LASER-PLASMA WAKEFIELD ACCELERATION: CONCEPTS, TESTS AND PREMISES

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Abstract

The concepts of laser-plasma based accelerator and injector are discussed here. Recent tests done at LOA as well as design studies of high-quality few GeV's electron beam with low energy spread (1%) are presented. These laser-produced particle beams have a number of interesting properties and could lend themselves to applications in many fields, including medicine (radiotherapy), chemistry (radiolysis), accelerator physics, and as a source for the production of γ-ray beams for non-destructive material inspection by radiography, or for future compact XFEL machines.

CONCEPTS

High-gradient acceleration techniques rely on electron plasma waves to efficiently accelerate particles. The concept of laser plasma acceleration was originally proposed twenty-five years ago by Tajima and Dawson [1]. In a plasma medium, the electric field in a plasma wave can attain extremely high values, of the order of $E_0=cm_e\omega_p/e$, E_0(V/m) $\approx 96\ n_e$(cm^{-3})$^{1/2}$ (E_0=190 GV/m for n_e=3.9 × 10^{18} cm^{-3}). Plasma waves can be excited by the propagation of laser pulses in a transparent plasma, i.e. in plasmas with density below the critical density, n_c (cm^{-3})$=1.1\times 10^{21}/\lambda_0^2$(µm). In the scheme known as laser wakefield acceleration, the plasma waves are generated in the wake of the laser pulse, like waves in the wake of a ship. Efficient energy transfer between the wave and the particles requires that both move at the same speed. High energy gain can be reached by using low density plasmas, in which the phase velocity of the laser-excited plasma wave, which is equal to the laser pulse group velocity, is very close to the speed of light in vacuum. The longitudinal electric fields associated with this fast plasma wave is then able to accelerate relativistic particles injected into the plasma or even, if its amplitude is large enough, to trap particles from the plasma itself. By "surfing" on this electrostatic wave, particles can be boosted to high energies over very short distances.

Laser plasma acceleration techniques have successfully been used either for acceleration of injected electrons or as a source of electron beam, the later will be called "plasma injector".

Excitation of relativistic plasma waves by intense laser pulses is made via the ponderomotive force (related to the "light pressure"), which expels electrons from regions of high laser intensity. Since this force is proportional to the laser intensity gradient, large amplitude plasma waves can be excited using relatively modest laser energies by using very short pulses. In the wake field regime, the optimum laser pulse duration τ_L is half of the period τ_p, relationship known as the resonant condition. The plasma period is related to the electron density by $\tau_p=2\pi/\omega_p$, with $\omega_p^2=n_e e^2/m_e\varepsilon_0$. The resonant condition in practical units is then given by n_e(cm^{-3})$=3.5\times 10^{21}/\tau_L^2$(fs), for a 30 fs laser, this gives a resonant density of 3.9 × 10^{18} cm^{-3}.

On the other hand, the phase velocity of the wake v_{plasma}, which is equal to the group velocity of the laser v_{glaser}, increases when the electron density decreases, indicating that higher energy gain can be reached in lower density plasmas according to $v_{plasma}=v_{glaser}=c(1-\omega_p^2/\omega_0^2)^{1/2}=c(1-n_e/n_c)^{1/2}$.

Acceleration of injected electrons in laser-plasma wakefields has been successfully demonstrated using one laser beam in the laser wake field regime (LWF) or two lasers beams in the laser beat wave regime (LBW).

Electrons injected at 3 MeV have been accelerated by this scheme up to 4.7 MeV [2]. In the LBW, the plasma wave is driven by the interference of two laser pulses (not necessary short) at two different wavelengths. Electric fields close to the GV/m level were measured for this experimental configuration using mid-infrared laser beams [3] and injected electrons have been accelerated up to 30 MeV at UCLA [4]. In both LWF and LBW, only electrons injected by an external source into the wave have been accelerated.

In those experiments, the injected electron beam always had a duration much greater than the plasma period and as a consequence, the electrons of the bunch experienced the whole sinusoidal electric field, and had an output spectra with a maxwellian-like distribution. The production of bunches with narrow energy spreads in plasma accelerating structures needs the development of bunches of electrons with duration much shorter than the plasma period. For example, for a plasma wave structure with 100 fs the electron bunch should be 10 fs or less, in order to be accelerated in a constant electric field.

The interaction length is limited in homogenous plasmas by the natural diffraction length, the Rayleigh length, given by the numerical aperture of the laser beam and its wavelength λ_0, $L_{int}=\pi Z_R$, with $Z_R=\pi w_0^2/\lambda_0$ where w_0 is the laser waist. In the linear wakefield regime, the plasma waves amplitude, E_{max}/E_0 (or $\delta n/n$), is related to a_0, the laser strength parameter according to $E_{max}/E_0\approx 0.8\times a_0^2$, which is related to the laser peak intensity : $a_0\approx 8.6\times 10^{-10}\,(I_L\lambda^2)^{1/2}$ (I_L and λ_0 are respectively expressed in W/cm^2 and in µm). In order to get intense but linear plasma waves, a_0 must be of the order of unity, in other words, the laser peak intensity (for λ_0=800 nm) must be of the order of 10^{18} W/cm^2. With current laser technology (in the level of tens of TW), laser beam focused with an f/20 aperture can generate a plasma wave in the linear regime ($a_0 \sim 1$) with interaction lengths of a few millimetres. This value has to be compared to the dephasing length, which is the maximum length over which electrons are accelerated: $L_d \approx \gamma_p^2 \lambda_p$ where the relativistic factor of the plasma wave $\gamma_p = (1-v_p^2/c^2)^{-1/2}$ is close to λ_p/λ_0 for tenuous plasmas. The plasma wavelength is related to the electron density by λ_p (μm) $\approx 3.3\times10^{10}$ n_e(cm^{-3})$^{-1/2}$. For a 30 fs laser pulse, the dephasing length, $L_d \approx \lambda_p^3/\lambda_0^2$, at the resonance is of the order of 7 mm. The maximum energy gain $W_{max} \approx 4\gamma_p^2 (E_{Max}/E_0) mc^2$ is then given by or W_{max}(GeV) ≈ 1.6 n_c/n_e a_0^2 which is close to 700 MeV. In the above mentioned experimental studies of acceleration of externally injected electrons, the energy gain was limited by the length of interaction, which was much smaller than the dephasing length.

Since the physics of laser interaction with underdense plasma in the weakly relativistic regime is mainly governed by linear processes, the corresponding accelerating structures have very good stability, only limited by the laser or target shot to shot fluctuations. The problem of stability in these schemes does not seem to be a real one for future accelerators due to the rapid progress in laser and target technologies. On the other hand, when the laser power exceeds the self-focusing power, plasma waves can reach very high levels and trap plasma electrons directly without external injection. Several experiments have been performed in these conditions, with laser powers in the range of tens of TW and laser energies (and durations) in the range of 0.1 J (~30 fs) to 100 J (ps). Those "plasmas injectors" were the subject of intense research efforts during these last years.

TESTS

In 1995, at Rutherford Appleton Laboratory, a collimated beam of 44 MeV electrons was generated in the self-modulated laser wakefield regime (SMLWF) [5-7] by focusing a 50-terawatt laser onto a gas jet target [8]. Electron beams generated by ultrashort laser pulses have been then produced in many laboratories around the world. In those experiments electron spectrum had always a maxwellian-like distribution.

In 2002, the quality and the electron maximum energy was improved in experiments made using a 30 fs laser and a very underdense plasma. By choosing a plasma density close to the resonant one, non linear plasma waves were excited, permitting the production of electrons with a maxwellian shape and with a plateau extending up to 200 MeV [9]. In addition, the electron beam quality was enhanced due to the reduction of laser-electron beam interaction. For the above parameters, the electric field inside the plasma was estimated to locally reach a record value of more than 1.4 TV/m. Under these extreme conditions, it takes less than 1 mm of laser propagation in the plasma to accelerate electrons up to 200 MeV.

In addition to the electron energy gain, the emittance was also improved to values comparables with those of modern conventional accelerators [10]. Whereas accelerated electron distributions previously suffered from a very large energy spread, a new and extremely exciting milestone has been reach recently, when three groups, from Imperial College London[11], Lawrence Berkeley National Lab[12] (LBNL), and LOA[13], independently produced quasi mono-energetic, high energy electron beams directly by focusing a laser pulse onto an homogenous plasma [11,12] or into a plasma channel [13], as predicted by numerical simulations [14,15].

Experimental tests on laser-plasma acceleration were made recently at LOA by focusing a 20 TW laser with a f/18 off axis parabola onto a gas jet target. The focal spot had a radius at full width half maximum of 18 μm and the corresponding laser intensity was I=3.2×10^{18} W/cm^2. This choice of small aperture gave a long Rayleigh length of about 1.3 mm, which is the range of interest for high energy gain as mentioned above. Measurements of the electron beam distribution, in energy and in space are a powerful way to gain a better understanding of processes involved in laser-plasma interaction. We developed a new method of beam characterisation based on the use of a compact spectrometer consisting of a 0.45 Tesla, 5 cm long permanent magnet and a LANEX phosphor screen. Doing so, we were able to measure, in a single shot, the whole spectrum and to record its image on a 16 bit Charged Coupled Device (CCD) camera. Since we do not use a collimator, the vertical direction on the LANEX screen corresponds to the angular aperture of the electron beam. The LANEX screen was protected by a 100 μm thick Aluminium foil in order to avoid direct exposure to the laser light. The resolution was respectively 32 MeV and 12 MeV for 170 MeV and 100 MeV energies. Spatial electron beam distribution has also been measured by removing the magnet. The charge of the electron beam was measured using an integrating current transformer placed 30 cm behind the LANEX screen and the LANEX screen which has been absolutely calibrated [16]. The location of the ICT (after the magnet), allows the measurement of the charge of electrons with energies greater than 100 MeV. A schematic description and a picture of the inner vacuum chamber are presented in Fig. 1.

Fig. 2 shows the electron spectra obtained in the optimal condition. At higher densities the spectra has a maxwellian like distribution. This transition occurs for densities around 1.0×10^{19}cm^{-3}. The best coupling for obtaining a high charge and a quasi-monoenergetic electron beam is at n_e=6×10^{18}cm^{-3}. For this density, the image shows a narrow peak around 170 MeV, indicating efficient monoenergetic acceleration with a 24% energy spread (corresponding to the spectrometer resolution). The charge contained in this bunch can be inferred using the integrating current transformer: the whole beam contains 2±0.5 nC and the charge at 170±20 MeV is 0.5±0.2 nC. The electron beam energy was estimated to be close to 100 mJ, which correspond to almost 10% of the laser energy.

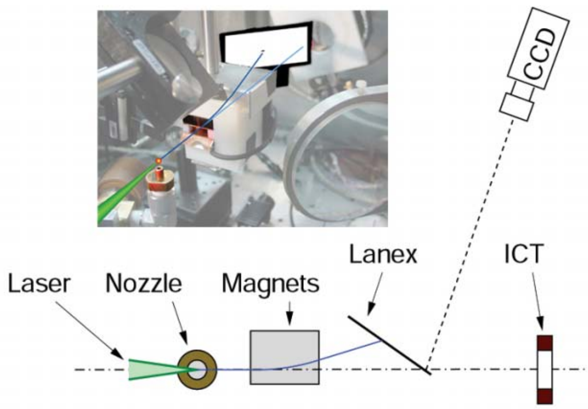

Figure 1: Picture and layout of the experimental set-up. The compact spectrometer consisting of a permanent magnet and a phosphor screen recorded the whole spectra on a 16 bit Charged Coupled Device (CCD) camera. The integrator charge transformer (ICT) measures the charge of electrons with energies greater than 100 MeV

At lower plasma density, $n_e=3\times10^{18}cm^{-3}$, the peak energy is approximately at the same position whereas the number of electrons is reduced by a factor of 10. The spatial distribution of the electron beam is also indicated in figure 2 showing that the beam is collimated with a 6 mrad aperture.

Similar results have also been achieved using a preformed plasma channel with a gas jet target [12]. Quasi monoenergetic beams have also been produced with homogenous or parabolic plasmas at higher density and even with longer laser pulses (with $\tau_L>\tau_{plasma}$). However, in order to optimise the energy transfer to the electron bunch, the laser pulse duration must be of the order of the plasma period.

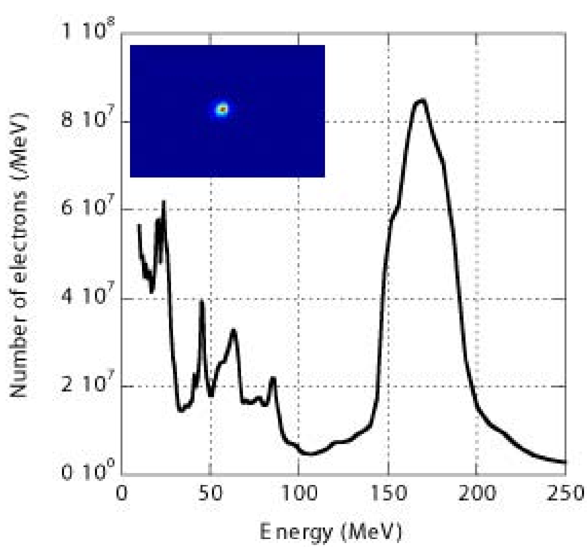

Figure 2: Typical electron spectrum obtained at 6×10^{18} cm^{-3} with 1J, 30 fs laser pulse focused down a 18 micron focal spot. Electron beam profile with 6 mrad aperture.

Particle in cell (PIC) simulations reveals that the laser pulse self-focuses as it propagates in the plateau region of the gas jet. As the effective radius of the laser pulse decreases, the laser intensity increases and finally becomes sufficient to generate a highly nonlinear plasma wave [14]. The laser ponderomotive force expels the plasma electrons radially and leaves a cavitated region behind the pulse. This region is referred to as the plasma bubble. Since the laser also pushes electrons forward, the laser pulse is propagating in a plasma with rising density. The laser group velocity will then be higher on the back of the pulse than on its front. This will compress the laser pulse temporally (this was recently measured experimentally [18]), and will also contribute to the generation of the bubble. When the beam charge becomes comparable with the ion charge in the cavity, the injection stops and produces a monoenergetic electron beam.

Temporal information based on THz emission measurements indicates that temporal structures with duration shorter than 50 fs are present in the electron bunch [19].

PREMISES

It has been shown that the bubble or blow out regime can produce electron beams at high energy with an energy spread of about 5 to 10 %. Numerical simulations show that with a 200 TW laser, electron energies of 1.5 GeV can be achieved in an homogenous plasma. Using a plasma channel, the laser power needed to reach similar gain is reduced to the 50 TW level. Nevertheless, since the energy transfer from the laser to the electron beam is the same, one has to find a compromise between the charge and the energy. The typical value for the laser-to -electrons energy transfer is of the order of 10 %. Assuming this value and a final electron energy of 1.5 GeV, for a 200 TW-50 fs laser (i.e 10 J) the charge will be limited to 666 pC, whereas for a 50TW-50fs (i.e 2.5 J), the maximum charge will be 166 pC.

In order to reduce the energy spread we propose here to inject the ultra short bunch of electrons we produced at LOA into a long plasma wave generated by a laser pulse in a low density plasma. We performed numerical simulations using the code WAKE. The laser is guided through a parabolic plasma channel with a radial density profile given by $n(r)=n_0\ (1+0.585\ r/r_0\ )$, with $n_0 = 1.1\times10^{17}$ cm^{-3} and r_0 =47 µm and 24 cm long. The laser pulse duration is 60 fs, its energy, power and maximum intensity are respectively 9 J, 150 TW and 4.2×10^{18} W.cm^{-2}. The initial bunch mean energy is 170 MeV with an energy spread FWHM of 40 MeV, and its angular divergence is 10 mrad, The bunches are injected in the first wake with a radius of 8 µm. Figure 3 shows the energy spectrum of the extracted bunch. We can see than roughly half of the electrons have been accelerated to 3.5 GeV, with a relative energy spread FWHM of 1% and an unnormalized emittance of 0.006 µm. The trapped fraction can be increased by reducing the initial bunch radius or by using wider pulses, which implies more laser energy.

Numerical simulations show that multi-GeV electron beams with low energy spreads can be produced in a very compact way by injecting electron beams produced today in the bubble regime into a long plasma wave structure. Importantly, the beam quality is preserved as well as its very short duration. On a longer time scale, developments of these novel beam acceleration techniques should also be of interest for high energy physics experiments.

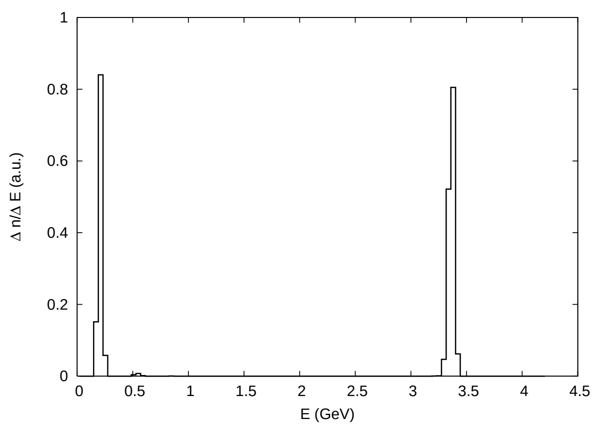

Figure 3: Final energy spectrum calculated for a guided laser pulse (60 fs, 9 J, 150 TW) and an acceleration length of 24 cm. Injected bunch spectrum is shown in figure 2.

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