High Electron Doses from a GW Laser Interacting with Solid Aluminum Targets

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Abstract. We report dose measurements of electrons emitted in the interaction of a kHz laser of 1GW with a solid target of aluminium. By using a microscope objective we are able to obtain high intensities I~10^{16} W/cm^{-2}, with less of 1mJ before the objective. For *p*-polarized laser pulses and an oblique incidence of 45 degrees, we report high doses of electrons in the specular reflection direction. Energy spectra of the electrons show a bi-Maxwellian distribution with characteristic energy of T=13.8 and 60 keV. These distributions are obtained using an array of TLDs placed at different distances from the source. We take advantage of the stopping power of air to estimate the energy distribution.

Keywords: Laser-matter interaction, electron heating mechanism, laser polarization effect.
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INTRODUCTION

If ultrashort high-intensity laser pulses interact with a solid target a substantial part of the laser energy can be converted into kinetic energy of electrons. These electrons are accelerated through different mechanisms depending on the parameters of the laser pulse and the plasma that is formed in the interaction.

In this work we present measurements of the dose and energy spectra of electrons emitted as a result of the interaction of an intense infrared laser (λ = 800 nm) having less than 1mJ of energy with a solid aluminium target. The measurements were made using an array of TLDs which can be used to measure the dose and the energy spectrum using absorption of the emitted radiation in air. Studies in air have generally been lacking. However femtosecond lasers are becoming an important tool in material microprocessing and knowledge of the doses produced in this process may contribute to design more efficient setups. Furthermore they provide a simple way to estimate the electron energy distribution by measuring dose as a function of the distance.

MATERIALS AND METHODS

The experiments were performed with a Ti: Sapphire laser at the Salamanca Optic's group. The system is a CPA amplifier that provides pulses with 110 fs and E = 900 μJ. The laser is centered at λ = 793 nm and it has 1 kHz repetition rate. The size and the high spatial quality of the beam allow us to use a microscope objective (Edmund 10x NA=0.25) to focus the laser. Such a system is very efficient to achieve a focal spot close to the diffraction limit, by measuring the spot size in the low intensity regime we have found a FWHM radius of 3.8 μm; although some energy is lost at the entrance of the microscope, ending with E = 450 μJ. Supposing a Gaussian distribution, the estimated intensity in the focus is 1.7 x10^{16} W/cm^{-2}.

The experimental array is shown in Fig 1. An optical bench allows us to deliver the beam on target and change the polarization and focus position. A λ / 2 plate is used to control the polarization and an electronic shutter controls the number of shots into the target. The beam insides obliquely onto the target which in this case consist of an aluminium sheet with some 100 μm thick without any optical quality. The laser collides at 45 degrees respect of the plane defined by the aluminium sheet which is placed on top of a 3D motorized stage to avoid multiple incidences in the same point. The target velocity was 5 mm/s and each of the shots interacts with a fresh sample of the target.

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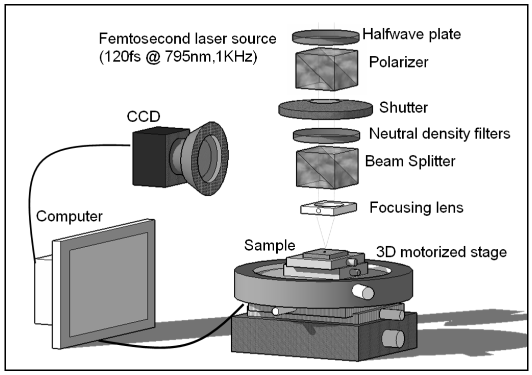
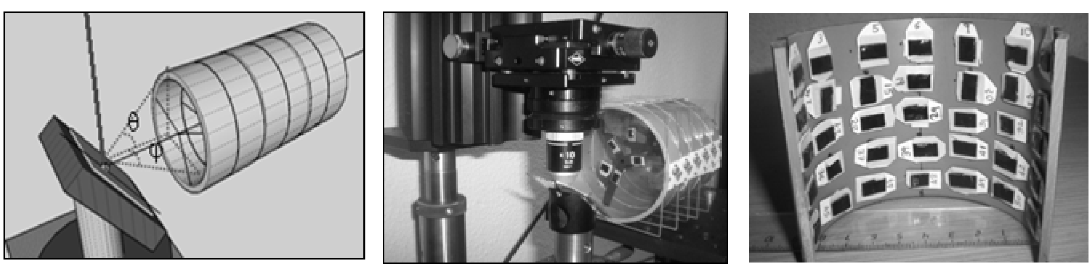


FIGURE 1. Experimental setup: a CPA laser with $E = 900\mu J$ and 110 fs is focused by an optical bench onto a solid target of aluminium placed into a 3D motorized translation stage. The focusing system is a microscope objective 10x NA = 0.25. The focal spot has a radius of $r = 3.8\ \mu m$ resulting an intensity of I = $1.7\text{x}10^{16}$ W/cm^2.

When a fast charged particle interacts with matter it undergoes a progressive loss of kinetic energy until it is stopped. Stopping power depends on the incident electron energy and material properties. By using a stack of sensitive layers located at different distances to detect such energy losses, we can deduce the energy and the type of the incident particle. Moreover, using a specific array with spatial resolution we can measure the angular distribution of the emitted particles. The setup of detectors that we have designed consists of different arrays of thermoluminiscence crystals of LiF (TLD 700) and is shown in Fig 2.

The angular distribution was measured using either an array of 35 TLDs located in the inner surface of a semi-cylinder for short distances or another array with 30 TLDs for long distances. In the first detector the TLDs are distributed in 7 columns separated by 30 degrees each one containing 5 crystal detectors while the second one has only 5 detector columns separated 45º.

An array of detectors consisting of 18 TLDs distributed in 6 parallel planes is used to measure the dependence of the dose with distance. Each of these planes contains 3 crystals inside a circumference spanning angles of 120º among them. Every plane has different location of the detectors to avoid the screening among them. Fig 2(a) shows the exact structure of the array, the main idea behind this design is to have measurements of the doses at different distances from the source. The three crystals in each plane are equidistant to the target and their results are equivalent. By collecting the energy versus distance and supposing a known energy distribution, the characteristic temperature can be inferred taking into account the absorption of electrons in air. Furthermore, some other materials like methacrylate or aluminium -Fig 2(b) - have been inserted between the different planes of detector, in order to complete the information about stopping power effect on the emitted radiation.



(a) (b) (c)

FIGURE2. Some of the TLDs arrays used to measure the dose of the emitted radiation. (a) Diagrammatic scheme of the experimental setup, the laser insides in the vertical direction from above and collide with the target located at 45 degrees. The reflected beam direction is shown as a black line coming out of the target. The distance from each of three crystals in the same plane to the target is equal. (b) A picture of the actual system in the laboratory. (c) The 35 TLDs array used to measure the angular distribution of the emitted radiation.

RESULTS AND DISCUSSIONS

In Table 1 we present the measured dose rate when *p*-polarized laser pulses with ~1.7x 10^{16} Wcm^{-2} are used. These measurements are the result of accumulating 855360 shots in 864 seconds.

TABLE 1. Dose rate measured along of specular reflection direction at 30 cm of the target. *p*-polarized laser pulses

Angles (degrees)	Dose Rate (μGy /s)
0	8.25
45	2.45
90	0.50
135	0.20
180	0.25

The integrated dose contains all type of radiation without distinction. The high dose rates reported show that the energy transfer is very efficient, being in agreement with measurements that different authors have reported for laser systems with similar intensity [1], [2].

A detailed angular distribution of the emitted radiation with *p*-polarized pulses was measured with the 35 TLDs array described before. The study of the dependence of the emitted radiation with polarization will be discussed in a future work since the angular distribution of the radiation has been shown to change dramatically with it.

The measurements in Fig. 3 show a narrow distribution of the emitted electrons. The peak of the distribution is in its center which corresponds to the specular reflection direction. Such distribution also shows the potential applicability of this emission as a source, as the divergence of the emitted electrons seems to be very low.

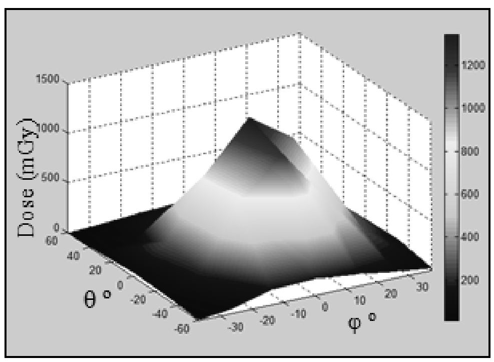


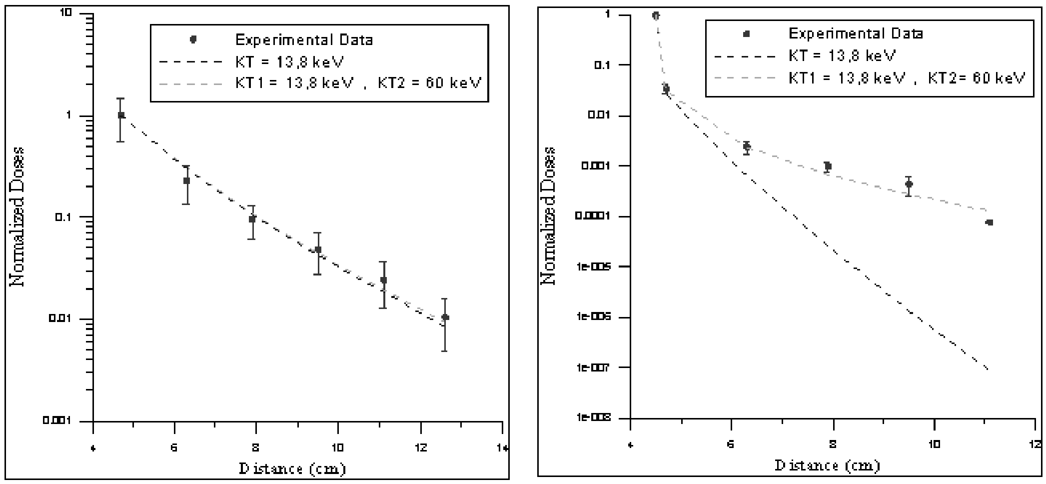
FIGURE 3. Angular distribution of the emitted radiation in the case of *p*-polarized laser pulses.

The energy distribution of the electrons can be inferred from the measurements of the doses as a function of the distance to the source. The emitted radiation is composed basically of electrons which reach the thermal equilibrium in few micrometers and therefore the resulting energy distribution consists of a sum of Maxwellian distributions with characteristic temperature KT. Taking into account the absorption of the electrons in air or any material placed into the detector at different distances, it is possible to obtain the temperature of the distribution from the experimental data.

In our experiment the electron energy distribution could be characterized by a Bi-Maxwellian distribution with KT_1 = 13.8 keV and KT_2 = 60 keV respectively, being the first contribution, 10^5 times larger than the second one. Figure 4 shows the normalized doses as a function of the distance for electrons in air (4a) and electrons traveling in air and aluminium (4b). As the range of the electrons in air is greater than in aluminium, the first experiment allows us to determine the low energy part of the electron spectrum. Figure 4(b) shows the dose distribution against distance when aluminium foils of 50 μm are inserted among the planes of the detector. This experiment is useful to observe the higher energy part of the spectrum, although this is a minor contribution to the overall distribution, it shows that there is some efficient acceleration mechanism that is occurring in this interaction.

Taking into account our laser parameters, the most probable mechanism for electron acceleration in this intensity regime and incidence angle is *resonant absorption* [3]. By fitting the empirical formula for this heating mechanism for KT_1 = 13 keV, we found an intensity of I = $1.6x10^{16}$ W/cm^2, which is consistent with the estimated one in the experiment. This result is quite surprising for us since we had expected having nonlinear effects in the propagation of the pulse towards the sample; such as air ionization, changes in temporal duration and Kerr effect. Additionally, all the measurements are consistent with having intensity close to the one estimated with the measurement of the linear pulse on the sample which suggests us that Kerr effect is helping to maintain a high intensity compensating the rest of nonlinear effects.

On the other hand, the high energy distribution could be attributed to the effect of a preplasma created by the pulse pedestal which could help to increase the energy of the electrons [4].



(a) (b)

FIGURE 4. Dose-distance dependence for electrons traveling in air (a), for electrons traveling in air and aluminium (b); in this last case the TLDs were covered with a different number of aluminium foils of 50 µm thickness.

CONCLUSIONS

During the experiments high doses of radiation were measured. The highest equivalent dose rate that we measured at 30 cm of the interaction centre was 8.25 µSv/s (~ 260 Sv /year), which exceeds any reasonable limit recommended by safety standard [5]. The first conclusion is that even for tabletop laser systems with low power and high repetition rate, which are common in any laser lab, suitable radiological safety measures should be taken.

The emitted radiation in the interaction of laser pulses with intensity of $I \sim 10^{16}$ W/cm^2 on aluminium targets is composed basically of electrons with energy close to 13 keV and another lower component with energy of 60 keV. The angular distributions measurements show that the electron beam is well directed along the reflected beam. This fact, together with the high repetition rate makes this emitted radiation can be a potential source of fast electron.

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