Electron and Photon Production From Relativistic Laser-Plasma Interactions

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Abstract: The interaction of short and intense laser pulses with plasmas is a very efficient source of relativistic electrons with tunable properties. In low density plasmas, we observed bunches of electrons up to 200 MeV, accelerated in the wake field of the laser pulse. Less energetic electrons (tens of MeV) have been obtained, albeit with a higher efficiency, during the interaction with a solid target. When these relativistic electrons slow down in a thick tungsten target, they emit very energetic Bremsstrahlung photons which have been diagnosed directly with photoconductors, and indirectly through photonuclear activation measurements. Dose, photoactivation, and photofission measurements are reported. These results are in reasonable agreement, over three orders of magnitude, with a model built on laser-plasma interaction and electron transport numerical simulations.

1. Introduction

The interaction of a short-duration, high-intensity laser pulse ($I > 10^{18}$ W/cm^2) with a plasma is a very efficient source of relativistic electrons. When the interaction takes place in a low density plasma, very large electrostatic fields can be excited in the wake of the pulse, and they are able to accelerate small bunches of electrons to hundreds of MeV over millimeter distances [1], with good collimation along the laser direction. On the contrary, when the laser is incident on an overdense plasma, the hot electron emission is colder and much more isotropic, and a large fraction of the incident energy can be coupled to electrons with a mean temperature of a few MeV [2]. Irrespectively of their origin, when these electrons propagate in a material with high atomic number, they lose part of their energy due to the emission of Bremsstrahlung photons which also reach MeV energies [3]. The resulting short and intense x ray burst could have interesting applications in the field of flash x ray radiography [4] and nuclear physics [5,6]. Knowledge of the laser-plasma coupling, of the electron acceleration mechanisms, and of the electron transport is also essential to assess the viability of the fast ignitor scheme for inertial confinement fusion [7]. The experiments presented in this paper study these phenomena for a variety of targets and interaction parameters.

We have used a number of simulation codes to model and study these experiments:

- A two- or three-dimensional Particle-In-Cell (PIC) code, CALDER, that we use to simulate the interaction of the high-intensity pulse with the plasma, and the ensuing generation of multi-MeV electrons. That kind of code is most appropriate to simulate the kinetic and highly non-linear phenomena that occur during the interaction at relativistic power. However, it is necessary to use a second code to model Bremsstrahlung emission by the laser-accelerated electrons.
- To this end, we use an electron transport and electron-photon conversion code which is able to compute the propagation of fast electron in the whole target, their slowing down,

the Bremsstrahlung emission they produce, and the resulting photonuclear reactions. This code uses approximate analytic laws or tabulated data taken from the literature for the target stopping power, the electron distribution angular broadening under the effect of multiple small-angle collisions, and the electron Bremsstrahlung and photonuclear cross sections [8,9]. It has been benchmarked with comparison to published results obtained on accelerators with monoenergetic electron beams.

2. Wakefield Electron Acceleration in Low-Density Gas Jets

A high-intensity laser pulse is able to propagate in a low-density plasma (electron density of a few percent of the critical density), and can leave very large (electron plasma wave) electrostatic fields in its wake. These waves, in turn, can accelerate injected or plasma electrons to very high energies, and with very good collimation along the laser axis. In the so-called "self-modulated laser wakefield" scheme, a picosecond-long pulse gets fragmented by self-modulation into a train of shorter pulses which are matched to the electron plasma wave period and can excite a large amplitude wake. According to this scheme, the laser duration must be much longer than the plasma period, which is e.g. 22 fs for a plasma electron density of 2.5×10^{19} cm^{-3}. In recent experiments with the "Salle Jaune" 1 J, 30 fs laser at Laboratoire d'Optique Appliquée (LOA), incident on helium gas jets, we have showed that not only can short pulses also be used to accelerate electrons by a wakefield effect, but that they lead to substantial energy and emittance improvements of the accelerated particles. In this "Forced Wakefield" regime that our experiments and simulations reveal, the plasma wave is excited up to its wavebreaking amplitude, accelerating plasma electrons up to 200 MeV [10].

A typical electron spectrum obtained for a laser irradiance of 3×10^{18} W·cm^{-2} and a plasma density of 2.5×10^{19} cm^{-3} is shown in Figure 1. It can be fitted to a Maxwellian distribution up to 120 MeV, with a characteristic temperature of 18 MeV. The 3D, relativistic, Particle-In-Cell (PIC) code CALDER has been used to simulate this experiment: the spectrum plotted in Figure 2 illustrates the very good agreement that we observe between the experiment and the 3D calculation. According to this simulation, the laser pulse is strongly self-focused over the first 300 µm of plasmas, leading to a ten-fold increase in intensity. At 550 µm in the plasma, the wakefield reaches its maximum value at 3.2 $m_e c\omega_p/e$, or close to 1.4 TV/m, and the electron spectrum does not evolve substantially afterwards.

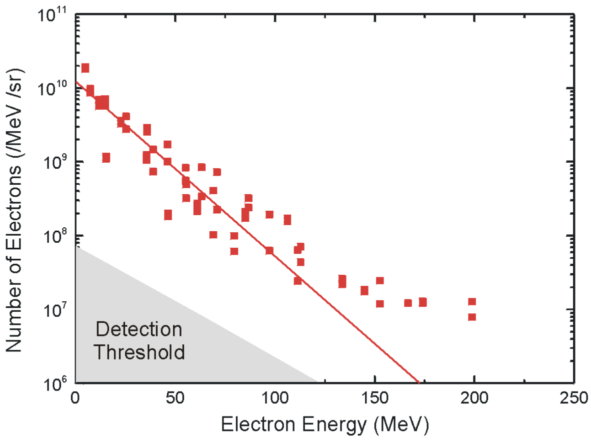

FIG. 1. Measured spectrum of electrons accelerated along the laser axis.

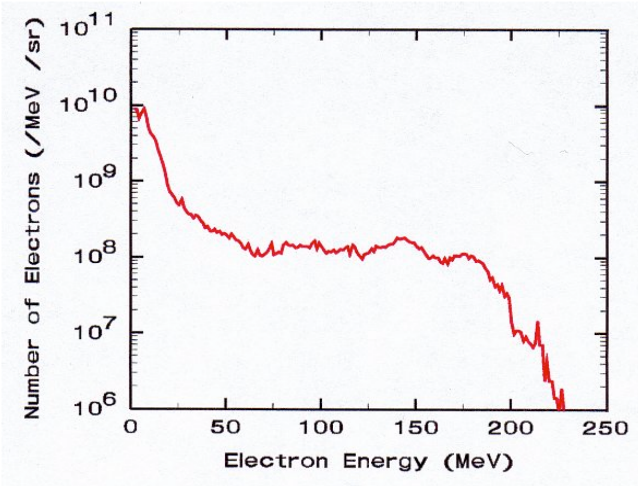

FIG. 2. Calculated spectrum of electrons accelerated along the laser axis.

3. Electron Acceleration in Intermediate-Density Targets

On the same LOA laser facility, another experiment used thin plastic foils exploded by the laser prepulse, giving a shorter, denser, and less homogeneous plasma. For the optimum case of a 6 µm thick plastic target, the resulting hot electron spectrum can be fitted to a Maxwellian distribution with a temperature of 9.3 MeV. A 2 mm thick tantalum slab was placed behind the plastic target to convert the hot electron kinetic energy into hard photons through the Bremsstrahlung mechanism. Behind this converter, cm-sized secondary targets made of ^{63}Cu and ^{197}Au were exposed to this photon flux. The number of ^{62}Cu and ^{196}Au atoms produced by photonuclear reaction inside these targets was measured after series of consecutive shots [11]. We found that 9×10^{3} ^{62}Cu atoms and 5×10^{4} ^{196}Au atoms were produced for each shot.

Using a Monte-Carlo model to compute the propagation, slowing down, and Bremsstrahlung of hot electrons with a 9.3 MeV temperature in the tantalum slab, we found that these results were consistent with a total number of 5.7×10^{8} electrons accelerated above 5 MeV at each shot, inside a relatively small solid angle along the laser direction. A similar analysis was performed with another Monte-Carlo code and yielded comparable results [11].

4. Electron Acceleration and Photon Production in Solid Tungsten Targets

In another series of experiments [12], the 100 TW laser facility at LULI/Ecole Polytechnique was used to irradiate solid tungsten strips with 0.5, 1, or 2 mm thickness. The 1 µm wavelength laser pulse, focused to an intensity ranging from 1.5×10^{18} to 3.2×10^{19} W/cm^2, was always normally incident on the targets. The x ray emission produced by the relativistic electrons slowing down in the tungsten target was diagnosed on six channels, situated at 8, 15 and 45° from the laser axis, 60 cm behind the target. The detectors were nominally shielded with 2 mm of lead and 5 mm of steel. This shielding cuts off photons below 200 keV and has a maximum transmission of 80% at energies of a few MeV.

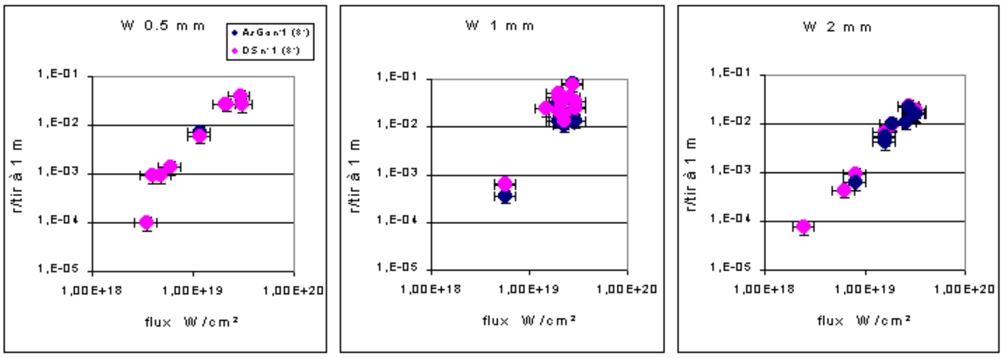

FIG. 3. Doses measured at 8° from the laser direction, as a function of laser irradiance, for three different kinds of tungsten targets.

Figure 3 sums up the results obtained at 8°, for our three different targets. Hard x ray production is measured in terms of dose in air at 1 meter, which is the energy the photons would deposit per unit mass in air at that distance from the source. The spectral response of both detectors (silicon diode and AsGa) were evaluated with the ITS / Cyltran code. These calculations show that the detector and filter package has a relatively flat response to the incident dose above photon energies of 200-300 keV, up to more than 10 MeV. The dose in air at 1 m obtained for each laser shot exhibits a clear variation as a power law of the laser intensity, especially for the 0.5 and 2 mm thick tungsten targets. This variation is not so clear for the 1 mm thick targets, which were shot early in the experiment without a systematic scan in laser energy. The maximum dose obtained during these shots was recorded at 8° for a 1 mm target irradiated at 3×10^{19} W/cm^2. It reached 80 mrad in air at 1 m.

During a second series of experiments at the same facility, thin ^{238}U slabs in carbon containers were placed just behind the tungsten targets. They were not directly irradiated by the laser, but the hard x ray photons produced inside the tungsten target could photofission a number of U atoms inside the slab. The resulting fission products were diagnosed by Germanium spectrometry after each shot. For the highest laser irradiation, around 3×10^{19} W/cm^2, 3.4 million photofission events were measured in the sample. A Monte-Carlo analysis of these results indicates that these results are consistent with a two-temperature electron distribution: photofission data are consistent with a 8.6 MeV distribution directed along the laser axis and carrying slightly less than 5% of the laser energy. The dose data imply the existence of a second, colder (3 MeV) and broader distribution, carrying a larger fraction of the incident energy.

5. Conclusions

Overall, the agreement (on electron spectra, radiation dose, and photonuclear activation measurements) that we obtain between our simulations and the various experiments presented above is quite good, considering the variety of plasma and laser parameters involved in these experiments. This lends credence to the very kind of tools that are needed, together with experiments, to make progress towards fast ignition of DT targets. The large quantities of relativistic electrons and MeV photons that have been measured in these experiments also point at the need for adequate radiological protection and safety measures around such high-intensity laser facilities [13].

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