

# Enhanced laser coupling and proton acceleration in grating targets by surface wave excitation in the relativistic regime

A. Sgattoni<sup>1,2</sup>, A. Bigongiari<sup>3</sup>, T. Ceccotti<sup>4</sup>, V. Floquet<sup>4</sup>, O. Klimo<sup>5</sup>, A. Macchi<sup>2,6</sup>

<sup>1</sup> *Department of Energy, Milan University of Technology (Politecnico), Italy*

<sup>2</sup> *CNR, National Institute of Optics, Pisa, Italy*

<sup>3</sup> *LULI, Université Pierre et Marie Curie, Ecole Polytechnique, CNRS, CEA, Paris, France*

<sup>4</sup> *CEA, IRAMIS, Service des Photons Atomes et Molécules, F-91191 Gif-sur-Yvette, France*

<sup>5</sup> *FNSPE, Czech Technical University, Prague, Czech Republic*

<sup>6</sup> *Department of Physics, University of Pisa, Italy*

Experimental and simulations results are presented for laser ion acceleration using solid Mylar “grating” targets with a periodically structured surface on the irradiated side. The experiments was performed with the 100TW 25fs Ti:Sa UHI-100 laser pulse at CEA Saclay [1] using a double plasma mirror which raised the contrast ratio to  $\sim 10^{12}$  and allowed the structures of the front surface to withstand the prepulse. The “grating” target modulation had a regular modulation of  $0.5 \mu\text{m}$  depth and  $1.6 \mu\text{m}$  ( $2\lambda$ ) period, corresponding to an angle of incidence  $\theta = 30^\circ$  for the resonant excitation of surface waves (SWs). For a target of  $20 \mu\text{m}$  and changing  $\theta$  between 15 to 45 degrees, a broad maximum in the proton energy cut-off  $E_{\max}$  was observed around  $30^\circ$ , with a peak value  $E_{\max} \simeq 5 \text{ MeV}$  for a laser intensity of  $1\text{e}19 \text{ W/cm}^2$ . In contrast, for flat targets no maximum was observed and  $E_{\max} \simeq 2 \text{ MeV}$  at  $\theta = 30^\circ$ . This observation suggests that SWs are excited, for the first time in the relativistic regime, as also shown by numerical simulations.

## Introduction

The laser-plasma interaction taking place when a high power laser pulse is focussed on a solid target is the base scheme for several application and in particular for the ion acceleration via Target Normal Sheath Acceleration mechanism (TNSA). The TNSA regime is not the only possible mechanism for accelerating ions with laser-plasma interaction, but it is certainly the one that so far has been most widely investigated. Apart from increasing the laser-pulse parameters (energy, power, peak intensity), an improved efficiency of the coupling between the laser pulse and the the plasma obtained by the ionization of the target is strongly sought after for enhancing the ion acceleration in the TNSA regime. In the context of experiments, high intensity laser pulses with near optical wavelength ( $\lambda = 0.8 - 1 \mu\text{m}$ ) are focused on solids. The plasma obtained from the ionization of the material is highly overdense  $n_e \sim 200 \div 400 n_c$  where

$n_c = 1.56 \times 10^{21} \text{ cm}^{-3}$  is the cut-off density. The laser-plasma interaction is then limited in the thin “skin” layer of thickness  $\sim c/\omega_p = (\lambda/2\pi)\sqrt{n_c/n_e}$ . During the interaction, via several absorption mechanisms, a considerable fraction of the laser energy is transferred to the electrons which expands around the target and build up the electrostatic field that accelerates the light ions present on the surfaces of the foil.

### Grating targets

Several recent works aimed to optimize the laser-target coupling in the context of ion acceleration considering various types of surface structuring. Enhanced energy absorption and possibly particle acceleration to higher energies has been shown in several configurations. In particular, if a target with a periodic surface modulation on the irradiated side is considered, a resonant coupling of the laser pulse with surface waves (SWs) [2] can be achieved at a particular angle of incidence. Most studies on structured targets and on SW-induced absorption have been limited to relatively modest intensities ( $I \lesssim 10^{16} \text{ W/cm}^2$ ) because of the effects of “prepulses”, typical of chirped pulse amplification (CPA) based laser systems, which can destroy the surface structures before the interaction with the short intense pulse. Moreover, in the high-intensity regime a nonlinear theory of surface waves is needed to take into account relativistic effects which may become dominant. Particle-in-cell (PIC) simulations [3] of laser interaction with a grating target (designed for resonant SW excitation according to linear, non-relativistic theory), however, suggested the possibility of SW coupling at high intensity and showed a strong enhancement of both absorption and energetic electron and ion emission.

### Experimental results

The experiments exploited the UHI100 laser system obtaining a *P*-polarized beam which reached an intensity of about  $2.5 \cdot 10^{19} \text{ W/cm}^2$  [1]. The grating target (GT) have been manufactured by thermal imprinting of a  $2\lambda$  periodic structure on a Mylar<sup>TM</sup> foils. Three different foil thickness (20, 40 and  $0.9 \mu\text{m}$ ) and two peak-to-valley depths (500 and 300 nm) have been used. The proton spectra emitted from the rear side of the target have been recorded with a Thomson Parabola (TP). We tested the configuration changing the angle of incidence of the laser around the resonant angle of  $30^\circ$  (from  $15^\circ$  to  $45^\circ$ ). The laser light reflected by the target has been collected on a frosted glass and for selected shots a stack of radiochromic films (RCF) was placed around the target collecting particle and radiation emitted over an angle of about  $300^\circ$ .

Both the RCF stack and the frosted glass imaging line, gave confirmation that the grating structure was preserved during the interaction with the short ultra-intense pulse. Two spots were observed both on the RCF and the frosted glass at two different angular positions corresponding

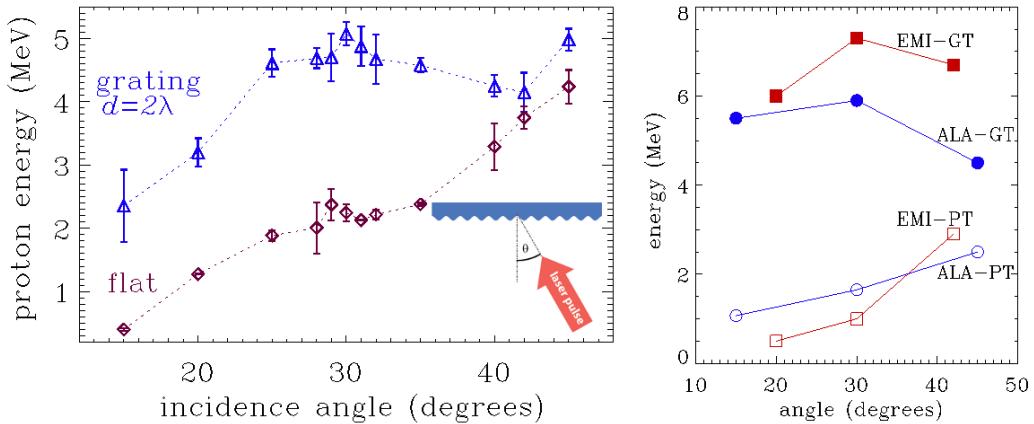


Figure 1: Left: Maximum proton energies for grating ( $23\ \mu\text{m}$  thick,  $500\ \text{nm}$  depth, blue triangles) and plane (Mylar,  $20\ \mu\text{m}$  thick, red diamonds) targets in  $P$  polarization as a function of the laser incidence angle. Right: 2D PIC results for two sets of simulations using EMI2D (EMI, squares) and ALaDyn (ALA, circles), with grating (solid symbols) and without (open symbols).

to the 0 and +1 grating diffraction orders. The multiple-reflection disappeared in the low contrast configuration when the double plasma mirror was removed. Figure 1(left) shows a survey of the proton maximum energy obtained using  $20\mu\text{m}$  flat simple target (ST) and  $23\mu\text{m}$  grating target (GT). Whereas the ST data show the expected variation of proton energy due to the variation of the normal component of the electric field ( $\propto (\sin \theta)^2$ ) and of the focal spot size ( $\propto 1/\cos \theta$ ), the GT energies clearly show the presence of a local maximum at about  $30^\circ$  ( $\approx 2.5$  times the ST energy for the same angle), which corresponds to the grating resonant angle. At large incidence angle the cut-off proton energy was similar with GT and ST, whereas for small angle of incidence, the GT give much higher energies than ST. This observation suggests that out of the resonance and at large angles, the role played by the grating is marginal and dominated by the increased coupling efficiency coming from the large component of the laser electric field normal to the target. On the other hand, at small angle of incidence, where the laser-coupling with a plain target is weak, the engraved surface contributes to enhance the energy absorption due to a local increase of the angle of incidence.

### Numerical results

Two sets of 2D particle-in-cell (PIC) simulations are presented, which have been performed independently using different configurations and codes, EMI2D [3] and ALaDyn [4]. The simulations with EMI2D considered a thick proton plasma target ( $20\ \mu\text{m}$ ) with density  $n = 100n_c$  irradiated by a plane wave with a peak intensity  $1.6 \times 10^{19}\text{W/cm}^2$  ( $\lambda = 0.8\mu\text{m}$ ) and temporal duration of 30fs (FWHM). The simulation performed with ALaDyn considered a thin-

ner two-species target composed by a main layer of ions with  $Z/A=1/2$  ( $0.8\mu\text{m}$ ,  $n = 120n_c$ ) and a rear layer of proton on the rear side ( $0.05\mu\text{m}$ ) and a laser pulse with peak intensity  $I = 2 \times 10^{19} \text{ W/cm}^2$ , duration  $\tau = 25 \text{ fs}$  and focal waist  $w_0 = 4 \mu\text{m}$ . In both simulation campaigns, as in the experiments, the target considered was either plain or with a periodic surface modulation of  $2\lambda$  and depth (peak-to-valley) of  $0.53\mu\text{m}$  (EMI2D) or  $0.4\mu\text{m}$  (ALaDyn). In Figure 1(right) the values of the proton cut-off energy obtained in the different cases are represented as function of the angle of incidence. It is apparent how in both cases,  $E_{\max}$  with GT shows a relative maximum at  $30^\circ$  in agreement with the experimental results. The relative enhancement in the proton energy is higher in the simulations than in the experiment and the energy vs. angle dependance is also smoother. These discrepancies are not of a great concern, given the number of simplification which are necessary in the PIC simulations.

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