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PERFORMANCE OF BGO IN A HIGH RADIATION ENVIRONMENT*

G.J. BOBBINK, A. ENGLER, R.W. KRAEMER, J.NASH, R.B. SUTTON
Department of Physics
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

R.A. GEARHART, F.L. LINDE[a], J.C. SENS[a]
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94035

Presented by G.J. Bobbink

INTRODUCTION

Bismuth Germanate ($Bi_4Ge_3O_{12}$), an inert, high Z, and non-hygroscopic material, with a short radiation length L_{RAD} = 1.1 cm, has been proposed as the scintillator in a 4π electromagnetic calorimeter at LEP. Recently long BGO crystals have become available and studies of the effect of radiation have been made by several groups[1,2,3,4]. We report here on the decrease of the light output of long BGO crystals due to irradiation by ^{60}Co γ-rays and 25 MeV electrons with doses from 50 to 5000 rad and on the performance of a 4×4 matrix of BGO crystals located at small angles (5-9 mrad, a high radiation environment) at the e^+e^- storage ring PEP at SLAC. All crystals used[5] are $2 \times 2 \times 23$ or $2 \times 2 \times 24$ cm^3, have all six faces polished, and are wrapped in white teflon tape.

TESTS WITH γ-RAYS AND 25 MeV e^-

For these tests the crystals were viewed by Hamamatsu R1306 photomultipliers (PM). They were coupled to the PM with optical grease and rigidly held in place. The anode signal of the PM was connected to a multichannel analyzer (Tracor Northern 7200). Drifts of the PM and its associated electronics were monitored with Na(Tl+^{241} Am) lightpulsers. All tests were made at room temperature and the temperature of the crystals was monitored with a thermistor.

To induce radiation damage, the crystals were irradiated by γ-rays from a Picker ^{60}Co therapy unit, equipped with a multiplane collimator, and with 25 MeV electrons from a betatron, both located at St. Francis General Hospital in Pittsburgh. The crystals were irradiated uniformly over the top 6 cm (*i.e.* away from the PM) at a rate of 100 rad per minute. Care was taken to shield the remainder of the crystal, the light pulser, and the photomultiplier.

Radiation damage was determined from the change in pulse height of a ^{137}Cs source mounted opposite the photomultiplier as would be done if large arrays of BGO crystals were to be monitored with low energy sources. Figure 1 shows the change in pulse height of the ^{137}Cs photopeak and the NaI(Tl+^{241}Am) light pulser during a 300 minute time interval following the start of the irradiation for a typical crystal. The pulse height is normalized to the pulse height immediately before irradiation. It is seen that the pulse height decreases after each dose of 100 rad. This decrease is followed by a spontaneous recovery of about 30% of the damage during the first 300 minutes. Figure 2 shows that this initial recovery is followed by a much slower one. Plotted is the induced damage as function of time, defined as $D(t) = (PH_0 - PH(t))/PH_0$ with PH(t) the pulse height as function of time and PH_0 the pulse height immediately before irradiation. The time-evolution of the damage can be described by a sum of at least three exponential functions:

$$D(t) = A_1 e^{-t/\tau_1} - A_2 e^{-t/\tau_2} - A_3 e^{-t/\tau_3}$$

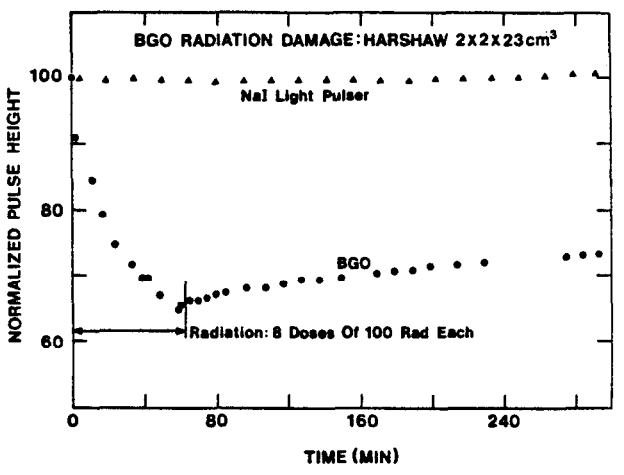

Fig. 1. Pulse height of the ^{137}Cs test source, normalized to that immediately before irradiation, versus time for a 300 minute interval.

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The line in fig. 2 represents the best fit. Similar results were obtained for other crystals. Averaged over six crystals and 11 irradiations we find: $\tau_1 = 86 \pm 40$ minutes, $\tau_2 = 60 \pm 6$ hours, $\tau_3 = 25 \pm 1$ days, $A_1 = 0.04 \pm 0.01$, $A_2 = 0.22 \pm 0.01$, $A_3 = 0.32 \pm 0.01$.

The fact that the total dose in each irradiation was given in several shots of relatively short duration made it possible to measure the change in pulse height as a function of applied dose. The results are summarized in fig. 3, where we show the pulse height (normalized to that immediately before irradiation) versus dose. It is seen that the results of multiple irradiations of a given crystal agree reasonably well and that the radiation damage is not linear with the applied dose, but in fact saturates for doses above 1000 rads. All six crystals saturate, but the saturation dose varies. No noticable difference is observed between the effect of irradiation by ^{60}Co γ-rays and 25 MeV electrons when the dose is expressed in rads.

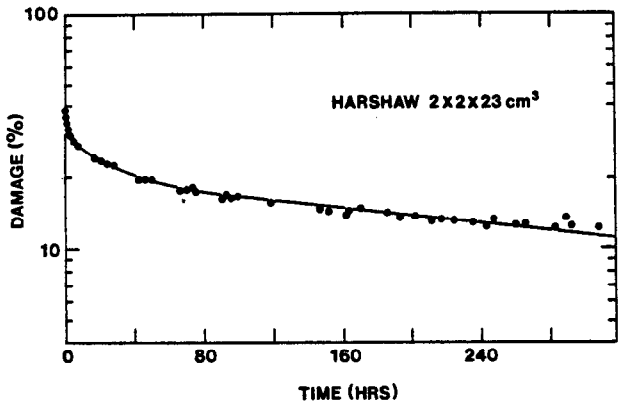

Fig. 2. Spontaneous recovery of the induced radiation damage over a 300 hour period. The line represents the best fit as described in the text.

From the variation of the damage with the length over which the crystal was irradiated, it followed that mainly the absorption properties and not the scintillation properties of the crystal have changed. Figure 4 shows the percentage of light transmitted along the 12 cm length of a $2 \times 2 \times 12$ cm^3 crystal as a function of incident wavelength before irradiation (a), 45 minutes after (b), and 235 hours (c) after irradiation of the whole crystal with 1000 rad of ^{60}Co γ-rays, as measured with a Beckmann photospectrometer[6]. After 45 minutes there is a significant difference in transmission in the wavelength region 400–600 nm —the BGO emission spectrum peaks around 500 nm—, while after 235 hours the crystal has recovered to within 5% of the transmission before irradiation.

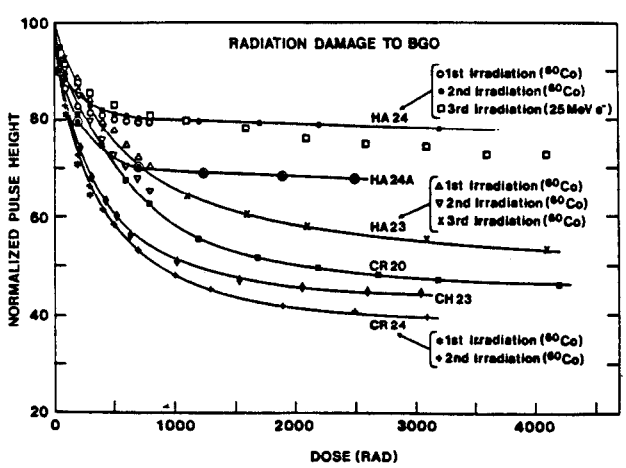

Fig. 3. Pulse height, normalized to that immediately before irradiation, versus dose.

A more extensive description of these tests is given in ref. 7.

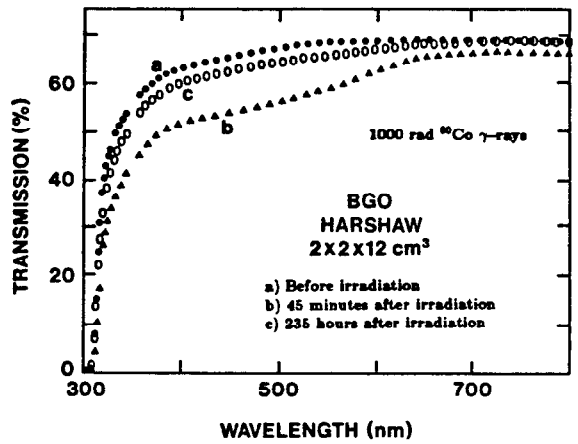

Fig. 4. Transmission of a 12 cm long BGO crystal before and after irradiation, not corrected for reflection losses.

TESTS AT SLAC

Testbeam Results

Before installation in PEP the performance of a 3×4 matrix was evaluated using positron beam P19 of the SLAC LINAC. The beam had a small momentum bite, $\sigma(p)/p = 0.1\%$, and a small beam spot with 90% of the beam particles within a radius r=1 mm. The beam was operated at energies 4, 6, 10, and 17.5 GeV/c at 10 pulses per second with an average varying from 0.5 to 4 positrons per 100 ns pulse. The crystals were viewed by Hamamatsu S1790 photodiodes. A yellow LED was mounted opposite the photodiode. The photodiodes were connected to low-noise charge-sensitive preamplifiers[8] with 50 cm coaxial cable. Shaping amplifiers[8] with a time constant $\tau = 500$ ns were located about 50 m away from the preamps. The output signals were recorded with peak sensing ADC's (Lecroy model 2259A) and written to magnetic tape using a LSI 11/2 computer. The BGO was used in self triggering mode.

The crystals were calibrated by rotating them one by one in the central position with the beam energy set to 10 GeV. Figure 5 summarizes the response of this matrix to the beam. The data shown are the pulse height distributions corresponding to 1, 2, 3,..., 9 positrons per LINAC pulse with the beam set at 6 GeV. The intensities are Poisson-distributed with a mean of $\bar{n} = 3.6$ positrons/pulse. Figure 6 shows the energy dependence of the resolution, defined as the r.m.s. width of the peaks, for three different crystals in the central position. In these measurements the pulse heights of 12 crystals were

added; typically 70% of the energy was deposited in the central crystal. In the energy range of a two-photon tagger at PEP or LEP, *i.e.* above 10 GeV, the r.m.s. energy resolution is about 1%, in agreement with the results obtained at CERN[9]. The impact point of the positron on the matrix was determined from a fit of the observed energy distribution over the crystals to:

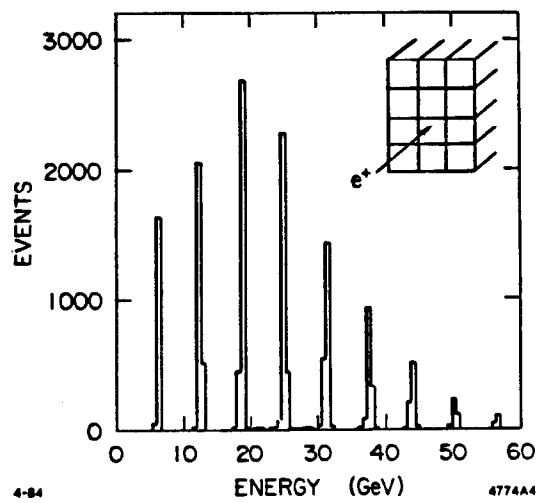

Fig. 5. Energy spectrum of the 3 × 4 BGO matrix.

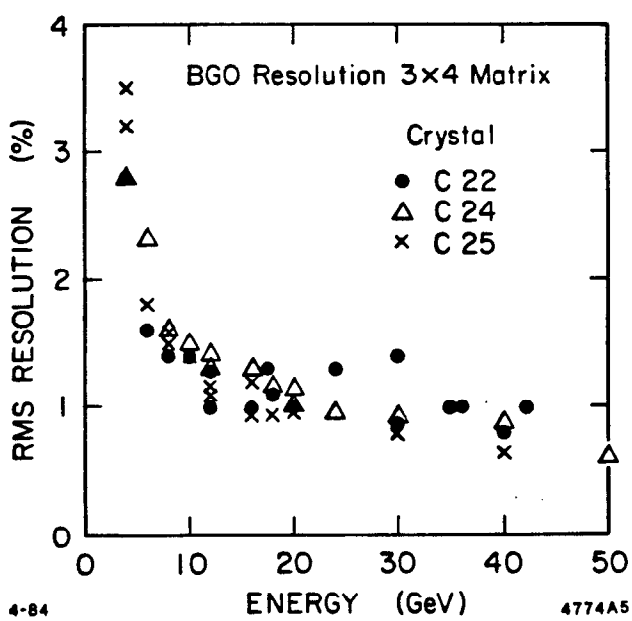

Fig. 6. Energy resolution of the 3 × 4 BGO matrix versus energy. The data come from beam energies of 4, 6, 10, and 17.5 GeV.

$$E(x,y) \propto e^{-(|x-x_{in}|+|y-y_{in}|)/\sigma} .$$

The results of a scan of the BGO matrix across the beam is shown in fig. 7, which shows the reconstructed impact points as function of the position of the matrix w.r.t the beam. The dependence of the energy resolution on the impact point of the positron on the matrix is shown in fig. 8.

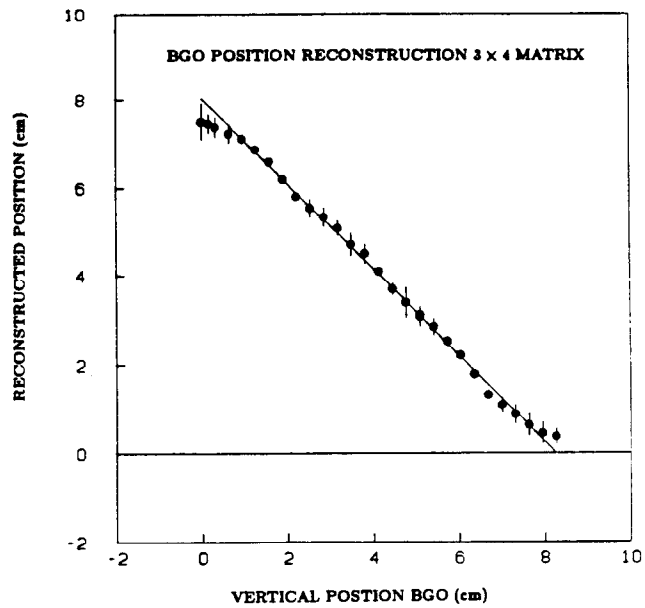

Fig. 7. Reconstructed shower position versus the vertical position of the BGO. The error bars indicate the position resolution.

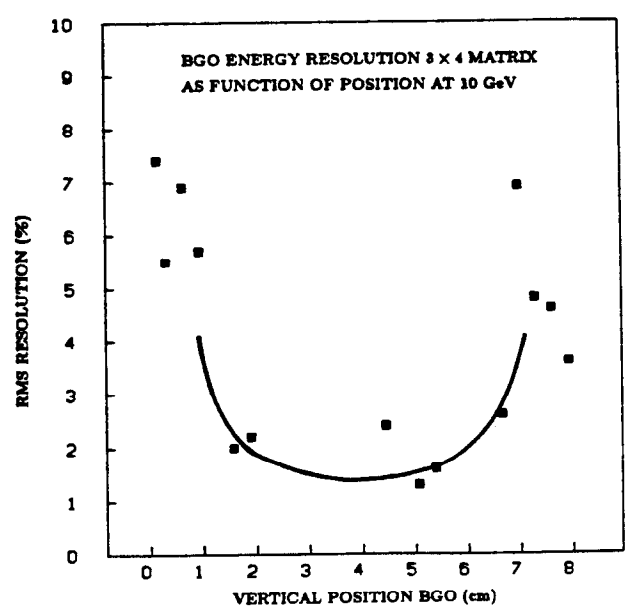

Fig. 8. Energy resolution of the BGO versus the vertical position of the BGO.

Performance at PEP

A 4 × 4 matrix of 16 BGO crystals was positioned on a remote controlled elevator table and mounted 9 m from the interaction point in intersection IR2 of PEP, behind a mini-β quadrupole. The vacuum chamber was suitably modified to accommodate the crystals in the 5-9 mrad range of polar angle. The output signals from the shaping amplifiers were recorded using charge sensitive ADC's (Lecroy model 2249W) with a 45 ns gate and were written to tape using a VAX 780.

Bhabha events were defined by means of a rough collinearity and pulse height requirement in a Pb-scintillator sandwich located at 9 m from the interaction point at the opposite side. The crystals were calibrated using these Bhabha events. Figure 9a shows the distribution of the sum of the energies deposited in the 16 crystals, corrected for side-leakage using the reconstructed impact point. Figure 9b shows the same for events with shower centers within a specified 1×1 cm^2 area. The r.m.s. resolution is 3.8% and 2.5% respectively at 14.5 GeV. Initial problems with background and R.F. pick-up were reduced to tolerable levels by appropriate shielding. Pulse height spectra recorded with random triggers indicate that approximately half of the resolution results from the combined effects of residual synchrotron radiation and RF pick-up. The counting rate of the BGO was approx. 5 kHz at a luminosity of 10^{31} cm^{-2}s^{-1}, while the Bhabha rate was $\approx$ 100 Hz. With the BGO setup in the 'in' position during 'stable' PEP performance, the pulse heights remain stable to a few percent, see fig. 10. On one occasion a heavy beam loss caused the light output to collapse and recover slowly thereafter. An example of the effect of this loss in one crystal is shown in fig. 11. Heavy losses occur frequently during refills of the ring, but rarely in between refills.

We conclude that even close to the beam the BGO setup is sufficiently stable for the purpose of tagging two photon events, provided the crystals are moved away from the beam during refills and that LED's and prescaled triggering on Bhabha's will allow us to keep track of pulse height drifts.

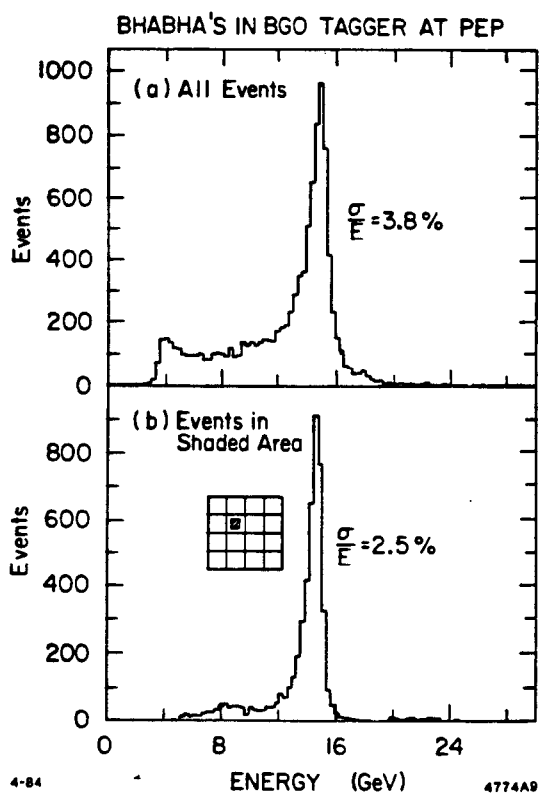

Fig. 9. Energy spectrum for Bhabha triggers: a) All triggers b) Triggers from a 1×1 cm^2 area at 3 cm from the vacuum chamber.

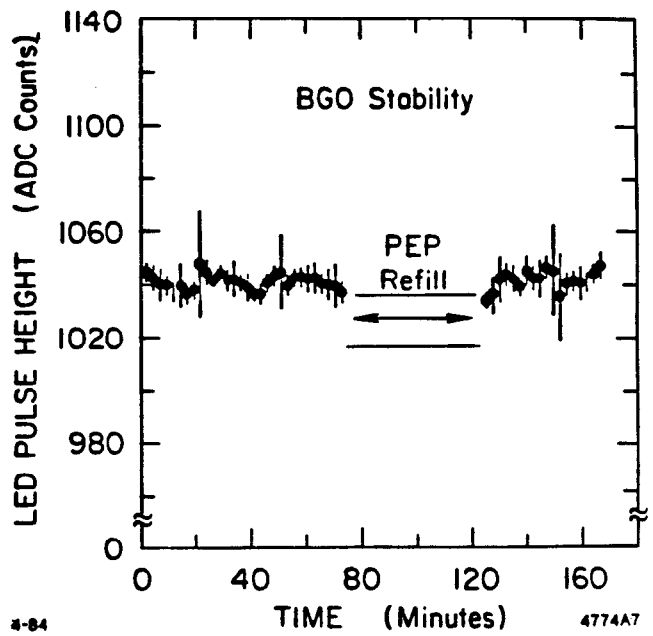

Fig. 10. Stability of the BGO as measured with the LED.

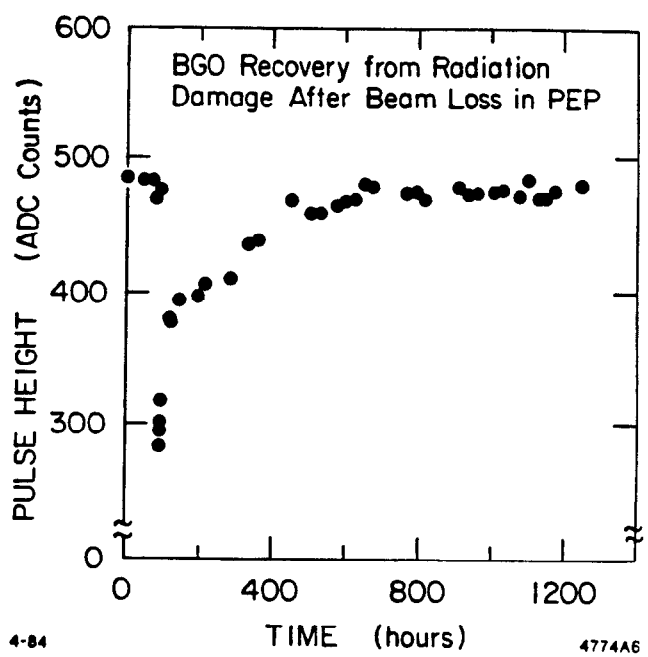

Fig. 11. Spontaneous recovery of the BGO from radiation damage after severe beamloss in PEP, as measured with the LED.

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