The spatial contrast challenge for intense laser-plasma experiments

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Abstract. Achieving the highest peak intensity possible is a key requirement of a majority of laser-plasma experiments. This requires confining laser energy to a small volume. The experimental determination of the spatial focus distribution is therefore important, especially to connect theoretical and experimental results. In this paper, we revise a new method to evaluate the spatial performance of a laser focus. Obtaining low- and high-dynamic-range (LDR/HDR) images of the laser focus profile is described for a typical high-intensity laser setup, and present data from our case study. We compare standard evaluation procedures based on both images quantitatively and determine the accuracies and associated errors. A spread out intensity distribution below the detection limit of the LDR is observed in the HDR acquisition. Our evaluation reveals that only considering LDR can overestimate the enclosed energy as well as the peak intensity by factors of 1.5. With our method we estimate the required dynamic range for this case to 4 orders of magnitude. Our discussion sheds light on possible causes for the deteriorative effect to targets in the vicinity of the primary focal spot.

1. Introduction
Laser systems exceeding one peta-watt (PW) peak power have started operation or are currently under construction. Achieving intensities beyond $10^{21}\text{Wcm}^{-2}$ will become possible on a regular basis, which is of interest for applications of laser-plasma interactions, such as laser-driven ion acceleration [1], laser-driven electron acceleration [2] or high harmonic generation [3]. An accurate measurement of the laser fluence profile in the target plane is typically used to derive a spatial intensity distribution, peak intensity and the energy enclosed in focus. These quantities are essential for simulations and analytical models that supplement experimental data and steer future experiments. These laser-parameters have also particular impact on establishing and extrapolating analytical models and scaling.

Peak intensity of a laser focus might be in future determined by measuring the phase after the focus [4] or by measuring the ionization induced by the laser field [5]. The most common method is based
on imaging the focal plane onto a camera chip [6] and recording the attenuated, time-integrated laser fluence distribution $F(x, y)$, which is typically normalized $\int F(x, y) dx dy = 1$. Analogously, the temporal intensity distribution $f(t)$ is usually obtained from Frequency Resolved Optical Gating (FROG) measurements [7], providing typically a few orders of magnitude dynamic range with fs resolution, or autocorrelation measurements [8], offering many orders of magnitude dynamic range with typically ~>100 fs resolution. Assuming the spatio-temporal intensity distribution to be separable and $I_0$ as the peak intensity, $I(x, y, t) = I_0 F(x, y) f(t)$. A Gaussian or a $\text{sinc}^2$ distribution can be fitted to the data, and the full width at half maximum distributions (FWHM) $d_x$, $d_y$, and $\tau$ obtained.

In practice it is not necessary to make an assumption for the distribution function. Instead, the focal spot image is numerically evaluated and required to fulfill $\int I_0 F(x, y) f(t) dx dy dt = E_L$, with $E_L$ being the laser energy. It is immediately obvious that the dynamic range with which the spatial (and temporal) distribution is obtained will influence the determination of the peak intensity. Here, we concentrate on evaluating the spatial intensity distribution but note, that the methodology can be transferred to the temporal domain for low temporal contrast systems.

2. Case Study
The data have been acquired at the Advanced Ti:Sa LASer system (ATLAS), during operation at the Laboratory of Extreme Photonics (LEX-Photonics) in Garching bei Muenchen, Germany. The system runs at a central wavelength of 800 nm and is capable of delivering 25 fs pulses with 2 J on target at a repetition rate of up to 5 Hz.

Figure 1. Case study setup. Raw images acquired with different filter settings are shown in the inset. The strongest filtered image is magnified 5 times relative to the others. Figure made using [9].

Figure 1 shows the experimental setup. Prior to re-compression, the wave-front of the pulse is corrected by a deformable mirror (DM). The laser beam can be attenuated with a combination of neutral-density filters with extinction ratios of 0.3, 0.5 and 1 order of magnitude, and a dielectrically coated mirror filter with an extinction of 7 orders of magnitude. It is then guided via six mirrors through an evacuated laser beam delivery into the experimental chamber, in which a $f/2$, $f = 20\,\text{cm}$, 90° off-axis parabolic mirror (OAP) focusses the laser. A vacuum compatible magnification images the focus onto the complementary metal–oxide–semiconductor (CMOS) camera chip UI-5241-LE [10], with an analog-digital conversion of 10-bit corresponding to a dynamic range of three orders of magnitude, assuming ideal signal to noise ratios.
Focal spot images are recorded with an attenuated laser beam. The filters are set such, that the dynamic range provided by the camera is well exploited. We define such an image, if it has less than three orders of dynamic range, as low-dynamic-range (LDR).

The high-dynamic-range (HDR) approach starts with this LDR-setting. The filters are then removed stepwise and a picture is captured for each attenuation. This leads to a deliberate saturation of the focus center, but lifts outer parts beyond the signal-to-noise-ratio (SNR). The images are stacked on top of each other, where slight lateral shifts due to focus jitter or filter usage have to be accounted for. This is done manually for each picture. The contours of line-out distributions for each spatial dimension (such as Figure 2 c) through the image center are compared, and shifted until the best match is achieved. With respect to the previous image, I5 has been shifted 0.8 µm, I6 2.4 µm and I7 17 µm.

As a result of the stacking, the pixels which have been overexposed in the lesser filtered image are replaced by the accordingly scaled values in the follow up (stronger filtered) image. The dynamic range is hence extended in our case by two orders of magnitude. It is practically limited by laser-induced damage (or blooming) of the camera chip.

A line-out of the HDR fluence distribution is shown in Figure 2 c) to demonstrate the process of stacking the images. I1 contains only the information gathered by the lowest filter setting, I2 contains I1 and a second image and so forth. I7 is the final result and is referred to as HDR focus. The dashed blue line indicates the detection limit of the camera chip. It is scaled with the same factors used for stacking the image data on top of each other. The two-dimensional HDR distribution is shown in Figure 2 a).

![Figure 2](image)

**Figure 2.** a) Reconstructed HDR fluence distribution of the laser focal spot, normalized to a maximum of 1. b) Apparent LDR image as it would be observed by a 8-bit camera. c) Line-out through the maximum along the vertical red axis of the HDR-image in a)
In order to suppress noise, a constant pixel value of 47 has been subtracted from the picture, where pixel values < 0 have been set to zero. This results in 95% of the maximum dynamic range of this camera chip being used, which is nearly approaching three orders of magnitude. The indicated detection limit in Figure 2 c) is the equivalent of one pixel value, multiplied with the same scaling factor applied to the corresponding pixel in the fully stacked imaged I7.

In order to compare the differences between the HDR and LDR method, a LDR picture (Figure 2 b) has been derived from the HDR image (Figure 2 a), by setting pixels with values \( P(x, y) < 10^{2.4} \) to zero, thus simulating a typical 8-bit camera acquisition.

**Figure 3.** Energy enclosed in FWHM for evaluations considering a hypothetical dynamic range of the employed camera-chip for focal spot imaging. Dynamic ranges corresponding to typical linear camera A/D converter bit depths are indicated. The error bars indicate values at +/- 5% of the half maximum.

Direct comparison of the HDR and LDR fluence distributions in Figure 2 a) and b) reveal the important additional information obtained by the HDR approach. The lower detection threshold indicates a pedestal with ~ 100 µm in diameter. In order to quantify the impact of detecting this pedestal on determining essential laser pulse parameters, we devised the following method: Using the same procedure that yielded Figure 2 b), we generated images at dynamic ranges from \( 10^1 \) to \( 10^5 \). The energy enclosed in the FWHM diameter \( E_{FWHM} = \frac{E_{>0.5}}{E_L} = \int F_{>0.5}(x, y) dxdy \) has been evaluated for each range and the result plotted in Figure 3. The graph is converging at an inverse dynamic range of \( 10^{-4} \), therefore a single shot image by a camera with 16-bit should suffice to extrapolate meaningful laser parameters for this particular case.

The peak intensity was calculated by dividing the largest fluence value in the processed focus image by the FWHM pulse duration, with \( I_0 = 3.3 \times 10^{20} W/cm^2 \) for the HDR case, and \( 4.8 \times 10^{20} W/cm^2 \) in the LDR case. Considering the LDR only would hence have introduced a systematic overestimation of peak intensity by a factor of 1.5.

3. Discussion
We described a procedure to acquire HDR and LDR laser focus fluence images. Evaluating the HDR image allows to simulate the effect of insufficient dynamic range. In our specific case, a dynamic range of 16-bit seems sufficient for capturing the majority of the energy. We note though, that this procedure is not mathematically strict. It would still allow for a very wide spread contribution at even lower intensity that we would miss. Ideally one should perform an additional measurement to obtain the energy fraction that is indeed contained within the area were the signal is larger than the noise, for example by introducing an appropriate aperture.
We recorded the spatial intensity distribution over five orders of magnitude. Scaled to the estimated peak intensity, the current detection limit still remains as high as $10^{15} \text{Wcm}^{-2} \gg 10^{13} \text{Wcm}^{-2}$, which is the damage-threshold of solid-density plastic targets used in laser-plasma experiments. Our pedestal already has a diameter of $\sim 140 \mu\text{m}$, and it is uncertain if an even larger pedestal below our HDR detection threshold exists.

It is worth noting that, during laser-driven ion acceleration experiments with solid-density plastic targets, we compared shots with target foils facing the laser, with shots where the foil was on the non-irradiated side of the target-holder. For the laser-side case, we observed mm-scale burn spots, whereas if the foil was shielded by the target-holder, the damage to the foil is contained to a small radius around the target-hole. It will be interesting to determine the laser focus pedestal to even lower intensities in the future, in order to investigate potential correlation with target damage.

Assuming a similar focus performance, the transition to even higher intensities leads to significantly larger areas around the laser focus to be exposed to laser induced damages. Depending upon design, solid-density or gas-nozzle target systems might suffer from collateral laser-damage. In the near future achieving laser peak-intensities by focus optimization up to $10^{24} \text{Wcm}^{-2}$ is feasible. As this is eleven orders of magnitude larger than the damage threshold of current targets, monitoring this spatial contrast requires devices of very high dynamic range and therefore is going to become a challenge. Camera chips capable of more than four orders of dynamic range have been developed [11] and are commercially available.

Achieving high intensity requires both good spatial and temporal confinement of the laser energy. The influence of insufficient temporal contrast, for example due to amplified spontaneous emission and coherent contrast is critical to most state-of-the-art experiments, but not necessarily through is impact on estimating the peak intensity. Due to the similarities with our observation, we refer to the topic of this work as the spatial contrast challenge.

For efficient use of PW-lasers, it will be important to identify the sources of the degradation of this spatial contrast. Amongst possible candidates are imperfections in laser-beam transport or final focusing optics. Irregularities on a sub-mm scale are currently not very well identifiable by established means such as interferometry. Using the described method to qualify optics with large aperture, in particular ones with strong curvature (low f# off-axis parabolic mirrors) could become an important tool complementing interferometric surface analysis.

**Author Contribution**

D. H., C. K., T. O., P. H. and S. L. built the experimental infrastructure in LEX-Photonics and designed the experiment setup. D. H., J. H., M. S., J. B., performed the experiment at LEX-Photonics. J.H., J. S., M.S., and J. B. analyzed the data, discussed and interpreted the results and prepared the manuscript.

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