## 7.9 BGO for the L3 Experiment: Betting on Precision

Paul Lecoq

At the time the LEP programme was launched the top quark had yet to be discovered, and its mass was expected to be within the energy range of the collider. The electromagnetic calorimeter of the L3 experiment was therefore designed to achieve the best possible energy resolution down to 100 MeV in order to explore the detailed spectroscopy of the toponium system, the putative bound state of the top–antitop quarks. A similar situation had been encountered a few years earlier, after the discovery of the J/ψ, the charm–anticharm bound system, by B. Richter and S. Ting (also spokesman of L3): the high precision study of charmonium states took advantage of the unprecedented performance of the thallium-doped sodium-iodide (NaI(Tl)) Crystal Ball at PEP. This success convinced the community that a homogeneous crystal-based electromagnetic (e-m) calorimeter would be the best way to achieve good energy resolution in the 100 MeV to 10 GeV energy range. Indeed, one hallmark of the L3 concept was the state-of-the-art performance of the calorimeter in terms of energy and angular resolution for photons and electrons over this wide energy range.

The L3 collaboration "put its money" on a recently discovered crystal, bismuth germanate (BGO). This material had been known as a scintillator for less than ten years [57]. In 1983 measurements in a test beam at CERN had demonstrated that BGO, with PIN silicon photodiode readout, had excellent properties as a homogeneous e-m calorimeter [58]. The reason for the choice of BGO was motivated by the much higher stopping power for photons and electrons compared to NaI(Tl). This meant that a compact, highly granular and high performance calorimeter could be built with minimum impact on the dimensions and cost of the external detectors (hadron calorimeter and muon spectrometer). Moreover, besides having good scintillation properties, BGO is not hygroscopic, unlike NaI(Tl).

The calorimeter was installed in a 0.5 T solenoidal magnet of almost 10 metres in diameter, and surrounding a high precision vertex detector [Highlight 7.7]. It consisted of nearly 12 000 BGO crystals with readout provided by photodiodes insensitive to magnetic field. It was composed of a cylindrical barrel with 7680 crystals and two endcaps of 1536 crystals each in a pointing geometry with a small offset of 10 mrad to avoid photon leakage in the gaps between crystals. Each 24 cm long crystal had the form of a truncated pyramid, about $2 \times 2$ cm$^2$ at the inner face and $3 \times 3$ cm$^2$ at the exit.

Transforming the BGO crystal from laboratory curiosity to mass-producible technology meeting the stringent L3 experimental specifications required a new style of R&D. A large-scale multidisciplinary effort had to be organized, a novelty for detector R&D in high energy physics. This involved a number of institutes of

the L3 collaboration, but also experts in crystallography, solid state physics and luminescence. A decade later this same collaboration would become the seed of the Crystal Clear collaboration, which made major contributions to the development and construction of the Lead Tungstate based calorimeter of the CMS experiment at the LHC [Highlight 8.8]. As a result of this effort (and thanks to the contacts of the L3 spokesman), technology for the mass production of BGO was developed at the Shanghai Institute of Ceramics (SIC), where 12 000 BGO crystals of excellent and reproducible quality were produced over a period of three years with monthly batches of 130 to 400 crystals.

The 10 t of germanium oxide needed for this production were provided as an in-kind contribution to the experiment from the strategic reserve of the former Soviet Union. The bismuth oxide was provided by China. The very pure bismuth and germanium oxides (impurity level $< 10^{-6}$) were carefully mixed in the correct stoichiometric proportions. The resulting polycrystalline powder of $Bi_4Ge_3O_{12}$ (BGO) was then poured into a platinum foil, folded and welded in the shape of the crystal (trunk of pyramid) and only slightly larger than the final crystal to minimize the losses at the mechanical processing phase. These crucibles were introduced vertically in an oven for growing the crystal, with a small seed crystal in contact with the powder. After heating-up the crucible at a temperature slightly higher than the BGO melting point (1040°C) a temperature gradient was slowly displaced along the crucible from the seed to the end. The long term stability of the electricity supply was crucial, and the interest of the Shanghai authorities in the project certainly helped in ensuring it was stable.

An accurate ($\approx 50$ μm), fast, cheap and safe method for cutting and polishing the crystals was developed at CERN and transferred to SIC. Diamond disks were used to saw the ingots to the required dimensions. The surface finish was good and reproducible enough to proceed directly to simultaneous mechanical polishing of nine crystals on a spinning table. Automatic mechanical and optical characterization benches were also developed at CERN and installed in Shanghai for systematic evaluation of all crystals prior to shipment. The yield of the crystal growth procedure was over 99%.

Because of the 0.5 T magnetic field the BGO crystals could not be read out by regular photomultipliers. Instead, two 1.5 $cm^2$ PIN photodiodes with high (70%) quantum efficiency were glued to the rear face of each crystal. The absence of gain and stringent requirement of good resolution at energies down to 100 MeV imposed severe constraints on noise in the readout electronics. A charge sensitive amplifier was mounted directly on the back of the crystals, using a low noise FET in cascade mode, with an output rise time (300 ns) matching the decay time of BGO scintillation.

Material in front of and between crystals was minimized by using carbon fibre honeycomb material, an audacious choice at that time (see Fig. 7.20). Support was provided by thin (200 μm) carbon fibre-epoxy walls between crystals and a cylindrical inner tube coupled at each end of the barrel to a conical funnel, which carried the 10 t weight of the full barrel calorimeter at four bearing pads. The light yield of BGO depends on its temperature (−1.55% per °C), so the mechanical structure also featured a complex cooling and thermal regulation system to remove heat produced by the front end electronics close to the crystals, and stabilize the temperature to within 0.5°C. This unique calorimeter, the success of a very large world-wide collaboration, achieved the original design goals: low energy 100 MeV photons could be measured with 5 MeV precision, high energy photons in the region of 10 GeV to better than 1% [24].

The mass production of BGO became a mature technology so that the excellent properties of this crystal could be exploited in other domains, such as nuclear and space experiments, as well as in medical imaging devices, where BGO became the crystal of choice for the second generation of PET scanners for about two decades.

BGO is now progressively replaced by LSO (lutetium orthosilicate), a crystal discovered in the 1990s, having a higher light yield and a shorter decay time.

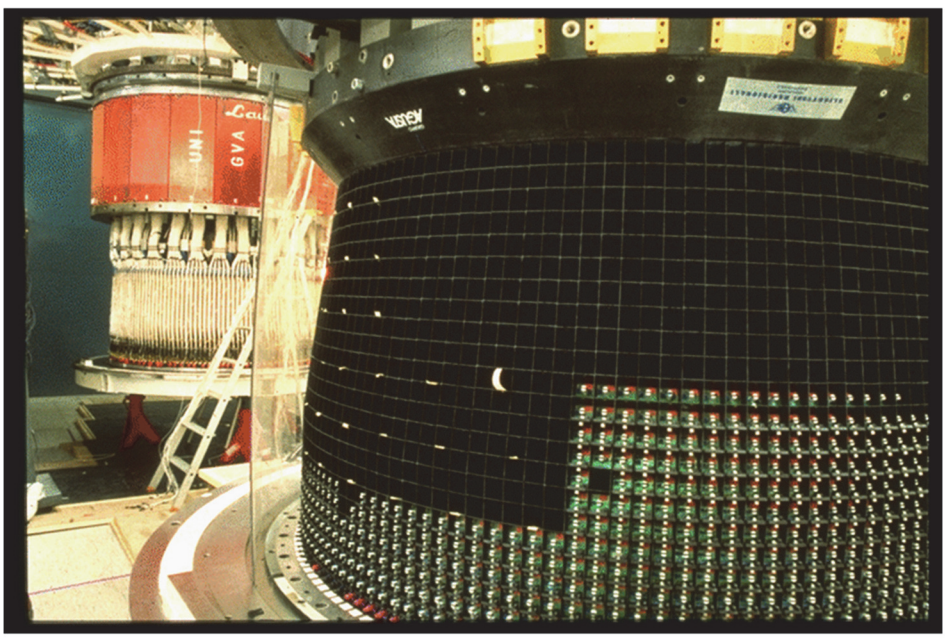

Fig. 7.20. The BGO calorimeter barrel during assembly at CERN.