Laser and Particle Beams (2004), *22*, 399–405. Printed in the USA.

DOI: 10.1017/S0263034604040042

Electron and proton beams produced by ultra short laser pulses in the relativistic regime*

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(RECEIVED 20 January 2004; ACCEPTED 15 June 2004)

Abstract

It is known that relativistic laser plasma interactions can already today induce accelerating fields beyond some TV/m, which are indeed capable to efficiently accelerate plasma background electrons as well as protons. An introduction to the current state of the art will be given and possible applications of these optically induced charged particle sources will be discussed.

Keywords: Electron beams; Laser plasma interaction; Plasma waves; Proton beams; Relativistic regime

1. INTRODUCTION

Since their discovery, elementary particles like electrons and protons are of great interest and relevance in various scientific domains, and as their intrinsic parameters are well understood, their implementation is even today of great actuality. Implementing such particle sources, their basic parameters like luminosity, bunch length, source size, as well as quality in terms of angular divergence and emittance are of great importance. A higher luminosity can obviously be preferential for the number of experimental events. Shorter particle bunches permit to investigate phenomena with higher temporal resolution, and in case they are used for radiography, a small, point-like source could be desirable to enhance the resolution.

Today, the most efficient pulsed electron sources are photo-injector guns, where lasers with energies of some tens of μJ and pulse durations of some ps irradiate cathodes to liberate electrons. However, in this case, these lasers are not intended to accelerate electrons to high energies. With the advent of the Chirped Pulse Amplification (CPA) (Strikland & Mourou, 1985), high power, sub-ps laser pulses became available. Focusing such lasers down to focal waists of some μm and intensities beyond 10^{18} W/cm^2, intrinsic electric fields of several TV/m can be obtained. At such high intensities these lasers can create quasi-instantaneously plasmas on targets they are focused onto, i.e., they generate a medium consisting of free ions as well as electrons. Inside this plasma, the transverse electric laser fields can be turned into longitudinal plasma electron oscillations, known as plasma waves, which are indeed suitable for electron acceleration (Tajima & Dawson, 1979). Additionally, due to the high laser intensity, strong quasi-static electric fields can be induced, which are capable to subsequently accelerate ions.

In this article, a brief overview of theoretical aspects on charged particle generation induced by relativistic laser plasma interactions will be given. Recent experiments on electron as well as proton generation will be described, and an outlook on near-future experiments will be given. Finally, possible applications of these charged particle sources will be discussed.

2. THEORETICAL BACKGROUND

2.1. Electron beam generation in under dense plasmas

Electron beams can easily be generated by the breaking of relativistic plasma waves in an under dense plasma, where the plasma electron density is below the critical density, $n_e < n_c$, which limits the laser beam to propagate through matter. Due to the non-linear interaction that occurs at laser powers beyond some tens of TW, initially low-amplitude plasma waves can be very efficiently driven to wave breaking if the laser pulse length, $c\tau_L$, is of the order of the plasma wavelength, λ_p, i.e., if the condition for classical wake field acceleration is not met. In this forced laser wake field (FLW) regime, a combination of laser beam self-focusing, front edge

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*This paper was delivered at the International Workshop on Laser and Plasma Accelerators, held at Portovenere, Italy, September 29 to October 3, 2003.

laser pulse steepening, and relativistic lengthening of the plasma wave wavelength can result in a forced growth of the wake field plasma wave (Malka *et al.*, 2002; Najmudin *et al.*, 2003). In the FLW regime the interaction of the bunch of accelerated electrons and the plasma wave with the laser is reduced, this can yield the highest known electron energy gains attainable today with laser plasma interactions.

Indeed the maximum energy in the FLW is significantly greater than in any other regime known so far, suggesting the growth of plasma waves with peak amplitudes greater then the initial plasma density. Interestingly, the plasma wake is mostly formed by a fast rising edge, and the back of the pulse has little interaction with the relativistic longitudinal oscillation of the plasma wave electrons. Graphically speaking, the relativistic laser plasma interaction occurs solely on one single plasma wave cycle, which is a subtle difference to other regimes. Indeed the increase of plasma wave wavelength due to relativistic effects means that the breaking and accelerating peak of the plasma wave sits behind most, if not all, of the laser pulse. Hence, its interaction and that of the accelerated electrons with the laser pulse is minimized, thus reducing possible undesirable emittance growth.

2.2. Proton beam generation in over dense plasmas

In contrast, proton beams are more efficiently generated in over dense plasmas, $n_e > n_c$. Even though the laser beam is prevented from propagating through this medium, its ponderomotive force nevertheless accelerates electrons in the plasma skin layer. These are electrons which can propagate through the target setting, up a space-charge field at the rear surface once they escape the plasma. Importantly, this space-charge field is quasi-static, i.e., protons which have a higher mass than electrons can respond to these fields, and can therefore be accelerated to high energies since these space-charge fields can exceed several TV/m as well.

The above mentioned optically induced particle sources currently have a Maxwellian-like energy distribution, they already have some interesting features like: (1) their accelerating field gradients are by 4 orders of magnitude higher than those attainable with today's standard techniques, which can indeed cut down the accelerating length significantly; (2) the required lasers are rather compact and cheap compared to current RF-structures; (3) no shielding for radio-protection is required up to the point where the laser creates a plasma on the target; and (4) the same laser can be used to generate electrons or protons simultaneously.

3. ELECTRON BEAM GENERATION IN THE FLW REGIME

3.1. Experimental set-up

The very first experiment of the FLW regime was performed on the "salle jaune" laser at Laboratoire d'Optique Appliquée (LOA), operating at 10 Hz and a wavelength of 820 nm in the CPA mode. It delivered energies on target of 1 J in 30 fs, full width at half maximum (FWHM) linearly polarized pulses, the contrast ratio was better than 10^{-6} (Pittman *et al.* 2002). Using an $f/18$ off-axis parabolic mirror, the laser beam was focused onto the sharp edge of a 3 mm supersonic helium gas jet. The focal spot had a waist of 18 μm, this resulted in peak intensities of up to 3×10^{18} W/cm^2. The plasma period was chosen to vary between 25 and 14 fs by selecting initial electron densities, n_e, between 2 and 6×10^{19} cm^{-3}, which was achieved by changing the backing pressure of the gas jet. Figure 1 shows the subsequently installed experimental set-up.

In order to obtain information about the opening cone of the generated electron beam as a function of its energy, a secondary detector was implemented. This consisted of a stack of radiochromic film (RCF) to visualize, and copper pieces of various thicknesses to stop the electron beam. To avoid illumination of the RCF by the laser, this stack was completely shielded with aluminium wrapping. It was placed on the laser beam axis behind the center of the gas jet nozzle. The emittance of an electron beam is usually normalized to the usual relativistic electron parameters. As the energy spectrum of the electron source generated in this experiment is expected to be broad, the single electron energies need to be dispersed. This was achieved by implementing a secondary magnet, which was installed directly behind the gas jet nozzle. Electrons could enter this non-focusing magnet through two different stainless steel collimators. These collimators served to obtain a reasonable energy resolution while taking into account the opening cone as well as the halo of the

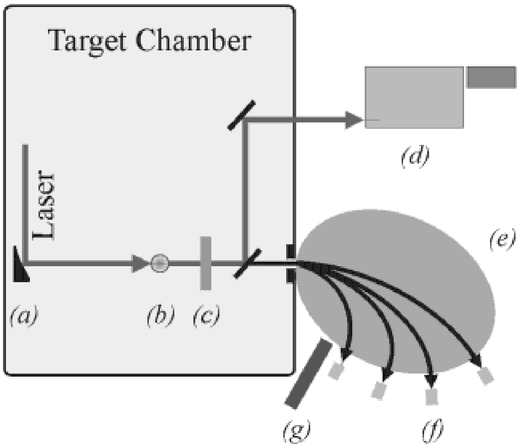

Fig. 1. Experimental set-up at "salle jaune" laser. The laser beam was focused with an off-axis parabolic mirror (a) onto the edge of a 3 mm helium gas jet (b). The total number of generated electrons was determined with an Integrating Current Transformer (ICT) (c), which could be replaced with a secondary set-up for emittance measurements. The transmitted laser beam was analyzed with an optical spectrometer and recorded onto a CCD camera (d). A glass plate with a center hole separated the laser and electron beams non-destructively. The electron yield as a function of energy was determined with a spectrometer, which electrons could entered through a collimator (e) and measured with silicon barrier detectors (f). Lead walls shielded those from bremsstrahlung (g).

electron beam. Since the emittance can be seen as the area of the electron divergence distribution as a function of position within the beam envelope, the electron beam envelope was partially masked, solely permitting single electron beamlets at a defined position to pass through these holes. This arrangement is known as a "pepper-pot" (Yamazaki *et al.*, 1992). Here, lead plates of varying thicknesses were implemented, which were sufficient to stop electrons at the regarded energy bins. These masks were fixed directly next to the magnet and were displaced vertically. The electron beam passing through these holes was visualized at various distances behind the mask with RCF, which has a spatial resolution below 10 μm, and which was scanned with the same resolution directly after the experiment. To avoid illumination of the RCF by the laser beam it was shielded with aluminium wrapping correcting afterward the scattering of electrons within this wrapping.

3.2. Results

The resulting electron spectrum for a neutral plasma electron density, n_e, of 2.5×10^{19} cm^{-3} is shown in Figure 2. Although it is possible to fit to the lower energy electrons a relativistic Maxwell-Jüttner distribution, which results in an electron temperature of (18 ± 1) MeV for electrons of less than 130 MeV, this description is not adequate to describe the higher energy electrons. A significant number of electrons exists in a "hot tail" that extends beyond 200 MeV. Measurements with the ICT showed that the total beam charge was (5 ± 1) nC. As can be seen in Figure 3, the higher the energy of electrons within this electron bunch, the better the collimation.

Numerical simulations of this experiment indicated that during this relativistic laser plasma interaction accelerating fields of around 1.4 TV/m were induced when wave breaking occurred. As for this experiment, the laser pulse duration was of the order of the plasma wavelength, one might conjecture that only a single electron bunch is accelerated, with a bunch duration of the order of tens of fs. This was also verified numerically as the plasma wave generated in this experiment suffered strong wave breaking and accelerated electrons up to 200 MeV, it is also rapidly damped after its first accelerating extremum. As a result these simulations showed that there is little or no wave breaking for the plasma

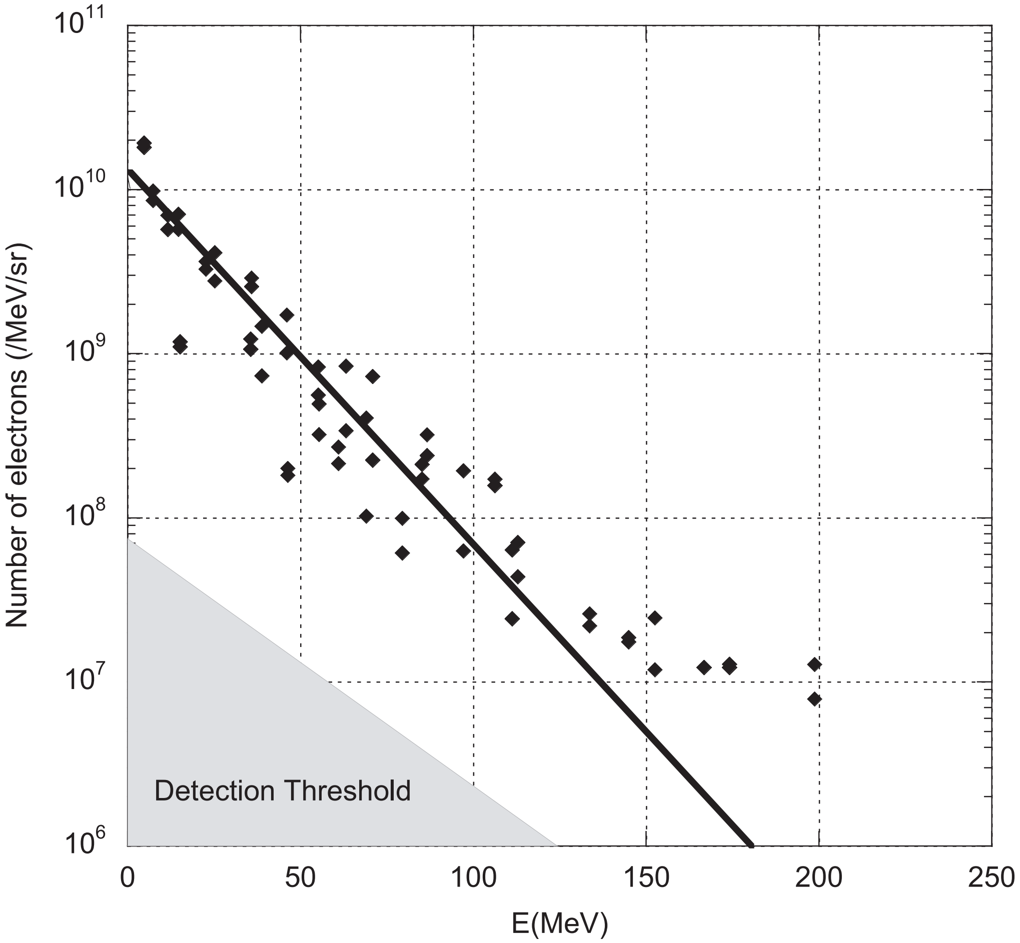

Fig. 2. Electron energy spectra for 2.5×10^{19} cm^{-3} electron density and a laser irradiance of 3×10^{18} W/cm^2. An effective longitudinal electron temperature of (18 ± 1) MeV can be derived for electrons of less than 130 MeV (continuous line).

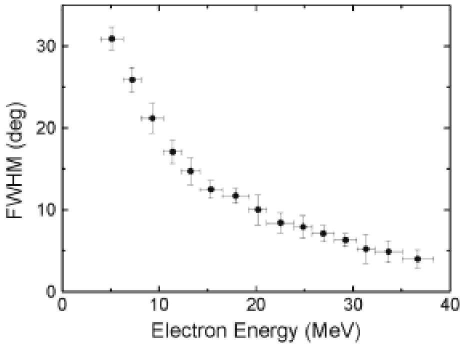

Fig. 3. FWHM of the angular distribution of the electron beam as measured with RCF and copper stack.

wave oscillations behind the first extremum, so that the hot electron population is localized in space. Importantly, only in the first plasma wave wavelength electrons are accelerated above 50 MeV and the duration of this 50-plus MeV bunch at the exit of the plasma extends over less than 20 μm, which corresponds to a pulse duration of 67 fs (Fritzler *et al.*, 2003*a*).

Figure 4 shows the experimentally determined emittance of this electron beam as a function of its energy. Interestingly, the normalized vertical emittance was found to be as low as (2.7 ± 0.9) π mm mrad for (54 ± 1) MeV electrons. It is clear that this emittance does indeed cope with today's standards in accelerator physics—in particular combined with its very short pulse length (Fritzler, 2003*b*).

3.3. Applications and outlook

Conventional accelerators typically provide energetic electron bunches with pulse duration in the ps order and an energy resolution of less than 10^{-3}. To achieve these performances, such devices are precisely designed and, hence, for a fixed electron energy only. Even though this high energy resolution is not met in the FLWF scheme, it enables to select an arbitrary energy bin out of the entire spectrum of up to 200 MeV at low emittances and with sub-ps pulse lengths over a wide range of electron energies. However, the convolution of the measured electron yield and its angular distribution shows that the bunch charge of high energy electrons does not compare so far to accelerators' that typically operate at several pC and even nC. Additionally, peak electron currents of about 10 A for 45 MeV electrons is not competitive, even though the quantity is favored by the ultra short bunches. However, simulations for a 12 J, 33 fs laser pulse interacting with an under dense plasma suggest that a large beam charge increase could be obtained in an improved mode of the FLW regime, where the laser pulse propagates inside a solitary plasma cavity (Pukhov & Meyer-ter-Vehn, 2002). In this case, the distribution of the accelerated electrons is no longer Maxwellian but shows a clear peak with charges as high as, say, 5 nC at (300 ± 25) MeV. Up to now, this "broken wave" regime cannot be experimentally verified, since such challenging laser systems do not currently exist. Nevertheless, they are already today an issue for laser development.

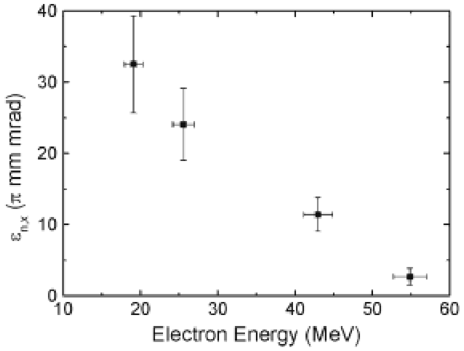

Fig. 4. Normalized vertical emittance $\lambda_{n,x}$ as a function of electron energy.

Another interesting feature of such sub-ps electron bunches showed an experiment on ultra-fast radiation chemistry. In this pump-probe experiment such a sub-ps electron bunch was propagating through a suprasil cell containing pure liquid water. Importantly, radiolytic events induced by electrons today only well-known on ns time scales, have been studied for the first time in the sub-ps regime at LOA (Gauduel *et al.*, 2003) will potential impact for modern oncology.

4. PROTON BEAM GENERATION WITH SOLID TARGETS

As already mentioned above, the same laser can well be implemented to generate proton beams with solid targets, which subsequently turn into overdense plasmas.

4.1. Experimental set-up

Here, the laser with an on target energy of up to 840 mJ and an FWHM duration of 40 fs was focused using a $f/3$ off-axis parabolic mirror. The focal waist was 4 μm, this resulted in peak intensities of up to 6×10^{19} W/cm^2. For these impulsions, the laser contrast ratio was, again, found to be of the order of 10^{-6}. In this experiment the target were 6 μm thick aluminium foils.

The energy, yield as well as the opening cone of generated protons were determined with CR-39 nuclear track detectors, which were partially covered with aluminium foils of varying thicknesses, which served also as energy filters.

4.2. Results

Figure 5 shows the measured proton energy distribution. Clearly, the energy of this beam reaches 10 MeV. As can be seen in Figure 6, the proton beam is more collimated at higher energy. NB, that recently only proton beams of up to 1.5 MeV have been reported with similar short pulse and

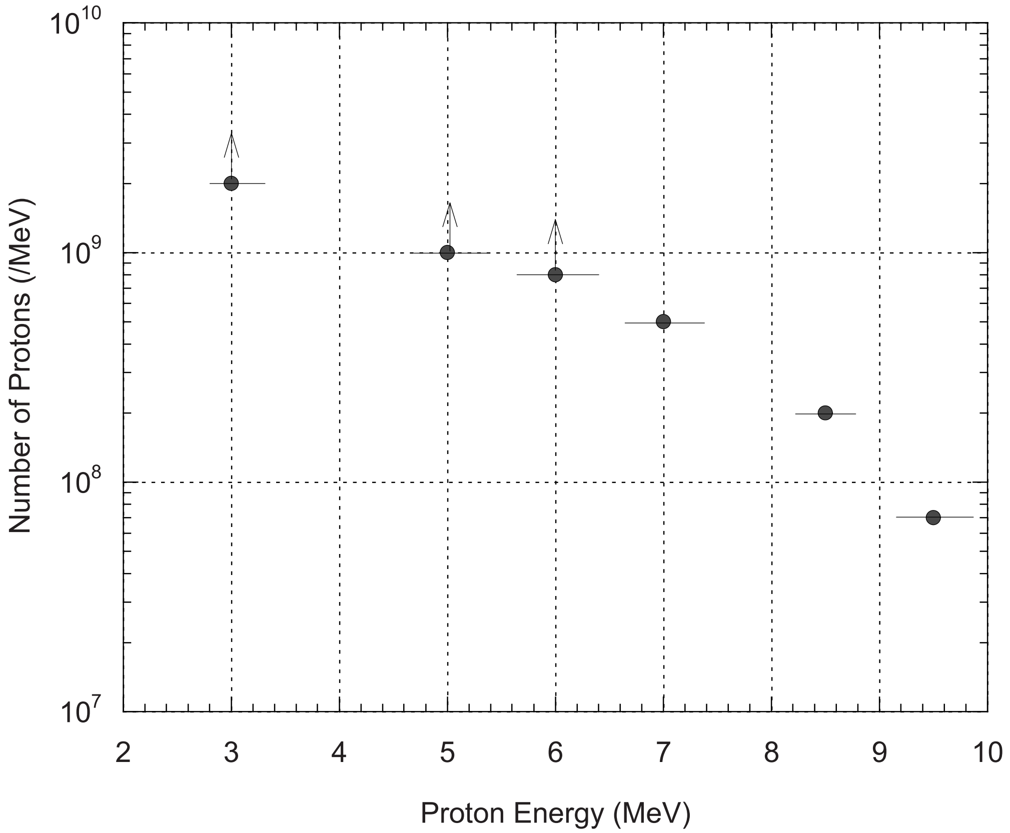

Fig. 5. Proton energy spectra at a laser irradiance of 6×10^{19} W/cm^2 for a 6 μm aluminium target. The arrow indicate the minimum number of protons, which results of the saturation of the detectors.

high repetition rate lasers. Interestingly, these measurements are in qualitative agreement with kinetic simulations, which again demonstrate numerically the generation of accelerating fields beyond some TV/m at the space-charge field induced on the rear surface of the target. The regular variations, followed by an abrupt cut-off at the maximum energy and the smooth transverse variations of the accelerating field fully reproduce the experimental findings.

4.3. Applications

Even though the energy spectrum of this proton beam has a broad Maxwellian-like distribution, it can nevertheless be interesting for the generation of Positron Emission Tomography (PET) radio-isotopes since its energy is greater than the Q-value, i.e., the threshold of the corresponding (p,n) reactions. Since the Q-values for most prominent isotopes, ^{11}B and ^{18}O, are 2.8 and 2.4 MeV, respectively, this laser produced proton beam might therefore represent an alternative method for PET isotope production than it is pursued today. Naturally, this possibility favors all of the above mentioned benefits of relativistic laser plasma interactions. Calculating the expected PET isotopes activity after an irradiation time of 30 min and a repetition rate of 1 kHz, which is indeed feasible in the very near future, activities of the order of 1 GBq can be obtained for ^{11}B and ^{18}O, which are required in order to separate the tracer from the inactive carrier with fast chemistry techniques. Interestingly, numerical simulations indicate that a modest increase in laser intensity to 8×10^{19} W/cm^2 can result in even more protons at higher energies and can lead to a sevenfold increase in ^{18}F activity (Fritzler *et al.*, 2003*c*). This favorable intensity scaling is supported by recent experimental observations at 5×10^{20} W/cm^2 which measured 3 MBq of ^{11}C, more than one order of magnitude greater than what was obtained at 5×10^{19} W/cm^2 with the same experimental set-up.

Another very interesting challenge concerns the use of optically induced proton beams for proton-therapy. Some groups already started to investigate this approach on the basis of numerical simulations, and have shown that implementing a PW laser with a pulse duration of 30 fs, and a repetition rate of 10 Hz will indeed meet the requirements for this purpose (Fourkal *et al.*, 2002), as the dose the delivery delivered with such an adjustable proton beam spectrum within the therapeutic window (in between 60 and 200 MeV) is already expected to be beyond some few Gy/min. Importantly this approach would provide a double benefit:

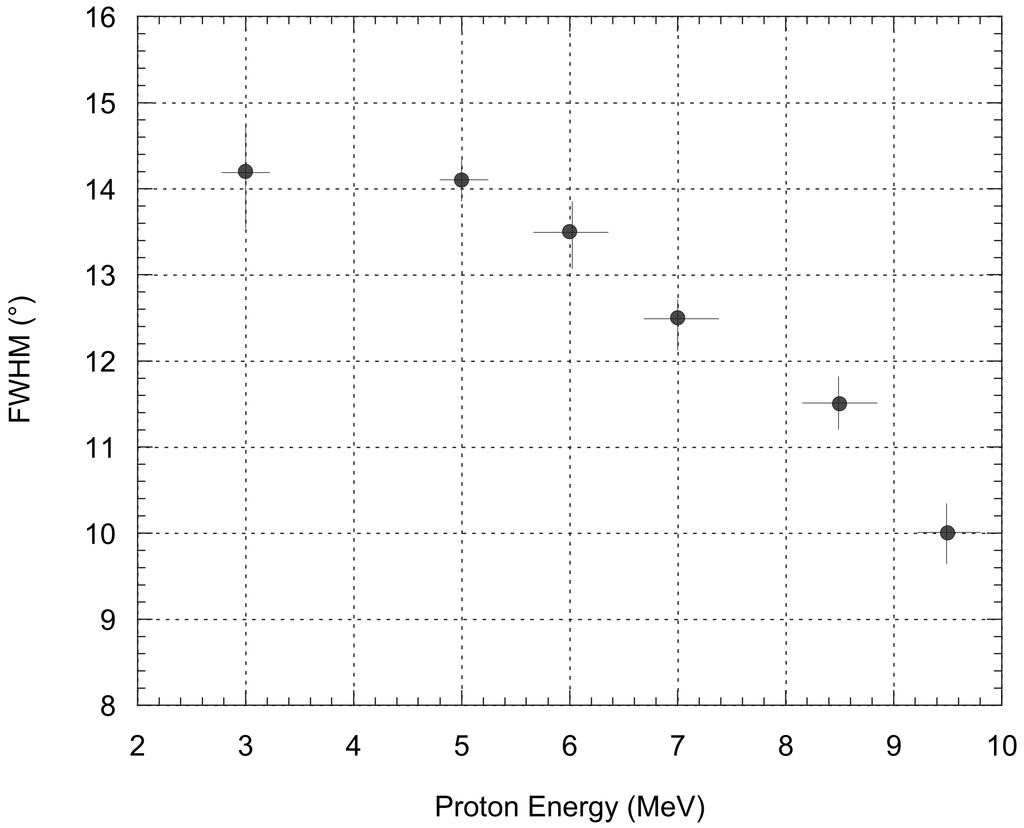

Fig. 6. FWHM of the proton beams shown in Figure 5.

1. As high-intensity lasers can generate very large accelerating fields, the acceleration length and hence the size and weight of the facility is tremendously reduced, allowing a possible installation inside standard radiotherapy departments. This significantly reduces the costs and provides larger accessibility.
2. As the main beam in this "accelerator" is just a laser beam, while proton generation only occurs at the end, one could also expect to considerably reduce the size and weight of the gantries and the radiation shielding.

The development of such a laser will permit to confirm the benefit of this approach, to investigate the shot-to-shot study reproducibility of the generated proton beam as well as the optimization of the laser and the target parameters (contrast, focal spot, thickness, etc. . .) (Malka *et al.*, 2004).

5. CONCLUSIONS

In this article it was shown that relativistic laser plasma interactions in the under- as well as over dense regime with high repetition rate lasers can lead to the generation of extreme accelerating fields, typically of the order of some TV/m. These can accelerate charged particles to high energies—200 MeV for electrons and 10 MeV for protons—both originating most likely from sources corresponding to the laser focal volume and on sub-ps time scales. Note closely, that for either particle, the same laser was implemented. Furthermore it was shown that these high-quality since low-emittance particle beams can already today be implemented for pending quests on ultra rapid phenomena in physics as well as chemistry. Interestingly, by focusing the laser beam with an even shorter off axis parabolic mirror, the electron beam parameters are easily controllable by changing the electron density or the laser intensity (Malka *et al.*, 2001), whereas the total charge can be changed by controlling the pulse shape (Leemans *et al.*, 2002). Applications of this source have been considered for the production of THz radiation (Leemans *et al.*, 2003) and for production of ultra-short X rays flashes (Fritzler *et al.* 2003*a*).

Even though entirely mono-kinetic electron or proton beams seem to be unlikely with laser plasma interactions, even though a "perfect" reproducibility is still a matter of investigation, even though the generation of any particle is always accompanied with the generation of other particles as well as radiation, this approach to use optically induced particle sources has plenty of advantages as it was discussed above in detail. "Clearly, the future is, of course, full of challenges and uncertainties, but it is also full of exciting chances to make a difference . . ." (Joshi & Katsouleas, 2003).

ACKNOWLEDGMENTS

The authors greatly appreciate the support and the quality of the “salle jaune” laser, which was ensured by the entire LOA staff. Experimental data on electrons have been obtained in collaboration with Imperial College and on protons in collaboration with University of Strathclyde. Additionally, we are indebted to the fruitful discussions with E. Lefebvre of CEA on theoretical issues.

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