Results of L3 BGO Calorimeter Calibration using an RFQ accelerator [1]

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Abstract

A novel calibration system based on a radio-frequency-quadrupole (RFQ) accelerator has been installed in the L3 experiment. Radiative capture of 1.85 MeV protons from the RFQ accelerator in a lithium target produces a flux of 17.6 MeV photons which are used to calibrate 11,000 crystals of the L3 BGO calorimeter. In this paper, we present results of the RFQ run taken in November 1997. A calibration precision of 0.6% was reached in the barrel of the L3 BGO calorimeter, and 0.7% in the BGO endcaps.

I. Introduction

L3 is one of the four experiments operating at the LEP e^+e^- collider at CERN. The L3 electromagnetic calorimeter (ECAL), composed of bismuth germanate (BGO) crystals, is one of the key parts of the detector. The crystals are arranged in two endcaps (each of 1527 crystals) and two half-barrels (7680 crystals combined) [1]. In order to maximize the discovery potential of the detector one of the performance goals of L3 is to measure electron and photon energies with 1% resolution over the energy range from a few GeV up to 100 GeV. This requires a precision calibration of the L3 ECAL *in situ*, consisting of the determination of calibration constants for each crystal.

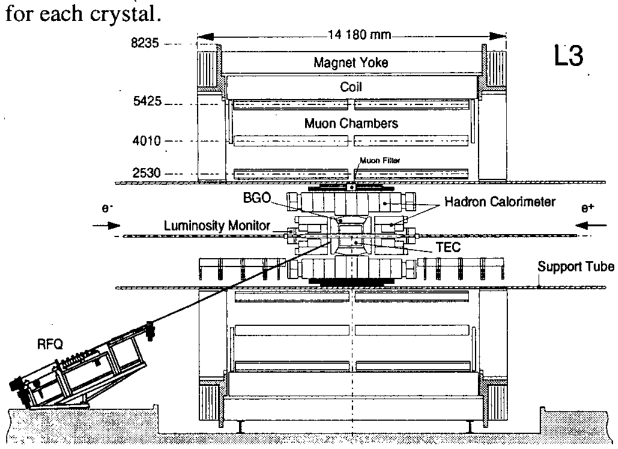

Figure 1: A side view of the RFQ system installed in the L3 detector.

The first BGO calorimeter calibrations were performed at test beams in 1987-88, prior to the ECAL installation at LEP, where resolutions of $\simeq 1\%$ were observed [2]. Since then several calibration techniques have been applied, e.g. using cosmic rays [3], xenon lamps [4], and using a Radiofrequency Quadrupole (RFQ) accelerator [5]. The RFQ system is shown together with the L3 detector in Figure 1. This system, developed by Caltech in collaboration with the World Laboratory, has provided the most precise calibration.

We present here results of the November 1997 RFQ run, which represented a major step forward: a calibration precision of 0.6% and 0.7% was achieved for the barrel and endcaps, respectively. This corresponds to an intrinsic resolution comparable to that achieved in test beam runs 10 years ago [2].

II. L3 RFQ calibration system

The L3 RFQ calibration system (Figure 2) consists of the following components:

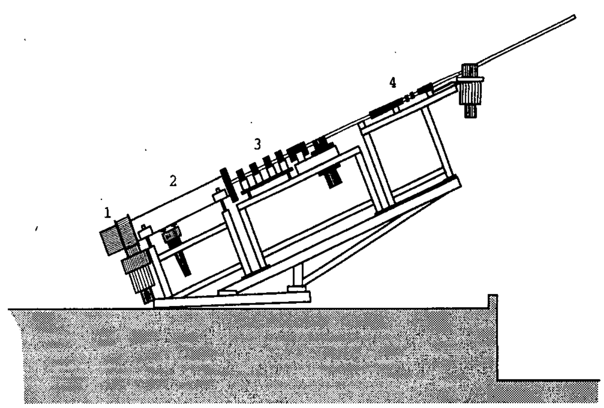

Figure 2: The RFQ system: 1. H^- ion source; 2. RFQ ion accelerator; 3. high energy beam transport and 4. beam neutralizer.

- A 30 keV RF-driven (2 MHz) volume H^- ion source and a low-energy beam transport;
- A 1.85 MeV RFQ (425 MHz) accelerator, which can provide an H^- current of 7.5 mA;
- A high-energy beam transport, consisting of quads and an xy-steering magnet;
- A beam neutralizer ($H^- \to H^o + e^-$), consisting of a 1 m long N_2 gas cell, at a typical pressure of $5 \cdot 10^{-4}$ Torr corresponding to a neutralization efficiency of 55%;

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- A 10 m long beam pipe, equipped with a star-cell ion pump (20 LPS) and a non-evaporable getter ribbon pump (3 LPS);
- A water-cooled LiH target, mechanically sealed with a thin Ta foil, mounted on the end of a 10 m long beam pipe. The position of the target is shifted [2] vertically, with respect to the geometric center of the BGO calorimeter, by -27.8 cm and horizontally by 68.9 cm (Figure 3);
- Calibration data acquisition and readout systems.

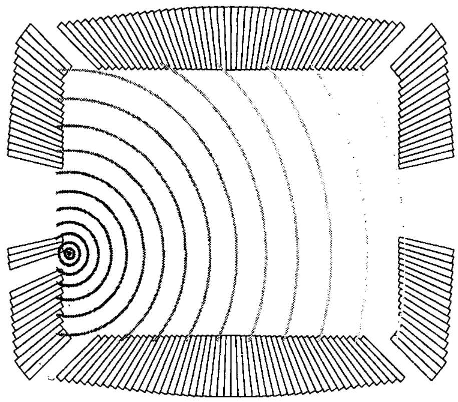

Figure 3: A side view of the BGO calorimeter with concentric circles representing the photon flux originating from the RFQ target.

The RFQ system is shielded from the residual fringe magnetic field outside the L3 magnetic door, so that RFQ calibration runs can be taken with the L3 magnet on. The RFQ calibration technique uses a pulsed H^- beam from the RFQ accelerator to bombard a lithium target installed inside the BGO calorimeter. After focusing and steering, the beam is neutralized to allow it to pass undisturbed through the magnetic field of L3. Radiative capture of the protons

$$p +^7_3 \mathrm{Li} \rightarrow^8_4 \mathrm{Be} + \gamma \qquad (1)$$

produces 17.6 MeV photons that are used to calibrate the calorimeter. Figure 3 shows the target location with respect to the BGO crystals and the propagation of the calibration photon flux. The RFQ accelerator is synchronized to the BGO calorimeter readout system, so that the calibration signal from the photon flux receives the same integration gate as the data coming from the LEP e^+e^- collider.

The photon energy spectrum of each crystal is histogramed in a readout memory. A veto on the energy deposition in the eight adjacent crystals is implemented to reject photons with energy shared between two crystals. The components of the RFQ system are described in more detail in [5].

[2]The RFQ target position had to be chosen off center as the central region inside the BGO calorimeter is occupied by the L3 Time Expansion Chamber (TEC) vertex detector.

III. CALIBRATION *in situ*

A. "RFQ Only" Calibration

The RFQ-97 run was taken from November 11 to November 15, 1997. With an average DAQ rate of 70 Hz, we recorded about 9 million triggers. The photon rate is characterized by the *photon occupancy*, defined as the fraction of triggers with energy deposition in one crystal larger than 14 MeV. The occupancy differs from crystal to crystal due to the varying location of the crystals relative to the Lithium target, and the material between crystals and the target. The typical occupancy in the barrel region was 0.08% for the half-barrel nearest to the target (Figure 4), and 0.03% for the half-barrel on the far side.

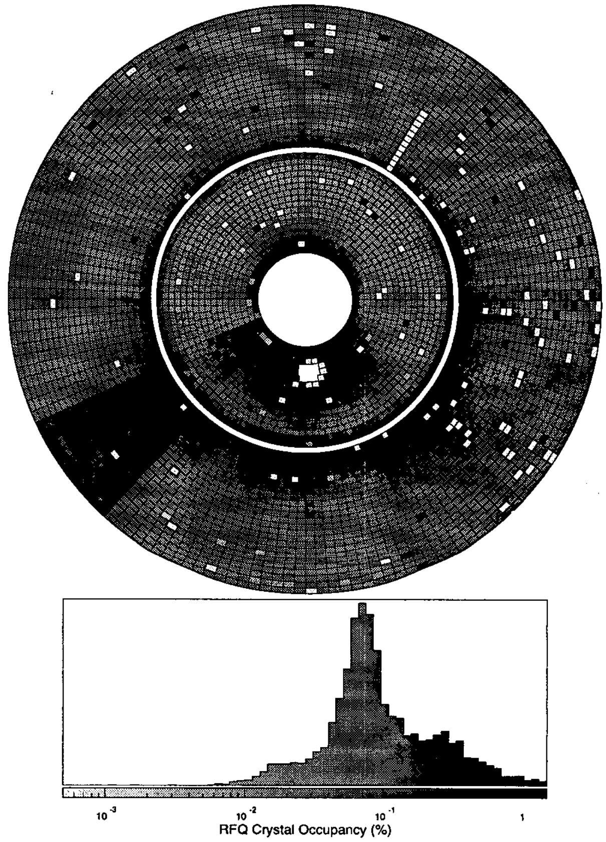

Figure 4: The photon occupancy for the near half-barrel (outer rings) and endcap (inner rings). The central hole in the endcap is for the passage of the LEP beam pipe. The smaller hole located just below is for the RFQ beam pipe and target insertion.

A typical photon energy spectrum deposited in a BGO crystal is shown in Figure 5. For each crystal the "RFQ Only" calibration constant, $C.C.$ (kev/ADC Channel), is then obtained by

$$C.C. = \frac{E_{HH^+}}{HH^+ - Pedestal}, \; E_{HH^+} \approx 17.6\,\mathrm{MeV} \qquad (2)$$

where the "HH^+" point is defined as the point half-way below and to the right of the calibration signal peak.

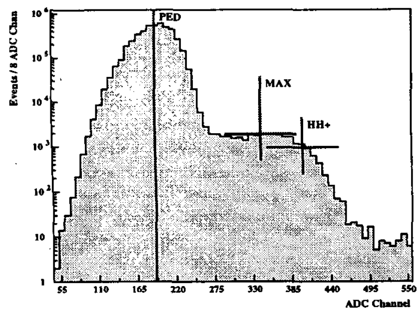

Figure 5: A typical photon energy spectrum shown with the definition of the HH^+ calibration point.

As the RFQ target position is off center, the radiative capture photons enter BGO crystals at angles up to 60 degrees with respect to the normal of the crystal. Other factors which induce systematic changes in "HH^+" point position are: 1) photon conversions or Compton scattering in the TEC chamber aluminium end wall between the RFQ target and the BGO crystals; 2) uncertainty on the energy measurement in neighboring crystals used as veto; 3) uncertainty on the wall thickness of the carbon fiber structure that holds each crystal. To evaluate systematic error stemming from the above factors, a study was carried out at AccSys. The overall systematic error in the energy measurement was found to be 1.6% [6]. This result is in a very good agreement with simulation studies performed earlier [7]. The statistical error of the "HH^+" points for November 97 run was estimated using the technique described in reference [6]. On average, it was found to be equal to 1.4%.

The "RFQ Only" calibration constants can be used as an absolute energy calibration to reconstruct the electron energy from Bhabha scattering (described below). The Bhabha peak resolution obtained using this method is approximately 2.5%. The absolute energy scale of the "RFQ Only" calibration is shifted by 8% towards higher energy. This is largely due to the BGO calorimeter non-linearity in extrapolating from the energy scale of the calibration (17 MeV) up to the 90 GeV beam energy range. Other factors contributing to the resolution are the electromagnetic shower leakage, the light collection non-uniformity and the energy loss in the material between the BGO crystals.

Most of the systematic bias in the calibration constant for each crystal, arising from the above mentioned contributions, remains unchanged in time. To correct for this bias the "RFQ+Bhabha" method was developed.

B. *"RFQ+Bhabha" Method*

At e^+e^- colliders, such as LEP, Bhabha scattering ($e^+e^- \rightarrow e^+e^-(\gamma)$) produces electrons of energy close to that of the beam. The beam energy known with a very good precision is widely used as a high-energy calibration point.

The "RFQ+Bhabha" method uses the "RFQ Only" calibration as an inter-calibration. The energy spectrum from high-energy electrons from the Bhabha scattering process is then systematically applied to correct for geometrical effects and the non-linearity of the calorimeter energy response. The correction factor for a given crystal is obtained through:

$$C.F. = \frac{1}{\sum_{i=1}^{N_{ee}} w_i} \sum_{i=1}^{N_{ee}} \frac{E_{beam}}{E_i} w_i \tag{3}$$

where:

1. N_{ee} is the number of selected BGO "bumps"[3] containing this crystal in the 3×3 crystal matrix centered on the crystal with the maximum energy deposition ;
2. E_{beam} is the beam energy;
3. E_i is the energy of the ith bump computed using ADC values and the calibration constants from the "RFQ Only" method;
4. w_i is the weight assigned to the ith event for the crystal, which we put to be equal to the ratio of the energy deposited in the crystal to the total energy deposited in the 3×3 crystal matrix. (Both energies were computed using the calibration constants from the "RFQ Only" method and ADC values.)

Special care was taken when a bump contained a dead crystals in its 3×3 matrix or when it was on the edge of the BGO detector. To evaluate E_i and w_i for such bumps we used a shower-fitting algorithm, which corrects for bump energy loss due to dead or missing crystals in the 3×3 matrix. For each crystal the calibration constant is multiplied by the corresponding correction factor. Then we again computed correction factors for the new calibration constants. We needed to repeat this procedure a few times before the calibration constants converged to stable values. Doing such iterative computation significantly improves the precision of the calibration.

The ECAL resolution obtained using the "RFQ+Bhabha" method is significantly better than the resolution obtained with the "RFQ Only" calibration constants. However, the precise ECAL inter-calibration done with RFQ data is the cornerstone of the "RFQ+Bhabha" method. Special studies have shown that the best calibration accuracy obtained using only Bhabha events is more than two times worse than the accuracy achieved using the RFQ inter-calibration.

To increase the Bhabha statistics it was necessary to use the data collected at all LEP beam energies from 1995 to 1997. To correct for L3 ECAL response evolution both in time and in energy we performed careful studies of the calorimeter non-linearity and aging.

It was noticed that the response of the BGO calorimeter drifts with time towards lower values. The decay trend is described quite well with a function

[3] A BGO bump refers to a local maximum of energy deposition in the calorimeter and the surrounding region of crystals containing energy.

$$F(t) = \frac{a}{t - t_0} + C \qquad (4)$$

where a, t_0, and C are free parameters, and t is time elapsed since April 1995. These parameters are different for all four L3 calorimeter subdetectors[4], as they were manufactured and installed separately. The evolution plots and fitted functions are shown in Figure 7. As one can see, the decay trend is more pronounced in the endcaps than in the barrel, which is explained by the fact that the endcaps were installed two years later. This L3 ECAL aging is most probably caused by a degradation of the coating paint covering the BGO crystals.

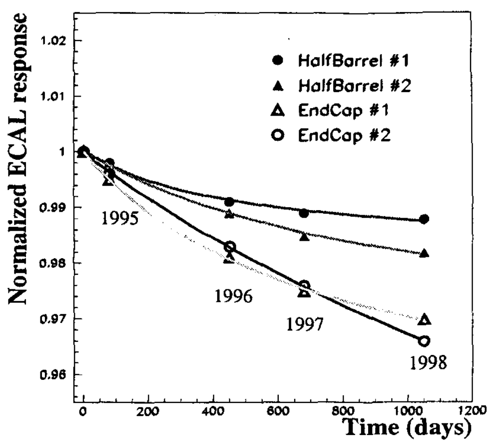

Figure 6: The L3 ECAL aging curves obtained with several LEP runs at a fixed beam energy of 45.6 GeV.

Another effect which had to be taken into account was ECAL non-linearity. During the years 1995-1997, LEP machine gradually increased center-of-mass energy, going from 91 GeV up to 183 GeV. We discovered that the calorimeter response is non-linear with energy. Every year LEP performs at least one calibration run with a 91 GeV center-of-mass energy ("Z peak" runs). To determine the non-linearity function we measured the difference between the Bhabha peak position at an energy higher than 91 GeV and the position of the Bhabha peak obtained with a 91 GeV run performed in the same year. Thus, we were able to separate aging and non-linearity effects. As can be seen in Figure 8, the L3 ECAL response shift between the beam energy of 91.36 GeV and that of 45.6 GeV is about 0.6%, i.e. almost the same as the calibration accuracy.

IV. Calibration Accuracy Measurement

The BGO calorimeter overall resolution was determined using a large sample of Bhabha events collected in 1998. This sample was not used by the "RFQ+Bhabha" method, and, therefore, the measured overall BGO calorimeter energy resolution from this data sample is unbiased. To fit the Bhabha energy spectrum we used the lineshape function obtained by

[4]The L3 BGO calorimeter consists of two half-barrels and two endcaps.

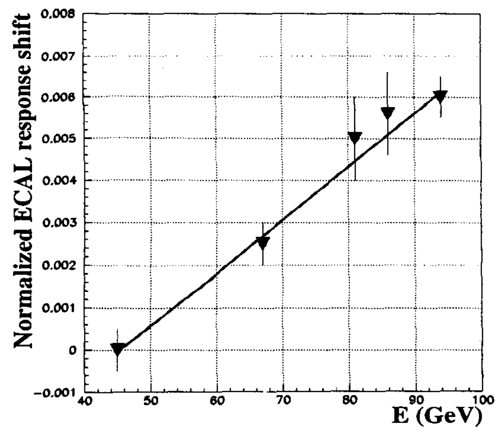

Figure 7: The L3 ECAL non-linearity function obtained with LEP runs at different center-of-mass energies.

the Crystal Ball experiment given by the following formula [8]

$$\begin{aligned}
\Psi(E_m|E_t,\sigma,A,a,n) &= A\,\exp\Big(\frac{-(E_t-E_m)^2}{2\sigma^2}\Big) \\
&\quad \text{if } E_m > E_t - a\,\sigma \\
\Psi(E_m|E_t,\sigma,A,a,n) &= A\,\Big(\frac{n}{a}\Big)^n \frac{\exp(\frac{-a^2}{2})}{\big(\frac{E_t-E_m}{\sigma}+\frac{n}{a}-a\big)^n} \\
&\quad \text{if } E_m \le E_t - a\,\sigma \qquad (5)
\end{aligned}$$

where n and a are empirical parameters, E_m is a measured energy, E_t is the Bhabha peak position and σ is the energy resolution.

The measured ECAL overall resolution is 1.1% in the barrel and 1.2% in the endcaps, as shown in Figure 9.

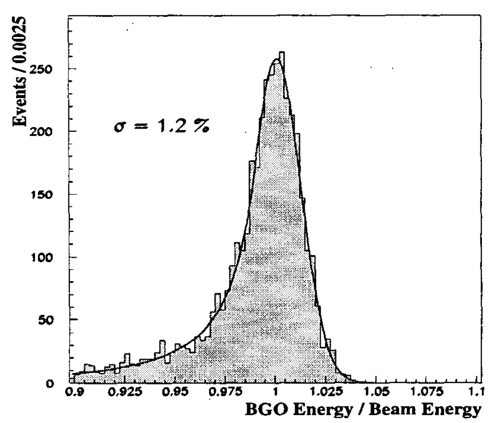

Figure 8: The 1998 endcap Bhabha energy spectrum fitted with the Crystal Ball lineshape function.

Several other factors together with the RFQ calibration accuracy contribute to this resolution. Most notable are the smearing of the Bhabha peak by the radiative events, "intrinsic" detector resolution effects, such as electromagnetic shower fluctuation and shower leakage, and the accuracy of the temperature determination.

The light response of a BGO crystal is strongly correlated to the crystal temperature with a coefficient of $-1.55\%/°C$. The temperature at the front and the back side of the BGO calorimeter is constantly monitored by 1280 sensors. On the basis of this data, a two dimensional fit is performed yielding the temperature of each crystal. A temperature correction is then applied further to the measured BGO energy. The estimated errors on the temperature measurement contribute 0.6% to the overall ECAL resolution in the barrel and 0.8% in the endcaps. The error on the measured temperature is smaller in the barrel due to its more stable cooling system and better performance of the temperature sensors.

The contribution of the Bhabha radiative smearing and the intrinsic detector resolution effects to the overall resolution was estimated using a large sample of Monte Carlo Bhabha events, which were processed through a detailed simulation of the ideal L3 detector. "Ideal" in this case means that the calibration constants and the temperature measurements of all BGO crystals are assumed to be perfectly known in the simulation. However, other detector imperfections and electromagnetic shower fluctuations are accurately simulated. The Bhabha radiative smearing and the intrinsic BGO resolution were estimated to contribute in total 0.8% in the barrel and 0.6% in the endcaps.

Subtracting in quadrature the "radiative", intrinsic and temperature resolutions from the overall ECAL resolution, we obtained the calibration accuracy of 0.6% for the barrel calorimeter and 0.7% for the endcaps. Factors contributing to the overall BGO calorimeter resolution are summarized in Table 1.

Table 1
The L3 ECAL resolution achieved with the RFQ Calibration.

	Barrel	Endcaps
"Radiative" + Intrinsic error	0.8%	0.6%
Temperature error	0.6%	0.8%
Calibration error	0.6%	0.7%
Overall	1.1%	1.2%

V. Conclusion

By analyzing data from the RFQ-97 calibration run, we have obtained a significantly more precise BGO calorimeter calibration than was previously available. This calibration is now in use for the L3 data reconstruction and physics analyses, both for a wide range of new particle searches and for the study of electroweak and radiative QED processes at LEP2.

A calibration precision of 0.6% in the barrel and 0.7% in the endcaps of the L3 BGO calorimeter is achieved. The RFQ-97 calibration, including high statistics and new analysis, has been shown to provide the highest resolution since the BGO calorimeter was installed in LEP. The RFQ calibration, and the new calibration analysis, will be used throughout the remainder of the LEP2 physics program, up to center-of-mass energies of approximately 200 GeV by the year 2000.

VI. References

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