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Laser–plasma acceleration of electrons for radiobiology and radiation sources

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ABSTRACT

Laser-driven acceleration in mm-sized plasmas using multi-TW laser systems is now established for the generation of high energy electron bunches. Depending on the acceleration regime, electrons can be used directly for radiobiology applications or for secondary radiation sources. Scattering of these electrons with intense laser pulses is also being considered for the generation of X-rays or γ-rays and for the investigation of fundamental electrodynamic processes. We report on laser-plasma acceleration in the 10 TW regime in two different experimental configurations aimed at generating either high charge bunches with properties suitable for radiobiology studies or high collimation bunches for secondary radiation sources with high quality and good shot-to-shot stability. We discuss the basic mechanisms and describe the latest experimental results on injection threshold and bunch properties.

1. Introduction

Laser-plasma acceleration (LPA) [1–3] driven by ultraintense Chirped Pulse Amplification (CPA) lasers [4] is being considered for the development of novel radiation sources and applications to medical sciences. In this context, given the ever increasing level of control and reliability of these schemes, compact, laser-driven accelerators may have soon an impact on radiotherapy and diagnostics in areas where electron beams with energy up to several tens of MeV are used as primary radiation. In this energy range, table-top laser systems of peak power below 10 TW can be used to drive electron acceleration and the potential for future use in a clinical environment is high [5]. A laser-driven electron accelerator may have several advantages compared to conventional linacs. First of all, given the small size of the acceleration region, the active part of the source could be enclosed in a volume, the "head" of the accelerator, as small as a few tens of cm, reducing the impact of radiation protection measures. In addition, given the possibility of transporting the laser pulse more easily than an electron beam, in the case of a medical use a single ultrashort laser system could be used to drive multiple heads for different treatment areas. In addition, higher energy bunches could be available for applications in which higher energy spread can be accepted. Finally, laser-plasma acceleration does not require UHV or high power supplies close to the utilisation area.

Moreover, given the ultra-short duration of laser accelerated bunches compared to conventional RF linacs, a new regime of ultrafast radiation biology may be activated which represents a newly emerging interdisciplinary field driven by the emerging of laser-driven particle accelerators [6]. One of the key aspects to be investigated is the very short bunch length, typical of LPA electron bunches, that leads to ultra-high instantaneous dose-rate, orders of magnitude higher than conventional sources. In view of this, pre-clinical studies are needed to address the radiobiological effectiveness of laser-driven electron sources compared to conventional linacs used in medical applications, with a particular attention to the intra-operatory radiation therapy (IORT) [7,8].

Along with radiobiology studies, all-optical X-ray and γ-ray sources [9] based upon Thomson or inverse-Compton scattering, are also rapidly emerging [10–14] as potentially competitive with existing similar sources based on conventional linear accelerators and already feasible with existing established acceleration regimes. Thomson scattering from free electrons is a pure electrodynamic process in which each particle radiates while

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interacting with an electromagnetic wave [15,16]. From the quantum–mechanical point of view Thomson scattering is a limiting case of the process of emission of a photon by an electron absorbing one or more photons from an external field, in which the energy of the scattered radiation is negligible with respect to the electron's energy. If the particle absorbs only one photon by the field (the linear or non relativistic quivering regime), Thomson scattering is the limit of Compton scattering in which the wavelength of the scattered photon observed in the particle's rest frame is much larger than the Compton wavelength of the electron. An all-optical Thomson scattering scheme can be based upon a counter-propagating configuration of two ultraintense laser pulses focused in a gaseous target. In this configuration, one of the laser pulses generates a bunch of energetic electrons while the other, counter-propagating pulse interacts with the energetic electrons generating γ-ray radiation along the bunch propagation direction.

Motivated by these considerations, we have identified LPA accelerating regimes suitable for either dosimetric and radiobiological studies or Thomson scattering aimed at validating the source for future studies [9]. Here we briefly describe the physical properties of the source, including the interaction scheme, the acceleration regimes and the characterisation of the accelerated electrons. In the first paragraph we describe the interaction scheme and list the main experimental parameters. In the second paragraph we show the main results concerning the characterisation of the laser-plasma interaction. In the third paragraph we provide an overview of basic properties of accelerated electron bunches for radiobiology studies, while in the fourth paragraph we summarise the main features of electron acceleration for Thomson scattering.

2. The experimental set up

The experiment was carried out at the Intense Laser Irradiation Laboratory (ILIL) of the INO of the CNR in Pisa using the 10 TW Ti:Sa laser system. The laser delivers 40 fs pulses up to 400 mJ on target, and features an M^2 quality factor close to 1.5 and a nanosecond contrast better than 10^9 which enables pre-plasma free interaction [17]. A summary of the laser and gas-jet target set up used for the two experimental configurations is summarised in Table 1 where $a_0 = eE_L/m_e\omega_L c = 0.85\lambda_{L,\mu m}\sqrt{I_{L,18}}$ is the laser normalised vector potential, P_0 is the laser power and $P_{cr} = 17\omega_L^2/\omega_p^2[\text{GW}] = 17n_c/n_e[\text{GW}]$ is the critical power for relativistic self-focusing. Here E_L, $\lambda_{L,\mu m}$, $I_{L,18}$ and ω_L are the electric field amplitude, the intensity expressed in units of 10^{18} W/cm^2, the wavelength expressed in μm and the angular frequency associated with the laser pulse, e and m_e are the electron charge and mass and n_e and $n_c = m_e\omega_L^2/4\pi e^2 = 1.1\times 10^{21}/\lambda_{L,\mu m}^2[\text{cm}^{-3}]$ are the plasma electron density and the critical density. In the first case "A", the laser was focused using an f/4.5 Off-Axis parabolic mirror (OAP) in a spot size of 6.2 μm FWHM, giving an intensity on target of about 2×10^{19} W/cm^2. This configuration features a relatively large divergence electron beam and is tuned for radiobiology studies where the electron beam is delivered on a sample for dosimetry and in vitro sample exposure. A different acceleration set up for extended acceleration length. Case "B" of Table 1 was based on a f/10 OAP, generating a spot size of 20 μm FWHM, giving an intensity on target of about 2×10^{18} W/cm^2. This configuration is characterised by a very low divergence electron bunch.

Table 1
Main parameters of the laser focusing configurations and the corresponding values of the gas-jet used for the two experimental configurations described here. The maximum gas-jet atom density is given, along with corresponding value of the electron density for ionisation degree N^{5+}. The last column reports the corresponding value of P_0/P_{cr}.

Case	f/#	I_L (W/cm^2)	a_0	P (bar)	N/cm^{-3}	$n_{e,5}$/cm^{-3}	P_0/P_{cr}
A	4.5	8×10^{18}	1.92	40	1.6E19	8.0E19	27
B	10	2×10^{18}	0.96	3.5	1.4E18	7.0E18	2.36

A schematic layout of the set-up inside the interaction chamber is provided in Fig. 1. In both cases the target consisted of a supersonic nitrogen (N_2) gas-jet from a rectangular nozzle with a size of 4×1.2 mm^2, with the laser propagating across the 1.2 mm side. An accurate off-line characterisation of the gas-jet profile and temporal evolution was carried out using a dedicated interferometric set up. The characterisation enabled us to obtain a back-pressure dependence of the maximum atom density for relatively high pressures above 10 bars, for which sufficient phase shift can be detected. The plot of Fig. 2 shows the temporal dependence of the maximum atom density at two back pressures of 10 and 30 bars of N_2, respectively equal to 4×10^{18} and 1.2×10^{19} atoms/cm^3. A linear behaviour of the gas-jet density vs. gas pressure is found, with a coefficient equal to 4×10^{17} for each bar of backing pressure.

An auxiliary, frequency doubled probe pulse, was used for optical shadowgraphy of the plasma along the axis perpendicular to the main laser pulse propagation direction. In addition, a Thomson imaging diagnostic system (not shown in the figure) was used to follow propagation of the main laser pulse in the plasma. Electron acceleration was characterised using a LANEX scintillator screen imaged out by a commercial reflex (Pentax100D) camera and NaI(Tl) scintillators coupled to photomultipliers. The electron spectrum was measured using a magnetic dipole equipped with permanent magnets generating a quasi-uniform magnetic field. Depending on the electron energy range, two different size dipoles were used, a 25 mm × 50 mm for high energy and a 12.5 mm × 25 mm for low energy electrons. The configuration of the low energy spectrometer allowed electron energy above 4 MeV to be detected. A tube was inserted into the chamber flange along the electron propagation direction, ending with a vacuum-air interface for the electron beam made up of a 50 μm kapton layer. The electron beam production and total charge was measured on each shot using an Integrating Current Transformer (ICT) device.

3. Laser–plasma interaction

Laser–plasma interaction plays a fundamental role in the control of the acceleration process. We used Thomson scattering from free plasma electrons and optical shadowgraphy to monitor the interaction. In the classical picture of Thomson scattering, free electrons oscillate in the laser field and, in turn, emit radiation. The properties of this scattered radiation are thus related to the properties of the medium. The particle will move mainly along the direction of the oscillating electric field, resulting in dipole electromagnetic radiation. The scattering can be described in terms of the emission coefficient defined as ϵ where $\epsilon dt dV d\Omega d\lambda$ is the energy scattered by a volume element dV in time dt into solid angle $d\Omega$ between wavelengths λ and $\lambda + d\lambda$. In our case, with the diagnostic placed perpendicularly to the plane in which the laser field oscillates, assuming a non-relativistic approximation, the emission coefficient can be written:

$$\epsilon = \frac{\pi\sigma}{2} I n_e \tag{1}$$

where σ is the Thomson differential cross section, n_e is the electron density, and I is the incident flux.

This result simply shows that the Thomson scattering provides combined information on the laser intensity and electron density. Since, in our case, knowledge on the plasma density can be derived