Adjustable temporal contrast for laser plasma experiments at the PHELIX laser facility

F. Wagner[1,2], S. Bedacht[3], C. P. João[4], A. Ortner[3], M. Roth[3], T. Stöhlker[1,2], A. Tauschwitz[5] and V. Bagnoud[1,2]

[1] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*

[2] *Helmholtz Institute Jena, Jena, Germany*

[3] *Technische Universität Darmstadt, Darmstadt, Germany*

[4] *GoLP/IPFN Instituto Superior Técnico, Lisbon, Portugal*

[5] *Frankfurt University, Frankfurt, Germany*

Temporal contrast in laser plasma experiments

The temporal contrast of short laser pulses, which is defined by the ratio of the peak intensity to the intensity at a given time before this maximum, is an important parameter for experiments using ultra-intense lasers. The intrinsic noise in laser amplifiers results in degradation of the temporal contrast, leading to pre-ionization of the target material already a few nanoseconds before the impact of the laser pulse maximum. This early interaction creates a pre-plasma that strongly influences laser-matter-interaction and even compromises several physical phenomena. Some applications such as high harmonic generation from the surface of solid targets [1] or experiments which are based on the interaction with ultrathin targets, e.g. exploring new laser ion acceleration mechanisms [2, 3], cannot tolerate pre-ionization up to a given time before the impact of the pulse maximum. On the other hand in some cases a certain pre-plasma can even improve the outcome of the experiment [4], e.g. due to enhanced absorption and self-focusing effects. Consequently, the optimum pre-plasma depends on the application and an adjustable contrast level is very beneficial for user laser facilities which undertake a wide spectrum of experiments. Different contrast improvement techniques such as plasma mirrors (PM) [5] or cross-polarized wave generation (XPW) [6] are currently applied at several high-power laser systems around the world. However, all these methods either allow for switching between only two configurations, enabling high- and low contrast pulses, respectively, or they even enable just one option that features the highest contrast possible.

We developed a novel technique which allows for continuous tuning of the temporal contrast in petawatt-class lasers [7]. Our method was applied to the PHELIX (Petawatt High Energy Laser for heavy Ion eXperiments) [8] user laser facility at GSI Helmholtzzentrum für Schwerionenforschung GmbH and has been used there as a standard option for the last two years. An arbitrary level of amplified spontaneous emission (ASE) from the standard contrast ratio of 10^6 to an optimum of 10^{11} can be applied and this range can be further extended to an ultrahigh contrast ratio of approximately 10^{13} by combining our technique with an additional plasma mirror. This unique feature of the PHELIX laser enables performing several new experiments of which a few have been carried out within the last 24 months.

Tunable contrast at the PHELIX laser facility

In Fig. 1 a schematic of the PHELIX short pulse beamline is shown. The short (100 fs) pulses from the oscillator are directly amplified in an ultrafast optical parametric amplifier (uOPA). Using a dedicated laser-diode-pumped pump laser [9] which provides 5 mJ pulses at 520 nm with a pulse duration of about 1 ps the oscillator pulses can be amplified up to 100 µJ without any degradation of the nanosecond and picosecond temporal-contrast. These pulses are then amplified in the PHELIX chirped pulse amplification (CPA) system [8] up to maximum energies of 250 J with minimum pulse durations of 500 fs. By focussing these pulses peak intensities between $10^{20}\,\mathrm{W/cm^2}$ and $10^{21}\,\mathrm{W/cm^2}$ are achieved depending on the used focussing parabola.

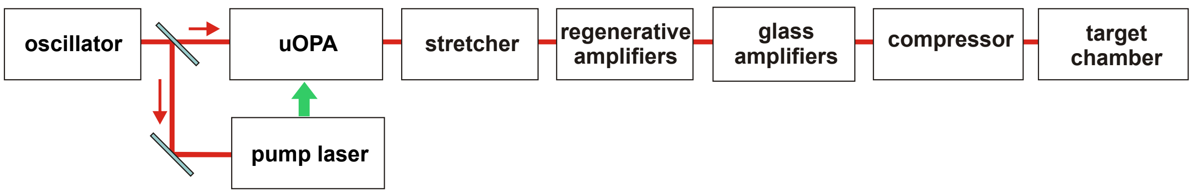

Figure 1: *Schematic of the PHELIX short pulse beamline*

The adjustable ASE level is accomplished by tuning the gain between the ASE-free uOPA and the first of two regenerative laser amplifiers which generates ASE, while the total gain of the system is kept constant. Fig. 2 (left) shows two pulse profiles recorded with a scanning third order cross-correlator (Sequoia, Amplitude Technologies) at an auxiliary compressor after the regenerative amplifiers. When the total gain is provided by the laser amplifiers the pulse profile (red curve) is similar to the profiles measured with standard CPA systems. The ASE level is about six orders of magnitude below the peak corresponding to an intensity of approximately $10^{14}\,\mathrm{W/cm^2}$ clearly above the ionization threshold of any target material (indicated as a coloured bar in the graph). However, when a gain of 10^4 is provided by the uOPA (black curve) the ASE is reduced by four orders of magnitude reaching a contrast level of 10^{10}, which equals the detection limit of the used cross-correlator. Fig. 2 (right) shows the ASE levels that are accessible for different gain values of the regenerative amplifier. A higher gain in the regenerative amplifier corresponds to less gain in the uOPA, and vice versa. The graph shows a nearly linear lowering of the ASE level when the gain of the regenerative amplifier and the uOPA are decreased and increased, respectively. The minimum ASE level which can be achieved with the maximum parametric gain value of 10^5 can be determined by extrapolating the experimental values. Whith this maximum contrast pre-ionization is precluded up to an instant of 100 ps before the peak for most of the used target materials. This measurement shows that an arbitrary ASE level between six and eleven orders of magnitude below the peak intensity can be applied with our particular design of the uOPA. Furthermore it demonstrates that our concept is scalable to even higher contrast values proving its suitability for future laser systems which are aimed at intensities beyond $10^{21}\,\mathrm{W/cm^2}$ and ultrahigh temporal contrast.

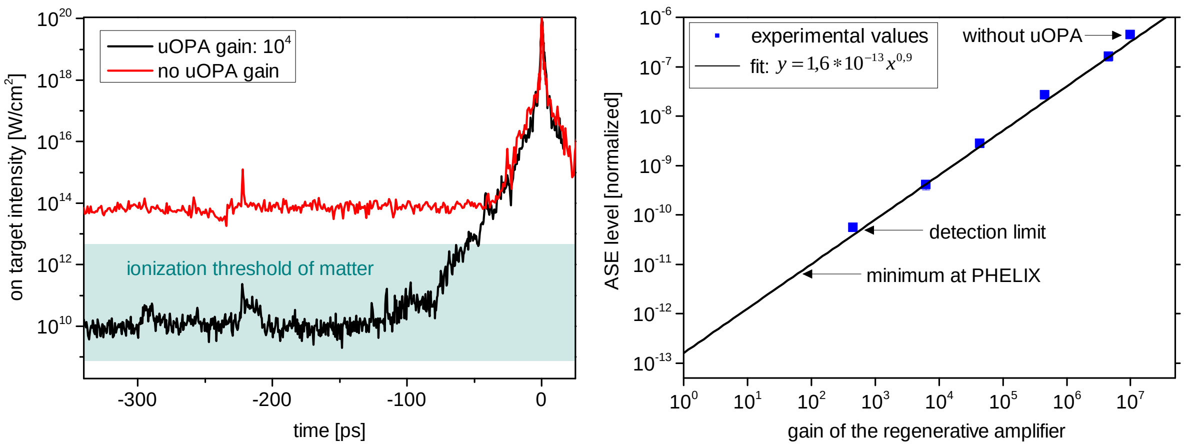

Figure 2: *Left: Temporal profile of the PHELIX pulse scaled to a peak intensity of* $10^{20}\,\mathrm{W/cm^2}$ *for an uOPA gain of* 10^4 *(black) and no uOPA gain (red). Right: ASE levels normalized to the pulse maximum for different gain values of the regenerative amplifier. The combined gain of the uOPA and the regenerative amplifier was kept constant at* 10^7 *for this measurement. Blue squares are experimental values taken from measured pulse profiles. The black line represents a fit to the experimental values.*

Effect on laser plasma experiments

The effect of different ASE levels on the produced pre-plasma during the interaction of an ultra-intense laser pulse with solid targets has been studied with 2-dimensional hydrodynamic simulations which were affirmed by time-resolved shadographic measurements [10]. The results for the pre-plasma size, which we define as the distance from the initial target surface to the position where the electron density goes down to a value of $10^{20}\,\mathrm{cm^{-3}}$, are summarized in table1. The used targets were flat copper foils and the duration of the ASE was 2.5 ns. These results identify the initial conditions for experiments exploring the interaction of high-power lasers with matter and can help to analyze experimental results. Furthermore they allow for applying the optimum pre-plasma for each experiment by choosing appropriate gain values for the uOPA. A more detailed description of this pre-plasma characterization is given in [10].

ASE intensity [W/cm^2]	$2.5 \cdot 10^{10}$	10^{12}	$5 \cdot 10^{13}$
preplasma size[μm]	6 ± 1	13 ± 3	34 ± 5

Table 1: *Pre-Plasma size (defined as the distance from the initial target surface to the position where the electron density goes down to* $10^{20}\,\mathrm{cm}^{-3}$*) from flat copper targets for different ASE intensities.*

This unique tunable contrast feature facilitates various new experiments at the PHELIX facility. In particular the ultra-high contrast enables the investigation of new effects that require ultrathin targets. Several experiments with sub-μm targets have been successfully performed within the last two years. For instance, using plastic targets with thicknesses between 100 nm and 1200 nm shot under an angle of incidence of 10° we could observe two angularly separated laser-driven proton beams which can be attributed to two different acceleration mechanisms acting simultaneously [11]. For an optimum match of target and laser conditions we observed maximum proton energies beyond 60 MeV. In a similar experimental configuration and by the use of deuterated plastic targets deuterons have been accelerated to energies greater than 85 MeV which were used to generate intense bursts of neutrons [13]. Even thinner targets (< 100 nm) have been successfully used for laser ion acceleration by combining the ultra-high contrast frontend with an additional plasma mirror [14].

Acknoledgments

This work was supported by the BMBF project 05P12RDFA1 and the Helmholtz Institue Jena and it has received funding from the European Unions's Horizon 2020 research program under grant agreement number 633053.

References

[1] B. Dromey, et. al., Nature Physics **2**, 456 (2006)
[2] A. Henig, et. al., Physical Review Letters **103**, 245003 (2009)
[3] L. Yin, et. al., Physics of Plasmas **14**, 056706 (2007)
[4] P. McKenna, et. al., Laser and Particle Beams **26**, 591 (2008)
[5] B. Dromey, et. al., Review of Scientific Instruments **75**, 645 (2004)
[6] A. Jullien,. et. al., Optics Letters **30**, 920 (2005)
[7] F. Wagner, et. al., Applied Physics B **116**, 429 (2014)
[8] V. Bagnoud, et. al., Applied Physics B **100**, 137 (2010)
[9] C. P. João, et. al., Applied Physics B **118** (3), 401 (2015)
[10] F. Wagner, et. al., Optics Express **22**, 29505 (2014)
[11] F. Wagner, et. al., Physics of Plasmas **22**, 063110 (2015)
[12] M. Roth, et. al., Physical Review Letters **110**, 044802 (2013)
[13] G.A. Wurden, et. al., EPS 2015 conference contribution P5.214
[14] L. Senje, et. al., Review of Scientific Instruments **85** (1), 113302 (2014)