Electron acceleration in laser-plasma interaction at moderate intensity and perspectives of application

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Introduction

Effective electron acceleration in plasmas driven by ultra-short (tens of femtoseconds) laser pulses has been widely demonstrated in experimental and theoretical works since its first theorization [1,2]. High-energy electron bunches with high-current and ultra-short duration (picoseconds time scale) can be produced with all-optical technique in millimeter acceleration distances. A promising class of experiments exploits laser systems with peak power of a few up to 10 TW in order to optimize the stability and reliability of a laser-plasma accelerator. This can lead also to a practical usage of such a device for several kinds of applications, ranging from medical to nuclear science fields. The use of laser systems with not extreme peak power makes it possible either to study the acceleration process far from heavily non-linear phenomena that may negatively affect the reproducibility of the process, and to deal with commercially available instruments accessible by many laboratories. With 10 TW laser pulses focused on gaseous target, an intense gamma-ray source can be produced [3], while electron acceleration with 2 TW systems has been widely demonstrated [4,5].

In the following, the results of an electron acceleration experiment performed with a 2 TW laser system at the Intense Laser Irradiation Laboratory of IPCF-CNR in Pisa (Italy) will be presented, in particular for what concerns the search of conditions for stable and reproducible generation of multi-MeV electrons [6]. Then, the perspectives of employment of the electron bunches from a similar laser-plasma cathode for radiobiological and nuclear studies will be briefly addressed.

The laser-driven electron acceleration experiment

The Ti:Sa CPA (chirped pulse amplification) laser system provides pulses with 67 fs duration and peak power exceeding 2 TW, which were focused by a f/6 off-axis parabola onto a helium or nitrogen gas-jet flowing from a 4mm x 1.2mm supersonic slit-shaped nozzle. The layout of the interaction is described in Fig. 1. Accurate scans of gas pressure and of the position of the focal plane in the direction of laser propagation have been performed. Several advanced diagnostics were used to characterize the interaction and the generated high-energy electrons. The plasma key parameters, such as electron density, shape, dimensions, were measured by means of ultra-fast interferometry with a femtosecond probe laser beam, while further information on laser propagation came from Thomson scattering diagnostic. The accelerated electrons were monitored by means of scintillators coupled to photomultipliers, a phosphor screen (LANEX) which acted as a beam profile monitor and a magnetic spectrometer.

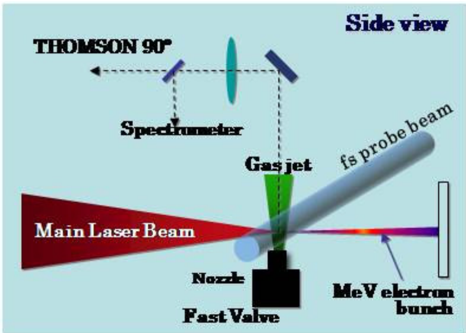

Figure 1: Schematic layout of the experimental set-up.

A maximum plasma electron density of $7x10^{19}$ cm^{-3} was measured, and accelerating gradients exceeding 50 GeV/m were reached, leading to relativistic electrons production in laser interaction with both N_2 and He gas-jets.

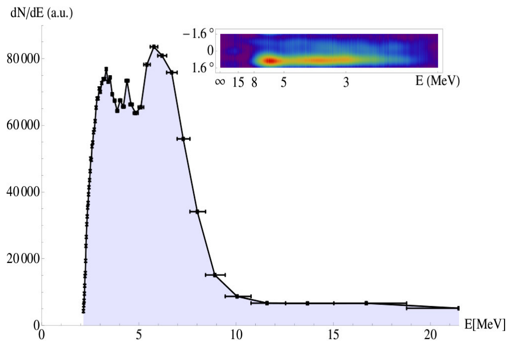

Figure 3: Accelerated electron energy spectrum corresponding to a shot with N_2 at 35 bar.

Electron bunches with energy between 5 and 10 MeV were obtained, with angular divergence

< 3° for helium and ~10° for nitrogen. The N_2 target yields electron bunches with higher charge (> 0.1 nC) and stability, while best quality was obtained in interactions with the He jet. Figure 2 shows a spectrum of accelerated electrons obtained with N_2 gas at 35 bar backing pressure.

Perspectives of application of the laser-accelerated electron bunches

For what concerns medical application of laser-generated electron bunches, Radio-Therapy and Intra-Operative Radiation Therapy (IORT) are receiving great attention as a complementary treatment after surgical removal of tumor masses, and represent a growing field of application due to their efficiency to deliver the prescribed dose to a highly selected target [7,8]. The IORT approach relies on the use of electron bunches with energies of a few up to ~15 MeV from radio-frequency based medical linacs. Each bunch used in IORT treatment has duration in microsecond time scale and peak current of the order of few mA. The main difference between electron packets produced in laser-plasma interactions and in RF-based medical linacs is thus the time duration, which makes the bunch current be a million times higher in the first case with respect to the second case. The radiobiological effect of ultra-short electron bunches from a laser-plasma source and their therapeutic potential is however still basically unknown, and is object of current investigation.

On the other hand, electrons from a laser-plasma cathode can be exploited to perform studies of relevant nuclear reactions, induced by gamma radiation produced by bremsstrahlung of such electrons in suitable targets. This case is usually mentioned as "photo-activation" and is particularly efficient for photons of energy close to the Giant Dipole Resonance (GDR) of the cross section for photo-absorption of many nuclei. The GDR lies in the range 10-30 MeV for most of the medium and heavy nuclei [9]. A typical set-up for nuclear activation of materials is sketched in Fig. 2.

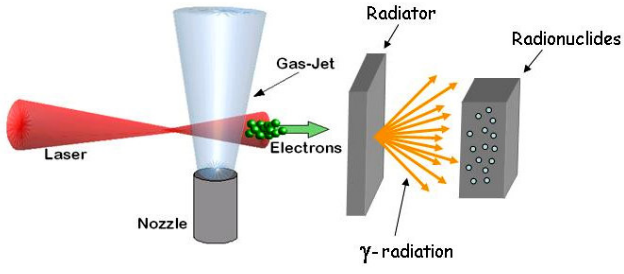

Figure 2: Layout of a typical experimental set-up for nuclear activation driven by electrons generated in laser-plasma interaction

A laser-based activation experiment consists in concept of three stages: the first stage can be regarded to as the "accelerator", in which the laser, interacting with matter, produces relativistic electrons; the second stage, called “radiator", converts the relativistic electrons in γ-rays via bremsstrahlung in a solid. The third stage, called "activation sample" or simply "sample", consists of a target whose material is partially activated by the γ-rays.

Furthermore, different employment of laser-plasma produced electrons can be foreseen, ranging from basic investigations, such as measurements of Compton transmission polarimetry, to practical and social important applications like laser-driven photo-fission of uranium and thorium (in which the fission energy is supplied by the incident photons, which would allow the decoupling from standard neutron-induced fission), transmutation of long-lived nuclear waste products (i.e. ^{129}I whose $T_{1/2}$=15.7 Ma and which represents the most radiotoxic of the fission products), production of radioisotopes usually employed for clinical imaging (i.e. ^{11}C, ^{13}N, ^{18}F, ^{99}Tc, ^{128}I, typically used in nuclear medicine).

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