Radiation Effects & Defects in Solids
Vol. 163, Nos. 4–6, April–June 2008, 411–417

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Ionizing radiation sources based on laser produced plasmas and applications

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(*Received 1 May 2007; in final form 2 September 2007*)

In this paper, we present experimental results concerning (1) the study of hot electrons emerging from the rear side of a target irradiated by ultra-short laser pulses and the K_α radiation related to the interaction of the hot electrons with the cold target, (2) the production of energetic electrons in laser plasma acceleration experiment and their use for photonuclear material activation.

Keywords: ionizing radiation; particle acceleration; plasmas; high energy beams; X-ray radiation

1. Introduction

The understanding of the properties of the ionizing radiation emerging from present-day particle accelerators, which essentially consists of X-rays and of electron and ion beams of extremely high energy, has opened new frontiers in many research fields besides fundamental physics. Present-day applications for instance include many of the diagnostic and clinical treatments which are currently performed in hospitals and in modern biology research, which range from radiographic and computerized axial tomography (CAT) techniques (*1, 2*) to innovative cancer therapies (*3, 4, 5*), as well as the modification of the physical and chemical properties of materials via ion implantation (*6*). However, the high costs of conventional accelerators prevent such ionizing-radiation-based, extremely innovative techniques from widely diffusing worldwide. For this reason, prevalently in the course of the last two decades, a significant part of the scientific community has been induced to investigate, both theoretically and experimentally, new schemes for producing the aforementioned ionizing radiation which could be alternative to those taking place in particle physics colliders. In this context, due to the astonishingly rapid increase in the energy deliverable onto targets by the present-day ultra-short (≈few tens of fs) laser systems (based, in particular, on the so-called

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ISSN 1042-0150 print/ISSN 1029-4953 online

DOI: 10.1080/10420150701777967
http://www.informaworld.com

chirped pulse amplification technique (*7*)), which can now reach tens or even hundreds of Joules, a major attention is currently reserved to the laser-produced plasmas, regarded as compact sources of ionizing radiation (*8*). In fact, the possibility of obtaining ionizing radiation suitable for the aforementioned applications through laser-matter interactions is very appealing, as it could lead to a drastic reduction of both the dimensions of the facilities devoted to the production of such radiation and of the associated costs.

A lot of physical mechanisms exist in laser-matter interactions at high intensity, *i.e.* above $10^{16}\,\mathrm{W/cm^2}$, which account for the production of ultrashort X-ray, electron and ion beams, as observed in many experiments around the world in the last years (*9*). A lot of theoretical and experimental work is currently going on worldwide, aimed at better clarifying the physics underlying these processes, also in order to make these sources suitable for medical and biological applications (*10*). In particular, aspects such those concerning the energy spread together with both the stability and the reproducibility issues of the photons, electrons, and ion beams emerging from laser-plasma sources are currently recognized as critical to this purpose.

In Italy, the group operating at the Intense Laser Irradiated Laboratory (ILIL) of the IPCF–CNR, located at the CNR research area in Pisa, is currently deeply involved, from both a theoretical and an experimental viewpoint, on such field. In particular, the experimental activity focused in the last few years on the production and detection of K_α radiation and fast electrons from ultrashort laser interactions with solid targets, as well as on the production of relativistic electron bunches in ultraintense laser-plasma interactions and their use for efficient photonuclear activation of solid samples.

In this paper, we first report on the direct observation of fast electrons on the rear side of a Ti thin foil irradiated by an ultrashort laser pulse at a moderate intensity ($a = p_e/m_e c \approx 0.15$), typical of many high repetition rate laboratory K_α sources. The K_α emission from the target was also monitored. In the following section an overview of the experimental setup is given and the basic diagnostics for the detection of the fast electrons generated in the forward direction is described. The K_α emission diagnostics are also briefly introduced. The experimental results are then presented and discussed. A brief discussion of the physical processes accounting for the forward electrons follows. As a final example of ionizing radiation source based on laser produced plasmas, some results from a recent experiment carried out by the ILIL group at the CEA in Saclay will be briefly presented, concerning the production of relativistic electron bunches from ultraintense laser interactions with gas-jets and their use for photonuclear activation of gold samples.

2. Kalpha and fast electron studies at the ILIL laboratory

A schematic view of the experimental setup is shown in Figure 1. The laser pulse is generated by a Ti:Sa system delivering an energy up to 15 mJ on the target at a repetition rate of 10 Hz. The FWHM of the temporal profile of the pulse, measured by means of a second-order auto-correlator, is about 65 fs. The pulse is focused using an $f/20$ lens onto the surface of a 12.5 μm thick Ti foil at an angle of incidence of about 40°. The target is moved horizontally or vertically to ensure a fresh interaction surface for each laser pulse in multi-shot measurements. The size of the focal spot was evaluated by means of an equivalent plane monitor technique to be of about 15 μm. The Rayleigh length is approximately 400 μm. Considering these values, the peak intensity on the target can be estimated to be $I_L \approx 5 \times 10^{16}\,\mathrm{W/cm^2}$. We observe here that the relatively long Rayleigh length ensures that a plane wave is interacting with the target, even for small displacements from the focal spot, so that a well defined laser wave-vector exists whose direction can be safely identified with respect to that of the detected electrons.

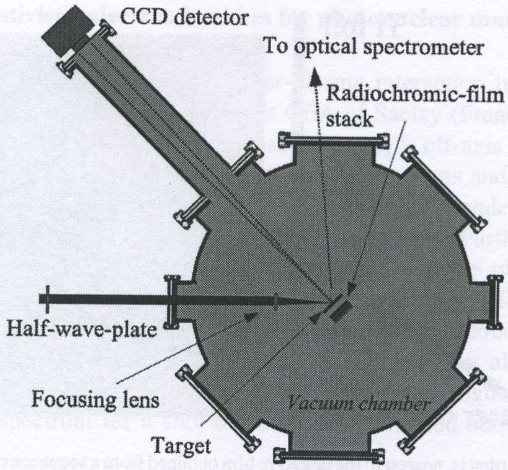

Figure 1. Schematic view of the experimental setup.

The fast electrons generated during the interaction, and passing through the Ti foil, were detected by means of a stack of radiochromic (rc) films placed behind the target, at a distance of about 5 mm from it. The energy and the angular distribution of the electrons could be retrieved by means of an original reconstruction algorithm (*11*) based upon a Monte Carlo simulation employing the CERN library GEANT 4.2.0 (*12*). In particular, two HD810 rc layers were used in our case, packed in a 12.5 μm Al foil. We observe here that energetic particles leaving a detectable signal onto the rc films were identified as electrons since the usage of proton sensitive CR39 films led to a null result.

The X-ray emission from the Ti target was also analyzed using a back-illuminated cooled charge coupled device (CCD) detector placed at about 1 m from the source. This distance allowed the CCD detector to operate in the so-called single photon regime. As it is well-known, provided the detector response to different energy photons is known, this detection technique enables the spectral properties as well as the incident X-ray flux to be simultaneously measured (*13*). Therefore, a reliable estimate of the X-ray photon yield without an independent calibration was possible in our experiment.

Figure 2 shows a typical spectrum of the X-ray emission from our p-polarized laser irradiated target around the Ti K_α line at 4.51 keV. Taking into account the solid angle of view of the CCD

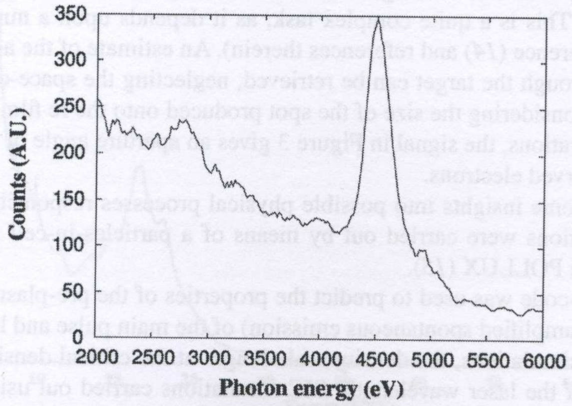

Figure 2. X-ray emission spectrum around the cold Ti K_α line. Adjacent to this line at 4.51 keV, the K_α line at 4.93 keV is also visible.

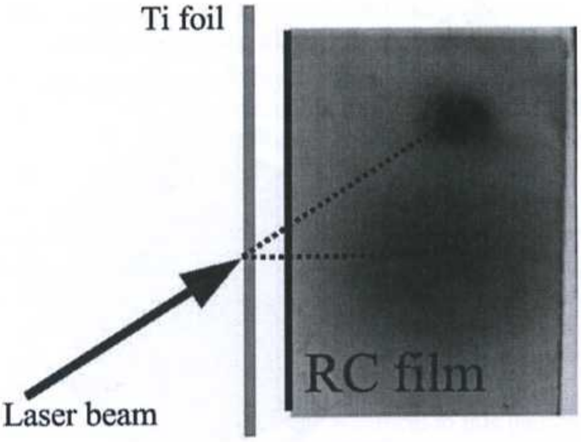

Figure 3. Image of the first (that is, nearest to the target) rc film obtained from a sequence of 100 p-polarized laser shots.

detector and assuming an isotropic distribution of the emission, we estimated that approximately $10^7 K_\alpha$ photons per pulse are emitted by our source.

The first layer of a couple of rc films, shown in Figure 3, shows the signal obtained from a sequence of 100 p-polarized laser shots. A broad spot is visible in the lower part of the rc film image. According to the geometry of the experiment, the center of this spot corresponds to the direction of the target normal. Therefore, this spot is due to the presence of energetic electrons accelerated in this direction and passing through the target. The smaller, darker spot visible in the upper region, is a marker obtained by firing a sequence of some shots while keeping the target in the same position (and thus producing a hole). This marker thus provides a reference for the direction of the laser beam, at around 40° with respect to the target normal. According to these considerations, we can conclude that in our experiment the electrons are emitted forward in the direction perpendicular to the target plane.

The energy of the electrons forming the broader spot can be estimated (some tens up to hundreds of keV) by means of Monte Carlo (library GEANT 4.2.0 (*12*)) simulations accounting for the energy deposition in each of the rc film layers as stacked in our experimental conditions.

Beside their temperature, the distribution of the initial propagation direction of the fast electrons is of a major concern when considering the size of the X-ray emission region in ultrashort laser-plasma K_α sources. This is a quite complex task, as it depends upon a number of parameters (see for example reference (*14*) and references therein). An estimate of the angular spread of the electrons passing through the target can be retrieved, neglecting the space-charge effects of the electron bunch, by considering the size of the spot produced onto the rc film. By making simple geometrical considerations, the signal in Figure 3 gives an aperture angle of 17° HWHM for the direction of the observed electrons.

In order to gain some insights into possible physical processes responsible for the observed features, 2D simulations were carried out by means of a particles-in-cell (PIC) code and the hydrodynamics code POLLUX (*15*).

In fact, the hydro-code was used to predict the properties of the pre-plasma generated by the pedestal (due to the amplified spontaneous emission) of the main pulse and low level pre-pulses. According to these simulations, the density scale-length at the critical density layer is expected to be of the order of the laser wavelength. PIC simulations carried out using this value of the scale-length at the critical density show that most of the fast electrons are generated in a thin layer around the critical surface.

3. Production of relativistic electron bunches for photonuclear material activation

The production of high-energy electrons in laser-plasma interaction has been investigated in detail in an experimental campaign carried out at CEA of Saclay (France). The 10 TW UHI10 laser, delivering up to 0.8 J in 65 fs was focused by a f/5 off-axis parabola at intensities $>10^{18}\,\mathrm{W/cm^2}$ onto a helium gas-jet with different nozzle diameters and backing pressures. The electron signal was monitored by three different diagnostics independently employed: a beam profile monitor, a magnetic spectrometer and a stack of rc foils. Furthermore, high-visibility femtosecond interferometry has been used to measure and map the plasma density at which the acceleration process took place. As a result of the fine-tuning of focusing conditions, we found that for 4 mm nozzle operating at 25 bar, very stable and reproducible (even over several days) electron bunches were produced, as consistently detected by all the diagnostics, with energies in the 10–40 MeV range, FWHM of about 8 MeV and angular divergence less than 50 mrad. The electron spectrum for a shot taken in the mentioned above conditions is shown in Figure 4.

In Figure 5 is reported the schematic set up used for the photonuclear activation of materials. The electron bunches accelerated in the plasma waves by using the laser plasma acceleration techniques hit a Ta target where energetic Bremsstrahlung radiation is generated suitable for efficient photonuclear activation of gold samples (Au^{196} radioisotope).

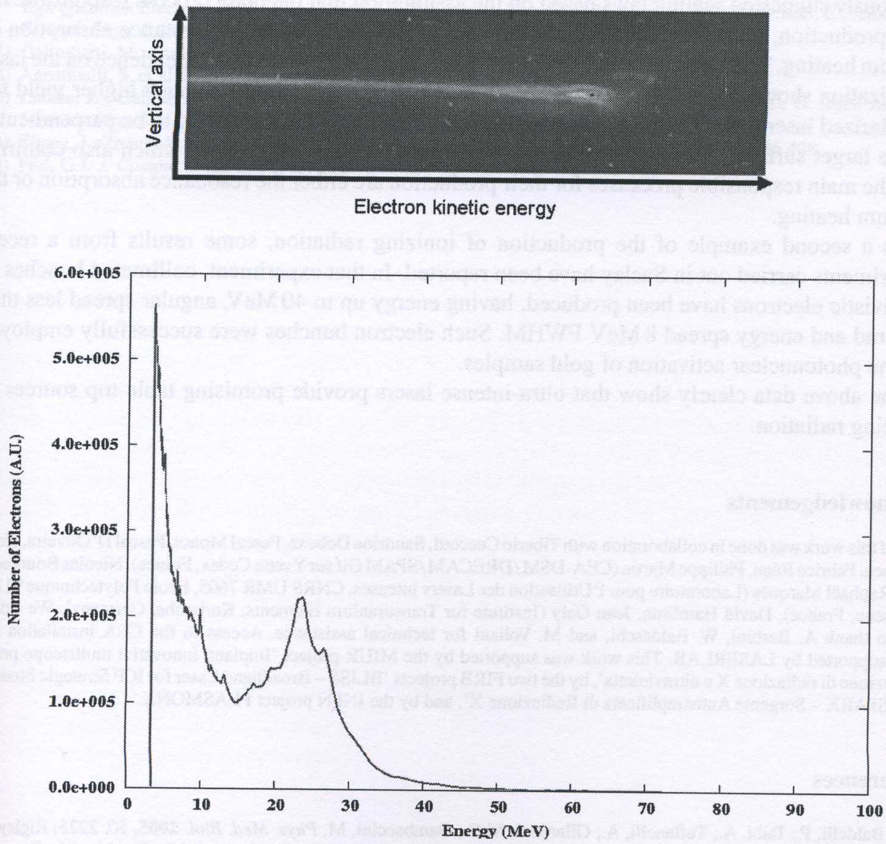

Figure 4. (top) Magnetic spectrometer image of the electron signal. (bottom) Correspondent electron spectrum.

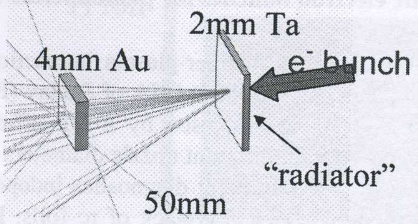

Figure 5. Photonuclear activation of gold samples via Bremsstrahlung of energetic electrons, accelerated in a laser plasma acceleration experiment, hitting Ta target.

4. Summary and conclusions

In this paper, we reported the results of some experiments, carried out both at the ILIL lab in Pisa and at the CEA lab in Saclay (France), showing how ionizing radiation can be produced in ultra-intense laser-matter interaction.

In particular, the observation of a population of forward accelerated electrons through Ti foils irradiated at an intensity of about $5 \times 10^{16}\,\mathrm{W/cm^2}$ has been reported. The electrons were observed at the rear side of a 12.5 μm thick target by means of an rc film stack detector. The electron energy and their angular spread was estimated. The temperature of the observed electrons fits well with previously suggested scaling laws based on the assumption that the main process responsible for their production, in conditions similar to the ones of this experiment, is resonance absorption or vacuum heating. This was confirmed in our work by the K_α emission yield dependence on the laser polarization showing a strong dependence on the polarization and with a much higher yield for *p*-polarized laser light. The propagation direction of the electrons was found to be perpendicular to the target surface, *i.e.* parallel to the expected plasma density gradient, which also confirms that the main responsible processes for their production are either the resonance absorption or the vacuum heating.

As a second example of the production of ionizing radiation, some results from a recent experiments carried out in Saclay have been reported. In that experiment, collimated bunches of relativistic electrons have been produced, having energy up to 40 MeV, angular spread less than 50 mrad and energy spread 8 MeV FWHM. Such electron bunches were successfully employed for the photonuclear activation of gold samples.

The above data clearly show that ultra-intense lasers provide promising table-top sources of ionizing radiation.

Acknowledgements

Part of this work was done in collaboration with Tiberio Ceccotti, Sandrine Dobosz, Pascal Monot, Pascal D'Oliveira, Horia Popescu, Fabrice Réau, Philippe Martin (CEA-DSM/DRECAM/SPAM Gif sur Yvette Cedex, France), Nicolas Bourgeois, Jean Raphaël Marquès (Laboratoire pour l'Utilisation des Lasers Intenses, CNRS UMR 7605, Ecole Polytechnique 91128 Palaiseau, France), David Hamilton, Jean Galy (Institute for Transuranium Elements, Karlsruhe, Germany). We would like to thank A. Barbini, W. Baldeschi, and M. Voliani for technical assistance. Access to the CEA installation has been supported by LASERLAB. This work was supported by the MIUR project ‘Impianti innovativi multiscopo per la produzione di radiazione X e ultravioletta’, by the two FIRB projects ‘BLISS – Broadband Laser for ICF Strategic Studies’ and ‘SPARX – Sorgente Autoamplificata di Radiazione X’, and by the INFN project PLASMONX.

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