STEMS – A Stimulated Emission Sensor

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ABSTRACT

In this project we have investigated the possibility to realise a detector based on a laser cavity that hosts a target crystal for the incident ionizing radiation, in optical communication with the cavity mode. We have considered and experimentally tested two different detection mechanisms: (1) a process of coherent scintillation related to the rapid decay via stimulated emission of the excited atomic or molecular levels of the target material; (2) activation of states that absorb intracavity photons, which correspond to introducing an additional loss as in Q-switched laser oscillators. We have used a solid-state laser to understand the dynamic response of our prototype sensor and the related intrinsic limitations, and demonstrated capability to detect X-ray energy down to 10 GeV in the Q-switching approach.

Keywords: Scintillation; laser; radiation detection; optical fibre

1. INTRODUCTION

Scintillation is the key physical process in medical imaging systems as positron emission spectroscopy (PET) and computed tomography (CT). Both these technologies would strongly benefit from improved scintillation timing and efficiency, and much has been done in this direction, mainly by developing new scintillating materials [1]. The current request in TOF-PET is to accomplish sub-100 ps time resolution.

Another research area in which important challenges are still open is dosimetry, in which more accurate and reliable dosimeter technology is required, following the improvements of radiation delivery methods through the use of small fields [2]. Hadron therapy would also greatly benefit from a fast online monitoring of the dose, requiring high sensitivity, high resolution, and fast reconstruction imaging of $\beta+$ -emitting isotopes produced during the irradiation [3].

A paradigm change in ionizing radiation (IR) detection has been addressed in this project, by introducing the possibility to enhance the intrinsic emission process of the scintillator when it is inserted in a laser cavity, via the stimulated emission process. Following the same basic idea of using a laser cavity to detect ionizing radiation, we have also explored a scheme in which the absorption of the incident radiation in a target determines the laser switch off. The first approach will hereafter be referred to as *gain-switching*, akin to the technique exploited in semiconductor lasers to obtain short laser pulses [4], while the latter is called the *Q-switching* approach, as the rapid change of intracavity losses due to IR is also the basic mechanism in Q-switched laser systems [5].

We have built prototype laser cavities to understand the limiting factors in the response time of the proposed *gain switching* approach, and conducted tests with an X-ray source to measure the energy threshold in the *Q-switching* approach. We have observed that relaxation oscillations related to the laser active material used might significantly limit applicability of the *gain switching* approach to TOF-PET, even though mitigation strategies can be found. The absorption scheme should be more promising as concerns response time, and we demonstrated capability to detect 10 GeV energy, X-ray pulses. This result is regrettably yet several orders of magnitude from single gamma level in PET systems, but possibly of interest for dosimetry applications.

2. STATE OF THE ART

Beyond developing new scintillation materials, several approaches have been recently pursued to improve scintillation timing and efficiency, including the improvement of the read-out electronics. An interesting pathway concerns the light extraction efficiency, with the introduction of photonic crystals as impedance matching layers between the scintillator and the photodetector [1].

A radical change in this effort to overcome the intrinsic limitations of scintillators has been reported recently, in which index of refraction modulation of cadmium telluride, induced by IR, have been used to obtain a modulation signal of a radionuclide source. It is however evident that the demonstrated detection capability is only reached at the cost of a very long integration time [6].

The same index of refraction change by the incident IR is the mechanism recently exploited to demonstrate detection down to biomedical doses (160 mGy) in optical fibers [7].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In general dosimetry optical fibers mainly serve as light transmitters from the sensor's head, whether it be a diode, scintillator or a thermoluminescent material [8]. We envisage the utilization of our concept in this field, with a fiber laser becoming both the true sensor, with improved sensitivity and response time, and the light guide.

To reduce the dose in PET systems is a most important objective. Improving PET performance has meant up to now in improving scintillating materials properties (resolution, timing) and readout techniques. With the STEMS project a thoroughly new approach has been studied: to use a prompt "coherent scintillation" instead of isotropic, incoherent spontaneous emission. With a fiber laser, the device is naturally connected to fibre optic platforms for direct signal processing.

4. PROJECT RESULTS

A picture of the laser prototype during X-ray tests is displayed in Fig. 1, which includes a schematic view of the investigated concepts.

The laser that was developed to obtain an experimental proof of the illustrated concepts is a diode-pumped solid state laser. The laser active material is 2%-doped Nd:YVO_4, in which population inversion on the lasing transition at 1064 nm is accomplished by pumping at 808 nm with a fibre coupled laser diode. The optical cavity is approximately 20 cm long and hosts a 5 mm target crystal, of the same material as the active crystal. Tests have been conducted using also other target materials, as for instance Yb:KGW to verify the obtained preliminary results as detailed in the following.

To maximize sensitivity to the incident IR, during the tests we operated the laser at threshold, a condition in which relatively large intensity fluctuations can be observed. It is also worth noticing that the cavity has not yet been stabilized by any feedback electronics, and at threshold the output power exhibited long term (several seconds) drifts from approximately 100 nanowatt to a few microwatt.

Gain switching approach

The results of the tests we did to address the timing issue have been done by injecting in the target crystal light from LED and laser sources of photons in the absorption band of Nd:YVO_4. The results of these tests are concisely reported here, while a detailed description has been given elsewhere [9].

The temporal response of the prototype detector, recorded at an InGaAs photodiode, displays damped relaxation oscillations whose characteristic frequency is related to Nd atomic lifetime. The response time in the prototype detector cannot be much shorter than a fraction of the observed ringing period of about ten microseconds, clearly not compatible with the requirements of TOF-PET. A study with a target crystal whose doping atom has a much shorter lifetime is required, as for instance Ce:LYCAF, to improve on this figure of merit.

Q-switching approach

In principle, in this detection scheme the temporal response is independent of the level lifetime.

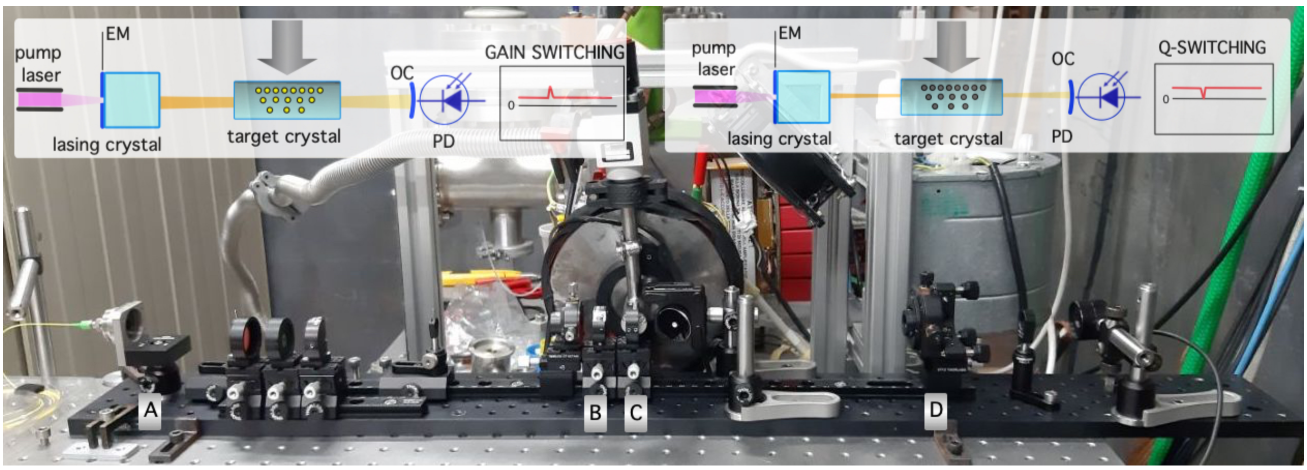

Fig. 1. Picture of the prototype detector in place for X-ray tests. Key elements are: (A) fibre output of the pump laser; (B) laser active medium holder; (c) target crystal holder and (D) output cavity mirror holder OC. The target crystal is set at a few mm distance from the electron gun Tantalum foil. The insets are a schematic representation of the investigated concepts.

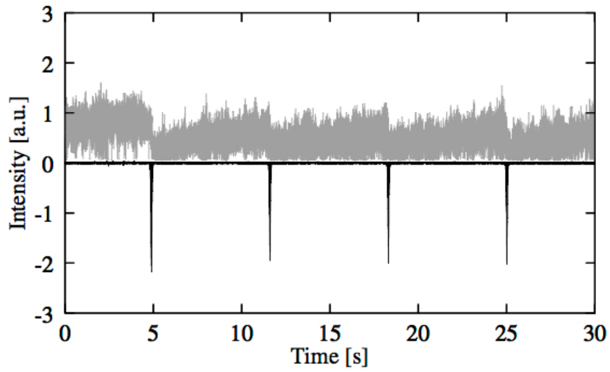

Fig. 2. The laser output power is influenced by X-ray pulses (black peaks in the bottom part) absorbed in the target crystal.

This is demonstrated by microchip Q-switched lasers, where pulses as short as 30 ps have been obtained by exploiting a passive absorption mechanism [10] with $Nd:YVO_4$ as active medium.

We have thus focused our efforts in this direction, starting from the measurement of X-ray pulses detection threshold.

We have modified a battery-operated, 75 kV pulsed electron gun available in our laboratory to obtain X-ray pulses. To accurately estimate the detection threshold, we measured the pulse energy and the X-ray pulse with independent measurements [9]. For the pulse energy, a scintillation detector (CsI:Tl) has been used, whereas for the latter the spectrum acquisition at a Ge detector has been calibrated via a ^{241}Am source.

The main result is reported in Fig. 2, where it is evident that the laser output power changes when a (9 ± 0.5) GeV X-ray pulse is absorbed in the target crystal. To assess systematic errors, these measurements have been repeated for different positions of the optical beam relative to the interaction region. In addition, we validated our experimental procedure by using as a target crystal 10% Yb:KGW, a material with much stronger X-ray absorption coefficient. In this case, we observed that the laser oscillator was unperturbed during irradiation.

Another important figure of merit of the detector is the dead time. We have observed that, depending on the initial intracavity laser intensity, our prototype detector may take up to a few seconds to reset after the X-ray pulse. This is probably related to the long lifetime of the absorbing centres, that might correspond to deep traps.

5. FUTURE PROJECT VISION

In ATTRACT Phase 1 we have demonstrated that it is possible to detect 10 GeV energy X-ray pulses absorbed in an intracavity crystal. If we address dosimetry in radiotherapy, this result can be considered TRL3, whereas a much lower level has been achieved in applicability to TOF-PET. In this case we must honestly state that the project is still at the proof of concept level, as the following milestones have not been obtained: (1) capability to detect 511 keV photons; (2) sub-100 ps temporal resolution.

5.1. Technology Scaling

The main step required to scale the STEM sensor's TRL is related to identifying and testing the most suitable material, which should have the following properties:

- it is transparent to the laser emission when there is no IR;
- it offers maximum absorption to IR, possibly through the rapid generation of states with high cross section at the laser emission wavelength, and with low lifetime

This materials research activity could also consider semiconductors. Every exciton generated by the IR can likely absorb several photons within a few cavity round trips, to quickly return on the initial energy level. Thus a fast exciton relaxation would ensure also a short detector dead time and a high detection rate.

As concerns cerium-doped materials employed in PET systems, the STEMS sensor would promptly probe the creation of self-trapped exciton instead of detecting the cerium emission subsequent to an energy transfer process. In this way, the time resolution would be improved. In addition, as the infrared laser field should not affect the scintillation efficiency and detection, the STEMS sensor could be implemented in current PET devices, allowing a higher rejection of random coincidences.

5.2. Project Synergies and Outreach

Due the explorative character of our project, synergies with industrial partners have not yet been found in ATTRACT Phase 1. Moreover, we did not find strong connections with other funded projects ATTRACT Phase 1, therefore the research has been conducted within a small group of researchers belonging to national institutions (INFN and the University of Padova).

In ATTRACT Phase 2 the following synergies will be necessary:

- materials science experts in academia, as the project requires substantial improvement of the target material properties as previously detailed;
- medical imaging industrial partners as Siemens [];
- dosimetry technology experts
- fibre laser companies

5.3. Technology application and demonstration cases

A highly sensitive dosimeter would accurately verify dose delivery during radiotherapy. We expect to be able to give a complete demonstration of this technology during ATTRACT Phase 2.

5.4.Technology commercialization

Concrete steps in the commercialization of the technology in the dosimetry field have not yet been done. We expect that with the publication of our preliminary results, industrial partners might be interested to our developments.

Concerning application to TOF-PET, the low TRL we accomplished during the project did not encourage us to contact medical imaging companies [12]. This will be done if the TRL scaling to 3 will be accomplished with the strategy described in section 5.1.

5.5.Envisioned risks

The project will involve main experts in the fields of semiconductors and scintillators, as the core risk that the project might face in a potential ATTRACT Phase 2 project is related to limitations in the investigated materials.

5.6.Liaison with Student Teams and Socio-Economic Study

A related ecosystem will be created by integrated academic, industry groups working together. The necessary elements of such an ecosystem include research laboratories, and people aware of industry standards for product development and specification.

Most importantly, new basic research is needed to uncover the best possible materials for STEMS. In this direction collaboration with MSc. Level student teams will be central, to make tests on the prototypes, who will in this way achieve an even deeper insight of the project technology. This will put them in the condition to provide ideas for addressing the Societal Challenge: "Health".

The project leads will contribute to the expert-driven socio-economic study of the ATTRACT initiative and ecosystem with interviews and technology impact references.

6. ACKNOWLEDGEMENT

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