Proton and heavy ion acceleration driven by high intensity – short pulse Lasers.

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The production and the acceleration of ions by means of high-intensity laser irradiating thin foils is an appealing field of research which has seen a growing attention during the past decade. The emitted ions and, in particular, protons pulses contain large particle numbers between 10^{10} and 10^{13} with energies in the MeV [1,2] and multi-MeV range [3–6] and are tightly confined in time (~ps) and space (source radius of a few micron). These outstanding characteristics triggered speculations about a wide range of applications in nuclear and medical physics.
More specifically, laser-matter interaction experiments involve high energy ions generated in the interaction of laser pulses with solid targets [7,8], gas jets [9,10], and clusters [11,12]. Part of the current research in this area is directed towards the development of a compact neutron source, while several other nuclear applications have recently been proposed: isotope production and start-up of fission reactions.

For most applications, however, a collimated ion beam would be preferable. Collimation requires a planar charge separation, which can be achieved by focusing an intense laser onto the surface of a planar solid-density film. In this case laser light terminates at the target surface and drives high-energy electrons generated in front of it deep inside the target. Because of planar charge separation these electrons produce a strong electrostatic field accelerating ions in a forward direction [13].
An ultrahigh-intensity laser ($I\lambda^2 > 10^{18} Wcm^{-2}\ \mu\ m^{-2}$, where I is intensity and λ is wavelength) incident on a target accelerates a large number of electrons to multi-MeV energies [14,15]. These electrons traverse typical thin foil targets and set up a very strong electrostatic field exceeding 1 TV/m. This field ionizes the rear surface and accelerates ions to energies of many MeV. This process is known as target normal sheath acceleration (TNSA) [16], and it is schematically shown in figure 1.
This extreme regime of the laser matter interaction generates, other than multi-MeV proton beams, even multicharged ions. Experiments have demonstrated acceleration of protons to more than 60MeV[16], fluorine ions to above 100MeV [18] and high-Z palladium ions up to 225MeV [19], that is more than 2 MeV per nucleon. These ion beams have a much lower transverse temperature, a much shorter duration and a much higher current than those from conventional accelerators.

More in details, the physical picture of the acceleration process is the following: first, electrons are accelerated by the impinging relativistic laser pulse and penetrate the target driven by the Lorentz force; leaving the target at the rear side, they set up a huge electric field which, in essence, is pointed normal to the target rear surface. Most electrons are forced to turn around and build up a quasistationary electron layer. By this field surface atoms are field ionized and accelerated (target normal sheath acceleration [23]). In most experiments, a thin layer (~nm) of hydrocarbons, water, or oxides contaminates the target surfaces so that ions with the highest charge-to-mass ratio are accelerated predominantly.
Another possible acceleration mechanism is the so-called RPA: the electromagnetic wave is directly converted into ion energy via the space-charge force related to the displacement of all electrons in a thin (nm scale) foil, allowing to reach GeV-scale energies in case of extremely high intensity lasers.

In any case, the laser pulse duration and the total energy of the pulse are critical parameters, as reported in figure 2.

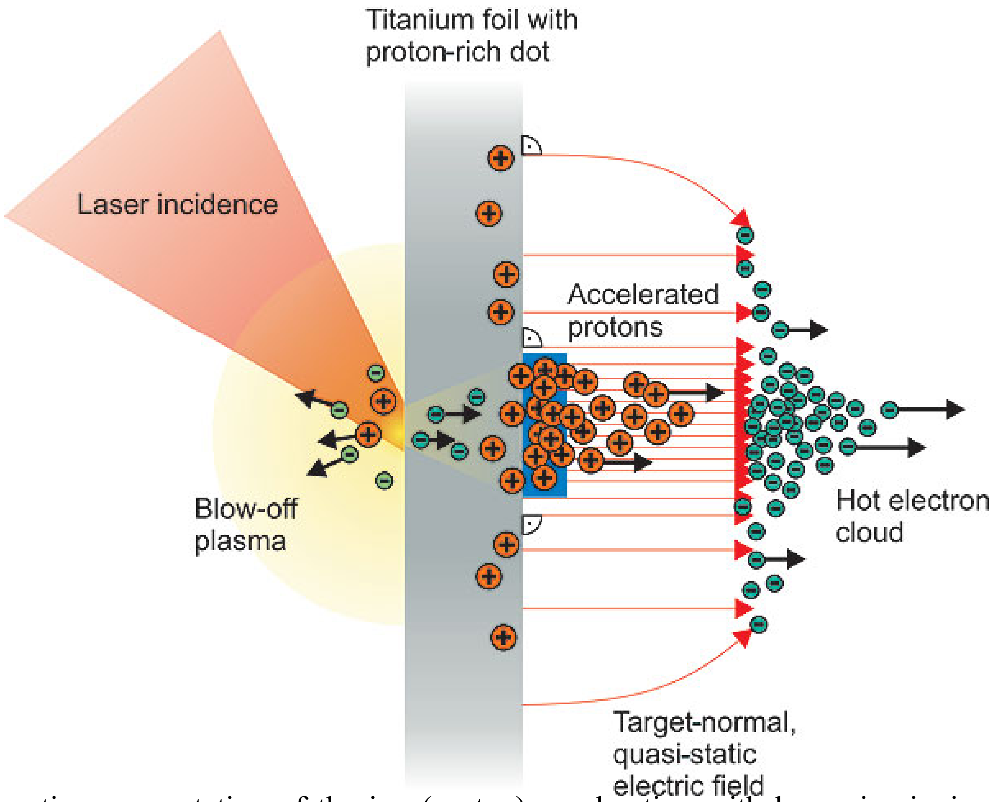

Figure 1: schematic representation of the ion (proton) acceleration with lasers impinging on thin foils.

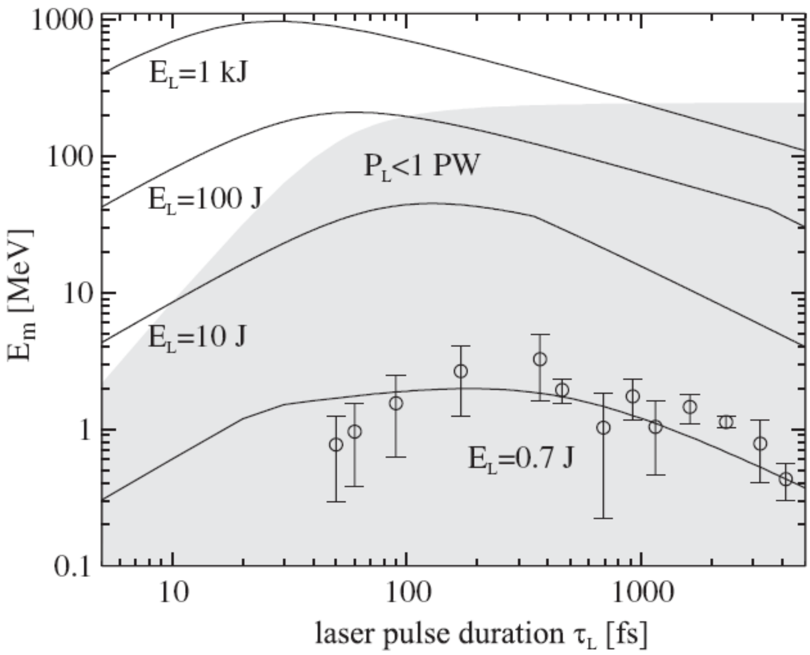

Figure 2: Dependence of maximum proton energies on the laser pulse duration for four constant laser energies. The circles represents the experimental data obtained with lasers at 0.7 J. Solid curves are calculations. The grey shaded area denotes the region where the laser pulse power is smaller than 1 PW [26].

Thermal expansion of a laser-driven plasma and ponderomotive electron expulsion constitute the most well-known examples of electrostatic-field production. While the former mechanism has been observed for many years [27], the latter one has only recently been observed in experiments with gas targets [28,29]. For the gas targets, when the laser pulse duration t is long, $t > r_0/c$, where r_0 is the laser focal spot radius and *c* is the speed of light, the radial component of the ponderomotive force dominates, and ions are accelerated radially.
Other data about the production of multicharged ions come from [30]: Pb^{46+} ions up to 430±40 MeV as well as protons with energies up to 30 MeV were obtained. These experiments were carried out at the Rutherford Appleton Laboratory using the VULCAN laser [31] (pulses energy up to 50 J at 1.053 mm and temporal duration of 0.9–1.2 ps). The maximum intensity on target was up to $5 \cdot 10^{19}$ W/cm^2. In the same experiments fully stripped aluminum ions up to 150±10 MeV and carbon ions at 90 ± 10 MeV were also measured. The peak ion energy was observed to increase with the mass of the ion and its charge state.
Figure 3 is an interesting plot showing the scaling laws of the maximum energy per nucleon obtainable at increasing laser intensities, that can be used to predict the energies achievable with future facilities.

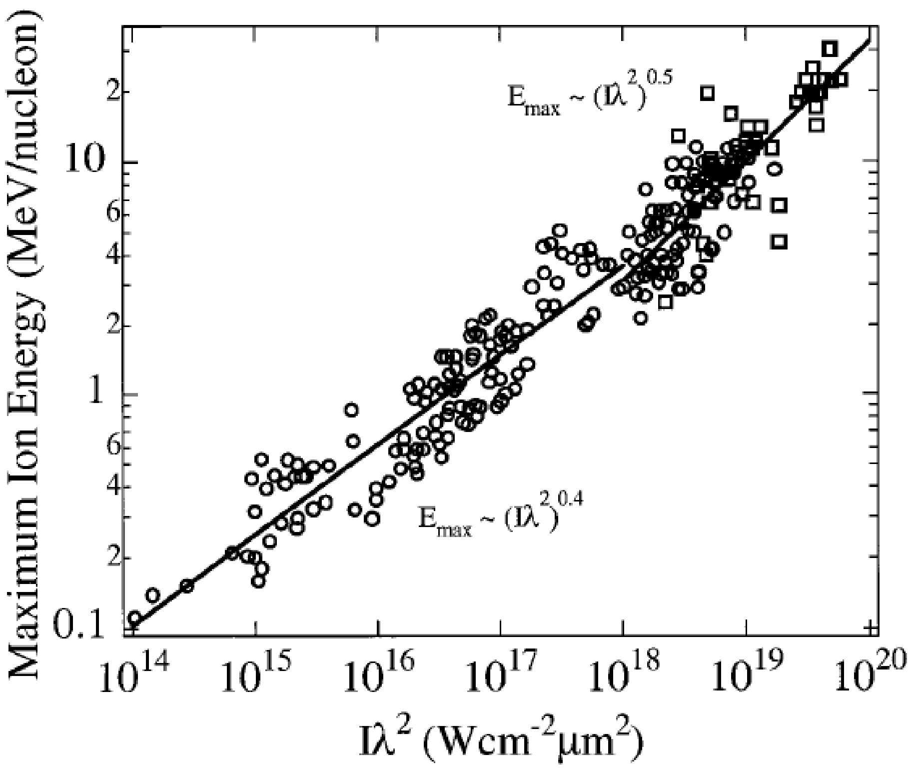

Figure 3: Scaling laws and experimental results concerning the maximum achievable energy per nucleon of ions accelerated by laser generated plasmas at different laser intensities [21].

Many efforts have been devoted to the design of the targets where the laser pulse impinges: the ions located superficially over the rear side of the target are more suitable for an efficient acceleration; impurities or appositely deposited layers can be used. Protons are more favourite because of their charge over mass ratio.

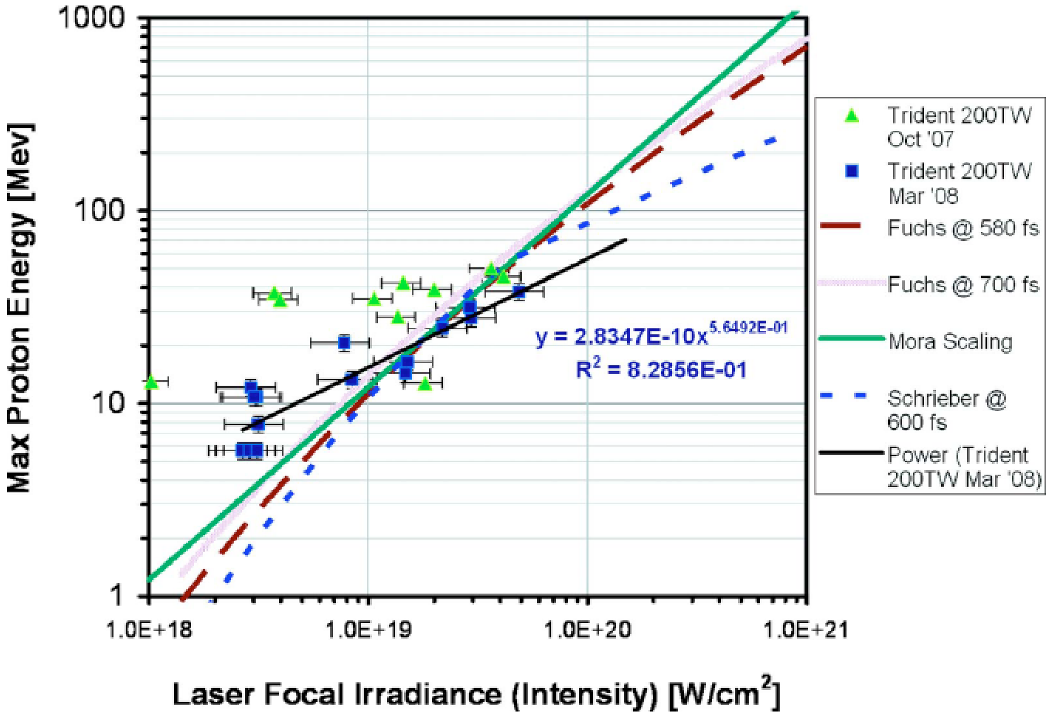

Figure 4: Comparison between theoretical scaling laws and experimental results obtained at the Trident laser facility of LANL, USA, concerning the maximum achievable energy of protons (in MeV) accelerated after the laser-matter interaction [32].

About protons, in fig. 4 the Trident laser (operating at LANL, USA) results are compared to some scaling laws [33,34,35,36] in terms of proton energy and focal intensity. Most reported values above 1 10^{19} W/cm^2 fall below these scalings. A fit to the March 2008 Trident data was performed, and a curve with an exponent of 0.565 was found. This exponent fits the ponderomotive scaling of $I^{0.5}$ as discussed in [23] within the ~20% error of the intensity measurements.

PERSPECTIVES ABOUT THE FLAME AND ELI FACILITIES

According to the above mentioned results on proton and multicharged ions production presented in literature one can argue some prediction for the forthcoming facilities. Scaling laws are available, and they permit to extrapolate rough predictions on proton energies obtainable by the two projects of our interest: FLAME (FLAME: Frascati Laser for Acceleration and Multidisciplinary Experiments) at INFN-LNS and the largest laser European facility named ELI (Extreme Light Infrastructure). A strategic project of INFN, named PLASMONX [38], aims to the development of innovative laser-plasma acceleration techniques and X-gamma ray sources. The main parameters of the FLAME laser facility, measured during the final acceptance test at the factory, during full energy operation at 10 Hz rep. rate are: 5.6 J (energy after compression); 23 fs (pulse duration); 250 TW(peak power), < 10^{10} (ASE contrast); < 10^{-8} (pre-pulse contrast). The average energy (before compression) was measured to be 7.07 J. On the basis of these parameters the intensity on target may be of the order of 10^{20} - 10^{21} W/cm^2, with a focal spot radius of about 5 μ m.

Therefore, according to figures 4 and 5 and to numerical calculations, the expected proton energy may overcome the 50 MeV in the TNSA regime, while for heavier ions, according to figure 3, energies of the order of ten MeV/A or higher may be obtained.

Quasi-monochromatic ion beams can be produced. On this purpose targets with controllable nanostructures will be realized. An adequate diagnostics for the characterization of the ejected ion beams and for the beam control is needed. In order to provide intense beams with a high enough number of particles per time unit the high repetition rate of the FLAME laser will be crucial. Ultra-high contrast (UHC) pulses effects on beam properties will be carefully investigated.
Other acceleration regimes may be studied, especially that ones based on circularly polarized laser light and/or on the radiation pressure.
As mentioned in the previous section, a critical aspect of the ion acceleration is the choice of targets: a fraction of the activities in the framework of the FLAME experiments will be devoted to several tests of different kinds of targets: clusters, foams, gas jets, etc.

These characteristics will made FLAME an interesting facility to deeply investigate future "table-top" accelerators of protons and heavy ions, with the possible applications discussed already initially: isotope creation, subcritical fission reactors, fundamental nuclear spectroscopy, medical applications like the protontherapy for oncological purposes, etc.

In the framework of the European and worldwide activities in this field, FLAME is then a sort of bridge towards the next large scale facilities whose target is to overcome the barrier of GeV for the ions acceleration (see figure 5), like the above mentioned Extreme Light Infrastructure (ELI). The HiPER project [39] has been also proposed, which aims to the laser induced thermonuclear fusion.
The ELI project is characterized by multi-line pulses lasting around 15 fs. The "initial source" parameters available for ion beam acceleration at ELI will be 50 J per beam laser pulses, with a repetition rate of ~10 Hz and with an important constraint for ion generation which is the prepulse laser contrast (about 10^{10}). The intensity on the target will reach the value 10^{25} W/cm^2.
Figure 5 is a summary of the maximum energy and proton number obtained in various experiments. The potentialities of ELI are clearly evidenced. The expected position of the FLAME facility is also shown. As shown in figure several hundred of MeV, or even up to a few GeV protons may be achievable with the planned on-target intensities at ELI in its final stage (i.e. up to 10^{25} W/cm^2). Supposing that the proton number would be similar to that obtained currently on existing facilities, and considering a high repetition rate (e.g. 10 Hz), then currents up to a few tens of nA may be obtained, that are comparable with a conventional accelerator.

A comparison between the expected beam characteristics and beam quality for FLAME and ELI is shown in table 1.

	FLAME	ELI
Proton energy	> 50 MeV	200 MeV
Heavy ions energy	~10 MeV	50 MeV/nucleon
Duration at the source		< ps
ΔE / E		%
Virtual source size		μ m
Angular distribution		Few degrees
Current at the source		~ kA

Table 1.

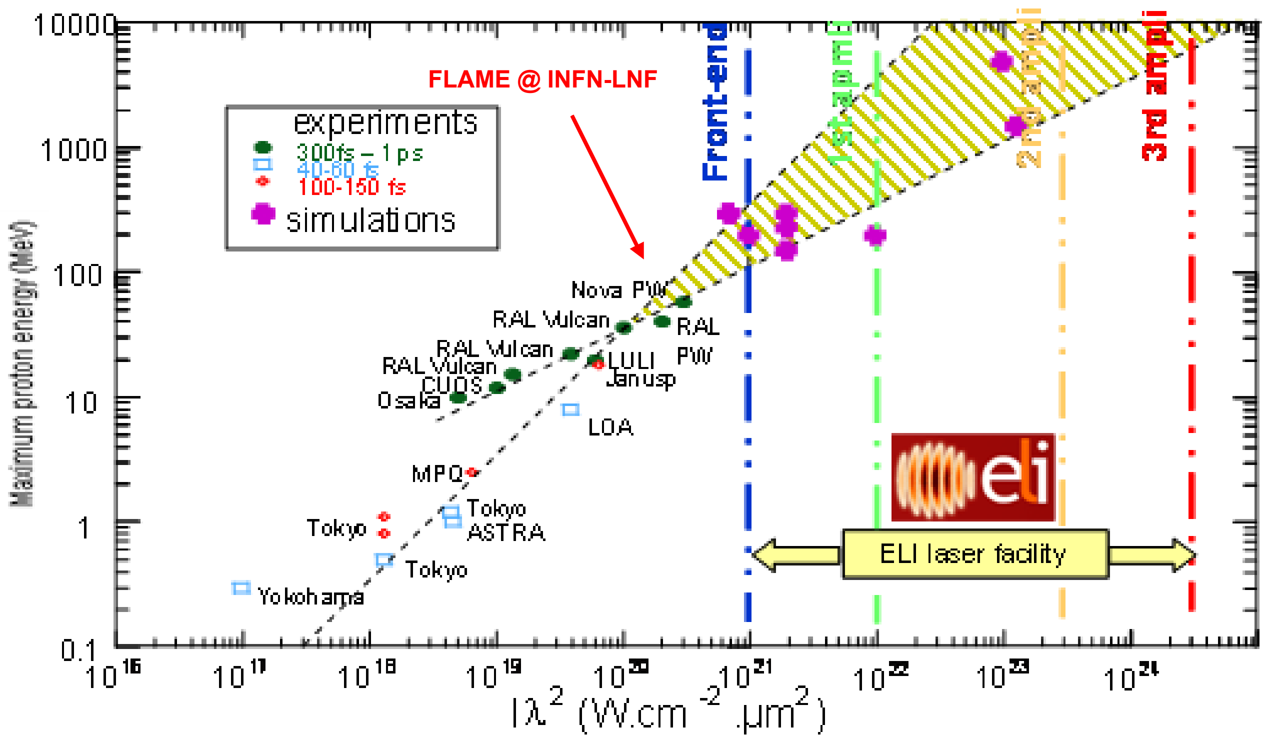

Figure 5: summary of the maximum proton energy dependence on laser intensity for the existing and forthcoming facilities, paying a particular attention to the large scale project of the European Community named ELI, and to the FLAME facility of INFN. The expected energies of the FLAME project is put in evidence. Experimentally measured data are small dots, boxes and crosses corresponding to three pulse duration ranges are shown. Simulations performed at higher laser intensities planned for ELI are reported as big purple dots. Note that, as experimentally proven up to 10^{20} W.cm^{-2}, the maximum proton energy for the extreme short pulses is ~ I, whereas for the longer pulses ~ $I^{1/2}$.

According to simulations, the predominant ion acceleration regime at the expected intensities (i.e. $I \geq 10^{23}$ W/cm^2) should be the radiation pressure acceleration (RPA). Multiple stage acceleration using stacked foils would offer the additional prospect of further increase of the ion maximum energy. At a similar intensity regime, other simulations have also shown that ions could be accelerated to energies higher than 10 GeV in the “bubble” regime of wakefield acceleration using near-critical density plasmas and mixed ions. Such underdense plasma targets would have the benefit of allowing high repetition rate operation.

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