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Electrons beam produced by ultra short laser pulses in the relativistic regime

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Abstract

It is known that relativistic laser plasma interactions can induce accelerating fields beyond TV/m, which are capable of accelerating efficiently plasma background electrons up to 200 MeV. Recent results obtained at LOA are presented. On the basis of energy conservation we estimate the laser performance requirements for high energy physics.

Introduction

Elementary particles like electrons, positrons or protons have been of great interest since their discovery. Their relevance in various scientific domains have been demonstrated for several decades. The implementation of such particle beams with new parameters such as luminosity, bunch length, source size, as well as quality in terms of angular divergence and emittance are of great importance for the discovery of new phenomena in science. A higher luminosity can obviously be preferential for the number of experimental events for example in colliding experiments. Shorter particle bunches permit 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.

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. With the advent of the Chirped Pulse Amplification (CPA) [1], high power, sub-ps laser pulses became available. Focusing such lasers down to focal waists of some µm and intensities beyond 10^{18} W/cm², intrinsic electric fields of several TV/m can be obtained. At such high intensities, these lasers ionize quasi-instantaneously the targets they are focused onto and create plasmas. Thus, they generate a medium consisting of free ions as well as electrons. 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. This approach can be viewed as the next generation of photo cathodes or the new generation of photo injectors which will permit within the CARE/PHIN project to produce at LOA an electron beam with energy up to 1 GeV using different approaches as discussed in this paper.

A brief discussion on physical aspects of electron beam generation induced by the use of ultra short laser pulses is presented. Recent experiments on electron beam generation will be described and an outlook on near-future experiments will be given. Finally, possible applications for high energy physics will be discussed.

Theoretical background

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, low-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[2,3]. 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.

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 than 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.

Electron beam generation in the FLW regime

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 a 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, whose contrast ratio was better than 10^{-6}[4]. 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 3×10^{18} W/cm². 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 on the gas jet. Figure 1 shows the subsequently installed experimental set-up.

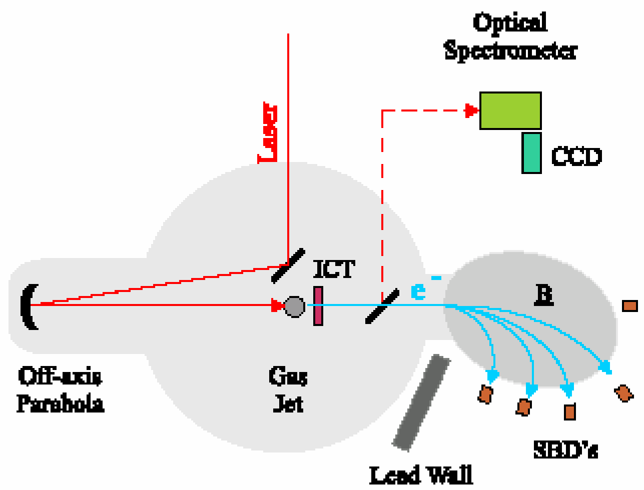


Figure 1 :experimental set up

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) 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 centre 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 whilst taking into account the opening cone as well as the halo of the 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. Such an arrangement is known as a “pepper-pot.” [5]. 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 afterwards the scattering of electrons within this wrapping.

The resulting electron spectrum for a neutral plasma electron density, n_e, of 2.5×10^{19} cm^{-3} is shown in Fig. 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.

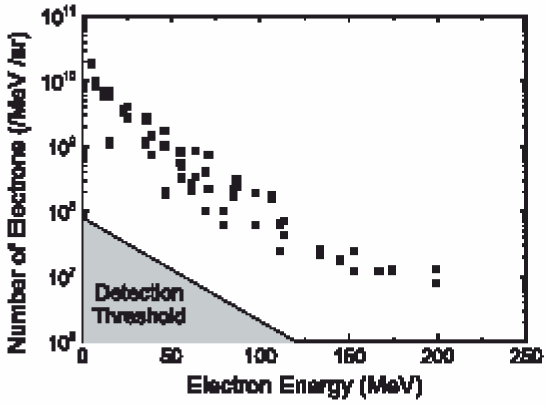


Figure 2 :
Electron energy spectra for 2.5×10^{19} cm^{-3} electron density and a laser irradiance of 3×10^{18} W/cm^2. An effective longitudinal electron temperature of (18 ± 1) MeV can be derived for electrons of less than 130 MeV (continous line).

Numerical simulations of this experiment indicated that during this relativistic laser plasma interaction accelerating fields of around 1.4 TV/m were induced when wavebreaking 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 suffered strong wavebreaking 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 wavebreaking for the plasma wave oscillations behind the first extremum, so that the hot electron population is very localized in space. Importantly, only in the first plasma 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 [6].

Figure 3 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 [7].

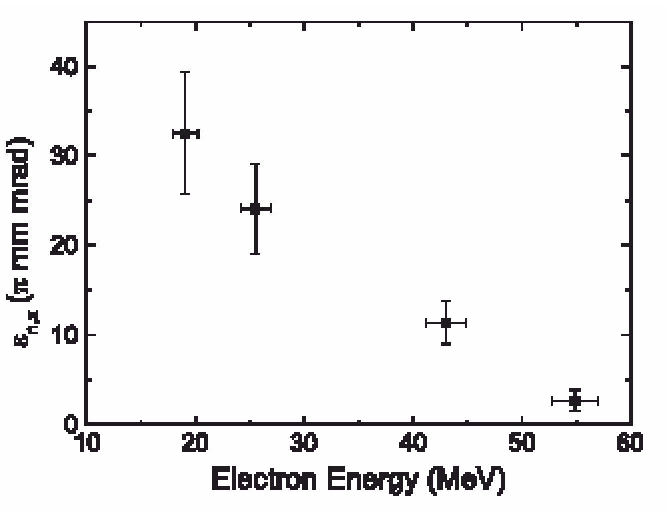


Figure 3 :
Nomalized vertical emittance $\varepsilon_{n,x}$ as a function of electron energy.

LOA strategy to reach GeV range

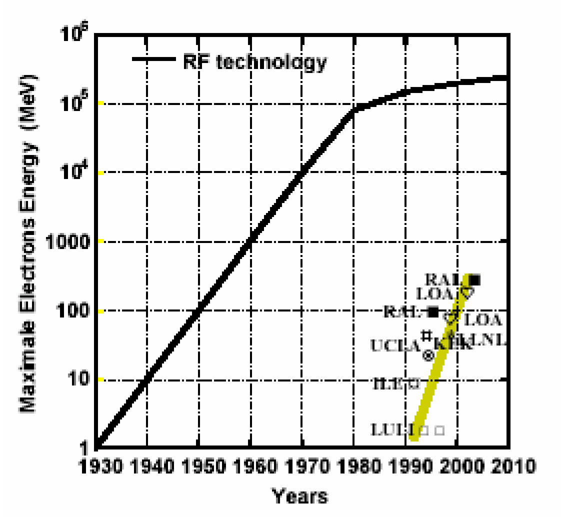
Conventional accelerators typically provide energetic electron bunches with a pulse duration in the ps range and an energy resolution of less than 10^{-3}. To achieve these performances, such devices are precisely designed and, hence, for a fixed electron energy only. Even though this high energy resolution 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. Electrons maximum energies can be increased and several method have been proposed.
The LOA strategy to reach higher energy is based on a fully optical approach : (i) using a laser directly focused onto a plasma (homogenous or a plasma channel) or (ii) by injecting an electron beam generated by a laser into a laser wake field.

In the simpler approach, by improving the coupling between the laser beam and an homogenous plasma we expect to improve the electron beam energy. Indeed, simulations for a 12 J, 33 fs laser pulse interacting with an underdense plasma suggest that a large beam charge increase could be obtained in the so called light bullet regime, where the laser pulse propagates inside a solitary plasma cavity [8]. 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. Similar electron beams, even at higher energy, have been calculated using

3D PIC simulations of the propagation of an intense laser beam (with parameter close to the LOA laser) into a plasma channel [9]. In addition, a second approach ("the two stage laser plasma accelerator"), will permit the generation of electrons up to the GeV level. This can be achieved by injecting an electron bunch generated in a first high density stage into a second low density stage where high energy gain is possible. This method would result in the generation of a electron beam with a broad energy distribution. For generating monoenergetic electron beams, a narrow energy bin can be selected using a monochromator.

Considerations for high energy physics

Several relevant applications of electron beams produced by laser have been identified. Different scheme and estimation has been discussed from the electron energy gain point of view. A view of the Levingstone graph presented here shows the evolution of electron beam energies obtained by conventional accelerators and laser plasma accelerators. The fast rising curve of plasma accelerators seems promising for the laser approach (see the two slopes). 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 a real application, one has to consider the luminosity requirement which must be of the order of $10^{34}cm^{-2}s^{-1}$. This value corresponds to the production of 1000 electrons bunch of 1 TeV with a at least 1nC per bunch[10]. 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 efficiency is today below 1%, one needs 500 MJ/s, ie a 500 MW or equivalently a nuclear power plant machine to reach this goal. It could be that the laser efficiency conversion will increase up to 50%, by using diode pumped systems, thus reducing the needed power to 10 MW. By limiting the energy at 1GeV, the production of 1000 bunches of 1nC, 1 GeV using a laser plasma approach will require a few tens of PW (30J, 30 fs) working in the kHz range. 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 laser working at 1 Hz and with shorter pulses, in the ps range (pulse duration of interest to reach the TeV range) will probably cost much more. Note that such laser technology does not exist at the moment. The considerations presented here have completely neglected several other approaches such as the propagation of electron beams into a plasma medium, laser coupling problems, laser depletion, emittance requirement and others. Nevertheless, before reaching a 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 which will have to be solved will permit to estimate the risk (electrons in plasma medium, hot or cold technology, or others).



Conclusions

In this article, it was shown that relativistic laser plasma interactions in the underdense 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 electrons to energies up to 200 MeV. Furthermore, it was shown that these high-quality, low-emittance particle beams can already today be implemented for pending quests on ultra-rapid phenomena in physics as well as chemistry [11]. 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 [12] whereas the total charge can be improved by controlling the pulse shape [13]. Applications of this source have been considered for the production of THz radiation [14] and for production of ultra-short X rays flashes[6].

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