ON QUALITY REQUIREMENTS TO THE BARIUM FLUORIDE CRYSTALS

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1 INTRODUCTION

Total absorption shower counters made of inorganic scintillating crystals have been known for decades for their superb energy resolution and detection efficiency. In high energy physics, large arrays of such counters have been assembled for the detection of photons and electrons at e⁺e⁻ storage rings. A recent example is an electromagnetic calorimeter consisting of 12,000 large size BGO crystals constructed for the L3 experiment at LEP [1]. Because of its unique physics capability, crystal calorimeter has also attracted much attention in high energy physics community proposing experiments for next generation accelerators: Superconducting Super Collider (SSC) at U.S. and Large Hadronic Collider (LHC) at Europe.

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Much progress has been made towards the choice of material, and production of large size crystals for SSC and LHC, where high speed and superb radiation resistance are primary requirements. Attention is now concentrated on three fluoride crystals: barium fluoride (BaF₂) [2], cerium fluoride (CeF₃) and lead fluoride (PbF₂) [3].

The BaF₂ calorimeter is one of two principal options for electromagnetic calorimetry in the “Gammas, Electrons and Muons” (GEM) experiment [4], which is one of the two major general-purpose detectors proposed for the SSC experimental program. To maximize its discovery potential, the GEM detector has been designed to be a precision lepton and photon detector. A precision electromagnetic calorimeter, as well as a high resolution muon system, are the two principal ingredients of the GEM detector design.

This report concentrates on expected performance of BaF₂ electromagnetic calorimeter at the SSC, and corresponding requirements to the quality of BaF₂ crystals to be used in constructing calorimeter. Section 2 of this report gives a brief description of the concept of BaF₂ calorimeter design. The performance of the BaF₂ calorimeter is illustrated in section 3. The systematic effect on energy resolution from light response uniformity, radiation resistance and inter-calibration accuracy are deliberated in sections 4, 5 and 6. The specifications for BaF₂ crystals are discussed in section 7.

2 BaF₂ CALORIMETER DESIGN

Barium Fluoride (BaF₂) is a unique high density inorganic scintillator with three emission spectra peaking at 195 nm, 220 nm and 310 nm, with decay time constants of 0.87, 0.88 and 600 nsec respectively [5]. The intensity of the fast components have no temperature dependence — which should give a BaF₂ calorimeter greater intrinsic stability than the L3 BGO calorimeter — while the slow component increases with decreasing temperature at a rate of -2.4%/°C [6]. The speed of the fast components enable the detector to be gated in a single beam crossing at the SSC. Table 1 lists the basic properties of barium fluoride, as compared to other commonly used scintillation crystals: NaI(Tl), pure CsI, CsI(Tl), CeF₃ and BGO.
Table 1: Properties of Scintillation Crystals.

<table>
<thead>
<tr>
<th>Material</th>
<th>NaI(Tl)</th>
<th>Pure CsI</th>
<th>CsI(Tl)</th>
<th>BaF$_2$</th>
<th>CeF$_3$</th>
<th>BGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.88</td>
<td>6.16</td>
<td>7.13</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.85</td>
<td>1.85</td>
<td>2.06</td>
<td>1.68</td>
<td>1.12</td>
</tr>
<tr>
<td>Moliere Radius (cm)</td>
<td>4.8</td>
<td>3.5</td>
<td>3.5</td>
<td>3.39</td>
<td>2.63</td>
<td>2.33</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>41.4</td>
<td>37.0</td>
<td>37.0</td>
<td>29.9</td>
<td>26.2</td>
<td>21.8</td>
</tr>
<tr>
<td>$X_{rad}/X_{int}$</td>
<td>0.063</td>
<td>0.051</td>
<td>0.051</td>
<td>0.068</td>
<td>0.065</td>
<td>0.051</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.85</td>
<td>1.80</td>
<td>1.80</td>
<td>1.49</td>
<td>1.62</td>
<td>2.15</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Luminescence (nm)</td>
<td>410</td>
<td>300</td>
<td>565</td>
<td>310</td>
<td>340</td>
<td>480</td>
</tr>
<tr>
<td>(Peak Wavelength)</td>
<td></td>
<td></td>
<td></td>
<td>210</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Decay Time (nsec)</td>
<td>230</td>
<td>10</td>
<td>900</td>
<td>630</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>Light Output</td>
<td>100</td>
<td>20</td>
<td>45</td>
<td>20</td>
<td>6</td>
<td>15</td>
</tr>
</tbody>
</table>

2.1 Design

Figure 1 shows the conceptual design of the BaF$_2$ calorimeter, which consists of two parts:

- A central barrel calorimeter with an inner radius of 75 cm and an outer radius of 140 cm, covering a rapidity range of $|\eta| \leq 1.32$ ($30^\circ \leq \theta \leq 150^\circ$).
- Two endcaps, located at $z = \pm 164$ cm, covering a rapidity range of $1.32 \leq |\eta| \leq 2.5$ ($9.4^\circ \leq \theta \leq 30^\circ$ and $150^\circ \leq \theta \leq 170.6^\circ$).

The total crystal volume of the BaF$_2$ calorimeter is 10.6 m$^3$, with a total crystal weight of 51.8 t. Table 2 shows the basic parameters of the BaF$_2$ calorimeter.

The fine granularity ($\Delta\eta \approx \Delta\phi \approx 0.04$) and hermetic design of BaF$_2$ calorimeter provides a uniform response over the phase space coverage and a small 2.7% dead space for the cable path of central tracker. In summary, the BaF$_2$ calorimeter has the following features which are deliberated in the next section.
Table 2: Features of the BaF$_2$ Calorimeter

<table>
<thead>
<tr>
<th>Detector</th>
<th>Barrel</th>
<th>Two Endcaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidity Coverage (cm$^2$)</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Crystal Front/Rear Face (cm$^2$)</td>
<td>$3.1 \times 3.1$ / $5.2 \times 5.2$</td>
<td>$2.3 \times 2.3$ / $3.1 \times 3.1$</td>
</tr>
<tr>
<td>Crystal Length (cm)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Crystal Number</td>
<td>10,880</td>
<td>4144</td>
</tr>
<tr>
<td>Crystal Volume (m$^3$)</td>
<td>8.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Crystal Weight (t)</td>
<td>41.1</td>
<td>10.7</td>
</tr>
</tbody>
</table>

- Time Resolution: gating time in less than 16 ns (a single beam crossing);
- Position Resolution: $\delta x$ and $\delta y \approx 1$ mm at the front surface of crystals;
- Energy Resolution: $(2.0/\sqrt{E} \oplus 0.5)\%$.

Figure 1: Conceptual view of the BaF$_2$ EM calorimeter.
3 BaF\(_2\) CALORIMETER PERFORMANCE

3.1 Time Resolution

The intrinsic intensity of the slow scintillation component (600 nsec) in BaF\(_2\) is 5 times higher than the fast components. Although the slow component may be suppressed in a relatively straightforward way by sampling the output of each channel just before, and a few fast-decay-time constants after the start of a pulse [7], the intrinsic slow component could limit the dynamic range of photosensitive device, and could lead to pileup noise that could degrade the energy resolution.

Direct approaches for suppressing the slow component have been pursued over the last three years. An intrinsic suppression was discovered by Schotanus et al. [8]. They found that a small amount of lanthanum added to the crystal during growth greatly suppressed the slow component without significantly affecting the fast component. A subsequent study by Woody et al. [9] showed that there are several dopants which produce strong slow component suppression and retain high fast component light output. However, only lanthanum still preserves the radiation hardness of the pure material up to a level beyond 10\(^6\) Rads.

Figure 2 shows the emission spectra for pure BaF\(_2\) and BaF\(_2\) doped with 1% of lanthanum. The peak intensity of the slow component (310 nm) is reduced by a factor of about five with little change to the fast components (195 and 220 nm).

Since the manufacture of large undoped high quality BaF\(_2\) crystals is inherently simpler, and since the fast and slow scintillation components of BaF\(_2\) peak at different wavelengths, a UV-selective photodevice (optimised for maximum sensitivity in the 220 nm region) is proposed to partially suppress the slow component. The slow component suppression is completed by a fast shaper, and by readout samples just before and shortly after the peak of the pulse. This technique of selecting the fast component does not restrict the dynamic range, and it allows us to maintain very low noise because of the low capacitance of the vacuum photodevice.

Figure 2 also shows the spectral sensitivity of a UV-selective 'solar-blind' photomultiplier (PMT) with a Cesium Telluride (Cs-Te) photocathode (Hamamatsu R3197) and a PMT with a bialkali photocathode (Hamamatsu R2059). Both PMT's have a synthetic silica (quartz) windows. The Cs-Te photocathode has a
quantum efficiency of 10% around 220 nm, while the bialkali photocathode has a quantum efficiency of about 18% around 220 nm. It is clear that the solar-blind photocathode (Cs-Te) is mainly sensitive to the fast scintillation light.

An additional optical suppression of the slow component recently has been achieved by using new photocathodes, K-Cs-Te or Rb-Te, developed by Hamamatsu [10]. Both cathodes have about 10% quantum efficiency at 220 nm and provide better suppression of the slow component (by around a factor of 2 relative to Cs-Te). Figure 3 shows pictures of the scintillation light pulses recorded on an HP54111D digital scope using a bialkali photocathode (a and c), a Cs-Te photocathode (b and f), K-Cs-Te cathode (c and g) and a Rb-Te cathode (d and h). The rise time of the scintillation light pulse in these pictures was completely dominated by the 2.3 nsec rise time of the PMT's. On an expanded scale (a, b, c and d) the full width at half maximum of the fast scintillation light is measured to be 4–6 nsec. The optical suppression factors (F/S) for the slow component, defined as the number of photoelectrons in the fast components (F) divided by the number of photoelectrons in the slow component (S), are also shown in the figure.

An existing photodevice, R4406, may be used in BaF₂ readout. It has quartz

![Figure 2: BaF₂ scintillation spectra and PMT quantum efficiencies.](image-url)
window and K-Cs-Te cathode. The triode also has a gain of more than 50% of its nominal value when operating in a 1 tesla magnetic field with an angle of 45° or less to its axis [11]. Note, the synthetic silica (quartz) window has very high radiation resistance against photon and neutron doses [12]. Another choice of photodevice is proximity focused 5 stage phototube, recently proposed by Hamamatsu [13], which has gain of >30 under 0.8 tesla magnetic field.

3.2 Position Resolution

The position of an electromagnetic shower without longitudinal sampling, i.e. the coordinate of the impact point of an electron or a photon on the front surface of
an electromagnetic calorimeter, is usually measured by using the center of gravity method. The position resolution of a calorimeter thus depends on its structure, especially the lateral cell size. For a calorimeter organized in pointing towers, the position resolution as a function of energy can be parametrized as:

$$\delta x \text{ (mm)} = \frac{3}{\sqrt{E}} e^{aD}$$  \hspace{1cm} (1)

where $E$ is the energy of the particle being measured in GeV, and $D$ is the cell size in radiation lengths.

A proper lateral cell dimension thus is very important. Its choice is usually a compromise between good position resolution, shower containment in a ‘tower’ consisting of a moderate number of lateral cells, and the total number of readout channels (which is reflected in the cost). Good position resolution as well as a good knowledge of the transverse shower shape (important for $e/\pi$ resolution) favour a small cell size, while shower containment in a few cells favors a larger size. A cell dimension in the neighborhood of approximately one Moliere radius is usually taken, corresponding to \approx 75\% of shower energy deposited in the center cell.

All of these factors taken together have led to a technical consensus that the optimum lateral segmentation is $0.04 \times 0.04 \ (\Delta \eta \times \Delta \phi)$ at the SSC as in the BaF$_2$ design. This segmentation results a position resolution, calculated according to Eq. 1 for a 20 GeV electron or photon, is 1.2 mm, which is comparable with what has been measured with L3 BGO calorimeter [1].

### 3.3 Energy Resolution

The energy resolution of an electromagnetic calorimeter can be parametrized as:

$$\left(\frac{\delta E}{E}\right)^2 = \left(\frac{a_0}{E}\right)^2 + \left(\frac{a_1}{\sqrt{E}}\right)^2 + b^2$$  \hspace{1cm} (2)

The contributions of each term to the resolution are:

- $a_0$ is the contribution from electrical noise, summed over a few Moliere radii around the maximum of the lateral shower distribution;
- $a_1$ is the contribution from the photoelectron statistics;
the systematic term b has three contributions:

\[ b^2 = b_a^2 + b_G^2 + b_C^2 \]

- \( b_G \) represents the geometry effect, including shower leakage at the front, side and back of the detector and inactive material between cells;
- \( b_a \) represents physics noise, including fluctuations of the shower and uniformity of light response etc.;
- \( b_C \) represents intercalibration error.

At low energy, the dominant contribution to the energy resolution is the noise term \( (a_0) \), which decreases quickly with increasing energy. The sampling term \( (a_1) \) dominates in the range of medium to high energies until a high energy limit is reached, where the systematic term \( (b) \) dominant.

In this section, only systematic term \( b_G \) is discussed. The systematic terms of \( b_a \) (light response uniformity) and \( b_C \) (inter-calibration) are deliberated separately in sections 4 and 5.

3.3.1 Light Yield: \( a_1 \)

It is not very difficult to build a homogeneous electromagnetic calorimeter with a small \( a_1 \) term. A photoelectron (p.e.) yield better than 10 p.e./MeV would be enough to provide an \( a_1 = 1\% \). Figure 4 shows the measured \(^{137}\text{Cs}\) spectra obtained from the same \( \text{BaF}_2 \) sample by using four PMTs with different photocathodes (bialkali, Cs-Te, K-Cs-Te and Rb-Te) for two different gate widths (55 ns and 2 \( \mu \)s). By comparing the spectra, it is clear that the K-Cs-Te cathode has good quantum efficiency (better than Cs-Te and Rb-Te) in detecting the fast components from \( \text{BaF}_2 \). Measurements at Caltech show that more than 50 p.e./MeV are obtained from typical 25 cm long \( \text{BaF}_2 \) crystals by using K-Cs-Te photocathodes.

The light yield of 50 cm long crystals has been measured at Caltech with \(^{137}\text{Cs}\) \( \gamma \)-ray source and at Fermi Lab with electron beam. For production quality \( \text{BaF}_2 \) crystals, photoelectron yield was measured to be 20 to 50 p.e./MeV by using K-Cs-Te or Rb-Te photocathode with good light response uniformity (see Section 4). This corresponds to an \( a_1 \) term of about 0.4—0.7\%. 

9
Figure 4: $^{137}$Cs spectra measured with 4 PMTs with different photocathodes for two different gate widths: 55 ns (a–d) and 2 µs (e–h).

3.3.2 Electrical Noise: $a_0$

Because of its small capacitance (10 pf) and small dark current (0.1 nA), it is not difficult for the R4406 vacuum phototriode and the front electronics to provide an electrical noise level of 2,000 electrons per channel [14]. In reality, one needs to sum over a few Moliere radii to reconstruct an electromagnetic shower. In the case of using $3 \times 3$ crystals, which contains more than 95% of shower energy according to GEANT simulations [15], the intrinsic electrical noise is 6,000 electrons without channel-to-channel correlations. Assuming the minimum gain of the R4406 phototube is 6, i.e. 50% of its nominal gain of 12 in the worst magnetic field situation [16], the signal corresponds to 120,000–300,000 electrons/GeV with a K-Cs-Te photocathode. This means an $a_0$ term of 2–5% for $3 \times 3$ crystal readout, if existing R4406 is used. The $a_0$ term can be further reduced if the proximity focused
5 stage phototube [13] is used. Since it has a gain of >30 under 0.8 tesla magnetic field, the $a_0$ term can be further reduced to 0.4—1%. The electrical noise introduced by channel-to-channel correlations, however, must be reduced by carefully implementing the electrical isolation between the readout channels.

3.3.3 Geometry Effect: $b_Q$

To reduce the systematic effects caused by shower leakage and inactive material, a precision electromagnetic calorimeter must be designed to contain nearly the complete electromagnetic shower, over the whole energy range. Since electromagnetic shower physics is well understood, a complete GEANT simulation would be able to predict the resolution of a calorimeter with proposed geometry configuration. To reduce the term $b_Q$, an electromagnetic calorimeter must be designed with enough length and have minimum dead material in the front, between cells and, especially inside the calorimeter.

A detailed GEANT simulation was carried out to estimate the effect of shower leakage and non-active material for the BaF$_2$ design [17]. Figure 5 shows a prototype of BaF$_2$ matrix used in this simulation, which consists of 121 (11 x 11) BaF$_2$ crystals with the proposed size: 3 x 3 cm$^2$ at the front, 5 x 5 cm$^2$ at the back and 50 cm long. Effects included in the simulation are:

- 250 μm carbon fiber wall between crystals;
- shower leakage because of summing a limited number (3 x 3 or 5 x 5) of crystals; and
- 0.30 radiation lengths of aluminum, representing the beam pipe, tracker, and carbon fiber mechanical support, at the front of the BaF$_2$ array.

Particles were shoot uniformly at the front surface of the center crystals of the array. The energies deposited in each crystal, in the carbon fiber walls between crystals, in the aluminum and leaking out sideways were recorded. The result of this simulation for electrons with different energies (5, 10, 100 ad 500 GeV), in terms of $\sigma$ of the peak, full width at half maximum (FWHM) divided by 2.35, is listed in Table 3.

A further study was carried to look the systematic effect of carbon fiber wall.
By varying the thickness of carbon fiber walls from 0 to 250 µm, the resolution obtained showed no observable difference [17]. This indicates that the systematic effect of support structure is negligible.

Table 3: Energy Resolution (%)

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>5</th>
<th>10</th>
<th>100</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Noise</td>
<td>0.4</td>
<td>0.2</td>
<td>0.02</td>
<td>0.004</td>
</tr>
<tr>
<td>Photoelectrons</td>
<td>0.2</td>
<td>0.14</td>
<td>0.045</td>
<td>0.02</td>
</tr>
<tr>
<td>GEANT</td>
<td>0.60</td>
<td>0.43</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>Intercalibration</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Total</td>
<td>0.85</td>
<td>0.63</td>
<td>0.51</td>
<td>0.49</td>
</tr>
</tbody>
</table>
3.3.4 Summary of the Energy Resolution

Table 3 summarizes the BaF₂ resolution, including the contributions from electrical noise, photoelectron statistics, intrinsic resolution from GEANT simulation and the intercalibration. Based upon the discussion in section 6, a precision of intercalibration of 0.4% is assumed. Note, in this simulation the light response uniformity was assumed to be under control. The real effect of light response uniformity is discussed in section 4. The result of the energy resolution is shown in Fig. 6b. It can be parametrized as \(2\%/\sqrt{E} \oplus 0.5\%\), which is also shown in Fig. 6b as a solid line.

As a comparison, Fig. 6a shows the energy resolution measured with 4000 BGO crystals (half barrel) in a CERN test beam [1]. In the energy range beyond 20 GeV, the dominant contribution to the energy resolution is the systematic intercalibration uncertainties. The resolution of the L3 BGO calorimeter may also be parametrized as \(2\%/\sqrt{E} \oplus 0.5\%\), which is also shown in the Fig. 6a as a solid line.

![Figure 6](image)

Figure 6: Energy Resolution of L3 BGO calorimeter (a), measured at CERN test beams with 4000 crystals, and BaF₂ calorimeter (b), calculated with GEANT simulation. The solid curves represent a simple parametrization of \(2\%/\sqrt{E} \oplus 0.5\%\).
4 LIGHT RESPONSE UNIFORMITY: $b_n$

Experience with the L3 BGO, and other precision crystal calorimeters, has shown that light response uniformity at the level of several percent over the length of the crystal (except for the first few and the last few radiation lengths), is important to maintain the resolution. This uniformity is also needed to maintain good linearity over a large dynamic range, e.g. from $\sim 10$ GeV up to the TeV range at the SSC.

4.1 Effect of Light Response Uniformity

The consequence of light response uniformity has been studied with a GEANT simulation [17] (as described in section 3.3.3), assuming the effect of non-uniform light responses can be parametrized as a normalized function:

$$Y = Y_{25} \left[1 + \delta(Z/25 - 1)\right]$$

where $Y_{25}$ represents the light yield at the middle (25 cm) of a BaF$_2$ crystal, $\delta$ represents the uniformity of the light response of a BaF$_2$ crystal, and $Z$ is the distance from the small end of the crystal.

The effect of $\delta$ values of 5%, 10%, 15%, and 20% has been simulated. Fig. 7 shows the result of the simulation for sum of $3 \times 3$ crystals. As seen from Fig. 7, the response of energy deposition decreases when $\delta$ increases, while the energy resolution degrades. It is clear from the figure that it is vital to maintain the light uniformity within 5%.

4.2 Light Response Uniformity of 25 cm Long Crystals

The light response uniformity of BaF$_2$ crystals can be achieved by using special wrapping or coating method. For a tapered crystal with its 6 faces polished, there are two complementary factors which affect the light uniformity along the crystal axis: the attenuation and the optical focusing. While the first factor causes a decrease of the response with the increase of the distance to the light-sensitive device, the second factor causes an increase of the response. For a BGO crystal, the second factor dominates: a strong increase of light response to the small end
Figure 7: Effect of light uniformity predicted with GEANT simulation.

was observed for the L3 crystals [1]. Only after extensive studies of controlled
depolishing of the surface, was light uniformity and high light collection efficiency
achieved by coating the polished BGO crystals with a 40 to 50 µm thick layer of
high reflective NE560 paint.

Figure 8a shows the light uniformity curves with and without the NE560 coating,
measured with a $^{137}$Cs source. The parameter R in Fig. 8a is the relative light
output difference for the source at 21 cm and 3 cm from the photodiode. The
crosses correspond to aluminized mylar wrapping and the diamonds to NE560
coating.

The optical focusing effect, however, is less important for the BaF$_2$ because of its
smaller refractive index. The light collection uniformity of a 25 cm long BaF$_2$ crys-
tal measured with a collimated $^{137}$Cs source is shown in Fig. 8b. The photodetector
used in this measurement is a photomultiplier (PMT) with a Cs-Te solar-blind pho-
tocathode (Hamamatsu R3197). With simple aluminum wrapping, the measured
response of the fast scintillation component shows a uniformity within ~2% in a 25 cm crystal piece. Because of a longer light attenuation length, the response of the slow scintillation component shows an increase with an increasing distance from the PMT, as shown in Fig. 8b.

### 4.3 Light Response Uniformity of 50 cm Long Crystals

In order to extend the light uniformity results of 25 cm long crystals to the 50 cm long crystal-pairs which make up the prototype BaF₂ detector, two important technical difficulties must be overcome:

1. Find a glue with good UV transmission down to at least 200 nm. This is needed to optically couple the two crystal pieces together, as well as to couple the crystal-pair to the photodevice.

2. A technique of crystal surface treating: wrapping, or UV-reflective coating, to combine good light collection efficiency with overall uniformity.
4.3.1 KE103 Glue

While the best UV-transmitting optical coupling material (down to 190 nm) is Dow Corning 200 Silicone fluid, the best viscous grease, which can be used for good long-term joints if set up and used with care, is GE Silicone based UISC 600M. Although grease of this type have been used successfully on large BaF$_2$ crystals in experiments: by Woody at BNL, and by the TAPS Collaboration [20], there is no doubt that a glue is more secure.

Recent measurements by Kobayashi et al. at KEK [18] indicated that KE103 (an RTV glue) [19] is a candidate of UV transparent glue. Note, KE103 was also measured to be radiation hard up to a level beyond $10^7$ Rads [18]. The transmission results were measured at Caltech with hard-cured samples of KE103, as summarized in Table 4 below. Thin joints of KE103 were made by pressing two pieces of quartz together (typically few tens $\mu$m), and the UV transmittance was measured, normalized to the results obtained with Dow Corning 200 fluid between two similar pieces of quartz. The results for the GE grease UISC 600M are shown for comparison. As shown in the table, the transmission of KE103 adhesive is nearly as good as the Dow Corning fluid down to 200-205 nm, and it shows good transmission down to 190 nm.

Table 4: UV transmission (%) relative to Dow Corning 200 fluid, for thin layers of KE103 RTV and GE UISC 600M grease

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>190</th>
<th>195</th>
<th>200</th>
<th>205</th>
<th>210</th>
<th>215</th>
<th>220</th>
<th>225</th>
<th>230</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE103/1</td>
<td>97.2</td>
<td>87.6</td>
<td>90.5</td>
<td>94.6</td>
<td>97.8</td>
<td>98.3</td>
<td>99.9</td>
<td>99.4</td>
<td>99.4</td>
</tr>
<tr>
<td>KE103/2</td>
<td>83.7</td>
<td>88.5</td>
<td>95.3</td>
<td>97.6</td>
<td>98.8</td>
<td>99.8</td>
<td>99.4</td>
<td>99.9</td>
<td>99.8</td>
</tr>
<tr>
<td>UISC 600M</td>
<td>90.0</td>
<td>94.4</td>
<td>96.4</td>
<td>96.2</td>
<td>97.5</td>
<td>97.3</td>
<td>97.5</td>
<td>97.7</td>
<td></td>
</tr>
</tbody>
</table>

However, it should be pointed out that if the layer of KE103 glue is too thick, e.g. 500 $\mu$m, the joint is no longer transparent at UV. Figure 9 shows the transmittance measured for 500 $\mu$m thick layers of various adhesives. The cut-off at 220 nm of KE103 shows clearly that a bad joint of crystal pair would destroy light response uniformity.
Figure 9: The Transmittance of 500 μm thick layers of various grease and glues.

4.3.2 Crystal Surface Treating

A simple wrapping technique, in which the region near the phototube is covered with aluminized mylar painted black to suppress direct light was used for 49 test crystals. The recipe of our wrapping is:

1. 3 to 4 layers of TETRATEX Porous PTFE film (1.5 mil thick) covers the small end to 24.5 cm from the small end;

2. 2 layers of aluminum foil (0.5 mil thick) covers 24.5 cm to 35 cm;

3. 2 layers of aluminized mylar painted black (1 mil thick) covers the rest of the crystal, i.e. from 35 cm to the large end.
\[ \frac{Y}{Y_{25}} = 1 + \frac{\delta(X-25)}{25} \]
\[ \delta = 0.4\% \quad \chi^2/\text{DoF} = 0.2 \]

Figure 10: Normalised pulse height obtained with a 50 cm crystal pair measured with muon beam at Fermi Lab.

Similar techniques have been used to obtain good light uniformity in BaF$_2$ crystals by B. Winstein et al. at Fermi Lab. By adjusting the wrapping, a uniformity at the level of $\approx 5\%$ or better over the length was obtained for 50 cm long BaF$_2$ crystals with a good glue joint. A result measured at Fermi Lab with a muon beam hitting a 50 cm long BaF$_2$ crystal pair transversely is shown in Figure 10.

Note, good uniformity was obtained in spite of the fact that there were substantial variations in the light output of the first crystal batches produced in 1990. It is also known that aluminum foil in contact with air is not a high-efficiency reflector for 200 nm light.

For the final BaF$_2$ system, one of the main R&D issues is investigation of a UV-reflecting coating, such as MgF$_2$ (used routinely for RICH Counter mirrors at 170 nm). The MgF$_2$ would be applied in a vacuum tank, immediately followed
by a sealing layer of quartz. A masked pattern of reflector would be used to achieve the uniformity. This technique, which is not available during small-scale prototyping at moderate cost, would improve our light collection efficiency as well as the uniformity during mass production.

5 BaF₂ RADIATION RESISTANCE

All above discussions have not touched an important issue of BaF₂ calorimeter for the SSC: the radiation resistance. In this section we discuss the phenomena of radiation damage of BaF₂ crystals. For more detailed discussions in this issue, see, for example, papers and talks presented in BaF₂ Workshop at Shanghai [21], May 1991, and in GEM BaF₂ panel meetings at SSCL [22,23], Beijing [24] and Shanghai [25], December 1991. Before discussing the radiation resistance, the production of BaF₂ crystals in China is addressed below.

5.1 Production of BaF₂ Crystals in China

The Shanghai Institute of Ceramics (SIC) is specialized in inorganic, non-metallic materials and materials science. The total work force of SIC consists of 200 professors, associate professors and senior engineers, 500 researchers and technicians and 300 skilled workers. SIC's research field includes synthetic crystals, advanced ceramics, special glasses and ceramic coatings, compositional analysis, structure analysis, instrumental design, and other related topics.

Studies of synthetic crystals started at SIC in 1960, including crystal growth, crystal physics, crystal chemistry and crystal devices. About 50 kinds of crystals have been studied so far, such as electro-optical crystals, acoustic-optical crystals, piezoelectric crystals and crystal scintillators. SIC has successfully studied the BGO crystals for L3, and established an R&D Center with a production capacity of 400 BGO crystals per month. By June 1990, 12,000 high-quality BGO crystals, meeting the specifications required for L3, were delivered to the L3 Collaboration.

Beijing Glass Research Institute (BGRI) has been working on synthetic crystal growth technology for many years. BaF₂ crystals were first developed at BGRI for infrared applications, and as crystal scintillators starting in 1985. During 1988-
1988 BGRI and SIC collaborated on producing BaF$_2$ scintillators. By 1987, BGRI had grown a crystal 30 cm in length and 10 cm in diameter, using a modified Bridgeman method in vacuum. The technique has since been successfully adapted, at SIC as well as BGRI, to produce large BaF$_2$ crystal boules with the characteristic long truncated-pyramid shape required for GEM BaF$_2$ calorimeter, with a boule size up to 45 cm in length. Using these boules, BGRI has successfully produced crystal-pieces of 35 cm in length [26] after Shanghai Workshop.

In 1990, 49 pairs of BaF$_2$ crystals were delivered to Caltech for constructing a test matrix in Fermi Lab test beam. These crystals, ordered under generic R&D funding, have a reduced dimension (2 x 2 cm$^2$ instead of 3 x 3 cm$^2$, at front) and do not meet radiation resistance requirement of SSC. Nevertheless, the transmittance of these crystals satisfies the specification proposed by BaF$_2$ collaboration.
Figure 11 shows transmittance curves of several 25 cm long BaF$_2$ crystals from SIC and BGRI, together with the specifications shown as crosses. The details of specifications is discussed in section 7.

Using their own funds, SIC and BGRI have installed a total of ten crystal furnaces, which will bring the total production capacity to 90 crystal boules per month. The first computer-controlled mass production furnace with a production capacity of 40 crystals per month is now under construction in BGRI. It is expected that the crystal production capacity will be 130 boules per month, for which and associated R&D, SIC and BGRI have invested the equivalent of approximately $1.3M U.S. in hard currency. This does not include the labor costs for 28 full time persons at SIC, and 21 full time persons at BGRI.

5.2 Understanding BaF$_2$ Radiation Damage (I)

BaF$_2$ is one of the most radiation resistant crystal known. It is understood that the fast component in BaF$_2$ is produced by the "cross scintillation" mechanism [27]. Studies on other fluoride crystals have shown that this mechanism occurs in crystals with very high radiation resistance, and that it produces scintillation light with only a weak temperature dependence [27].

Early work done by S. Majewski and D. Anderson [28] showed that no color centers were formed in BaF$_2$ up to a dose of $1.3 \times 10^7$ Rads in an 800 GeV proton beam. The crystals tested were from Harshaw. Many other works [28] confirmed this early observation for irradiations from either charged particles or photons. It is also known that impurities in the crystal will cause radiation damage. An absorption band around 205 nm was identified as originating from Pb contamination [29], and this was correlated with the susceptibility to radiation damage.

Systematic studies of the radiation damage phenomena of BaF$_2$ have been performed. Tests show that the radiation damage of BaF$_2$ caused by either γ-ray or neutron irradiation is recoverable by annealing the crystal at 500°C for 3 hours [30]. Figure 12a shows the light transmittances before and after $10^{14}$ neutrons/cm$^2$ irradiation for a BaF$_2$ sample of 2.5 cm length. Also shown in the figure is the full recovery after annealing. This measurement indicates that neutrons, as well as photons, do not cause permanent damage to BaF$_2$ crystals.
BaF$_2$ crystals irradiated with $\gamma$-ray doses up to 20 MRads, and at the UC Irvine reactor with doses up to $10^{12}$ neutrons/cm$^2$, show that some initial damage occurs after the first 3 kRads, and no further damage follows (Fig. 12b). This saturation effect hints that the radiation damage in BaF$_2$ is not caused by an intrinsic color center in the bulk material of crystal, such as O$^{2-}$ vacancies in BGO [32], but by externally-introduced impurities.

The consequence of this initial damage has also been investigated. Figure 13 shows that the transmittance of a 2.5 cm long BaF$_2$ crystal decreased by $\sim$1—2% after 2 MRad dose of $^{60}$Co $\gamma$-rays [33]. This expected that a $\sim$20% loss in transmittance for a 50 cm long crystal may be achieved for large size BaF$_2$ crystals with this quality.

Studies at Caltech, BNL, SIC and IHEP (Beijing) have also demonstrated that BaF$_2$ undergoes a striking recovery after a few hours' exposure to a UV lamp. The spectral component of the UV light in the 200 nm range required to break up the UV color-centers appears to be very low. A recent study by J.T. He (IHEP Beijing) for example, showed quite good recovery after two hours' exposure to sunlight [31].

![Figure 12: Transmittances before and after irradiation showing a) recovery from neutron damage; and b) typical saturation effect.](image-url)
Figure 13: The transmittance of a 2.5 cm long BaF₂ crystal, as a function of wavelength, before and after 2 MRads dose measured by Woody et al.

5.3 Radiation Resistance of 25 cm long Crystals

The first batch of 25 cm long BaF₂ crystals delivered by SIC/BGRI in 1990, however, show substantial radiation damage, as measured at BNL [22] and Caltech [23]. Figure 14 shows the transmittance spectra measured for two 25 cm long crystals before and after ⁶⁰Co irradiation with dosage in step of 100, 1k, 10k, 100k and 1M Rads. Figure 14a shows that the transmittance of a crystal from SIC/BGRI is reduced from 70—80% to 10—20% at 220 nm (fast scintillation components) after 10 kRads of ⁶⁰Co γ-ray irradiation. The saturation after 100 kRads is observed. Similar reduction of transmittance was observed for a crystal from Merck, as shown in Fig. 14b. The situation of unsatisfactory radiation resistance of large size BaF₂ crystals was first extensively reviewed in May, 1991, in BaF₂ Workshop at Shanghai, and then in early December, in GEM BaF₂ panel meetings at SSC Laboratory, Beijing and Shanghai.
It is interesting, however, to note that the spontaneous recovery of radiation damage has very long time constant at room temperature, in the wavelength range of fast scintillation components. Figure 15 shows the recovery of transmittance of the same two crystals, as shown in Figure 14. The spectra shown were obtained before and after 1 MRads $^{60}$Co $\gamma$-ray irradiation with a time interval between the irradiation and measurements ranged from 0 to 68 days. For each crystal, the spectra obtained from 0 to 68 days after irradiation are almost undistinguishable between 200 to 400 nm.

Looking into the details, Fig. 16 shows the transmittance data measured at 200 and 800 nm for different irradiation dosages.

![Figure 14: Transmittance spectra, obtained from 25 cm long BaF$_2$ crystals from SIC/BGRI (a) and Merck (b), before (1) and after $^{60}$Co $\gamma$-ray irradiation with dosage of 100 (2), 1k (3), 10k (4), 100k (5) and 1M (6) Rads.](image-url)
220 nm as function of time after irradiation for these two crystals, in an expanded scale. It is clear that the spontaneous recovery at these two wave lengths has very long time constants, especially for the crystal from SIC/BGRI. This observation indicates that a stable detector may be constructed by using BaF$_2$ crystals even with some level of radiation damage. The key issue of a precision BaF$_2$ calorimeter thus is to control the damage before saturation.

It is also interesting to note that the radiation damage of BaF$_2$ does not have strong dependence on the rate of irradiation. Figure 17 shows two sets of transmittance
spectra of a 25 cm long BaF₂ crystals from SIC/BGRI with different dose rate. The crystal was first irradiated up to 1 MRads with fast dose rate. It was then annealed in an oven under 500°C for three hours, so that it was fully recovered. The crystal then was irradiated again with a slow dose rate. Figure 17a shows the measured transmittance spectra with dose rates of 1 (for 100 Rads), 11 (for 1k and 10k Rads) and 24 (for 100k and 1M Rads) Rads/sec. Figure 17b shows the measured transmittance spectra with dose rates of 0.03 (for 100 Rads), 0.3 (for 1k Rads), 3 (for 10k Rads) and 20 (for 100k Rads) and 15 (for 1M Rads) Rads/sec. The small difference between the spectra obtained after the same integrated dosage, but with

Figure 16: Transmittance data at 200 and 220 nm, obtained from 25 cm long BaF₂ crystals from SIC/BGRI (a) and Merck (b), are plotted as function of time after 1 MRads of ⁶⁰Co γ-ray irradiation.
30 times different dose rate, can be attributed to the uncertainty in measurement of integrated dosage. In general, this measurement indicates that the damage of BaF₂ has almost no rate dependence. The full recovery of the annealing also indicates that there is no permanent damage in BaF₂ crystals.

Since May, 1991, substantial progress have been made at SIC and BGRI (see section 5.5). Figure 18 shows the transmittance spectra measured for two 20 cm long crystals before and after ⁶⁰Co irradiation with dosage in step of 100, 1k, 10k, 100k and 1M Rads. Both crystals were produced recently at SIC with improved

![Figure 17: Transmittance spectra of a 25 cm long BaF₂ crystals from SIC/BGRI before and after ⁶⁰Co γ-ray irradiation, with dosage of 100, 1k, 10k, 100k and 1M Rads for fast (a) and slow (b) dose rate.](image-url)
processing technique. Figure 18a shows that the transmittance of a crystal is reduced from 70—80% to 50—60% at 220 nm (fast scintillation components) after 10 kRads of $^{60}$Co $\gamma$-ray irradiation. The saturation after 100 kRads is also observed. Similar reduction of transmittance was observed for another crystal, as shown in Fig. 18b.

Note, both crystals were irradiated in Shanghai for 1 MRads before delivery. They were annealed at Caltech. Systematic measurement on their radiation resistance was carried out at Caltech by using a radiation facility at JPL. The dose rate is identical to the slow rate indicated in Fig. 17b. Comparing with Fig. 14a, it is

Figure 18: Transmittance spectra of two 20 cm long BaF$_2$ crystals, recently produced at SIC, before (1) and after $^{60}$Co $\gamma$-ray irradiation with dosage of 100 (2), 1k (3), 10k (4), 100k (5) and 1M (6) Rads.
clear that these two crystals have much better radiation resistance.

As discussed in section 5.5, the Chinese scientists at BGRI, SIC and Tongji University have made significant progress in understanding the radiation damage mechanism of BaF₂. They are confident in providing solutions for the problem. It is expected that 10% loss of transmittance may be achieved for 25 cm long crystals.

5.4 Consequences of Radiation Damage

There are three consequences in BaF₂ radiation damage:

1. radiation introduce color centers which cause absorption of scintillation light and thus reduce the light attenuation length;
2. radiation introduce phosphorescense which causes random background;
3. there might be a damage of the scintillation mechanism, and thus reduce the light yield.

Most early radiation damage studies were concentrated on the light absorption, i.e. the transmittance loss. Recent studies [22,34], however, reported observations of radiation introduced phosphorescense, which in many cases prohibits measurements of light yield of large size BaF₂ crystals by using a conventional ¹³⁷Cs γ-ray source. Although causing inconvenience for laboratory study, the phosphorescence can be treated as a random noise. Since its energy scale is very low, particularly since it is mainly in wavelengths longer than the fast components, we do not expect phosphorescence would degrade the precision of BaF₂ calorimeter.

It, however, is not clear if the radiation causes damage to the scintillation mechanism of BaF₂ crystals. Controversial results were reported in literature, e.g. [33,35], by comparing measured loss of light yield with simulated result of radiation-introduced decrease of light collection efficiency. It should be pointed out that the surface effect is not negligible in light collection simulation, and it is difficult to simulate. To reduce surface effect, test result of large samples are preferred in comparison with simulation.

By using a ray-tracing program originally used in BGO radiation damage study [36], a preliminary study done at Caltech showed that, to the first order, the
measured loss of light yield can be explained by radiation introduced decrease of light attenuation length [23].

One important input for a ray-tracing program is the light attenuation length which usually is a function of wavelength. Figure 19a shows refractive index of BaF$_2$ crystal as a function of wavelength [37]. The theoretical transmittance of BaF$_2$ crystals, assuming the crystal has infinite light attenuation length, is shown in Fig. 19b, taking into account of multiple bouncings of light between two faces. It is clear that at the UV edge (~200 nm), both the refractive index and the light attenuation

![Graph of BaF$_2$ Refractive Index](image1.png)

![Graph of BaF$_2$ Transmittance (No Light Absorption)](image2.png)

Figure 19: Refractive index (a) and theoretical transmittance (b) with infinite light attenuation length of BaF$_2$ crystal as functions of wavelength.
length have a stronger wavelength dependence. Note, if a measurement is done in air, result below 200 nm is usually not accurate because of the UV absorption of the air.

By using following formula, we calculate light attenuation length corresponding to a measured transmittance \( T_m \) for a 25 cm long BaF\(_2\) crystal:

\[
\ell = \frac{25}{\ln(T_s/T_m)}
\]

where \( T_s \) is the theoretical transmittances with infinite light attenuation length (Fig. 19b).

Table 5: Comparison of Measured and Calculated Light Yield

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Dose (Rads)</th>
<th>( T_{220\text{nm}} )</th>
<th>( \ell ) (cm)</th>
<th>( \eta ) (%)</th>
<th>( \eta_m )</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC/BGRI</td>
<td>0</td>
<td>84.9</td>
<td>354</td>
<td>44</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>78.0</td>
<td>162</td>
<td>35.4</td>
<td>0.80</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>52.1</td>
<td>45</td>
<td>16</td>
<td>0.36</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>16.5</td>
<td>15</td>
<td>3.0</td>
<td>0.07</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Merck</td>
<td>0</td>
<td>75.9</td>
<td>137</td>
<td>33</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>69.2</td>
<td>91</td>
<td>27</td>
<td>0.81</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>49.0</td>
<td>40</td>
<td>14</td>
<td>0.42</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>20.4</td>
<td>17</td>
<td>4.0</td>
<td>0.12</td>
<td>&lt;0.23</td>
</tr>
</tbody>
</table>

Using a ray-tracing program [36], incorporating correct geometry, light attenuation length of the fast component at 220 nm \( \ell \), 2.5 cm mass attenuation length of 0.662 MeV \( \gamma \)-ray from Cs source in BaF\(_2\), light collection efficiency can be calculated, and can be compared to measurements. Table 5 shows calculated light collection efficiencies (\( \eta \)) at 220 nm before and after irradiation, with dosage of 100, 1k and 10k Rads, for two 25 cm long BaF\(_2\) crystals from SIC/BGRI and Merck. The light collection efficiency normalized to before irradiation (\( \eta_m \)) and corresponding data measured at Caltech are also shown in the table.

It is clear from Table 5, that, to the first order, the measured loss of light yield can be explained by radiation introduced decrease of light attenuation length. Further work is needed to refine the program for an accurate prediction. Note, the data
measured after 10 kRads is not accurate because of phosphorescence background and severe absorption of these two crystals.

The BaF$_2$ crystals recently produced by SIC have much less absorption and phosphorescence, which allows us to measure light yield with $^{137}$Cs source. Figure 20 shows the transmittance (a) and light attenuation length (b) at 220 nm, as a function of dosage. Also shown in the figure is the normalized light yield (c) of fast components and total, measured with a gate of 30 ns and 2 μs respectively, as a function of dosage.

![Figure 20: Transmittance (a) and light attenuation length (b) at 220 nm and the light yield (c) measured with 2 different gate width for a 20 cm long BaF$_2$ crystal from SIC are shown as function of dosage.](image-url)
The fact that we observe saturation in all these measurements after 100 kRads indicates that the light loss indeed is caused mainly by absorption.

Table 6 lists theoretical transmittance ($T_{\text{surf}}$, i.e. Fig. 19b), specification from BaF$_2$ collaboration without radiation damage requirement ($T_{\text{spec0}}$) and corresponding light attenuation length ($\ell_{\text{spec0}}$). Assuming that a 5% light uniformity may be achieved with an adequate light attenuation length ($\ell_{\text{spec1}}$) at 220 nm of longer than 100 cm, Table 6 shows that a transmittance ($T_{\text{spec1}}$) of 10% less than original specification of BaF$_2$ collaboration may be allowed. Note, the light attenuation length specification of TAPS collaboration is 75 cm [38]. However, the effect on light uniformity of BaF$_2$ crystals with $\ell = 100$ cm must be further studied with simulation and measurements in technical proposal stage.

<table>
<thead>
<tr>
<th>$\lambda$(nm)</th>
<th>$T_{\text{surf}}$ (%)</th>
<th>$T_{\text{spec0}}$ (%)</th>
<th>$\ell_{\text{spec0}}$ (cm)</th>
<th>$T_{\text{spec1}}$</th>
<th>$\ell_{\text{spec1}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>90.6</td>
<td>75</td>
<td>130</td>
<td>66</td>
<td>79</td>
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<tr>
<td>220</td>
<td>91.1</td>
<td>80</td>
<td>190</td>
<td>70</td>
<td>95</td>
</tr>
<tr>
<td>550</td>
<td>92.7</td>
<td>85</td>
<td>290</td>
<td>77</td>
<td>135</td>
</tr>
</tbody>
</table>

5.5 Understanding BaF$_2$ Radiation Damage (II)

The basic understanding of BaF$_2$ radiation damage has been significantly progressed since Shanghai Workshop, May 1991. Summarized below is basic experimental result and understanding on the mechanism of BaF$_2$ radiation damage, mainly achieved by Chinese scientists.

A paper of Z.W. Yin et al. [21] shows the effect of various impurities as cations: Pb, rare earth elements (Ce, La and Eu) and transition metals (Fe and Co), and as anions: OH$^-$ and oxygen. The difference in radiation resistance of different parts (top versus bottom) of BaF$_2$ crystals was observed. Based upon the result obtained by oxygen doped crystals, it was proposed that the radiation damage of BaF$_2$ was caused by O$^{2-}$ ions (absorption in 190—250 nm) or O$^{2-}$—F$^+$ dipoles (absorption at 290 nm), where F$^+$ is fluorine vacancy in BaF$_2$. The formation
and decomposition of \( \text{O}^2-\text{F}^+ \) dipoles were suggested to be responsible for the existence and disappearance (under irradiation) of the famous 290 nm absorption peak in Chinese crystals.

A more detailed study done by G. Chen et al. [24] examined the effect of trace metals of alkali, earth alkali, transition metals (Fe, Co, Ni, Mn, Cr and Cu) and rare earth elements (Ce, Pr, Nd, Eu, Tb, Dy, Ho, Tm, Yb, Y, La, Lu and Sm). While the alkali and earth alkali metals do not cause obvious damage, the transition metals do cause damage, and the rare earth elements, depending on the element, have various effects. However, the impurities were not measured after crystals were grown. The experience of higher radiation resistance for Eu doped BGO [32] did not help in BaF\(_2\) case. The same conclusion was obtained by Yin et al. [21].

G. Chen et al. [24] also examined the effect of vacuum of the oven. Although there was no ultra high vacuum available in this experiment. The tests using ovens at 15, 53, 230 and 600 \(\mu\)torr during crystal growing period show clearly that the highest vacuum, i.e. 15 \(\mu\)torr, gives the best result (Fig. 13 of [24]). The study further pointed out that the vacuum at low temperature (< 600°C) is also important (Fig. 14 of [24]), which was explained by hydrolysis process of BaF\(_2\) at low temperature.

To understand the mechanism of BaF\(_2\) radiation damage, some theoretical work was carried out by physicists from Tongji University: L.M. Wang et al. and L.Y. Chen et al. [25]. The absorption bands of different impurities (cations or anions) were calculated by using a simple cluster model. It is interesting, however, to find that the absorption peaks of Eu doped crystal measured at 230, 347 and 370 nm (Fig. 4 of [21]) and Sm doped sample measured at 263, 334, 412, 575 nm (Fig. 12 of [24]) agree quite well with the calculation (Table 1 of [25]). This provides some confidence on the prediction ability of this calculation. The most interesting result is the Table 2 of [25], which shows calculated broad absorption bands caused by color centers or anions.

The Tongji paper [25] further described one important experiment. They took one piece of the new SCI crystal (#12), and made several samples with it. One sample was doped with OH\(^-\) by heating it at 700°C under wet conditions for 12 hours. The surface hydrolysis and subsequent migration of OH\(^-\) ion in crystal introduced OH\(^-\) doping:

\[
\text{BaF}_2 + 2\text{H}_2\text{O} \rightarrow \text{Ba(OH)}_2 + 2\text{HF}
\] (6)
They then compare the absorption measurements of this sample together with two undoped control samples: one from the same crystal #12 and another from crystal #3 which is from an early batch. The measurements show obvious absorption band in the sample treated with OH\(^-\) doping. It was at 192 nm before irradiation, and was shifted to 204 nm after. They concluded that OH\(^-\) (absorption at 191 nm, Table 2 of [25]) was decomposed through radiolysis, and a U center (substitutional H\(^-\) ion, absorption at 191 nm, Table 2 of [25]) was formed:

\[
OH^- \rightarrow H_i^0 + O^-  \text{ or } H_o^- + O_i^0
\] (7)

This was further confirmed by an IR absorption at 793.75 cm\(^-1\) originated from the U center, comparing with undoped sample #3. They also found VUV absorption edge shift towards lower energy (134 → 150 nm) for OH\(^-\) doped crystal. The 204 nm U center absorption is also observed clearly in VUV spectrum.

An interesting comparison made by Tongji group was for oxygen doping. They tried to dope oxygen in a sample obtained from sample #12 by heating the sample in dry oxygen at 700°C for 12 hours, i.e. under the same conditions as OH\(^-\) doping described above, except no water. Contrary to the sample doped with OH\(^-\), the result, however, showed no obvious change. They explained this observation by the difficulty of diffusion of oxygen ions into the BaF\(_2\) crystal lattice.

Tongji group also has a different explanation of the famous 290 nm absorption. They think it is caused by OH\(^-\) ion: the absorption peak of free OH\(^-\) radical has shifted a little to red because of lattice field.

In summary, there are consensus among chinese researchers upon the radiation damage of BaF\(_2\):

- Higher vacuum in oven improves the radiation resistance of BaF\(_2\) crystals.
- It is not conclusive yet what is the origin of 290 nm absorption common in chinese crystals.
- While most cations are not main cause of radiation damage, some rare earth cations do produce distinguished absorption peaks. It is thus vital to remove rare earth elements in raw material.
- The OH\(^-\) and oxygen impurity are most fatal to the radiation resistance of BaF\(_2\). In a matter of fact, the improved BaF\(_2\) crystals were produced with
improved processing technique which pays special attention to the removal of OH\textsuperscript{-} and oxygen.

In summary, chinese scientists think that they are now in correct path in understanding the radiation damage mechanism of BaF\textsubscript{2} crystals, and in providing solutions for the problem.

6 INTERCALIBRATION ACCURACY: $b_C$

Precise calibration in situ is vital in maintaining the high resolution of a precision detector. As shown in Table 3, the dominant contribution to the resolution of BaF\textsubscript{2} calorimeter at high energies is assumed to be the uncertainty of the intercalibration. It is even more so, since the radiation at the SSC would degrade the performance of the BaF\textsubscript{2} crystals. Assuming three sources of the irradiation: electromagnetic energy deposited in BaF\textsubscript{2} crystals, hadronic energy partially deposited in BaF\textsubscript{2} crystals and the neutron albedo \cite{39}, typical dose rate is from 50 kRads/year at $\eta = 0$ to 5 Mrads/year at the largest rapidity ($|\eta| = 2.5$) for GEM detector design.

Since the radiation damage of BaF\textsubscript{2} crystals saturates after initial dose and the fact of essentially no spontaneous annealing at room temperature, the BaF\textsubscript{2} crystals satisfying GEM specification (section 7), would remain to be a stable detector, although frequent and precise calibration must be provided to maintain the high resolution. In this section, we discuss two calibration schemes. One uses physics of collider — calibrate BaF\textsubscript{2} crystals with longitudinally penetrating minimum ionizing particles (MIP). The other uses a special calibration tool — a Radio Frequency Quadrupole accelerator (RFQ) \cite{40}.

6.1 MIP Calibration

The high flux of minimum ionizing particles produced by the collider can be used as a calibration source. A MIP passing through a BaF\textsubscript{2} crystal longitudinally would deposit 0.33 GeV energy in the crystal which would be readout by the crystal with a few percent resolution. With a statistics of a few hundreds tracks, the peak position or the calibration point can be determined to 0.4%. The multiplicity of
charged hadrons at SSC is estimated to be large enough to provide a calibration within few working days during SSC running. Detailed study on feasibility of this calibration will be carried out in technical proposal stage.

The promise of this technique has been emphasised by recent analysis of hadronic $Z^0$ decays in L3, where the minimum ionizing peak signal was cleanly extracted with a simple cut on the energy in neighboring crystals, and which was observed to have a resolution $\sigma = 6\%$ (summed over all crystals). Tests with cosmic rays at UCSD, using a BaF$_2$ crystal pair 50 cm in length showed a resolution of 3%.

6.2 RFQ Calibration

One novel precision calibration technique for precision electromagnetic calorimeter is based on an RFQ [40]. Depending on the type of target, this calibration scheme can be run in two different modes.

The first mode uses a lithium target: the reaction $^7$Li$(p,\gamma)^8$Be produces a flux of 17.6 MeV photons which can be used to calibrate the thousands of electromagnetic calorimeter cells at once, with an absolute accuracy of better than 1% in 1—2 hours. The feasibility of this calibration mode has been proven in an experimental test of a 4 x 5 L3 BGO crystal array [40]. An absolute calibration precision of 0.7% was achieved in the test. This low energy photon calibration, however, is not directly relevant to an SSC electromagnetic calorimeter.

The second mode [41] uses a fluoride target: the reaction $^{19}$F$(p,\alpha)^{16}$O*, and the subsequent decay of the excited oxygen nucleus $^{16}$O*, produces hundreds to thousands of 6 MeV photons per millisteradian per beam pulse. These photons, functioning as a synchronised "equivalent high energy photon" of up to 30 GeV per calorimeter cell, would serve as a calibration source for SSC electromagnetic calorimeters. With a proper normalization, this technique provides a relative calibration with precision of 0.4% in a few minutes. The feasibility of this calibration mode has been proven in another experimental test with 4 BaF$_2$ counters and a 7 x 7 L3 BGO crystal array [40]. Figure 21 shows the normalized ADC distributions of a crystal for runs with different beam intensities. The perfect Gaussian distribution and the correlation between the r.m.s. width and the total energy deposited in the crystal is clearly seen.
Figure 22 shows that the deviation of the peaks of 49 BGO distributions, normalized to the sum of BGO energy in the $7 \times 7$ matrix, 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 $2.38 \text{ GeV}/0.1 \mu\text{Coulomb}/1.6 \text{ mrad}$ was observed for a 1.92 MeV beam. There are much stronger fluorine resonances between 2.0 and 4.0 MeV [42], beyond the 1.92 MeV beam energy used in the test. 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 [42], an EPE of $30 \text{ GeV}/0.1 \mu\text{Coulomb}/1.6 \text{ mrad}$ or more is expected. Table 7 lists EPE's 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 [42], are also listed in the

![Normalized ADC distribution of a crystal at different energies.](image-url)
Figure 22: Variation of the normalized peak positions from BGO crystals.

Table 7: Measured and Calculated Equivalent Photon Energy.

<table>
<thead>
<tr>
<th>Proton Energy (MeV)</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>3.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPE_{meas} (GeV)</td>
<td>1.5</td>
<td>13</td>
<td>22</td>
<td>30</td>
<td>37</td>
</tr>
<tr>
<td>EPE_{cal} (GeV)</td>
<td>2.6</td>
<td>14</td>
<td>24</td>
<td>33</td>
<td>38</td>
</tr>
</tbody>
</table>

Two RFQ systems with exactly the specifications required for our calibration system are currently under construction at AccSys Technology, Inc. for the U.S. Navy (for a different application). One of the accelerators is expected to be available by mid-1992 for a full scale test of our technique at 3.85 MeV, using a BaF₂ prototype matrix. At least one of the accelerators could be acquired at very low cost by 1995, once the Navy's test program is completed.
7 BaF₂ SPECIFICATIONS

The specifications of the BaF₂ crystals finally will be accepted for GEM BaF₂ calorimeter are summarized in this section. The dimensional tolerances, especially for a 50 cm long crystal pair, the UV transmittance and radiation resistance are the three vital requirements.

The stringent dimensional tolerances is required to achieve a thin glue joint, e.g. few tens of µm of KE103, and thus maintain the light uniformity. Good UV light transmittance through the crystal is vital to guarantee adequate light attenuation length for a uniform light response, and thus maintain the intrinsically high resolution of the BaF₂ calorimeter. We have specified the transmittance requirement in terms of the minimum fraction of the light passing through a 25 cm long BaF₂ crystal at specified wavelengths. For simplicity, these specifications include ~8% loss at two interfaces between air and BaF₂.

The radiation resistance requires that after a saturated radiation dosage the BaF₂ crystals have more than 100 cm light attenuation length for the fast component at 220 nm. We thus propose the following specifications:

- Dimensional tolerances are dictated by the need to mount the crystals safely in the support structure, with a minimum of dead space between the crystals:
  - from -300 µm to 0 µm in the transverse dimensions (typical deviations from nominal 100µm)
  - from -400 µm to 0 µm in length
  - less than 50µm in planarity of all faces after coupling two 25 cm long half crystals.

- Transparency before irradiation, specified in terms of the minimum fraction of the light at specified wavelengths which passes through 25 cm of crystal length:
  - ≥ 75% at λ = 200 nm
  - ≥ 80% at λ = 220 nm
- ≥ 88% at \( \lambda = 550 \text{ nm} \)

- Transparency after 1 MRads irradiation, specified in terms of the minimum fraction of the light at specified wavelengths which passes through 25 cm of crystal length:
  - ≥ 66% at \( \lambda = 200 \text{ nm} \)
  - ≥ 70% at \( \lambda = 220 \text{ nm} \)
  - ≥ 77% at \( \lambda = 550 \text{ nm} \)

References


[3] Crystal Clear Collaboration at CERN, Spokesman P. LeCoq. Note, lead fluoride is a crystal with high density which does not yet scintillate. R&D is under way to make it scintillating.


[10] The K-Cs-Te cathode has been implemented in R4406 triode for BaF\(_2\) readout. The Rb-Te cathode has been implemented in R4480 PMT for BaF\(_2\) readout. Both tubes use quartz window and are commercially available.


[16] The nominal gain of R4406 is 4 in the Hamamatsu specification. The reason of its lower gain, compared to the gain of 12 of Hamamatsu’s standard R2148 triode, is due to the processing technology used. At present, the K-Cs-Te cathode has been evaporated inside the closed triode envelope. This contaminates the dynode. The lower gain of R4406 is due to the lower efficiency of the secondary electron emission from the K-Cs-Te contaminated dynode. By using a remote transfer technology in a large vacuum tank, this contamination will be eliminated. It is therefore expected (as indicated by Hamamatsu themselves) that R4406 triodes produced in future, under standard production conditions, will have a nominal gain of 12.


[34] Z. Wei *et al.*, *A Study on Radiation Damage of Barium Fluoride Crystals*, to be submitted to *Nucl. Instr. and Meth.*

The ray-tracing program was originally written by L. Gatingnon and D. de Lang of University of Nijmegen, and was substantially modified by R.Y. Zhu in 1986.

I. H. Malitson, J. of Optical Society of America Vol 54 No. 5 (1964) 628.


