BaBar Note 270
Oct 1995

Development of Direct Readout for CsI(tl) Calorimeter and light yield specification for crystal vendors

C Jessop

SLAC

In a previous note we described two possible readout schemes for the *BaBar* CsI calorimeter [1]. The first solution uses a 58 mm × 58 mm × 3.5 mm wavelength shifter mounted on the back face of the crystal with a 0.5 mm air gap between the crystal and the wavelength shifter. The wavelength shifter acts as a planar waveguide and concentrates the light onto two 30 $\times$ 3.4 mm^2 photodiodes (Hamamatsu S3588-03)mounted on the thin edges of the shifter. The second solution uses two 20 $\times$ 10 mm^2 photodiodes (Hamamatsu S2744-08) directly optically coupled to the back face of the crystal. This note describes in detail the direct coupled solution.

1 Direct Diode Solution

We use two diodes because a dual redundancy is required in the readout scheme to ensure the necessary reliability [2]. The performance and reliability criteria for the diodes (Hamamatsu S2744-08) are described in detail in reference [3]. All studies so far have used Bicron optical grease (refractive index n = 1.46) to couple the diodes directly to the crystal. The grease is not mechanically rigid but it is optically equivalent to a typical optical epoxy. It was used because disassembly was required for multiple tests but is clearly inappropriate for the full detector. The criteria for a proper coupling scheme are

- Maximal light transmission from crystal to diode.

- Mechanically Stable.
- Chemically Stable.
- Reliability: Optically,Mechanically and Chemically stable for 10 years
- Ease of assembly and cost.

2 Chemical Stability

Like common salt, CsI(tl) is an extremely corrosive material. If CsI(tl) is put into direct contact with the substrate of a silicon photodiode, ions will migrate into the silicon and cause a serious degradation of noise performance. This was observed in the early prototypes of the CsI(tl) calorimeter for the CLEO II experiment [4]. As a consequence Hamamatsu subsequently developed a protective epoxy coat (n=1.53) [5]. It is this protective coat that ultimately limits the quantum efficiency of the diode since 10% of light is trapped in the epoxy. However, optical epoxies are designed to bond highly unreactive materials such as glass and acrylic and are not explicitly designed for chemical resistance. Since we require no degradation in performance for a period of 10 years it is prudent to explore whether an epoxy barrier is sufficient. The epoxy barrier is both the epoxy used by Hamamatsu and some optical epoxy to cement the diode to the crystal (Hamamatsu will not supply their epoxy for such purposes). An accelerated test could be performed on such a bond however the derating factor in such tests is always an estimate at best. As such tests are unreliable we prefer to use a highly chemically resistant coupling plate between the diode and the crystal. The diode is epoxied to the coupling plate and the coupling plate is in turn epoxied to the crystal. This arrangement guarantees no migration of ions to the diode and reduces the reliance on accelerated tests. However the introduction of another medium reduces the light transmission to the diode. We then need to investigate the correct coupling media and epoxies to use for maximal light transmission.

3 Maximal Light Transmission

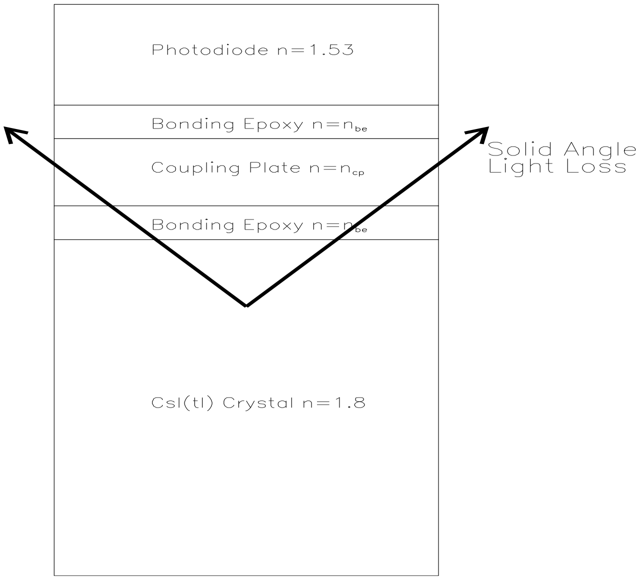

Figure 1: Optical coupling of photodiode to crystal using an epoxied coupling plate. Light loss is due to index mismatch and solid angle loss

Figure 1 shows the optical configuration of direct coupled diodes. Light loss occurs due to refractive index mismatch and solid angle leakage. Attenuation is negligable since the epoxy and coupling layers are relatively thin. We first consider what the optimal refractive indices are for the epoxy (n_{be}) and the coupling plate (n_{cp}). This is readily answered with a simple calculation. The Fresnel equations give the reflected (r) and transmitted (t) amplitudes for the two orthogonal components of a propagating electromagnetic field as shown in figure 2.

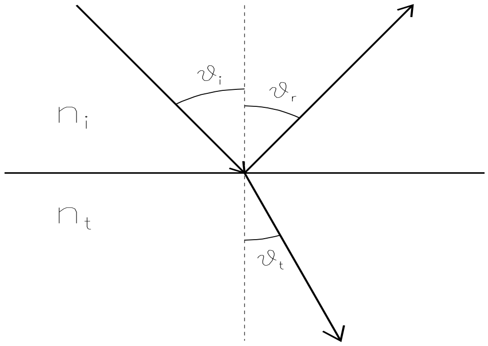

Figure 2: Definition of angles for light incident at a boundary. The two electric field components $E_{||}$ and $E_{\perp}$ are in the plane of the paper and perpendicular respectively

$$r_{\perp} = \frac{E_{r\perp}}{E_{i\perp}} = \frac{n_i cos(\theta_i) - n_t cos(\theta_t)}{n_i cos(\theta_i) + n_t cos(\theta_t)}$$

$$r_{||} = \frac{E_{r||}}{E_{i||}} = \frac{n_i cos(\theta_i) - n_i cos(\theta_t)}{n_i cos(\theta_t) + n_t cos(\theta_i)}$$

$$t_{\perp} = \frac{E_{t\perp}}{E_{i\perp}} = \frac{2n_i cos(\theta_i)}{n_i cos(\theta_i) + n_t cos(\theta_t)}$$

$$t_{||} = \frac{E_{t||}}{E_{i||}} = \frac{2n_i cos(\theta_i}{n_i cos(\theta_t) + n_t cos(\theta_i)}$$

The reflected and transmitted intensities are given by

$$R_{\perp} = r_{\perp}^2$$

$$R_{||} = r_{||}^2$$

$$T_{\perp} = \frac{n_t cos(\theta_t)}{n_i cos(\theta_i)} t_{\perp}^2$$

$$T_{||} = \frac{n_t cos(\theta_t)}{n_i cos(\theta_i)} t_{||}^2$$

For unpolarised light we average over all possible polarisations so that the transmitted (T) and reflected (R) energy is given by

$$T = \frac{1}{2}(T_{\perp}^2 + T_{||}^2)$$

$$R = \frac{1}{2}(R_{\perp}^2 + R_{||}^2)$$

We calculate the energy transmitted across an infinite plane by integrating over all possible incident angles assuming unpolarized light.

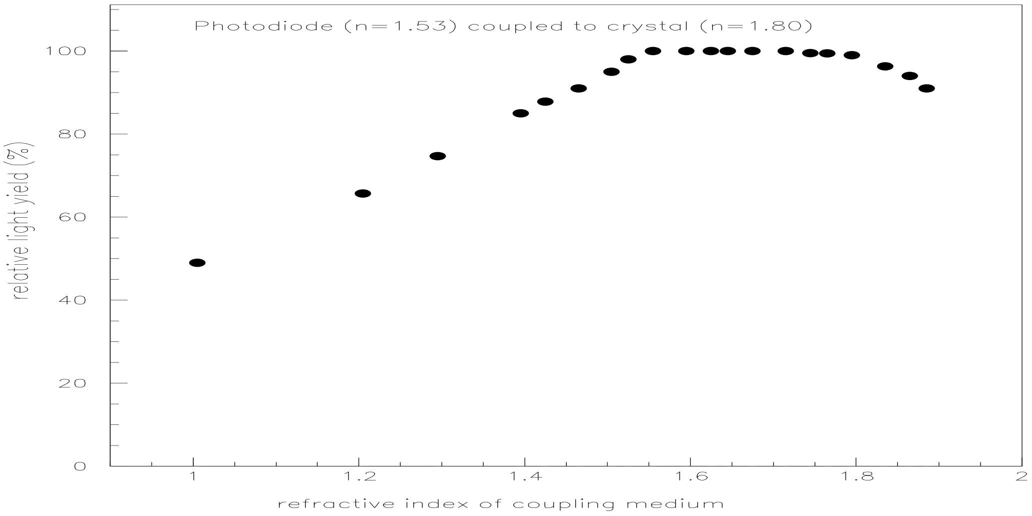

Figure 3: The dependance of light transmission from the CsI(tl) crystal to photodiode on the refractive index of the coupling material. Calculation assumes an infinite plane and integrates over all possible incident angles for unpolarized light.

We first consider the optimal refractive index of a medium that couples the diode and the crystal. The epoxy coat that protects the diode has a refractive index of 1.53. The CsI(tl) has a refractive index of 1.80. Figure 3 shows the relative light transmission versus refractive index The plot is normalized so that the maximum value of transmitted light is 100 %. It is apparent that the refractive index for the coupling medium should be $1.50 < n < 1.80$. Note that if there is an air gap (n=1) then there is approximately 50 % loss of light. Experimentally this is measured as 54 ± 5 %. This is convenient since all commercially available optical epoxies have $n \approx 1.50$.
However in reality we will use an optical coupling plate which will be epoxied to both the crystal and the diode. If we use an epoxy of 1.53 what is the optimal refactive index of the coupling plate. Figure 4 shows the relative

light yield versus the coupling plate refractive index for this situation. The refractive index of the coupling plate should be approximately the same as the epoxy.

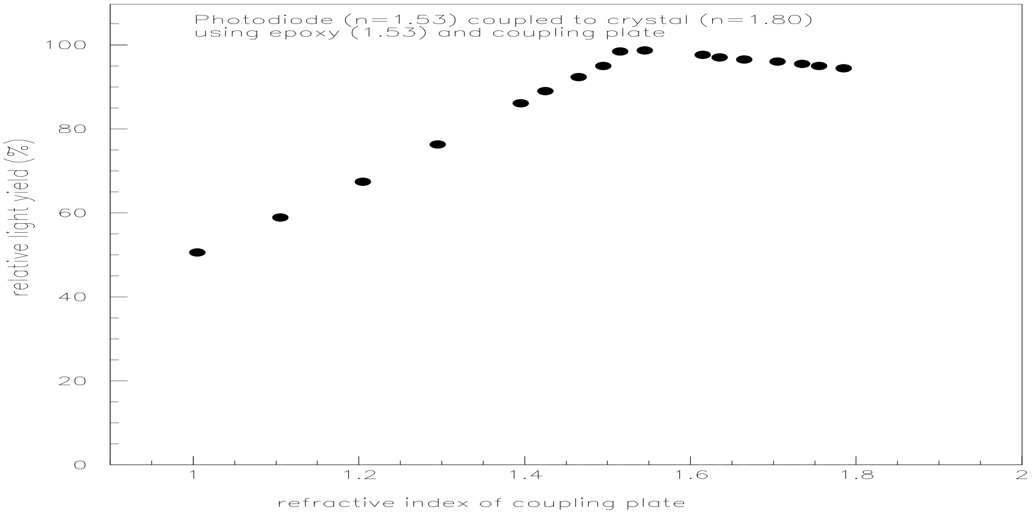

Figure 4: The dependance of light transmission from the CsIT(tl) crystal to the photodiode on the refractive index of the coupling plate. Calculation assumes an infinite plane and integrates over all possible incident angles for unpolarized light.

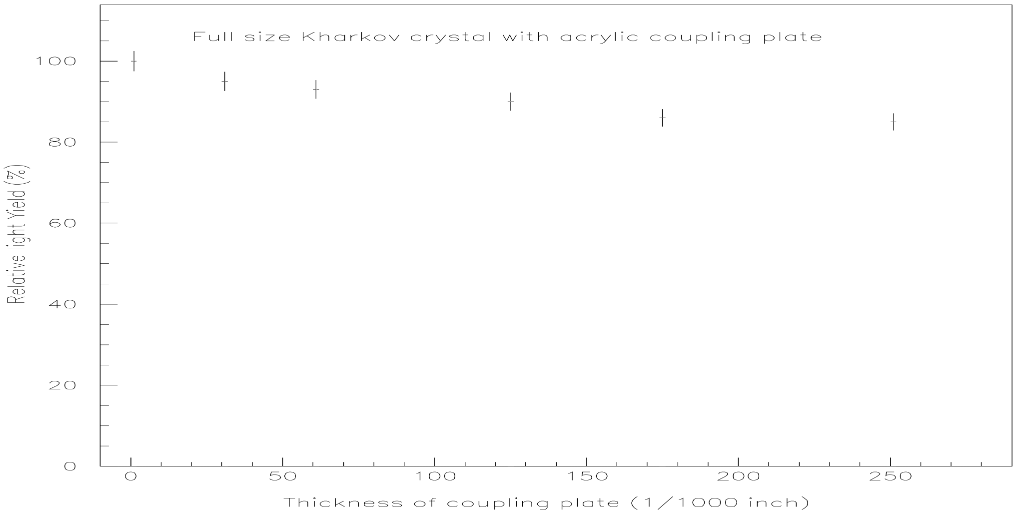

Figure 5: The dependance of light transmission from the CsIT(tl) crystal to the photodiode on the thickness of the coupling plate. A fullsize Kharkov crystal is used with and acrylic coupling plate. Optical grease is used rather than epoxy.

We next consider the light loss due to solid angle leakage. Figure 5 shows the measured light loss versus thickness of coupling plate. An acrylic coupling plate (n=1.5) is used with optical grease (equivalent to an epoxy). The data is normalized so that 100 % is no coupling plate (i.e just optical grease). The thinner the coupling plate the less the light loss. A 1/4 inch plate loses 15 % light.

4 Coupling plate

The requirements of the coupling plate are

- High light transmission in CsI(tl) emission range.

- As thin as possible yet maintaining mechanical strength.
- High resistance to chemical attack.
- Refractive index matched to optical epoxy index ($n \approx 1.5$)

Two possibilities exist. These are either acrylic or glass. We have tested a standard Lucite acrylic and Schott D263 glass. The latter is a very pure glass with high resistance to chemical attack that is used in the opto-electronics industry to provide protective covers for CCD's and LCD displays. It is available in a range of thicknesses from 30 microns upto 1.1 mm. The refractive indices of the acrylic and the glass (1.49 and 1.53 respectively) match well to the available optical epoxies. Both have an optical transmission of 92 % measured in air. However when optically coupled (i.e to the epoxy) the transmission rises to 97 % because in air there is 5 % reflection. We have tested both on a full size kharkov crystal with the entire back face covered by the coupling plate and using optical grease. We used a thickness of 1mm and found that the light yield in both cases was 95 ± 5 % relative to the case where the photodiodes were coupled to the crystal directly with optical grease. The acrylic has the advantage that it is easier to machine. While both acrylic and glass give equivalent light yield performance the glass is preferable since it has high resistance to chemical attack which is the primary purpose of the coupling plate.

5 Epoxies

The requirements of the epoxy are

- High optical transmission in CsI(tl) emission spectrum
- Refractive index close to the coupling plate refractive index
- Low viscosity. Any air bubbles in the epoxy bond will seriously degrade the ligh transmission. Air bubbles are removed from an epoxy by pumping under vacuum. This is most easily done if the epoxy has low viscosity
- Strain relief. When an epoxy cures it can cause strains on the component parts. CsI(tl) crystals often have grain boundaries which could

crack under strain. It is highly desirable that the epoxy sets with a small degree of flexibility such that any strains are absorbed by the epoxy rather than the crystal. Certain types of optical epoxy are manufactured with this property and are used for bonding brittle components such as lens and glass fibres.

- Short cure time. The pot life of the epoxy once mixed should be of the order of a few hours and the cure time approximately a day to allow ease of assembly.
- Good bond strength. The epoxy should make a good bond to glass/CsI.
- Long term stability. The mechanical and optical properties of the epoxy should not degrade over a period of 10 years.

We have tested a number of optical epoxies. Two of them have all the above qualities. Bicron-600 is an optical epoxy designed for bonding plastic scintillators. It has a refractive index of 1.56, is easy to use and possesses the degree of flexibility required. Epotech 301-2 has identical properties. We are currently performing accelerated (high temperature) and work-stress tests (temperature cycling) on CsI(tl)-epoxy-glass-epoxy-diode bonds in order to evaluate the long term reliability of these epoxies.

6 Construction

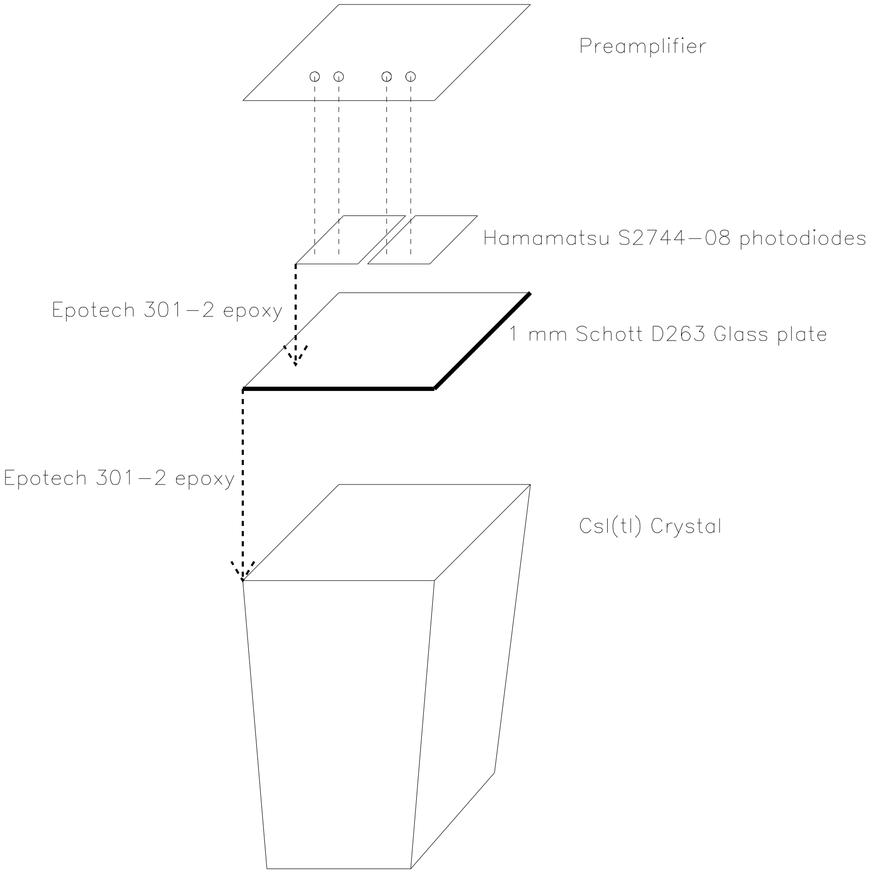

Figure 6: Schematic of the construction of the front end package for the direct diode readout

Figure 6 shows a schematic of the construction of the front end readout package. The glass plate is epoxied to the entire rear face of the crystal. The diodes are epoxied to the central part of the glass plate. The light output across the rear face is uniform to approximately 1 % and so the exact position of the diodes is not critical. The diode pins emerge at 90° to the plane of the diode and penetrate through oversize holes in the preamplifier board where they are soldered. There is no cable connector from diode to preamplifier. This reduces the possibility of pickup and also minimizes the capacitance at the preamplifier input which decreases incoherent noise. The diode connectors are positioned as far away from the preamp input/output cable to minimize pickup. In addition since the preamplifier is firmly affixed to the outer package housing (not shown) there is no probability of a connector coming loose once the package is assembled. Also the preamplifier can easily be unsoldered and removed from above if replacement is necessary.

7 electronic noise performance of direct photodiodes

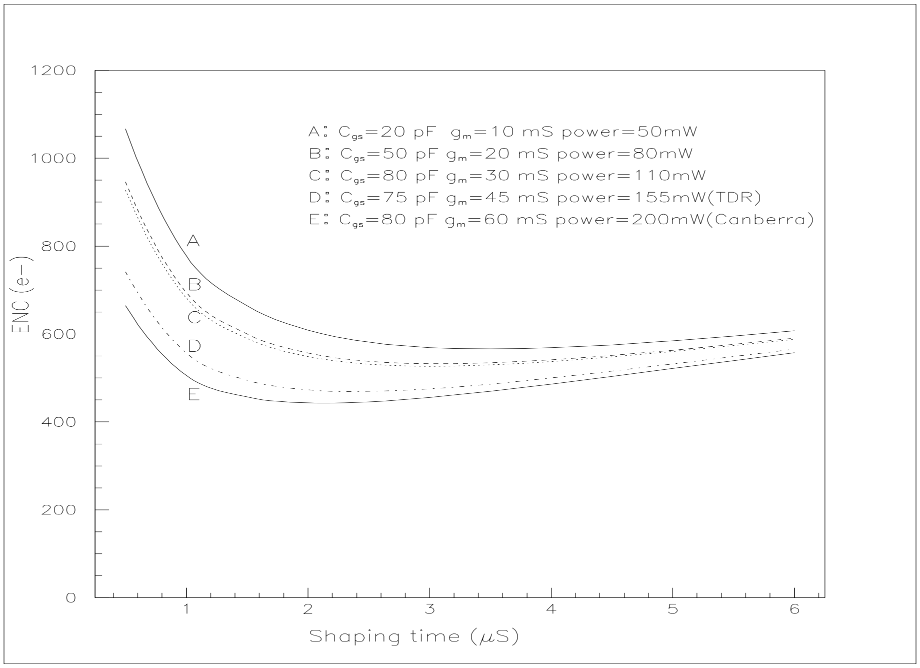

Figure 7: Noise performance of front end readout with 2744-08 Hamamatsu photodiodes and different front end FET's

The electronic noise performance of the Hamamatsu Photodiodes with the BaBar preamp is described in detail in references [1] [3]. We note here that the noise depends upon the choice of front end FET. If the FET is run at higher current there is less noise but more heat dissipation. Figure 7 gives the noise versus shaping times for a variety of commercially available FETs. The curves are for a single channel of electronics. There are two channels per crystal which when summed incoherently will give $\sqrt{2}\times$ noise per single channel. The BaBar preamp used in references [1], [3] is curve D. We use this curve for our noise figure with a shaping time of 2 μs. The power dissipation is 155 mW per channel.

8 Performance of direct photodiodes

The equivalent noise charge for the direct photodiodes is 680 e^- per crystal [1]. The light yield is measured on a full sized Kharkov crystal wrapped in one layer of 1056 D tyvek. The diodes and coupling plate are optically coupled with grease rather than epoxy. The crystal is scanned with a collimated source and the mean is value of the light yield quoted. The error quoted is a 5 % error due to the reproducibility. This is estimated from a set of measurements in which we unwrapped and disassembled the front end readout and then rewrapped and recoupled the diodes several times. The light yield is measured as 6000 pe^-/MeV which then gives an equivalent noise energy of 113 KeV. Table 1 contains these numbers and also measusrements for full-sized crystals from the vendors Hilger and Shanghai Institute of Glass. In addition the light yield for the Kharkov crystal is measured for two layers of 1056D Tyvek.

Vendor	Wrapping	Front Dim. (cm^2)	Rear Dim. (cm^2)	Length (cm)	LY Rel. to Std (%)	LY Direct (pe/MeV)	ENE (KeV)
Kharkov	1 × 1056D Tyvek	34	20	34	31±2	6000±300	113
Kharkov	2 × 1056D Tyvek	34	20	34	38±2	7700±380	88
Hilger	1 × 1056D Tyvek	36	25	27	30±2	5400±270	126
Shanghai	1 × 1056D Tyvek	34	20	27	22±2	4200±200	162

Table 1: Light yield (LY) measurements (as described in the text) for full-sized crystals.

9 Specification of Crystal Light Yield

The light yield is very dependent on the intrinsic crystal properties. It must be specified to the crystal grower in order to ensure acceptable performance. It is specified by measurement with an R669 photomultiplier tube relative to a standard 1 inch diameter by 1 inch length cylindirical crystal. The reference crystal is wrapped in three layers of 1.5 mil Teflon. The percentage value required (LYREQ)is given in terms of the desired equivalent noise energy performance (ENE)in KeV, the equivalent noise charge of the electronics(ENC), the light yield of a crystal measured with photodiodes (LYPD$_{crystal}(pe/MeV)$) and the light yield of a crystal measured relative to a standard crystal (LYREL$_{crystal}$(%)) by

$$LYREQ = \frac{ENC \times LYREL_{crystal} \times 1000}{ENE \times LYPD_{crystal}}$$

If we use the values measured for the Kharkov crystal with one layer of tyvek (table (1).

$$LYREQ(\%) = \frac{3500 \pm 300}{ENE}$$

For example if we require an ENE of less that 150 KeV then relative to the reference crystal the light yield must be 23 ± 2 %. To ensure that the crystal achieves the correct performance we must use the upper bound on the error is 25 %. The required light yield for different ENE is given in table 2.

ENE desired (KeV)	Light Yield required rel std (%)	Light Yield with two diodes (pe/MeV)
250	14 ± 1	2700
200	18 ± 2	3400
150	23 ± 2	4500
125	28 ± 2	5400
100	35 ± 3	6800

Table 2: Light yield required to get a desired equivalent noise energy (ENE). The light yield is given both relative to a standard crystal (Photomultiplier measurement for vendor) and in pe/MeV (diode measurement for experimeter).

References

[1] C. Jessop *et al.* "Development of front end readout for the *BaBar* CsI calorimeter", *BaBar* Note #216, 1994.

[2] C. Jessop *et al.* "Reliability Issues for the *BaBar* CsI calorimeter front end readout ", *BaBar* Note #217, 1994.

[3] C. Jessop *et al.* "Performance tests of Hamamatsu 2744-08 diodes for the calorimeter front end readout and proposal for reliability tests" *BaBar* Note #236, 1995.

[4] C. Bebek CLEO collaboration Nucl. Instrum. Methods **265**, 258 (1988)

[5] Dr. Yamamoto, Hamamatsu Corporation, Japan. Private communication