Target Normal Sheath Acceleration effective modeling study

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In the past decade several experiments demonstrated how ultra-intense laser interaction with planar solid targets can provide a solution to obtain accelerated ions up to energies in the multi MeV range. The features of so-produced ion beams happen to be very attractive for several foreseen applications such as hadron therapy, PET isotopes production or fast ignition inertial fusion. However, in order to control the parameters of the accelerated ions, a deep theoretical understanding of the physical process is required.

In the interaction regime allowed by the present laser technology it has been shown that the process takes place via the so-called Target Normal Sheath Acceleration (TNSA) mechanism [1]. According to this scheme the target ions are accelerated by a huge charge separation, due to the relativistic electron sheath created next to the target surface. This sheath is the result of the expansion into vacuum of a fraction of the target electron population, which is heated up to MeV temperatures as a consequence of laser absorption.

Such kind of process involves an extremely complicated plasma dynamics which can hardly be numerically simulated with a complete set of realistic parameters, since it requires a huge computational power. For this reason several models, analytical and semi-analytical, have been published. Such kind of descriptions simplify the physical picture of TNSA in order to explain some of the experimental results and to give reliable predictions to be a guideline for future experiments.

In the present work we show a quantitative comparison among some of the available theoretical models, which exploits a database of experimental results documented in the literature (see Ref. [2] and references therein). Since the maximum energy $E_{\max}$ of the ions is a crucial parameter for the potential applications of laser driven ion acceleration, such a comparison is focused on the predictions of $E_{\max}$ provided by the models. The descriptions which have been considered are the fluid expansion models proposed by Mora [3], the quasi-static approaches of Schreiber et al. [4] and Passoni-Lontano [5] and the "hybrid" descriptions published by Albright et al. [6] and Robinson et al. [7], combining some features of both the former approaches.

Before we focus on the results of this quantitative comparison, which are displayed in Fig. (1), it is important to underline the limits of such an analysis. Indeed, the evaluation of the

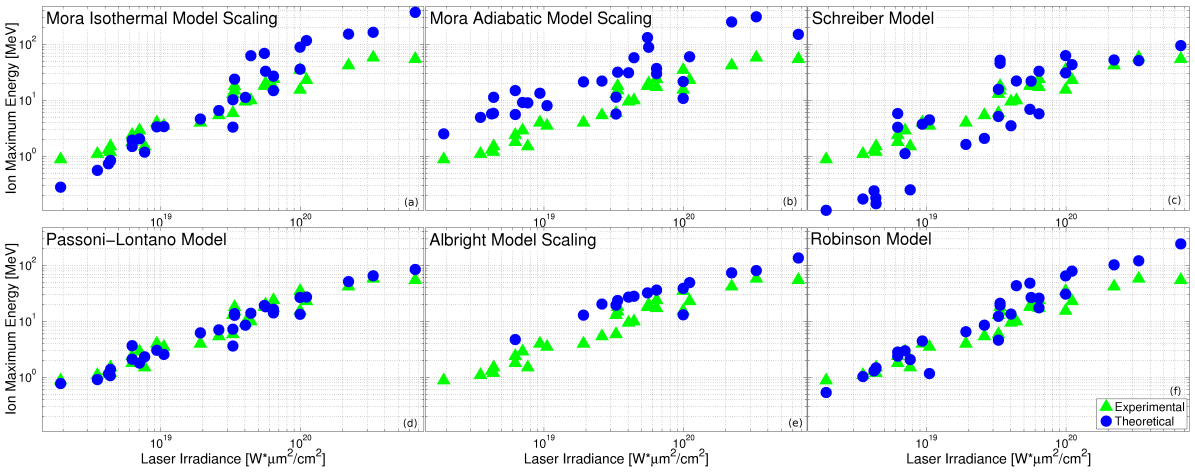

Figure 1: Theoretical predictions of $E_{\max}$ for each model, compared to the experimental results. The energy is plotted against the laser pulse irradiance in double logarithmic scale. Some predictions relative to Albright's description are missing because the parameters fall outside the validity range of the scaling law used.

predicted $E_{\max}$ requires for each model different parameters. Among these parameters there can be, depending on the description considered, quantities as the laser absorption efficiency η, the details of the hot electron distribution function (namely temperature T_{h}, density n_{h}, peak energy and so on), the duration of the acceleration process t_{acc}, that the experimental papers usually do not provide. Thus one has to resort to some empirical or theoretical scaling laws to evaluate such quantities [8–10]. The use of such estimates introduces some arbitrariness and limits in our analysis, and it hampers the effort to obtain an unbiased picture of TNSA effective modeling.

Nonetheless, the results showed in Fig. (1) provide an extensive and useful picture of the models' predicting capability and make it easier to point out advantages as well as drawbacks of each different description, enlightening the critical issues of TNSA modeling. The deviation between experimental measurements and theoretical predictions happen to be quite large, but the wide range of experimental parameters covered by the database suggests that the agreement with the measurements is in some cases still remarkable. In particular we can conclude that the quasi-static description proposed in Refs. [5] and, to a lesser extent, the quasi-static model of Ref. [4], as well as the hybrid scheme presented in Ref. [7] show a satisfactory predicting capability.

On the basis of such a comparative study, further attention is focused on the quasi-static description proposed in Refs. [5]. In this scheme, the electric field set up by the hot electron sheath is assumed static, and the accelerated ions are studied as test particles moving along the self-consistent potential slope, while most of the target ions are supposed immobile during the

timescale of interest, thus preserving the charge separation.

In Passoni-Lontano's model the basic idea that the most energetic fraction of the hot electrons can overcome the potential barrier and escape the system is introduced. Such an assumption provides a physical truncation mechanism for the acceleration process, leading to a limited potential difference. As a consequence, the test ions accelerated by the electrostatic field, reach a well defined maximum energy $E_{\max}$. Both in classical and in relativistic frameworks an analytical form for $E_{\max}$ can be obtained from the self-consistent potential ϕ, which is derived solving the Poisson equation. However an external parameter, namely the maximum bound electron energy E_{h}^{*}, is required to fix the boundary condition of the differential equation well inside the target domain. At this boundary the plasma is assumed to be quasi-neutral, and the potential is imposed by the constraint [5]:

$$e\phi = E_{\mathrm{h}}^{*} = T_{\mathrm{h}}\varphi^{*} \tag{1}$$

in Refs. [5] a scaling law for φ^{*} in function of the laser pulse energy E_{L} has been deduced from experimental results:

$$\varphi^{*} = 4.8 + 0.8\ln(E_L) \tag{2}$$

Therefore, it would be an interesting theoretical task to justify eq. (2), giving more satisfactory foundations on this TNSA theory. To this purpose, we consider the whole process of TNSA, including the laser-interaction phase, the electron transport dynamics, and the subsequent ion acceleration. Passoni-Lontano model actually describes just the last phase of the process, reducing the earlier dynamics to the assumption of an hot electron population in thermal equilibrium at temperature T_{h}, including just electrons with energies up to E_{h}^{*}. In order to improve the description, further detail about the laser-interaction can be introduced thanks to the relation $N_{\mathrm{h}}\langle K\rangle = \eta E_{\mathrm{L}}$, that is a balance between the absorbed laser energy and the mean kinetic energy $\langle K\rangle$ (related to T_{h}) assigned to each of the N_{h} hot electrons. If we define the density $n_{\mathrm{h0}} = N_{\mathrm{h}}/V_{\mathrm{int}}$, in which V_{int} is the laser-matter interaction volume, we can equate it to $n^{*} = \tilde{n}\exp(\varphi^{*})$, that is the hot electron density evaluated deep inside the target, where condition (1) holds. This leads to a new relation for the parameter φ^{*}:

$$\varphi^{*} = \log\left(\frac{\eta}{V_{\mathrm{int}}\langle K\rangle\tilde{n}}\right) + \log\left(E_{\mathrm{L}}\right) \tag{3}$$

where $\tilde{n}$ is the normalizing constant of the hot electron charge density. We underline that eq. (3) holds in both the classical and relativistic descriptions. Such a relation provides a reasonable theoretical explanation to a behavior similar to the scaling of eq. (2) and, at the same time, connects the results of the Passoni-Lontano model to some key parameters of the system as V_{int},$\langle K\rangle$ and η. Usually, the volume of interaction is roughly estimated as $V_{\mathrm{int}} = A_{\mathrm{fs}}c\tau_{\mathrm{L}}$, in

which A_{fs} is the focal spot area and τ_L is the laser pulse duration, introducing also these two laser parameters in the model. However, the estimate of V_{int} is turns out to be a subtle issue and it goes beyond the scope of the present work.

Furthermore the relations (2) and (3) can be exploited to estimate the normalizing coefficient $\tilde{n}$, with the other quantities given as experimental parameters. Once $\tilde{n}$ in known, it's actually possible to evaluate, according to the effective model, the dimensional self-consistent potential, the electro-static field and the hot electron density. This extends considerably the predicting capability of the theoretical model and further comparison with numerical and experimental results are allowed, leading to a more detailed test of the model's predictions.

The theoretical achievements showed in the present work will be associated with the experimental data collected in the next proton acceleration campaign at the LOA European high power laser facility.

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