Developments in Target Normal Sheath Acceleration theoretical modeling: ion cut-off energy dependence on target thickness and transverse size

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Ultra-intense laser driven ion acceleration has turned out to be an extremely interesting phenomenon, capable to produce beams which are potentially suitable as sources for a number of applications. The Target Normal Sheath Acceleration (TNSA), that is the dominant accelerating mechanism so far, has been widely studied both experimentally and theoretically, and several simplified models have been proposed to give reliable predictions on the acceleration features. In this work we focus on the Quasi-Static approach proposed in Refs. [1, 2, 3], which turned out to provide reliable predictions for the maximum energy E_{max} of the accelerated ion beam. The considered model studies the process as an electro-static problem, in which the laser-generated hot electrons overflow into the vacuum, while bulk ions are fixed in their initial position. This determines a strong charge separation, which is the source of the electric field accelerating light ions at the target surfaces. Such a picture is reasonable in the first stage of the TNSA process, on a timescale of the order of 100 fs, too fast to allow a relevant collective ion reaction. Since the most energetic ions are accelerated during this first phase, such a description is suitable for the determination of E_{max}. The resulting solution [3] depends on the temperature T_{h} of the hot electrons and on the energetic cut-off of their distribution φ^*. While the first is evaluated by means of the well-known ponderomotive scaling [4], the second has to be estimated using an empirical law which depends on the laser pulse energy [2]. In Ref. [5] the E_{max} estimate provided by this description is tested on a wide experimental database showing satisfactory agreement. The model in its original formulation is suitable only for optimum thickness targets, while no description for the E_{max} dependence on the foil thickness is provided. Moreover, the logarithmic scaling with the pulse energy, used to retrieve φ^*, requires theoretical support. In the present work we aim at overcoming these limits.

First of all we point out that the main flaws in such a TNSA theory, common to almost all the available TNSA models, concern the description of hot electron generation and transport, that is the physics preceding the electro-static phase. For this reason we implement further information about the hot electron dynamics into the model, at the same time trying to keep the attractive simplicity of the electro-static approach. The main purpose is to obtain a reliable estimate for the hot electron density n_{h0} inside the foil, where the ions shield the electric field, to use it as a boundary condition for the Poisson equation. The number of hot electrons generated by the laser pulse N_{h} can be estimated by imposing a simple energy balance relation: $N_{\mathrm{h}}\langle K\rangle = \eta E_{\mathrm{p}}$. We underline that the reliable estimate of T_{h} and the laser energy conversion efficiency η is still an open problem, which would require a deeper understanding of the laser-matter interaction physics in order to be solved. Here we chose to retrieve the mean kinetic energy $\langle K\rangle$ assuming a 3D relativistic Maxwellian distribution with ponderomotive temperature T_{h} and we evaluate η using the scaling proposed in Ref. [7]. We then assume that these hot electrons are transported through the target by a collision-less ballistic dynamics, due to the relativistic energies and short timescales involved in this phase of electron transport. This leads to an easy estimate of the hot electron density n_{h0}, along the acceleration axis, after the 50-100 fs time needed to reach the electro-static equilibrium (the duration depending also on the target thickness). Such an estimate, the detailed explanation of which will be the topic of a more extended work, depends, among the other parameters, on the target thickness D and on the hot electron divergence angle θ. Moreover n_{h0} takes into account the hot electron recirculation due to the strong electric field at the foil boundaries [6], that is a key factor for TNSA in thin targets. Substituting such n_{h0} value into the boundary condition of the electro-static problem the following equation is obtained:

$$\varphi^* + \log\left[\frac{T_{\mathrm{h}} I(\varphi^*, T_{\mathrm{h}})}{m_{\mathrm{e}}c^2 \mathscr{K}_1(m_{\mathrm{e}}c^2/T_{\mathrm{h}})}\right] = \log\left[\frac{n_{\mathrm{h0}}}{\tilde{n}}\right] \qquad (1)$$

in which I is an integral function defined in Ref. [3], $\mathscr{K}_1$ is a modified Bessel function of the second kind, and $\tilde{n}$ is a normalization factor for the electron density in the Poisson equation. The logarithm at the left hand side is almost equal to zero over a wide range of input parameters, reducing Eq. (1) to a simple expression for most of the typical experimental systems. Since n_{h0} is quasi-linear in the laser energy E_{p} such a relation provides a theoretical explanation to the empirical scaling of Ref. [2], connecting it to the Maxwellian nature of the assumed hot electron distribution. Furthermore Eq. (1) reflects the n_{h0} dependences on D and θ on the parameter φ^*, and thus on the estimate of E_{max}. So, once the normalization $\tilde{n}$ is fixed, it becomes possible to use Eq. (1) to test the E_{max} prediction dependence on target thickness, which has been studied in several experimental works. In order to find the normalization $\tilde{n}$ we rely on the empirical scaling law of Ref. [2], assumed to hold for the experimental optimum thickness $\tilde{D}$, corresponding to low contrast pulse ($< 10^8$ for few ns pre-pulse duration). We thus use the scaling law in Eq. (1) for $D = \tilde{D}$ and retrieve $\tilde{n}$, which is then kept fixed for the whole thickness range considered, since the variations of the hot electron density have to be reflected on the parameter φ^* to affect E_{max}, and not on the normalization of the density.

As a test of the theory we show a comparison involving the experimental results of Ref. [8], in which Al foils of different thicknesses have been illuminated at the ATLAS 10 TW laser facility. In such a work the E_{max} dependence on target thickness is studied for variable laser intensity and pre-pulse duration. In Fig. 1a-b-c theoretical predictions are compared with three experimental thickness scans, performed at fixed pulse duration and focal-spot, but different intensities. The theoretical trend, displayed as the region of solutions obtained for θ ranging from 30° to 90° degrees full open angle, shows a nice agreement with experimental evidences, reproducing the measured intensity dependence in a satisfactory way. The calculations are performed considering a normalization thickness $\tilde{D} = 9\,\mu$m, corresponding to the experimental optimum thickness for the 2.5 ns ASE pre-pulse. Ref. [8] also provides two further scans at fixed intensity but different ASE pre-pulse duration. As it is shown in Fig.1d the theoretical predictions obtained for $\tilde{D} = 9\,\mu$m provide a nice agreement also with the energies measured for shorter pre-pulses.

Moreover, the present model provides a basis for the study of the ion cut-off energy enhancement which takes place when mass-limited-targets (MLTs) are properly illuminated [9]. Since this effect is due to hot electron recirculation in the transverse direction, the ballistic picture of electron transport inside the target volume is suitable to describe the reduction of transverse target dimensions of MLTs. However, the uncertainties in predicting the hot electron divergence angle and the highly dynamical features in the transverse electron motion impose a limit in the reliability of our static description for MLTs. Moreover the few experimental results still do not provide an homogeneous and complete picture to test the model. Therefore quantitative predictions on MLTs maximum energy behavior are still beyond the purposes of the present work.

In conclusion an extension of an electro-static TNSA model has been described. Introducing new informations about hot electron generation and initial dynamics the physical content of the description is enriched, making possible to include the effects of geometrical target features into maximum ion energy predictions.

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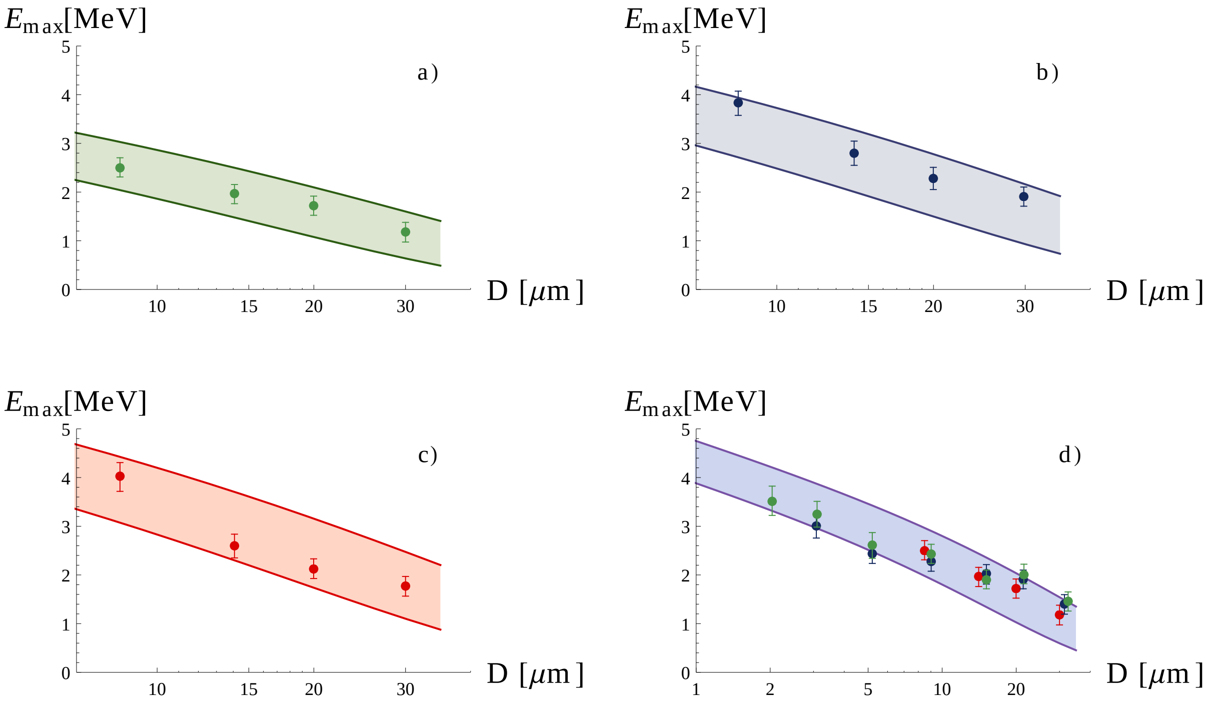

Figure 1: Comparison of the results in Ref. [8] with predicted thickness scalings for the ion maximum energy $E_{\max}$ at $\tilde{D} = 9\,\mu$m. Subplot a) and d) correspond to a laser intensity of $10^{19}\,\mathrm{W/cm^2}$, subplot b) to $1.3 \times 10^{19}\,\mathrm{W/cm^2}$ and subplot c) to $1.5 \times 10^{19}\,\mathrm{W/cm^2}$. In subplot d) the experimental results are obtained at different prepulse durations, 2.5 ns for the red dots, 0.7 ns for the blue dots and 0.5 ns for the green dots. Theoretical predictions are displayed over a range of divergence angles from 30 to 90 degrees.

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