The effects of ASE contrast and beams mutual alignment on the γ-ray yield in laser-plasma interactions with artificial prepulse

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Abstract. We present experimental study of the bremsstrahlung γ-rays generation in a plasma interacting with 50 fs laser pulse in slightly relativistic regime (intensity ~2 · 10¹⁸ W/cm²). A pre-plasma layer on the surface of the molybdenum target is formed by an additional laser pulse with a duration of 8 ns and an intensity of ~2 · 10¹² W/cm². The energy and intensity of the artificial prepulse exceed those of the amplified spontaneous emission (ASE) pedestal of the main pulse by ~10³ and 10 times (for contrast 10⁻⁶), respectively. It was shown that the low ASE contrast (>10⁻⁷) is the crucial condition for increasing (in comparison to the case without artificial prepulse) of the integral γ-rays yield when the nanosecond pulse is ahead of the femtosecond one by >20 ns. Interferometry data show that the reason of the γ-rays yield increasing is a pre-plasma layer initially produced by artificial pre-pulse and re-created by the ASE. The optimum conditions for γ-rays yield achieved if (i) the pre-pulse comes ~25 ns in advance, (ii) ASE contrast is 10⁻⁷ and lower and (iii) the femtosecond focal point is shifted by ~100 μm from the center of the nanosecond pre-pulse focal spot and by ~100 μm above the target surface.

1. Introduction
Femtosecond laser plasma is a brilliant source of ultra-short bursts of high energy electrons, which lead to the generation of bremsstrahlung hard X- and γ-rays [1–3]. Electron acceleration mechanisms depend significantly on the parameters of the plasma layer (scalelength L and electrons density n_e), created by pre-pulses or ASE [4–6]. To generate the optimal plasma layer providing effective electrons acceleration, additional laser pulses with variable parameters can be used [7,8].

In previous works [7,9] we used a nanosecond (NS) duration (~10 ns) pulse as an artificial pre-pulse for a femtosecond (FS, 50 fs) main pulse of the relativistic intensity (1·3 · 10¹⁸ W/cm²) with ASE contrast ~10⁻⁷-10⁻⁶. We found that there exist the optimal ranges of the time delays between NS and FS pulses where integral γ-ray yield maxima were observed (0-10 ns – “first” and 20-40 ns – “second”). Energies of the γ-quanta were 5-7 times higher in maxima compared to the case of single FS pulse. We also found that the relatively short (L/λ ~1-2) plasma gradient in the region of the quarter critical electron density
\((n_e - n_{cr})/4\) is required for the efficient excitation of parametric instabilities followed by electron acceleration [10,11].

Presence of the artificial NS pre-pulse is crucial for the phenomena described above, but the ASE impact is also significant. The intense ASE (with the contrast \(<10^5\)) itself can form the proper gradient [5]. Such a gradient can be also produced by the NS pre-pulse without ASE impact and these conditions correspond to the first maximum in our previous studies. In this work we show that the relatively low ASE pedestal (with the contrast \(>10^3\)) can create conditions for the efficient electron acceleration in the presence of artificial NS pre-pulse at longer delays (the second maximum). We present experimental results on \(\gamma\)-emission from plasma in the case of different ASE contrast levels (10^{-9}, 10^{-7}, 10^{-5}) and different mutual alignments of the artificial NS pre-pulse and the main FS pulse beams on the target surface. It was shown that the second \(\gamma\)-ray emission maximum disappears at a high ASE contrast (10^{-8}). It also was shown that for lower ASE contrast (>10^{-7}) \(\gamma\)-ray yield maximum achieved when the focal spots of the FS and NS beams shifted from each other in target surface plane. Comparison of the obtained data with the interferometry results clarified the laser-plasma interaction processes.

2. Experimental setup

In our experiments we used Ti:Sapphire laser system to generate a main pulse with duration \(\tau = 50\pm5\) fs (FWHM), repetition rate of 10 Hz and on-target energy of 30 mJ. The radiation was \(p\)-polarised, had a central wavelength of \(\lambda = 813\) nm. Figure 1 depicts the scheme of the experimental setup.

![Figure 1. Experimental setup. (1) Ti:sapphire laser radiation; (2) Nd:YAG laser radiation; (3) motorized mirror; (4) parabolic mirror; (5) target; (6) vacuum chamber; (7) scintillation detector; (8) collimators; (9) metallic (W, Pb, Cu) filters; (10) photodiode. Interferometry: (11) Probe pulse delay line; (12) BBO crystal; (13) Objective; (14) Michelson interferometer; (15) CCD camera. The inset shows the time delays between the pulses.](image)

We used Nd:YAG laser with a wavelength 1064 nm to generate an artificial pre-pulse with duration of 8 ns (FWHM), on-target energy of 100 mJ. The delay between the maxima of the FS and NS pulses was changed from \(-50\) to \(10\) ns with an accuracy of \(-1\) ns, which was checked by the fast photodiode EOT ET-2000.

The FS and NS beams were focused onto the surface of a thick metal (Mo) target at an incidence angle of \(45^\circ\) by off-axis parabolic (OAP) mirror with a focal length of 101.6 mm (an aperture \(f/6.8\) for FS and \(f/10.7\) for NS pulses). This gives on-target intensities of \(I \sim 2 \cdot 10^{15}\) W/cm² and \(\sim 2 \cdot 10^{18}\) W/cm² for the FS and NS pulses respectively. The focal area was imaged by the micro-objective (NA = 0.3) to a CCD camera that allowed us to control coincidence of the focal spots of the FS and NS pulses (diameters (FWHM) were \(\sim 4\) and \(\sim 15\) \(\mu\)m, respectively). The focal spot of the NS beam could be shifted relative to the FS one in the OAP focal plane by the adjusting of the motorized mirror 3 in figure 1. Since the Rayleigh length of the NS beam (~200 \(\mu\)m) significantly exceeds those one for the FS beam (~25 \(\mu\)m), distance between the focal point of the FS beam and the target surface can be adjusted by shifting target along beam axis without significant changes of the plasma gradient. The target assembly was also moved after each laser shot by \(\sim 100\) \(\mu\)m to provide a clean target surface for each laser shot. Laser-plasma interaction occurred in the vacuum chamber at a residual gas pressure of \(\sim 10^{-2}\) Torr.

The integral \(\gamma\)-rays yield from plasma was registered by the NaI(Tl) scintillation detector (with 63-mm-thick crystal) shielded by lead blocks. The metal filters were used for the \(\gamma\)-rays flux attenuation.

The interferometry technique (described in detail in [12]) was used to observe the evolution of the plasma cloud. Plasma cloud could be produced by a single NS pulse or combination of the NS and FS (an intensity \(\sim 10^{18}\) W/cm²) pulses. The probe pulse could arrive 2 ps before or 1 ps after the FS pulse. In first case the probe scanned the plasma layer produced by the NS pulse and the FS pulse pedestal.
The probe pulse had a wavelength of 406 nm, a duration of 50 fs and could propagate both in the plane of incidence of the FS and NS pulses and perpendicular to it.

2.1. Main pulse contrast variation

The third-order autocorrelation function of the FS pulse is shown in Figure 2a. The temporal profile of the FS pulse contains pre-pulses on the delay of -20 ps and -14 ns with the contrast of \(4 \cdot 10^{-5}\) and \(5 \cdot 10^{-8}\), respectively (negative delays mean that the pre-pulse is ahead of the FS pulse). The ASE contrast is \(10^{-7}\) for delays \(\leq 50\) ps, it can be increased up to \(10^{-9}\) by using a scheme based on the generation of a cross-polarized wave (XPW) [13]. In our laser system the intensity level of the FS pulse pedestal can be increased by the increasing of the master oscillator pump power (Figure 2b). The master oscillator begins to generate continuous wave (CW) radiation easily viewed at 4.7 W pump power (Figure 2c).

![Figure 2](image)

**Figure 2.** a) Third-order autocorrelation function of the FS pulse without using the XPW scheme (black line) and ASE level when using it (red line). b) Front of the FS pulse pedestal at different pump powers of the master oscillator. Measured by the fast photodiode (-3 - 0.6 ns, dashed lines) and the third-order autocorrelator (-0.6 - 0.05 ns, solid lines). c) FS pulse spectra at different pump powers of the master oscillator.

The CW presence decreases the FS pulse pedestal contrast from \(10^{-7}\) to \(10^{-5}\). The duration of the pedestal is determined by the time window of the Pockels cells and lasts 1.5 ns. Thus, we can switch the FS pulse contrast between: \(< 10^{-9}\) (with XPW), \(10^{-7}\) (ASE) and \(10^{-5}\) (CW presence).

3. The Gamma-radiation diagnostics

Figure 3 shows dependences of the integral \(\gamma\)-rays yield \(N_\gamma\) from plasma on the delay time between the NS and FS pulses and the position of the FS beam focal point relative to the target surface (hereinafter maps). Maps were measured at different levels of the FS pulse pedestal contrast: \(< 10^{-9}\), \(10^{-7}\), \(10^{-5}\) and \(10^{-5}\).

![Figure 3](image)

**Figure 3.** Maps of the integral \(\gamma\)-ray yield \(N_\gamma\) from plasma at the different contrast levels of the FS pulse pedestal: a) \(< 10^{-9}\) (using XPW), b) \(10^{-7}\) (normal ASE), c) \(10^{-5}\) (pump power = 4.7 W) and d) \(> 10^{-5}\) (pump power = 4.8 W).
The axes of the FS and NS beams exactly coincided. The transmittance of the filter (4 mm Pb) mounted in front of the detector was 90% for γ-quanta with energies >250 keV. Each data point within a map was averaged over 30 laser shots.

In the maps there are two regions with an increased γ-rays yield: for small delay times between pulses (from +5 to -10 ns) and for large delays < -20 ns (hereinafter, the first and the second maxima). Also, there is the delay times range from -10 to -20 ns, in which γ-radiation almost completely disappears (hereinafter, a gap). The processes taking place at the first maximum and at the gap were discussed earlier in works [7,10,11]. At the first maximum, hybrid Raman – two plasmon instability develops on a short pre-plasma gradient (L/λ ~1-2) created by the NS pulse [11]. Those electrons that have received energy as a result of the wavebreaking can be accelerated in the FS pulse field (Vacuum Laser Acceleration) if injected into an appropriate phase. A relatively short pre-plasma gradient (near the $n_e \sim n_{cr}/4$) maintained while the NS pulse acts on the plasma and spreads after. The γ-radiation gap is result of the laser beam distortion and ionization defocusing in the long plasma layer formed after the NS pulse termination.

Consider the second maximum. Figure 3 shows that there is no second maximum at the contrast <10^{-9}, it starts to appear when the contrast is 10^{-7}. The optimal focal point position of the FS pulse shifts further above the target surface in the second maximum with further decrease in the contrast. It can be assumed that ASE recreates plasma if delay is large and the ASE creates like the NS pulse relatively short plasma gradient near $n_e \sim n_{cr}/4$ which is required for electron acceleration.

It should be noted that presence of the artificial NS pre-pulse is critical for the γ-yield increase described above. In the case of the single FS pulse the γ-yield is much lower in both maxima at any ASE contrast higher <10^{-5}.

4. Interferometry and beams alignment

Figure 4 shows the distributions of the phase incursion in the probe beam obtained by the interferometry for the cases of single NS pulse and combination of the NS pulse and the FS pulse pedestal (probe arrives before the main pulse). They show that the ASE indeed increases the plasma electron concentration if delay falls into the second maximum range.

![Figure 4](image)

**Figure 4.** The probe pulse phase incursion reconstructed from the interferograms of the plasma cloud produced by a) single NS pulse and b) combination of the NS pulse and the FS pulse pedestal. The ASE contrast of the FS was $10^{-5}$ (CW). The probe pulse propagates along the normal to the incidence plane of the beams and arrives 2 ps before the FS pulse.

Moreover, the plasma cloud interferograms obtained for the cases of the single NS pulse and combination of the NS and FS (figure 5, probe arrives after the FS pulse) are almost same for delays >-20 ns (first maximum and γ-yield gap). Most likely, the reason for this is that the energy of the NS pulse significantly exceeds the energy of the ASE front (in ~10^3 times for the ASE contrast 10^{-7}). Therefore, ASE cannot change the plasma cloud created by the NS pulse until it has cooled down. At larger delay times (the second maximum region), the FS pulse creates a narrow plasma cloud, which is not observed on interferograms in the case of the single NS pulse.

Another crucial parameter in our study is the mutual alignment of the NS and FS beams. Figure 5 shows dependences of the integral γ-rays yield $N_\gamma$ from plasma on the shift of the NS pulse focal spot relative to the FS one (see figure 1a). In other words, these dependences show how the γ-rays yield from the plasma changes when the FS pulse is focused into different areas of the plasma cloud. The energy of the registered γ-quanta is >250 keV. The width of the area where we observed increase in γ-yield corresponds to the width of the plasma cloud. This is clearly seen at short delays between the
pulses where plasma cloud expands. In the second maximum the optimal focal point of the FS pulse shifts by ~100 µm above the target surface. It is interesting that exact coincidence of the laser beams does not correspond to the γ-ray yield maximum. It is observed when the FS pulse goes through the plasma cloud and focused onto its side (x<0, where electron temperature is lower than in the center). In the case of the proper beam separation the γ-ray yield in the second maximum is greater (in ~1.5 times) than in the first one (figure 5d). Note also that even between the maxima one can find conditions for efficient γ-ray production (see the left picture in figure 5c).

Figure 5. a) The location of the NS and FS beams focal points: the NS beam focal spot shifts in the target surface plane (Oxy), the FS beam focal point moves along its axis (focus). Dependences of the integral γ-ray yield on the NS beam focal spot shift and the plasma cloud interferograms obtained for time delays between NS and NS pulses corresponding to b) the first maximum, c) the γ-ray yield gap and d) the second maximum. The contrast of the FS pulse pedestal was 10⁻⁷-10⁻⁶ for interferograms and 10⁻⁵ for γ-ray yield distributions. Interferometry probe propagates in the incidence plane of the beams and arrives 1 ps after the FS pulse. In c) and d) cases the γ-ray yield dependences are given for two focal positions of the FS pulse: on and above the target surface; interferograms – for plasma clouds produced by the single NS and both the NS and FS pulses.
5. Discussion and conclusions

Previous studies [7,10,11] showed that pre-plasma layer with relatively sharp edge ($L/\lambda \sim 1$-2, near $n_e \sim n_e/4$) is required for excitation of the parametric plasma waves which lead to electron acceleration. Pure ASE pedestal (without an artificial pre-pulse) with a contrast $\sim 10^7$ cannot create the required pre-plasma gradient before the arrival of the main pulse ($I = 1.3 \cdot 10^{18}$ W/cm$^2$, $\tau = 50$ fs). Experiments showed that the $\gamma$-yield is much lower if the NS pre-pulse is absent and the ASE contrast is better than $\sim 10^7$-$10^6$. It increases at the significantly lower ASE contrast $\gamma > 10^{-5}$ [5]. Note, that there is no visible ASE-produced plasma cloud in interferometric experiments if the contrast is $\sim 10^7$-$10^6$ and it exists if the contrast is $\sim 10^{-5}$.

On the other hand, ASE pedestal with a contrast $\sim 10^7$-$10^6$ can re-create the pre-plasma layer originally created by the artificial pre-pulse. The second maximum of the $\gamma$-rays yield is the result of the combined action of the artificial pre-pulse and ASE pedestal: pre-pulse heats the target, but the ASE re-create the pre-plasma layer for the long delays ($< -20$ ns) providing optimal conditions for efficient electron acceleration.

The sketch in figure 6 shows our vision of the pre-plasma layer evolution at the exact coincidence of the NS and FS beam axes. The $\gamma$-radiation is generated on the short pre-plasma layer produced by the NS pulse if delay is small, while the pre-plasma gradient spreads out in the gap (-10 to -20 ns delays), and the FS beam undergoes defocusing and distortion. Finally, temperature of the plasma cloud decreases at longer delays, and the ASE can re-create the sharp pre-plasma gradient (near $n_e \sim n_e/4$) above the target surface. This is confirmed by the appearance of the second and three-half’s harmonics generation similar to the radiation in the first maximum described in [7]. This also explains the shift of the FS focal point above the target surface.

![Figure 6. Sketch of the pre-plasma layers at the different time delays between the NS and FS pulses: a) $+5 - 10$ ns (first maximum), b) $-10 - 20$ ns ($\gamma$-yield gap), c) $<-20$ ns (ASE contrast $<10^{-7}$) and d) $<-20$ ns (ASE contrast $>10^{-7}$, second maximum).](image)

The role of the ASE discussed above is important for understanding other effects associated with the second maximum. For example, for the effect of the additional increasing of the $\gamma$-rays yield (more than 10 times) with an increase in the FS pulse duration up to 1700 fs at the large delays between the NS and FS pulses [14].

The $\gamma$-yield increase at the first maximum with the change of the relative position of the beams is probably associated with the focusing of the FS beam into the more optimal region of the plasma cloud produced by the NS pulse. In the second maximum, the shift of the NS beam by 100 μm in focus and by 100 μm along the target surface (see Figs 5a and 5d) is equivalent to the shift of the FS beam focal point along the target surface normal above the central region of the plasma cloud, where the plasma re-creation under the action of the ASE occurs.

The $\gamma$-ray yield can exceed at the second maximum the yield at the first one with the appropriate adjustment of the relative beam positions. However, the second maximum has significant instability in the yield and quanta energies due to stochastic variations in the large number of parameters required to achieve it.

Clear understanding of plasma gradient peculiarities within each given set of experimental conditions (the NS to FS pulses delay, the FS beam focal plane position and mutual displacement of the NS and FS beams) is needed to get more insight into the complex picture described above. The crucial point here is the plasma gradient near the $n_e/4$ electron density. Unfortunately, the interferometry/shadowgraphy and optical harmonic measurements are insufficient, and the only way is 3D hydrodynamic modeling of plasma creation and expansion verified by the interferometry/shadowgraphy.
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