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Design concepts of a new imaging system for a high-intensity XUV source beam by colour centres excitation in lithium fluoride crystals

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Abstract. Stable colour centre production in lithium fluoride (LiF) crystals can employ as a high-spatial-resolution imaging tool for extreme ultraviolet (XUV) irradiation, as well as the possibility for images of the unfocused beam and the beam focused by a multi-layer mirror.
The LiF crystal sensitivity has sufficient to impress high-contrast photo-luminescent patterns with XUV single-pulse irradiation on an area up to $40mm^2$. The suggested imaging technique, using LiF as a detector, can contribute to reducing the lack of sufficient knowledge for XUV beam characterization and profile featurization which can open a very wide range of XUV metrology and tomography applications.
The experimental results explain the concepts of detection of high-intensity source at13.5nm using a YAG:Ce scintillator crystal embedded with a CMOS camera, additionally using LiF as a 2D high-resolution detector, and the work shows investigations outcomes and improvement procedure and analysis.
The results demonstrate the potential of LiF crystals as a sub-micrometre resolution two-dimensional imaging tool for XUV irradiation applications. Moreover, the research study explains the optimization sequences of the new imaging technique that will play an important role to predict the achievable spot size, geometry, beam profile and intensity distribution, as well as the characterization complexity of XUV source features.

1. Introduction

High-energy ultraviolet radiation (i.e., EUV or XUV "Extreme ultraviolet radiation") is electromagnetic radiation in the part of the electromagnetic spectrum which has promising and advanced applications, especially in the definition of the new wavelength for semiconductor lithography within the XUV range, additionally, the deep understanding and detection of technology-based high-energy ultraviolet radiation are important in solar atmosphere studies. One of the classical and available techniques for detecting and measuring the XUV beam and its spectral distribution spatially is the method based on single diffraction imaging, although the spatial resolution of the contemporary imaging system is not sufficiently high - it is in the scale of ~ 10 microns [1], [2], [3].

Therefore, the new approach is based on LiF crystals (or films) and the unique dynamic of colour centre (CC) formation inside it which opens the door for new imaging tools with single-shot in situ imaging as well as opportunities for performing a high-quality images [4], [5]. This new kind of detection system has also more stable to direct intense XUV radiation compared with the other available systems besides the ability to provide good-quality measurements of high-intensity beam distribution in the focusing position (or out-of-focus locations, as well) and characterization of the spectral and spatial of the target beam.

Moreover, several CCs generated in LiF are stable at room temperature (RT), which is very important for various applications. The band gap is about 14 eV, which is the largest among all other alkali halides or dielectric materials. This means that CCs cannot be easily generated by visible and near UV radiation (unless at extremely high intensities and involving multiphoton absorption processes), so a LiF-based detector does not require any filter for protection from such radiation [4].

The present work provides a systematic investigation to design the required imaging system based on LiF crystal as an XUV detector and explains the detailed challenges of writing stages for high-intensity setup at Fraunhofer-Institute for Laser Technology ILT (ILT-Aachen) to achieve the desired measurements as well as the suggested solutions for some technical issues.

2. Technical setup

The assembled setup of the table-top high-intensity 13.5nm system is shown in Figure 1. The source is connected to a six-way-cross vacuum chamber. Via this chamber, several measurement devices, a turbomolecular pump, and gas inlets for venting are connected to the setup. The chamber also contains the optical shutter and feedthrough for the control cable of the shutter.

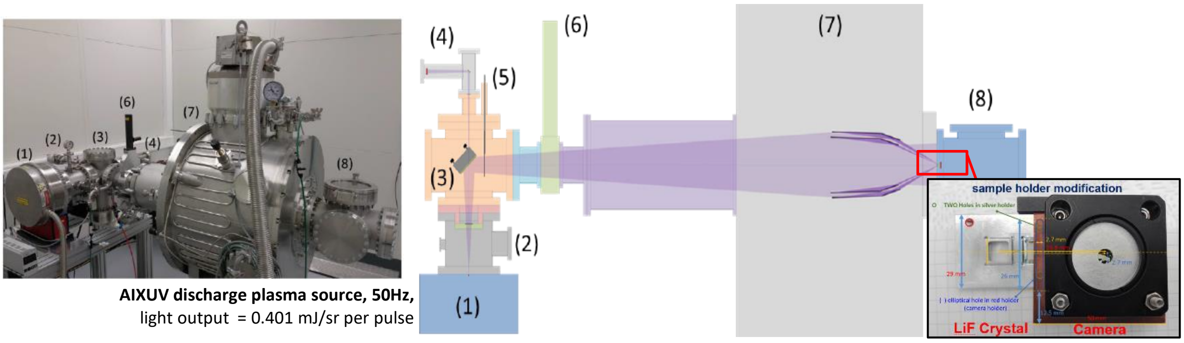

Figure 1: Photograph and scheme of the experimental setup at ILT with (1) source, (2) 6-way-cross connector, (3) multilayer mirror, (4) reference diode, (5) removable collector blocker (not visible in the photograph), (6) gate valve, (7) collector chamber and (8) sample chamber. Not shown here is the control rack for the source.

The six-way cross is connected to the chamber that contains the multilayer mirror. The mirror is mounted on a mirror holder that allows to precisely adjust the tilt of the mirror in all directions. The holder itself is mounted on a base that additionally allows for adjusting the height and position of the mirror. The chamber with the mirror also contains a collector block that can be moved in and out of the beam path. The collector block is an aperture that allows for direct illumination of a sample while blocking the light to the collector.

As a light source, an AIXUV discharge plasma source with a repetition rate of 50 Hz was used. The expected emission spectrum of around 13.5 nm for operation with xenon can be seen in Figure 2(a). The light output for this type of source has been measured to be 0.401 mJ/sr per pulse within a 2% bandwidth of around 13.5 nm [6]. Noteworthy, 2 % bandwidth here means a wavelength range of 1% times the central value in both directions around this central value (for λ = 13.5 nm, it is the wavelength range from 13.365 nm to 13.635 nm). This value includes self-absorption in the xenon that leaves the source together with the light.

A molybdenum/silicon multilayer mirror optimized for 13.5 nm was used to filter a smaller band around the desired EUV wavelength. Choosing an incidence angle of 45° on the mirror allows deflecting

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the beam by 90°, thus making the setup more compact. The mirror was produced at the Fraunhofer Institute for Material and Beam Technology (*Fraunhofer-Institut für Werkstoff- und Strahltechnik* "IWS") which quotes a peak reflectivity of 35-36 % at 13.5 nm.

As the mirror is also highly reflective in the VIS (cf. Figure 2(b)), a 200 nm thin zirconium foil (cf. Figure 2(c))) is inserted (with a CCD camera) into the beam path to absorb light with longer wavelengths. The reflectivity of the multilayer mirror $R_{\mathrm{ML}}(\lambda)$, the transmission of the zirconium foil $T_{\mathrm{Zr}}(\lambda)$ and the total transmission of the combination of mirror and foil (i.e., $R_{\mathrm{ML}}(\lambda)\cdot T_{\mathrm{Zr}}(\lambda)$) are shown in Figure 2(a).

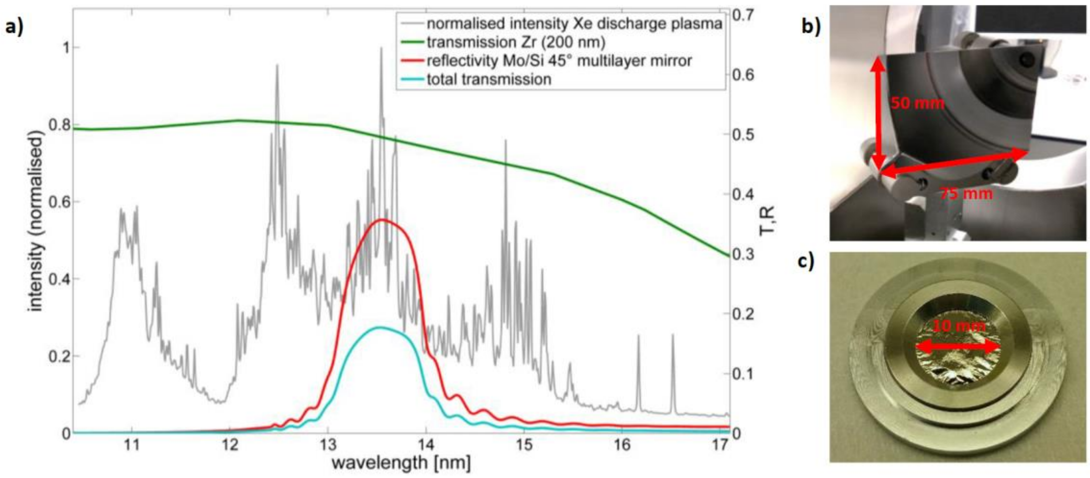

Figure 2: (a) Normalized spectral intensity of the xenon discharge plasma measured at a source of the same type as the one used in this setup, transmission of a 200 nm zirconium foil, reflectivity a of molybdenum/silicon multilayer mirror optimized for an incidence angle of 45° and the total transmission of the last two combined; for the multilayer reflectivity, interdiffusion layers between the molybdenum and silicon layers with a thickness of 1.1 nm (RMS) have been considered to match the peak reflectivity with the manufacturer information [7,8]. **(b)** Photograph of the multilayer mirror and its holder; **(c)** Photograph of the zirconium foil within its mounting ring.

3. Investigated results

The intensity distribution of the focused/out-of-focused high flux setup beam at 13.5 was measured using scintillator plate detectors (YAG-Ce Scintillators) as shown in Figure 3(a) and Figure 3(b), that has performance-limiting effects because of loss of spatial resolution due to divergence of the scintillation light as well as reduction of the outcoupling efficiency due to total internal reflection.

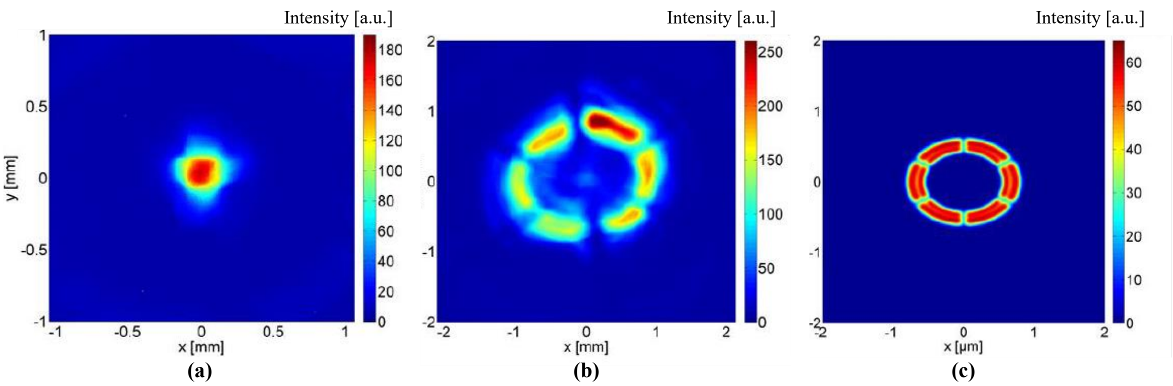

Figure 3: (a) CMOS image (with 0.03 % neutral-density filter) of the light spot in the focus plane with a square LED at the source position; the spot FWHM (in x- and y-direction) is around 300 µm. **(b)** image (with 1 % neutral-density filter) of the light spot a few millimeters behind the focal plane. The spot is elliptical and the intensity is shifted towards the top-right corner of the spot. **(c)** Simulation of the light spot 1 mm behind the focal plane with a radius of curvature of the multilayer mirror of 10 m in x-direction.

The CMOS camera images can help to find the beam and give an initial low-resolution image of the beam profile. Figure 3(c) gives the ideal based on Simulation within Zemax OpticalStudio.

Together with the known xenon spectrum $I_\lambda(\lambda)$ and frequency f of the source, its light output within a 2% bandwidth around 13.5 nm and the total spectral filtering $R_{ML}(\lambda)\cdot T_{Zr}(\lambda)$, the effective power per solid angle of the source (P_Ω) is 4.8 µJ per pulse (before collector). The total energy flux based on a 13.5 nm high-intensity setup, was calculated for one, 50 and 3000 pulses, as shown in Figure 4, to understand the whole energy flux during a specific exposure time. The first experiment was done for irradiation of the LiF crystal through a specific time duration (at ~1 second or 60 seconds), and the initial experimental outcome was unpromising with exposure time ≥ one second.

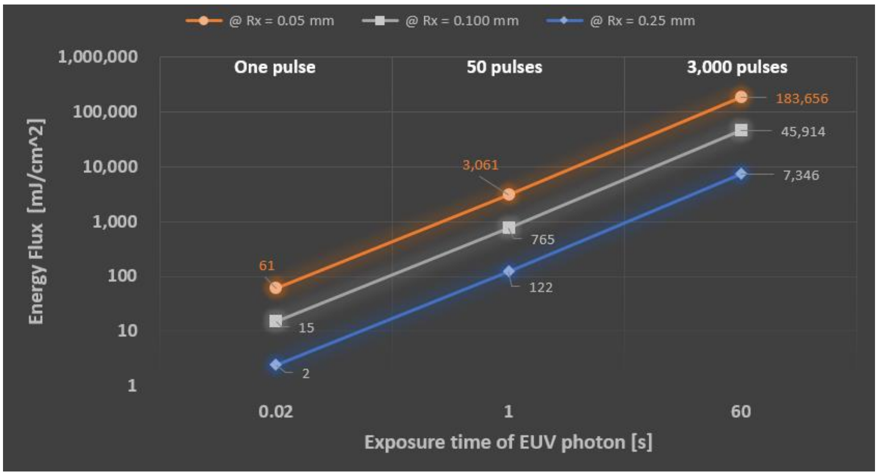

Figure 4: Total energy flux of High-Intensity Setup @ 13.5 nm at different time durations.

The preliminary results based on the colour centres excitation in lithium fluoride crystals were set up as shown in Figure 5. It is clear how one can observe the initial beam profile near to focusing position or out-of-focus.

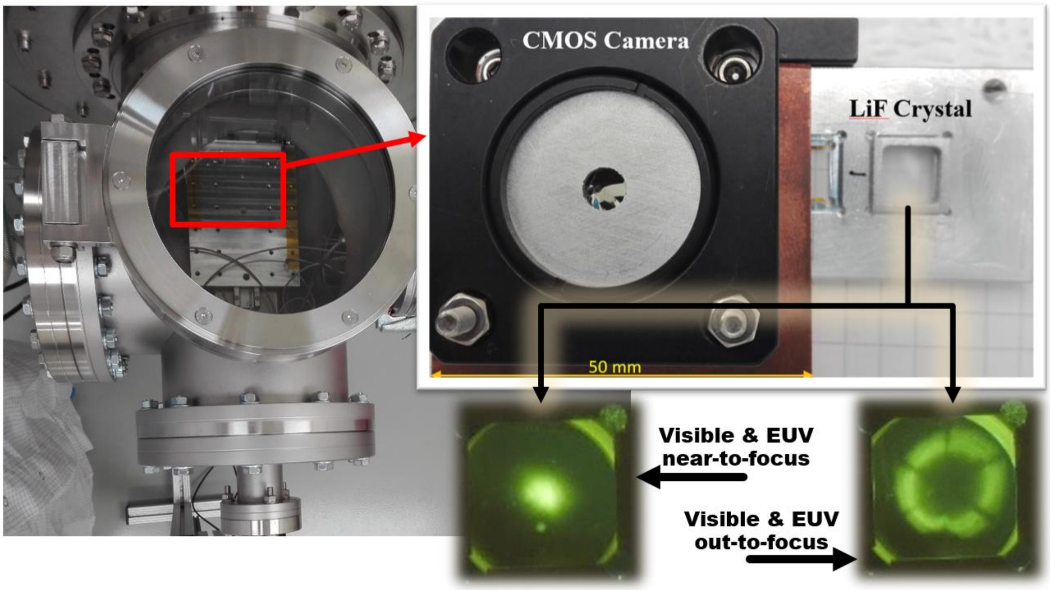

Figure 5: Initial observation of the focused visible and EUV beam propagation through and out of the waist inside the LiF crystal.

A more deep analysis will be required to realize the fluorescence quenching boundary and the dynamic of the colour centre under EUV exposure. It should be noted that, in principle, fluorescence quenching may arise at high irradiation intensity due to the nonradiative decay of the electrons from the valence band, leading to a nonlinear response of the crystal to the EUV or x-ray flux. Figure 6 shows the boundary of the calculated value of fluorescence quenching, and permanent fluorescent patterns for F_2 and F_3^+ defects in LiF crystal that can be produced by using several EUV or x-ray sources in different configurations (such as contact mode).

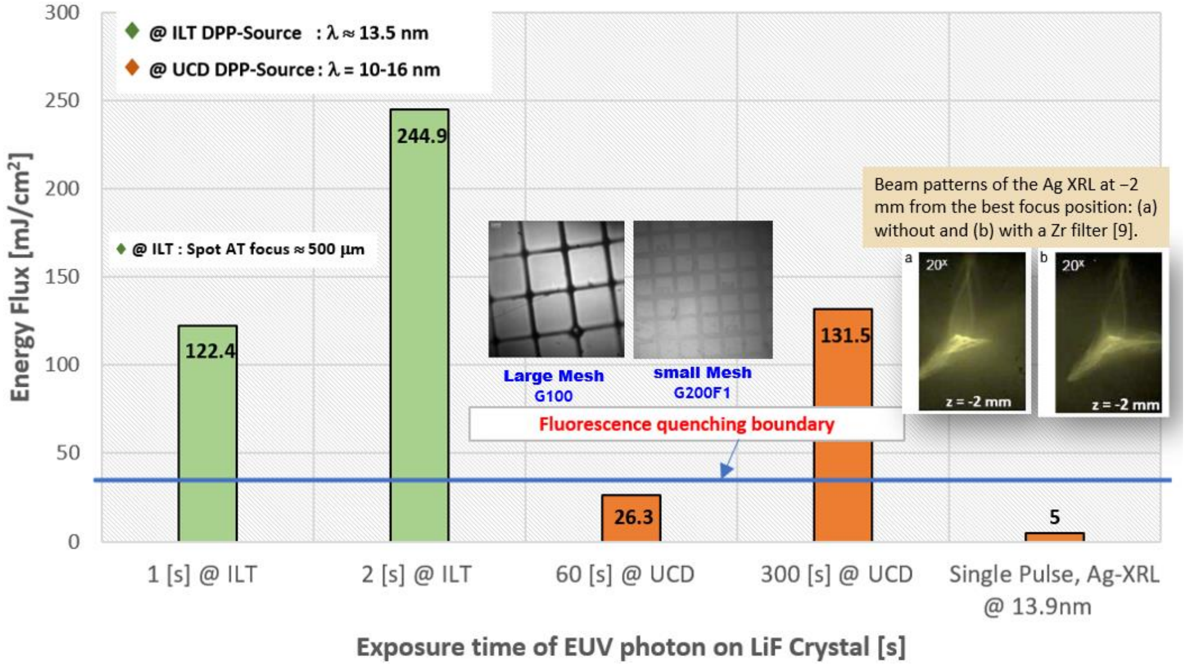

Figure 6: The energy flux values generate at, 13.5nm high-intensity setup at institute of laser technology (ILT- RWTH Aachen University), EUV-setup a University College Dublin (UCD), and soft X-ray laser (SXRL-Japan facility).

4. Conclusions

In this work, we show the preparation and systematical procedures to use LiF crystal as EUV-detector, which is already known as a very powerful tool to detect the soft x-ray spectral range, effectively employ in situ (i.e., the detector placed in the propagation direction of EUV beam at near as can to the focusing position).

The boundary value of fluorescence quenching shows the necessary experimental modification to verify the single-shot measurements, or use millisecond digital shutter for single pulse studies and imaging that can achieve sub-micrometre resolution in situ imaging of the focus pattern of High Flux Setup-ILT at 13.5 nm.

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