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Precision calibration of electromagnetic calorimeters with a radio-frequency quadrupole accelerator *

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Over the last six years, Caltech and AccSys Technology, Inc. have developed fast calibration techniques by using a pulsed proton beam from a radio-frequency quadrupole (RFQ) accelerator. The RFQ beam bombards a lithium (Li) or calcium fluoride (CaF_2) target permanently installed in an experiment. Radiative capture of the proton yields a flux of single 17.6 MeV photons from a Li target or short bursts of thousands of 6 MeV photons from a CaF_2 target, which simulate a high energy photon of up to 40 GeV per calorimeter cell. This pulsed photon source can be used to calibrate thousands of crystals in the experiment with an absolute accuracy of 0.7% in a few hours or with a relative accuracy of 0.4% in a few minutes, using the two types of targets.

1. Introduction

Rapid and precise calibrations in situ have always been essential to maintain the design performance of high resolution calorimeters in high energy physics experiments. This will be particularly true in the case of calorimeters at the future high luminosity and high center of mass energy accelerators, such as the Superconducting Supercollider (SSC) or Large Hadron Collider (LHC), where high radiation doses may cause rapid gain shifts in individual calorimeter elements, especially near the beam line.

Over the last six years, the Caltech group together with AccSys Technology, Inc. have developed a novel calibration technique [1] by using a pulsed proton beam from a radio-frequency quadrupole (RFQ) accelerator. Photons produced by a radiative capture of the proton beam will serve as a calibration source for electromagnetic calorimeters.

Two types of targets may be used: a lithium target or a calcium fluoride (CaF_2) target. The radiative capture in a Li target, $^7Li(p, \gamma)^8Be$, produces monochromatic photons (17.6 MeV). A single 17.6 MeV photon hits a calorimeter cell and can be used to provide an absolute calibration with an accuracy of 0.7% in a few hours. The radiative capture in a CaF_2 target, $^{19}F(p, \alpha)^{16}O^*$, and the subsequent decay of the excited oxygen nucleus ($^{16}O^*$), produces hundreds to thousands of 6 MeV photons, or up to 40 GeV, per calorimeter cell. These short bursts of photons can be used to provide a relative calibration with an accuracy of 0.4% in a few minutes.

This report describes the RFQ-based calibration and summarizes the results of tests done at AccSys Technology, Inc. Section 2 describes the AccSys RFQ and the detector setup used in the test. The results of beam tests for lithium and fluoride targets are presented in sections 3 and 4. A summary is presented in the last section.

2. RFQ accelerator and experimental setup

The RFQ is a quasielectrostatic accelerator, with advantages of a high beam current (up to 100 mA of protons) and a very compact size. The AccSys RFQ uses an H^+ ion source and produces a 1.92 MeV pulsed proton beam. The principal specifications of the AccSys RFQ are listed in table 1. The targets were mounted in a vacuum glass tee on movable shafts connected through an O-ring assembly to the outside. The target and mounting shaft were electrically connected to ground through a 100 Ω resistor. The charge of the beam pulse was integrated by a LeCroy 2249W ADC. Fig. 1 shows a schematic view of the detector setup for the test, together with the RFQ accelerator and the target, at AccSys.

A 7 × 7 crystal matrix was used as a test detector. The crystals used are made by bismuth germanate ($Bi_4Ge_3O_{12}$, i.e. BGO) [2]. All the BGO crystals were of the L3 standard size, approximately 2 × 2 cm^2 in the front, 3 × 3 cm^2 in the back and 24 cm long [3]. The readout of the BGO matrix is the same as the standard

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Table 1
AccSys RFQ specification

Accelerated particle species	H^+
Input ion energy	30 keV
Normalized input emittance (95%)	$< 0.04\pi$ cm mrad
Nominal current limit	63 mA
Nominal phase-space acceptance	0.116π cm mrad
Final synchronous phase	30°
Nominal output energy	1.92 MeV
Operating frequency	417.7 MHz
Beam pulse width	1–50 μs
Beam repetition rate	1–150 Hz
Input beam current (peak)	35 mA
Intervene voltage	65 kV
Maximum surface gradient	35 MV/m
Required rf power (peak)	200 kW minimum
Output beam current (peak)	up to 30 mA
Residual vacuum	$< 1 \times 10^{-6}$ Torr
Output energy spread (90%)	$< \pm 20$ keV
Output phase spread (90%)	$< \pm 15°$

L3 readout [3]. A Motorola 68020 based single board computer was used to control a token-passing ring of ADC boards, and to communicate with a VAXStation II computer through a home-made CAMAC FIFO module.

Four barium fluoride (BaF_2) counters were constructed for the test. Hamamatsu R2078 and R3197 PMTs were chosen to read out the fast components (195 and 220 nm) [4], while a Hamamatsu R1306 PMT was chosen to read out the slow component (310 nm). The output of the PMTs was integrated and digitized by using a LeCroy 2249W ADC.

3. Lithium target test result

The Li target was encapsulated in a molybdenum holder, with a 15 μm Mo foil facing the beam. The foil was designed to help conduct heat away and to prevent the proton beam from hitting the ^{7}Li neutron resonance which has a threshold of 1.88 MeV. The foils also served as an energy degrader for the proton beam, allowing protons to hit the 441 keV resonance while avoiding undesired resonance at 1.03 MeV.

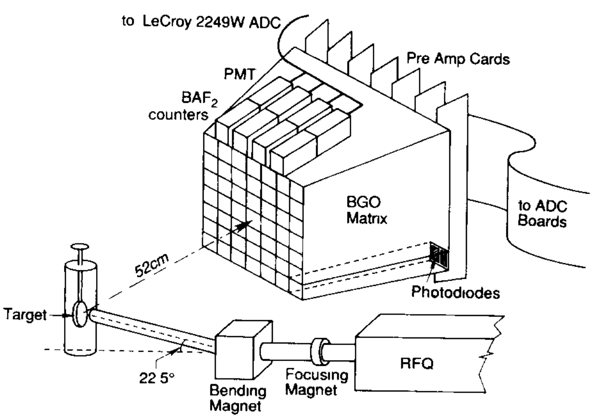

Fig. 1. AccSys test experimental setup.

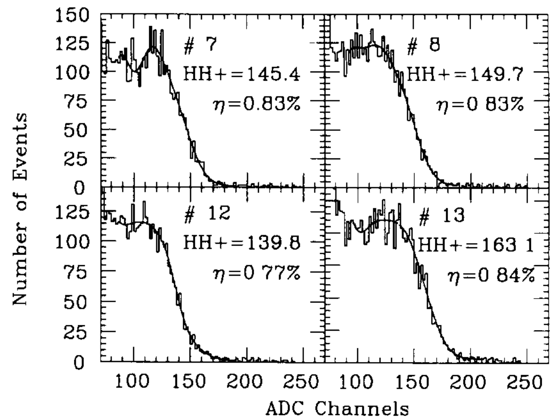

Fig. 2. Photon energy spectra and HH^+ points for four BGO crystals without veto cuts.

For the Li calibration, the photon rate was adjusted to a 2% hit probability per RFQ pulse for a single L3 BGO crystal which has a solid angle coverage of 1.6 msr. This corresponds to 1.7 nC per beam pulse. A high beam current would not help, since one has to reject events with a photon whose energy was shared by two neighboring crystals and events with more than one photon hitting two neighboring crystals. To reject these events a "veto" option may be used in data analysis.

The details of the data analysis can be found in ref. [1]. Fig. 2 shows a set of typical spectra obtained from four BGO crystals in the array plotted without the veto option, together with a spline fit. The HH^+ values (defined as the energy at which the upper edge of the spectrum falls to half of its maximum height) and the efficiency (defined as the ratio of the sum of number of events with deposited energy greater than 14 MeV to the total trigger) are also shown in the figure. It is clear

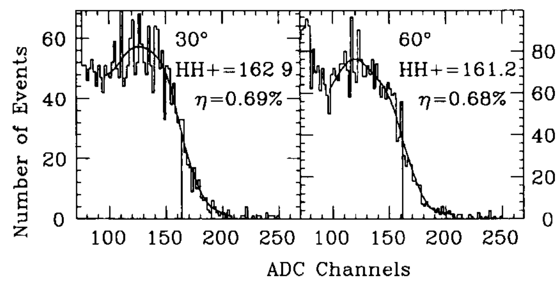

Fig. 3. A comparison of photon energy spectra of a BGO crystal with 5 MeV veto cut for two different incident angles: 30° and 60°.

Table 2
The averaged HH^+ variation (%) in comparison with Monte Carlo simulation

Case	3 MeV veto		5 MeV veto		No veto	
	M.C.	Data	M.C.	Data	M.C.	Data
30°	−0.7	−0.6	−0.8	−0.6	−0.9	−1 3
50°	−1.8	−1.4	−2.2	−1.4	−2.4	−2.5
5 cm Al	−0.5	−1.2	−0.5	−1.1	−0.8	−1.6

from the figures that in standard conditions the calibration point can be obtained without using the veto option.

A comparison of two spectra obtained from a BGO crystal for two different incident angles, 30° and 60° respectively, is shown in fig. 3. The decrease of the HH^+ points and the efficiency versus incident angle is as predicted by Monte Carlo simulations [5]. Table 2 compares the HH^+ variation with the Monte Carlo simulation for different incident angles and when aluminum is in front [5]. The overall agreement is very good.

The angle effect and the aluminum effect are fixed for each crystal for a fixed geometry, so these effects will not result in a systematic calibration error. Overall, the systematics will be dominated by the long term stability. Within the limited time of several days during the test the stability of the system appeared excellent. Table 3 lists the HH^+ points of the central six crystals without veto cut for different run conditions. Also listed in the table are the statistical deviation extracted from two identical runs. The absolute average of all 24 deviations in the table is 0.8%. The same absolute average for the case with 5 MeV veto cuts is 0.7%. The test has thus shown that a precision calibration of 0.7% may be achieved in practice for the BGO crystals in the L3 detector.

4. Fluoride target test result

The LiF target was used in an RFQ beam test. The LiF target was also encapsulated in a molybdenum holder with very thin (5 μm) Mo foil facing the beam. For the fluoride target test the photon yield was adjusted up to several GeV per crystal.

Fig. 4 is a picture taken from an oscilloscope showing typical 3 μs wide RFQ beam pulses together with the scintillation light pulses from a BaF_2 counter. As shown in the figure, a pulse-generator-like scintillation light pulse is obtained, because so many photons strike the crystal within the pulse.

A precise normalization is needed to convert the integrated pulse read out for each crystal into a calibration constant. Two normalization schemes can be chosen for this purpose: 1) the total electric charge (proportional to the number of incident protons) collected from the target for each beam pulse, or 2) the response of a stable, external "standard" (i.e. a separate) counter or a set of counters with high precision ADCs. A cross-check showed that these two normalization schemes are consistent. We used the total energy in the BGO array as our external normalization standard.

The details of the data analysis can be found in ref. [1]. Fig. 5 shows the normalized ADC distributions of a crystal for runs with different beam intensities. The perfect Gaussian distribution and the correlation between the rms width and the total energy deposited in the crystal is clearly seen.

Assuming that the shape of the energy spectrum for the individual photons emitted by the target does not change as a function of beam intensity, then the width of the observed energy distribution should be a measure of the inverse of the square root of the average number of photons. In order to test this, we defined the "relative rms", σ_R, as the ratio of the rms width divided by the energy corresponding to the peak (i.e. the average obtained with a Gaussian fit) of the distribution. Fig. 6

Table 3
HH^+ points deviation (%) of central six crystals with no veto cut

Case	Crystal number					
	7	8	9	12	13	14
0°	0.9	0.9	0.0	1.4	0.5	1.1
30°	0.3	0.0	0.7	0.5	0.2	0.3
50°	2.3	0.1	1.7	0.8	1.2	1.1
5 cm Al	0.5	0.7	1.3	0.6	0.7	0.8

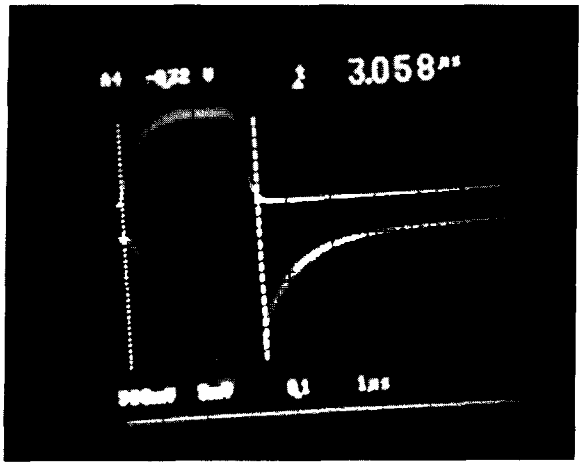

Fig. 4. RFQ beam pulse and the scintillation light pulse from a BaF_2 counter.

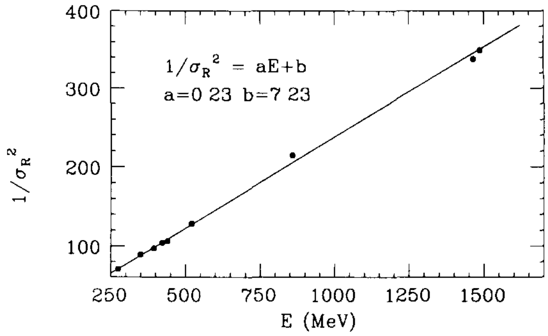

Fig. 6. Correlation between the relative rms and the average energy in a BGO crystal.

is a plot of $(1/\sigma_R)^2$ versus the observed average photon energy for a BGO crystal, for a series of nine runs where the beam intensity varied by a factor of 6. The excellent linearity shown in the figure confirms that the widths of the distributions are due to statistical fluctuations. This excellent linearity over a large dynamic range will itself provide an important piece of calibration information.

Another striking feature of the test results was the fact that the distributions were perfect Gaussians, with no sign of tails down to a level of less than 0.1%. At lower intensities, the difference between a Poisson distribution corresponding to 100 photons per pulse, and the corresponding Gaussian, could be clearly seen in the analysis. The calibration is therefore extremely clean.

Fig. 7 shows that the relative deviation of the peaks of 49 BGO distributions, normalized to the sum of energies in 49 crystals, for several runs. This distribution has a Gaussian shape with a standard deviation of 0.34%. It is therefore evident that a stability of 0.4% may be achieved.

The equivalent photon energy (EPE), defined as the sum of the energies of photons from one beam pulse hitting one crystal detector, was measured at AccSys with a LiF target. Up to 2.38 GeV/(0.1 μC 1.6 msr) was observed for a 1.92 MeV beam. There are much stronger fluorine resonances between 2.0 and 4.0 MeV [6]. By using a 3.85 MeV RFQ and a CaF_2 target, which would have no neutron production as a by-product below 4.05 MeV [6], an EPE of 40 CeV/(0.1 μC 1.6 msr) or more is expected.

Table 4 lists EPEs measured with a CaF_2 target bombarded with a proton beam from a Van de Graaff at Kellogg Lab at Caltech. The expected equivalent photon energies, calculated with an integration of the resonances [6], are also listed in the table. It is clear that with a 3.85 MeV proton beam up to 40 GeV/(0.1 μC 1.6 msr) is achievable.

In addition, the equivalent neutron energies (ENE) from a beryllium target were also estimated according to ref. [7], and are also listed in table 4. It is clear that 20 GeV/(0.1 μC 1.6 msr) ENE or more can be achieved. Further study of the signal produced by this flux of low energy neutrons in a hadronic calorimeter will be car-

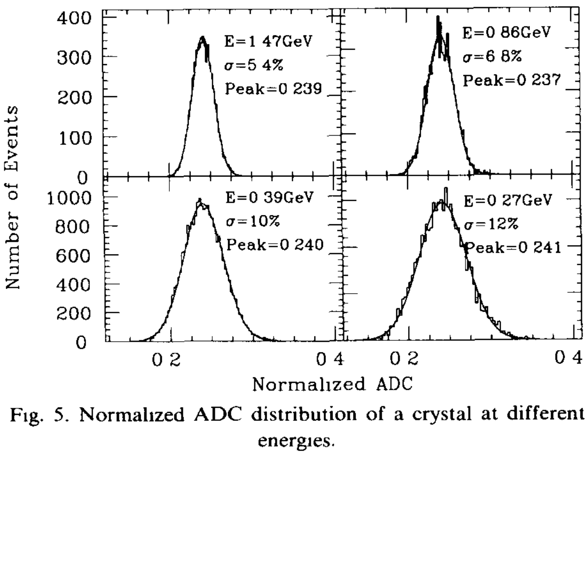

Fig. 5. Normalized ADC distribution of a crystal at different energies.

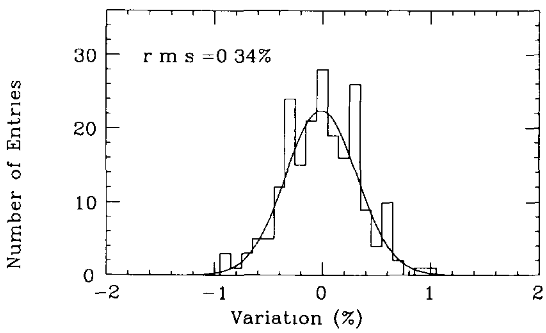

Fig. 7. Variation of the normalized peak positions from BGO crystals.

Table 4
Measured and calculated equivalent photon energy

Proton energy [MeV]	2.0	2.5	3.0	3.5	3.85
EPE_{meas} [GeV]	1.5	13	22	30	37
EPE_{cal} [GeV]	2.6	14	24	33	38
ENE_{est} [GeV]	0.0	0.3	3.5	12	24

ried out to determine if this could be the basis of another, "hadronic", calibration technique.

5. Summary

The result presented in this report demonstrates that the RFQ calibration technique with a Li target can provide a low energy (17.6 MeV) absolute calibration with an accuracy of 0.7% in a few hours. By using a CaF_2 target, this technique can provide a relative calibration up to 40 GeV per calorimeter cell with an accuracy of 0.4% in a few minutes. The first calibration RFQ will be installed in the L3 experiment in the spring of 1991.

The technique described here could be used without modification to calibrate calorimeters at the present generation of accelerators (such as LEP and HERA). This method can also be adapted for use at the next generation of hadron colliders, such as the SSC or LHC [8].

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