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SCINTILLATOR NON-PROPORTIONALITY STUDIES AT PITZ

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Abstract

A standard method to measure beam profiles is to use scintillating screens. Such technique is used e.g. at the European XFEL in order to overcome coherence effects in case of OTR based diagnostics. However, already during the XFEL commissioning, the standard screen material LYSO:Ce has revealed a new problem - non-proportionality effects. The reason is a high electron bunch density. Therefore it was decided to exchange LYSO:Ce by GAGG:Ce, as the material has not shown any signs of non-proportionality in a series of measurements at the XFEL. Nevertheless, further studies are ongoing. The last measurement campaign has been carried out at PITZ (DESY Zeuthen) which has two important advantages compared to the XFEL: (1) a higher bunch charge and (2) a lower electron energy. Five different scintillating materials have been investigated: LYSO:Ce, YAP:Ce, YAG:Ce, LuAG:Ce and GAGG:Ce. The present work comprises the results of the latest measurements.

INTRODUCTION

The European XFEL uses scintillating screens for standard beam profile diagnostics. $Lu_{2(1-x)}Y_{2x}SiO_5$:Ce (LYSO) has been chosen as its resolution was the best compared to other materials [1, 2]. However, during the commissioning of the XFEL the measured emittances were larger than expected [3, 4]. In addition, bunches with charges above a few hundreds of pC showed a *smoke-ring* like shape with a drop of intensity right in the center. An example of such shape is shown in Fig. 1. It was supposed that this observation is caused by the scintillator material itself [5].

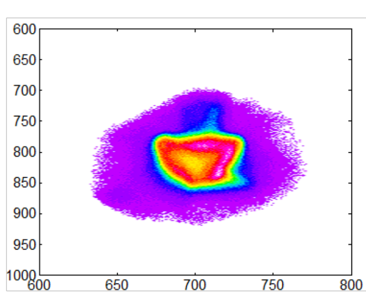

Figure 1: A typical picture received with the LYSO screen.

This effect in principle is well-known in high-energy physics and is called *non-proportionality of scintillators* [6–8]. The more energy a particle looses per unit length in a scintillator volume, the less light output the scintillator will produce. In other words, the light output depends on the deposited energy density. In calorimetric measurements in high-energy physics it results in a non-proportional response [8] at different energies of an incoming particle, as the energy losses depend on its energy (see Fig. 2).

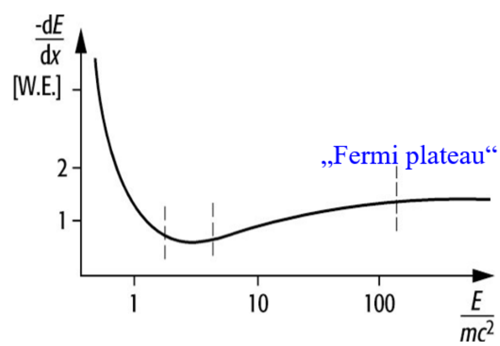

Figure 2: The dependence of particle energy losses in a media on the particle energy.

The effect is especially pronounced at low particle beam energies because the losses per unit length are largest, see Fig. 2. However, in the case of particle beam diagnostics for ultra-relativistic electron beams (as it is the case for the XFEL) the energy losses are smaller, characterized by the so called *Fermi plateau* in the energy loss curve Fig. 2. In addition, scintillators normally used for diagnostics purposes have thicknesses in the order of only a few hundreds of microns, hence the energy loss in the material is negligible compared to the total particle energy. As pointed out in Ref. [5], in this situation it is not the particle energy but the density of the impinging particles which leads to excitonic quenching effects, thus resulting in a non-linear light output. At the XFEL an electron bunch may contain up to 10^{10} particles with a typical size of $\sigma_x \times \sigma_y = 200 \times 200\ \mu m^2$, and the energy density necessary for quenching is reached directly via the initial particle density. This is nicely demonstrated in Fig. 1 where the lowest light output is located exactly in the center of the beam, i.e. the region with the largest particle density.

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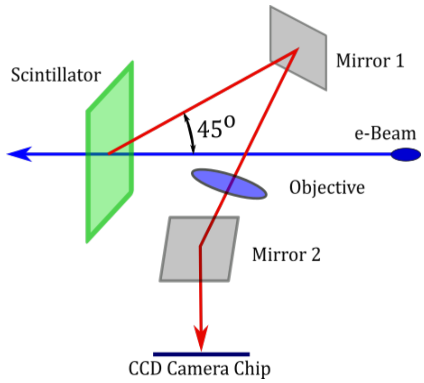

Figure 3: Scheme of the measurements.

In order to investigate this effect in more detail, a series of measurements was conducted at the XFEL which are partly described in Ref. [9]. Four additional scintillators have been selected in order to prove the assumption and to find a possible substitutes for the LYSO target:

- $Y_3Al_5O_{12}$:Ce (YAG)
- $YAlO_3$:Ce (YAP)
- $Lu_3Al_5O_{12}$:Ce (LuAG)
- $Gd_3Al_2Ga_3O_{12}$:Ce (GAGG).

Main criteria was the linearity of the light output as function of the charge density, while the scintillator with the most linear dependence is the most suitable one. It was demonstrated that GAGG screens show a very proportional light output which coincides with the theoretical assumption in Ref. [5].

Nevertheless, the subject of scintillator linearity is of utmost interest for the diagnostics community because several screen materials are in use at various accelerators with a wide range of parameters, see e.g. Ref. [10]. Especially particle densities available at modern linac based FELs may reach the critical limit, thus deteriorating beam profile measurements. In order to explore the limits of non-proportionality it was decided to continue the studies at the Photo Injector Test Facility PITZ at DESY Zeuthen. PITZ is advantageous for such kind of measurements because of the higher achievable beam charge compared to the XFEL and its lower electron energy.

EXPERIMENTAL SETUP

PITZ is used for the optimization of high-brightness electron guns for the European XFEL and FLASH. The beam main parameters are

- elctron energies up to 22 MeV
- bunch charges up to 5 . . . 6 nC
- bunch repetition rate 10 Hz.

The measurement principle was to investigate the light yield dependency as function of the bunch particle density (as it was already the case for the XFEL studies). A scheme of the experimental setup is shown in Fig. 3. Five scintillating screens (YAG, YAP, LuAG, GAGG and LYSO) are installed on a single holder and can be moved in the beam path by a stepper-motor driven mover. The screens are oriented perpendicular to the electron beam axis.

The optical part of the setup consists of 2 mirrors, an objective lens and a camera. The mirrors are used to extract the light out of the vacuum chamber and to guide it through the optical components to the camera system. A *Schneider-Kreuznach 5.6/180* objective was used in so-called Scheimpflug geometry, thus compensating depth-of-field effects caused by the 45° observation geometry. An *Allied Vision GC1350* CCD camera was used for image detection. Beam focusing in the screen plane could be performed by a set of 5 quadrupoles right before the experimental station. In order to modify the charge density the bunch charge was varied. The camera settings were chosen such that the gain was set to 0 (lowest electronical noise contribution), and the smallest possible exposure time was selected (which typically amounted to 10 µs). However, a larger exposure time would not change anything because the scintillator decay times are in the nano second region which is fast enough compared to the micro second exposure times.

RESULTS

Figure 4 show images of the same beam spot, but taken with different scintillators for a bunch charge of 2 nC and a spot size of $\sigma_x \times \sigma_y = 120 \times 50\ \mu m^2$. The spot size was determined by means of the GAGG scintillator because it is the most reliable material. Even at high charge densities the GAGG based beam spot is well fitted by a Gaussian distribution, while the YAG and LuAG based images are already clearly saturated, resulting in a flattening in the center of the beam image. As can be seen from this figure, the only material that clearly demonstrates a smoke-ring shaped

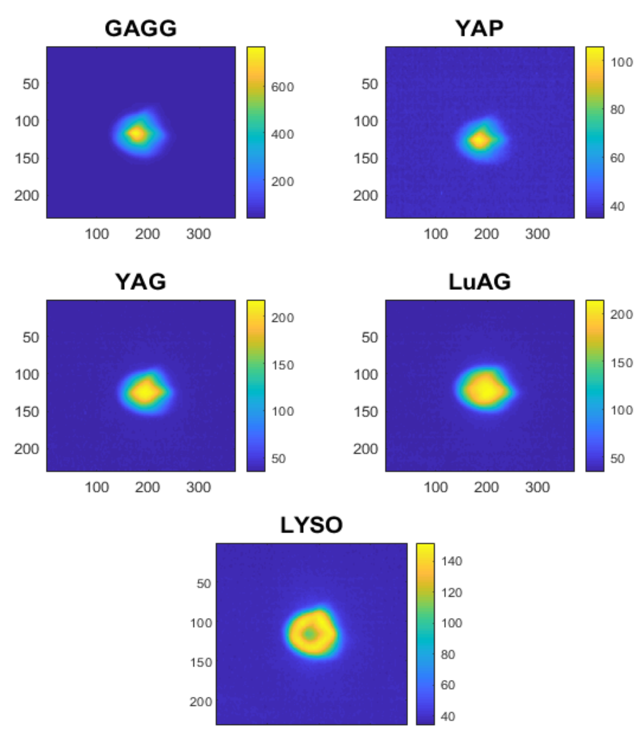

Figure 4: Comparison of the same beam spot measured with different scintillators.

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beam profile is LYSO, an observation which reproduces the results from the XFEL measurements. Nevertheless, both YAG and LuAG seem to be close to the quenching threshold of the excitation carriers inside the crystal. However, during the course of this measurement it was not possible to reach higher charge densities and to produce a smoke-ring shaped beam profile with YAG and LuAG as a consequence.

As expected from the discussion in Ref. [5], GAGG and YAP show the best results. Reason seems to be (1) for GAGG the gadolinium content which allows that excitation carriers can rapidly transfer their energy to excited states of gadolinium, thus resulting in a rapid migration of this energy among the Gd sub–lattice, resp. (2) for YAP the high mobility of excitonic carriers which may reduce the quenching probability. The only difference between GAGG and YAP image is the much smaller light output from YAP. Besides the YAP light yield which is much smaller than the one for GAGG, the YAP radiation spectrum peaks at about 375 nm which is quite off from the maximum of the camera quantum efficiency at about 540 nm. As result the YAP image is more noisy than the GAGG based beam spot.

Figure 5 shows the results of the next measurement series. In this case the bunch charge was increased while the quadrupole settings were kept constant, and for each charge

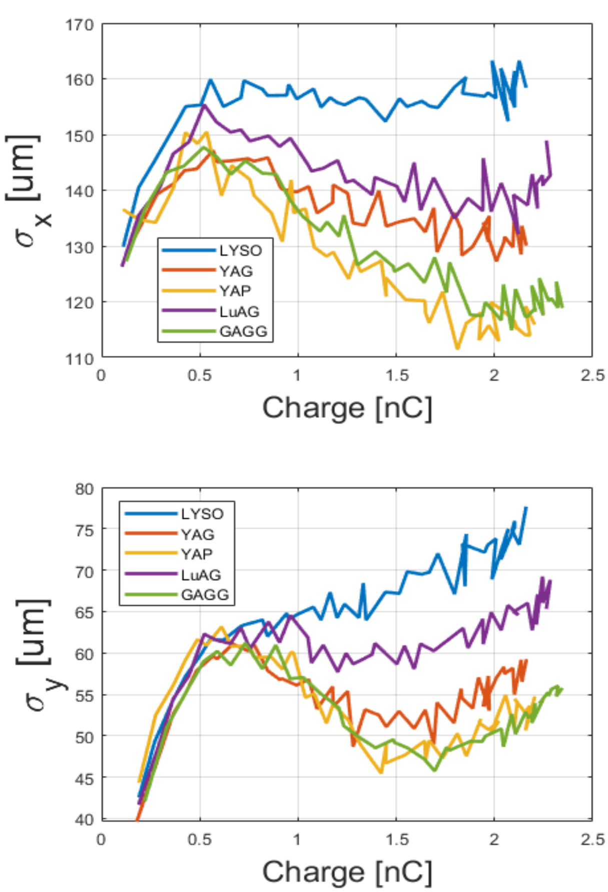

Figure 5: Comparison of projected horizontal (top) and vertical (bottom) beam sizes as function of the bunch charge.

and scintillator material a series of spot size measurements was taken. For each recorded image the projected beam spot was fitted with a Gaussian distribution, and the results are combined in this figure. It should be noted that a variation of the bunch charge automatically results in a small change of the beam size due to the modification of the injector laser attenuation and the space charge as the consequence. However, even with this small additional size modification the peak charge density was increased with increasing charge which was the primary intention of this measurement.

Comparing the projected beam sizes, it is obvious to see large differences between YAG/LuAG at the one hand and GAGG/YAP at the other hand. While the spot sizes are in agreement up to charges between 0.5 nC and 1 nC, for larger bunch charges the difference is steadily increasing. It is interesting to note that the smoke-ring shapes for LYSO clearly appears only at charges above 1 nC (20 fC/μm^2), however the measured sizes are already much larger at smaller bunch charges compared to the measurements from other scintillating materials.

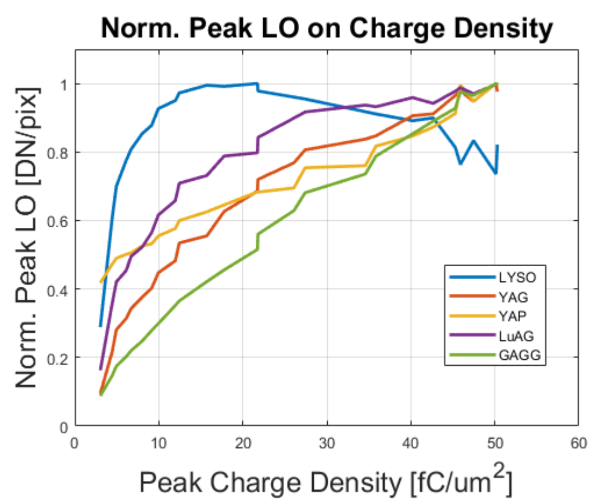

Figure 6: Normalized peak light output as function of the peak charge density.

The experience with the analysis of scintillator non-proportionalities based on beam spot measurements indicated that the extracted beam sizes are not the proper way to estimate this effect. For this purpose the light output as function of the charge density dependence is a better measure as indicated in Fig. 6. The peak charge density was defined by the beam sizes derived with the GAGG and the charge measured at each measurement. And the peak LO is an average of the 3×3 pixels area of the exact scintillator picture. As can be seen, the LYSO light output grows up to a level of ≈15 fC/μm^2 (≈0.75 nC), afterwards it even drops due to quenching of the excitonic carriers. Hence the level is a critical one for the LYSO. Also from the figure it may be concluded that both YAG and LuAG based measurements seem to approach a plateau at the end of the graph. On the other hand, YAP and GAGG based measurements show a more or less linear increase of the light output with increasing charge density. This linear behavior is exactly

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what is needed from a scintillator for accurate beam profile diagnostics.

CONCLUSION

The measurements presented in this article extend the range of charge densities for five scintillating materials in use for electron beam profile diagnostics. As expected from previous measurements, the scintillator material which is mainly affected by non-linearity effects is LYSO. Besides, it could be shown that materials like YAG and LuAG which are widespread in use indicate significantly higher measured spot sizes at beam peak charge densities larger than 20 fC/μm^2 (corresponding to a charge of about 1 nC and a beam spot size of about $\sigma_x \times \sigma_y = 140 \times 55$ μm^2). However, at the other hand it could be demonstrated that GAGG and YAP behave very linear over the whole range of bunch charges under investigation. As consequence, the presented measurements underline the necessity to replace LYSO based screens by GAGG in order to achieve reliable beam profile measurements. This is especially true having in mind that the planned maximum beam charge at the XFEL will not be larger than 1 nC.

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