Fermi National Accelerator Laboratory

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# Technical Memo on $PbF_2$ as a Cherenkov Radiator for EM Calorimetry

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It is apparent that the ever increasing rates and radiation levels found in high-energy physics are excluding more and more instrumental techniques. Those techniques that are remaining are often pushed to their theoretical limits. This situation reaches an extreme at the proposed luminosity of the SSC. Also, it is fair to say that at the SSC, after the accelerator itself, calorimetry will be the next most important physics tool. Therefore, we should be ever alert to new calorimetry techniques which may operate in this demanding environment. The material lead fluoride, $PbF_2$, has a real potential of yielding a very compact, high-resolution electromagnetic calorimeter that is both fast and radiation hard.

$PbF_2$ is not a scintillator but a Cherenkov radiator like lead glass, but with a radiation length even shorter than that of BGO. For comparison, tables of properties of $PbF_2$ and some scintillators and lead glasses are included at the end of this proposal. $PbF_2$ has a density of 7.66 g/cm$^3$ and a radiation length of <1 cm. Although it has the same Moliere radius as BGO, its "apparent" Moliere radius is about 20% smaller. This is because, as a Cherenkov radiator, one does not see the soft particles at the outside of the shower. Thus, $PbF_2$ is the most compact non-sampling material for electromagnetic calorimetry. Also, since it is a Cherenkov radiator, if one can get the light out quickly, it is one of the fastest techniques available.

Figure 1 shows the transmission of a sample of $PbF_2$ obtained from Engelhard Corp. (used to be Harshaw) along with the cutoffs of a glass PMT and of a "typical" lead glass. The relative intensity of Cherenkov radiation (marked $1/\lambda^2$) and the spectral response of a bialkali photocathode are also included. The first point to note is that $PbF_2$ transmits much farther into the blue than lead glass and thus more Cherenkov photons will be produced per unit particle track length. This is also in a spectral region where the PMT has its highest quantum efficiency. Also, from the table one can see that its index of refraction is also very favorable for good light production. An additional point to be taken from figure 1 is that a glass PMT cuts off the blue edge of the $PbF_2$ transmission. This is very desirable since it removes the bluest light which is the most sensitive to the opacity of the material. Often in lead glass this is accomplished with a filter on the PMT which improves the energy resolution but reduces the detected light by a factor of 2.

Twenty years ago Hofstadter also looked at it and published two short papers [1,2]. With a crystal 5.25 inch diameter by 5 inch long (13.8 Xo $\phi$ x 13 Xo) he obtained an energy resolution of about $6.4\%/\sqrt{E}$. Craig Woody has placed a poor quality $PbF_2$ crystal in a BNL electron test beam for us. This crystal was 134 mm long and 44 mm in diameter (4.6 Xo $\phi$ x 14 Xo). Although the material was yellow and we estimate that the light output was down by at least a factor of 4, 1000 photoelectrons were detected per GeV. This would imply that with a good crystal, the contribution of photon statistics to the resolution would be about 1.5%. Figure 2 shows the signals for 3 GeV electrons and for minimum ionizing particles. Without any effort to optimize the optical coupling or reduce the signal reflection (20 ns) the signal is still down to about 20% of its peak value 20 ns after its beginning. With a little work, $PbF_2$ should easily work at SSC rates.

Radiation hardness is also an important question for any material considered for use at the SSC. Two samples cut from the sample given us by Engelhard Corp. have been irradiated in the research reactor at the University of Michigan. There was some degradation in the transmission of the samples but there was a remarkable recovery after exposing the samples to a UV light for 10 minutes. Figure 3 shows the transmission a sample exposed to $3\times10^5$ rad of gamma rays and $1\times10^5$ rad of neutrons, followed by a 10 minutes exposure to a UV light. Figure 4 shows the transmission a sample exposed to $3\times10^6$ rad of gamma rays and $1\times10^6$ rad of neutrons, again followed by a 10 minutes exposure to a UV light. The sample receiving the higher dose shows some permanent damage. Although the $PbF_2$ had a good transmission, we cannot be certain of its purity. In the case of $BaF_2$ it has been shown that the radiation hardness is very dependent upon the purity of the material. In general the fluorides are among the most radiation hard materials and there is hope that $PbF_2$ will also share that characteristic. All that can be said is that $PbF_2$ does not appear to be radiation soft.

Finally, there is the issue of the expected cost of $PbF_2$. With the exception of the one piece of material that we have from Harshaw, all of my material has come from Optovac, Inc. (North Brookfield, Mass; contact: Rob Sparrow, 508/867-6444). They have grown some 1 kg pieces for me and their best guess for the cost of $PbF_2$ in large quantities is <\$3/cm$^3$. This is using the best starting material available. The price could come down by as much as \$1/cm$^3$ if cheaper material can be used. To put that in perspective, BGO and $BaF_2$ cost about \$15/cc and \$8/cc, respectively. In terms more appropriate for computing the price of a calorimeter $PbF_2$, BGO, and $BaF_2$ cost about \$3, \$16, and \$17 per cm$^2$-Xo. Even at \$3/cm$^3$ it is quite competitive as a calorimeter technique.

**References**

1) E.B. Dally and R. Hofstader, IEEE Trans. Nucl. Sci. NS-15 #3 (1968) 76.

2) E.B. Dally and R. Hofstader, Rev. Sci. Instr., 39 #5 (1968) 658.

## Physical Properties of $PbF_2$ and Some Scintillators

| | **$PbF_2$** | **BGO** | **$BaF_2$** | **CsI** |
|---|---|---|---|---|
| **Density** | 7.66 | 7.13 | 4.87 | 4.51 |
| **Radiation length** (cm) | 0.95 | 1.1 | 2.1 | 1.9 |
| **Moliere radius** (cm) | 2.22 $(1.8)_{apparent}$ | 2.24 | 3.45 | 4.35 |

## Physical Properties of $PbF_2$ and Some Lead Glasses

| | **$PbF_2$** | **F-2** | **SF-5** | **SF-6** |
|---|---|---|---|---|
| **Density** | 7.66 | 3.61 | 4.08 | 5.20 |
| **Pb** (% by wt) | 85 | 42 | 51 | 66 |
| **Radiation Length** (cm) | 0.95 | 3.22 | 2.54 | 1.69 |
| **Critical Energy** (cm) | 8.96 | 17.3 | 15.8 | 12.6 |
| **Index of Refraction** | 1.86 | 1.62 | 1.67 | 1.81 |

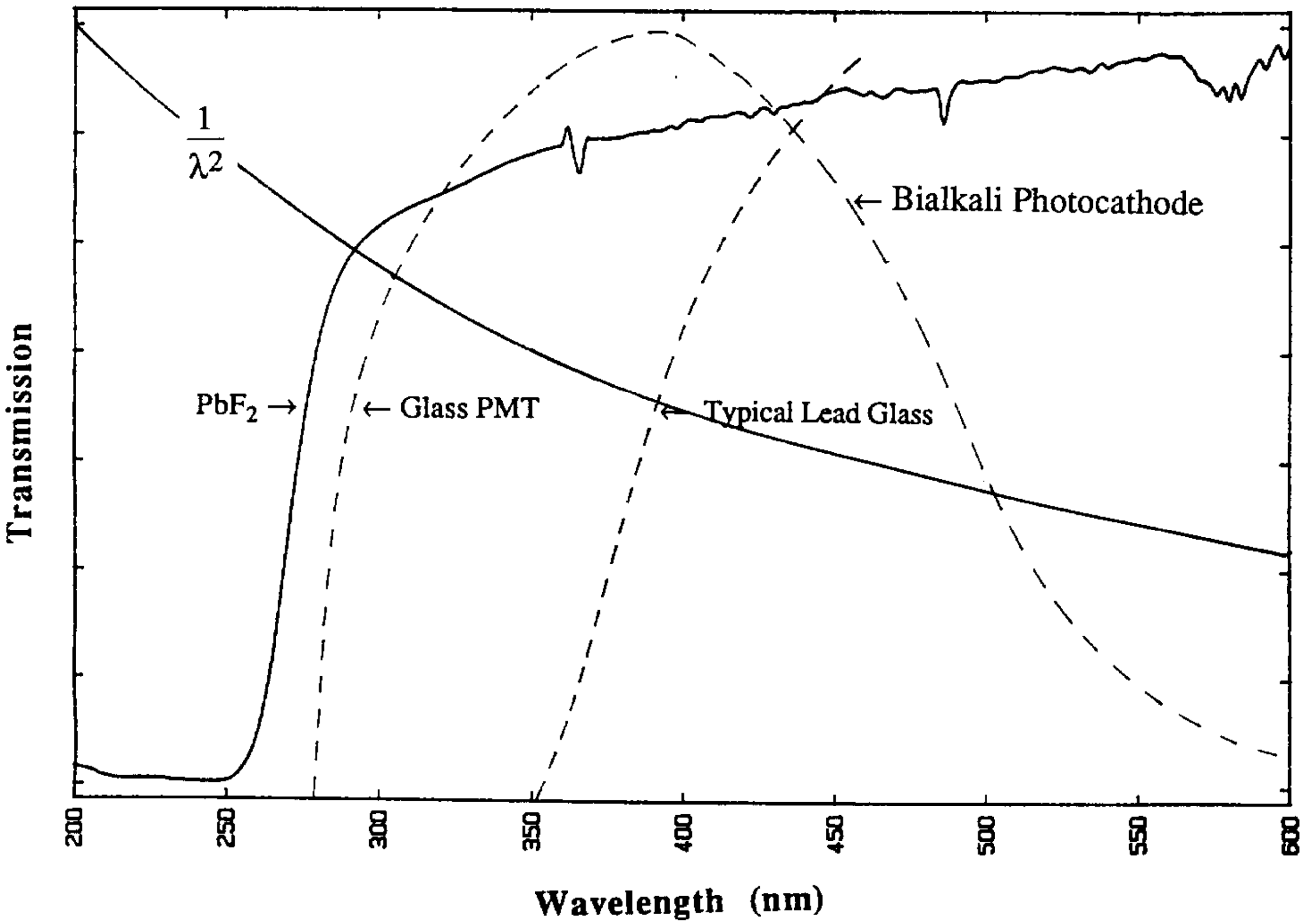
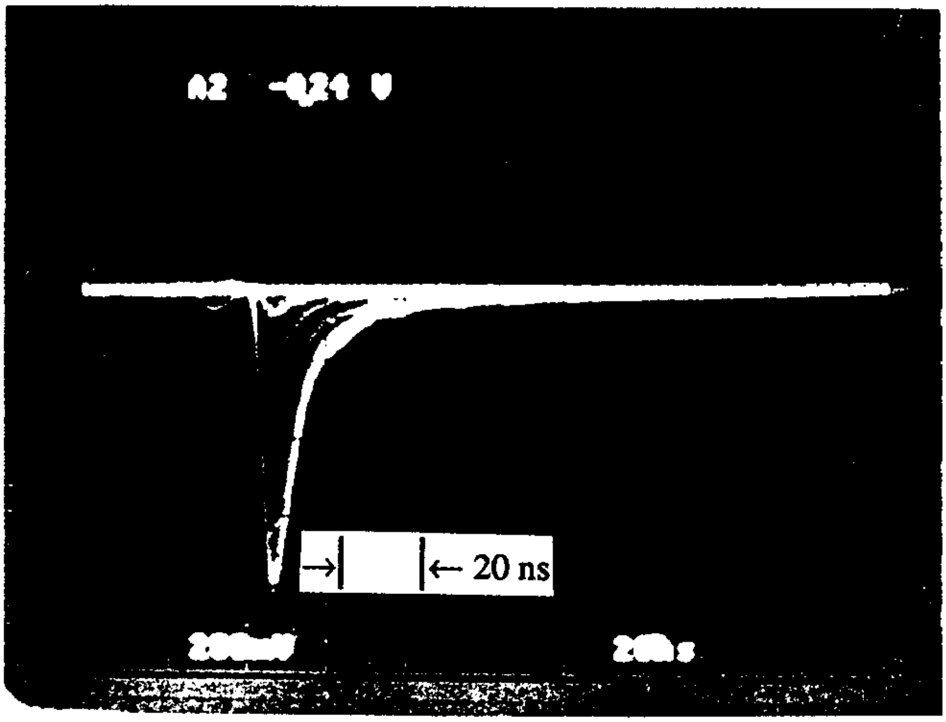
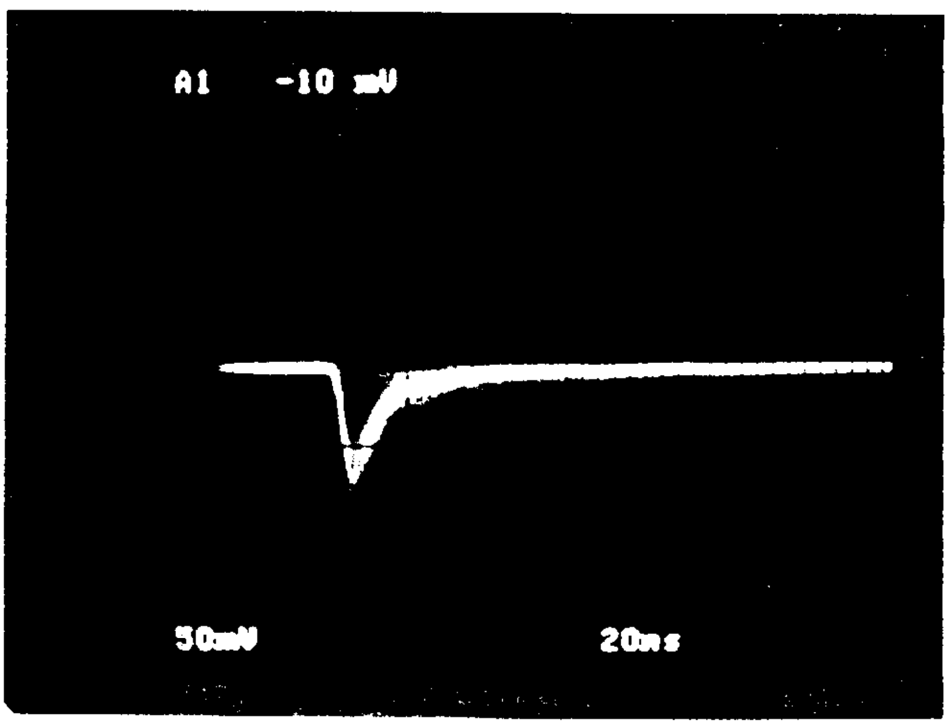

Transmission
Wavelength (nm)
200
250
300
350
400
450
500
550
600
$\frac{1}{\lambda^2}$
← Bialkali Photocathode
$PbF_2$ →
← Glass PMT
← Typical Lead Glass

Figure 1




3 GeV electrons




Minimum Ionizing Particles

Figure 2

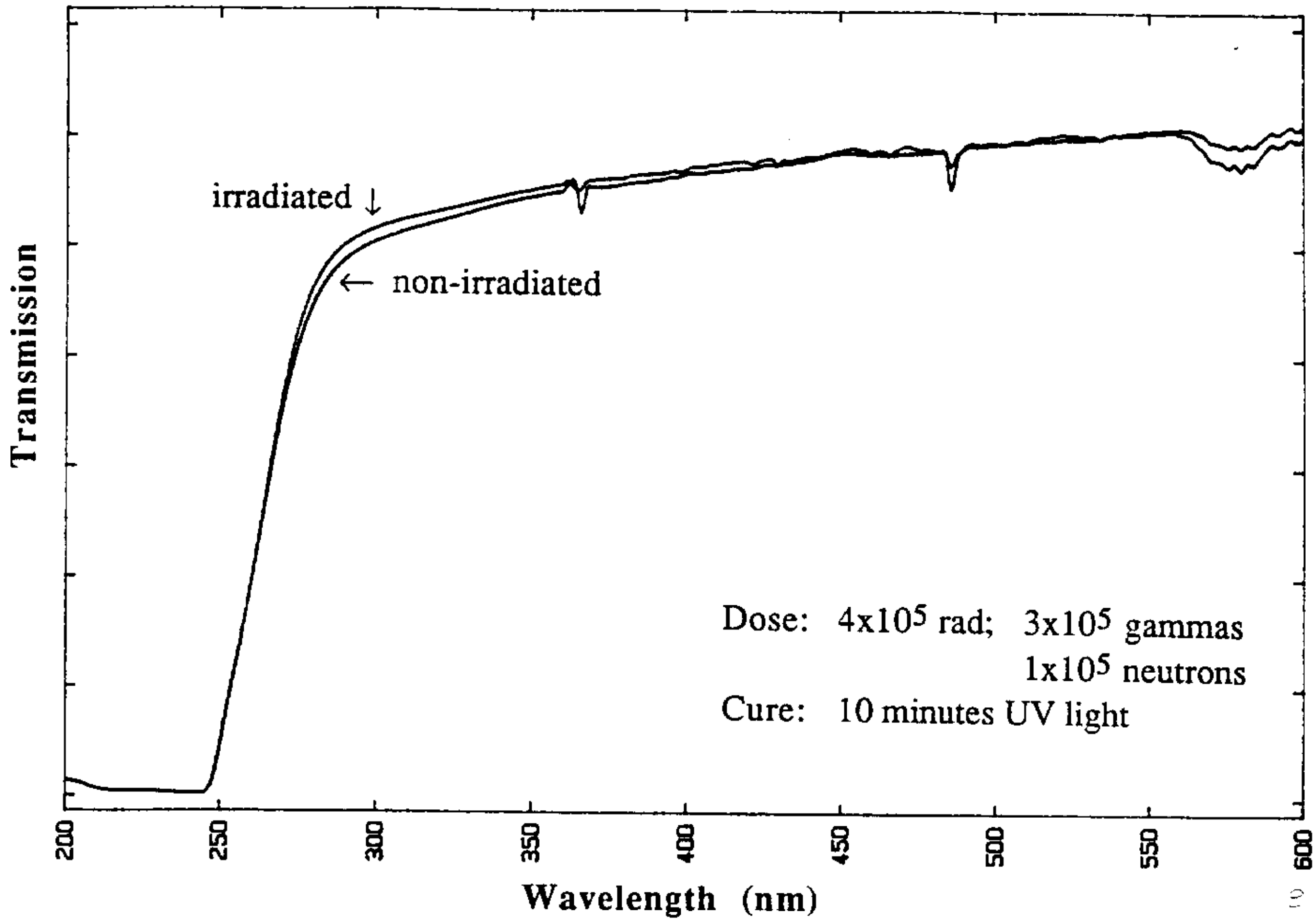



Figure 3

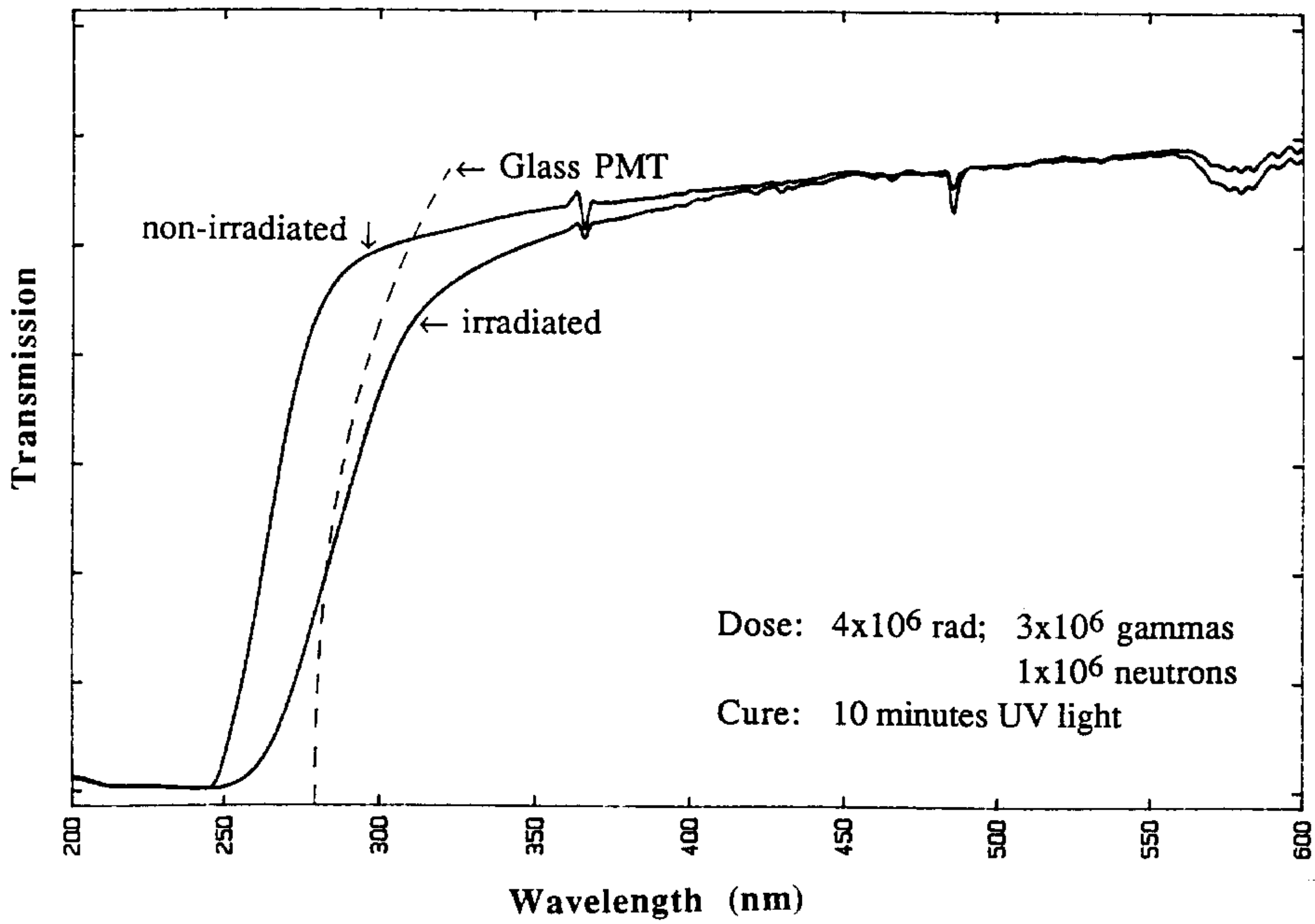



Figure 4