Simulation studies on transmissivity of silicon nitride plasma shutter for laser pulse contrast enhancement

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Tightly focused petawatt laser pulse is usually accompanied by low-energy prepulses, composed of Amplified Spontaneous Emission (ASE) part and picosecond pedestal [1]. These prepulses can cause ionization and heating of the target and consequently create a low density preplasma [2] before the main pulse arrives. Mitigation of these effects, i.e., increasing the laser pulse contrast, is beneficial for several application, e.g, Radiation Pressure Acceleration in the light sail regime [3], High Harmonic Generation in the relativistic regime [4] or use of nanostructures on the target [5]. The nanosecond ASE prepulses can be efficiently reduced by a reflecting plasma media, e.g. double planar plasma mirror, which have already been implemented on many laser facilities [6]. On the contrary, reduction of picosecond prepulses is more difficult using reflecting plasma media, while a transmitting plasma media, so-called plasma shutter seems to be a very promising filter of these prepulses [7].

In this work we study the utilisation of silicon nitride target as a plasma shutter for laser pulse contrast enhancement in the sub picosecond time domain with realistic parameters with the help of numerical 2D3V particle-in-cell simulations [8] and effects of pulse modification caused by its propagation through the plasma shutter on acceleration of ions from the second target located behind the plasma shutter.

The parameters of laser pulse are same in all included simulations and are relevant to PEARL laser (PEtawatt pARametric Laser) at IAP RAS (Institute of Applied Physics-Russian Academy of Science, Nizhny Novgorod, Russia). This laser pulse is linearly p-polarised, incident normally on the target and have diameter of 3 μm (at FWHM), wavelength 910 nm and pulse duration 60 fs (approximated by 127.8 fs full $\sin^2$ pulse) and laser peak intensity of 1×10^{21} W/cm^2. Plasma shutter consists of fully ionized silicon nitride (Si3N4) with parameters relevant to commercial Si3N4 foil of density 692 n_c and thickness varying from 20 nm to 50 nm, where n_c is the critical density.

Incident laser pulse, represented by the dimensionless amplitude of electric field in the y-direction a_0 ($a_0 = e\mathrm{E}_y/(m_e c\omega)$, at the beginning of the laser shutter interaction is presented in Fig. 1) and corresponding reflected and transmitted pulses at time instant 34 T (T is the laser period) later are presented in fig. 2). The plasma shutter is initially opaque for the incident laser pulse and significant part of the laser pulse is reflected back as can be seen in Fig. 2. The laser pulse is burning through the plasma shutter, resulting in partial absorption of the laser pulse and self-focusing of its propagating part. The increase of the maximum of dimensionless amplitude (a_0) of the electric field from 24 to 30 can be observed by comparing figures 1) and 2). Reflection of the lower intensity parts of the laser pulse also leads to a steeper-front pulse which is favourable for radiation pressure acceleration [3]. However, the modified pulse becomes shorter and loses a significant part of its initial energy. The percentage of transmitted energy is rising with the reduction of the thickness of the plasma shutter. Using plasma shutter with thickness of 40 nm more than 5% of energy of laser beam is transmitted and transmissivity of 35% is reached in the case of 20 nm target.

To study the differences in ion acceleration caused by the pulse modification after it propagates through the plasma shutter, another set of simulations was made with the second solid foil target located behind the plasma shutter (see Fig. 3) and reference simulation with only the solid foil target without the plasma shutter. The plasma shutter with thickness of 20 nm has been chosen due to its highest transmissivity from all the previously simulated

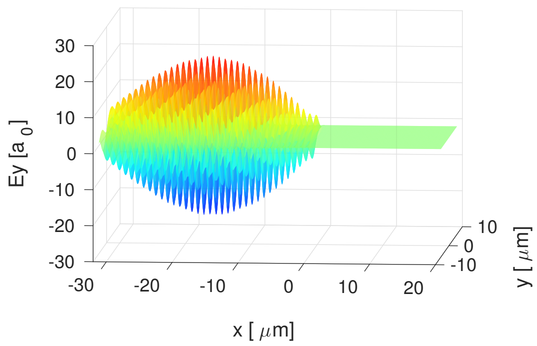

Figure 1: *Incident laser pulse at the beginning of the laser-shutter interaction (time instant 0 T)*

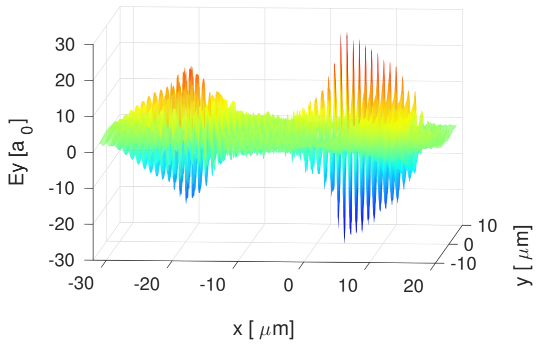

Figure 2: *Reflected and transmitted laser pulses near the end of laser-shutter interaction (time instant 34 T)*

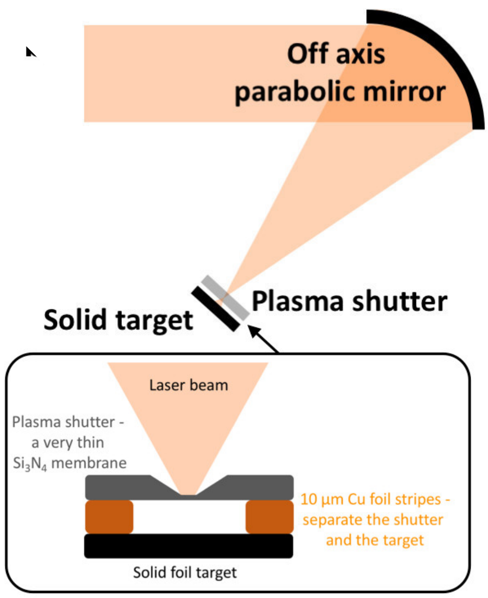

Figure 3: *Scheme of planned experiment with the plasma shutter and a solid foil target*

cases for the same laser pulse (with wavelength λ = 910 nm). Fully ionized (charge number $Z = 1$) hydrogen target with density initial density n_0 = 250 n_c and thickness l_0 = 50 nm was used. These target parameters fulfil the condition for efficient light sail radiation pressure acceleration mechanism with initial peak intensity around 1×10^{21} : [3]

$$\frac{1}{\pi}\frac{n_c}{n_0}a_0 < \frac{l_0}{\lambda} < \frac{1}{2\pi}\sqrt{\frac{n_c}{\gamma n_0}}a_0 \exp\left(\sqrt{\frac{Zn_c}{n_0}}\frac{a_0}{\sqrt{\gamma-1}}\left(\frac{n_0}{\gamma n_c}\right)^{(1/4)} + \frac{1-\ln 2}{2}\right). \tag{1}$$

Time evolution of maximum proton energy is shown in Fig. 4. Ion acceleration is more efficient in the simulation with the plasma shutter till time 26 T. Change of acceleration mechanism is visible at time 12 T in the case of simulation with the plasma shutter. The solid foil target becomes relativistically transparent to laser pulse at this time instant as can be seen in Fig. 5) and ions are accelerated via transparency acceleration mechanism (sometimes referred as break-out afterburner mechanism [9]). After time instant 26 T, protons in the simulation without the plasma shutter reaches higher maximum energies than protons in simulation with plasma shutter. This corresponds to the shortening of propagated laser pulse in the case of simulation with the plasma shutter. Therefore, the interaction time of laser pulse with particles is reduced compared to the simulation without plasma shutter. This behaviour can be observed by comparing Fig. 6 and 7. In Fig. 6 the laser pulse already exit the area where accelerated protons (and electrons) are located. On the contrary the laser-particle interaction continues in Fig. 7. Moreover, more significant dispersion in the y-direction is visible in the case of the simulation with plasma shutter, resulting in lower amplitude of the electric field (around 10 a_0) of the laser pulse at the end of the interaction compared to the simulation without (around

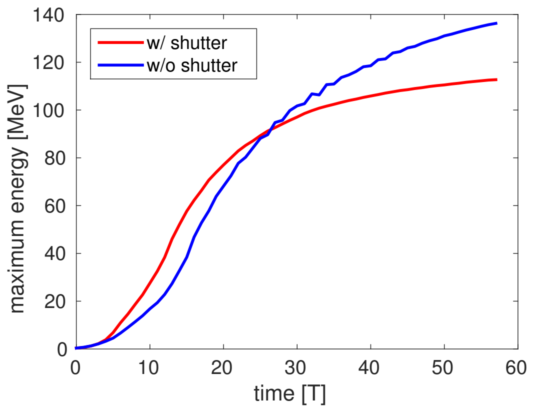

Figure 4: *Time evolution of maximal energy of accelerated protons since the beggining of laser interaction with the hydrogen target*

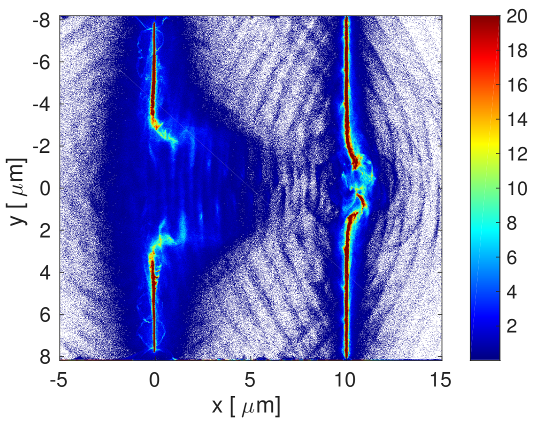

Figure 5: *Electron density in simulation with plasma shutter and hydrogen target at time instant 12 T after the beginning of laser interaction with the hydrogen target*

30 a_0).

In conclusion, the produced simulations with intense laser pulse proved the possibility of utilisation of the thin silicon nitride foil as plasma shutter for filtering picosecond prepulses with transmissivity of 35% in the case of 20 nm foil. Moreover the generation of steeper-front pulse with increased intensity was observed in our simulations. This modified laser pulse shape improves efficiency of radiation pressure acceleration, however, shortens the laser pulse and reduces the efficiency of transparency regimes.

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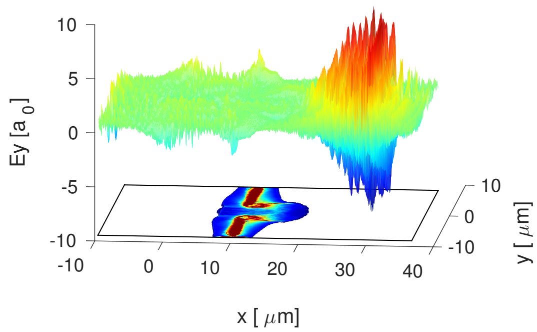

Figure 6: *Elecric field of laser pulse and corresponding proton density at time instant 22 T in the simulation with the shutter*

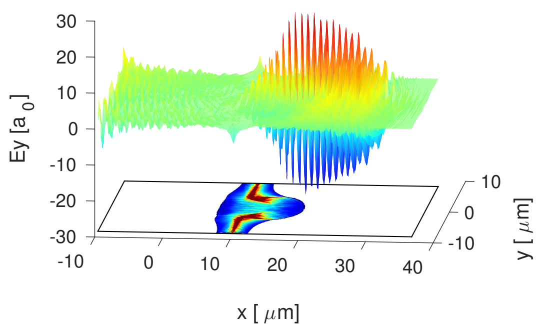

Figure 7: *Elecric field of laser pulse and corresponding proton density at time instant 22 T in the reference simulation without the shutter*