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On the effect of rear-surface dielectric coatings on laser-driven proton acceleration

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Laser-driven ion acceleration has been experimentally investigated by irradiating, with tightly focused femtosecond laser pulses at 5×10^{19} W/cm^2, thin metal foils, which have been back-coated with a μm thick dielectric layer. The observation we report shows the production of MeV proton bunches with an unexpected highly uniform spatial cross section. © *2009 American Institute of Physics*. [doi:10.1063/1.3251425]

All-optical laser-based ion accelerators[1–13] are presently considered as a promising opportunity for applications because of the extremely low emittance (<0.004 mm rad) and the high currents (>1 kA) typically characterizing laser-accelerated bunches,[14,15] together with the potentially smaller environmental and economical impact of a laser-driven accelerator if compared with a conventional one. These circumstances make laser-accelerated ion bunches even more attractive when table-top high-repetition rate laser systems are used in place of large single-shot systems.

At present, restless effort is being devoted worldwide to the improvement of the quality of these laser-accelerated bunches, with particular reference to the spectral and angular features as well as to the total ion yield and spatial cross section uniformity. Indeed, high quality of the ion bunch is desirable, in particular if conventional devices are to be used for applications, e.g., for advanced probing[16] or for an efficient extraction, transport, and focusing of the laser-accelerated ions in an user-oriented setup, as recently explored in Ref. 17.

Since the initial experiments showing emission of protons originating from the rear target surface,[18] additional experiments have clarified the role of prepulse,[19] leading to efficient acceleration from ultrathin targets using high-contrast laser systems.[20] Moreover, significant reduction in the overall energy spread was demonstrated[21–23] using custom targets.

Many of the above experiments and models show that a systematic approach to quality control of laser-driven ion bunches may rely on the use of double-layer targets,[24,25] as originally proposed in Ref. 26. In particular, on the experimental side, the use of target back-surface coating was found in the picosecond laser pulse regime to have a beneficial effect on proton acceleration by significantly increasing the accelerated ions yield.[27] More recently, the role of double-layer targets has been further investigated experimentally in the femtosecond regime, again showing strong proton yield enhancement.[28,29]

Unfortunately, despite the aforementioned beneficial effects in terms of the number of high energy protons per jet, systematic experimental studies[30] have also revealed that the presence of plastic coatings may have a strong detrimental effect on the uniformity of the spatial cross section of the accelerated ions. Such an effect, which was observed for plastic coatings thicker than 0.1 μm,[31,30] has been attributed to the disruption of the fast electron current, which in many experiments has been observed to occur inside dielectric layers.[32] The laser-target coupling mechanisms giving rise to the fast electrons[33] and the transport dynamics of the fast electron current occurring inside the target[34,35] have thus emerged as a fundamental issue to be carefully addressed also in the study of laser-driven ion acceleration.

Here, we show preliminary results of an experiment carried out using a table-top femtosecond laser system in which the opposite effect is found and the production of MeV proton bunches with a highly uniform spatial cross section has been achieved in the presence of a rear-surface dielectric coating. In the following, we will present measurements of both energy and spatial cross sections of a proton bunch, which is typically obtained in our experimental conditions by irradiating a metal foil with a rear-surface plastic coating. To our knowledge, this is the first direct observation of laser acceleration of a proton bunch with a high spatial cross section uniformity with targets that have been back-coated with a μm thick insulator layer. As discussed below, our results give new enlightening insights into the transport dynamics of the fast electron current occurring inside back-coated targets.

In our experiment, an $f/1.2$ off-axis parabola was employed to focus, with an angle of incidence of 10° on the target, 80 fs laser pulses into 5 μm^2 diameter focal spot. The

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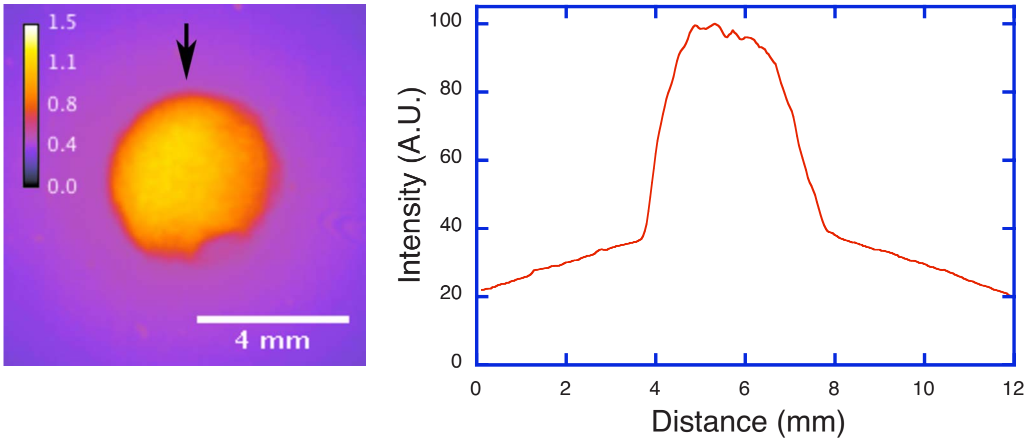

FIG. 1. (Color online) (Left) ion bunch image after irradiation of a rear-side coated, 10 μm thick Ti target. The image shows the optical density of the RCF after exposure. (Right) lineout taken along a diameter as indicated by the arrow of the image on the left, showing the flat-top ion bunch pattern superimposed on the smooth background generated by the fast electrons.

average intensity on target was up to 5×10^{19} W/cm^2, with an intensity contrast ratio, i.e., the ratio between the main pulse intensity and the intensity of the amplified spontaneous emission, of 10^{10}.[36] The normalized vector potential was $a_0 = eA_L/m_e c^2 \approx 0.85\lambda_0\sqrt{I_L} = 4.8$, e and m_e being the electron charge and mass, A_L being the laser vector potential, c being the speed of light, λ_0 being the laser wavelength in μm, and I_L being the intensity in units of 10^{18} W/cm^2, respectively.

Targets consisting of 10 μm thick rear-surface coated Fe foils were used. The coating consisted of a nitrocellulose lacquer, a material characterized by a high content of light elements such as H and C [e.g., $C_6H_7(NO_2)_3O_5$]. The thickness of the coating was measured to be 1.5 μm, and its resistivity was found to be greater than 1.5×10^7 Ω/m. Due to the properties of lacquers, the coating should be regarded as a dielectric layer characterized by hardness, flexibility, and high adhesion to the substrate.

Particle detection was carried out using radiochromic films (RCFs), which were stacked behind the target at a distance of 7 mm and were shielded from direct laser radiation by a 20 μm thick Al foil. The response of RCF was fully characterized[37] using Monte Carlo simulations based on the numerical code GEANT4.[38] As discussed in details elsewhere,[35,39,40] our dosimetric measurements also give information about the spatial uniformity, energy, and angular distribution of the forward-propagating fast electrons with energy between approximately 100 keV and up to several MeV, plus an estimate of the total number of fast electrons in the detected spectral range.

Figure 1 (left) shows the optical density scan of the first RCF layer of the stack after irradiation of a target. The image shows a main ion signal superimposed on a smooth background signal visible on the entire exposed area of the RCF.

The ion signal consists of a regular (circular) and uniform region, whose baseline level size is 4.3 mm in diameter. As it is clear also from the lineout of Fig. 1 (right), the spatial cross section of the ion bunch shows a remarkable uniformity.

Given their much more favorable charge to mass ratio, we might expect the bunch detected in Fig. 1 to be mainly consisting of protons. This consideration allows us to obtain an estimate of their minimum energy U_{min}. In fact, by taking into account that the protons were transmitted through the 20 μm thick Al foil placed in front of the RCF stack, numerical calculations carried out using the code SRIM (Ref. 41) give $U_{\text{min}} \approx 1.2$ MeV. Information regarding the upper limit for the energy of the detected protons has instead been obtained by performing a radiographic image of a Ta mesh made of 35 μm-diameter wires. The image in Fig. 2 (left) shows the RCF proton signal after transmission through the Al foil and through the Ta mesh. The plot of Fig. 2 (right) shows the detected transmission profile across a single Ta wire. According to this plot, the protons propagating along the diameter of the Ta wire are completely stopped. These measurements set an upper limit of the proton energy that, according to SRIM calculations, is $U_{\text{max}} \approx 3.56$ MeV.

A further characterization of the proton bunch produced with our back-coated targets has been obtained by analyzing the optical density of the RCF layer of Fig. 1. By assuming a flat proton energy distribution, which gives a proton average energy of roughly $(U_{\text{max}} + U_{\text{min}})/2 \approx 2.38$ MeV, we thus estimate the number of protons detected in case of a back-coated target to be 6.7×10^7.

These values of proton energy and number are consistent with one-dimensional particle-in-cell numerical simulations discussed in detail elsewhere[42] and carried out assuming a 5.7 μm thick target coated on the rear side with a 20 nm witness hydrogen layer. In these conditions we find that roughly 95% of the protons acquire an energy of less than 4.4 MeV, consistent with the experimentally detected upper threshold.

We are aware that these experimental results are different from what might have been expected on the basis of the work presented in Ref. 30. In fact, in that work dielectric rear-surface coatings consisting of plastic layers thicker than 0.1 μm were found to have a detrimental effect on the uniformity of the spatial cross section of the laser-accelerated proton bunch. We believe that a possible explanation for this difference could be attributed to the quality of the metal-dielectric interfaces. In fact, according to the Target Normal

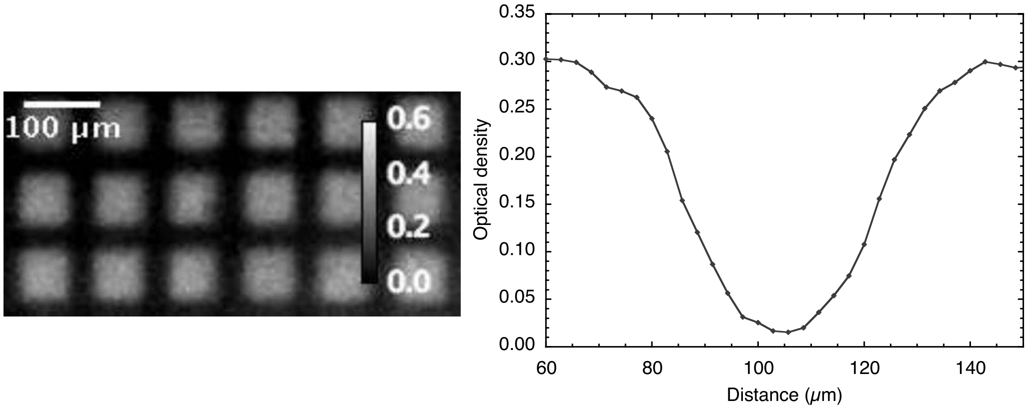

FIG. 2. (Left) scan of a magnified portion of the ion bunch image in Fig. 1 after transmission through a mesh made of a 35 μm diameter tantalum wire with a 100 μm period. The image was recorded by a RCF and converted in optical density units. (Right) profile across an entire period of the mesh.

Sheath Acceleration model,[10–13] ion acceleration is due to a strong electrostatic field that builds up when fast electrons produced by the interaction of the laser pulse with the front surface propagate through target and reach the rear surface. However, the transport of the huge currents of fast electrons typical of these interaction conditions, well above the Alfven limit,[43] is known[44] to depend on the conductivity of the background medium that allows cold return currents to be established to enable propagation. In particular, in case of propagation through dielectric targets[45] or low density materials, such as gas targets[46] and foams,[47] these conditions are not fulfilled and inhibition of the fast electron transport occurs due to the low number of electrons available for establishing return currents. Thus, we might expect strong modifications on the fast electron bunch also to arise during the propagation through vacuum gaps, which are well known to be usually present when standard plastic coatings are employed. Conversely, in our case the strong adhesion, typical of lacquers, of the dielectric coating to the metal surface may have played a beneficial role by ensuring a sharp metal-dielectric interface with no vacuum gaps. This fact, together with the different characteristics between the laser pulses adopted here and those employed in the experiment described in Ref. 30, might therefore qualitatively account for the differences observed.

In conclusion, a table-top tightly focused 80 fs and 600 mJ Ti:Sa laser has been adopted to study laser-driven proton acceleration. The experimental results show that acceleration of proton bunches with energy between 1.2 and 3.6 MeV and with a remarkable spatial cross section uniformity has, up to our knowledge, for the first time been achieved by employing targets consisting of thin metal foils, which have been back-coated with a dielectric layer of μm thickness. Our study suggests that the presence of a plastic rear-surface coating, which in recent experiments has been proved to be useful for enhancing the total ion yield, is not necessarily to be paid with a loss of uniformity of the bunch spatial cross section.

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