SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Analysis and Optimization of a Scintillator Calorimeter System for Pulsed Radiation Spectrometry at ELI Beamlines

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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1. Introduction

During the generation of a laser-induced particle beam, a non-negligible fraction of the laser energy is dissipated in the form of ionizing radiation, whose characteristics strongly depend on the underlying physics of the laser-plasma. For this reason, an online analysis of the produced radiation field would represent a useful diagnostic tool for the plasma produced [1].

Laser-induced radiation fields are extremely short-lived, of the order of the laser pulse, that is a few femtoseconds [2]. Typical spectrometry techniques in radiation detection rely on single-quanta measurement, therefore a conventional online detector exposed to a burst of radiation would be subjected to pile-up that would make the reading of the instrument meaningless.

In this context, the OSCAR detector (Online Scintillator Calorimeter for the Analysis of Radiation) has been developed from the Radiation Protection Group at ELI Beamlines – a leading laser research center in Dolní Břežany (Czech Republic) hosting some of the world most intense lasers – to perform shot-by-shot energy spectrum measurements in high intensity and pulsed radiation fields typically produced in laser-target experiments.

2. Design and Light Output Optimization of OSCAR

The OSCAR detector is composed by a stack of scintillating crystals that emit visible light as a consequence of the interaction with ionizing radiation. A readout system collects the light from the crystals, and from the relative variation of the light output among the various crystals it is possible to estimate, through an unfolding procedure, the Maxwell-Boltzmann temperature of the radiation interacting with the detector, that is mainly constituted by electrons and photons.

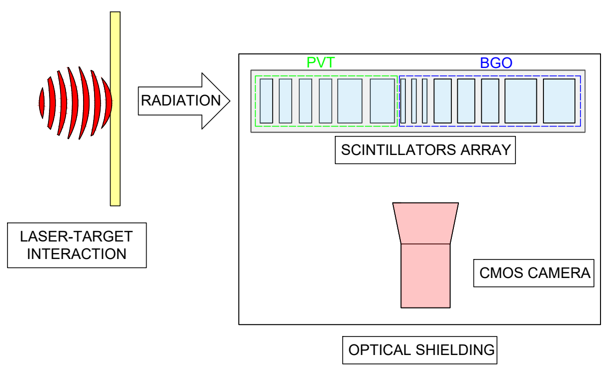


Figure 1: The OSCAR detector working principle.

The stack of scintillating crystals is composed by EJ-200 – a plastic material made by PVT – and BGO scintillators. The laser-induced radiation impinge the plastic scintillators first, as shown in Figure 1. The radiation that has not interacted with EJ-200 encounters the BGO crystals, that have a much higher density and so a higher capability of interaction with radiation [3]. All the scintillators have a cross-section of 2x2 cm^2, and their thickness typically increases as the radiation penetrates in the detector: this helps in capturing the beginning of the dose-depth curve in high detail, ensuring better energy resolution at the peak region, while limiting the noise in the second part [1, 3].

To enhance the fraction of scintillation light collected by the readout system, all the faces (except the one facing the readout system) of the scintillating crystals in OSCAR are covered with a PTFE tape, a highly reflective material. A more intense signal from the crystals helps in reducing uncertainties on the OSCAR results. However, it is important to guarantee uniformity of the PTFE coating, to limit the uncertainty associated to the reflector effectiveness, which has a direct impact on the accuracy of the unfolding procedure.

In order to evaluate the uniformity of the PTFE wrapping, the light output from the same crystal with four different PTFE wrappings has been investigated. The observed fluctuation in the light output of more than 5% indicates the presence of significant non-uniformities in the coatings. A calibration for every wrapped crystal would be therefore required, which is impractical. For this reason, the titanium oxide (TiO_2) painting has been explored as an alternative reflector to the PTFE coating.

The TiO_2 is widely used as a reflector material for scintillator detectors, since it is a diffusive reflector with good reflective properties, even though reflectivity is not as good as PTFE. However, the TiO_2 also offers other interesting properties: in fact, it is available as liquid paint to spray on the crystal faces, therefore it is possible to apply the reflector layer with a more standardized method and more uniformly with respect to PTFE wrapping, reducing, for example, the possibility of having non-uniformities due to air bubbles in between reflector and crystal.

Analogously to the analysis previously performed on the PTFE wrapping [1], it has been found that the maximum reflectivity and uniformity of the painting are achieved after five layers of TiO_2.

3. Readout System of OSCAR

The light sensor in the current readout system in OSCAR is a CMOS camera, which takes a picture of the entire stack of scintillating crystals when the detector is exposed to radiation. From the picture, it is possible to assess for each crystal the mean pixel value (MPV) calculated on a certain region-of-interest (ROI) inside the crystal area, that is strictly related to the light output.

An alternative light sensor to CMOS camera is offered by silicon photodiodes (SiPD). A SiPD directly converts the optical light output from the crystal in electric signal, that has to be handled by a dedicated amplification circuit before arriving to the digitizer.

3.1. CMOS Camera - Background Analysis

The MPV evaluated from the picture over a certain ROI needs to be subtracted by the background, and this requires a precise knowledge of the background of the camera itself. However, it has been noticed that the background fluctuates quite significantly in time, and this aspect deserved a further investigation.

In recent measurements, it has been observed that the background progressively increases of a factor two in the first two hours from the switching on of the camera, probably due to the heating up of the system. Then, a saturation level is reached, but peaks from the saturation level have been observed for every new series of picture acquisition. These peaks are quite important, since the background value progressively increases with the number of pictures acquired, up to 20% with respect to the saturation level. A possible explanation of this phenomenon is given by the camera image processing, that heats up the camera and increases thermal noise.

Fluctuations in background are undesired, since it is more difficult to assess the background level, and also measuring the background shortly before the shot doesn't completely solve the problem since, as previously reported, the picture acquisition leads itself to an increase in the background. This is a quite important limitation of the readout system, that leads to considering a completely new optical light sensor as an alternative to CMOS camera, as presented in Section 3.3.

3.2. CMOS Camera - Point of View Effect

The amount of light collected by the camera lens depends on the lateral position of the camera with respect to the crystal: in fact, the camera placed in front of the crystal acquires a more intense signal than when positioned at a certain lateral distance from the crystal. This effect is called the "point of view" effect (POV effect), and it is an important systematic effect that must be corrected during the analysis of OSCAR data.

An experimental campaign has been conducted measuring the crystal light output for various distances of the camera optical axis with respect to the front face axis of the crystal, going from the central position to an offset of 8.8 cm, that is slightly more than maximum crystal-camera offset in OSCAR. The response from crystals with different widths ($w = 0.2$, 0.3, 0.5, 1.0 cm) and materials (BGO and EJ-200) has been measured, to explore the influence of these parameters on the POV effect. Experimental results are reported in Figure 2.

Currently, the unfolding procedure takes into account of the POV effect using correction coefficients obtained experimentally. However, it would be useful to predict the POV curve shape and amplitude through Monte Carlo simulations, and this topic is discussed in detail in Section 4.

3.3. SiPD Readout - Preliminary Evaluation

Camera based data acquisition presents several problems, as the data post-processing difficult to automatize (ROI is user-defined), the large noise variations over time, the bulky light-tight setup, and POV effects to be corrected on the measured data. A promising alternative to the CMOS camera is offered by the SiPD. Other than mitigating the above-mentioned problems, SiPD features an efficient light collection, fast time response and compact size.

The complete readout system for OSCAR would

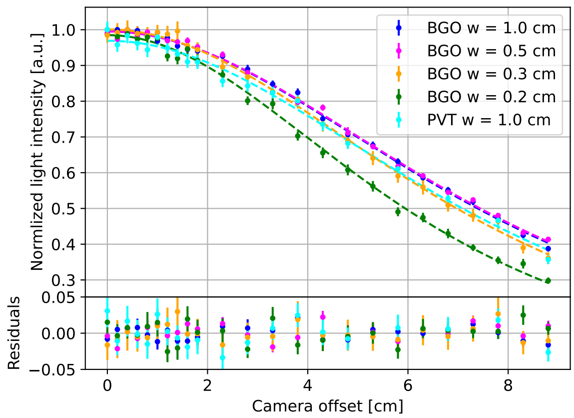


Figure 2: Normalized POV curves obtained from the experimental campaign.

consist of an array of SiPDs, one for each crystal, all connected to the same multichannel pulse analyzer. As a preliminary study, the response of one single channel line to the expected input signal – a short and intense burst of photons coming from the scintillator – has been analyzed. The readout system has been developed starting from an existing SiPD amplifier circuit currently used for the diagnostic of laser beamlines at ELI, and it is composed by:

- trans-impedence amplifier (TIA): amplifies and integrates the input signal;
- inverter amplifier: inverts the polarity and perform an amplification of the signal;
- peak holder: integrates and keeps the peak of the signal for a time long enough for the digitalization;
- digitizer: converts analog signals to a digital form.

Few improvements have been performed with respect to the original electronic scheme in order to obtain, with the minimum number of new components, a sufficiently high voltage at the output of the peak holder, in the order of mV-V, such that the signal can be read by the digitizer. In addition, linearity of the output voltage with respect to the deposited charge in the SiPD was aimed, as a low electronic noise.

The improved circuit design has been achieved proceeding by trial and error using LTspice XVII, a popular schematic-driven circuit simulation program, and an output signal of about 400 mV for 1 pC of charge in input – that is the expected charge produced in the SiPD – has been obtained. In addition, the linearity range

extends for two order of magnitude around the expected input charge.
The newly proposed design will be a useful starting point for the next experimental sessions, where the electronic circuit and the SiPD will be tested using pulsed light from a laser diode.

4. Simulation of Optical Photons Propagation

Optical simulations allow predicting the propagation of optical photons in space and time. A refined optical model for OSCAR would be helpful in predicting the response of the crystals in terms of visible light output, that is the experimental quantity observed in practice. In general, the propagation of optical photons in matter is far from being an easy topic in physics, and Monte Carlo techniques offer a valid approach to this problem.
The physics of propagation of photons in matter in the FLUKA.CERN code – one of the most popular Monte Carlo code in the field of detector development – is implemented at a very elementary level: all the interfaces in between different materials are assumed to be smooth surfaces, and so only specular reflection can occur. For this reason, two new optical models have been developed and implemented using user routines into the FLUKA.CERN code. Overall, three models have been explored for optical simulations with OSCAR:

- "Ideal" model: specular reflection is the only reflection mechanism possible (default FLUKA.CERN optical model, already implemented in the code).
- "LUT" model: photons are reflected from the PTFE layer following experimental distributions collected in the so-called "Look Up Tables" (LUT) [4]. In addition, to mimic the effect of roughness of the crystal surface exposed to air, a reflection/refraction specular lobe is included in the model.
- "Detailed" model: photons are reflected from the PTFE layer according to four different mechanism of reflections, namely the specular peak reflection, specular lobe reflection, backscatter reflection and Lambertian (diffuse) reflection, that are shown in Figure 3 [4]. A reflection/refraction lobe is also included in the model for the surface exposed to air, to mimic the effect of surface roughness.

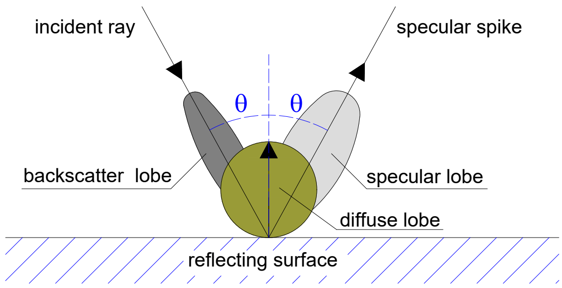


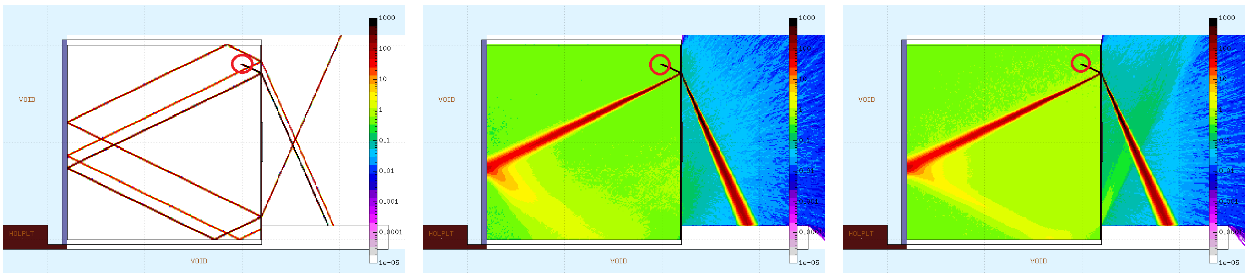
Figure 3: Four main mechanisms of reflection of light from a reflecting surface.

4.1. Optical Model Comparison

A qualitatively first sight comparison among the three models is reported in Figure 4. In this illustrative simulation, the source of optical photons is placed inside the crystal, and photons are emitted as a pencil beam towards the front face of the crystal (the one on the right in each view). In the ideal model, photons are not diffused in reflection/refraction, while in the newly proposed models the photon beam is spread every time it reaches an optical surface, and in the end photons are everywhere inside and outside the crystal.
As a more quantitative comparison, the experimental POV curves reported in Section 3.2 have been used as a benchmark for the three models: the goal was predicting the POV curve shape shown in Figure 2, with a uniform "scale factor" among different crystals. The scale factor is defined as the ratio between the measured and simulated POV curve amplitudes, and it should be independent on the crystal properties, since it should depend only on the various and unknown parameters of the camera.
Measurements and simulation results have been compared using the following metrics:

1. root-mean-square value (RMS) of the differences in between the experimental and simulated normalized POV curves;
2. scale factor;
3. single-core computational time per simulated primary.

The three models presented a comparable performance in terms of RMS of the residuals, ex-



(a) (b) (c)

Figure 4: Optical photon fluence inside and outside the crystal obtained using ideal model (a), LUT model (b), and detailed model (c). In these simulations, an optical photon beam is emitted from the center of the red circle inside the crystal, with a certain direction towards the front face of the scintillator. The crystal is supported by a plastic holder (brown color), and air is surrounding the scintillator (light blue color).

cept for the LUT model, which gave the worst RMS values for smaller crystals. However, the RMS values obtained are always lower than 3%, that is compatible with the experimental error of the normalized POV curves. For the scaling factor, the detailed model achieved more uniform values among different crystals, with a variation of few percents, thanks to the higher number of degrees of freedom available. The ideal model is, as expected, also the fastest one, while the computational time for the LUT is the highest one, mainly due to the slow angle lookup algorithm.

4.2. Time Evolution of the Light Signal

The distribution in time of the light collected by the readout system is the convolution of the scintillation time and the straggling due to the propagation of optical photons inside the crystal. It is important to assess the light output time structure to perform e.g. time-resolved measurements, and the newly developed optical models allowed a more accurate evaluation of the time straggling of photons.
The estimated time straggling is of the order of 1ns, that is negligible with respect to the characteristic scintillation time of BGO, but it is comparable to the characteristic time of EJ-200. Therefore, straggling should be taken into account in the development of the detection system for neutrons proposed in Section 5, that is based on pulse-shape discrimination.

5. Neutron Detection with OSCAR

In a laser-target interaction, neutrons are produced through nuclear reactions induced by photons, electrons, and protons emitted from the target. Neutrons contribute to the background signal, therefore there is a strong interest in estimating the level of neutrons produced, in order to better evaluate their importance in the experimental background.
Based on the latest available data from ELI-MAIA experiments, several Monte Carlo simulations have been performed in FLUKA.CERN to estimate the yield of neutrons emitted from the target. Hence, the response of OSCAR to neutrons has been compared to the one to electrons and photons for the same temperatures and relative amplitudes used to obtain the neutron yields. The response to photons-induced neutrons resulted in a factor 10^6 smaller than the one to electrons and photons, and a similar response is expected also for protons-induced neutrons. The lower sensitivity to neutrons in addition to the small neutron yield results in a negligible contribution to the experimental background.
Neutrons could be also seen as the main signal to detect instead of a mere background, and for this purpose OSCAR should be evidently adapted in the design, to significantly improve its capabilities in detecting this type of radiation. In this context, it could be interesting to explore the use of scintillating crystals with ^{6}Li impurities, and the discrimination of the signal from neutrons to

electrons/photons could be performed through:

- Material discrimination: the OSCAR detector could be segmented in various portions with different kinds of scintillators with different neutron sensitivities.
- Temporal discrimination: information related to the type of particle interacting with a scintillating crystals can be obtained observing variations in the signal pulse shape, and this is at the basis of the so-called pulse shape discrimination method. Although this technique proved to work well with plastic scintillators, it cannot be used with BGO crystals because of the long scintillation time. An additional complication also comes from the electronic readout circuit.

6. Conclusions

The OSCAR calorimeter is a novel concept of active detector specifically designed for online diagnostics and radiation spectrometry for laser-driven experiments conducted at ELI Beamlines. Although the detector has already been largely tested, and its development is quite advanced, several aspects related to light output optimization and readout system limitations deserved a deeper envelopment. Therefore, the use of TiO_2 painting as reflector layer has been explored, and the current CMOS camera based readout system has been analyzed in more detail. In particular, the camera background has been measured over long time scales, and results highlighted important variations in time that could affect the quality of the measurements. In addition, point-of-view effects related to the camera have been discussed. An alternative readout system, based on silicon photodiodes, has been also proposed, and a preliminary evaluation of the electronic hardware connected to the photodiode has been performed.

The strong interest in exploring the propagation of the scintillation light inside the crystal pushed the development of two new optical models to be implemented in the FLUKA.CERN code. These optical models have been compared to the basic model available in FLUKA.CERN, and point of view experimental data has been used for benchmarking. The POV curves obtained from measurements have been reproduced through simulations with an error comparable to the experimental one and variations of few percent on the scaling factors.

Starting from the newly developed optical models, it has been also possible to analyze the time structure of optical photons propagating in the crystal, and so to predict the time straggling. This could be important to discriminate different type of particles using pulse shape discrimination techniques, expanding the detection capabilities of OSCAR.

Finally, the OSCAR's sensitivity to neutrons has been better understood: starting from neutron spectra obtained through simulations, the response of the detector to neutrons has been compared to the one to electrons and photons, showing six order of magnitude lower sensitivity than to the latter. The low neutron sensitivity indicates that further development in design and readout techniques are necessary to achieve direct neutron detection with OSCAR, and possible improvements have been proposed.

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