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Preparation of the high power laser system PETAL for experimental studies of inertial confinement fusion and high energy density states of matter

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Abstract. The paper describes the preparation of the short-pulse high-energy laser PETAL that will be coupled to the French megajoule laser (LMJ) of CEA. The LMJ/PETAL facility will be opened to academic access for the international research community. In parallel diagnostics are being developed within the PETAL project and many physical problems are being addressed ranging from the study of the problems of radiation generation and activation issues to the problem of generation of large amplitude electromagnetic pulses.

1. Introduction

The high power laser system PETAL (http://petal.aquitaine.fr) is funded by the Regional Council of Aquitaine and French government and constructed by the CEA/CESTA, for academic studies of high energy density states of matter and inertial confinement fusion. It will be commissioned in 2015 and will be operated together with the Laser MégaJoule (LMJ) as a joint facility [1]. Significant theoretical, numerical, experimental and technical developments are still needed during the final period of PETAL construction and the starting phase of its exploitation. This period of 4 years, from 2013 to 2016 implies a tight and efficient collaboration between the scientific and technical staff of the academic groups and laboratories and the CEA engineers in order to attain the expected laser characteristics in a short time scale of two years and to assure all necessary conditions for efficient and secure operation of this unique installation. The results presented in this article were obtained in the context of this collaboration and are related to planning and realization of the first phase of the PETAL operation so that it will be compatible with the safety requirements, the characteristics of the diagnostic equipment planned in the PETAL+ project and with the planned regular operation of PETAL together with the LMJ as an international user facility. In Section 2, new results on the expected activation in the LMJ chamber induced in high power PETAL experiments by the radionuclides generated by energetic photons and protons are presented. In the first phase of the PETAL operation, the compatibility of PETAL experiments in the context of national nuclear activity regulations has been evaluated for two regimes of operation. In Section 3, new results on the studies of strong electromagnetic fields produced during the interaction of a high intensity laser with a solid target are presented. This effect will be of prime importance for the PETAL diagnostics and experimental equipments. A model of the target electric polarization induced by a short and intense laser pulse has been developed and verified in an experiment with a sub-picosecond laser pulse.

2. Radiation and Activation issues

Shooting the PETAL laser pulse on targets will induce the generation of large radiation fluxes, which in turn may generate radionuclides in the LMJ chamber by energetic photons and protons, i.e. activate the materials of the diagnostics and the chamber itself, causing issues both for radioprotection and nuclear safety, and for the correct operation of diagnostics. In the first phase of the PETAL operation, the compatibility of PETAL experiments with respect to national nuclear activity regulations has been evaluated for two regimes of operation. The characteristics of X-ray photons and protons originating from typical experiments that will be conducted with the PETAL laser were studied in order to estimate the activation coming from the interaction with matter of these particles, either originating directly from the interaction of the laser or from secondary interactions with the diagnostics instruments or the materials of the chamber wall [2]. Two dimensional (2D) Particle-In-Cell simulations using the code PICLS [3] were performed to obtain the electron and proton sources produced during the interaction of a PETAL pulse with a solid target. The maximum electron density used in the simulation is $300n_c$ with a 20 μm long preplasma (with an exponential shape, as deduced from the 2D hydrodynamic simulation). The target is 10 μm thick and is composed of protons, deuterons and electrons (it is equivalent to a CH target as collisions are not treated). The laser pulse has a Gaussian profile in time with a FWHM of 0.5 ps and also in space with an FWHM of 30 μm. The pulse is linearly polarized (p-polarization). The total number of protons per MeV is obtained using the conservative estimate that the length in the third dimension is of the order of the laser FWHM. Collisions are not taken into account as the high laser energy and the small target thickness will lead to a rapid heating of the target. 2D PIC simulation results cannot be taken as precise predictions for experiments but they nevertheless provide a good idea of the involved particle energies in a reasonably majoring fashion. Laser energy was varied from 0.2 to 3.5 kJ corresponding to laser intensities of 1.4 $\times 10^{19}$ W/cm^2 to 2.5 $\times 10^{20}$ W/cm^2. Examples of proton angular and energy distributions for the laser energy of 1 kJ are presented in Fig. 1. Unlike electrons, the proton angular distribution is strongly collimated. The emission angle decreases with increasing proton energy and is not very sensitive to the laser energy in the conditions studied here. The energy distribution can be approximated by an exponential function characterized by a certain temperature with a sharp cut-off. These results allow to use the proton characteristics directly for activation calculations and the electron characteristics for photon conversion calculations.

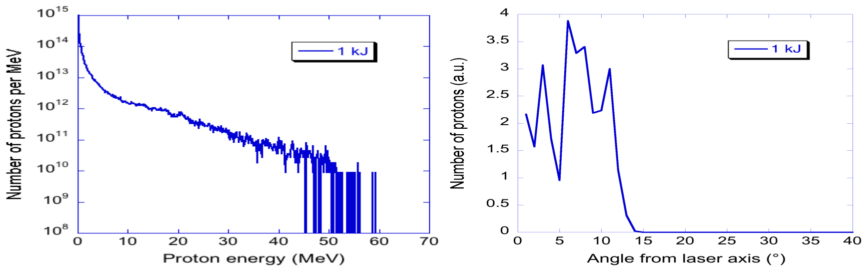

Figure 1. Energy (a) and angular (b) distributions of the protons simulated by the code PICLS for a total laser energy of 1 kJ.

Simulations of the electron transport and interaction with a tungsten target were performed using the Monte Carlo code GEANT4 [4]. The electrons produced with the PICLS simulations are used as initial parameters for the bremsstrahlung calculations. As the process of photon production is linear in the electron number, the input parameters of the GEANT4 simulations are the energy and angular distribution of the electrons. The characteristics of the incident electron beam obtained from the PIC simulations were the following: a Maxwellian distribution with the high energy cut-off depending on the considered laser energy and Gaussian angular and spatial distributions. In GEANT4 simulations we calculated the characteristics of exiting electrons, photons and positrons from a tungsten target. A significant fraction of incident electrons is reflected, and the majority of electrons penetrating the target are absorbed. Figure 2 shows an example of the photon energy spectra emitted from the back and the front target surface for the laser pulse energy of 1 kJ. The maximum photon energy is 43 and 59 MeV, respectively for the reflected and transmitted fractions. Similarly to the electron and the proton spectra, the photon energy distributions can be characterized by an exponential function with a sharp cut-off. The photon distributions obtained for laser energies up to 3.5 kJ have similar characteristics with more energetic photons, more photons at a given energy and more photons at a given angle being emitted when the laser energy is increased. The goal of this study was to estimate the activation induced by PETAL experiments in its early phase of operation. A complete calculation sequence consists in the simulation of the interaction of the PETAL laser with solid targets, leading to the production of energetic particles, for two types of generic experiments, TS1 for photons and TS2 for protons. This sequence takes into account the transport and the conversion of particles and radiation, and then estimates the global activities of the experiment system to determine regulatory levels expressed through the Q factor defined as the ratio between the activity computed with the simulation and its exemption value given by the French nuclear regulations. The calculation results, performed for four different levels of irradiation from 0.2 to 3.5 kJ identify two regulatory thresholds (both corresponding to Q = 1, the lower limit defining a non-nuclear facility according to French regulations) that depend on the type of experiment: a threshold of 1 kJ for TS1 experiments (x-ray generation through bremsstrahlung conversion of electrons in a massive target), and 300 J for TS2 experiments (generation of energetic protons using a thin solid foil) [2]. Although the calculations are performed specifically for the LMJ-PETAL installation, the methodology is rather general and may be applied for design of experiments with other high power laser systems.

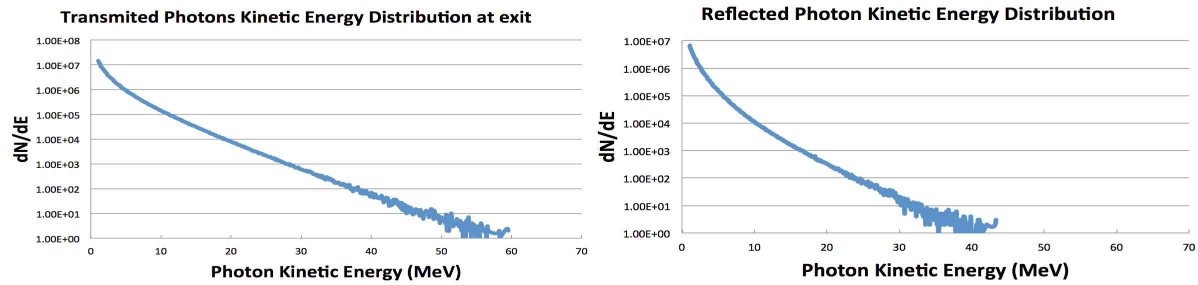

Figure 2. Energy distributions for a laser energy of 1 kJ (a): of photons transmitted at the back surface of the target, (b): and photons reflected at the front surface.

3. Electromagnetic Pulse Generation

The generation of strong electromagnetic pulses (EMP) from the target irradiated by the PETAL laser is a critical issue. Very high electric fields can be generated which will primarily affect the diagnostic equipment and they may break down the electronics and manipulators in the target chamber. For this reason, in the initial phase of the PETAL project, we did choose to rely on passive diagnostics (IP, films, etc.). Nevertheless understanding EMP generation and its impact remains a fundamental task. The origins of electromagnetic fields induced by the interaction of high intensity laser on targets are not well known. Comparison and extrapolation of the measurements from other high-intensity facilities indicate expected chamber field exceeding the MV/m level, which is of major concern with respect to vulnerability of equipments. In this context, we started a multi-year program for the comprehension of the underlying mechanisms of EMP generation. Final objectives are to produce a complete line of simulation, to provide recommendations concerning the target design and to develop mitigation procedures. A significant part of the EMP stems from the bunch of electrons ejected from the target and from the discharge current through the target support. In this context, a specially designed experiment was conducted in 2012 to provide direct measurements of the target polarization and the discharge current, the objective being to validate and enhance the accuracy of an analytical model of ejected charge [5]. The experiment was performed on the Eclipse laser system at CELIA

(Bordeaux University, France). The facility delivers a maximum energy of 100 mJ on target for a minimum pulse duration of 50 fs (800 nm) with the contrast of 10^{-7} and a 7.5 μm (FWHM) focal spot. The induced discharge current and the radiated field were measured in function of the laser energy, pulse duration and target size (copper, diameter 5, 10 and 15 mm). Experimental results corroborated by the model and simulation, indicate that the total charge increases approximately linearly with the laser energy, independently on the target size. In contrast, the maximum current decreases with the target diameter. According to our measurements, the charge and the maximum current depend essentially on the laser energy and much less on the laser intensity (no influence of laser pulse duration in the considered range). A suite of numerical codes integrating a PIC code (Calder) for the source term and the transport codes of particles (MCNP) and fields (Sophie) were employed to simulate the experiment. Comparison of the calculated current waveform with the experimental results shows a very good agreement and demonstrate that the target electric polarization is responsible for generation of high amplitude GHz electromagnetic pulses in the interaction chamber. However, some quantitative differences still remain and need further analysis and experiments.

4. Conclusion

A large effort is undergoing in France to install the short-pulse high-energy laser PETAL as a high-intensity companion to the LMJ laser. The LMJ/PETAL facility will be opened for the academic access. In parallel diagnostics are being developed within the PETAL project and many physical problems are being addressed ranging from study of the problems of radiation generation and activation issues to the problem of generation of large EMP signals. In the first phase of the PETAL operation, the compatibility of PETAL experiments in the context of national nuclear activity regulations has been evaluated for two regimes of operation. The characteristics of x-rays and protons originating from typical PETAL experiments were studied in order to estimate the activation coming from their interaction with matter. The conclusion of this study is that in order to comply with a non-nuclear classification status of facility during the first stage of operation, the PETAL energy should be limited by chamber activation at the level of 300 J for proton backlighting experiments and at around 1 kJ for X-ray backlighter experiments for a pulse duration of 500 fs. The study of strong electromagnetic fields produced during the interaction of a high intensity laser with a solid target is of prime importance for the development of PETAL diagnostics. A model of the target electric polarization induced by a short and intense laser pulse has been developed and verified in an experiment with a sub-picosecond laser pulse with energy of 100 mJ and compared with numerical simulations demonstrating that this effect is responsible for generation of high amplitude GHz electromagnetic pulses in the interaction chamber.

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