**High charge (0.5 nC) monoenergetic 170 +/-20 MeV electrons beam
generated by 30 fs laser pulses**

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Abstract

It is known that relativistic laser plasma interactions can induce accelerating fields beyond TV/m, which are capable of efficiently accelerating plasma background electrons up to 200 MeV. By optimising the plasma parameters it is now possible, with a compact 1J, 30 fs laser, to enhance the shape of the electron spectra and to produce a high charge electron beam with an energy peak centered at 170 MeV with an extremely good quality.

Contribution to the 11th AAC Workshop 04, Stony Brook, NY, USA

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Abstract. It is known that relativistic laser plasma interactions can induce accelerating fields beyond TV/m, which are capable of efficiently accelerating plasma background electrons up to 200 MeV. By optimising the plasma parameters it is now possible, with a compact 1J, 30 fs laser, to enhance the shape of the electron spectra and to produce a high charge electron beam with an energy peak centered at 170 MeV with an extremely good quality.

INTRODUCTION

Particle beams have permitted many discoveries in science and have found many applications in several domains. Particle sources generated by lasers have extended the field of applications for research because of their specificity: short bunch length, small source size, as well as low angular divergence. Some of these characteristics cannot be reached using conventional technology. These important new sources will permit the discovery of new phenomena in science : in particular shorter particle bunches allow the investigation of phenomena with higher temporal resolution. For applications like radiography, a small, point-like source is desirable for enhancing the resolution, making electron beams from laser-plasma accelerators ideal candidates. Since they are produced with compact laser, these sources will be complementary to the conventional ones for application in medicine, radiography or material science.

For high energy physics, since the size of accelerators cannot be increased over a reasonable distance, the generation of higher electric field, generated in a plasma medium could be an asset to boost particles at higher energies over small lengths.

Nowadays, 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 in order to liberate electrons. However, in this case, these lasers are not intended to accelerate electrons to high energies. Since the advent of the Chirped Pulse Amplification (CPA) [1], high power, sub-ps laser pulses have become available. By focusing such lasers down to focal waists of a few microns and intensities beyond 10^{18} W/cm², intrinsic electric fields of several TV/m can be obtained. At such high intensities, those lasers ionize quasi-instantaneously the targets on which they are focused and create plasmas. Thus, they generate a medium consisting of free electrons

and ions suitable for particle acceleration [2]. The interaction of the laser with the plasma results in the generation of high electric fields which can efficiently trap and boost electrons at high energy. Such electron spectra have generally a maxwellian distribution which under certain conditions, can extend to a plateau in the high energy part of the spectra [3]. By optimising the laser plasma interaction, a control of the spectrum shape has been performed. In agreement with previous numerical simulations [4], an experimental regime has been found where a monoenergetic 170 MeV electron beam has been produced.

ELECTRON BEAM GENERATION IN NON LINEAR PLASMA WAVES

Electron beams can easily be generated by the breaking of relativistic plasma waves in an underdense plasma, where the plasma electron density is below the critical density, $n_e < n_c$ (light cannot propagate in a plasma with density $n_e > n_c$). Due to the nonlinear interaction that occurs at laser powers beyond some tens of TW, high-amplitude plasma waves can be very efficiently amplified and driven to wavebreaking if the laser pulse length, $c\tau_L$, is of the order of the plasma wavelength, λ_p . In this forced laser wakefield (FLW) regime, a combination of laser beam self-focusing, front edge laser pulse steepening and relativistic lengthening of the plasma wave wavelength can result in a forced growth of the wakefield plasma wave [3,5]. In the FLW regime the interaction of the bunch of accelerated electrons and the plasma wave with the laser is reduced. Thus, so far, this mechanism yields the highest electron energy gain attainable with laser plasma interactions, and at the same time a very good, low emittance, electron beam.

Indeed, the maximum energy in the FLW is significantly greater than in any other known regime so far, due to the highly non linear behaviour of the plasma wave. Interestingly, as the plasma density is decreased, i.e. the plasma wavelength is increased, the plasma structure shows a cavity free from electron which looks like a bubble behind the laser pulse, with electrons flowing around it before being trapped at the opposite side of the bubble, and injected locally in one well defined position of phase space, causing an identical acceleration for all of them and therefore the generation of an ultra short and monoenergetic spectrum. Since electrons do not interact with the laser beam, the electron beam quality is enhanced [6].

EXPERIMENTAL RESULTS

The very first experiment on the FLW regime was performed on the “salle jaune” laser at *Laboratoire d’Optique Appliquée* (LOA), operating at 10 Hz and at wavelength of 820 nm in the CPA mode. It delivered on-target energies of 1 J in 30 fs full width at half maximum (FWHM) linearly polarized pulses, with contrast ratio better than 10^{-6} [7]. Using a $f/18$ off-axis parabolic mirror, the laser beam was focused onto the sharp edge of a 3 mm supersonic helium gas jet. Since the focal spot had a waist of 18 μm , this resulted in peak intensities of up to $4 \times 10^{18} \text{ W/cm}^2$. The plasma period was chosen to vary between 25 and 7 fs by selecting initial electron densities, n_e , between 0.5 and $6 \times 10^{19} \text{ cm}^{-3}$, which was monitored by changing the backing

pressure of the gas jet. Figure 1 shows the subsequently installed experimental set-up. In order to obtain a single-shot spectrum, we have used a compact electron spectrometer and detected the electron signal using a LANEX phosphor screen. Using this apparatus the full spectra was imaged with a high dynamic (16 bit) charge coupled device camera. The charge was carefully measured using an integrating charge transformer (ICT) placed about 30 cm behind the LANEX screen. By changing the gas density, a transition in the electron shape appears. In the high density case, a maxwellian spectra appears whereas a monoenergetic spectra is obtained in the lower density case.

FIGURE 1. Experimental set-up permitting in a single shot to measure the whole electron spectrum

Monoenergetic electron distributions were observed for densities of $n_e=6\times 10^{18}\text{ cm}^{-3}$, for which the plasma wavelength ($\lambda_p=13.6\text{ }\mu\text{m}$) is comparable to the laser pulse length ($c\tau=9\text{ }\mu\text{m}$) and diameter ($r_0=21\text{ }\mu\text{m}$). This was the optimal set of parameters for the formation of a plasma bubble with our laser conditions.

Experimentally, this regime could be reached in a very narrow range of parameters: stretching the pulse duration above 50 fs was sufficient to loose the peaked energy distribution. Similarly, when the electron density was increased from $6\times 10^{18}\text{ cm}^{-3}$ to $7.5\times 10^{18}\text{ cm}^{-3}$, the energy distribution became maxwellian, similar to results obtained in the forced laser wakefield regime [3]. Fig.2 shows an electron spectrum after deconvolution obtained at two electron densities. The spectrum clearly shows a quasi-monoenergetic distribution peaked at 170 MeV, with a 24% energy spread (at FWHM). This peaked energy distribution is a clear signature of the formation of a plasma bubble as seen in computer simulations [4]. Above, 10^{19} cm^{-3} , the electron distribution was Maxwellian-like with very few electrons accelerated at high energy. Below $6\times 10^{18}\text{ cm}^{-3}$, the number of accelerated electrons decreased dramatically.

Electron beam distributions were measured with the same setup when no magnetic field was applied. The electron beam is very well collimated with a 10 mrad divergence at FWHM, the smallest divergence ever measured for a beam emerging from a plasma accelerator. One can explain this low divergence using several arguments: (i) electrons are accelerated in the plasma bubble but they stay behind the laser pulse and do not interact with its defocusing transverse field, (ii) when the electron beam exits the plasma, its energy is very high and therefore, the effect of space charge is greatly diminished.

Finally, the charge contained in this bunch can be inferred using the ICT. Without the magnet, the whole beam charge measured on the ICT is 2 ± 0.5 nC. The ICT signal can be correlated to the LANEX images to infer the charge at high energy. This shows that the charge at 170 MeV ± 20 MeV is 0.5 ± 0.2 nC. From the above, one can deduce that the electron beam energy was 100 mJ, so that the energy conversion from the laser to the electron beam was about 10%.

FIGURE 2 : Electron distribution obtained using a scintillator (continuous line) and using a silicon biased detectors (as described in [3]).

CONSIDERATIONS FOR HIGH ENERGY PHYSICS

The quality of electron beams produced by lasers are in progress and different schemes and estimations have been discussed from the electron energy gain point of view. A view of the Livingston graph shows the evolution of electron beam energies obtained by conventional accelerators and laser plasma accelerators. The fast rising curve of plasma accelerators seems more promising for the laser approach. But the electron energy is not the only important parameter and one has to consider the extremely high luminosity value required for high energy physics applications. For this application, one has to consider the luminosity requirement which must be of the order of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This value corresponds to the production of 1000 electrons bunch of 1 TeV with a at least 1nC per bunch [8]. The corresponding electron energy per time unit is therefore of about 1MJ/s. Assuming in the better case a coupling of 20 % from the laser to the electron beam one has to produce at least 5MJ/s of photons. Since the laser wall-plug efficiency is below 1%, one needs 500 MJ/s, ie a 500 MW of electrical power or equivalently a nuclear power plant machine to reach this goal. The laser efficiency conversion could be increased up to 50% by using diode pumped systems, thus reducing the needed power to 10 MW. The competition with conventional accelerators will for sure require extremely sophisticated and expensive machines. For comparison, a 1MJ- few nanoseconds laser, working at low repetition rate costs about 1 billion of euros, the cost of such a laser working at 1 Hz and with shorter pulses, in the ps range (pulse duration to reach the TeV range) will probably cost much more. Note that such laser technology does not exist at the moment. These considerations were done neglecting several other problems such as the propagation of electron beams into a plasma medium, laser plasma coupling problems, laser depletion, emittance requirement and others. Nevertheless, before reaching an objective and more accurate conclusion on the relevance of the laser plasma approach for high energy physics, it will be necessary to design a prototype machine (including several modules) in coordination with accelerators physicists. An estimation of the cost and an identification of all the technical problems that are to be solved will permit an estimation of the risk with respect to other approaches (particle beam interaction in plasma medium, hot or cold technology, or others).

FIGURE 3 : Evolution of electron maximum energy by laser-plasma and by conventional accelerators

CONCLUSIONS

In this report, it was shown that relativistic laser plasma interactions in the underdense regime with high repetition rate lasers can lead to the generation of monoenergetic and high charge electron beams. Beyond the generation of extreme accelerating fields, typically of the order of some TV/m, this approach will give birth to the second generation of accelerators. Furthermore, it was shown that these high-quality, low-emittance particle beams can already today be implemented for the pending quests of ultra-rapid phenomena in physics as well as chemistry [9]. Interestingly, the same experiment has permitted the generation of an extremely collimated and bright X-ray beam by betatron radiation [10] and will allow the generation of X-rays beam by Thomson scattering [11]. The evolution of lasers, laser plasma theory, modelling and experimental work is so impressive that exciting results are still bound to be discovered in this field. This approach is expected to lead to the production of a compact tunable monoenergetic electron beam.

ACKNOWLEDGMENTS

The authors greatly appreciate the support and the quality of the “salle jaune” laser, which was ensured by the entire LOA staff. We acknowledge the support of the European Community Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395).

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