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ADVANCED SCINTILLATION MATERIALS FOR CALORIMETRY AT CIRCULAR COLLIDERS

Abstract. The most probable scenario for the development of experimental high-energy physics in the next 50 years is the creation of a family of Future Circular Colliders (FCC) at CERN, a Circular Electron–Positron Collider at China, and a Future Electron-Ion Collider at Brookhaven (USA), which continue the Large Hadron Collider (LHC) scientific program within the framework of the Standard Model and beyond it. The first generation of colliders to be put into operation will utilize the electron beam as one of the colliding species to provide precise mass spectroscopy in a wide energy range. Similarly to the measurements at the high luminosity phase of the LHC operation, the most important property of the detectors to be used in the experimental setup is a combination of the short response of the detectors and their high time resolution. The radiation tolerance to a harsh irradiation environment remains mandatory but not the main factor of the collider's experiments using electronic beams. A short response in combination with high time resolution ensures minimization of the influence of the pile-up and spill-over effects at the high frequency of collisions (higher than 50 MGz). The radiation hardness of the materials maintains the long-term high accuracy of the detector calibration. This paper discusses the prospects for using modern inorganic scintillation materials for calorimetric detectors at future colliders.

Keywords: collider, detector, scintillator, time response, time resolution

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СОВРЕМЕННЫЕ СЦИНТИЛЛЯЦИОННЫЕ МАТЕРИАЛЫ ДЛЯ КАЛОРИМЕТРИИ НА ЦИРКУЛЯРНЫХ КОЛЛАЙДЕРАХ

Аннотация. Наиболее вероятным сценарием развития экспериментальной физики высоких энергий в ближайшие 50 лет является создание семейства кольцевых коллайдеров будущего (FCC) в ЦЕРНе, кольцевого электрон-позитронного коллайдера (CEPC) в КНР и будущего электрон-ионного коллайдера в Брукхейвене (США), которые продолжают научную программу Большого адронного коллайдера (LHC) в рамках Стандартной модели и за ее пределами. Первое поколение коллайдеров, которые введут в эксплуатацию, будут использовать электроны в качестве одной из сталкивающихся частиц для обеспечения точной масс-спектроскопии в широком диапазоне энергий. Подобно измерениям в фазе высокой светимости LHC, наиболее важным свойством детекторов, которые будут применяться в экспериментальных установках, является сочетание короткого отклика детекторов и высокого временного разрешения. Радиационная стойкость в условиях радиационного фона экспериментов остается обязательной, но не основным фактором коллайдерных экспериментов с применением электронных пучков. Короткий отклик в сочетании с высоким временным разрешением обеспечивает минимизацию влияния эффектов перекрытия сигналов событий и наложения отклика детектора при высокой частоте столкновений, превышающей 50 МГц. Радиационная стойкость материалов обеспечивает долгосрочную высокую точность калибровки детектора. В настоящей статье обсуждаются перспективы использования современных неорганических сцинтилляционных материалов для калориметрических детекторов на коллайдерах будущего.

Ключевые слова: коллайдер, детектор, сцинтиллятор, время отклика, временное разрешение

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Introduction. To date, a number of scintillation materials have been developed; however, only few of them are widely used for the construction of detectors in high-energy physics experiments [1, 2], the reason for this being the need to combine in one material several key properties, namely, high den-

sity, high light yield, fast scintillation response, and high tolerance to the irradiation environment of the experiments. Involving in the research high-luminosity hadron emitters, like particle colliders [3], demanded the development of even better radiation-hard scintillation materials for detectors of ionizing radiation. A systematic study of the radiation effects in inorganic crystalline scintillation materials [4–12] resulted in the development of several families of irradiation-tolerant to different kinds of irradiation Ce doped materials, namely, aluminates and gallates with garnet structure, and oxyorthosilicates. A comparison of the tolerance of some scintillation materials to the different kinds of ionizing radiation is represented in Table 1. The parameter dk is an induced absorption coefficient at the wavelength of the scintillation spectrum maximum.

Table 1. **Comparison of the tolerance of the scintillation materials of the garnet and oxyorthosilicate families to γ-quanta and high energy protons**

Crystal	Type of irradiation	Dose of γ-quanta (kGy) / proton fluence (p/cm^2)	dk, m^{-1}	Ref.
GAGG:Mg,Ti	^{60}Co, gamma-rays	0.1 – 1	1	[13]
GAGG:Mg,Ti	24 GeV protons	$3.1 \cdot 10^{15}$	3	[14]
$Y_3Al_5O_{12}$:Ce (YAG)	^{60}Co, gamma-rays	100	2.1	[15]
$Y_3Al_5O_{12}$:Ce (YAG)	24 GeV protons	10^{14}	0.6	[15]
$Lu_3Al_5O_{12}$:Ce (LuAG)	^{60}Co, gamma-rays	100	1.6	[15]
$Lu_3Al_5O_{12}$:Ce (LuAG)	24 GeV protons	10^{14}	0.5	[15]
Lu_2SiO_5:Ce (LSO)	^{60}Co, gamma-rays	200	0.5	[6]
Lu_2SiO_5:Ce (LSO)	24 GeV protons	10^{14}	2	[6]
$(Lu,Y)_2SiO_5$:Ce (LYSO)	^{60}Co, gamma-rays	10^4	0.5	[8]
$(Lu,Y)_2SiO_5$:Ce (LYSO)	24 GeV protons	10^{15}	10	[8]

Moreover, these materials demonstrate a combination of spectacular scintillation properties, particularly, the high light yield, fast scintillation kinetics, and chemical and mechanical stability, which makes them perfect candidates for a number of applications in HEP experiments. All mentioned crystals doped with Ce could be manufactured by the well-established Czochralski method. Moreover, these crystals of cubic symmetry can be obtained by micro-pulling down (μ-PD) [1] crystal growth techniques for equipping the large square detectors. Due to its cubic crystalline structure, the garnets may be obtained as polycrystalline ceramic using various techniques, including 3D-printing [16].

The widely spread in high energy physics experiments lead tungstate scintillator $PbWO_4$ (PWO) [1], invented at the Institute for Nuclear Problems of BSU, still has a potential to be improved to the level of new colliders. It played a crucial role in the electromagnetic calorimetry of the CMS Experiment to discover the Higgs Boson [17] and the characterization of a quark-gluon plasma by ALICE [18] at LHC. Nowadays a second, faster and brighter, generation of the lead tungstate scintillator is utilized to construct a Electromagnetic calorimeter of the PANDA Experiment at FAIR (Darmstadt, Germany).

Materials. ***Crystalline scintillation materials with a garnet structure.*** In the sixties, the study of inorganic scintillation materials was a side line in the development of crystalline active media for solid-state lasers. The technology for growing single crystals of yttrium aluminum garnet $Y_3Al_5O_{12}$ (YAG) was developed first. Later, YAG:Ce was proven to be a promising scintillator material [19]. The substitution of yttrium by lutetium in the garnet structure resulted in a higher density and effective atomic number as well as expanded applicability of $Lu_3Al_5O_{12}$:Ce (LuAG:Ce) [15] for detection of hard X-rays and γ-quanta in a harsh irradiation environment [20]. The light yield of the binary Ce-doped garnet-type scintillators is quite high, though three times smaller than that of novel alkali halide scintillators like $LaBr_3$:Ce and GdBr3:Ce [1]. Their luminescence decay time is only slightly shorter than 100 ns, and their emission band peaks are in the range 520–560 nm.

The next step in improving the scintillators of the garnet type structure was an attempt to combine the advantages of the transfer from binary to ternary garnet type crystals. Ternary garnet type scintillation crystals are the result of the purposeful engineering of the electronic state's density in the crystal, particularly, conduction zone. The compositionally disordered garnet-type scintillators, combining two isovalent cations with an ability to occupy the same sites in the crystal net, in particular,

Ce-doped $Gd_3Al_2Ga_3O_{12}$ (GAGG) crystalline compounds, show spectacular progress in the improvement of their scintillation properties, particularly, coincidence time resolution measured with annihilation γ-quanta [21]. The creation of the compositionally disordered cationic sublattice under conditions of ordered anionic lattice introduces in the crystal a few novities. Crystal symmetry was maintained, so the influence of the crystal field on the energy levels of activating ions remained the same. However, the dynamics of nonequilibrium carriers created by ionizing radiation and the process of energy transfer became accelerated. The scintillation properties of ternary garnet type scintillators are superior to those of binary garnets as a result of a positive influence of the compositional disorder due to a random distribution of Al and Ga ions in tetrahedral and octahedral oxygen coordinations in the matrix host. In such crystalline compounds, the hot carrier scattering length becomes smaller, the density of nonequilibrium carriers becomes larger, and the probability of Coulomb iteration with the emitting Ce centers increases, respectively [22]. GAGG scintillator exhibits an attractive combination of a high light yield of up to 46 000 phot/MeV, a short average scintillation decay time at the level of 80 ns, and good matching of the emission spectrum peaked at 520 nm with the sensitivity spectra of silicon photomultipliers (SiPM). Finally, the codoping, even at small concentrations of less than 10 ppm, improves the coincidence time resolution of the annihilation γ-quanta down to 165 ps. A similar mixing of Ga and Al had been arranged in doped with Ce yttrium-aluminum-gallium garnet $Y_3(Al,Ga)_5O_{12}$ [23]. The crystal demonstrated spectacular shortening of the scintillation kinetics at a certain ratio Al/Ga. However, a remarkable increase of the light yield was not observed like in GAGG.

The further improvement of the scintillation properties was achieved by fabrication of quarternary $(Gd_{0.5}–Y_{0.5})_3Al_2Ga_3O_{12}$ (GYAGG) garnets doped with Ce [24]. The first crystals evaluation performance test demonstrated spectacular progress in the improvement of the light yield and scintillation kinetics. The confidence time resolution with 511 keV γ-quanta was achieved at the level of 120 ps. The tolerance of the material to irradiation with γ-quanta is confirmed as well.

Crystalline scintillation materials with an orthosilicate structure. Oxyorthosilicate of lutetium turned out to be the scintillator of choice in positron emission tomography (PET) [25, 26]. The fast scintillation response is the key advantage of LSO:Ce in ionizing radiation detection applications. The fast response enables increasing the signal-to-noise ratio and improving the coincidence time resolution [27] to the level of 100 ps. Moreover, the faster signal readout followed by fast signal processing ensures the observation of spill-over at acquisition online [28].

The substitution of a part of lutetium by yttrium in the crystal matrix to fabricate compositionally disordered oxyorthosilicate $(Lu_x–Y_{1–x})_2SiO_5$ (LYSO) not only reduces the cost of the material but diminishes the scintillation afterglow and improves the light yield of the material.

Similar to the compositionally disordered garnets, the scintillation properties of LYSO:Ce can be improved by aliovalent codoping of the crystals. Codoping with divalent calcium improves the light yield, shortens the luminescence decay time, and suppresses the afterglow [29, 30].

Contrary to the cubic symmetry of the garnet structure, the crystal system of LSO and LYSO is monoclinic, and Ce ions occupy in the crystal lattice two nonequivalent sites with 7- and 6-fold oxygen coordination, respectively. The luminescence bands of Ce^{3+} in different coordinations strongly are overlapped and unresolvable at room temperature.

The Ce^{3+} luminescence in the mentioned compounds has a relatively short Stokes shift, only ~0.25eV. Due to this, both GAGG and LYSO are less likely suitable to be used in homogeneous detecting cells of calorimeters. LYSO:Ce found an application in the timing layer detector [31], which will be installed in a CMS detector during Long Shutdown 2 to acquire the data at the high luminosity LHC operation. The detector of 33 m^2 will consist of roughly 250 000 bars with dimensions 3 × 3 × 45 mm. In the meantime, GAGG is considered for the upgrade of the detector of LHCb Collaboration, sited at LHC as well. Here the composite modules consisted of 50 and 10 cm long units of SPACAL type are considered for application [28].

The lead tungstate scintillation material. The benchmark of PWO is the discovery potential of the Higgs boson through its 2γ decay mode. In the relatively low mass range where the Higgs was expected (less than 130 GeV, which was confirmed by its discovery at 125 GeV), a very good energy resolution can be achieved for which the narrow Higgs signal is isolated from a large γ background produced by minimum biased events.

A homogeneous calorimeter based on PWO [32] crystals readout by avalanche photodiodes was proven to be the optimum choice to fulfill these requirements. The results obtained at the end of Run 1 at LHC in 2012 brilliantly confirmed the soundness of this analysis [33].

The outstanding energy resolution of the PWO crystal-based calorimeter is mandatory to observe the very narrow Higgs peak in the invariant mass distribution of the two photons.

The PANDA Collaboration Experiment at FAIR (GSI, Darmstadt) is the third-largest lead tungstate based electromagnetic calorimeter [34]. The physics goals of the experiment require the energy threshold of at least Ethreshold ≤20 MeV. For this reason, the calorimeter requires very ambitious specifications to be adapted to the physics program. The main features of the scintillation material included: high-rate capability, which requires fast scintillation kinetics; scintillation yield to achieve good energy resolution, in particular, at the lowest photon energies in the MeV range which goes in parallel with a minimum energy threshold of the individual crystal; γ-radiation hardness to limit the loss in optical transparency to a tolerable level. The efforts of the PANDA Collaboration resulted in the development of a new generation of the lead tungstate crystal technology named as PWO-II. The different steps to achieve the quality of PWO-II have shown that radiation hardness becomes a very sensitive parameter when the operating temperature of the calorimeter is close to $T = 0$ °C or below it. As the first step, different doping ions and their combinations have been tested. Codoping with yttrium and lanthanum at a concentration bellow 80 ppm provided a light yield at the level of 25 phe/MeV and scintillation kinetics shorter than 8 ns at room temperature [35].

The detecting properties of the prospective scintillation materials. Table 2 summarizes the features of crystalline scintillation materials. It is seen that all garnets are superior to detect minimum ionizing particles in comparison with the plastic scintillator. The addition of Gd and Ga makes crystal sensitive to neutrons, which can be utilized in hadron calorimeters to increase the energy deposit from the neutral component of the shower. All the considered materials are doped with Ce^{3+} ions, the Stokes shift of the luminescence is ~0.25 eV, which is two times smaller than in the $PbWO_4$ self-activated scintillation crystal. This limits the application of the materials in homogeneous detecting cells with the length ~$20X_0$. However, the crystals quite well meet the requirements of the heterogeneous detecting modules where the radiation length is provided by the heavy absorber, usually tungsten or its composite with the lighter metals or alloys. The PWO_4 scintillator still remains the best option for the spectroscopy in the range of tens of GeV to tens of TeV. Under the conditions of the large energy deposition from the electromagnetic particles having energy in this range, it provides high time resolution, better than 50ps. It makes lead tungstate material still the most optimal choice for the calorimetry at future Colliders.

Table 2. **Some detecting properties of crystalline materials**

Material	PWO	$(Lu,Y)_2SiO_5$	$Gd_3Al_2Ga_3O_{12}$	$(Gd_{0.5}–Y_{0.5})_3Al_2Ga_3O_{12}$
Density, g/cm^3	8.28	7	6.63	5.58
Radiation length X_0, cm	0.89	1.47	1.53	1.9
Coincidence time resolution with 511 keV γ-quanta	50ps (100 GeV)	100+/–2	165+/–2	160+/–2
dE/dx @ e-, MeV/mm	1	0.85	0.81	0.68
Yield, ph per 1 mm per mip	200	23 500	32 400	34 000

Conclusions. Advanced scintillation materials have herein been considered. The scintillation properties of the PWO, LYSO, and GAGG crystal families were found to be promising for application at future Colliders. We expect that combining the technological achievements in the crystals production with the outstanding progress in the SiPM production technologies will enable us to obtain new and better-operating detectors of ionizing radiation suitable for application at future Colliders.

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