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Crystals for high-energy calorimetry in extreme environments

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Crystals are used as a homogeneous calorimetric medium in many high-energy physics experiments. For some experiments, performance has to be ensured in very difficult operating conditions, like a high radiation environment, very large particle fluxes, high collision rates, placing constraints on response and readout time. An overview is presented of recent achievements in the field, with particular attention given to the performance of Lead Tungstate (PWO) crystals exposed to high particle fluxes.

Keywords: Lead Tungstate; calorimetry; crystals; radiation

This report is a brief overview on the existing knowledge about scintillating crystals performance, when they are used for high-energy physics calorimetry, with particular attention given to the behavior under high radiation levels and intense particle fluxes. The way high ionizing radiation levels affect crystal performance will only be briefly summarized, since it has been thoroughly studied and reported upon by many authors in the past, as crystals were used e.g. in e^+e^- collider experiments, and their growth parameters were optimized for best performance in such environments. Today's renewed concern deals with crystals exposed to high particle fluxes, running conditions expected in several experiments under construction or designed, such as hadron collider detectors. Some recent and older results are thus collected herein, to provide, as far as possible, a complete picture.

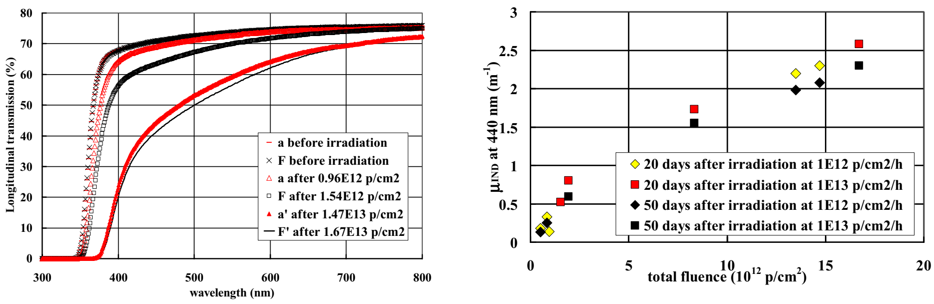
Ionizing radiation produces absorption bands through formation of color centers, which reduce the Light Transmission (LT) and thus the Light Output (LO), whose importance is related to oxygen contamination in alkali halides like BaF_2 and CsI, and to oxygen vacancies and impurities in oxides like BGO and PWO [1]. Phosphorence or afterglow may also appear [2], which increase the noise levels in the detected light, possibly worsening the energy resolution (in a negligible way for PWO in LHC experiments [3]), while the scintillation mechanism is not damaged. Recovery of damage at room temperature can occur depending on crystal type, and growth parameters, giving rise to a dose-rate dependence of damage equilibrium levels [4], and to a recovery speed dependent on the depth of traps. That ionising radiation only affects LT, means the damage can be monitored through light injection and corrected for, as it is done in the CMS Electromagnetic Calorimeter (ECAL) [5].

The way hadron fluxes affect crystals has been studied to a lesser extent, but crucial questions arise while detectors are being constructed, namely, whether such fluxes cause a specific, possibly cumulative damage, and if so, what its quantitative importance is, whether it only affects LT or also the scintillation mechanism. Tests were recently performed on PWO at IHEP Protvino [6] for the BTeV experiment and at CERN and ETH-Zürich [7] for the CMS ECAL.

In BTeV, 94% of the crystals will see relatively low particle fluxes, corresponding to ionizing dose rates below 36 rad/h and doses up to 100 krad/y, while at the other end, 0.5 % of the crystals will experience high fluxes ($\sim$ 200 rad/h and beyond, up to 2 Mrad/y). These regimes were tested in crystals using e^- and π beams and γ sources up to a few krad at 1 to 60 rad/h at one end, and a very intense mixed beam of charged hadrons, neutrons and γ up to 3 Mrad at 1 krad/h and 100 krad/h equivalent fluxes at the other end. In e^-, π and γ irradiations, the signal loss behavior is qualitatively similar between electrons and pions, and the damage appears to reach equilibrium at a dose-rate dependent level. Furthermore, no indication of damage to the scintillation mechanism from π irradiation is found [8]. A concern remains however, that for the dose-rates used, the total absorbed dose expected in the experiment is not explored and thus an additional, specific, possibly cumulative damage from hadrons cannot be excluded. This concern is partially answered by the irradiations in the very intense, mixed beam, where the absorbed doses correspond to 3 y running for the most exposed crystals, yielding thus an upper limit to the damage expected in the experiment. At the constant flux used, the damage appears in fact to be steadily increasing with accumulated dose. This is unlike pure ionizing radiation damage, which reaches equilibrium at a level depending on dose rate, not beyond what saturation of all color centers can yield, and thus it constitutes an indication for an additional, cumulative, hadron-specific damage.

For CMS, hadron fluences have been calculated [7] for 5×10^5 pb^{-1} (10 y running at LHC), yielding in the ECAL barrel (end caps) $\sim 10^{12}$ ($\sim 10^{14}$) cm^{-2} . Hadron-specific damage could be due to the production, above a $\sim$ 20 MeV threshold, of heavy fragments ("stars"), with up to 10 μm range and energies up to $\sim$100 MeV, which cause displacement of lattice atoms and energy losses along their path up to 10000 $\times$ the one of minimum-ionizing particles. The damage caused by these processes is likely different from the one of ionizing radiation, thus possibly cumulative. The primarily investigated quantity was the induced absorption coefficient at peak-of-emission wavelength, defined as $\mu_{IND}(440\text{ nm}) = \frac{1}{L}\ln\frac{LT0}{LT}$, with LT0 and LT the longitudinal transmission at 440 nm before and after irradiation, respectively, measured through the crystal length L. Transmission measurements are very accurate and directly related to LO changes provided scintillation is not affected. For CMS production crystals, $\mu_{IND}(440\text{nm}) = 1$ m^{-1} corresponds to a relative LO loss of 25% [9].

Several CMS production crystals of consistent quality[a] were irradiated in a 20 GeV proton flux of 10^{12} p/cm^2/h (*a,b,c,d*) and a few more (*E, F, G*) in 10^{13} p/cm^2/h. The LT data in Fig. 1(a) show a possible flux dependence



(a) LT for crystals *a* and *F* before, after a first and after a second irradiation.

(b) Correlation between μ_{IND}(440nm) and proton fluence.

Fig. 1. Proton irradiation results of PWO

at low fluence, no flux dependence at high fluence and a transmission band-edge shift, unlike what happens in purely ionizing radiation [1]. The correlation in Fig. 1(b), between μ_{IND}(440nm) and fluence, is consistent with a linear behavior, showing that proton-induced damage in PWO appears to predominantly yield a cumulative effect. Taking into account the difference in composition and energy spectra between 20 GeV protons and CMS, the test results cover the CMS running conditions over the entire high-precision ECAL pseudo-rapidity region, up to ~ 2.9.

Proton and γ data are compared in a study performed on BGO [10]. The changes in band-edge are similar to what is seen in PWO, and long enough after irradiation, when the ionising-radiation damage contribution has recovered, one can extract a remaining p-damage that behaves linearly with fluence, as visible in Fig. 2. The same exercise is not possible on CsI data from the same authors [11] because

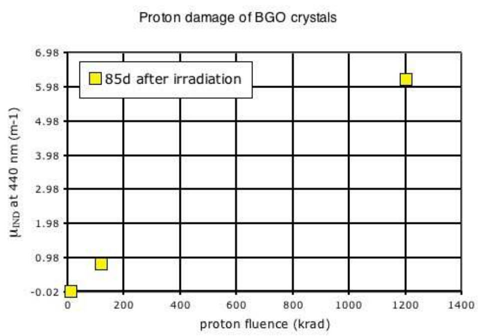


Fig. 2. Correlation between μ_{IND}(440nm) and proton fluence in BGO extracted from published data.

[a]Prime indicates a second irradiation of the same crystal.

the damage caused by ionizing radiation gives a too important constribution to allow observing the proton-specific one.

In conclusion, one can say that for all crystals commonly used in calorimetry, beyond the well-studied damage from ionizing radiation, the understanding of additional contributions to the damage, when crystals experience a substantial hadron flux, has become important since experiments are being built having to cope with such running conditions. A hadron-specific, cumulative contribution, likely due to the intense local energy deposition from heavy fragments, has been observed in tests on PWO and BGO. Within the explored flux and fluence ranges, this contribution only seems to affect Light Transmission, and thus can be monitored. Additional studies, taking into account the range of operation of the envisaged experiments, are expected to consolidate the present understanding of hadron damage.

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