This is the published version of a paper published in Physical Review Letters.

Citation for the original published paper (version of record):

Multicascade proton acceleration by a superintense laser pulse in the regime of relativistically induced slab transparency.
Physical Review Letters, 102: 184801

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:
http://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-84236
Multicascade Proton Acceleration by a Superintense Laser Pulse in the Regime of Relativistically Induced Slab Transparency

A. A. Gonoskov, A. V. Korzhimanov, V. I. Eremin, A. V. Kim, and A. M. Sergeev

Institute of Applied Physics, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia

(Rceived 12 December 2008; published 7 May 2009)

The regime of multicascade proton acceleration during the interaction of a $10^{21}–10^{22}$ W/cm$^2$ laser pulse with a structured target is proposed. The regime is based on the electron charge displacement under the action of laser ponderomotive force and on the effect of relativistically induced slab transparency which allows realization of the idea of multicascade acceleration. It is shown that a target comprising several thin foils properly spaced apart can optimize the acceleration process and give at the output a quasi-monoenergetic beam of protons with energies up to hundreds of MeV with an energy spread of just a few percent.

Introduction.—Modern laser technology offers a wide range of possibilities for exploring those regimes of interaction between a laser pulse and a plasma where effects such as relativistic and striction nonlinearities play a fundamental role in determining the dynamical evolution of the system (see, for example, [1], and references therein). These effects become very important in the proposed scientific and technical applications which range from plasma-based particle accelerators [2] to inertial confinement fusion [3,4], including compact ion accelerators for hadrontherapy in biomedicine and proton imaging [5,6]. The present Letter is concerned with the problem of obtaining high-energy proton or light ion monoenergetic beams from the interaction of superintense laser radiation with solid-state targets. It should be noted that this problem was an area of active research during the past decade. The emitted ion and, in particular, proton pulses contain a large number of particles between $10^{10}$ and $10^{13}$ with energies in the multi-MeV range [7–13]. Different mechanisms for ion acceleration have been examined in kinetic simulations; these include target normal sheath acceleration (TNSA) at the rear side [14,15], hole boring and shock acceleration at the front side [16–18], and in the so-called piston regime [19] as well. Last year a few papers were published where new mechanisms of ion acceleration for $10^{21}–10^{22}$ W/cm$^2$ laser pulses were actively discussed [20–24]. Unlike the TNSA regime, the proposed techniques are based on electron charge displacement due to ponderomotive force of laser radiation which is much more effective when circularly polarized light is used for ion acceleration at the considered intensities.

Concept.—In this Letter we propose a new regime of ion acceleration that is effective for the laser intensity range of $10^{21}–10^{22}$ W/cm$^2$, which is accessible in several labs today. This regime is capable of accelerating both light ions and protons, but for the sake of brevity we will further speak about protons only.

The proposed regime consists of three phases of acceleration. The first phase is acceleration inside the target. In this range of intensities, under the action of the ponderomotive force of a circularly polarized laser pulse the electrons within the thin solid-density target may be appreciably shifted from their initial positions without strong heating, whereas the heavy ion component remains almost unchanged, thus producing a substantial charge separation field. This quasi-static field within the target may be used for effective acceleration of protons that were initially at the front side of the target [21], unlike the TNSA regime where protons are accelerated from the rear side. We will refer to this process as to a capacitorlike acceleration phase.

The second acceleration phase sets in for thin targets when the electron layer is ponderomotively compressed for high-intensity lasers down to the skin-layer thickness. In this case, the effect of relativistically induced slab transparency (RIST) takes place. The crucial point of this effect is the sharp dependence of transparency coefficient on incident intensity. Thus, if the incident laser pulse is short enough, it results in the transmitted laser pulse with sharp intensity distribution which is able to push electrons forward as well. These electrons may be emitted at distances of several microns to produce an additional charge separation field that can accelerate protons passing through the created capacitorlike structure to higher energies.

The key point is also that the pulse that has passed through the layer may be used again in the next foil by producing potential difference in the latter and also making it transparent. The protons accelerated in the first layer get into the accelerating potential produced in the second layer and gain additional energy. This will be referred to as the third phase of acceleration. In this fashion it is possible to realize the idea of cascadable proton beam acceleration. By adjusting the distance between the targets it is possible to control acceleration efficiency and proton beam properties, which is especially important in the context of practical applications. We will also demonstrate that with optimal choice of target structure the proposed scheme allows one to obtain proton beams with energies of hundreds of MeV.
and a few percent energy spread in laser facilities available today.

Accelerating potential in the RIST regime.—Consider irradiation by a superintense laser pulse of a thin foil with ions heavy enough to be supposed to be immobile. Further we will consider the laser pulse to be circularly polarized so as to be sure that the electron dynamics is dominated by radiation pressure and also to avoid effective electron heating by the $j \times B$ mechanism. We will also suppose the problem to be one dimensional assuming the foil thickness to be much less than the transverse size of the laser beam. It is also important to note that, although filamentation instability may occur in 3 dimensions, particle-in-cell (PIC) simulations [23,24] showed that the 1D model not only well describes the fundamental features of the laser-foil interaction but is capable of providing quantitative description as well. In this system one of the two regimes is realized: if the intensity does not exceed some threshold value, an electromagnetic wave is reflected almost completely (the reflection regime); otherwise, a substantial part of the incident energy flux can be transmitted through the layer (the RIST regime).

In the reflection regime, an electromagnetic wave penetrates into the electron layer only at the thickness of the skin layer which is less than the foil width. The plasma-field distributions during such interaction at relativistic intensities were considered in [25]. The analysis was based on Maxwell’s equations and hydrodynamic equations for the electron component of plasma where the ion motion and plasma temperature were neglected. An example of such a steady-state structure is given in Fig. 1(a). Besides, charge redistribution in the plasma results in a considerable drop in electrostatic potential that may be used for acceleration of positively charged particles in case they pass through the layer from the front to the rear boundary. The displacement of electrons [see Fig. 1(a)] and, hence, the magnitude of the potential drop depend on the incident radiation intensity and increase with increasing intensity by the law [21]

$$kz_b = \frac{2\sqrt{I}}{n},$$

(1)

where $z_b$ is the coordinate of the shifted electron boundary, $k$ is the wave number of the incident wave, $I$ is the laser intensity normalized to the so-called relativistic intensity $I_{rel} = 2.75 \times 10^{18} \lambda^{-2}$ (with $I_{rel}$ in W/cm² and $\lambda$ in μm), and $n$ is the unperturbed electron density normalized to its critical value at a given laser frequency (for overdense plasma $n \gg 1$).

However, taking into account that $z_b$ cannot exceed the layer thickness $L$ and making use of Eq. (1) at $z_b = L$, we can conclude that the reflection regime occurs only when the incident intensity is less than a certain threshold value

$$I_{th} = \left( \frac{nKL}{2} \right)^2.$$  

(2)

If the incident intensity is comparable to or exceeds the threshold value, the RIST regime is realized. The important point is that the coefficient of transparency is quite rapidly increasing with intensity [see Fig. 1(b)] [25]. This means that the profile of the transmitted pulse may be significantly sharpened, which results in enhanced ponderomotive force acting effectively on electrons. This force is able to push part of the electrons out of the slab, thereby generating an additional accelerating field outside the slab. The areal density of the ejected electrons $\sigma$ may be estimated to be

$$\sigma = \frac{1}{4\pi c} \max \left[ \frac{\partial A_{tr}(z, t)}{\partial t} \right].$$

(3)

Here, $A_{tr}(z, t)$ is the shape of the transmitted pulse. Simple calculations show that the transmitted pulse growing up to the maximal value of about $10^{22}$ W/cm² during two wave periods is able to carry away about 10 mC/cm² and produce an electric field of the order of $10^{14}$ V/m which is comparable with that inside the slab. The one-dimensional fully relativistic PIC code verified that the accelerating potential outside the slab may be comparable with or even more than that inside the slab. This effect occurs in the case of ultrashort (≤30 fs) laser pulses when the transition from reflection to transparency is rapid.

Proton acceleration in a single layer.—Results of the interaction of a 30 fs (at the Gaussian profile FWHM) laser pulse with a 100 nm gold foil are shown in Fig. 2. The gold foil was placed at the interval [0 nm; 100 nm]. The simulation was done for a system domain 16 μm long with absorbing boundaries for fields and particles. A laser pulse with wavelength 1 μm and maximum intensity $10^{22}$ W/cm² enters from the left boundary and interacts with a target located 2 μm from the left boundary. The target is composed of electrons and gold ions of Au^{6+} with plasma density $n = 100$. The simulation cell size is
protons and electrons in equal densities of thick spaced apart by 200 nm. The first layer consisted of layers like in Fig. 2. The target comprised two layers 100 nm presented in Fig. 3 we used a laser pulse with the parameters in which we found an optimal position of the proton layer. In the numerical experiment numerical computations in which we found an optimal position of protons was chosen empirically on the basis of theory concerning the initial position of a proton layer will be considered elsewhere. In the current work the initial position of protons has different initial positions in the case of a target comprising proton and gold layers spaced apart and irradiated by a 30 fs laser pulse of peak intensity $10^{22}$ W/cm$^2$. The black-to-white shades show the longitudinal accelerating electric field as well; (b) diagram of final energy as a function of initial proton position; (c) final proton energy distribution.

We have observed the described dynamics in a series of numerical computations in which we found an optimal position of the proton layer. In the numerical experiment presented in Fig. 3 we used a laser pulse with the parameters like in Fig. 2. The target comprised two layers 100 nm thick spaced apart by 200 nm. The first layer consisted of protons and electrons in equal densities of $1.12 \times 10^{22}$ cm$^{-3}$ (the overdense parameter being about 10). The second layer was taken like in Fig. 2. Our simulations demonstrated that more than half of the protons from the proton layer formed a quasi-monoenergetic proton beam that was accelerated up to energies of about 50 MeV.

Note that the plasma slab works also as a temporal lens for protons and we obtained the effect of temporal proton beam focusing. The focusing occurs because the faster protons in the leading part of the proton bunch have smaller acceleration than the lagging protons that move with smaller velocity and get into a high accelerating field. This results in formation of a proton beam with small energy spread that is strongly localized in space (or in time—short proton pulse) as well.

Multicascade regime.—As was stated above, one of the essential advantages of the proposed scheme is that after the RIST effect occurs, the laser radiation begins to penetrate through a gold foil almost without any reflection, so that the process of proton acceleration may be repeated again in the next plasma layer. For this we should place the heavy ion foil following the first substrate at a distance such that the protons could get into it at the instant the laser pulse passes through the first accelerating layer and produces the largest potential drop in the second layer. To achieve the best result we must fit both, the interval between the layers and layer thickness. However, numerical modeling shows that quite a good result may be obtained using the second plasma layer having the same thickness as the first one. For optimal parameters of the first layer the accelerated proton beam escapes it almost at the instant it becomes transparent. It takes the transmitted laser pulse propagating with the speed of light less time to pass the interval between the layers than needed for the proton beam. As some part of the incident intensity is reflected from the first layer in the RIST regime, some time is needed for the transmitted intensity to reach the threshold value in the second layer. This time delay allows one to synchronize the moment of proton beam arrival at the second slab with the moment when the RIST effect occurs in this slab. This means that there exists a distance between the layers at which the proton beam transits into the second layer at the instant the RIST effect occurs. It is also important to note that accelerating layers do not work independently. The dynamics of the laser-slab interaction...
laser beams with energies up to several hundreds of MeV.

be used in real experiments for producing monoenergetic

chosen layer thicknesses and intervals between them may

enable us to state that multicascade targets with optimally

of the proposed scheme of proton acceleration. In other

real target but it gives a good illustration of the capabilities

parameters cannot determine accurately parameters of a

was used in the next slab, and so on. To realize this

regime in experiments, the main scaling should be such

that the incident intensity will exceed the threshold (2)

proportional to the foil density and thickness. Particle-in-

cell simulations show that this regime of ion accelera-

tion is especially effective in the range of intensities

10^{21}–10^{22} \text{ W/cm}^2\text{ and pulses with ultrashort durations}

less than 30 fs and allows one to generate actually mono-

energetic beams of ions. The main advantage of this

mechanism of acceleration is that the ion energy can be

eventually multiplied by using several space-separated

foils.

Conclusion.—We have examined a new laser driven

proton or the light ion acceleration regime that results

from the interaction of high-intensity circularly polarized

laser pulses with thin foils. This regime relies on the

acceleration by longitudinal charge separation fields gen-

erated in the ponderomotively predominant regime of

laser-plasma interaction which proceeds in two distinct

phases. In the first phase, the longitudinal accelerating field is produced inside the target due to electron displacements by the ponderomotive force of the incident laser pulse. When the electron displacement reaches the rear side, the thin foil is rapidly becoming transparent allowing the leading edge of the laser pulse passing through to be very sharp. This second phase, which we call the RIST effect, results in the enhanced ponderomotive force acting on the rear side electrons thus expelling them out of the target. These expelling electrons can contribute significantly to the accelerating field. The key point of the RIST regime is that the slab becomes almost transparent for radiation and thus allows it to pass through the layer, so that this radiation may be used in the next slab, and so on. To realize this regime in experiments, the main scaling should be such that the incident intensity will exceed the threshold (2) proportional to the foil density and thickness. Particle-in-cell simulations show that this regime of ion acceleration is especially effective in the range of intensities 10^{21}–10^{22} W/cm^2 and pulses with ultrashort durations less than 30 fs and allows one to generate actually monoenergetic beams of ions. The main advantage of this mechanism of acceleration is that the ion energy can be eventually multiplied by using several space-separated foils.