

# Feasibility Studies of Optical Curing of Radiation Damage to $\text{PbF}_2$ .

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## Abstract

I discuss several ideas for feasibility studies of optical curing of the radiation damage to the  $\text{PbF}_2$  calorimeter. Optical transmission studies will not give us directly the light yield and resolution of GeV showers. Radiation damage studies with 1-10 MeV side-on photons and electrons will give not necessarily give a realistic profile of the damage from 100 MeV front-on photons and electrons during a DVCS experiment. Elastic scattering and DVCS measurements with curing will provide the most specific information on the future performance of the calorimeter.

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## I. INTRODUCTION

The Hall A 12 GeV DVCS experiment will cause intense irradiation of the  $\text{PbF}_2$  calorimeter. Following the MAMI-A4 experience[1–3], we expect to be able to cure the radiation damage with blue light illumination of the calorimeter. However, the information from MAMI is somewhat ambiguous. We base our expected luminosity limits and optical curing plans on two statements:

1. With the exception of a few outlier blocks (that probably should be discarded), during E00-110 all calorimeter blocks sustained a downward shift in light response per GeV of up to 20%.
2. In the MAMI-A4 tests, blocks that sustained 25% attenuation from  $^{60}\text{Co}$  illumination recovered full (blue light) transmission after 17 hours of blue light illumination ( and 6 hours of rest before re-powering PMTs).

The difficulty for future DVCS experiments is that the 20% decrease in light output observed in E00-110 (1) is not equivalent to a 25% attenuation of transmission cured by blue light (2). This inconsistency is further confirmed by the anecdotal statement that many of the E00-110  $\text{PbF}_2$  blocks were “black” at the end of the run. These various statements can be reconciled if we recognize that the radiation damage during E00-110 may have been concentrated at the front face (first 1-2 radiation lengths). Thus even a “blackened” block (when viewed from the front face) may still give a good response to 1–3 GeV showers (since shower max is at about  $4X_0$ ).

Prior to launching a 100 day DVCS run at 6.6 – 11.0 GeV, it is critical to understand the radiation damage and optical curing of the calorimeter. In this note, I discuss several options for feasibility studies of the following type:

1. Off-site irradiation and curing studies
2. Parasitic in-beam tests
3. Dedicated in-beam tests via elastic scattering
4. A new 6 GeV DVCS experiment as a physics run and test run for 12 GeV.

## II. IRRADIATION AND CURING STUDY OPTIONS

### A. Off-Site Tests

It is possible to find a low energy source ( $^{60}\text{Co}$ , or a 1-10 MeV medical electron accelerator) and to repeat the MAMI-A4 studies. These studies could be structured as follows:

- Illuminate unwrapped blocks from the side with a low energy source.
- With either an array of light sources and sensors, or a single moving source/sensor pair, monitor the optical transmission (transverse) as a function of longitudinal position along the block.
- At an appropriate transmission loss (20%, 50%, 80%?), cure the block with blue light illumination.
- Remeasure the optical transmission, and repeat the irradiation cycle.

The principle virtue of this procedure is that it is completely independent of beam time at JLab. This would test the response of a cluster of blocks to multiple cycles of irradiation and curing. There is only one brief comment in the MAMI publications about repeated cycles of curing. However, there is a major limitation of this study. Without a detailed Monte-Carlo of the shower production **and** light collection, it is difficult to relate transmission losses measured with low energy irradiation to energy calibration or resolution shifts of GeV showers in the DVCS experiment.

### B. Parasitic in-situ Tests

In the DVCS experiment, for calorimeter blocks at angles larger than  $7^\circ$  the irradiation dose is dominated by Møller electrons (and radiative Møller photons) and  $\pi^0$  decay photons. Møller and radiative Møller events produce the same total shower energy:

$$\begin{aligned} k' &= \frac{m}{(m/k) + 1 - \cos \theta} \\ &\approx 70 \text{ MeV} \quad \text{at } 7^\circ \\ &\approx 35 \text{ MeV} \quad \text{at } 7^\circ \end{aligned}$$

The inclusive  $\pi^0$  decay photons have a similar typical energy. The same type of transmission/curing tests as in IIA could be performed  $\{\backslash\text{it in-situ}\}$  in Hall A, with a realistic irradiation of  $\text{PbF}_2$  blocks. This could possibly be accomplished parasitically as follows:

- Setup up one or more blocks is a black box above or below the beam line at 7 to  $10^\circ$  downstream. Placing the blocks out of plane may facilitate performing these measurements parasitically, without disturbing an ongoing experiment.
- The target should be liquid hydrogen, to minimize the neutron flux, since neutrons do not necessarily cause the same type of radiation damage as photons and electrons. Minimizing neutrons may be difficult with the conventional scattering chamber and its' thick neck.
- The optical transmission must be monitorred continuously.
- At appropriate intervals, the blocks can be cured with blue light.

This method has several limitations. Even for one block, the full apparatus for transmission monitoring and blue light curing may be sufficiently elaborate and bulky as to preclude truely parasitic operation. Radiation damage by electrons and photons is believed to be dominated by excitation of long-lived atomic or molecular states in  $\text{PbF}_2$ , which increase the optical absorption of the medium. On the other hand, neutrons will cause nuclear reactions, which may cause crystal dislocations that are less readily cured by blue light. Without replacing the scattering chamber with a version of the DVCS scattering chamber (and beam pipe), it may be difficult to control the neutron illumination. This method also does not determine the calibration and resolution of GeV showers as a function of irradiation/curing history.

### C. Dedicated Elastic Irradiation/Calibration

A  $3 \times 3$  or  $5 \times 5$  calorimeter could be used in coincidence with the HRS to measure  $H(e, e'_{\text{Calo}} p_{\text{HRS}})$  elastic events. At 7 to  $10^\circ$ , the primary background is a slowly varying function of beam energy. Studies at 4 to 6 GeV incident should be sufficient to calibrate the radiation effects at 11 GeV, provided secondary scattering from the beam line is under

control. Sample elastic kinematics are

$$\begin{aligned}
k &= 5 \text{ GeV} \\
\theta_e &= -10^\circ \\
k' &= 4.625 \text{ GeV} \\
Q^2 &= 0.703 \text{ GeV}^2 \\
p' = q &= 0.918 \text{ GeV} \\
\theta_p = \theta_q &= 61.02^\circ.
\end{aligned} \tag{1}$$

We define a polar coordinate system  $(\theta, \phi)$  with respect to the  $z$ -axis pointing along the beam axis downstream. Coplanarity requires  $\phi_{p'} = \pi + \phi_e$ . The cartesian angles  $(\theta_H, \theta_V)$  of the HRS are defined with respect to the transport coordinates of the spectrometer:  $z'$ -axis along spectrometer central ray,  $x'$ -axis in dispersive direction (down in laboratory), and  $\hat{y}' = \hat{z}' \times \hat{x}'$ .

$$\begin{aligned}
\tan \theta_H^{HRS} &= \frac{p' \cdot \hat{y}'}{p' \cdot \hat{z}'} \\
\tan \theta_V^{HRS} &= \frac{p' \cdot \hat{x}'}{p' \cdot \hat{z}'}
\end{aligned}$$

For the calorimeter, there is no dispersion, so it is more convenient to define a coordinate system with  $\hat{y}_C$  vertical (up),  $\hat{z}_C$  pointing to the center of the calorimeter, and  $\hat{x}_C = \hat{y}_C \times \hat{z}_C$ . Then:

$$\begin{aligned}
\tan \theta_H^{Calo} &= \frac{k' \cdot \hat{x}^C}{k' \cdot \hat{z}^C} \\
\tan \theta_V^{Calo} &= \frac{k' \cdot \hat{y}^C}{k' \cdot \hat{z}^C}
\end{aligned}$$

The vertical acceptance matching of the proton spectrometer and electron calorimeter is:

$$\tan \theta_V^{Calo} \approx \frac{\sin \theta_e}{\sin \theta_q} \tan \theta_V^{HRS}.$$

For the elastic kinematics above:

$$|\tan \theta_V^{Calo}| \leq 0.01.$$

This will match the acceptance of a single  $3 \times 3 \text{ cm}^2$  central calorimeter block  $\leq 1.5 \text{ m}$  from the target.

## D. DVCS

Do a 6 GeV DVCS experiment. Setup a blue light curing lamp inside the black box (instead of the LED?). Run at full luminosity ( $4 \cdot 10^{37}/\text{cm}^2/\text{s}$ ). Monitor the calorimeter resolution with  $\pi^0$  mass reconstruction, and [possibly] frequent elastic H( $e, e'_{Calo} p_{HRS}$ ) runs.

This option requires the largest investment of effort by the collaboration and by JLab, but gives the largest dividend in physics, and tells us exactly what we need to know, not more and not less.

## III. CONCLUSIONS

The first two tests don't tell us directly what we need to know about calorimeter response to GeV showers after multiple cycles of irradiation curing. Instead they give us far more information than we really need.

Elastic scattering tests can provide all of the answers we need. The elastic scattering option is a valuable precursor to a new 6 GeV DVCS experiment if the setup, beam-time, and analysis effort is significantly less than a DVCS experiment.

### A. Elastic Scattering

The elastic scattering irradiation and curing studies will be greatly simplified if they do not require coincident detection of the proton in the HRS. In particular, if the elastic scattering can be resolved at small angles via single arm measurements in the calorimeter, then it may be possible to conduct parasitic in-beam tests.

Using the elastic scattering kinematics of Eq. 1, the  $N\pi$  threshold is at

$$k' \leq \frac{k - [m_\pi + m_\pi^2/(2M)]}{1 + (k/M)(1 - \cos\theta)} = 4.49 \text{ GeV}.$$

With an estimated calorimeter energy resolution

$$\frac{\sigma(k')}{k'} = 1.5\% \oplus \frac{3.8\%}{\sqrt{k'/(1\text{GeV})}}$$

(consistent with 2.4% at 4.3 GeV), the  $N\pi$  threshold is  $1.2\sigma$  from the elastic peak.

What is the contribution of the angular resolution to elastic resolution? With a 15 cm long target, and the calorimeter at a distance  $D = 3$  m from the target, the angular resolution

from the vertex uncertainty (without a HRS coincidence) is:

$$\sigma_{\theta}(\Delta z) = \frac{\Delta z \sin \theta}{D\sqrt{12}} = 2.5 \text{ mr}$$

The contribution to the elastic resolution is

$$\Delta k'(\sigma_{\theta}) = -\frac{k'^2}{M} (\sin \theta) \Delta\theta$$

$$\sigma_{k'} = 10 \text{ MeV}$$

Thus the target length makes a negligible contribution to the elastic resolution at small angles. The purpose of the proton coincidence in the HRS is to veto inelastic events. However, at the  $1\sigma$  level, the calorimeter can resolve the elastic peak. Existing electron scattering data can be used to determine the expected ratio of elastic to inclusive (threshold) events. If the ratio is high enough for  $Q^2 \approx 1 \text{ GeV}^2$ , then single arm measurements are sufficient.

## B. Parasitic and Dedicated Measurements.

Before undertaking a new DVCS experiment at 6 GeV, it is useful to conduct elastic studies, especially if the elastic measurements can be done parasitically.

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