# Laser-driven collisionless shock acceleration of protons

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**Introduction** Experimental and numerical results have shown that collisionless shock acceleration is promising for generation of high energy proton beams [1]. There are many potential applications for such beams, for example: isotope generation for medical applications, ion therapy and proton radiography. Combining collisionless shock acceleration with a strong quasi-stationary sheath-field may be a way to reach even higher maximum proton energies and optimize the ion spectrum. Here we show that a layered plasma target with a combination of light and heavy ions leads to a strong quasi-static sheath-field, which induces an enhancement of the energy of shock-wave accelerated ions, without broadening their spectrum, if the heavy ion layer has high density.

**Vlasov-Maxwell solver** In laser plasma induced collisionless shock acceleration, a small fraction of the ion population is reflected by an electrostatic potential barrier set up by laser plasma interaction. The low density tail of the distribution function plays an important role for the dynamics, and therefore high resolution is needed. Eulerian methods, which discretize the distribution function on a grid have very low levels of numerical noise. They are therefore appropriate for the detailed study of processes where a small number of high energy particles play a significant role. For this reason, we developed VERITAS [2, 3], a 1D1P relativistic Eulerian Vlasov-Maxwell solver with block-structured adaptive mesh refinement. The discretization of the Vlasov equation is based on a high-order finite volume method. A flux corrected transport algorithm is applied to ensure the physical character of the distribution function. In this work, we use VERITAS to study the interplay of collisionless shock and target normal sheath acceleration.

**Results** For a target with a steep rear boundary, a strong sheath-field can be obtained and used to increase the energy of shock accelerated ions [4]. Targets with a single light ion species are subject to significant Target Normal Sheath Acceleration (TNSA) and hence the resulting ion energy-spectrum becomes broad. Furthermore, the acceleration of ions at the rear side leads to a decay of the sheath-field strength and hence its usefulness for post-acceleration is reduced. To combine the use of a strong sheath-field for post-acceleration and a low degree of TNSA, we consider a double layered rectangular target consisting of a layer of light ions (protons) at the front side ($x \in [2\lambda, 4\lambda]$) and heavy (immobile) ions at the rear side ($x \in [4\lambda, 6\lambda]$). Here, $\lambda$ is the laser wavelength. We use the density profile

$n(x) = 2.5n_c$ in the light ion part, where $n_c = m_e\omega^2\varepsilon_0/e^2$ is the critical density at which the laser frequency $\omega$ equals the plasma frequency. In the heavy ion part we consider two cases for the electron density profile, $n(x) = 2.5n_c$ and $n(x) = 25n_c$, respectively. For comparison, we also consider a single layer rectangular target with protons and $n(x) = 2.5n_c$ for $x \in [2\lambda, 6\lambda]$. The targets are irradiated by a linearly polarized laser pulse with Gaussian shape factor for the vector potential $a(t) = a_0 \exp[-2\ln 2(\tau/t_p)^2]$, where $\tau = t - t_p$ and $t_p$ is the pulse duration at FWHM. In the simulations, we have used the dimensionless laser amplitude $a_0 = 2.5$ and pulse length 50 fs. Here, $a_0 = 0.85(I\lambda^2/10^{18}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2)^{1/2}$, with $I$ the laser intensity.

Figure 1 shows snapshots of the ion distribution function for the single-species and double layered targets at $t = 39T$, $75T$ and $108T$. Here, $T$ is the duration of the optical cycle corresponding to the wavelength $\lambda$. The laser heats the front side of the target and launches a shock. Until the shock reaches the region with heavy ions in the double layer, its behaviour is similar to that in the single species target. For the double-layered targets the shock-wave is stopped at the interface between the layers, but the shock-wave reflected ions continue and finally cross the rear side of the target. When this occurs the ions are further accelerated due to the sheath-field, leading to higher proton energies than what they would have from the reflection by the shock-wave alone.

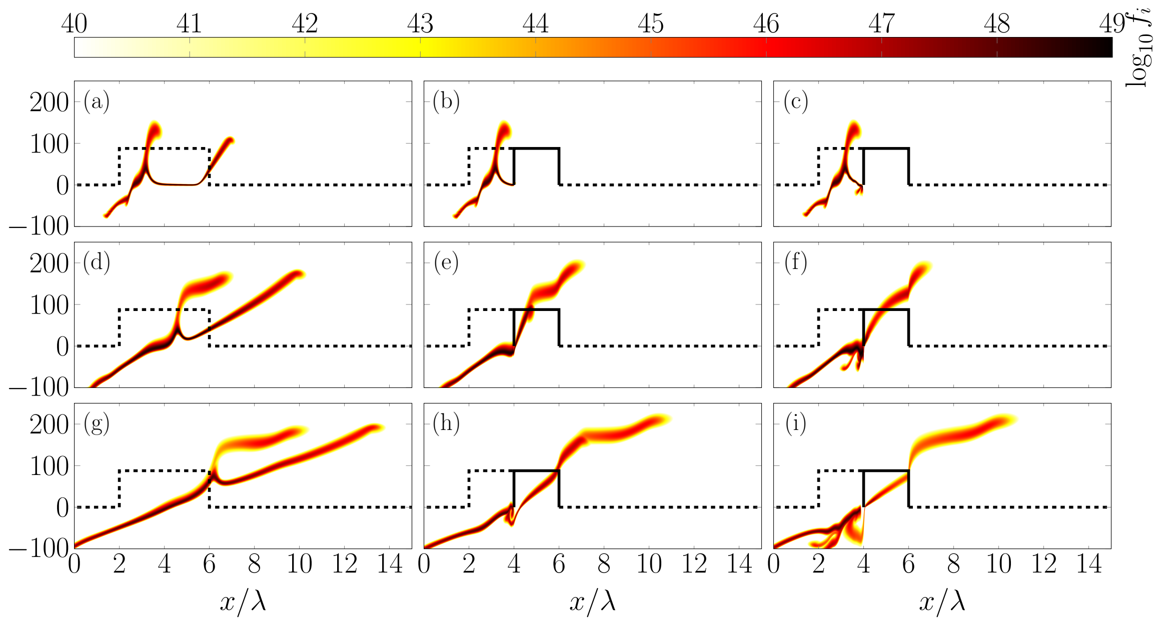


Figure 1: *Ion phase-space distribution for single- and double-layer target structures, irradiated by a linearly polarized pulse with $a_0 = 2.5$ and pulse length 50 fs at $t = 39T$, $75T$ and $108T$. (a,d,g) show the single-species target, (b,e,h) the layered target with $n = 2.5n_c$ and (c,f,i) the layered target with the high density heavy ion layer having $n = 25n_c$.*

If the heavy ion layer has higher density than the light ion layer, ions can be slowed down due to the sheath field that is created by the density difference at the interface. Those ions that have acquired enough energy from the shock-wave potential barrier can penetrate the interface and continue through the target. The interface between the layers acts effectively as a filter: it reflects the low energy ions and leads to a narrower energy spectrum after the interface. By comparing Figs. 1(h,i), we see that more protons penetrate the interface in the low density case, as can be expected since the size of the potential barrier associated with the sheath field at the interface between the light ion and heavy ion layers is smaller in this case.

Inside the heavy ion layer, the energy spectrum ranges from zero for protons that had initial energy just above the threshold for reflection, to the highest energy of reflected ions, reduced by the size of the potential barrier. The electric field inside the heavy ion layer is very small, so protons cross this layer without gaining much energy. As it takes less time for the higher energy light ions to cross the heavy ion layer, the distribution is rotated in phase-space, as can be noted by comparing e.g. Figs. 1(f,i). When the light ions reach the interface to vacuum, they are accelerated by the strong sheath-field there.

In all cases the maximum proton energies exceed the energy of 2.9 MeV for reflected ions by the shock-wave, as can be seen in Fig. 2, where the proton spectrums in the three cases are presented. Furthermore, in the single species case we have a broad TNSA-dominated proton spectrum. For the layered targets we observe that the range of the spectrum shrinks and the maximum proton energy increases compared to the single species case. The shrinkage of the spectrum is stronger in the high density case. In other words, by choosing the density of the heavy ion layer appropriately it should be possible to further optimize the monoenergeticity of the ion beam. As mentioned before, the reason is that the longitudinal electric field in the boundary region between the light and

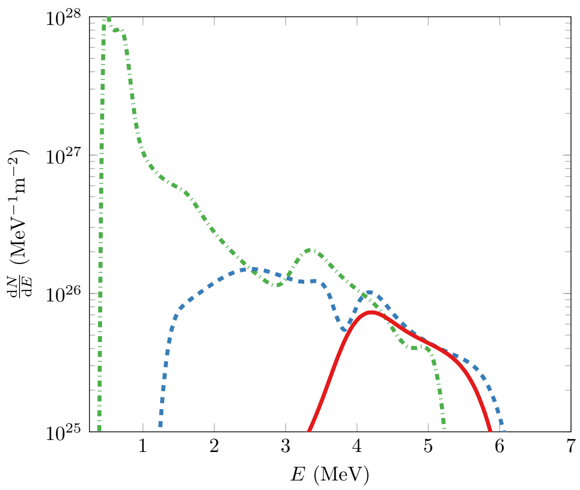


Figure 2: *Proton spectrum at $t = 108T$ for single-species and double-layered targets. Green dash-dotted line is for the single-species target. Blue dashed line is for the layered target with $n = 2.5n_c$. Red solid line is for the layered target with the high density heavy ion layer having $n = 25n_c$.*

heavy ion part of the layered target is stronger in the high density case, which hinders the penetration of low energy ions to the high density region. However, those ions that cross that boundary and reach the rear side of the target will be efficiently accelerated. The number of accelerated ions can be increased by using a thicker proton layer on the front side of a double-layer target. Then, the shock will be sustained for a longer time, as in the single species case, where the shock is sustained throughout the whole target width.

During the initial part of the simulation, the sheath-field is set up by the hot electrons that are generated by the laser-pulse. For the single-species target, the sheath field changes its structure in time as the plasma expands at the rear boundary. On the other hand, for the double layered targets, the sheath field is stronger and has less time variation. Our simulations show that as long as $A/Z \gtrsim 10$, the temporal variation of the sheath field will not affect the quality of the shock-accelerated protons. This is indicated by Figure 3, which shows the electric field for a case when the heavy ion layer has atomic/charge number ratio $A/Z = 10$.

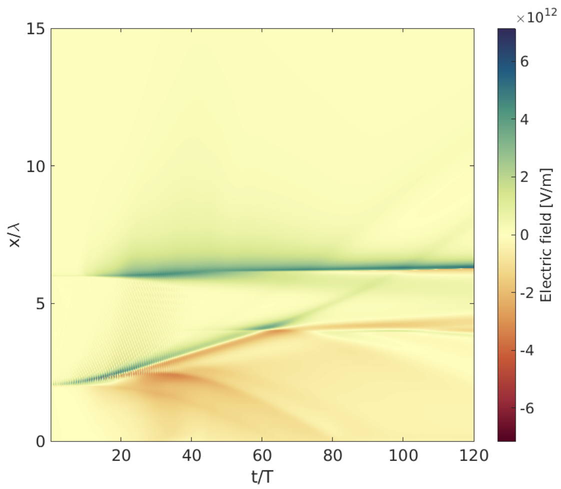


Figure 3: *Longitudinal electric field as a function of position and time for a layered target with a heavy ion layer of $A/Z = 10$ and density $n_e = 2.5n_c$, irradiated by a linearly polarized pulse with $a_0 = 2.5$ and pulse length 50 fs.*

**Conclusions** We find that combining collisionless shock acceleration with a strong quasi-stationary sheath-field may be a way to reach even higher maximum proton energies and optimize the ion spectrum. We show that a layered plasma target with a combination of light and heavy ions leads to a strong quasi-stationary sheath-field, which induces an enhancement of the energy of shock-wave accelerated ions, without broadening their energy spectrum, if the heavy ion layer has high density.

## References

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[2] B. Svedung Wettervik, T. C. DuBois, E. Siminos, T. Fülöp, *Relativistic Vlasov-Maxwell modelling using finite volumes and adaptive mesh refinement*, `arXiv:1606.08681`.

[3] VERITAS `http://ft.nephy.chalmers.se/veritas/`

[4] B. Svedung Wettervik, T. C. DuBois, T. Fülöp, *Phys. Plasmas*, **23**, (2016) 053103.