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Photoluminescent radiation-induced color centers in lithium fluoride for detection of pulsed 10 keV XFEL beam

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Summary. — Images of the Spring-8 Angstrom Compact free electron LAser (SACLA) 10 keV pulsed (10 fs) beam were recorded in a lithium fluoride (LiF) crystal by exploiting visible photoluminescence of radiation-induced color centers (CCs). Photoluminescent beam images stored in LiF, irradiated at several energies from 0.04 to 0.8 J, were acquired by a fluorescence optical microscope and processed with an algorithm developed in Matlab, allowing to reconstruct the transversal beam fluence distribution.

1. – Introduction

LiF crystals and thin films are used as X-ray imaging detectors by exploiting visible photoluminescence (PL) of radiation-induced F_2 and F_3^+ CCs, which emit in the red and green spectral range, respectively, under blue light excitation [1], so a fluorescence optical microscope can be used in the image reading process. Such detectors, due to their intrinsic high spatial resolution [2,3] over a large field of view and wide dynamic range (higher than 10^6) [4], were tested for beam characterization of several soft X-ray table-top sources and imaging experiments [5-7]. The above-mentioned characteristics of LiF radiation imaging detectors also make them extremely attractive for beam detection and characterization of ultra-high intensity pulses of XFEL sources, a topical task nowadays. Indeed, LiF crystals were successfully used as imaging detectors of SASE FEL soft X-ray pulses [8] and for characterizing soft and hard X-ray XFEL beams [9-11], as well as for phase contrast imaging experiments [12]. In this paper our latest achievements in characterizing the 10 keV pulsed XFEL beam at the Spring-8 Angstrom Compact free electron Laser (SACLA) are presented, in the energy range from 0.04 to 0.8 J, by using a LiF crystal. Some XFEL beam parameters, obtained by processing with an algorithm developed in Matlab the photoluminescent images stored in the LiF crystal after acquisition by a fluorescence optical microscope, are presented and discussed.

2. – Experiment and results

A LiF crystal (20 mm diameter, 2 mm thick) was irradiated at the Japanese Spring-8 Angstrom Compact free electron LAser (SACLA), in the EH5 experimental hutch of the BL3 beamline [13]. In our experiment, 10 keV (0.6% bandwidth) and ~ 7 fs photon pulses with a repetition rate of 30 Hz were used. The average energy per pulse, measured by a beam monitor made of a high-transmittance nanocrystal diamond foil, was 0.45 mJ with fluctuations of $\pm 10\%$ (σ). The LiF crystal was irradiated by the full size XFEL beam at normal incidence in four spots with different numbers of accumulated shots: 2000, 1000, 500 and 100 shots (spots 1, 2, 3 and 4, respectively). Taking into account the 27% of beam absorption through 540 cm of air (at room temperature and normal ambient pressure), the four accumulated energies delivered by the XFEL beam to the crystal were 0.780 J, 0.388 J, 0.195 J and 0.039 J, respectively. X-ray irradiation produces various kinds of CCs in the crystal, whose concentrations are locally proportional to the absorbed dose. X-ray penetration in solids strongly depends on the photon energy, thus the same behavior is expected for the depth of the colored layer in LiF [14]: the attenuation length in LiF of a 10 keV X-ray beam is about 670 μm. The irradiated spots in the LiF crystal were observed by a fluorescence optical microscope, equipped with a 4× objective and a 100 W mercury lamp illuminating the sample in the blue spectral range, to excite the PL of F_2 and F_3^+ CCs [1]. An s-CMOS camera (cooled at -30 °C, 16 bit) was attached to the microscope to acquire the visible photoluminescent images due to the CCs in the four irradiated spots. Figures 1(a) and (b) report images of spot 1 (2000 shots, 0.780 J) acquired at two different exposure times of the s-CMOS camera, 15 ms and 500 ms, respectively. At short exposure times, the external parts of the beam image are not distinguishable, while the central one is clearly resolved. By increasing the exposure time, visibility of the external part of the beam increases and pixels of its central part get brighter and brighter, until they saturate (see fig. 1(b)), so at a single exposure time, within that single image, it is not possible to resolve the full details of the whole beam cross section. To overcome this limitation, an algorithm was developed and coded in Matlab to process a set of several images taken with increasing exposure times and allowing to visualize, in a single composite image, the full details of the whole

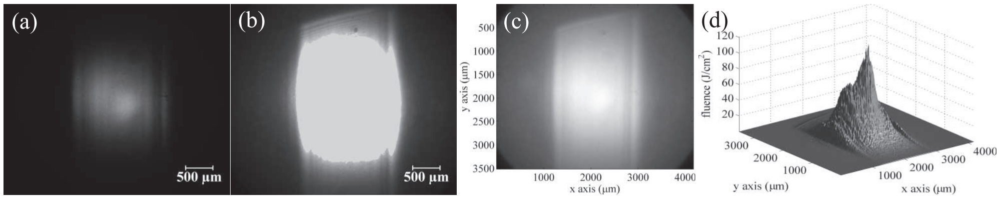

Fig. 1. – (a),(b) Fluorescence images of the colored spot with 2000 accumulated shots of XFEL beam in LiF crystal acquired at different s-CMOS camera exposure times ((a) 15 ms and (b) 500 ms). (c) Corresponding tone-mapped algorithm-reconstructed image. (d) X-ray fluence distribution of the XFEL spot.

XFEL beam cross section. The algorithm uses the following formula:

$$I(x,y) \propto \sum_{k=1}^{N} \frac{T}{t_k} S_k(x,y), \tag{1}$$

where the resultant PL intensity distribution $I(x,y)$ is obtained as proportional to the sum of the N non-saturated cut-outs $S_k(x,y)$ of the PL maps that were recorded at the t_k exposure times, and the T/t_k parameter is used to renormalize each term to a common arbitrary exposure time T. With this algorithm, which was applied to the four spots, the saturated pixels of a map are replaced by the corresponding non-saturated pixels belonging to maps recorded at shorter exposure times, obtaining a final mosaic map that covers the entire field of view, but without saturation. Figure 1(c) reports the reconstructed tone-mapped image of spot 1 (2000 accumulated shots) as obtained by applying the above-described algorithm to 12 PL maps, acquired at different exposure times ranging from 10 ms to 2 s with renormalized exposure time $T = 100$ ms. It is evident that by applying this procedure, the full details of the whole XFEL beam are well resolved in a single image. In fig. 1(d) the X-ray fluence of the spot is plotted as 3D distribution: it was evaluated from the reconstructed PL image by taking into account both the accumulated energy of 0.780 J and the saturation of CCs concentration after analyzing the PL intensity peak *vs.* accumulated energy of the four spots, as explained in [10]. The algorithm applied to obtain the fluence distribution from the PL intensity image is the same as that recently used to extract the dose map from the PL image of CCs created in LiF by proton irradiation [15]. In table I, besides the accumulated energies, two more parameters are reported for each spot: an equivalent beam waist $W_{86\%}$ and an average fluence value Φ. As the fraction of energy within the beam-waist circumference

Table I. – *Accumulated energies, equivalent beam waists and average fluences of the four XFEL spots.*

	Spot 1	Spot 2	Spot 3	Spot 4
E_{acc} (J)	0.780	0.388	0.195	0.039
$W_{86\%}$ (μm)	918	944	963	1209
Φ (J/cm^2)	29.5	13.9	6.70	0.851

of a Gaussian beam amounts to 86% of its total, the equivalent beam waist $W_{86\%}$ was evaluated for the XFEL irregularly shaped spots as $W_{86\%} = (A_{86\%}/\pi)^{1/2}$, where $A_{86\%}$ is the area of the PL map containing 86% of its total intensity and Φ is the fluence average inside the $A_{86\%}$ area.

3. – Conclusions

The very good performance and peculiarities of a LiF crystal used as imaging detector, by exploiting the PL of radiation-induced CCs, for characterizing the 10 keV SACLA XFEL pulsed beam have been discussed. The transversal beam intensity distributions, obtained at different accumulated energies, were stored in the LiF crystal and acquired as luminescent images by a fluorescence optical microscope. An algorithm was developed for reconstructing the beam transversal intensity distribution and evaluating the corresponding X-ray fluences. The obtained results are promising for using solid-state LiF passive detectors as diagnostic tools of XFEL beams, as well as for imaging experiments requiring high spatial resolution and large dynamic range within a wide field of view.

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