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ЭЛЕКТРОМАГНИТНАЯ КАЛОРИМЕТРИЯ НА ОСНОВЕ PWO ДЛЯ РАБОТЫ ПРИ НИЗКИХ ТЕМПЕРАТУРАХ

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Ухудшение оптического пропускания сцинтилляционного кристалла под действием ионизирующего излучения в сцинтилляционном спектральном диапазоне приводит к потерям светового потока, вследствие чего энергетическое разрешение снижается и время работы калориметра на основе сцинтилляторов ограничивается. Этот эффект особенно заметен для калориметров, работающих при низких температурах. Использование сцинтилляционного кристалла вольфрамата свинца ($PbWO_4$) в калориметрии при низких температурах (от –20 до –45 °C) обеспечивает трехкратное увеличение сцинтилляционного выхода, что приводит к значительному улучшению энергетического разрешения (до 10 МэВ). Сохранение этой особенности критически важно для адронной спектроскопии. Однако при понижении температуры кристалла $PbWO_4$ скорость спонтанной релаксации центров окраски, созданных под действием ионизирующего излучения, значительно замедляется, что смещает динамический уровень наведенного поглощения в сторону более высокого значения при длительном облучении в экспериментах физики высоких энергий. Проведено сравнение спонтанной релаксации наведенного поглощения в спектральной области сцинтилляций со стимулированным восстановлением при облучении образцов инфракрасными фотонами разных длин волн. Показано, что релаксация центров окраски может быть ускорена до тысячи раз. Таким образом, стимулированное восстановление позволяет быстро и эффективно возобновить оптическое пропускание кристаллов либо между периодами работы ускорителя, либо при сборе данных в онлайн-режиме, при этом извлекать кристаллы из экспериментальной установки не требуется. Применение стимулированного восстановления может существенно улучшить работу калориметров на основе

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$PbWO_4$ или продлить срок их службы при низких температурах с сохранением радиационного повреждения оптического пропускания кристаллов на приемлемом уровне.

Ключевые слова: электромагнитный калориметр; сцинтилляционный кристалл вольфрамата свинца; радиационное повреждение; световыход; оптическое пропускание; стимуляционное восстановление.

PWO BASED ELECTROMAGNETIC CALORIMETRY TO OPERATE AT A LOW TEMPERATURE

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The degradation of the optical transmittance under ionising radiation of the scintillation crystal in the scintillation spectral range leads to the losses of the light output, which results in the deterioration of the energy resolution and limits the operation time of the calorimeter made of the scintillator. This effect is especially prominent for calorimeters operating at a low temperature. The use of a lead tungstate scintillation crystal $PbWO_4$ in calorimetry at a low temperature in the range from –20 to –45 °C provides a threefold increase in its scintillation yield, which causes a significant improvement in the energy resolution in the range up to 10 MeV. Keep on this feature is critically important for hadron spectroscopy. However, as the temperature of the $PbWO_4$ crystal is lowered, the rate of spontaneous relaxation of colour centers created under ionising radiation significantly slows down, which shifts the dynamic level of the induced absorption towards a higher value under long-term irradiation of high-energy physics experiments. A comparison is made of the spontaneous relaxation of induced absorption in the spectral region of scintillations with stimulated relaxation upon irradiation of samples by infrared photons of different wavelengths. It is shown that the relaxation of colour centers can be accelerated up to one thousand times. Thus, recovery stimulation allows fast and efficient *in situ* recovery of the crystal optical transmittance either at beam-off periods or online at data acquisition. The application can substantially improve or extend the running period of the PWO based calorimeters at low temperatures by keeping the radiation damage at a tolerable level.

Keywords: electromagnetic calorimetry; lead tungstate scintillation crystal; radiation damage; light yield; optical transmittance; stimulated recovery.

Introduction

Nowadays, lead tungstate ($PbWO_4$, PWO) scintillation crystal is the most widely used scintillation material in modern electromagnetic calorimetry at high energy physics experiments [1; 2]. Deterioration of the optical transmittance of PWO crystals occurs in electromagnetic calorimeter (ECAL) operation in harsh irradiation environments due to the creation of colour centers under ionising radiation. The radiation-induced optical absorption, which overlaps the scintillation band, limits the energy resolution of the calorimeter.

Dependence of the ECAL energy resolution may be parameterised as the quadratic sum of three terms [3]:

$$\frac{\sigma_E}{E_0} = \frac{a}{\sqrt{E_0}} \oplus \frac{b}{E_0} \oplus c,$$

where the symbol $\oplus$ indicates a quadratic sum.

The first term, with coefficient a, is the stochastic term, arising from fluctuations in the number of signal photons generated by ionising particles. Fluctuations in the measurement of the signal contribute as well.

Moreover, the second term, with coefficient b, is usually referred to as the noise term. It receives contributions not only from noise in the readout electronics, but also from effects such as «pile-up» (simultaneous energy deposition by uncorrelated particles).

The third term is the constant term with coefficient c. It arises from several effects including imperfections in calorimeter construction (dimensional tolerances, etc.), non-uniformities in signal collection, calibration errors, fluctuations in longitudinal energy containment, etc.

Forexample, the stochastic term in the resolution function is dominated by statistical fluctuations in the number of detected photoelectrons and can be evaluated for an ideal crystal calorimeter by formula [3]

$$a = \sqrt{\frac{F}{n_e}}, \quad (1)$$

where F is the Fano factor, and n_e is the number of detected photoelectrons. Hence, the stochastic term is controlled by both the light yield of the scintillation material and the light collection affecting the transport of photons to the photoreceiver window. Thus, the deterioration of the response of the calorimeter is due to the loss in the light collection. At such conditions, the rate of the spontaneous recovery of the colour centers, in order to keep their dynamical concentration small at a given dose rate, becomes a crucial parameter of the detection material. For the lead tungstate scintillation crystal, the light yield of which might be increased by cooling, the fast recuperation of the colour centers at low operational temperature stands as a decisive property. Unfortunately, the spontaneous recovery processes are significantly slowed down in PWO by cooling [4].

A possible way to recuperate the radiation-induced optical transmission damage during the ECAL operation will be described here. The method is based on the implementation of stimulated recovery based on the injection of infra-red (IR) light into each crystal of the electromagnetic calorimeter.

Experimental results and discussion

Lead tungstate is a self-activated scintillator [5]. Therefore, the luminescence has a strong temperature quenching, which provides fast scintillation kinetics with a decay constant of about 10 ns. The light yield of the lead tungstate crystal varies with temperature coefficient (–3 %/°C) [6; 7] in the temperature range from +50 to –50 °C. Figure 1 shows dependence of the light output on the integration time of the ensuring electronics behind the fast readout photomultiplier tubes at different temperatures. The overall gain factor of the light yield at $T = -40$ °C compared to $T = +20$ °C is seven.

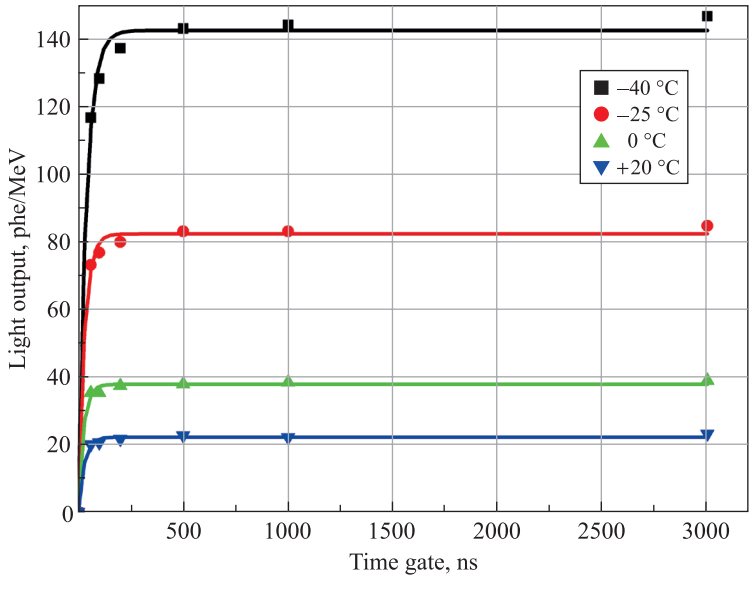

Fig. 1. Gated light output of PWO scintillator (20 × 20 × 200 mm) coupled to a Hamamatsu R2059 photomultiplier (Japan) tube at different temperatures

An increase of the light yield allows improving the energy resolution of the detector at hundreds of MeV photon energy, which is crucially important for precise spectroscopy in hadron physics. The gain in energy resolution obtained with a 3 × 3 matrix made of 200 mm long PWO crystals [8] confirms this statement and is presented in fig. 2. Apparently, a decrease of the PWO based detector operational temperature is a prospective way to achieve better energy resolution of the PWO based detector.

According to these experimental results, energy resolutions of $\frac{\sigma}{E} = 1.11/\sqrt{E} \oplus 1.67$ and $\frac{\sigma}{E} = 1.88/\sqrt{E} \oplus 1.79$ (in %; E given in GeV) were deduced at –25 and +10 °C, respectively. The reduced energy resolution at $T = +10$ °C is consistent with the lower light output due to thermal quenching and is quantitatively expressed by the higher stochastic term in the parametrisation of the resolution [10]. Assuming the ratio of light yields at –25 and +10 °C around 2.5–3.0 from fig. 2, the stochastic terms of energy resolutions from experiment agree well with equation (1).

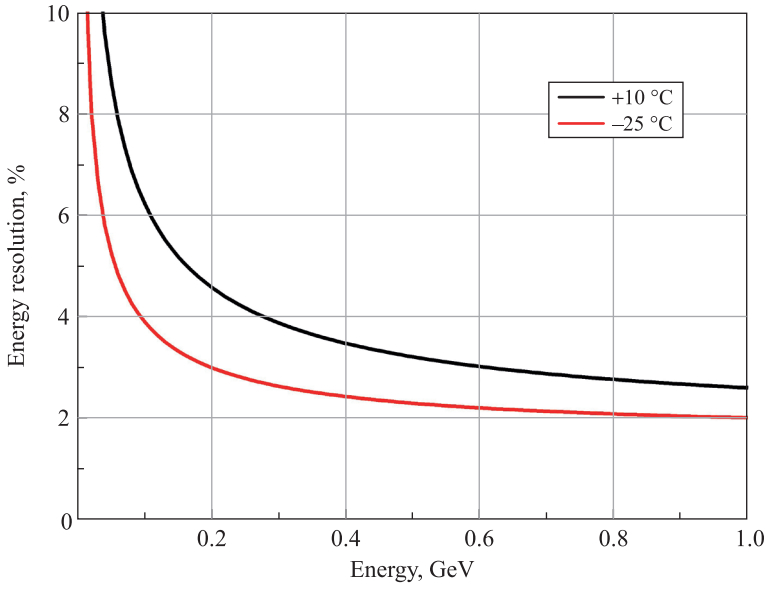

Fig. 2. The energy resolution of a 3 × 3 PWO matrix of 200 mm long crystals measured at two different operating temperatures of –25 and +10 °C, respectively (after [9])

When a lead tungstate crystal is exposed to ionising radiation, the pre-existing point defects of the crystal structure may act as traps for electrons or holes. The resulting charged defects have discrete energy levels and optical transitions can be induced, absorbing part of the scintillation light that propagates in the crystal toward the photodetector.

Ionising radiation damage of optical transmission of the inorganic crystal can be considered as a three step process consisting of creation of hot electrons and holes from the interaction of ionising particles with the crystal lattice; free carrier separation during the thermalisation (through strong coupling with lattice phonons) and diffusion process; localisation of electrons and holes near lattice defects, to balance local charge. This chain results in the creation of colour centers overlapping the scintillation band.

Up to five types of colour centers have been identified in lead tungstate with corresponding absorption bands at 350–400; 470; 520; 620 and 715 nm [11; 12]. Only three of them having absorption bands in the blue-green spectral range overlap the scintillation band. Absorption bands in the 350–400 nm spectral range are caused by the recharge of the WO_3^{2-} Frenkel-type defect centers, whereas 470 and 520 nm absorption bands, which also overlap the scintillation band, are caused by several types of di-O^- centers [5].

The slowing of spontaneous recovery becomes observable already at the cooling the crystal to +10 °C. The spontaneous recovery of the radiation induced absorption coefficient at 420 nm after irradiation of two PWO samples at +22 and +10 °C is shown in fig. 3.

Stimulated recovery of the optical transmittance was measured during 50 and 500 h for short and long PWO samples, respectively. Irradiation was performed using a ^{60}Co source to a radiation dose of 100 Gy. Recovery with a fast constant was not observed in the small samples, since the measurements were taken 30 min after irradiation. The measurements for full-size samples were taken 2 min after irradiation.

The experimental data of recovery kinetics are approximated and the parameters of spontaneous recovery of the radiation induced absorption coefficient for PWO samples at +22 and +10 °C are presented in table 1. The time constant was evaluated with an accuracy of better than 5 %.

Table 1

Spontaneous recovery parameters of the radiation induced absorption coefficient for PWO samples at +22 and +10 °C, respectively

PWO sample, cm	Temperature, °C	Recovery time constant, h			Fraction (f) of fast and slow constant, %			Amplitude, m^{-1}		
		τ_f	τ_1	τ_2	$f_{\tau f}$	$f_{\tau 1}$	$f_{\tau 2}$	k_f^{max}	k_1^{max}	k_2^{max}
2 × 2 × 2	+22	–	9.9	1541.0	–	–	–	–	0.205	1.040
	+10	–	18.7	4278.0	–	–	–	–	0.035	1.389
2.5 × 2.5 × 20.0	+22	0.18	71.0	109.6	0.0002	19.2	80.8	0.078	0.190	0.520
	+10	0.42	74.3	771.2	10^{-7}	3.0	97.0	0.120	0.240	0.800

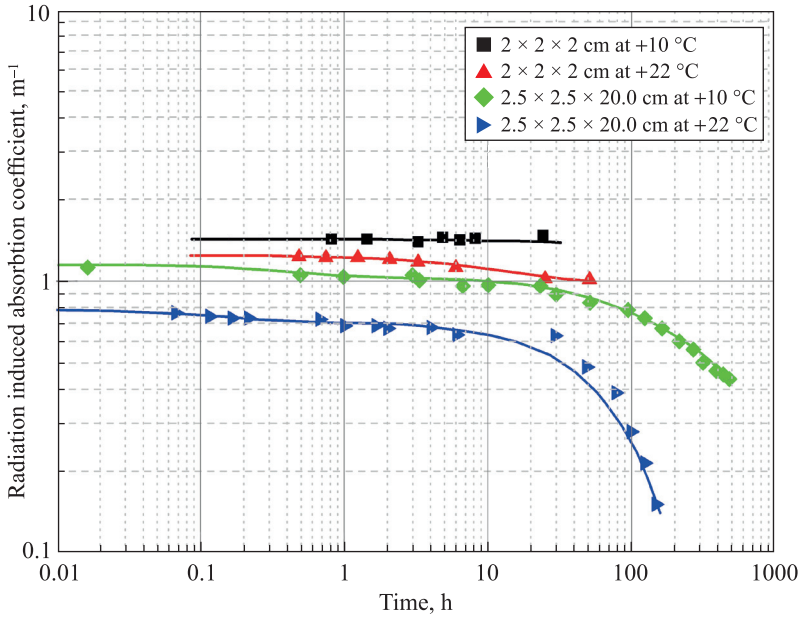

Fig. 3. Spontaneous recovery of the radiation induced absorption coefficient at 420 nm of two PWO samples irradiated and measure at +22 and +10 °C. Samples are courtesy of the PANDA Collaboration at FAIR (Darmstadt)

The contribution of the fast recovery constant is accounted for less than 20 % at +22 to +10 °C. This effect can be explained by low concentration of colour centers in the crystal. Decreasing the temperature significantly reduces the contribution of the fast recovery constant. The recovery time constant for PWO at –25 °C can be evaluated by linear approximation in the low temperature region of the recovery constants obtained for the 20 cm long PWO crystal. The recovery time constant for PWO at –25 °C was estimated at the level of as much as 260 000 h (~30 years). Conversely, radiation damage of optical transmittance for a PWO crystal can be reduced by application of stimulated recovery. The stimulated recovery can be carried out by annealing the crystal or by injection of visible light or even infrared radiation. The application of stimulated recovery makes it possible to restore optical transmittance *in situ* either during technological breaks in the operation of the accelerator or even during the operation of the accelerator if the photosensor is insensitive for the wavelength range of injected photons. The recovery of the optical transmittance of the detector modules of a calorimeter will increase their lifetime, maintaining the radiation induced absorption at an acceptable level.

There are two actual processes initiated by the photons: ionisation of colour centers and transport of the captured electron from ground state of the colour center to its radiation level. The first process depends on the energy width of the conduction band and the position of the colour center ground state in the forbidden zone and may be initiated in a wide spectral range from UV to visible light. However, ionisation of colour centers is an improvident way because the energy E_{ph} of the injected photons should be much greater than the thermal activation energy of colour centers E_{TA}. The second process, called stimulated recovery, is an intra-center resonant transition that can be initiated by photons with an energy E_{ph} even as low as $E_{ph} \sim E_{TA}$, so even infrared photons can initiate it. In this case, stimulation can even be applied simultaneously with ionising irradiation, in particular, if the photosensor used is blind for the chosen wavelength region. As a consequence, the level of the dynamic saturation of the induced optical absorption in the crystal will be reduced.

The spontaneous and stimulated recovery of the transmittance at 420 nm at –25 °C of a lead tungstate crystal after gamma-irradiation (30 Gy absorbed dose) is shown in fig. 4. The process of transmittance recovery was monitored with a 420 nm LED pulsed source with intensity stabilised at the level of 0.1 %. A significant acceleration of the recovery of the transmittance is observed with stimulation via intracenter transitions with IR photons in the range 850–1060 nm. This effects is achieved by illuminating with photons at different wavelengths produced by laser diodes with an intensity $1 \cdot 10^{17}$ photons per second in the wrapped lead tungstate crystal of 20 cm length cooled down to –25 °C. Deterioration of the relative optical transmittance of PWO crystals was controlled by the monitoring system which provides continuous measurements of the relative optical transmission in the blue spectral region with a peak around 420 nm after irradiation and during the stimulated recovery. The recovery curves are fitted with a double exponential function of the form $1 - a_1 e^{-\frac{t}{\tau_1}} - a_2 e^{-\frac{t}{\tau_2}} - c$, where $a = a_1 + a_2$ is the sum of recovery; τ_1 and τ_2 are the fast and slow recovery constants, respectively;

c is the residual damage according to range time of illumination; $1-(a+c)$ is the total initial damage. For more details, the experimental setup for studying stimulated recovery of the radiation damage of lead tungstate crystals is described elsewhere [13].

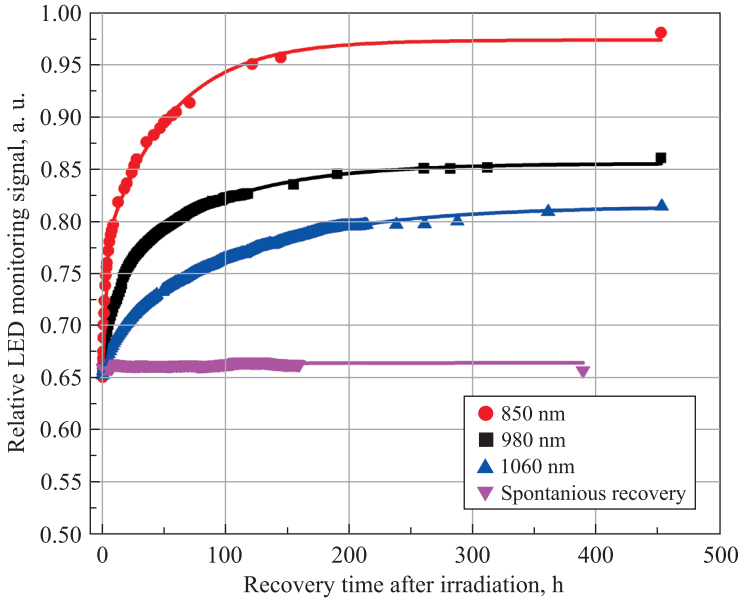

Fig. 4. Changes of relative transmittance at 420 nm of a PWO crystal at –25 °C due to spontaneous recovery and under stimulated recovery by photons with different wavelengths of intensity $1 \cdot 10^{17}$ photons per second after 30 Gy absorbed dose

Stimulated recovery provides simultaneous changes of relative transmittance in a wide spectral range. The stimulated recovery constants of a lead tungstate crystal for the transmittance at 420 nm and at –25 °C after gamma-irradiation measured for different wavelengths of injected photons are presented in table 2.

Table 2

Stimulated recovery parameters of the radiation induced absorption coefficient for PWO samples at –25 °C for different wavelengths of injected photons

Wavelength of injected photons, nm	Stimulated recovery constant, h		Fraction (f) of fast and slow constant, %		Total recovery, %	Residual damaged transmittance, %
	τ_f	τ_s	$f_{\tau f}$	$f_{\tau s}$	$a = a_1 + a_2$	c
850	1.9	52.6	2.0	98.0	32.0	3
980	10.7	81.5	8.6	91.4	19.6	14
1060	10.4	106.3	2.2	97.7	15.2	19

As seen, stimulation of the colour centers by IR photons is able to accelerate the recuperation of the crystal optical transmittance by three orders of magnitude. This finding makes a very perspective described approach to keep ECAL acquisition capabilities at the operation at low temperatures.

Conclusions

An approach to keep ECAL detector capabilities constant, while operating at low temperature is described. The PWO scintillator radiation-induced damage recovery stimulation by illumination with external light of IR photons was found to be an effective way to recuperate radiation-damaged optical transmittance.

Recovery time may be accelerated by a factor 1000 in a comparison with the spontaneous process. This finding may have a strong impact on future detector concepts, how to maintain the performance of electromagnetic calorimeters at accelerator experiments based on PWO scintillator. *In situ* recuperation of optical transmission of scintillator elements by stimulated recovery during the breaks between or even in parallel with the data acquisition can substantially improve the detector performance and prolong its lifetime under tolerable conditions. Since commonly used photosensors are blind in the IR region, stimulated recovery can possibly be applied even during detector operation and data acquisition.

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