Simulation study of TNSA from a double-layer target

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For intensities of the PHELIX laser [1] the Target Normal Sheath Acceleration (TNSA) is the relevant acceleration mechanism. In our simulation work we found that the phase-space distribution of the accelerated proton beam strongly depends on the thickness of the contamination layer, deposited on the target surface. In this report we present a parameter-scan over the layer thickness in 1D geometry. The simulations were performed using the VORPAL PIC code [2].

The laser-produced relativistic electrons create strong charge separation field at the plasma surface. The spatial profile of the electric field is known analytically [3] and it allows us to set up the initial electron density profiles with thermal Boltzmann distribution. The temperature ratio of hot (h) and cold (c) electrons is $T_h/T_c = 20$ and the density ratio is $n_c/n_h = 5$. The target consists of heavy ions and a proton layer on the surface.

The electric field penetrating into the target can be approximated with an exponential function [3] with the scale length: λ_D/r where $\lambda_D = (\epsilon_0 T_h/(e^2 n_h))^{1/2}$ and $r = \sqrt{1 + (n_c/n_h)(T_h/T_c)}$. The proton layer thickness should be compared to this length, therefore we introduce the dimensionless parameter:

$$D = \frac{rd}{\lambda_D} \qquad (1)$$

where d is the layer thickness. The quantity D characterizes the layer and defines in which regime will the protons be accelerated.

In Fig. 1 the resulting proton energy distribution is shown for different initial layer thicknesses. The main features of the two extreme cases are clearly visible: quasi-monoenergetic beam in the case of thin layer ($D \ll 1$, quasi-static acceleration [3]) and exponential energy distribution with large energy spread [4] in the case of thick layer ($D \gg 1$, plasma expansion).

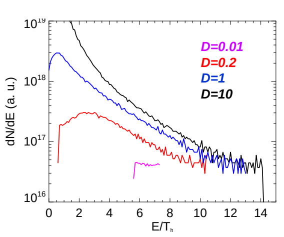

Figure 1: The energy spectrums of protons for different normalized layer thicknesses.

In the intermadiate regime the proton layer detaches from the target and expands in the Debye sheath, while it traps electrons, which means that the energy spread increases. Based on the work of Albright et al. [5] we could deduce an expression for the potential drop between the heavy target and the proton layer after detachment:

$$\varphi_d = 2\ln\left(e^{-\varphi_0/2} + \frac{\sqrt{2}n_h}{n_p(D/r + d_{min}/\lambda_D)}\right) \qquad (2)$$

where $d_{min} = \lambda_D n_p^{-1}\sqrt{2}/(e^{-\varphi_{min}/2} - e^{-\varphi_0/2})$, $n_p = n_c + n_h$ is the initial proton density and φ_0 is the potential at the surface of the heavy ion plasma. The minimum potential is defined by the maximum electron energy (ϵ_{max}): $-\varphi_{min} = \epsilon_{max}/T_h - 1$. In our simulations $\epsilon_{max} = 7.5T_h$ is arbitrary chosen. The potential is normalized to T_h/e.

The comparison of simulation results with our analytical estimation is shown in Fig. 2. We performed simulations with two plasma lengths: $L_p = 4\lambda_D$ (blue) and $L_p = 20\lambda_D$. The discrepancy at larger layer thicknesses is due to the different cooling time of the hot electrons.

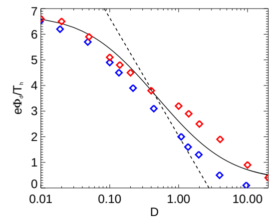

Figure 2: Potential drop measured from 2T simulations with $L_p = 4\lambda_D$ (blue) and $L_p = 20\lambda_D$ (red). The black full line represents Eq. (2) and the dashed line corresponds to the case, when $\epsilon_{max} \to \infty$.

The expression given in Eq. 2 can be used to estimate the energy conversion from the hot electrons to protons. If $D \ll 1$ the mean energy of the short bunch will be $-\varphi_{min}T_h/e$, while in the expansion regime the total energy of protons is the integral of the hot electron energy distribution form φ_d up to ϵ_{max}.

References

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