Principle and applications of electron beams produced with laser plasma accelerators

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Abstract : High quality electron beams produced by laser plasma accelerators, in the bubble regime or in the colliding laser pulse regime, have properties of interest for many applications in fields such as material science, medicine, and chemistry. We present shortly the principle of laser plasma accelerators and we show why these beams are of interest for radiography and radiotherapy.

1. Introduction

Electron beams produced with laser plasma accelerators have properties of interest in many fields such as material science, medicine, and chemistry. The shortness of the electron beam is of interest for example for fast chemistry. Successful experiments have permitted to follow the ionization dynamics of water in the so called prethermal regime¹. For material science, the collimation, the charge and the energy of electron beam which, by interacting with a dense target, can produce a sub-millimetric source of energetic photons (γ-rays) much smaller than those available with conventional accelerators. Such sources of radiation are of interest for a non destructive inspection of dense matter in aircraft or automobile industries. In medicine, several millions of patients with cancer tumours are treated in the world with X rays with energies of a few MeV. This treatment represents the majority of ionising radiations used for cancer radiotherapy. They are used successfully in many hospitals because they are produced using flexible, compact and affordable machines. Higher quality, Very High Energy (VHE) electron beams, such as those produced by laser plasma accelerator, could be used for radiotherapy and provide better clinical results². On part 2, we summarize the two options to generate high quality VHE beams with laser plasma accelerators. On part 3, we show the interest of these beams for material science and on part 4 we present their relevance to cancer therapy.

2. High quality VHE

In laser-plasma electron accelerators³, a longitudinal accelerating electric field is excited via the ponderomotive force of an ultra-short and ultra-intense laser. This force is proportional to the gradient of the laser intensity I. The ponderomotive force pushes the plasma electrons outward and separates them from the ions, thus creating a travelling electric field, with a phase velocity v_p close to the speed of light c, as required for accelerating particles to relativistic energies. This wakefield can have a longitudinal electric field of the order of E_z=m_e c ω_p/e, where m_e and e are respectively the electron

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mass and charge and $\omega_p$ is the plasma frequency. For example, a plasma with electron density $n_e=10^{19}$ cm$^{-3}$ can sustain electric fields of 300 GV/m. In addition, the characteristic scale length of the wakefield is the plasma wavelength $\lambda_p=10^{-30}$ µm, (for densities $n_e=10^{18}$-10$^{19}$ cm$^{-3}$). Consequently, if one manages to inject and accelerate electrons into a single period of the wakefield, it will lead to ultrashort electron bunches, with durations shorter than $\lambda_p/c$. Electrons need to be injected into the wakefield with a sufficient initial energy so that they can be trapped and accelerated. Experimentally, two injection mechanisms have permitted the generation of high quality quasi-monoenergetic electron beams. In the first mechanism, the so-called “bubble regime”, a single laser pulse is used (see fig.1). It drives the wakefield to extremely high amplitudes in a very nonlinear regime. Electrons are injected at the back of the wakefield through the transverse breaking of the plasma wave. With current laser technology, electron beams (e-beams) in the 100 MeV to GeV range can be produced in millimetre distances, with relative energy spreads in the 5-10 % range and charge of hundreds of pC.

The second mechanism is based on the use of several laser pulses. In its simplest form, the scheme uses two counter-propagating ultra-short laser pulses with the same central wavelength and polarisation (see fig. 1). The first laser pulse, the “pump” pulse creates a wakefield whereas the second laser, the “injection” pulse will only be used for injecting electrons. The laser pulses collide in the plasma and their interference creates a laser beatwave pattern. The beatwave pattern is a standing wave, with characteristic spatial scale $\lambda_0/2$ where $\lambda_0$ is the laser central wavelength. Because of this small scale length, the ponderomotive force of the beatwave is very large, it traps plasma background electrons and pre-accelerated them at the MeV energy level. Some of these electrons have gained enough energy to be trapped in the wakefield driven by the pump pulse and further accelerated to relativistic energies. Although this scheme is more complicated experimentally, it offers more flexibility: experiments have shown that the e-beam energy can be tuned from 10 to 250 MeV. The e-beam has a quasi-monoenergetic distribution with energy spread in the 5-10 % range, charges in the 10-100 pC range and its parameters are stable within 5-10%. This approach is promising for the control of the e-beam parameters, it might allow to tune the charge as well as the energy spread.

Figure 1): Injection mechanisms in the bubble regime (left) and in the colliding regime (right).

3. $\gamma$ Radiography
Energetic electron beams produced by laser plasma accelerators have been used to generate secondary radiation sources of interest for nondestructive material inspection with potential applications in motor engineering and aircraft inspection. The electron beam energy is efficiently converted into multi-MeV bremsstrahlung photons (photons produced by a rapidly decelerating charged particle) when it interacts with a solid target of high atomic number, providing a sub-millimeter pulsed $\gamma$-ray source that is significantly smaller and of shorter duration than other sources available today. An example of the use of $\gamma$-rays for radiography is shown in Figure 2. An electron pulse generated by laser plasma interaction is converted into $\gamma$-rays inside a Ta converter, placed 3 mm from the center of the nozzle. The bremsstrahlung radiation produced is used to irradiate a 20-mm-diameter spherical hollow object made of tungsten. A sinusoidal shape, with cylindrical symmetry, is etched on the inner part of the object. The transmitted radiation is then detected on a $\gamma$-camera and imaged on a CCD camera. To avoid bremsstrahlung of electrons inside the object that is radiographed, a magnetic field is applied behind the converter to deflect the electrons. Experimental measurement of the source size - 450 µm full-width at half maximum (FWHM) - has been done by radiography of an object with sharp edges. The experimental radiograph is presented in Figure 2. This example shows the benefit of the high
spatial quality of the electron beam produced with laser-driven accelerators for imaging dense matter. This photon source is also expected to be ultrashort because the electron source duration is comparable with the laser pulse duration (shorter than 10 fs according to simulations), and the broadening of the pulse by scattering in the Ta target is controlled by its thickness. Ultrashort γ-ray sources are interesting for several applications, including monitoring of fast moving objects or visualization of high-density metal compression. A train of short laser pulses may enable movies to be taken of the ballistic motion of objects into dense matter or the damage evolution of structures with a spatial resolution of <100 µm. Recent improvements in laser plasma acceleration have also demonstrated the production of monoenergetic electron beams. All these excellent characteristics, combined with the decreasing cost and size of terawatt lasers, will make such sources extremely useful for radiographic applications. To conclude, these electrons and γ-sources have a better spatial and temporal resolution than conventional sources and promise to play an important role in materials science.

![Figure 2](image1.png)

**Figure 2:** Experimental set-up for γ radiography (left) and image of test object (right).

### 3. Applications to radiotherapy

We show in figure 3 the dose deposition for different particles. The difference between VHE and low electron energy or photons indicates that (i) the dose deposited by electrons deep into the tissue is much higher than for low electron energy and photon, and (ii) the dose deposition is still efficient after few tens of centimetres. Reducing the dose deposition before the tumour will enhance the quality of treatment and having dose deposition after tens of centimetres could be beneficial to cure efficiently cancer tumours within obese patients.

![Figure 3](image2.png)

**Figure 3 :** Dose deposition for different particles (left), Contour plot of the dose deposited inside water, for an electron beam focused at 30 cm in the water phantom (right)
A detailed study of the dosimetric properties of monoenergetic VHE (very high energy) electron beams in the range of 150–250 MeV was published by DesRosiers et al.\textsuperscript{12} They have shown for instance that for parallel opposed beams the sharpness of the lateral penumbra is of comparable quality to that of clinical photon beams. The next step would be to evaluate the adequacy of VHE beams from laser-plasma interaction for IMRT. This requires a better knowledge of the dose deposition profile of a single electron bunch produced with present laser-plasma technology. Monte Carlo simulations with the code GEANT were performed in order to show the dosimetric properties of the electron beam produced in the bubble regime. We assume that the low energy part of the spectrum can be removed. Since electrons are accelerated in a small region with dimensions comparable to the laser waist, we will use a pointlike electron source whose energy is distributed along a Gaussian shape with 40 MeV width FWHM, centered at 170 MeV\textsuperscript{3}. The initial angular spread is chosen to be independent of the electron energy and corresponds to a Gaussian width of 10 mrad FWHM. A total of $10^5$ electrons are used in the simulation. This value is lower than the measured number of electrons, which is about $3\times10^7$. This choice is a compromise between the time needed to complete the simulations and the statistical fluctuations. All output values are normalized with respect to the incident bunch charge. In order to obtain the dose for a single laser shot, one needs to multiply the normalized dose (in Gy/nC) by the charge of an electron bunch (0.5 nC). The following simulations are performed for a single shot, but our laser system can operate at 10 Hz. Fig. 3 also show the contour plot of the dose deposited in water for a focused electron beam.

The dose distribution in water of a quasimonoenergetic electron beam with low divergence, produced by laser plasma interaction, reveals its interest for radiotherapy. Radially, the dose deposition profile is narrow and longitudinally, the penetration distance of these energetic electrons is higher than the 20 MeV conventional accelerators. The high laser energy conversion into accelerated electrons (10\%) and the control of the interaction parameters may allow to obtain a tuneable electron source adapted to radiotherapy. Recent calculations done by DKFZ (German Cancer Research Center) have shown that treatment planning quality in a prostate tumour can be improved by reducing the dose in safe tissue by 20%.

4. Conclusion

It was shown that electron beams produced by laser plasma accelerators are well suited for radiography of dense objects. These beams are also relevant for radiotherapy, which requires delivering a high dose peaked on the propagation axis, a sharp and narrow transverse penumbra, combined with a deep penetration. This may improve cancer treatment by sparing dose of sensitive structures. The lack of compact and cost-efficient electron accelerators could be overcome by laser-plasma systems using commercial laser systems delivering tens of femtoseconds, few Joule laser pulses, and working at 10 Hz repetition rate to deliver the required dose in a few minutes.

5. Reference

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