Towards Laser-Driven, Quasi-Monochromatic Ion Bunches via Ultrathin Targets Nano-Structuring?

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Abstract. The conditions for achieving the laser acceleration of quasi-monochromatic ion bunches with present-day, fs laser systems are theoretically discussed. The study suggests the possibility of achieving quasi-monochromaticity via irradiation of double-layer, nano-structured foils and the conjecture is numerically confirmed by means of two dimensional, Particle-In-Cell (PIC) simulations. A feasible setup in order to experimentally validate this approach is thus proposed.

Keywords: ion acceleration, proton acceleration, high energy bunches, laser-plasma acceleration, laser-driven bunches, ultrathin targets, PIC, monochromatic bunches
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1. INTRODUCTION

Despite laser-accelerated ion bunches [1–8] possess unique and highly spectacular characteristics, such as a low divergence and an ultra-low emittance, which are typically of the order of 10° and below 0.004 mm · mrad [9, 10], respectively, they also suffer of many drawbacks [11] which at present strongly prevent them from being employed in many applications. Among them, the almost thermal feature typically characterizing the spectra of laser-accelerated ion jets is probably one of the most serious, as applications conversely require the employment of quasi-monoenergetic ion bunches, a relative energy dispersion $\Delta E/E$ (full width half maximum) below 2% being a standard request. For such purpose, experiments [12, 13] aimed at reducing the laser-driven ion bunches relative energy spread have recently been carried out.

Here, we would like to focus our attention on presenting a combined theoretical and numerical investigation of the conditions which might be expected to be sufficient in order to achieve the experimental generation of quasi-monochromatic, multi-MeV ion bunches with the help of a present-day, fs laser system.

The paper is organized as follows. In Sec. 2 we will discuss the conditions for achieving the quasi-monochromatic laser acceleration of ion bunches, to which we will refer as Quasi-Monochromaticity Conditions (QMC). In Sec. 3 we will present the results of two dimensional, PIC simulations which indicate that with a laser-target setup structured according to the four QMC it is possible to achieve, with a fs, present-day laser system, the generation of multi-MeV ion bunches with a relative energy spread of roughly 11%. In Sec. 4, we propose an experimentally new and feasible approach towards the generation of laser-driven, quasi-monochromatic ion bunches which relies on the nano-structuring of a solid foil, and compare the approach here presented with those so far adopted [12, 13]. Finally, Sec. 5 is devoted to conclusions.

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2. QUASI-MONOCHROMATICITY CONDITIONS

Laser-generation of quasi-monochromatic ion bunches inherently relies on the employment of multi-layer targets, as in case of one-layer foils the energy spectrum of the accelerated ions is essentially thermal (see, for example, [6–8] and references therein). However, for the sake of simplicity, here we restrict our investigation to double-layer targets, in which a substrate is expected to be coated on one side with a dopant layer. The foil is thus assumed to be laser-irradiated on the substrate uncoated side. Laser-generation of quasi-monochromatic ion bunches can thus be achieved by separating the role of the *accelerator*, which in our case will be played by the laser-irradiated substrate foil, from the role of the *accelerated material*, which in our scheme will be played by the dopant layer. This can be done by ensuring the dopant plasma expansion timescale to be much shorter than the substrate one. This condition, by introducing the substrate and the dopant ion plasma frequencies, given, in MKSA units, by $\omega_{\rm si} = \sqrt{n_{\rm s}Z_{\rm s}e^2/\varepsilon_0 A_{\rm s} m_{\rm p}}$ and by $\omega_{\rm di} = \sqrt{n_{\rm s}Z_{\rm d}e^2/\varepsilon_0 A_{\rm d} m_{\rm p}}$, respectively, where $Z_{\rm s}$ and $Z_{\rm d}$ are the substrate and the dopant charge states, $A_{\rm s}$ and $A_{\rm d}$ their respective mass numbers, $n_{\rm s}$ and $n_{\rm d}$ their number densities, e the modulus of the electron charge, $m_{\rm p}$ the proton mass and ε_0 the vacuum absolute dielectric constant, can be written as $\omega_{\rm si}/\omega_{\rm di} \ll 1$ or, equivalently, as

$$\frac{n_{\rm s}Z_{\rm s}/A_{\rm s}}{n_{\rm d}Z_{\rm d}/A_{\rm d}} \ll 1, \tag{1}$$

to which we refer as "first quasi-monochromaticity condition".

However, in order to generate a quasi-monochromatic ion bunch we also need to ensure the dopant layer particles to experience almost the same electric field in the whole acceleration process. Unfortunately, the gradient of the charge-separation electric field which instaurates on the back of the target, and which is responsible of the dopant layer acceleration process, is very strong both in the longitudinal and in the transverse directions. Therefore, the ions of the dopant layer will in general experience different acceleration process. For the sake of simplicity, let us assume the dopant layer to be cilindrically symmetric and introduce its thickness δ and its radius r_0. If we denote with L and R respectively the longitudinal and transverse scale over which the electric field component which is responsible for ion acceleration varies, a quasi-monochromatic acceleration process can be achieved only as long as conditions

$$\delta/L \ll 1 \tag{2}$$

and

$$r_0/R \ll 1, \tag{3}$$

are satisfied, to which we refer as "second" and "third quasi-monochromaticity condition", respectively.

Finally, we observe that, even if conditions (1), (2) and (3) were satisfied, the quasi-monochromatic character of the laser-accelerated dopant ions spectrum might be spoiled by their self, repulsive electric field. Despite the latter might be expected to be at least partially shielded by the cold electron cloud accompanying the accelerated ions, its contribution to the spectrum widening might be significantly reduced also by properly controlling the dopant layer density. In fact, if for the sake of simplicity we restrict ourselves to an unidimensional treatment and introduce the electron density $n_{\rm e}$, together with a coordinate axis x oriented along the outward normal to the back target surface, Poisson equation, in MKSA units, reads

$$\frac{{\rm d}E}{{\rm d}x} = \frac{e}{\varepsilon_0}(Z_{\rm s}n_{\rm s} + Z_{\rm d}n_{\rm d} - n_{\rm e}),$$

where we have denoted with e the absolute value of the electron charge. By taking the x-coordinate axis origin to be located on the substrate symmetry plane, and by denoting with a the substrate thickness, one has

$$E(\frac{a}{2}+\delta) - E(0) = \frac{e}{\varepsilon_0}(Z_{\rm s}n_{\rm s}\frac{a}{2} - \int_0^{a/2+\delta} n_{\rm e}\,{\rm d}x + Z_{\rm d}n_{\rm d}\delta) = E_{\rm s} + E_{\rm d},$$

where we have introduced the electric field which is responsible of the acceleration process $E_{\rm s}$ and the dopant ions repulsive field $E_{\rm d}$, given by $E_{\rm s} = \frac{e}{\varepsilon_0}(Z_{\rm s}n_{\rm s}\frac{a}{2} - \int_0^{a/2+\delta} n_{\rm e}\,{\rm d}x)$ and by $E_{\rm d} = \frac{e}{\varepsilon_0}(Z_{\rm d}n_{\rm d}\delta)$, respectively. The dopant self repulsive field can be therefore neglected if compared with the accelerating field as long as one has

$$\eta = \frac{E_{\rm d}}{E_{\rm s}} = \frac{e(Z_{\rm d}n_{\rm d}\delta)}{\varepsilon_0 E_{\rm s}} \ll 1, \tag{4}$$

to which we refer as "fourth quasi-monochromaticity condition".

3. NUMERICAL SIMULATIONS RESULTS

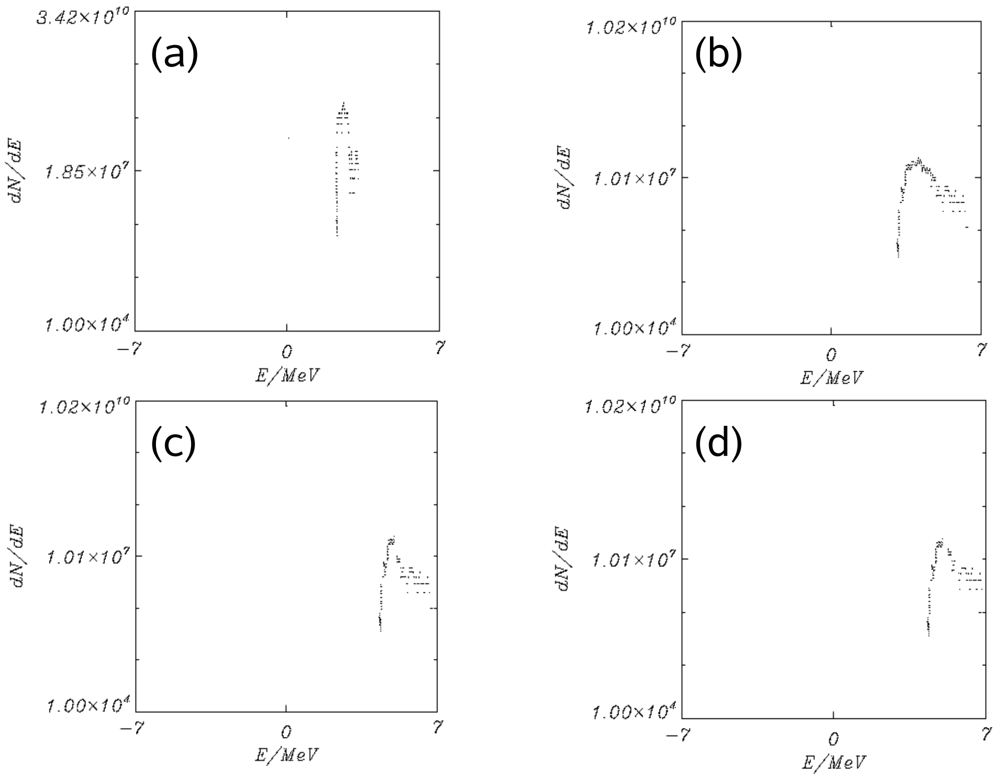

FIGURE 1. Top: Simulated energy spectrum of the proton bunch at 180 fs (panel (a)) and 300 fs (panel (b)). The proton disk thickness is 4 nm. Bottom: Simulated energy spectrum of the proton bunch at 266 fs (panel (c)) and 400 fs (panel (d)). The proton disk thickness is 2 nm.

In order to validate the theoretical predictions, we have thus run two sets of PIC simulations with laser-foil setups in which the target was structured according to the four QMC. A detailed description of the parameters choice can be found in [14]. All the runs performed are 2D in the Cartesian coordinates and 3D in the particles' momenta, while the box resolution is equal to 0.67 nm in both directions. The laser pulse is, in both simulation sets, Gaussian in both space and time, with a pulse waist and a duration given by $w_0 = 4\ \mu$m and $\tau_L = 25$ fs, respectively, and a peak intensity of 8×10^{19} $\mathrm{W/cm^2}$. The target substrate in both the simulation sets consists of a three times ionized, 100 nm thick Al foil at density equal to 3 $\mathrm{g/cm^3}$. A dopant layer consisting of a 400 nm diameter Hydrogen microdot, whose thickness is taken to be equal to 4 nm in the first set of simulations and to 2 nm in the second set, has been adopted. The density of the dopant layer has been chosen to be equal to 0.3 $\mathrm{g/cm^3}$. Electron pre-pulse heating has been artificially modeled by assigning the specie an initial temperature of 3 keV. It is worth to note that the choices adopted, which have been forced by computational reasons, are not optimal for what regards the fourth quasi-monochromaticity condition, i.e. Eq. (4).

The spectrum of the laser-accelerated protons typically obtained in each of the two simulation sets is shown, at two different times, in Fig. 1. At is clear from the figure, the parameters chosen have numerically proved to lead to the laser-generation of a proton bunch with a remarkable quasi-monochromaticity. Furthermore, the two simulation sets numerically confirm the theoretical prediction which is summarized by the second QMC, i.e. that reducing the dopant disk thickness increases the proton spectrum quasi-monochromaticity. In particular, as it is shown in the Figure, the employment of a 2 nm Hydrogen disk is numerically predicted to lead to the production of a proton bunch with a peak in the energy spectrum at roughly 5 MeV and with a relative energy spread FWHM (Full Width at Half Maximum) of about 11%. As discussed in detail in [14], the reasons for such a reduction of the relative energy spread with respect to the results [12, 13] can be attributed to the fact that, differently from those approaches, the present one satisfies all the four QMC.

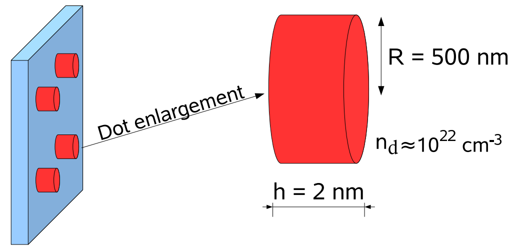

FIGURE 2. Sketch of the nano-structured target proposed.

4. DISCUSSION

On the basis of the combined theoretical and numerical discussion presented, we thus propose the employment of a double-layer, ultrathin target to be nano-structured on one side, as qualitatively shown in Fig. 2. In particular, in order to satisfy all the four QMC, we propose a 100 nm thick Au substrate on which to implant, on one of its sides, cylindrically-symmetric, 500 nm of diameter, 2 nm thick CH nano-dots at density of about 10^{22} cm^{-3}, the latter corresponding, in terms of H matter density, to roughly 0.02 g/cm^{-3}. According to the discussion presented in Secs. 2 and 3, the target should be laser-irradiated on its non-structured side.

5. CONCLUSIONS

In conclusion, we have theoretically discussed the conditions to achieve the laser-generation of quasi-monochromatic ion bunches with present-day, fs laser systems. For that purposes, four QMC conditions have been identified. Two dimensional, PIC numerical simulation indicate that with a laser-foil setup structured according to such four QMC it is possible to achieve the laser-generation of multi-MeV ions with a relative energy spread (FWHM) of about 11%. On such basis, a feasible setup in order to experimentally test the theoretical predictions has therefore been proposed.

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