Magnetic field induced by laser-driven target current

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Abstract — This contribution deals with direct observation of a transient magnetic field induced by a current flowing through the target holder to balance the target charging caused by intense laser radiation delivered by the 3 TW, 300 ps laser system PALS. Both the target and its holder fixed to the interaction chamber react to the target ablation as an electrical circuit, which emits electromagnetic pulses in the megahertz to gigahertz domain. For this reason the interaction chamber is considered as a resonant cavity in which different modes of EM field oscillate for hundreds of nanoseconds until EM waves are completely lost. We present an inductive target probe developed by Cikhardt et al. Rev. Sci. Instrum. **85** (2014) 103507, allowing the direct observation of the transient target current. Since the applied inductive target probe is resistive against the interfering electromagnetic pulse (EMP) occurred inside the interaction chamber where the charged particles are accelerated, the relationship between the magnetic part of the EMP elsewhere inside and outside the interaction chamber and the magnetic field induced by the neutralization target current can be obtained. Frequency analysis indicates a multimode frequency distribution of EMP spectra which arises as a mixture of large number of modes.

The irradiation of a solid target by laser intensity higher than 100 MW/cm^2 leads to the ionization of ablated target material. Independently of the applied laser intensity the fastest electrons escape into the interaction chamber ahead of ions. This separation of charges causes polarization of the target during which the target's voltage can reach a value in the order of hundreds of kV, as reported in [1]. The target's polarization drives a current from the target to the ground which can last up to several hundreds of nanoseconds till the time when the all the ionized species are neutralized [2]. The target holder, which behaves as an antenna, can emit an intense electromagnetic pulse (EMP) [3]. In general, the frequency spectrum of the EMP ranges from tens of megahertz up to gigahertz [4-7]. There are some aspects of the EMP emission: the EMP spectrum depends on the geometry of the interaction chamber [4] and of the antenna composed of the target and its support [3], the EMP strength is directly related to the amount of accumulated charge Q in the target, and the current oscillates in the target holder until the laser-produced plasma disappears [2].

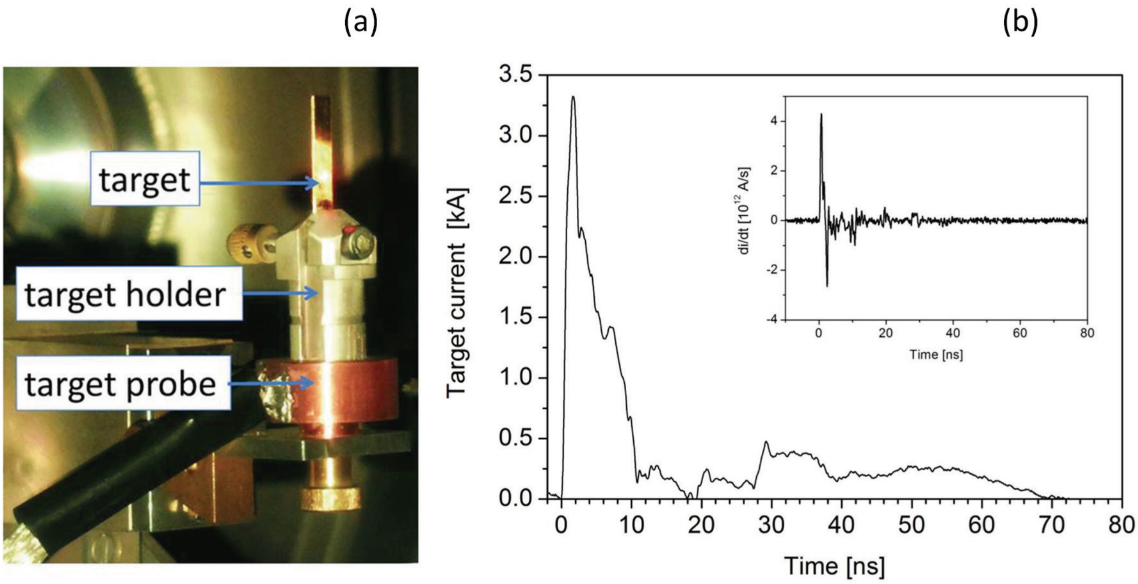

Fig. 1. (a) Snapshot of the target holder system containing the inductive target probe, as described in [7], (b) example of the current neutralizing the polyethylene target exposed to intensity of ~3×10^{16} W cm^{-2}. The inlet in (b) shows time derivative of the target current reaching a maximum value of ≈ 4×10^{12} A/s.

The target holder used at the PALS laser facility was completed with an inductive probe shown in Fig. 1a. The transient target current $I_T(t)$ flowing through the copper cylinder generates a toroidal magnetic field $B_T(t)$ in a groove inside the probe. The voltage $U_T(t)$ at the output of a small inductive probe, which is a part of the target manipulatoris [7], is defined by Faraday's law $U_T = \frac{d}{dt}\int B_T\, dS$, where dS is the element of the loop surface. The magnetic field B_T around a cylinder can be expressed in the form $B_T = \mu_0 I_T / 2\pi r$, where r is the radius of the magnetic field line. Finally, the target current can be determined by integrating the voltage on the inductive probe as $I_T = -\frac{1}{M}\int U_T\, dt$, where the value of M was determined to be 0.6 nH. As Fig. 1b shows, the target current is positively polarized and last up to ≈ 70 ns. Time variations in the target charging are affected by plasma expansion [2] because the target is in direct contact with the laser-produced plasma for tens of nanoseconds, as interferometric observations have shown under similar conditions [8].

The first group of partial current peaks occurring at the beginning of the plasma expansion to ≈ 10 ns corresponds to the fastest electrons followed by plasma bursts composed of ~ 4 MeV and slower protons and co-moving electrons which hit nearest accessories. The other peak of I_T reaching a few hundreds of amperes occurs in time of the impact of the plasma bursts on the walls of the interaction chamber. Then the neutralization of the polarized target continues until the plasma disappears [2]. Both the limited dynamic range of the oscilloscope used and noise level of the target probe signal do not allow measuring the lower target current occurring at a later stage of plasma expansion.

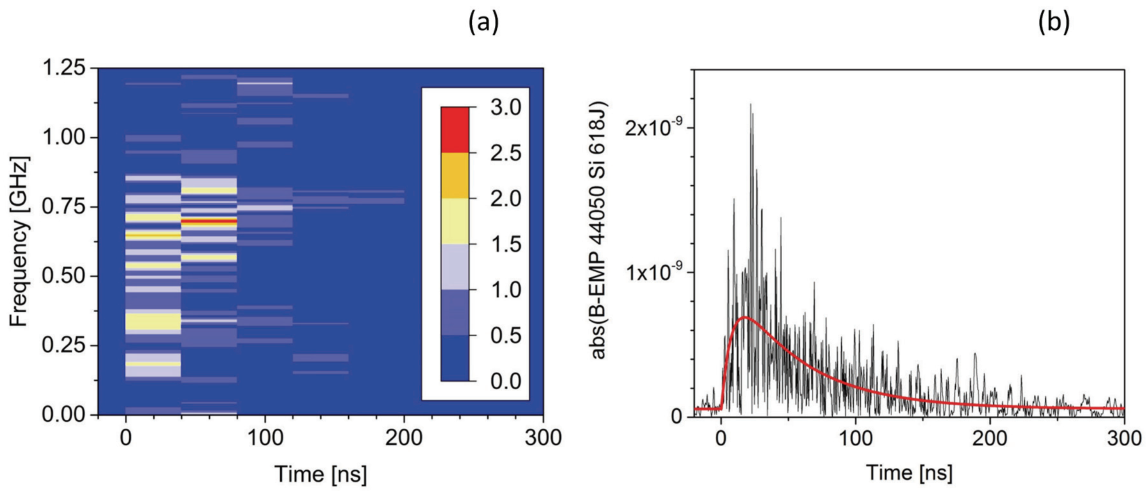

Fig. 2. (a) Time-frequency analysis of the $EMP_{Si}(t)$ signal of a loop antenna positioned in the laboratory room at a 1m-distance from the interaction chamber; (b) fit of double exponential pulse to absolute value of antenna signal integrated in time abs($B\text{-}EMP_{Si}(t)$). Si target was irradiated by intensity of 3×10^{16} W cm^{-2}.

The current flowing through the interaction chamber emits intense electromagnetic radiation, which passes through glass windows of the target chamber into the laboratory room [3-7, 9-11]. We observed the emitted EMP with the use of a Moebius antenna [12] near the main glass window at a distance of about 2 m from the interaction chamber. The voltage signal on the loop antenna induced by EMP is a non-stationary signal, the characteristics of which vary with time. Thus, a time-frequency analysis (short-time Fourier transform) was used, as Fig. 2a shows. There are several ranges of EMP frequency. The lower frequencies ranging from ≈100 to ≈400 MHz correspond to the resonant frequencies of the interaction chamber [4,10], which are influenced by the configuration and properties of accessories inserted into the interaction chamber. The resonant frequency of the PALS interaction chamber was calculated to be 262 MHz [10]. However, accessories inserted into the chamber alter the frequency spectrum. The other two ranges of high frequencies are well distinguishable: ≈ 500 to ≈ 800 MHz and ≈900 MHz to ≈ 1.2 GHz. They are partially affected by the design and impedance of the target-holder system, which acts as a dipole antenna [3]. The temporal analysis of EMP emitted by various targets also shows that the frequency spectrum exhibits a bimodal (eventually thrimodal) frequency distribution [9].

As a first approximation, the EMP envelope can be characterized by a double exponential pulse $B_D(t) = B_0(\exp(-t/\tau_1) - \exp(-t/\tau_2))$, where B_0 is the initial value of source function, τ_1 and τ_2, are the discharging and and charging time constants, respectively. The fitting $B_D(t)$ to the absolute value of a detected $|EMP(t)|$ allows us to estimate all the parameters, as Fig. 2b shows. This fit gives $\tau_{\mathrm{disch}} \approx 52$ ns and $\tau_{\mathrm{ch}} \approx 8$ ns. The value of 8 ns correlates with the duration of a peak dominating in the target current. The full width at half maximum of the $|EMP(t)|$ is $\tau_{\mathrm{FWHM}} \approx 67$ ns.

The duration of both the target current and EMP emitted by the interaction chamber is much longer than the duration of the laser-matter interaction and occur during the plasma expansion into the target chamber. The time constants characterizing the EMP envelope observed outside the interaction chamber correlate with the duration of both target current and plasma expansion.

Acknowledgments

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