Acceleration of spin-polarized proton beams from a dual-laser pulse setup

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Introduction

Spin-polarized particle beams are of interest for several applications, e.g. probing the structure of the proton or even polarized fusion [1]. Recently, several publications have investigated the acceleration of such particle beams from laser-plasma interaction. For spin-polarized electrons it was shown with particle-in-cell (PIC) simulations that both laser- and particle-beam driven wakefield acceleration are a promising option [2]. For protons/ions, the options are more restricted: while proton wakefield acceleration would be a possibility in theory, it is currently not feasible [3]. Other, more common methods of ion acceleration like Target Normal Sheath Acceleration are also not suitable since this would necessitate a pre-polarized foil target which is not a simple task to produce. One possible option is the mechanism of Magnetic Vortex Acceleration (MVA), where a strong laser pulse interacts with a (here: pre-polarized) near-critical density target [4, 5, 6, 7]. From this one is able to obtain well collimated particle beams of high polarization. In our present work, we study the acceleration of protons using two parallel propagating laser pulses with a phase difference of π. This allows for better polarization of the beam and is able to mitigate certain instabilities compare to the conventional single-pulse MVA; a full discussion of the results can be found in Ref. [8].

Simulation setup

We study our scheme with the aid of PIC simulations, specifically the code VLPL [9, 10]. Our simulation domain is of the size $(96 \times 64 \times 64)\,\mu\mathrm{m}^3$ and moves with the laser pulses. The spatial resolution is $h_x = 0.04\,\mu\mathrm{m}$ (direction of propagation), $h_y = h_z = 0.2\,\mu\mathrm{m}$. We further make use of the scaling feature of the code, which increases the transverse grid size by 5% per cell for $|y|, |z| > 16\,\mu\mathrm{m}$. The time step is set as $\Delta t = h_x/c$ in accordance with the rhombi-in-plane solver [11], where c denotes the vacuum speed of light.

The "dual-pulse" laser used throughout the simulations is implemented as two linearly polarized Gaussian beams that propagate side-by-side. Here it is important to note that they are set to have phase difference of π with respect to each other (see Fig. 1). Both pulses have a length of $\tau = 26.7$ fs and a focal spot size of $w_0 = 4\,\mu\mathrm{m}$. They are separated by a distance of $\Delta y = 8\,\mu\mathrm{m}$.

The normalized laser vector potential for both pulses is varied in the range $a_0 = 25-100$.

The target with which the pulses interact is the near-critical density (NCD) HCl target already used in several other spin-related publications like [2, 7]. The density of the components is $n_\mathrm{H} = n_\mathrm{Cl} = 2.074 \times 10^{20}$ cm^{-3}, thus leading an electron density close to the critical density. We assume that the two species are ionized to H^+ and Cl^{2+}. The constant-density part of the target is 200 µm long and is preceded/followed by a density-up/-down ramp of 4 µm.

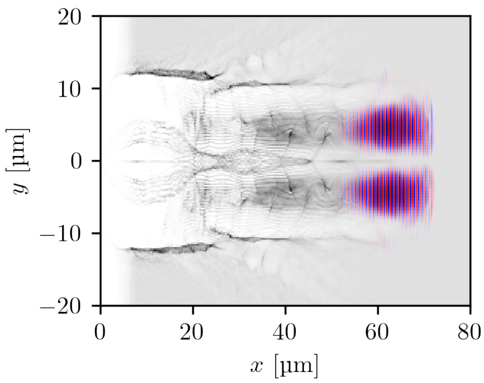

Figure 1: *The two pulses propagating through the NCD plasma, starting to form two channels and the central filament. Note the phase difference between the two lasers (red/blue regions).*

Since it is necessary in order to accelerate highly polarized particle beams [12], the target is fully spin-polarized in the beginning (in our simulations $s_y = 1$). The spin of the particles with charge qe and mass m is tracked according to the T-BMT equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = -\vec{\Omega} \times \vec{s}\,, \tag{1}$$

where

$$\vec{\Omega} = \frac{qe}{mc}\left[\Omega_B \vec{B} - \Omega_v \left(\frac{\vec{v}}{c}\cdot\vec{B}\right)\frac{\vec{v}}{c} - \Omega_E \frac{\vec{v}}{c}\times\vec{E}\right] \tag{2}$$

is the precession frequency that depends on the prevalent electric and magnetic fields $\vec{E}$ and $\vec{B}$ as well as the particle velocity $\vec{v}$. The three pre-factors

$$\Omega_B = a + \frac{1}{\gamma}\,, \qquad \Omega_v = \frac{a\gamma}{\gamma+1}\,, \qquad \Omega_E = a + \frac{1}{1+\gamma} \tag{3}$$

in turn depend on the anomalous magnetic moment a and the Lorentz factor $\gamma = 1/\sqrt{1-v^2/c^2}$. Other effects concerning spin like the Stern-Gerlach force and the Sokolov-Ternov effect can be neglected in our regime; see Ref. [13] for a more general discussion.

Results

For the various tested laser intensities, the basic laser-plasma interaction is the same: the two laser pulses each perform their own MVA, therefore creating two channels in total (cf. Fig. 1). Both contain a central filament from the laser-accelerated electrons with a strong current [5]. A corresponding return current is formed in the channel wall, giving rise to an azimuthal magnetic field. When exiting the plasma target, this field is able to expand transversely which leads to a

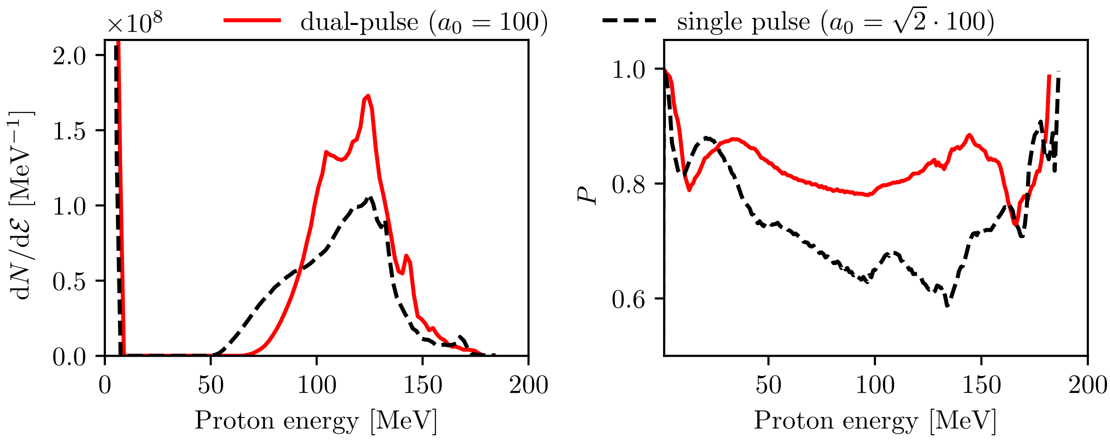

Figure 2: *Left: Energy spectrum for the dual-pulse and single-pulse scheme for protons with less than* $\pm 2^\circ$ *momentum spread. Right: Polarization spectrum for both setups. Note that the seeming polarization increase for very high energies is of statistical nature and not physical.*

displacement of electrons and protons. This leads to longitudinal and transverse electric fields that accelerate/focus exiting protons. On top of this two-fold MVA, a third filament is created: due to the opposing polarity of the two laser pulses, a strong longitudinal electric field is formed in the space between them. The particles in this "central filament" are partly shielded from the fields that the protons of the other two filaments experience allowing for high polarization.

In the case of $a_0 = 100$, protons with a maximum energy of 182 MeV can obtained. Restricting ourselves to particles with a momentum spread of $\pm 2^\circ$, we observe a well-defined peak in the energy spectrum around 124 MeV (cf. Fig. 2). In the full width at half maximum (FWHM) of this peak approx. 0.76 nC can be accelerated. The polarization of the beam can be calculated as $P = \sqrt{P_x^2 + P_y^2 + P_z^2}$ with $P_j = \sum_i s_{i,j}/N$ for N particles and $j \in \{x, y, z\}$. For the presented simulation with $a_0 = 100$, a polarization of 77% is reached (cf. Fig. 2). For lower a_0, the polarization is generally higher (not shown here, see Ref. [8]). For the displayed polarization spectra it has to be noted that the increase of polarization for very high energies is not physical. Instead, it comes from the fact that only a small amount of particles reaches this energy, leading to larger statistical error when computing the polarization.

For a better comparison we further perform a simulation with a single Gaussian laser pulse. This pulse has the same length and focal spot size, but an increased $a_0 = \sqrt{2} \cdot 100$ to compensate for the difference in pulse energy. As visible in the spectra in Fig. 2, the peak energy for the protons with $\pm 2^\circ$ spread is only marginally higher. In total, fewer particles can be accelerated: only 0.61 nC are in the FWHM around the peak for the single laser pulse. Further, the polarization is also significantly lower at 64%. The latter can be explained by the fact that for the dual-pulse case better shielding of the central filament occurs. The protons in conventional MVA experience comparatively more field inhomogeneities which induce increased spin precession and thus depolarization. Another interesting result is that for a single pulse, the angular spectrum is asymmetric around $\arctan(p_y/p_x) = 0°$ indicating some instability. This asymmetry is notably absent from the dual-pulse mechanism. There, it seems that the presence of the two pulses surrounding the central filament leads to improved guiding of this beam.

Conclusion

We have presented a setup consisting of two laser pulses that propagate side-by-side through a spin-polarized, near-critical density target. The two pulses both perform Magnetic Vortex Acceleration, but due to having a phase difference of π with respect to each other, an electric field in the space between them is able to accelerate additional protons. These protons are better shielded from the prevalent fields compared to conventional setups and thus deliver close beams with 0.76 nC charge and a polarization degree of 77% for $a_0 = 100$. Future work will investigate the possibility of using Laguerre-Gaussian modes for a similar setup, which already have been proven to enhance polarization in the context of spin-polarized laser wakefield acceleration [2].

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