A new and exciting optically induced electron source: Extreme acceleration gradients beyond 1 TV/m

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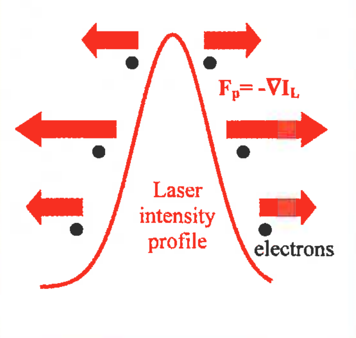
Even today short-pulse, high-power and high repetition rate laser performances do permit the generation of electron bunches with new and interesting properties—particularly as they are routinely accelerated with gradients beyond 1 TV/m. These ultra short electron bunches were demonstrated to be well collimated (within a few degrees), energetic (up to 200 MeV) and bright (few nC). Since the same lasers system can additionally produce energetic proton bunches, such optically induced particle bunches appear to have interesting characteristics, which might enable a broad variety of applications ranging from nuclear, solid state and accelerators physics, through chemistry to Medicine.

In conventional accelerators such as LINAC's, acceleration gradients are limited to some tens of MeV/m due to material break down considerations. Consequently, as the energy gain of particles is the product of such gradients times the acceleration distance one is obliged to extend the acceleration distances in order to reach high energies. This is why these tools for current quests in high energy physics are becoming larger, and, even more importantly, more expensive. In contrast, a plasma is an ionised medium consisting of free electrons and ions, which thus cannot break down anymore. Therefore a plasma can support extreme electric fields and is likely to be a candidate for the next generation of particle accelerators, as was initially proposed by Tajima and Dawson [1]. Today huge gradients beyond 1 TV/m, i.e., more than 4 orders of magnitude greater than those produced with standard technology have been reported on [2]. Note closely, that these values are indeed the highest ever induced in a laboratory. As a consequence, with regard to the energy gain of particles in accelerators, this can cut down significantly the acceleration distance to boost particles from rest to several MeV over short distances—below the millimetre range and still provide high quality.



◄ Fig. 1: **Ponderomotive Force**
This force expells electrons from regions of high laser intensity.

In order to understand the underlying laser plasma phenomena only a few parameters need to be defined in the following : the ponderomotive force, the plasma refractive index and finally the plasma wave with its associate electric field.

Ponderomotive force

As free electrons, such as are present in a plasma, can effectively quiver in the electric field of short-pulse lasers they are subjected to a variation of laser intensity. This can be expressed in the non-relativistic case with the fluid equation of motion within an electromagnetic field, which is also known as the Vlasov equation. This equation can be developed to second order to the ponderomotive laser force, which is a function of the laser intensity gradient. This ponderomotive force then, in particular present at the head of the laser pulse, pushes electrons ahead of the laser pulse—as is indicated in Fig. 1—in some kind of snow-plough effect. As a consequence, an electron plasma wave is created in its wake, which has a phase velocity equal to the laser group velocity, hence close to the speed of light. Note closely, as the ponderomotive force is proportional to the gradient of the laser intensity, this force is more dominant the shorter the laser pulse and the tighter its focussing.

Plasma index

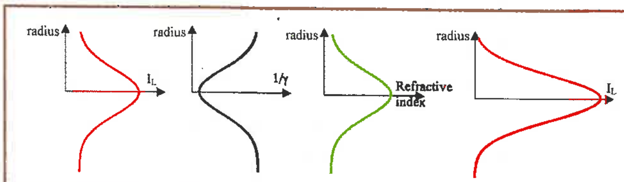
The refraction index in a low density plasma with an electron density n_e is given by $n = 1 - n_e/2\gamma_L n_c$, where n_c is the critical density, which limits in general the laser propagation within a medium. The Lorentz factor γ_L is given in the weakly relativistic regime by $\gamma_L = (1 + a_0^2/2)^{1/2}$, and it represents the relativistic mass correction of an electron oscillating in the laser electric field with a "laser vector potential," a_0, given by $a_0 = 0.86\ [I\ (\mathrm{W/cm^2})/10^{18}]^{1/2}\lambda(\mu\mathrm{m})$, where I is the laser intensity in (10^{18} W/cm^2).

Plasma wave and its associated electric field

A plasma wave is actually an electron density perturbation in space and time and its pulsation depends on the electron density, $\omega_p = (n_e e^2/\gamma_L m_0 \varepsilon_0)^{1/2}$. Such a plasma wave can easily be imagined by the oscillation of electrons around their initial nucleus. Due to this charge separation an electric field is induced, whose amplitude is given by $E = (m_e c\omega_p/e)\delta n/n$. An easy example shows that this can indeed yield tremendous values. Assuming a 1% electron density perturbation of a plasma with an initial density of 10^{17} cm^{-3} this corresponds to an electric field of 300 MV/m; and for a 100% density perturbation amplitude in a plasma at 10^{19}cm^{-3} the corresponding electric field even extends to 300 GV/m.

Producing electron bunches using only a laser beam

In order to realize this challenge a short-pulse laser with a power greater than a few TW has to be focused onto a gaseous target, typically a gas jet, since this can enable the laser to propagate through the medium. Assuming a laser peak intensity greater than 10^{18} W/cm^2, this gas jet is quasi-instantaneously ionised since the



▲ Fig. 2: **Relativistic self focusing**
The relativistic mass correction of electrons oscillating in the laser field can change the refraction index locally.

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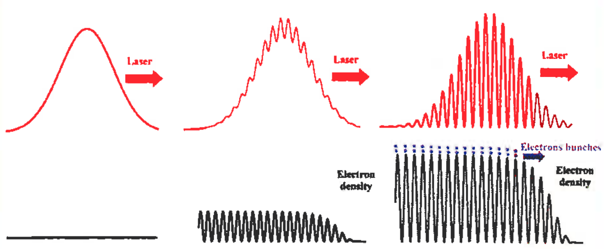
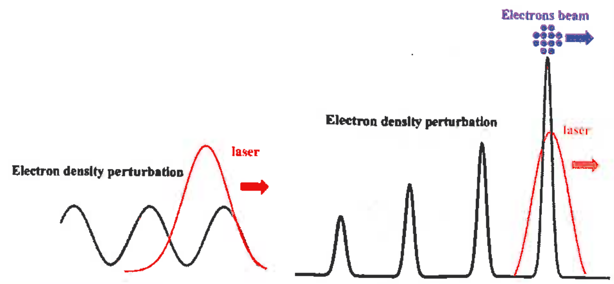


▲ **Fig. 3: The self modulated laser wake field scheme**
Here, the laser pulse length if much greater than the plasma wave wavelength.The initial Gaussian beam is modutated in a train of ultra short laser pulses whilst it is exicting a relativistic plasma waves. In case the amplitude of this plasma wave is high enough it can break and energetic electron bunches are generated.



▲ **Fig. 4: Forced laser wakefield scheme**
Here, the laser pulse length is similar to the plasma wavelength. This plasma wave can reach the non-linear regime (very high amplitude plasma wave) producing record electric fields and a single bunch of energetic electrons.

corresponding laser electric field is much in excess of the atomic electric fields within the gas target. Consequently, the atomic Coulomb barrier is suppressed, electrons are liberated and a plasma is created. Since the laser can still propagate through this plasma as long as the plasma density is below the critical density, the interaction of the laser ponderomotive force and the free plasma electrons can drive a plasma wave, continuously increasing its amplitude. In the case that the amplitude of the plasma reaches a particular value dependent on the electron distribution temperature, this plasma wave breaks and plasma background electrons are trapped and boosted to high energy. In the following, two schemes will be discussed for this scenario: the Self-Modulated and the Forced Laser Wake Field regime.

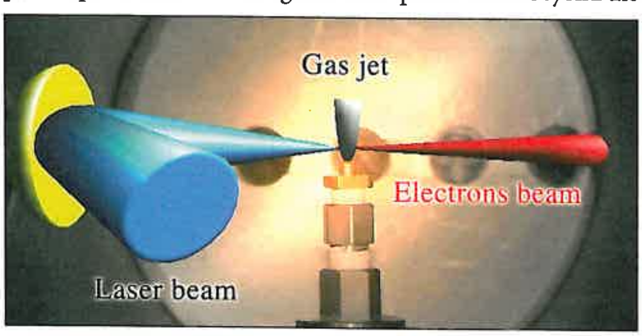
a) The Self-Modulated Laser Wake Field Regime

Identified from numerical simulations in 1992 pursued almost simultaneously by three different groups [3], this regime was first shown to excite a high amplitude plasma wave. Here, a laser with a pulse duration in excess of the plasma period is required. Typically this means laser pulse durations greater than a few hundred fs. However, since high laser intensities are nevertheless needed for this experiment and the laser pulse length is somewhat long, huge laser energies are required, typically greater than a few tens of J.

Three years after this theoretical demonstration we have experimentally demonstrated this regime at Rutherford Appleton Laboratory (RAL) in the UK. In collaboration with English and American researchers from Imperial College and UCLA respectively, we have obtained an electron beam with a maximum energy of up to 44 MeV [4]. In this experiment the VULCAN laser was utilised, which delivered at that time an energy of 20 J per laser shot with a pulse duration of approximately 1 ps and a repetition rate of one laser shot every 20 min. Consequently, the laser power (in this case 20 TW) was greater than the critical laser power for relativistic laser self-focusing, $P_c(GW)=17\, n_c/n_e$. This relativistic laser self-focusing is due to the radial dependence of the plasma refractive index with laser intensity. As such, laser focal spots typically have a spatial Gaussian profile, the maximum velocity of electrons oscillating in the laser beam being higher the closer they are to the centre of the focus, where the laser intensity is the greatest. As the plasma pulsation is proportional to $(\gamma_\perp m_e)^{-1/2}$ the index of refraction of a plasma increases the faster these electrons oscillate. Graphically speaking, the plasma acts then as a focusing lens cancelling the natural light diffraction. This permits one to reach higher laser intensity over a distance longer than the Rayleigh length, i.e., than one could ever obtain in vacuum (see figure 2) [5]. Since in the Self Modulated Laser Wakefield regime the laser pulse length is in excess of the plasma wave wavelength, every fraction of the laser pulse "sees", due to this plasma wave, a different plasma electron density, and hence a locally different refractive index. Consequently, the laser pulse has locally different group velocities, which yields a bunching of the laser pulse envelope. This subsequently changes the laser ponderomotive force, which enhances the plasma wave amplitude. At the end a loop in between these two effects is induced, which can fully modulate the laser pulse envelop at the inverse of the plasma pulsation. This effect will grow in time and during the laser propagation in the plasma will transform the initial Gaussian laser shape into a train of shorter laser pulses with a duration proportional to $1/\omega_p$ (see figure 3). For this regime the generation of some 100 GV/m electric fields have been shown experimentally, which corresponded at the very end to an electron acceleration of up to 100 MeV.

b) The Forced Laser Wake Field Regime

As mentioned above, for these kinds of experiments high laser intensities are required. Since for the Self-Modulated Laser Wake Field regime a laser pulse length in excess of the plasma wave wavelength is needed, great laser energies are required. Another possibility to increase the laser intensity is naturally to shorten the laser pulse length, and hence the energy of the laser pulses can be less. However, the initial condition that the plasma wave wavelength is shorter than the laser pulse length might not be met anymore and the laser envelope cannot be modulated at the inverse of the plasma pulsation, even though the laser power is still beyond the



▲ **Fig. 5: Schematic of set-up**
The laser beam is the input and the electron beam the output.

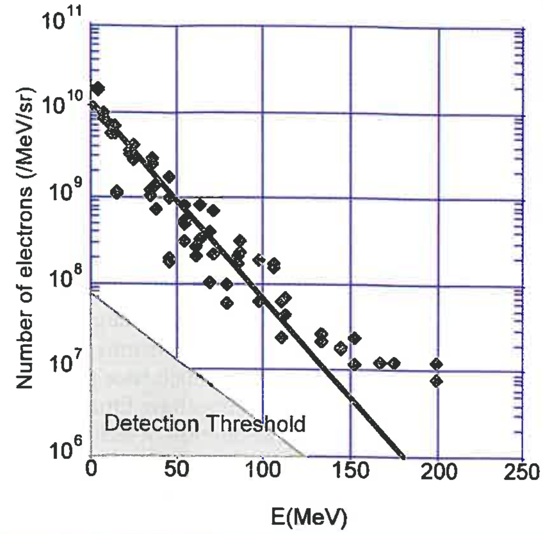
laser critical power. Nevertheless, we have obtained a novel and indeed very promising acceleration regime where the laser pulse length is of the order of the plasma wave wavelength. This regime we call the Forced Laser Wake Field. The experiment validating this regime has been recently performed at Laboratoire d'Optique Appliquée (LOA/ENSTA/CNRS/Ecole Polytechnique) in France in collaboration with French researchers from CEA/DAM/DIF as well as CENBG and English researchers from Imperial College.

In the Forced Laser Wake Field regime [2] the laser pulse is short and intense, hence, the initial push due to the laser poderomotive force is so high that the laser pulses actually see a rising density ramp. Consequently, the head of the laser pulse is propagating in a region of high electron density, whilst the tail of the laser pulse is propagating in a density depression. Since in turn the laser group velocity at the tail of the laser pulse is higher than at its head, the tail catches up and the entire laser pulse is compressed by an optical shock (see Figure 4). Interestingly, this effect is dominant in a very localised space, i.e., in one plasma wave wavelength solely, which yields in turn extreme electric fields given by $E_{WB}\sqrt{2}(\gamma_p-1)^{1/2}E_0$. Here, $E_0 = m_e c\omega_p/e$ is the electric field in the non-relativistic limit. Clearly, at an electron density of 2×10^{19} cm^{-3}, similar to the one defined in the experiment, the electric field reaches a record value of 1.4 TV/m.

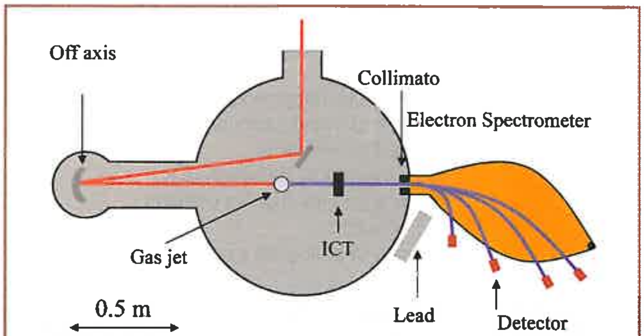
The experiment

In contrast to the VULCAN laser mentioned above, the Ti:Sa laser in the "salle jaune" at LOA that was utilised in this experiment delivers 1 J, 30 fs laser pulses at a wavelength of 0.82 µm and at a repetition rate of 10 Hz [6]. The laser beam after compression propagates under vacuum conditions and is focused onto a gas jet (see figure 5). The gas jet profile has been optimised for this purpose (the cylindrical jet is homogeneous in density, additionally providing a sharp edge). The laser irradiance is, for the 1 meter off axis parabola, close to 3×10^{18}W/cm^2. Due to the high-quality front phase of these laser pulses a large fraction of about 50 % of this laser energy was concentrated in a small surface close to the diffraction limit of the laser. The electron density was controlled by changing the gas backing pressure of the jet. Here and as mentioned above the plasma pulsation (25 fs) was about the laser pulse duration (30 fs). A sketch of the experimental set-up is shown on Figure 6.

The electron beam produced in this experiment was characterized on the laser propagation axis both angularly and energetically with radiochromatic film and an electron spectrometer, respectively. The magnetic field of this electron spectrometer can be changed from 0 to 1.5 T, permitting one to decipher the electron energy in between 0 and 200 MeV with the help of silicon barrier diodes. A typical electron spectrum is shown in Figure 7, indicating a maximum electron energy of 200 MeV, twice as much as in the Self-Modulated Laser Wake Field regime and with a laser energy 20 times lower. This spectrum has a Maxwellian-like shape for electrons with energies below 130 MeV and shows a clear plateau for electrons with energies greater than 130 MeV. The Maxwellian component has an effective longitudinal temperature on the laser axis of 18 MeV. The angular distribution as shown in Figure 8 indicates that the higher the electron energy the better its collimation. The total charge of the entire electron pulse has in addition been measured and is close to 5 nC. Interestingly, and following the principles of standard classical accelerator physics, the normalized emittance of this electron pulse has been measured using the "pepper pot" technique. This has proven to be of a high quality, similar to that routinely produced at today's LINAC's where a normalized emittance of (2.7 ± 0.9) π mm mrad for electrons with an energy of (55 ± 2) MeV has been reported. The pulse length of this electron pulse has also been evaluated numerically in [7] and has been shown to be of the order of the of the laser pulse length, and hence in the sub ps range.



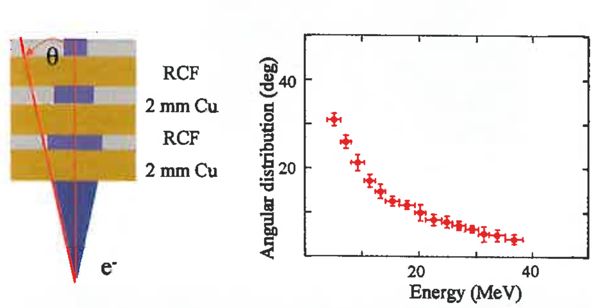
▲ Fig. 7: Electron spectrum



▲ Fig. 6: Experimental set up

Conclusions and perpectives

In this article it has been shown how a high charge, energetic, low emittance and ultra-short electron beam can be produced with a compact laser system operating at 10 Hz. This electron source may permit very attractive applications in the near future in different domains such as material science, physics, chemistry,



▲ Fig. 8: Angular distribution

features

accelerators physics as well as medicine. For example, irradiating a high Z target with this electron beam, a very small and energetic γ source could be generated. The perfect synchronisation of this electron beam with a laser beam might additionally permit new pump-probe experiments for example in ultra-fast chemistry [8]. An energetic X-ray source could be also produced by focusing the laser beam onto the electron beam. This X-ray flash would permit time-resolved studies of fast phenomena in biology within 30 fs accuracy [7]. Moreover the laser beam focused onto thin foil targets has already produced proton beams with energies up to 10 MeV. Such laser-generated proton beams may have future application in the production of radio-isotopes for PET [9], in proton therapy [10] and as a first stage of a proton accelerator. Indeed, the impressive progress seen in laser technology—more and more powerful, more and more compact and consequently less and less expensive laser systems—lead us and the entire laser plasma community to believe that this new approach to generating optically induced particle beams has the potential to change the scientific landscape in the near future.

This X-ray flash would permit time-resolved studies of fast phenomena in biology

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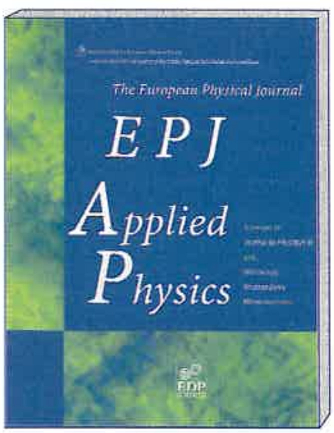

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