fully-optimized with high priority in the experiment and no compromise in quality whether in the design, construction, operation or analysis phase. In particular, at LHC, precise and frequent calibrations must be performed using electrons from Z and W, momentum analysed by a high-resolution tracking system. With crystal calorimeters, one can expect to reach such a level of performance as demonstrated by the physics results of several past and present experiments (Crystal ball, L_3 , etc.). Also, fine granularity and good hermiticity are relatively easy to achieve.

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The very high luminosities foreseen at LHC ($\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) bring additional severe constraints on the detectors, such as speed of crystal response and of electronics and resistance to radiations of all components. The operation of the collider with bunch crossings every 25 ns will cause pile-up of up to 20 events per crossing. This will complicate pattern recognition and background rejection (weakening of the isolation criteria). The detector must then be capable of π^0 identification by 2γ separation up to high momenta, in order to reject most of the QCD background. This requires a small crystal granularity. Moreover, the proton bunch length will result in an extended pp interaction region ($\sigma_z \sim 5.5 \text{ cm}$), thus causing an ambiguity on the 2γ vertex z-coordinate, which will increase the mass resolution. A pre-shower detector will be added for high luminosity runs allowing to reconstruct a first point of the pho-

ton shower axis. Together with the shower barycenter in the crystals, the photon angle will thus be obtained.

From all these considerations, one can deduce design goals and expected mass resolution for ECAL (Barrel), as shown in Table 1. From the design figures and from the signal and background calculated cross-sections, one can estimate the Standard model $H^0 \rightarrow 2\gamma$ signal significance (Signal/ $\sqrt{\text{Background}}$) reachable with ECAL in two luminosity conditions (see Fig. 1). One can see that for moderate luminosities ($\sim 3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$), one obtains in one year levels of significance only slightly lower than at high luminosity, due to better mass resolution (see Table 1). This feature will be used by CMS to try to establish the possible existence of a Higgs in the intermediate mass region during the few years of luminosity ramping-up of LHC.

Table 1

Design goals and expected contributions to mass resolution (2nd line, in MeV) for the ECAL Barrel ($M_H=100 \text{ GeV}$)

Contribution	Stochastic term (a)	Constant term (b)	Electronic noise (MeV)	Energy pile-up	γ angle reconstruction	Total (MeV)
Low luminosity	$\sim 2\%$ 150	0.5% 350	$\leq 150/\text{shower}$ 200	/	use char. tracks 200	475
High luminosity (with preshower)	$\sim 5\%$ 400	0.5% 350	$\leq 150/\text{shower}$ 200	250	$40 \text{ mrad}/\sqrt{E}$ 500	775

Figure 1. Cross-section times 2γ branching ratio required to give specified significance, as a function of Higgs mass at two different luminosities. The contour of $\sigma \times \text{BR}$ calculated for H^0 of the standard Model is indicated.

3. GENERAL FEATURES OF THE ECAL DESIGN

3.1. Crystal geometry

The choice of the internal radius of the calorimeter is important, since it is related to many items: pile-up of events in the calorimeter, cutting of low p_T tracks by the 4 Tesla solenoidal magnetic field, 2γ separation, vertex determination, radiation levels and detector cost. In the case of PWO, an internal radius of the order of 1.5 m was found to be a good compromise between these factors, ensuring an acceptable level of pile-up in ECAL even at high luminosities. The pseudorapidity ($|\eta|$) coverage should be as large as possible to maximize the 2γ signal significance, stopping at rapidities where pile-up and radiation levels may become too severe.

All crystals ($\sim 106\,000$) are towers pointing to the interaction region (or nearby) and arranged in a cylindrical barrel of 1.42 m inner radius, covering a rapidity range of $\eta = \pm 1.55$, and in two end-caps extending the coverage to $|\eta| \sim 2.6$. Fig. 2 represents a quarter view of an ECAL section in its baseline version. The acceptance losses are dominated by the cracks at $|\eta| \sim 1.55$ which are now being studied in view of their reduction.

Figure 2. Quarter of the longitudinal section of ECAL barrel and endcap.

The truncated pyramid-shaped crystals are 23 cm ($\sim 25X_0$) long in order to minimize shower rear leakage and nuclear counter effect in the photodetectors. The granularity ($20.5 \times 20.5 \text{ mm}^2$ front sec-

tion) was dictated by π^0 identification and position resolution. The crystal axis are tilted by 3 degrees in theta and in phi with respect to the vertex pointing direction, in order to eliminate most of the effect of the cracks between crystals and to alleviate the effect of cracks between modules.

3.2 Mechanical support structure

Recently, a task force appointed by the ECAL community in order to reach a unified mechanical design based on the different approaches proposed by several laboratories gave its conclusions. The main features of the common barrel design are:

- alveolar structures (glass fiber) for 2×6 crystals form self-contained submodules,
- modules of 24×24 or 24×30 crystals form the basic units for assembly in the regional centers and transportation to CERN,
- supermodules (4 modules), containing 24 crystals in phi and 102 in theta and supported by a U-shaped spine beam, constitute the independant (readout, cooling, monitoring) units for beam testing and installation.

The alveolar structures for 12 crystals with photodetectors (APD), cooling bars and optical fiber system will be held rigidly at the back and at the front, thus transmitting their weight without constraints on the nearby submodules. About 50 submodules will be stacked in a carbon fiber box forming the walls of a module. Space should be below 0.5 mm between crystals and ~ 6 mm between modules.

The mechanical design of the end-caps is well advanced and follows essentially the rules of the barrel. A detailed mechanical design study of barrel + end-caps is now underway with the aim of placing an order at the end of 1997.

3.3 Electronic readout and trigger

The ECAL crystal readout presents following specific features:

- the relatively low level of light collected from PWO crystals together with the presence of a high magnetic field (4T) implies the use of photodiodes with gain: Avalanche PhotoDiodes (APD);

- confinement of the front-end electronics very near to the crystal back face implies low power dissipation design and rad hard technology;
- a large dynamic range (25 MeV to 2.5 TeV) compared to the range available in high precision, high speed ADCs implies compression of the dynamic range.

APDs are now available commercially at prices progressively decreasing. For our application, further R&D is necessary to bring the characteristics near to our specifications. Contracts have been placed by CMS with Hamamatsu and EG&G for such development over ~2 years. New series were sent recently for our 1996 beam tests. Large progress was already achieved. In parallel, larger areas are being investigated.

Some data indicating a substantial effect of high neutron fluxes on the APD leakage current, several methods to reduce this effect are being studied. One of them would consist in reducing the ambient temperature to ~15 degrees or lower. The consequences on the crystals are being evaluated. Some typical values of APD characteristics as measured on a 1995 batch can be seen in Table 2.

Table 2

Typical characteristics of Avalanche Photodiodes (still in evolution!). G is the APD gain factor. The excess noise factor comes from the fluctuation of the gain. The effective depleted thickness is relevant for the nuclear counter effect.

Parameters	EG&G	Hamamatsu	Comment
Sensitive area (mm ²)	5 × 5	Φ = 5	
Sensitive layer (μm)	1-2	1-2	
Amplif. region (μm)	< 10	30	
Effective depleted (μm)	3.5	~5	G = 50
Capacitance (pF)	30	100	
Q efficiency (%)	75	80	(500 nm)
Excess noise factor (F)	2.8	1.8	G = 50
1/G × dG/dT (%)	3.5	2.5	G = 50
1/G × dG/dV (%)	2	4	G = 50

The main directions for further progress on APDs are: decrease of leakage current, of excess noise factor (<2 for G = 50), of nuclear counter effect and increase of the amount of light collected by improving the optical coupling of APD to crystal and by increasing the APD's sensitive area.

The design of the front end analogic electronics is still at the level of simulations and prototyping. Prototypes for the different approaches being studied were tested on a crystal matrix in a beam during Summer 1996. Improvements and hardened versions should be ready by end of 96 and decisions on the final choices should be taken before end of 97. The main issues for the preamplifiers are: signal/noise ratio, pulse shape, large dynamics, power dissipation, radiation hardness. For the compression, two approaches are explored: switched linear amplifiers (multiplier chain) and non linear active feed back chains with square root or pseudo-logarithmic compression.

3.4 Calibration and monitoring

The intercalibration of all channels to a level of ~ 0.25% is mandatory, if an energy resolution of better than 0.6% is the target at ~ 100 GeV. It is a very difficult task to maintain such a level on more than 100 000 channels in the LHC environment. The best hope comes from physics, which at LHC should help (more than at LEP!), if one uses the electrons from Z and W bosons. In fact, the crystal + readout calibration is planned in several steps:

a) Precalibration: it is foreseen just before assembly of a module. It represents a last test of the crystal +APD system and a precalibration of each channel. It can be performed on a wrapped crystal equipped with APD or on a fully equipped submodule of 2 × 6 crystals. The possibilities explored for the time being are cosmic rays, particle beams or ~ 100 MeV microtrons. Cosmic calibration can also be foreseen on a full module, while it is waiting for assembly.

b) Beam calibrations: all crystals (~110 000) should be calibrated in a direct electron beam at 2 or 3 energies to a precision of ~ 0.25%. Entire super-modules (~2500 crystals) equipped with final services (cooling, monitoring) will be handled in the beam by a special mechanical device.

c) Calibration by physics in-situ: Electron pairs from Z and E/p comparison for electrons from W bosons can be used, the momenta being analysed in the high precision CMS tracker. The rates, evaluated from known cross-sections and calculated efficiencies for isolation cuts, allow calibration of each crystal to ~ 0.25% in ~ 1 week at high luminosity and a few

weeks at lower luminosities. This is certainly the most powerful way to obtain very good intercalibration and absolute calibration of each crystal for gamma energies of 20 to ~80 GeV.

d) Monitoring: in spite of the large efforts of the crystal producers and of CMS to obtain radiation hard crystals, variations of a few % during high luminosity runs have to be expected. These variations could have the period of a fill, typically of the order of one day. Only regular monitoring runs (each hour for instance) with light distributed to each crystal and response measured to a precision of ~ 0.25% will allow corrections for these effects. It is planned to use pulsed laser light at two wavelength (480 nm and red) injected at the front of the crystals via quartz optical fibers. The light sources pulsed at a few kHz will be located outside the magnetic field and monitored by Si PIN diodes and PMTs. With this method, the readout but also the optical transmission of the crystals, which is very likely to be the only cause for eventual signal loss due to radiations, are monitored. A precision and stability level of 0.3 % was already obtained in the crystal monitoring system [6] of the L3 experiment at LEP.

4. PROGRESS ON PbWO_4 PRODUCTION

During years 1995–96, a large progress on the production of long crystals in terms of optical, scintillation and mechanical properties, was obtained. The main results, based on the study of more than 100 crystals with geometry close to that of the ECAL design, will be summarized in Section 4. Crystals are presently produced for CMS at different levels of development in three countries:

Bogoroditsk (Russia)

More than 127 PWO full size crystals produced by Csokralsky method were delivered in 1994–95 from Russia and many of them went in a high energy test beam. During this period, several important improvements took place:

- the quantity of raw material per crystal was reduced from 4 to 2 kg,
- the crystal length increased from 21.5 to 23 cm,
- the ingot's diameter increased from 30 to 34 mm,

- the average light yield increased by more than 30%.

Problems of high cracking probability during machining, due to the fact that the annealing process taking place after the growth was not well optimized for larger ingots are now solved. 100 new full size crystals were ordered from Bogoroditsk for the 1996 beam tests and many of them are now in the test matrix.

Ingots of 85 mm diameter and 230 mm long were also grown in Ukraine. They may be used for the larger end-cap crystals and perhaps for producing several crystals from one ingot.

Shanghai Institute of Ceramics (SIC, China)

The R&D on PWO crystals started in 1995 at SIC. Twelve good quality full size crystals were produced recently by the Bridgman-Stockbarger method using square-section crucibles and multiple pulling. Good transmissions and light yield were observed. This demonstrates that this method also works well for PWO. Nevertheless, SIC also experiences high cracking probability.

Crytur (Czech Republic)

The Crytur company started work on PWO only end of 1995 and produced already several samples (up to 15 cm) of good quality, by Csokralsky method. Moreover, a good collaboration with Bogoroditsk was established.

5. R&D ON PbWO_4 CRYSTALS

Large PbWO_4 crystals were produced and studied since 1991 by the Annecy-Kharkov-Minsk-Protvino collaboration [4]. At the Chamonix conference on heavy scintillators in 1992 [7], this collaboration proposed to use PWO for calorimetry at LHC and since then they performed R&D in close collaboration with Bogoroditsk. The Crystal Clear Collaboration worked extensively on PWO since 1993 concentrating on the generic aspects of this crystal [8]. The main results of CCC in the two last years on PWO scintillation properties are summarized hereafter. The very high density of PWO resulting in short radiation length and small Molière radius (see Table 3) makes this crystal very attractive, since it leads to

compactness (lower cost) and to fine granularity of the calorimeter.

Table 3

Density, radiation length and Molière radius of some typical crystals

Crystal formula	Density (g/cm ³)	X ₀ (cm)	L for 25 X ₀ (cm)	Molière radius (cm)
CsI	4.5	1.9	47.5	3.8
BaF ₂	4.9	2.06	51.5	3.4
CeF ₃	6.2	1.68	42.0	2.6
BGO	7.1	1.11	27.7	2.4
PbF ₂ *	7.7	0.94	23.5	2.2
PbWO ₄	8.3	0.90	22.5	2.2

* Is only a Cerenkov radiator

5.1. Transmission

For all the measured crystals, the optical transmission from 300 nm to 700 nm was measured transversally with a 2 cm step along the growth axis. In this region of wavelength, the theoretical transmission of PbWO₄ varies from 70% to 75% assuming a variation of refraction index from 2.75 to 2.24 for ordinary index and from 2.5 to 2.15 for extraordinary index. Above 500 nm, all crystals have a similar transmission close to the theoretical transmission. Below 500 nm, the behaviour of optical transmission can be classified into 3 types as shown on Fig. 3, depending on the slope of the transmission edge and of its homogeneity for transversal measurements all along the crystal.

Type 3 crystals show a steep rise of the transmission edge between 340 and 360 nm independently of the position along the growth axis. For type 1, the rise from 340 to 400 nm is much slower suggesting the presence of an intrinsic absorption band at 350 nm. For type 2, a position dependence of the transmission edge along the growth axis can be observed. At the seed part of the crystal, the transversal transmission is of the first type, whereas at the bottom part, the transmission edge increases steeply like crystals of type 3. It was observed that undoped crystals are generally of the first type of transmission, while Nb doped crystals are often of the third type. This observation shows that Nb doping suppresses the absorption band at 350 nm. In addition, an absorption band at 420 nm has been observed for certain crystals independently of the transmission type. We will see in section 4.3 that the behaviour of the transmission curve has some relation with radiation hardness.

5.2. Luminescence properties

The luminescence properties of PbWO₄ are known since a long time [9] and consist of a blue emission ascribed to regular lattice (WO₄)²⁻ group and a green emission related to the (WO₃) group possibly associated with a F-centre [10]. The ratio between the intensities of these two emissions as well as their decay kinetics may vary in a broad range depending on the crystal growth conditions, the thermal treatments made after growth and on doping.

Figure 3. The 3 behaviours of transversal transmission below 500 nm observed on PbWO₄ crystals.

As a consequence, scintillation spectra and decay time values reported by different authors are sometimes contradictory. Recent X-ray excited emission

spectra at room temperature [11] show that the relative intensity of the blue and green components is strongly sample dependant (Fig. 4). The decomposi-

tion in blue and green light as a function of temperature (inset of Fig. 4) shows the strong quenching of both components at room temperature which also explains the short decay time of PWO.

Figure 4. X-ray excited steady-state emission spectra of PWO crystals at room temperature.

Careful measurements made on larger scale PWO production showed that the fast scintillation decay is often accompanied by a slower component and even by a super-slow (up to 1 msec) component in some of the samples and in this case a shift to the green of the scintillation spectrum is present. Heating of these samples at 100°C for 5 hours did not change their scintillation decay characteristics. The effect was first put in evidence as an unusual rise of the background in scintillation decay measurements. Recent laser excited photoluminescence spectra [12], with very low background and ranging over many time decades, show clearly extreme behaviours for 2 PWO samples (Fig. 5).

It is also worth mentioning that the green emission is not the only responsible for a slow component in PWO scintillation decay. Slow component of the decay was also put in evidence in the blue component of both undoped and Nb doped PWO crystals. Migration of excitation on various kinds of defects can affect both green and blue components resulting in a slowing down of the scintillation decay.

Figure 5. Laser excited photoluminescence spectra of 2 PWO samples.

On PWO crystals produced on an industrial scale in 1995, a tendency of a light yield increase based on more slow component contribution can be observed. The light yield is defined here as the number of photons per MeV extracted from the crystal when excited by a Co^{60} source and impinging on the photocathode of a XP2262B Philips photomultiplier viewing the largest square end face of the tapered crystals. Efforts to obtain crystals with enhanced light yield without the effect of increased slow component contribution by growing PWO crystals doped with a divalent metal (Mg) or with a reduced proportion of some impurities (Mo) were undertaken. In the 1996 production, the amount of slow component was quite acceptable and well under control, even though a small increase in light yield was observed.

In fact, an improvement of the light yield by a factor ~ 1.5 was already observed between long crystals produced in 1994 (undoped) and in 1995 (Nb doped), due to an improvement of the raw material purity and growth conditions control as well as Nb doping (found to be good for increasing the radiation hardness [13]). Today, long PWO crystals ($2 \times 2 \times 23 \text{ cm}^3$) grown with good raw material and Nb doped with a concentration of 30 ppm have an average light yield of 70 ph/MeV. For small crystals, a typical value is 200 ph/MeV.

5.3. Radiation damage

Several long PWO crystals have been irradiated with a Co^{60} source at a dose rate of 3 Gy/mn. A correlation between the transmission type and the radiation hardness was found (Fig. 6). For crystals with transmission type 1, a grey coloration appears after irradiation due to the presence of two large and intense absorption bands at 400 and 600 nm. For type 3 crystals, the observed effect is extremely small. For type 2 crystals, a gradient in the damage is observed: at the end of the crystal characterised by transmission type 1, a radiation damage is observed, whereas at the other end (type 3), the effect is much smaller. This result shows a significant correlation between the radiation hardness and the presence of the intrinsic absorption band at 350 nm. The fact that Nb doping suppresses the absorption band at 350 nm

might be an explanation for the radiation hardness improvement in Nb doped PWO crystals [13].

After irradiation, all crystals present a recovery of the damage at room temperature. The recovery of the induced absorption can be described by a sum of 2 exponentials with time constant of typically 40 hours and of 50 days respectively (Fig. 7). Furthermore, a good correlation between the recovery of the light signal and the induced absorption is observed (Fig. 8), indicating that the loss of light observed was caused only by optical absorption and that the scintillation process was not affected by irradiation.

Nevertheless, all type 3 crystals are not radiation hard. In fact, irradiation test in a high-energy high-intensity electron beam have revealed significant losses of light at unexpectedly low doses such as 100 rad, even on some type 3 crystals.

Figure 6. Radiation damage effect on PWO crystals with different transmission behaviours.

Figure 7. Recovery of the induced absorption after irradiation.

Figure 8. Correlation between the induced absorption at 500 nm and the light yield recovery.

Other parameters must play a role in the radiation effects on PWO crystals. An intensive R&D work, apart from the specific studies on production problems, is under way with the aim of identifying all the parameters of the resistance to radiation (besides transmission behaviour), in order to guarantee a sufficient level of resistance for all the crystals of the calorimeter.

6. PERFORMANCE IN A TEST BEAM

In 1994 and 95, matrices of 25 tapered crystals of PWO with the ECAL design dimensions and readout by one or two APDs, were tested in an electron beam of 10 to 150 GeV [14]. An energy resolution of $\sim 0.6\%$ at 100 GeV (Fig. 9) was obtained for a sum of 9 crystals equipped with one APD and of $\sim 0.5\%$ with two APDs, thus showing that the collected light photostatistics contribution was still significant. The resolution in position reconstructed by barycentric methods was found to be better than 0.5 mm above 40 GeV. The APDs, produced by Hamamatsu or by EG&G, are still in the optimisation phase; they had gains of ~ 50 and little nuclear counter effect due to particles emerging from the crystals and traversing them was observed, thanks to their very thin effective depleted zone ($<10 \mu\text{m}$).

Figure 9. Energy resolution measured in S9 crystals as a function of beam energy.

The above energy resolutions, measured for electrons impinging near to the center of the crystals,

satisfy very well the 1995 milestone agreed between CMS and the LHC committee. In Summer 1996, a 50 crystal matrix is being studied with the aim of obtaining a similar level of performance all over the matrix, thus showing that the problems of intercalibrations, of uniformisation of the light collection along the crystals and of corrections for the effects of the gaps between crystals are completely mastered.

7. CRYSTAL PREPARATION FOR ECAL

It is currently planned to order crystals from 3 producers. In 1998, preseries of a few hundred crystals of homogeneous quality should be delivered and full production should start in 1999 for ~ 5 years (~ 1800 crystals/month). The crystals will be systematically checked at the production plants and again at the regional centers. Four such centers are now being installed at CERN, ENEA Rome, Serpukov and South England universities for receiving and testing the crystals and for assembling complete modules (~ 600 crystals).

Producers and regional centers will be equipped with an Automatic Crystal Control System (ACCOS), in which precise dimensions ($\pm 5 \mu\text{m}$), planarities and angles together with optical transmission, decay time and light yield of ~ 20 crystals will be measured in ~ 5 hours and the data recorded in an object oriented data base accessible from any laboratory in the world via WWW. A collaboration of 3 institutes is now designing such a system which should be operational in the seven plants and laboratories in 1998.

In 1999, the first 2×6 glass fiber submodules should be available and their filling with crystals equipped with APDs and optical fibers should start. The 12-crystal units should then be tested in a high energy or a Microtron beam, or with cosmic rays, and mounted in modules of ~ 600 crystals. These modules will be progressively shipped to CERN between 2000 and 2004. From 2002 to 2004, all crystals in fully equipped supermodules (4 modules) will be calibrated in an electron beam. The calorimeter should be installed in 2004 in the pit, if physics is to start in 2005.

8. CONCLUSION

One year and a half after the selection of PbWO₄ crystals as the baseline option for the CMS calorimeter, an important progress was made in the production of large series of full size crystals. In most cases, good optical quality and acceptable light yield and uniformity were observed. The mechanism of scintillation is established and Nb doping has proven to enhance the optical uniformity and radiation hardness of large crystals. The producers seem to have now good control over slow and super-slow components: all crystals delivered in 1996 have acceptable levels of slow components with nevertheless an average light yield in progress.

However, the resistance to radiations is still not satisfactory for most crystals and a large R&D effort is being performed in order to understand all parameters governing the hardness. Moreover, the production efficiency must be improved by all producers in order to reach economically viable conditions.

Reasonable progress in APD performance and production is observed. A large progress on the general design of ECAL was performed since the technical proposal (end of 1994), in particular on mechanical support structure, electronics, monitoring, temperature stabilisation with nevertheless several aspects not yet completely defined. Satisfactory results on energy and position resolution of a crystal matrix in a test beam were obtained in 1995, showing that crystals and APD are now rather near to what is needed for a very high performance calorimeter for CMS.

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