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Predicted Performance of the LCLS X-Ray Diagnostics

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Introduction

The purpose of the LCLS x-ray diagnostics is to support and verify independently from the electron beam-based alignment procedure the performance of the LCLS. The x-ray diagnostics consists of tools for measurements and analysis of the spectral and spatial characteristics of spontaneous and SASE radiation along the undulator line. The main goal is to measure the absolute flux of x-rays as a function of the distance along the undulator line. Furthermore, the diagnostics permits to verification of the overlapping of radiation cones from different undulator segments.

Undulator cell structure

The LCLS undulator line is designed as a set of standard cells shown schematically in Fig.1. Each cell consists of three 3.24-m long undulator segments with two 187 mm separation breaks and one 421 mm separation between undulators. The short breaks are filled with a focusing or defocusing lens, an electron BPM and a steering coil. The last break includes additional x-ray diagnostics set-up.

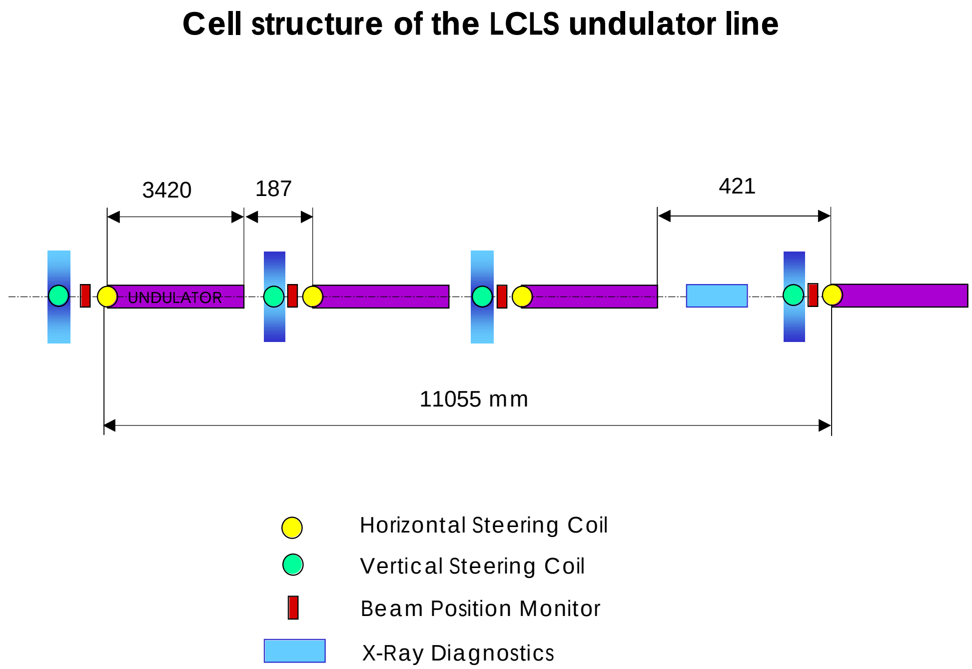

Figure 1. Structure of a standard cell.

X-Ray diagnostics specifications and experimental set-up

In order to utilize X-ray diagnostics efficiently and meaningfully it should satisfy the following requirements:

- one shot sensitivity for all types of spectral, flux and spatial measurements;
- several microradian angular resolution;
- accuracy of the absolute flux measurement better than 10%;
- many orders of magnitude in the dynamic range.

The experimental set-up that meets all the above requirements is shown on Fig.2. It consists of a 200-μm-thick diamond (111) crystal monochromator, x-ray CCD cameras and a PIN diode. The monochromator has a bandpass of 10^{-4} and can analyze x-ray radiation in the energy range between 4 to 9 keV. Combination of the monochromator and the CCD camera as an area detector are used for the spectral and spatial (angular) measurements, whereas the combination of the monochromator with the PIN diode provides the absolute flux measurements along the undulator line.

(The OTR part of the diagnostics will be described in a separate report later.)

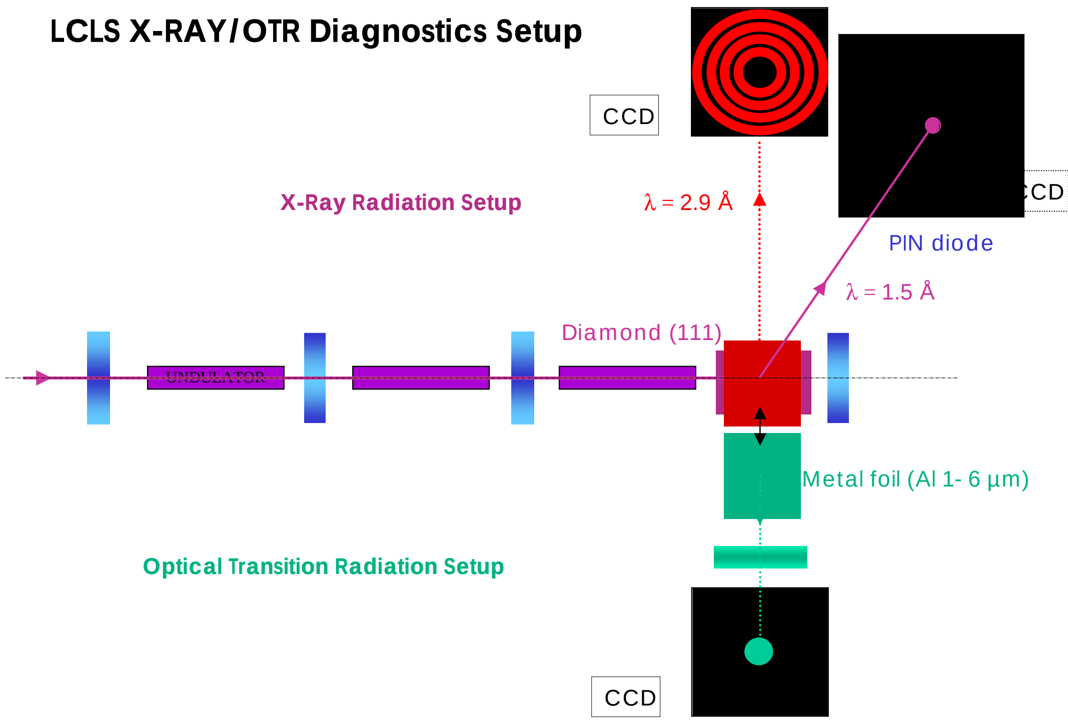

Figure 2. Diagnostics Setup.

On-axis x-ray diagnostics

The purpose of the on-axis x-ray diagnostics is to measure, in absolute units, the increase in the spectral flux along the undulator line and provide information about the spatial distribution of radiation. In order to analyze the performance of the on-axis x-ray diagnostics a set of calculations has been conducted with the program SRW for near and far field cases.

For on-axis x-ray diagnostics, the monochromator is set at a Bragg angle of 21.35 degree, which selects the fundamental undulator harmonic at the energy of 8.27 keV. Calculations of the spectral flux generated by the undulator cell and transmitted through the monochromator yield $5\cdot10^6$ ph/shot, or 1.6 nC charge registered by the silicon PIN diode. A cooled silicon PIN diode could detect a single x-ray photon. The dynamic range of the PIN diode covers ten orders of magnitude without any additional filtering.

X-ray diagnostics setup will provide absolute (within 10%) measurements of spectral flux after each undulator cell. The growth rate could be derived from the measured flux at consequent diagnostics stations. The growth rate of the flux is a reliable source for the evaluation and study of the development of the SASE process.

The spatial flux distribution for one undulator cell is the superposition of radiation from three undulators. In order to evaluate the sensitivity of the x-ray diagnostics to the angular misalignment of undulators, e-beam trajectories in the first and third undulators in the cell have been missteered by an angle θ_{mis} (Fig.3). A series of calculations of spontaneous radiation cell have been performed for nominal electron beam emittance of 0.05 nm·rad at a photon energy of 8.29 keV and at a distance of 60 m from the undulator. The results of these calculations are shown in Figs. 4 and 5. It is quite obvious from these data that at least 4 μrad angular resolution could be easily achieved if one would use the diagnostics station far enough from the undulator cell and introduce the necessary trajectory bump.

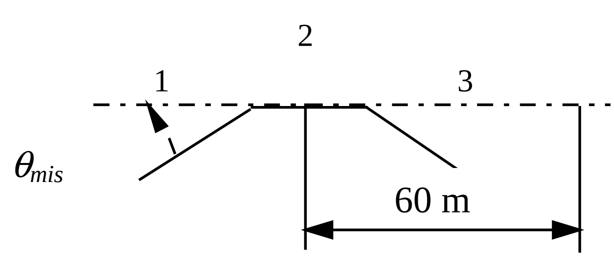

Figure 3. Undulator trajectories in the cell

Measurements of the spatial distribution of radiation generated in each undulator cell will compliment the electron beam-based alignment, but will not substitute it. X-ray diagnostics will be very useful especially in the first steps of the beam-based alignment procedure.

Knowing the calculated flux distribution and the efficiency of x-ray diagnostics one can estimate the sensitivity of the system, which was found to be $5\cdot10^2$ electrons/pixel/shot for a 7x7 µm pixel CCD This exceeds the noise level by three orders of magnitude. Appropriate filtering in front of the CCD will keep the flux in the last diagnostics stations within the dynamic range (about 10^5 e^-) of the detector.

In the case of on-axis diagnostics the e-beam will always hit the diamond crystal in one of the engaged diagnostics stations. The e-beam energy loss in a 200-µm-thick diamond crystal is equal to 0.25 MeV/particle and independent of the 4.5 or 14.5 GeV particle energy. As a result, a 1 nC e-beam deposits 30 mW average power for 120 Hz repetition rate. The finite element analysis shows that the use of the most simple cooling design (clamped crystal, no coolant) will lead to 0.06 µrad slope error on the crystal, which is negligibly small compared with the 10 µrad width of the crystal rocking curve. After exiting the crystal, the e-beam will have an angular spread of 40 µrad (rms).

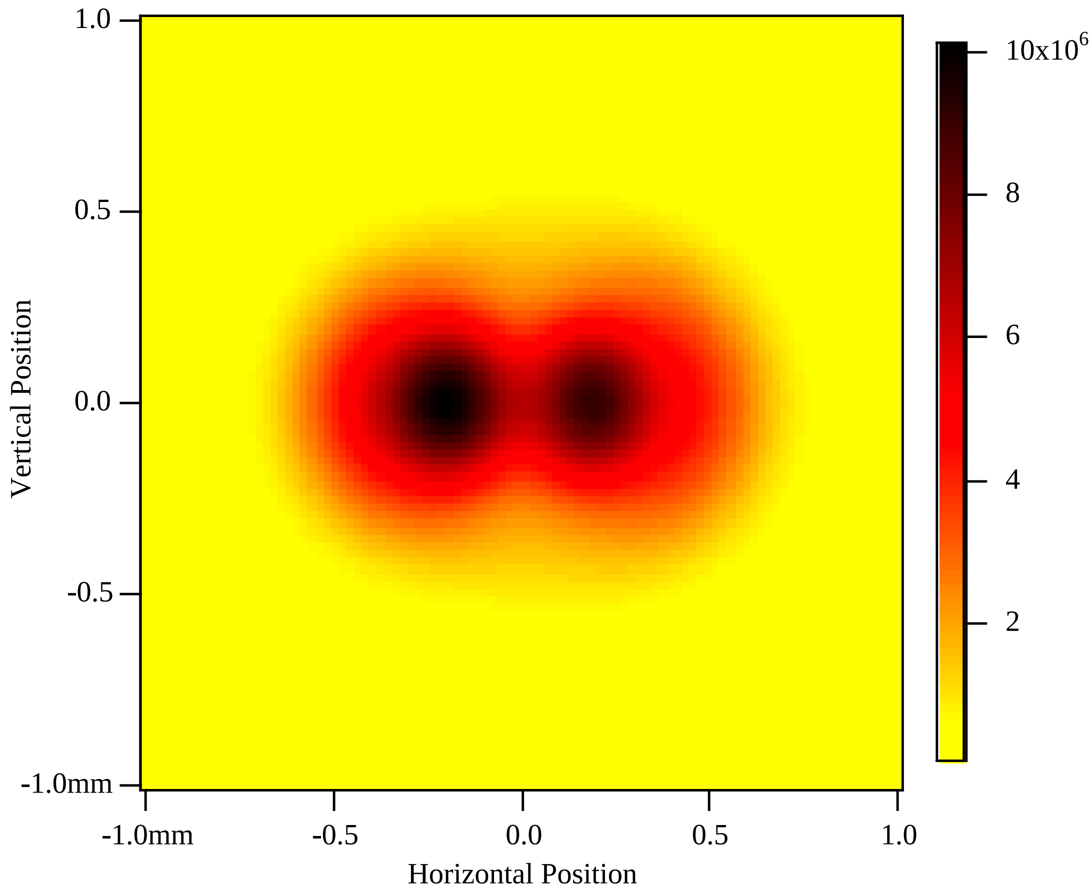

Figure 4. 8.29 keV, θ_{mis} = 4 μrad, 0.05 nm·rad, 60 m.

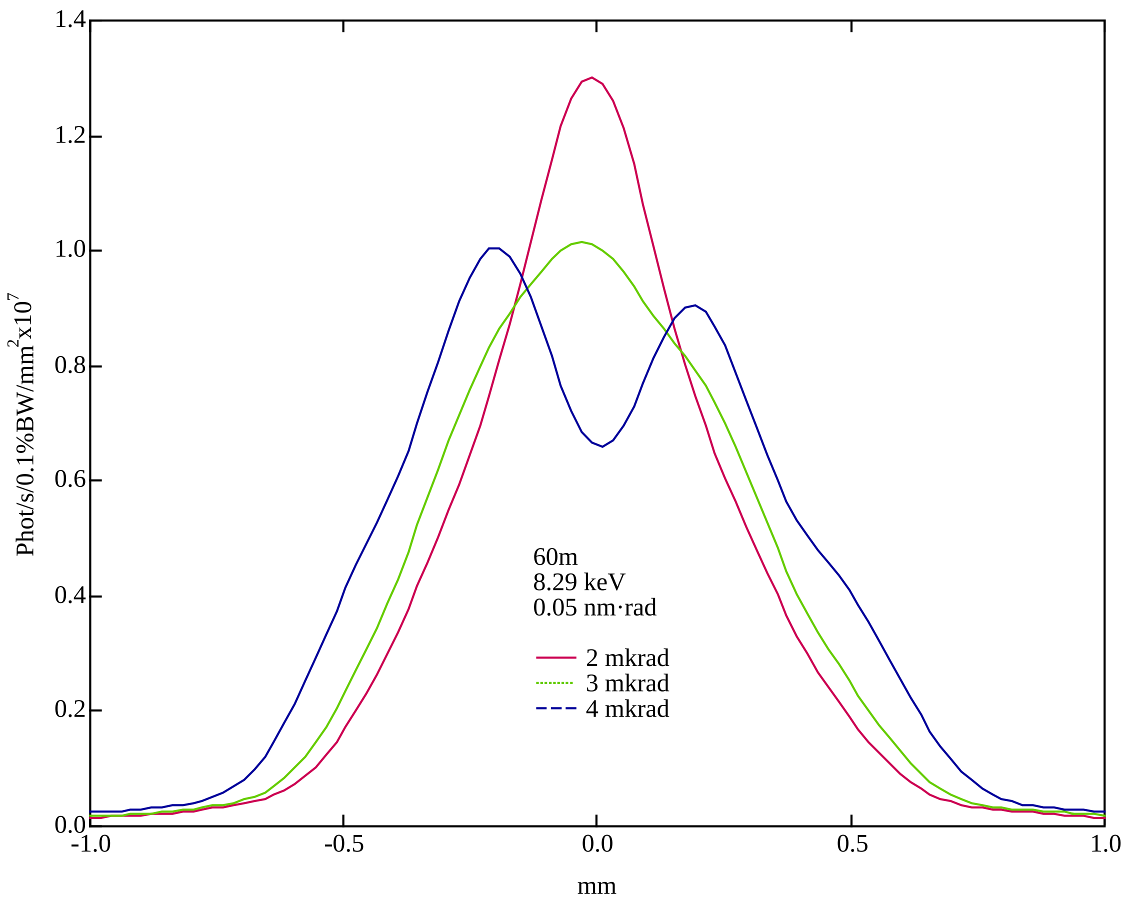

Figure 5. Horizontal profiles for θ_{mis} of 2, 3 and 4 μrad.

Off-axis x-ray diagnostics

The off-axis, "red-shifted" x-ray diagnostics is complimentary to the on-axis diagnostics. The crystal monochromator in this case can have a small hole to let the e-beam go through, unperturbed. It allows to observe radiation from each undulator cell without any trajectory distortion. A similar technique was successfully implemented for the LEUTL diagnostics, where a mirror was used instead of the crystal.

For the "red-shifted" radiation of 4.25 keV, the crystal monochromator has a Bragg angle of 45 degrees and the angle between the CCD camera and radiation is 90 degrees. The results of the calculated spatial distribution of undulator radiation at a distance of 6 m from two undulators are shown on Figs. 6 and 7. The intentional angular misalignment angle θ_{mis} =10 µrad has been introduced in the trajectory in this case.

Calculation of the detection efficiency shows that the CCD camera will get $4 \cdot 10^2$ e^-/pixel per one shot for the 20x20 μm^2 size pixel, which again is at least two orders of magnitude higher than the CCD noise level.

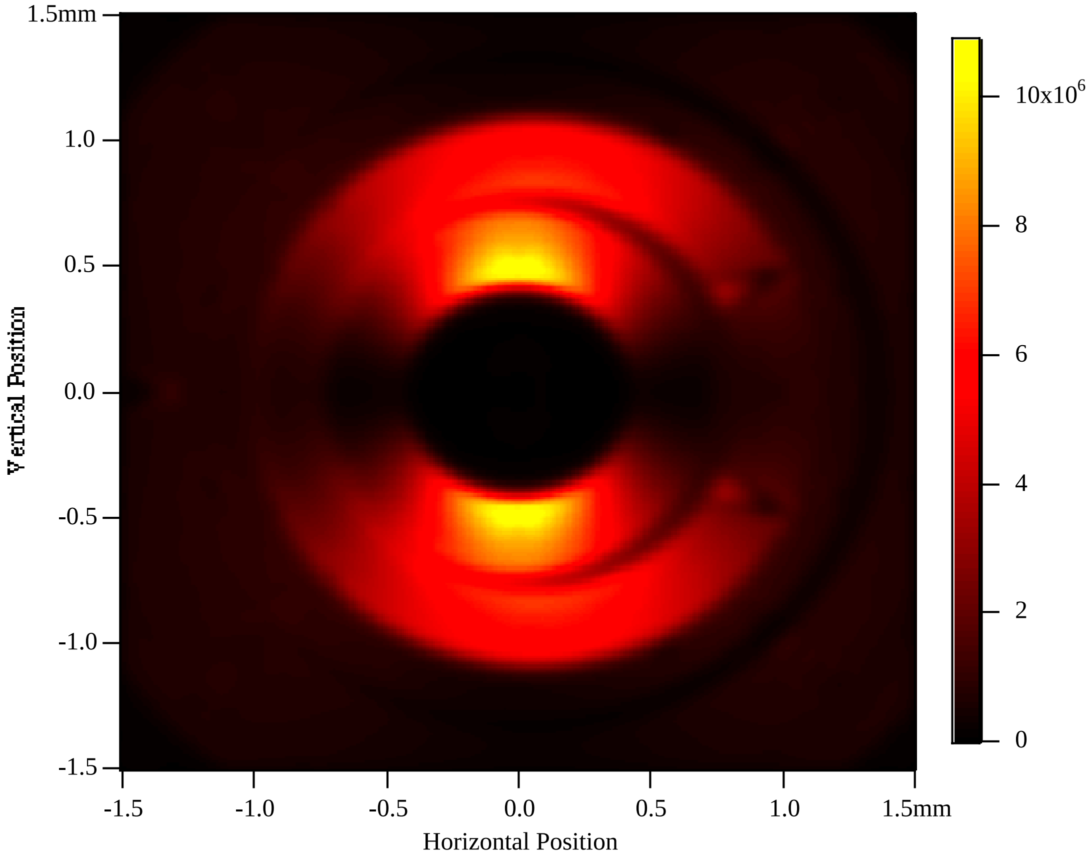

Figure 6. 6 m, 4.25 keV, θ_{mis} = 10µrad

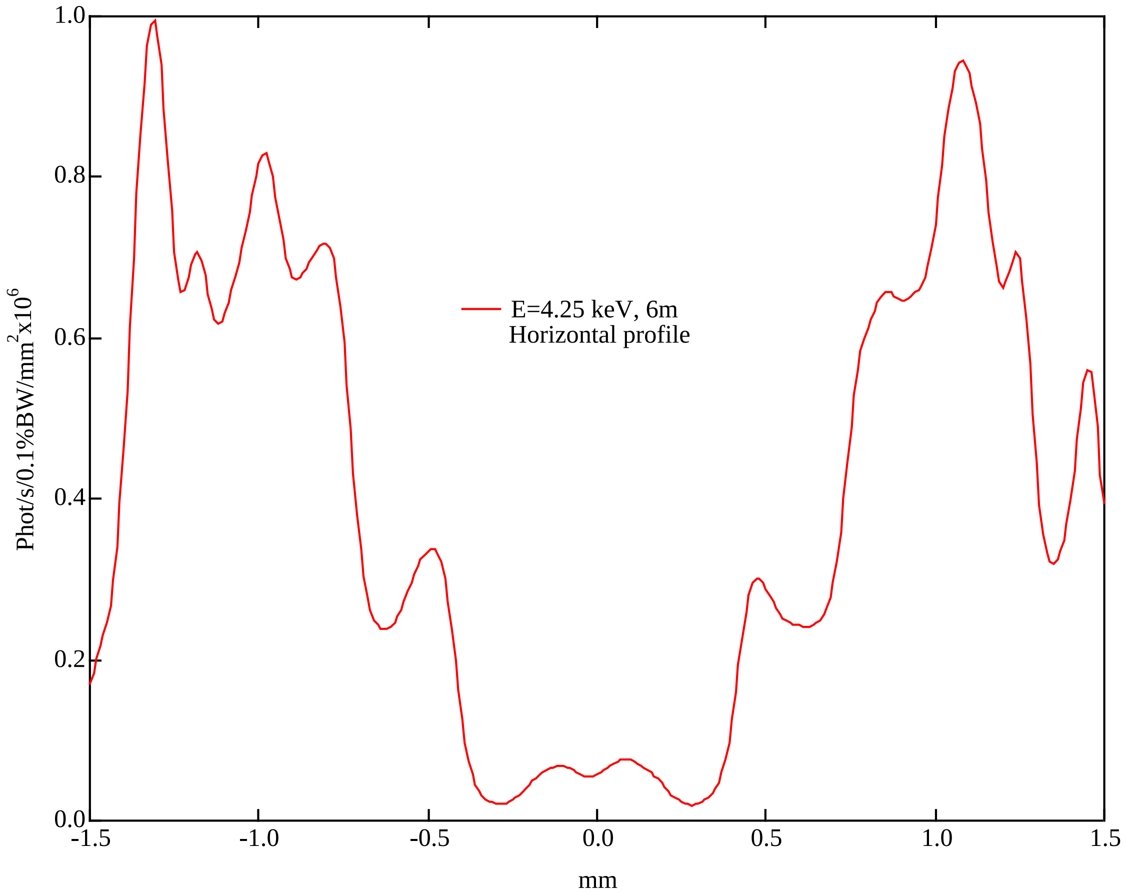

Figure 7. 4.25 keV, horizontal proflile, θ_{mis} = 10μrad.

Emittance influence

The influence of the beam emittance on the spatial distribution of radiation has been studied. The results are shown in Figs. 8, 9 and 10.

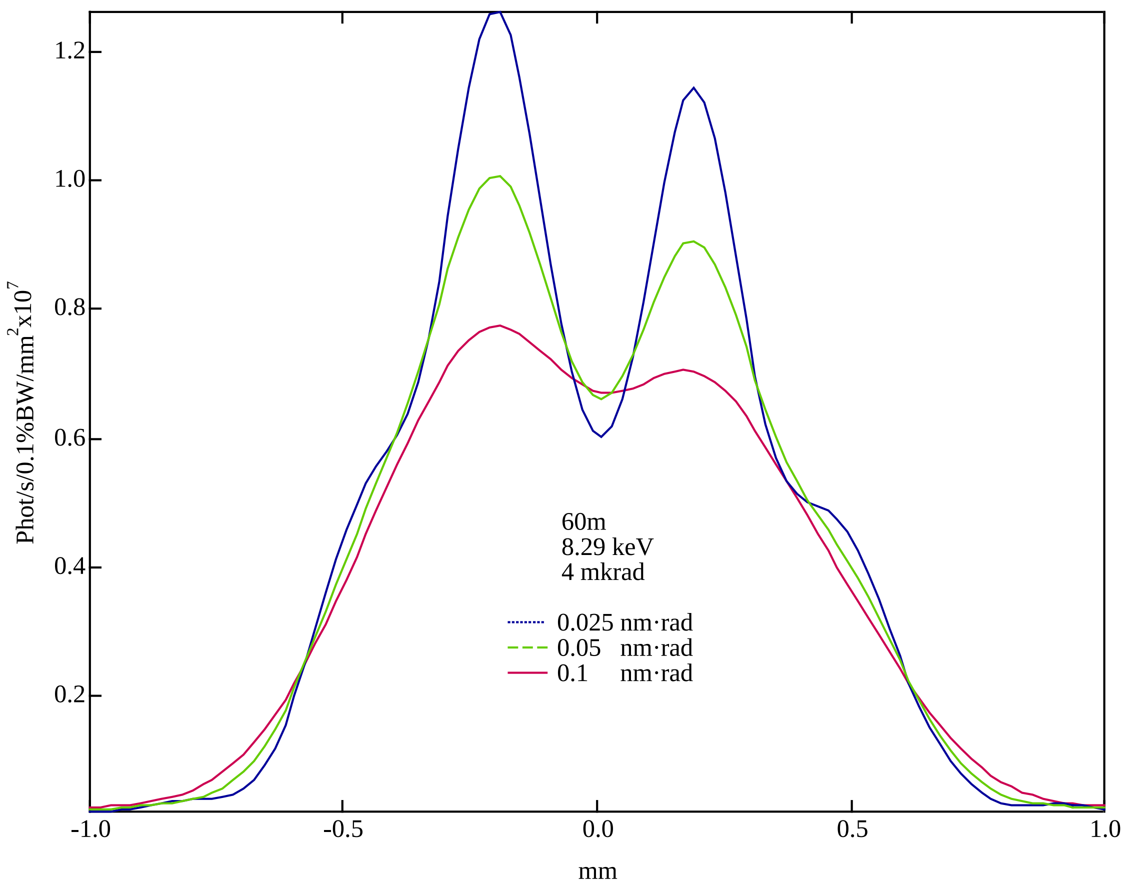

Figure 8. 8.27 keV, different emittances, $\theta_{mis.}$ = 4 μrad.

A spatial intensity distributions and horizontal profile at 60 m and a photon energy of 8.3 keV (detuned from the fundamental to high energy) for the cell structure where the first and third undulator are misaligned by 10 µrad, each, is shown in Figs. 10 and 11. Differences between 0.025, 0.05 and 0.1 nm·rad emittances could be clearly observed.

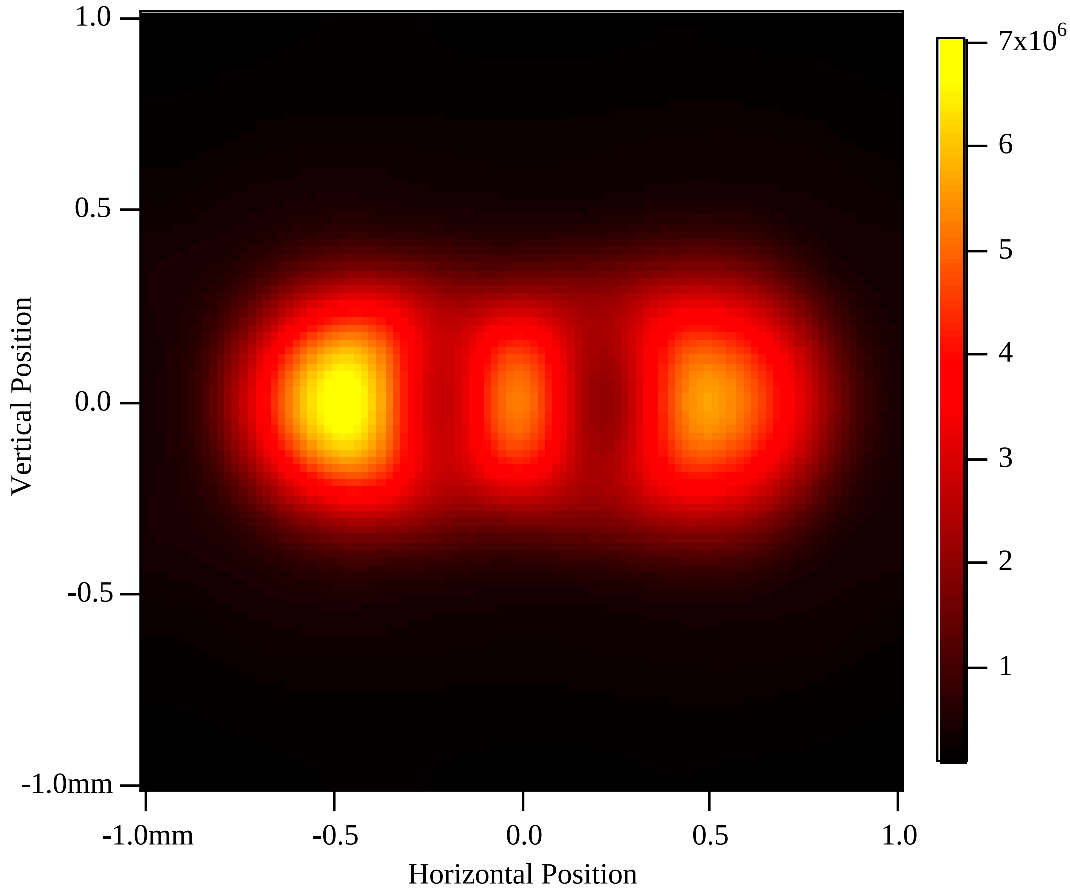

Figure 9. 8.3 keV, 0.05 nm·rad, $\theta_{mis.}$ = 10µrad

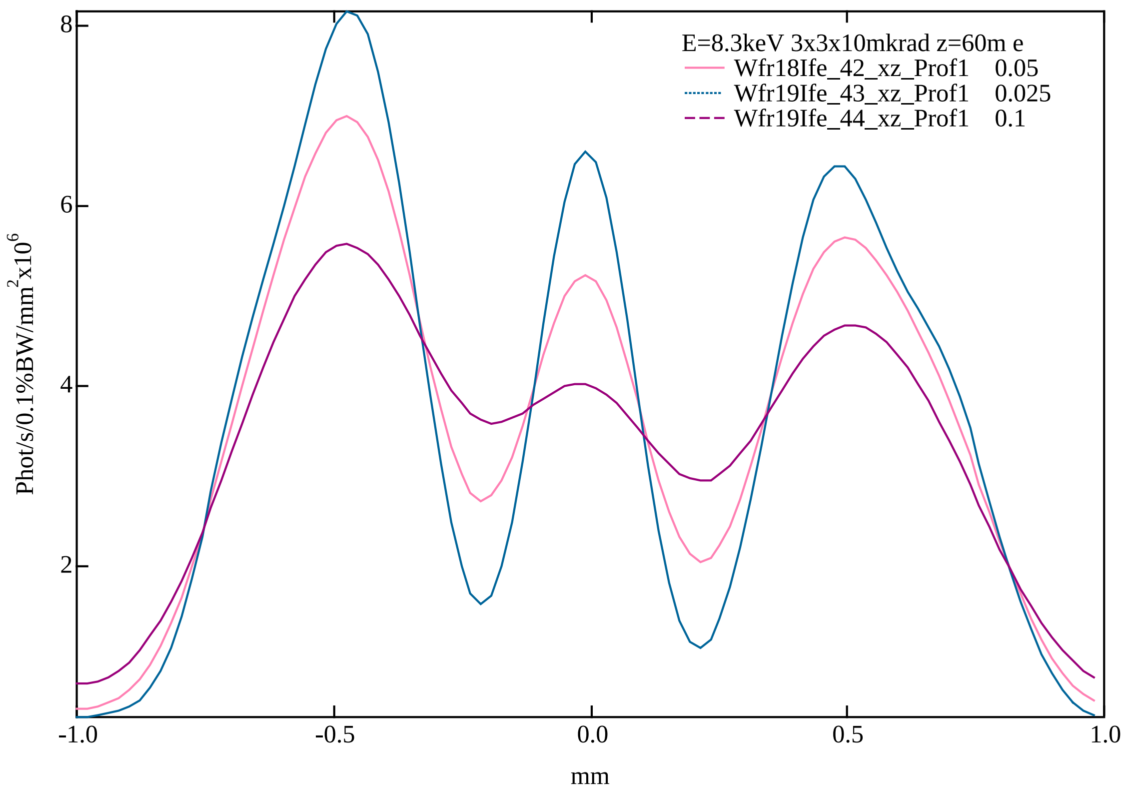

Figure 10. 8.3 keV, θ_{mis}. = 10μrad, horizontal profiles for different emittances.

Conclusions

The LCLS x-ray diagnostics will be a valuable tool that will support and independently verify the e-beam-based alignment. It will also provide feedback for the fine tuning of the undulator matching and verification of the development of the SASE process along the undulator line.

Acknowledgements

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